ICIMOD Research Report 2018/1

FOR MOUNTAINS AND PEOPLE

The Status of Glacial Lakes in the Hindu Kush Himalaya

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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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The Status of Glacial Lakes in the Hindu Kush Himalaya

Authors

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Contents

About This Report

This report provides information on the glacial lakes of five major river basins — Amu Darya, Indus, Ganges, Brahmaputra, and Irrawaddy — of the Hindu Kush Himalaya. The database of glacial lakes is generated using a consistent semi-automated method allowing less human error and quick delivery, single-source Landsat satellite images of a narrow time period (2005±2 years), and high accuracy overlain on Google Earth. This database and information will be a great asset to researchers for further analysis and water resources management. The database of this report has been served through ICIMOD Regional Database System (RDS) (http://rds.icimod.org) and Mountain Geoportal (http://geoportal.icimod.org).

This glacial lake database and report was prepared under the Cryosphere Monitoring Project, funded by the Norwegian Ministry of Foreign Affairs and in close collaboration with the partnering institution Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), Chinese Academy of Sciences (CAS) in Lanzhou, China.

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Landsat satellite images and Shuttle Radar Topography Mission (SRTM) digital elevation model data were major sources of this research work, and we are deeply indebted to the data providers — NASA, United States Geological Survey (USGS), NASA's Jet Propulsion Laboratory (JPL), and Consultative Group on International Agricultural Research (CGIAR).

We are also thankful to our ICIMOD Regional Database System (RDS) team for their support in structuring the database, developing the web portal, and publishing the database online.

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

Acronyms and Abbreviations

CAREERI	Cold and Arid Regions Environmental and Engineering Research Institute
CAS	Chinese Academy of Sciences
CGIAR-CSI	Consultative Group on International Agricultural Research-Consortium for Spatial Information
DEM	digital elevation model
ENVI	Environment for Visualizing Images
ETM+	Enhanced Thematic Mapper Plus
GIS	geographic information system
GL	Glacial Lake
GLIMS	Global Land Ice Measurements from Space
GLOF	glacial lake outburst flood
GloVis	Global Visualization Viewer
HKH	Hindu Kush Himalaya
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Intergovernmental Panel on Climate Change
IRS	Indian Remote Sensing
JPL	Jet Propulson Laboratory
LIGG	Lanzhou Institute of Glaciology and Geocryology
LISS	Linear Imaging and Self-Scanning Sensor
NASA	National Aeronautics and Space Administration
NDWI	Normalized Difference Water Index
NEA	Nepal Electricity Authority
RDS	Regional Database System
RGI	Randolph Glacier Inventory
RS	remote sensing
SLC	Scanned line corrector
SRTM	Shuttle Radar Topography Mission
SPOT	Satellite Pour l'Observation de la Terre
TM	Thematic Mapper
USGS	United States Geological Survey
WECS	Water and Energy Commission Secretariat
WGS	World Geodetic System

Executive Summary

This report provides comprehensive information about the glacial lakes of five major river basins of the Hindu Kush Himalaya (HKH) — Amu Darya, Indus, Ganges, Brahmaputra, and Irrawaddy, including Mansarovar Interior Basin — representing the year 2005, which helps to fill the data gap of glacial lakes information in the region. This is the first comprehensive knowledge upon the distribution of glacial lakes for the HKH providing baseline data for further investigation of glacial lakes, GLOF hazards and risk assessment, and mitigation measures.

This inventory of glacial lakes was prepared with consistent, homogeneous, much narrower temporal range and single source data with a semi-automatic method. For the consistency of glacier and glacial lakes data, the same time satellite images were used to delineate both glaciers and glacial lakes. The glacier inventory data and report was published in 2011. The glacial lake boundaries were delineated using an automatic method on Landsat images from the year 2005±2 years. The automatic method to delineate the glacial lake boundaries by defining the threshold condition of band ratio images made the process of mapping and monitoring of glacial lakes faster. It is challenging to apply the method throughout the region as it is difficult to get good quality of images with the least amount of snow cover, cloud cover, and shadow portion due to inconsistent and analogous climatic conditions in the region. So some of the lakes were manually digitized by validating on high resolution images in Google Earth as well as comparing with previous inventory data wherever available. This report also provides the modified classification schemes of glacial lakes from previous reports to make it consistent throughout the region. This inventory includes all the lakes in front of and on or beside a glacier or in the lowland formed by paleo-glaciation.

A total of 25,614 glacial lakes covering an area of 1,444 km^2 were identified within the five major river basins — Amu Darya, Indus, Ganges, Brahmaputra, and Irrawaddy, including Mansarovar Interior Basin — in the HKH. This includes all the glacial lakes greater than or equal to 0.003 km^2. The largest lake mapped, which lies in Amu Darya River Basin, is 15.1 km^2 and classified as other type of glacial lake. Almost 79% of lakes mapped in the HKH are less than 0.05 km^2 in size. The glacial lakes in the HKH are distributed at elevations from 2,200 masl to 6,200 masl. The majority of glacial lakes are located in elevation zones of 4,000–5,000 m followed by 5,000–6,000 m.

The number and area of the glacial lakes are much greater in the eastern part of the HKH, with much more concentration towards the east of central Nepal. Overall the number and area coverages of glacial lakes are greater within 5 km of the glaciers and most of the glacial lakes within 2 km of the glacier are directly fed by glacier melt, whereas the lakes farther away from the glaciers are non-glacier fed.

Introduction

The Hindu Kush Himalaya (HKH) contains the world's greatest areal extent and volume of permanent ice and permafrost outside the polar regions. Mapping based on 2005±3 years Landsat images provided 60,054 km^2 total area of glacier coverages with estimated ice reserves of 6,127 km^3 in the HKH (Bajracharya et al. 2014a and 2014b; Bajracharya and Shrestha 2011) and 40,800 km^2 for the Himalaya and Karakoram (Bolch et al. 2012). The Intergovernmental Panel on Climate Change (IPCC 2007) states that climate change is an ongoing and accelerating process as shown by a well-known rise of global temperature since the early 20th century and most notably since the late 1970s. Consequently, glaciers, snow, and permafrost as well as most other components of the cryosphere have undergone significant changes during recent decades, related to climatic forcing. Glaciers continue to shrink in the HKH, as in other parts of the world, although regional variations are known to occur (Bajracharya et al. 2007; Ives et al. 2010; Bolch et al. 2012). With the onset of atmospheric warming around 1850–1905, generally considered the end of the Little Ice Age, glaciers in the HKH are mostly retreating, as in many parts of the world (Ives et al. 2010; Bolch et al. 2012). However, some studies also show that in some areas, such as Karakorum (northern Pakistan), glaciers are advancing (Hewitt 1982, 1998) or at least were on average in balance since the 1970s in the Hunza River Basin (central Karakoram) (Bolch et al. 2017). Therefore, differences in glacier status exist from region to region in the HKH (Yao et al. 2012). However, most of the studies show that the greatest decrease in the length and area and the most negative mass balance have occurred in the Himalaya and Tibetan Plateau (Bolch et al. 2011; Bolch et al. 2012; Yao et al. 2012; Bajracharya et al. 2014a; Bajracharya et al. 2014b; Xiang et al. 2014).

One of the impacts of glacier recession or retreat is the formation of new glacial lakes by the accumulation of meltwater resulting from the glacier retreat between the frontal moraine and the retreating glacier or the expansion and merging of the existing ones. Sudden release of water held by more or less unstable moraine complexes due to its breaching or slope failure results in the phenomenon known as glacial lake outburst flood (GLOF). Expanding or new lakes as a result of icemelt at the margin of many shrinking glaciers in the Alps, Himalaya, Andes, and other mountain regions have increased the risk of glacial lake outburst floods (GLOFs) (WECS 1987; Richardson and Reynolds 2000; Ives et al. 2010). Consequently, this has required substantial risk reduction measures in the 21st century (Huggel et al. 2002; McKillop and Clague 2006; Cruz et al. 2007; Rosenzweig et al. 2007; Carey et al. 2012).

The HKH is also characterized by the widespread presence of such glacial lakes and many of them are potential sources of flood (Richardson and Reynolds 2000; Mool et al. 2001a and 2001b; Mool and Bajracharya 2003; Bolch et al. 2012). Study in the eastern Himalaya (Bhutan and Nepal) shows a substantial increase in glacial lake area between 1990 and 2009 and climate change has played a major role in it (Gardelle et al. 2011). Similarly, glacier wastage has caused the rising of lake levels and flooding of pastures in Tibet (Yao et al. 2007). Glacial lakes are thus also a natural hazard in the HKH mountains and damage people's lives and property in the mountains as well as in downstream areas (Bolch et al. 2012; Khanal et al. 2015).

The HKH has experienced numerous GLOF events, some of them with transboundary impacts (Xu et al. 1989; Yamada and Sharma 1993; Reynolds 1998; Ives et al. 2010). More than 50 glacial lake outburst events have been recorded in the HKH but records are available only for a part of China, Nepal, Pakistan, and Bhutan. There may be many more which were not documented or went unrecorded (Ives et al. 2010). An increase of GLOF events over the period 1940–2000 has been reported in the Himalaya although the trend has been considered statistically insignificant (Richardson and Reynolds 2000).

Although GLOFs are not a recent phenomenon in the HKH, they started drawing considerable attention among scientists only after the 1980s as the loss of life, property, and livelihood support systems, as well as the risk from potential GLOFs, has increased (Vuichard and Zimmermann 1986, 1987; Xu 1988; Chen et al. 2013). In addition to direct damages, indirect damages — business closures or revenue losses incurred from a breakdown in supplies, or costs incurred in ensuring people's health and wellbeing, and traffic stoppages due to damaged trails, roads, and bridges — are also commonly associated with GLOFs (ICIMOD 2011; Khanal et al. 2015).

It is therefore imperative to generate knowledge on widely distributed glacial lakes in the remote mountain areas of the HKH with very difficult and challenging accessibility. It is in this context that a comprehensive mapping using remote sensing (RS) and geographic information system (GIS) was carried out to provide the current status of glacial lakes of the HKH and ultimately to promote knowledge and understanding about glacial lakes distribution and estimate a qualitative or relative probability of GLOF.

This report provides information about spatial distribution of glacial lakes in the HKH which helps to fill the data gap on glacial lakes. This forms the first comprehensive knowledge on the distribution of glacial lakes for the whole of the HKH providing baseline data for further investigation of glacial lakes, GLOF hazards and risk assessment, and mitigation measures.

Previous Studies

In the HKH, the large-scale field investigation of glaciers and GLOFs started in the 1980s. The Water and Energy Commission Secretariat (WECS), Nepal, prepared the first inventory of glacial lakes of the Koshi Basin in Nepal based on intensive study of 1:63,360 topographic maps from the 1980s, aerial photographs from 1974, and field investigations of selected glacial lakes from 1987 (WECS 1987). In addition, an inventory of glaciers and glacial lakes including a study of the nature and causes of the GLOF phenomenon in the Pumqu (Arun) and Poiqu (Bhote Koshi/Sun Koshi) was carried out in collaboration between Nepal and China (LIGG/WECS/NEA 1988).

During 1999–2005, ICIMOD prepared an inventory of glaciers and glacial lakes of five HKH countries covering Bhutan, Nepal, all 10 sub-basins of the Indus River in Pakistan, all sub-basins of the Ganges River in Tibet Autonomous Region of China, and the Tista River Basin in Himachal Pradesh and Uttaranchal Himalaya, India. The inventory used analyses of 1:63,360 topographic maps published between 1960 and 1982 for Nepal and 1:50,000 scale topographic survey maps published between the 1950s and the 1970s by survey of India, together with Land Observation Satellite (Landsat) Thematic Mapper (TM) images, Indian remote sensing (IRS), 1D Linear Imaging and Self-scanning Sensor (LISS3), and some selected Système Probatoire d'Observation de la Terre/ Satellite Pour l'Observation de la Terre (SPOT) satellite images on a comparable to topographic maps. The inventory included a total of 8,790 glacial lakes, of which 203 were identified as potentially dangerous (Mool et al. 2001a; Mool et al. 2001b; Mool et al. 2003; Bhagat et al. 2004; Roohi et al. 2005; Sah et al. 2005; Wu et al. 2005; Ives et al. 2010). The main criteria used for defining potentially dangerous or critical lakes were lake size and rapid growth in area, increase in lake water level, activity of supra-glacial lakes at different times, position of the lakes in relation to moraines and the associated glacier, dam condition, glacier condition, and physical condition of surroundings (Ives et al. 2010).

ICIMOD also conducted a mapping of glacial lakes and an assessment of GLOF hazard and risk for Nepal in 2009–10. The study mapped 1,466 glacial lakes covering an area of 64.75 km^2 using Landsat images taken in 2005 and 2006. Among them, 21 lakes were identified as critical (potentially dangerous) with six lakes defined as high priority requiring extensive field investigation and mapping (ICIMOD 2011).

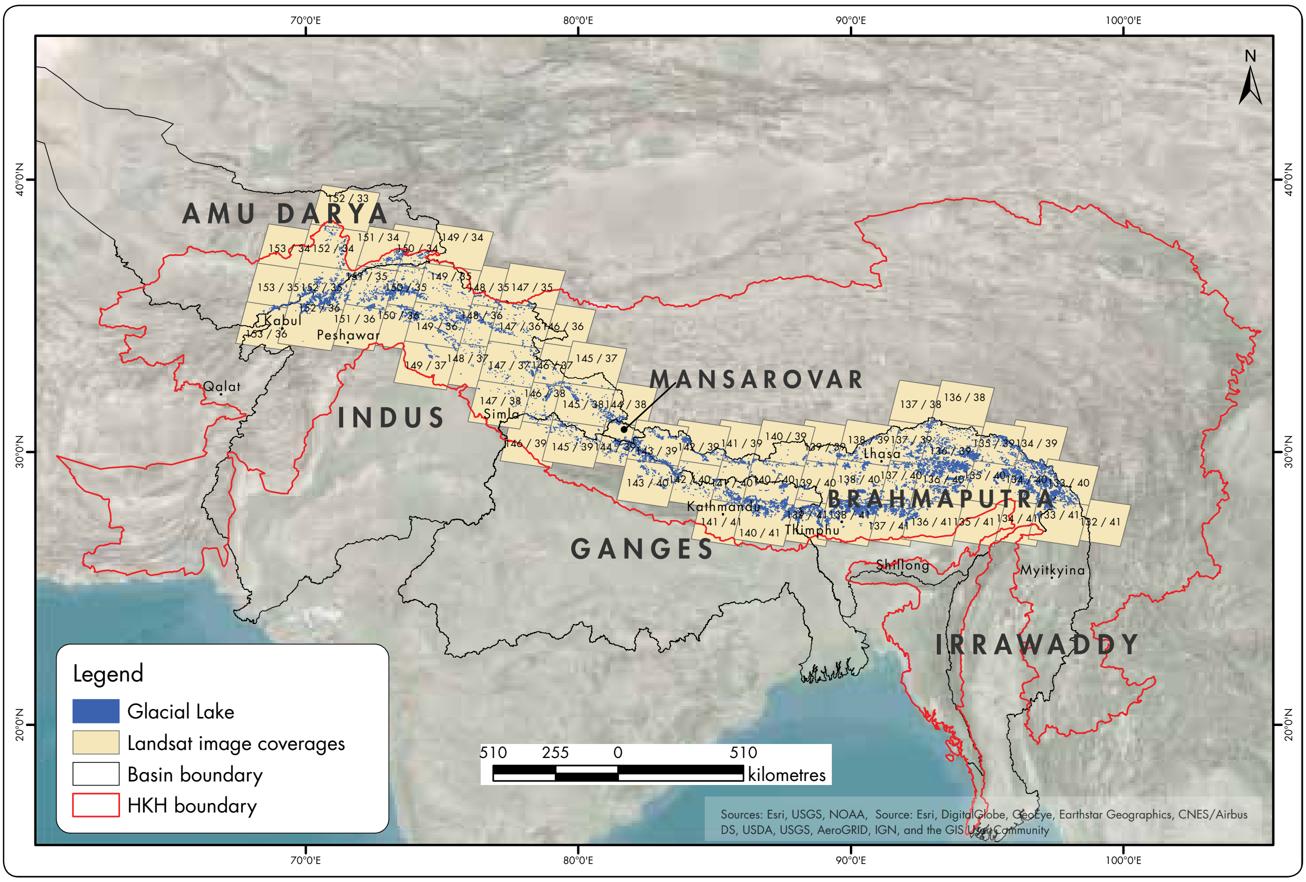
Mapping and assessment of glacial lakes using different methods had also been carried out in a few select areas of the HKH (Gardelle et al. 2011), in Indian Himalaya (Worni et al. 2012), and in Tibet, China (Wang et al. 2011; Wang et al. 2012; Nie et al. 2013; Che et al. 2014). Zhang et al. (2015) mapped the glacial lakes in the Third Pole region covering the Pamir-Hindu Kush Himalaya and the Tibetan Plateau. It used the manual digitization method using Landsat images and mapped the lakes within the buffer zone of 10 km of the glacier's boundary available in the Randolph Glacier Inventory (RGI v3.2). The number of lakes mapped — Amu Darya, 594, Indus, 1,607, Ganges, 364, and Brahmaputra, 2,247, based on Landsat image 2010 — were much fewer compared to other published papers (Bambari et al. 2015 mapped 1,266 glacial lakes in Uttarakhand, India; ICIMOD 2011 mapped 1,466 glacial lakes in Nepal).

ICIMOD's broad inventory in 1999–2005 did not cover Afghanistan, the Himalayan areas of Arunachal Pradesh and Jammu and Kashmir in India, or Myanmar (Ives et al. 2010). Ives et al. (2010) stated that "given the enormous extent and unusually challenging accessibility of the HKH region, application of remote sensing (and continued refinement of methodology) is a fundamental requirement for any assessment of the potentially large scale and widespread hazard posed by the rapid formation of new glacial lakes and the continued enlargement of existing ones". Also, glacial lake inventories conducted in the past covered a wide time range probably due to limited data sources available at the time. This has caused difficulty in glacial lakes change analyses and estimating relative probability of GLOF hazard and risk. A comparative assessment requires that the source and source date of the data be as narrow as possible so that it could represent the specific date of the data throughout the region. It has necessitated the mapping be carried out in a narrower time base and the invariable source of data be used.

Study Area

The HKH encompasses a mountainous area of more than 4,192,000 km^2 in eight countries: Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan (Bajracharya and Shrestha 2011). The present study area extends from 67° 33′ 54.4″ to 98° 44′ 27.2″ E longitude and 25° 23′ 39.7″ to 38° 31′ 57.8″ N latitude and lies within five river basins — Amu Darya, Indus, Ganges, Brahmaputra (Yarlung Tsangpo), and Irrawaddy, and the Mansarovar Interior Basin — of the HKH (Figure 1.1). For Amu Darya Basin, only part of Afghanistan falls in the present study area as based on the HKH boundary.

Figure 1.1: **Study area in the Hindu Kush Himalaya showing major river basins as well as Landsat TM/ETM+ images used as data sources**



Approach and Methodology

Water bodies in front of and on or beside a glacier or in the lowland formed by paleo-glaciation are the object of glacial lake inventory. As such this inventory includes all the water bodies formed (mainly) by glacier melt and located on the glacier surface, in immediate proximity or downstream of a glacier, or on the paleo-glaciation landforms. This study excludes englacial and subglacial lakes that may also exist in the study area but cannot be mapped from aerial/optical satellite images. The detection of such lakes is instrumental as it requires use of echo sounding to acquire the information about the ice-sheet base for the identification of basal water bodies (Siegert 2000) or other ground-based measurements such as ground-penetrating radar or seismic studies, and even with these it is difficult to map these lakes.

Classification of Glacial Lakes

Various authors have proposed glacial lakes classification schemes (Hewitt 1982; Liu and Sharma 1988; Clague and Evans 2000; Mool et al. 2001a and b). Mostly the glacial lake was classified based on dam type and process of lake formation. Similarly, ICIMOD (2011) developed a comprehensive classification scheme for an inventory of glacial lakes in Nepal based on dam type and process of lake formation. In this inventory, we have adopted the classification scheme used in the ICIMOD report and modified it to fit the entire region. The two-level classification is based on lake dam type and lake forms. The first level, based on dam type, broadly classifies the lakes into four types: 1) moraine-dammed lake, 2) ice-dammed lake, 3) bedrock-dammed lake, and 4) other dammed lake (Figure 2.1). The second level, based on lake form, classifies the lakes into seven subtypes. The symbol used for this classification is a capital letter (the first letter of the dam type) and a lowercase letter inside brackets (the first letter of the subtype), for example, M(e) for end-moraine-dammed lake. They are briefly described in Table 2.1.

Figure 2.1: **Illustration of different types of glacial lakes**

(e) = end-moraine-dammed lake, M(l) = lateral moraine-dammed lake, M(o) = other moraine-dammed lake, I(s) = supra-glacial lake, I(v) = ice-dammed lake dammed by tributary valley glacier, B(c) = cirque lake, B(o) = other bedrock-dammed lake, and O = other glacial lake

Table 2.1: **Classification of glacial lakes of the Hindu Kush Himalaya (modified after ICIMOD 2011)**

SN	Glacial lake type	Code	Definition
1	**Moraine-dammed lake**	**M**	**Lake dammed by moraine following glacial retreat.**
1.1	End-moraine-dammed lake	M(e)	Lake dammed by end (terminal) moraines. Usually touches the walls of the side moraines, but the water is held back by the end moraine (dam), lake usually, but not necessarily, in contact with the glacier, and may have glacier ice at the lake bottom.
1.2	Lateral moraine-dammed lake	M(l)	Lake dammed by lateral moraine(s) (in the tributary valley, trunk valley, or between the lateral moraine and the valley wall, or at the junction of two moraines). Lake is held back by the outside wall of a lateral moraine, i.e., away from the former glacial path.
1.3	Other moraine-dammed lake	M(o)	Lake dammed by other moraines (includes kettle lakes and thermokarst lakes).
2	**Ice-dammed lake**	**I**	**Lakes dammed by glacier ice, including lakes on the surface of a glacier or lake dammed by glaciers in the tributary/trunk valley, or between the glacier margin and valley wall, or at the junction of two glaciers.**
2.1	Supra-glacial lake	I(s)	Bodies of water (pond or lake) on the surface of a glacier. This is the most common type of ice-dammed lake in the Nepal Himalaya
2.2	Dammed by tributary valley glacier	I(v)	Lake dammed by glacier ice with no lateral moraines. Can be at the side of a glacier between the glacier margin and valley wall.
3	**Bedrock-dammed lake**	**B**	**Bodies of water that form as a result of an earlier glacial erosion process which accumulate in depressions after the glacier has retreated or melted away.**
3.1	Cirque lake	B(c)	A small pond occupying a cirque.
3.2	Other glacier erosion lake	B(o)	Bodies of water occupying depressions formed by the glacial erosion process. These are usually located on the mid-slope of hills, but not necessarily in a cirque.
4	**Other glacial lakes**	**O**	**Lakes formed in a glaciated valley and fed by glacial, snow, and permafrost melt, but damming material not directly part of the glacial process, e.g., debris flow, alluvial, or landslide blocked lakes.**

Data Sources

Landsat

Landsat data have been used widely to map glaciers and glacial lakes globally due to their high spatial resolution and accessibility (Bolch et al. 2010; Mergili et al. 2013; Xu et al. 2013; Zhang et al. 2015). In this study, due to the consistent coverages of Landsat data in the region, high spatial resolution, and free access through the GloVis web portal (http://glovis.usgs.gov), we have used the Landsat Level 1 Terrain corrected images of Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) to prepare the current glacial lake inventory of the region. Also, the use of satellite images of a much narrower time resolution (2004 to 2007) has been emphasised. The same time period of images has been selected for this inventory as in the glacier inventory published in 2011 (Bajracharya and Shrestha 2011), to make a consistent database of glaciers and glacial lakes.

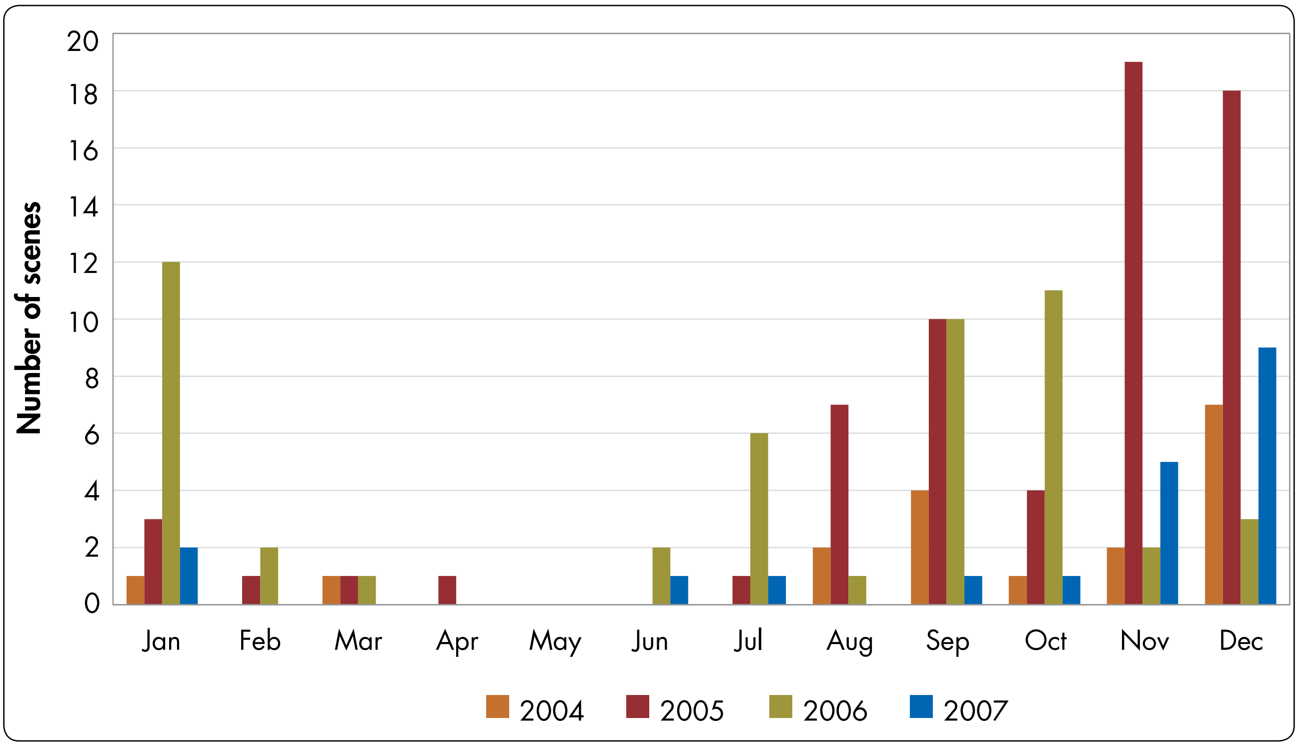
Landsat images acquired covering the region between 2004 and 2007 were used for mapping glacial lakes. However, the images from 2000 to 2003 and 2008 to 2010 were also referred to for verification of lakes. This has been useful for mapping lakes particularly in areas where there was cloud and snow cover in the used images between 2004 and 2007. Landsat scenes mostly from September to December were used because the chances of minimum snow or cloud cover during this period. The number of images of different months used for each year is shown in Figure 2.2.

Mostly the Landsat TM data was used for mapping the glacial lakes as the Landsat ETM+ data has scanned line corrector (SLC) failure from June 2003 onwards. This SLC failure in the images causes the scanning pattern to exhibit wedge-shaped scan-to-scan gaps which were filled using the IDL extension in ENVI image analysis software (Bajracharya and Shrestha 2011).

SRTM DEM

Topographic information also plays a vital role in identifying and categorising the various types of glacial lakes. This information can be derived from global digital elevation models (DEM) such as Shuttle Radar Topography Mission (SRTM) and Aster GDEM. This study used SRTM DEM for analysis and classification of glacial lakes. SRTM, a specially modified radar system flown on board the Space Shuttle Endeavour on an 11-day mission in February

Figure 2.2: **Number of Landsat TM/ETM+ images used by month and year**



2000 by NASA, obtained near-global scale elevation data. It represents the most complete high-resolution digital topographic database of Earth. In 2003, SRTM 90 m (3 arc seconds, which is 1/1,200th of a degree of latitude and longitude) resolution covering whole globe was released. The new SRTM DEM of 30 m (or 1 arc second) resolution was released in September 2014, covering the full resolution of the world's landforms (NASA JPL 2014). The new SRTM 30 m resolution data has larger voids in the higher elevation area of this region, so we have used the void-filled SRTM 90 m resolution DEM. The void-filled SRTM 90 m DEM for the entire world has been built in a mosaic of seamless near-global coverage (up to 60 degrees north and south) and can be downloaded as 5 x 5 degree tiles in the geographic coordinate system of the World Geodetic System – WGS84 Datum from the Consultative Group on International Agricultural Research-Consortium for Spatial Information (CGIAR-CSI) GeoPortal (http://srtm.csi.cgiar.org/Index.asp). The total number of tiles of SRTM DEM covering the five upper reaches of five major river basins is given in Figure 2.3. The SRTM DEM was also used to derive crucial parameters of glacial lakes such as altitude.

Mapping Method

A number of remote sensing methods had been developed for glacial lake detection and mapping or development of inventory (Kääb 2000; Mool et al. 2001a; Huggel et al. 2002; Huggel et al. 2006; Ives et al. 2010). The Normalized Difference Water Index (NDWI; Eq.(1)), which provides an automatic way to detect water bodies including glacial lakes on the basis of Landsat TM or ETM+ images, was adopted in the present study (Huggel et al. 2002) and the whole process is summarized in Figure 2.4. The NDWI is a ratio combining two different bands (Eq. 1) that enhance water spectral signals by contrasting the reflectance between different wavelengths and removing a large portion of noise components in different wavelengths (Ji et al. 2009). For the Landsat images of TM and ETM+, NDWI was calculated using the near infrared band (Band 4) and Blue band (Band 1) as used in Huggel et al. (2002).

$$\text{NDWI} = \frac{\text{NIR (or Band 4)} - \text{Blue (or Band 1)}}{\text{NIR (or Band 4)} + \text{Blue (or Band 1)}} \qquad (1)$$

First, the ratio images of NDWI were created by arithmetic calculation of Band 4 and Band 1 of the Landsat images and the NDWI threshold value was applied to map the water bodies (glacial lakes) in the ratio images. The NDWI threshold value of -0.6 to -0.9 adopted by Huggel et al. (2002) has been used in preparing the inventory of the HKH glacial lakes. Although this automatic mapping method can speed up the detection of glacial lakes easily, this method could not be applied to the whole HKH due to some atmospheric and physical processes of Earth.

Figure 2.3: **SRTM index map of the study area**

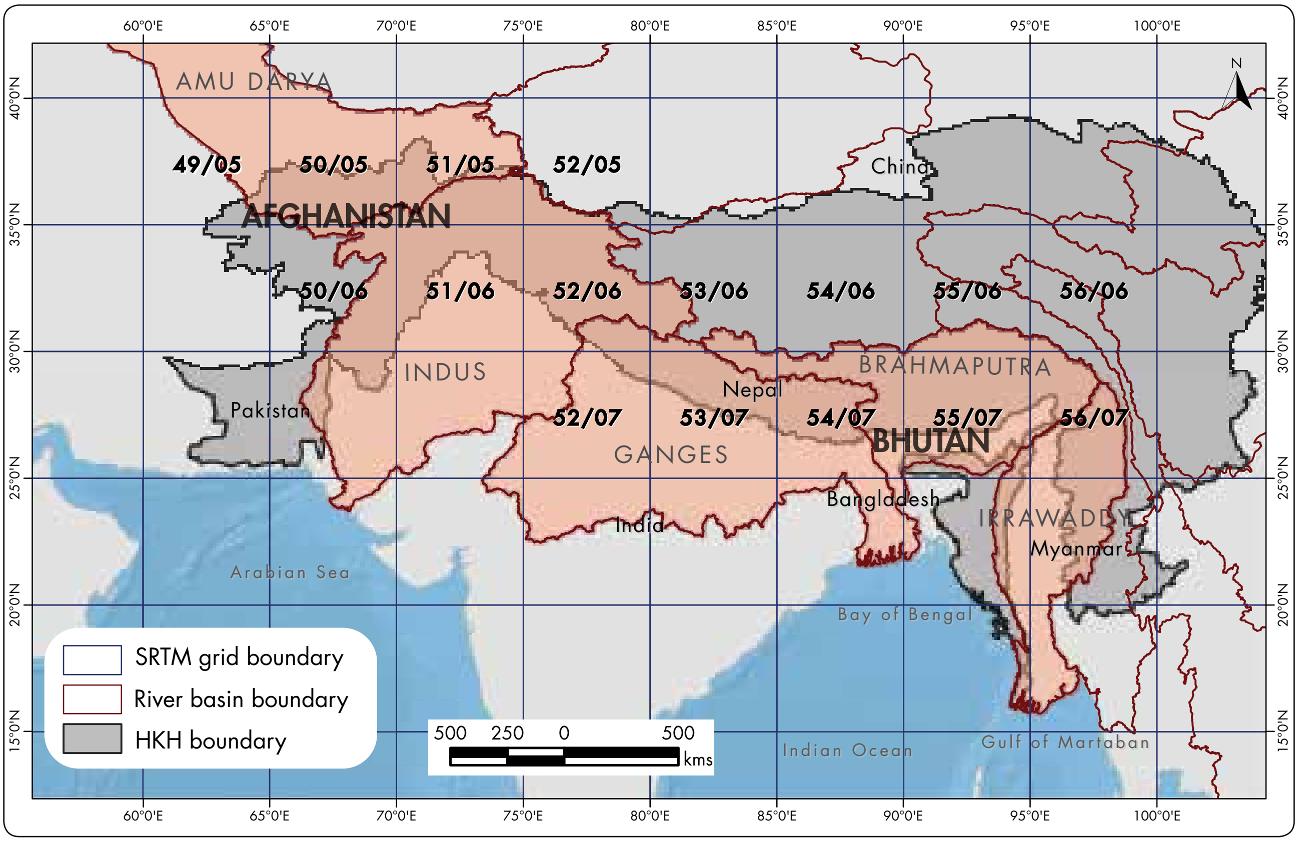
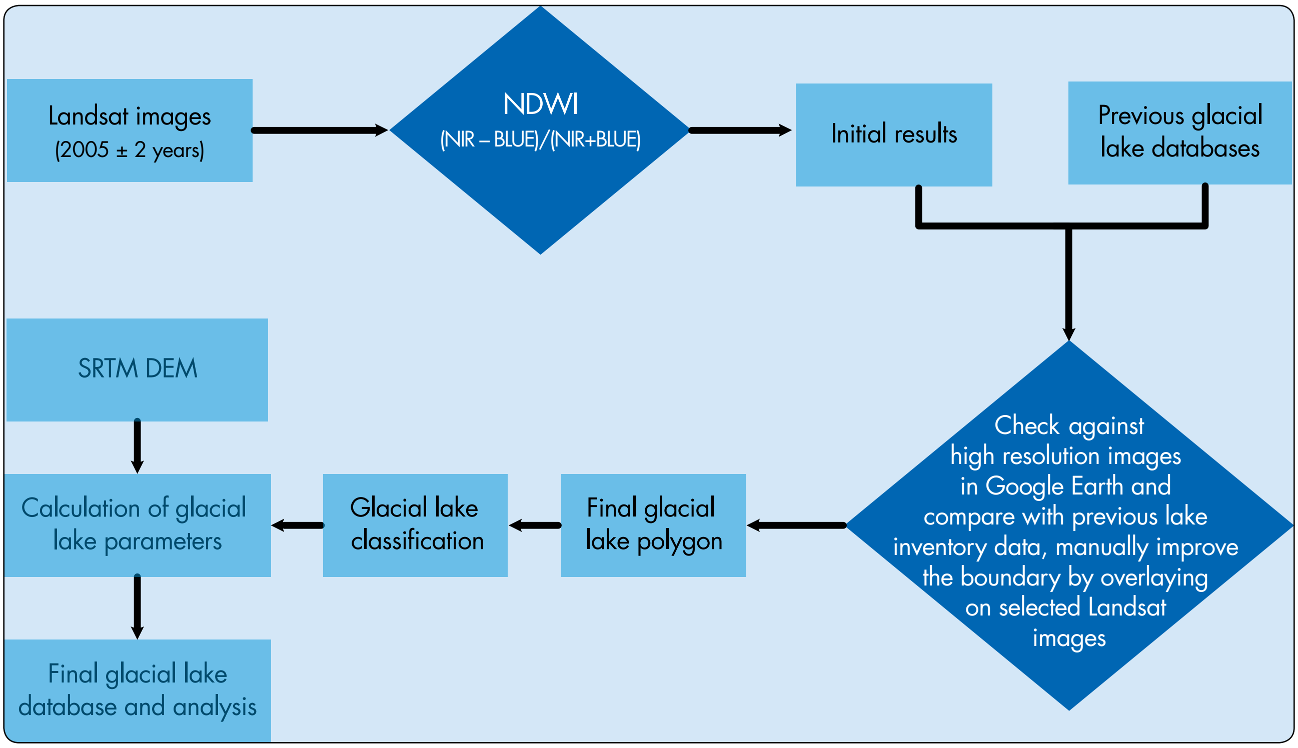


Figure 2.4: **The process adopted in the current glacial lake inventory**



For example, if lakes are frozen or covered with snow or cloud and lie in a shadow area, they cannot be detected using this automatic method. In such cases, the manual tracing method has been applied to map the lakes.

The mapped glacial lakes were rechecked by overlying the Landsat images over the previous inventory datasets wherever they are available (Mool et al. 2001a; Mool et al. 2001b; Mool et al. 2003; Bhagat et al. 2004; Roohi et al. 2005; Sah et al. 2005; Wu et al. 2005). Thus, the mis-mapped lakes were corrected and missing lakes were added manually. Further the mapped lakes were overlaid with high resolution images in Google Earth environment for validation.

Generally, pixels in the images do not give the homogenous reflectance and represent only one object in a ground unless the imaging is perfectly aligned in a single object. So, at least 4 pixels are required to represent the exact boundary of the object (lake) to map from the images. Therefore, the smallest glacial lake that can be mapped from the images should be covered by 4 pixels, which is 0.0036 km^2 in the case of Landsat images. The glacial lake boundary mapped from 4 pixels is smoothen and the boundary lies some level inside the 4 pixels, so we have consider the lower round up values as 0.003 km^2. Hence the glacial lake area of 0.003 km^2 is the threshold for the lake size that has been applied for mapping in the present glacial lake inventory.

The classification of the glacial lakes was done by visual interpretation by draping the final glacial lake polygon on high resolution images with 3D terrain view mode in Google Earth and separately overlapping on the Landsat images used for mapping. First the terrain characteristics, position of lakes, and its surrounding were visually analysed one by one in the Google Earth images. Then the similar features in the Landsat images were also visually identified and the lake polygons lies in these terrain features were assigned class names as defined in the classification scheme (Table 2.1).

Glacial Lake Attributes

Once the final glacial lake polygons were generated, the attributes of the glacial lake were generated in ArcGIS. The unique ID of the lake polygon is given with the combination of longitude and latitude of the centroid of the lake polygon in the same way a GLIMS ID is used for glaciers. GLIMS ID is a unique and unambiguous ID for glaciers developed by Global Land Ice Measurements from Space (GLIMS) using the combination of longitude and latitude of the glacier's centroid points (Raup and Khalsa 2010). In this study, the initial letter "G" in GLIMS ID is replaced by "GL" for 'glacial lake'. The other parameters of the lake such as area and elevation were calculated automatically in the ArcGIS platform using SRTM DEM data. The morphological classification of glacial lake was done by visual interpretation of the lake polygon overlaying onto high resolution images with terrain in Google Earth environment. The Albers equal area conic projection was used to calculate the area of glacial lake; the unit of the area adopted was square kilometre (km^2). The detail list of attributes of glacial lakes is given in Table 2.2.

Table 2.2: **Fields and formats of glacial lake attributes**

Field name	Type	Format	Description
Major basin name	string	text	Drainage basin name based on maps and literature reviews
Basin name	string	text	Drainage basin name based on maps and literature reviews
Sub-basin name	string	text	Drainage basin name based on maps and literature reviews
Longitude	string	DMS	Longitude of centre of glacial lake
Latitude	string	DMS	Latitude of centre of glacial lake
GLIMS_ID	string	GLXXXXXXEYYYYYN	Combination of longitude (X) and latitude (Y) of the centroid of the lake polygon. GL = glacial lake, E = East, N = North.
Altitude	integer	metre above mean sea level (masl)	Water level of glacial lake. Extracted from SRTM
Area	float	km^2	Area of glacial lake. Calculated based on the Albers equal area conic projection
Gl_Type	string	-	Type of glacial lake
Image_ID	string		Image ID same as downloaded images (includes row, path, and data of images acquisition)
Date	date	YYYYMMDD	Date of the image used for mapping GL

Accuracy

The accuracy of glacial lakes mapped from satellite images depends, typically, on the resolution of the images used, seasonal/temporal snow cover, shadow, and contrast between the glacial lakes pixels and surroundings pixels (DeBeer and Sharp 2007; Bajracharya et al. 2014c). Landsat images with the least snow cover and cloud cover were selected for mapping to increase the quality of the automatic mapping approach and reduce manual correction of the boundary. The lake data was overlaid on the high resolution images in Google Earth and also cross-checked with the previous inventory data wherever it is available in order to validate and improve the mis-mapped lakes from the automatic approach. Also the glacial lake data were thoroughly checked by overlaying on the same Landsat images used for automatic mapping along with cross-checking in the high resolution images in Google Earth and any mismatches of the boundary of the lakes due to the seasonal/temporal snow cover and shadows were manually corrected using additional Landsat images. Although this cross-checking improved the quality of the data, the mapped lakes boundary were affected by various other types of obscurities, which are mostly dependent on image resolution. The uncertainty of the glacial lake boundary could not be greater than half of the image resolution (i.e., ±15 m in TM and ETM+) (Bajracharya et al. 2014c). Hence the uncertainty of the glacial lake boundary was estimated by variation of area bounded by the lake polygon, which is calculated by number of image pixels bounded by each lake polygon and the total number of image pixels bounded by the 15 m buffer of each lake polygon. The equation used for calculating total uncertainty is given as:

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

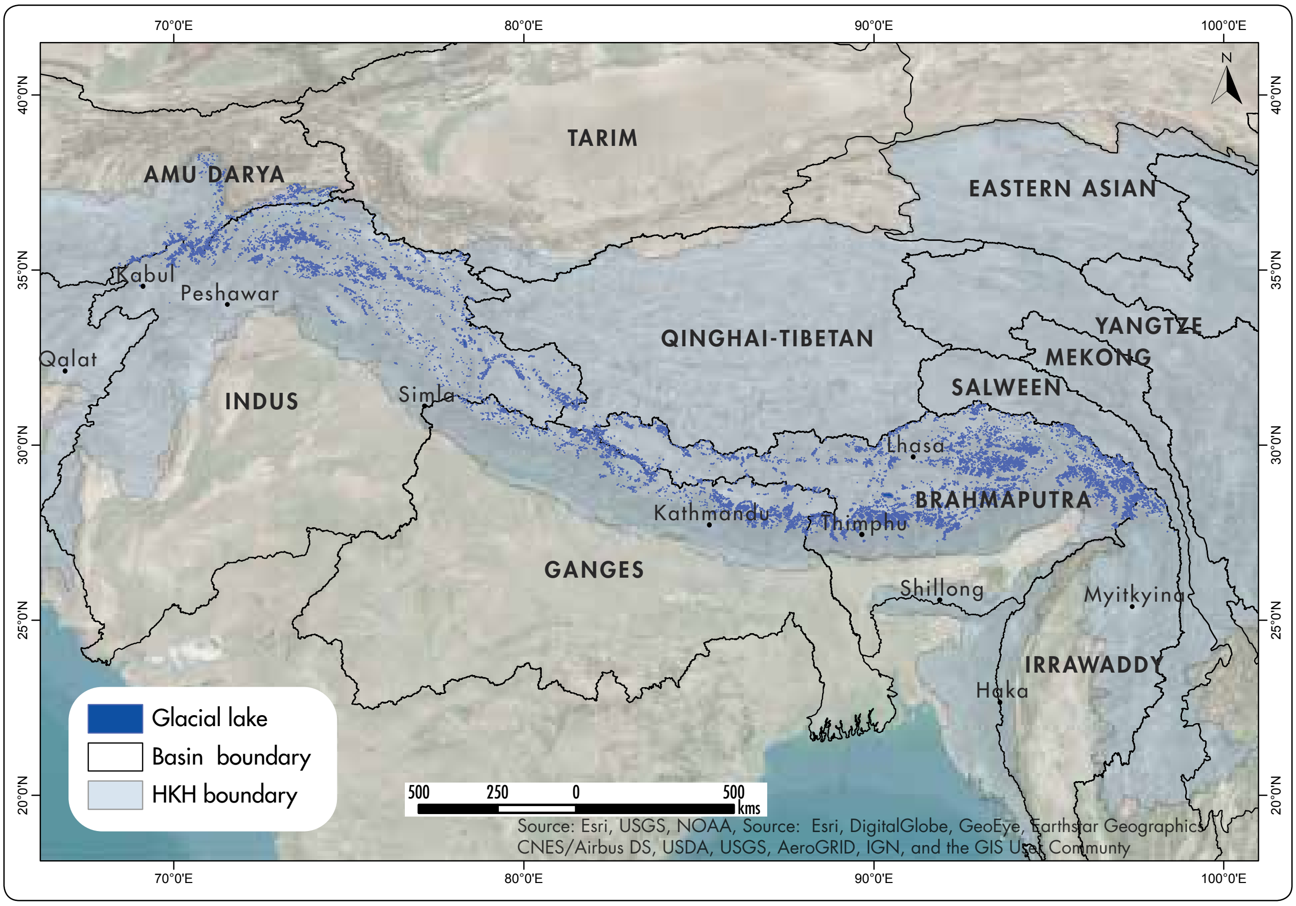
where a_i is the area of glacial lake from the total pixel bounded by glacial lake polygon and $\hat{a}_i$ is the area of glacial lake from the total pixel bounded by the 15 m buffer of glacial lake boundary.

The total uncertainty of glacial lake area ranges from ±1% to ±3% in the major basins of the HKH and the total uncertainty is ±2%. These ranges of uncertainty were also observed in the glacier mapping (Bajracharya et al. 2014c).

Status of Glacial Lakes in the Hindu Kush Himalaya

A total of 25,614 glacial lakes greater than or equal to 0.003 km^2 were mapped with a total area of 1,444 km^2 in five major river basins including Mansarovar Interior Basin within the HKH from the Landsat images (Figure 3.1). This inventory includes all lakes in front of and on or beside a glacier or in the landforms created by paleo-glaciation. The number, area, and distribution of various types of glacial lakes are summarized in Table 3.1.

Figure 3.1: **Distribution of glacial lakes in the HKH**



Number, Area, and Types

Amongst the 25,614 glacial lakes identified in five major river basins, Brahmaputra Basin has the highest number of glacial lakes followed by Indus, Ganges, Amu Darya, and Irrawaddy Basins (Table 3.1 and Figure 3.2). Lakes in the Mansarovar Interior Basin comprise less than one percent of the total glacial lakes in the HKH.

The total area covered by these glacial lakes is 1,444 km^2 (Table 3.1). Of the total area, 61.1% is in Brahmaputra Basin followed by 18% in Indus, 14.5% in Ganges, 4.6% in Amu Darya, 1.1% in Irrawaddy, and 0.6% in Mansarovar.

Figure 3.2: **Number and area of glacial lakes in major river basins of the HKH**

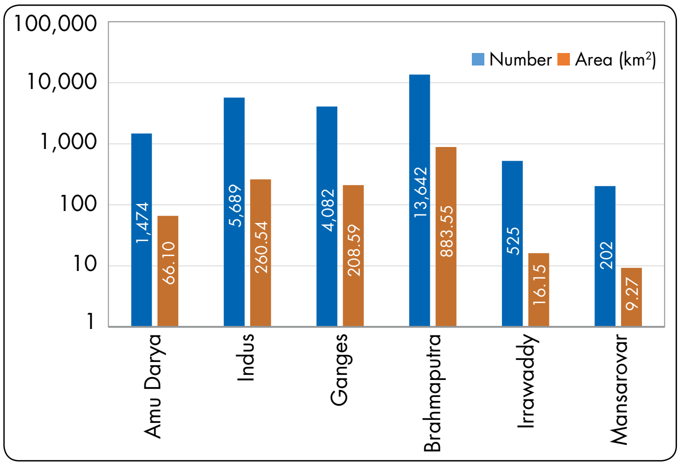


Table 3.1: **Number, area (in km²), and types of glacial lakes in five major river basins of HKH**

Major basin			Amu Darya		Indus		Ganges		Brahmaputra		Irrawaddy		Mansarovar		Total	
Type			Number	Area (km²)	Number	Area (km²)	Number	Area (km²)	Number	Area (km²)	Number	Area (km²)	Number	Area (km²)	Number	Area (km²)
Moraine-dammed lake (M)	End-moraine	M(e)	193	13.22	587	25.02	587	103.28	1,241	170.93	9	0.34	17	1.68	2,636	314.47
	Lateral moraine	M(l)	29	2.35	121	4.28	97	11.15	43	4.07	0	0	0	0	290	21.85
	Other moraine-dammed lake	M(o)	638	10.82	1,215	39.07	1,482	31.00	1,973	51.48	2	0.06	67	1.63	5,378	134.06
Ice-dammed lake (I)	Supra-glacial lake	I(s)	57	0.35	461	4.75	539	5.58	196	2.07	0	0	0	0	1,253	12.75
	Glacier ice-dammed lake	I(v)	1	0.03	13	0.56	7	0.10	5	0.10	0	0	1	0.01	27	0.80
Bedrock-dammed lake (B)	Cirque	B(c)	56	3.60	378	40.83	299	14.70	1,976	173.48	123	6.48	10	0.23	2,842	239.32
	Other bedrock-dammed lake	B(o)	430	12.45	2,611	107.86	1,045	34.35	7,809	351.52	385	9.16	107	5.72	12,392	521.06
Others		O	70	23.28	303	38.17	26	8.43	399	129.90	6	0.11	0	0	811	199.89
Total			1,474	66.10	5,689	260.54	4,082	208.59	13,642	883.55	525	16.15	202	9.27	25,614	1,444.20

The majority of glacial lakes are bedrock-dammed (59.45%). Moraine-dammed lakes comprise about 32.4% followed by ice-dammed lakes (almost 5%). Only 3.2% of the total glacial lakes in the HKH are categorised as other types, which includes those dammed by debris flow, alluvial, or landslide blocked lakes. Among moraine-dammed lakes, end-moraine-dammed lakes comprise about 10.3% of all the glacial lakes in the HKH. Similarly, nearly 1.1% of glacial lakes are lateral moraine- dammed whereas more than 21% are other moraine- dammed. Similarly, among ice-dammed lakes, supra-glacial lakes comprise 4.9% of the total glacial lakes while glacier ice-dammed lakes comprise only 0.1%. Cirque type bedrock-dammed glacial lakes comprise more than 11% of all the glacial lakes in the HKH whereas other bedrock-dammed glacial lakes comprise about 48.4%. The percentage distribution of various types of lakes within each basin is shown in Figure 3.3 and spatial distribution of various types of lakes are shown in Figure 3.4.

Figure 3.3: **Percentage distribution of types of glacial lakes in five major river basins**

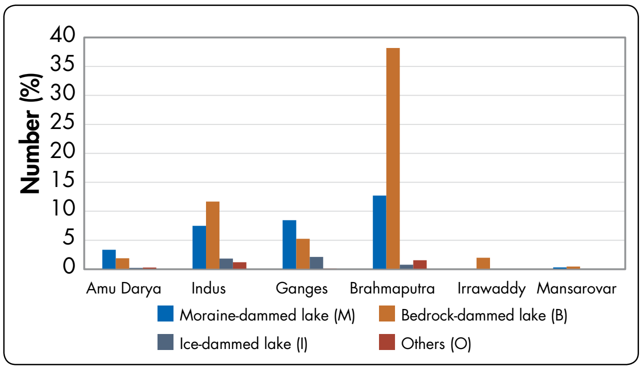
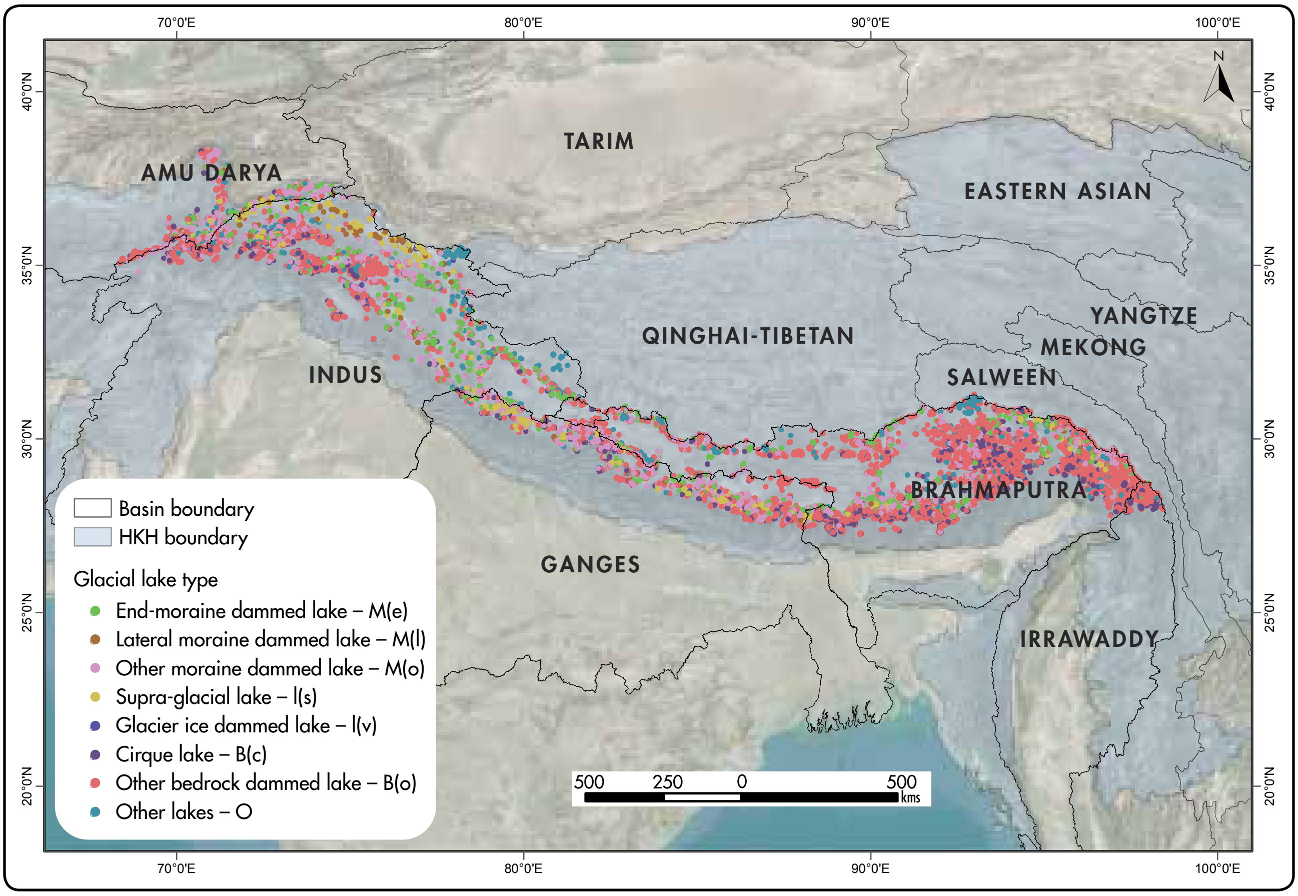


Figure 3.4: **Spatial distribution of different types of glacial lakes**



Glacial Lake Size

The size of glacial lakes in the HKH ranges from 0.003 km^2 to 15.1 km^2, with an average size of around 0.06 km^2 (Table 3.2). Glacial lakes are comparatively larger in the Indus and Ganges River Basins and comparatively smaller in the Irrawaddy River Basin (Table 3.3).

Glacial lake size was categorised into seven classes: Class 1 (<0.01 km^2), Class 2 (0.01 – <0.05 km^2), Class 3 (0.05 – <0.1 km^2), Class 4 (0.1 – <0.5 km^2), Class 5 (0.5 – <1 km^2), Class 6 (1 – <5 km^2), and Class 7 (≥5 km^2). For the whole HKH, 7,073 lakes are Class 1. Although class 1 lakes account for 27.61% of the total lakes

Table 3.2: **Number and area of different size category of glacial lakes in the HKH**

Glacial lake size	Number	%	Area (km²)	%	Average size (km²)
Class 1 (<0.01 km²)	7,073	27.61	43.97	3.04	0.006
Class 2 (0.01 - <0.05 km²)	12,809	50.01	289.87	20.07	0.023
Class 3 (0.05 - <0.1 km²)	2,992	11.68	208.07	14.41	0.070
Class 4 (0.1 - <0.5 km²)	2,415	9.43	463.49	32.09	0.192
Class 5 (0.5 - <1 km²)	203	0.79	141.78	9.82	0.698
Class 6 (1 - <5 km²)	111	0.43	209.18	14.41	1.875
Class 7 (≥5 km²)	11	0.04	88.84	6.15	8.076
Total	**25,614**	**100.00**	**1,444.18**	**100**	**0.056**

Table 3.3: **Percentage distribution of different size of glacial lakes in five major river basins of HKH**

Glacial lake size	Amu Darya	Indus	Ganges	Brahmaputra	Irrawaddy	Mansarovar	Total
Class 1 (<0.01 km²)	36.70	25.49	39.99	24.55	32.95	24.75	27.61
Class 2 (0.01 - <0.05 km²)	46.88	53.14	46.52	49.91	52.76	54.46	50.01
Class 3 (0.05 - <0.1 km²)	9.57	12.71	7.69	12.76	9.14	12.38	11.68
Class 4 (0.1 - <0.5 km²)	6.24	7.91	7.40	11.20	5.14	7.92	9.43
Class 5 (0.5 - <1 km²)	0.47	0.51	0.93	0.95	0	0	0.79
Class 6 (1 - <5 km²)	0.07	0.23	0.44	0.57	0	0.5	0.43
Class 7 (≥5 km²)	0.07	0.02	0.02	0.06	0	0	0.04

mapped, they cover a total area of only 43.97 km². The class 1, 2, and 3 lakes together comprise 89.3% of the total number of HKH lakes (Table 3.2 and Table 3.3). There is an inverse relationship between the total number and total area of lakes according to size. Class 1 lakes account for only 3.04% of total lake area. Although class 7 lakes account for only 0.04% of the total number of lakes, they account for 6.15% of total lake area (Table 3.2 and Table 3.3). Similar observations were made in the Pumqu River Basin (Che et al. 2014) and Poiqu Basin (Wang et al. 2014) with a large number of class 1 and 2 lakes.

The percentage distribution of glacial lake size in each basin is shown in Table 3.3. The glacial lake size class 2 within all basins is more than 40% of total lakes in each basin. Of the lakes mapped in each basin, 87% to 95% are less than 0.1 km². The percentage distribution of larger glacial lakes (0.5 – <5 km²) in each basin ranges from 0.5% to 1.5%, and just 11 lakes are greater than or equal to 5 km² (Table 3.2 and Table 3.3).

Figure 3.5 shows the proportional distribution of size versus types of glacial lakes in the HKH. Mostly class 7 lakes are identified as other glacier lakes. Of these 11 lakes, seven are other types, two are end-moraine-dammed, and two are bedrock-dammed. The distribution of bedrock-dammed lakes in all size classes is proportionally greater except in class 7, which has a higher number of other types of lakes. The average size of other glacial lakes is comparatively larger than the moraine-dammed and ice-dammed lakes. The size of end moraine and cirque lakes is larger than the average area of individual lakes in the HKH (Table 3.4).

Figure 3.5: **Proportional distribution of types and sizes of glacial lakes in HKH**

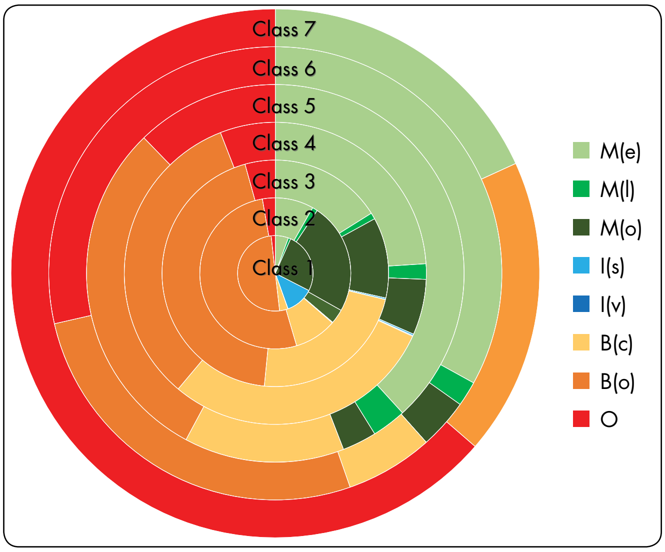


Table 3.4: **Average size of glacial lakes in different size classes and types of lakes**

Glacial lake size	Average size (km²)								
	Moraine-dammed lake (M)			Ice-dammed lake (I)		Bedrock-dammed lake (B)		Others	Total
	End-moraine M(e)	Lateral moraine (ice free) M(l)	Other moraine-dammed M(o)	Supra-glacial lake I(s)	Glacier ice-dammed lake I(v)	Cirque B(c)	Other bedrock-dammed lakes B(o)	O	
Class 1 (<0.01 km²)	0.006	0.006	0.006	0.006	0.007	0.007	0.006	0.006	**0.006**
Class 2 (0.01 - <0.05 km²)	0.026	0.022	0.021	0.017	0.022	0.027	0.022	0.025	**0.023**
Class 3 (0.05 - <0.1 km²)	0.071	0.073	0.068	0.069	0.059	0.072	0.068	0.07	**0.07**
Class 4 (0.1 - <0.5 km²)	0.204	0.23	0.173	0.19	0.152	0.184	0.185	0.228	**0.192**
Class 5 (0.5 - <1 km²)	0.722	0.563	0.746	0	0	0.642	0.689	0.733	**0.698**
Class 6 (1 - <5 km²)	1.811	1.835	1.404	0	0	1.277	1.825	2.188	**1.869**
Class 7 (≥5 km²)	5.487	0	0	0	0	0	8.271	8.76	**8.076**
Total	**0.119**	**0.075**	**0.025**	**0.01**	**0.03**	**0.084**	**0.042**	**0.249**	**0.056**

Altitudinal Distribution

The distribution of glacial lakes by 100 m elevation zones is shown in Figure 3.6. Only two lakes are located below 2,400 m and four lakes are above 6,000 m. The low-lying lakes are in the Indus Basin; of the high altitude lakes, one is in Ganges, one is in Brahmaputra, and two are in Mansarovar. The lowest elevation of glacial lake was mapped at 2,203 masl, which is in Gilgit Sub-basin. The majority of glacial lakes (58.8%) are located in the 4,000–<5,000 masl elevation zone. Similarly, 33.8% of the total lakes in the HKH are located in the 5,000–<6,000 m elevation zone. Such an altitudinal difference in the distribution of glacial lakes in the Himalaya has been reported earlier (Nie et al. 2013; Wang et al. 2014). For example, Wang et al. (2014) showed that in the Poiqu Basin glacial lakes are distributed within the altitudinal range of 4,420–5,860 masl with the majority of them (76%) situated at an elevation of >5,000 m. Figure 3.6 clearly shows that the proportion of moraine-dammed lakes is higher in the higher elevation and that mostly bedrock-dammed and other types of glacial lakes exist in the lower elevation. Distribution of various types of lakes in 1,000 m elevation zone is given in Table 3.5

Figure 3.6: **Altitudinal distribution of the number and various types of lakes**

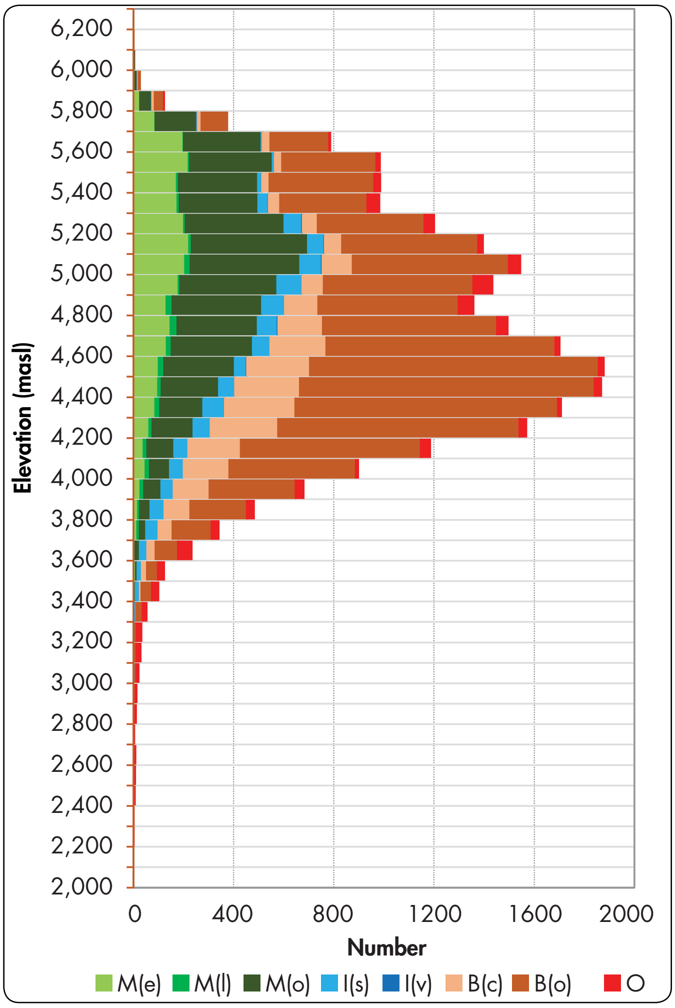
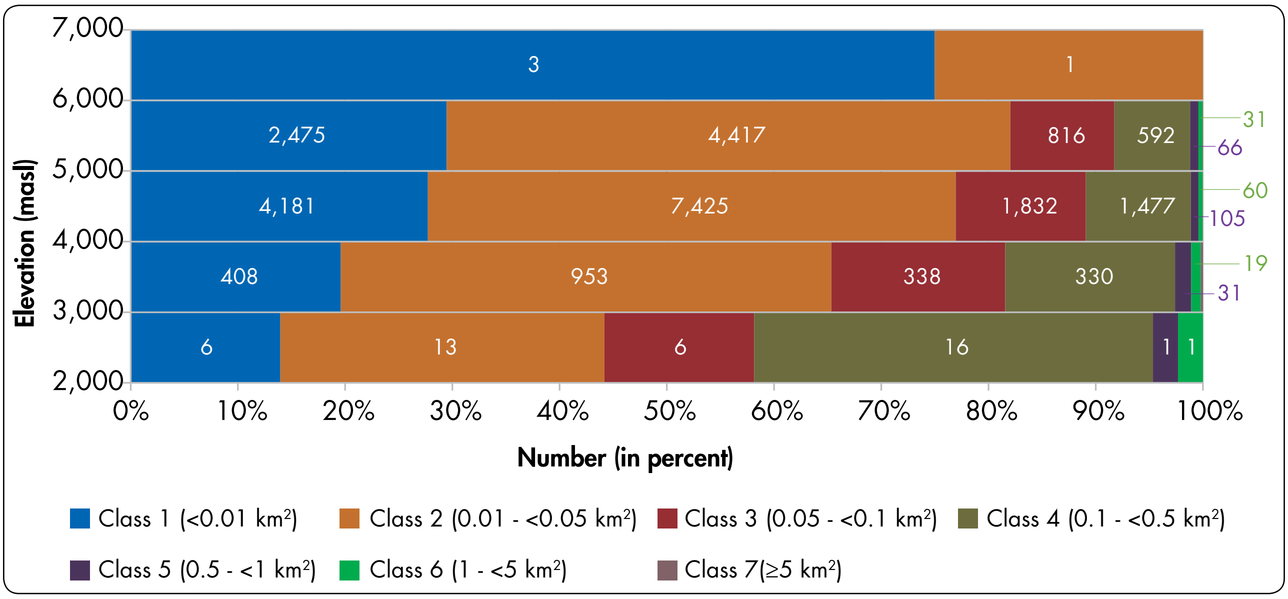


Figure 3.7 clearly indicates that the percentage share of smaller glacial lakes (<0.1 km²) is higher in all the 1,000 m altitudinal zones. However, the percentage share of larger glacial lakes (>0.1 km²) is comparatively higher in the 2,000–3,000 masl altitudinal zone.

Table 3.5: **Distribution of different types of glacial lakes in 1,000 m elevation zones (with lowest elevation at 2,203 masl)**

Type			Elevation (masl) zone <3,000	3,000 – <4,000	4,000 – <5,000	5,000 – <6,000	≥6,000	Total Number	Total %
Moraine-dammed lake (M)	End-moraine	M(e)	7	82	1,028	1,517	0	**2,634**	**10.28**
	Lateral moraine	M(l)	1	46	178	65	0	**290**	**1.13**
	Other moraine-dammed lake	M(o)	0	167	2,419	2,788	3	**5,377**	**20.99**
Ice-dammed lake (I)	Supra-glacial lake	I(s)	9	233	717	294	0	**1,253**	**4.89**
	Glacier ice-dammed lake	I(v)	0	0	10	17	0	**27**	**0.11**
Bedrock-dammed lake (B)	Cirque	B(c)	0	365	2,070	407	0	**2,842**	**11.10**
	Other bedrock-dammed lake	B(o)	3	931	8,334	3,118	1	**12,387**	**48.36**
Others		O	23	259	328	194	0	**804**	**3.14**
Total		**Number**	**43**	**2,083**	**15,084**	**8,400**	**4**	**25,614**	**100**
		%	**0.17**	**8.13**	**58.89**	**32.79**	**0.02**	**100**	

Figure 3.7: **Number of different sized glacial lakes in percent in different elevation bands**



Lake Density and Area Percentage

Figures 3.8 and 3.9 show the density and area percentage of glacial lakes, respectively. While calculating the density of glacial lakes, a 0.5 degree grid of the study area was generated. The density was obtained based on the total number of glacial lakes counted in each grid divided by the area of the grid cell, and the area percentage was calculated by the sum of the total area of glacial lakes divided by the area of each grid cell. It is evident that both the lake density and area coverage of lakes are much higher in the eastern part of the HKH with much more concentration towards the east of central Nepal. Coverage is low in the central part of the HKH and increases somewhat to the western part of the HKH but to a lesser extent than the eastern Himalaya. This indicates that the size and number of the glacial lakes is higher in the eastern part of the Himalaya.

Figure 3.8: **Density of glacial lakes in terms of number**

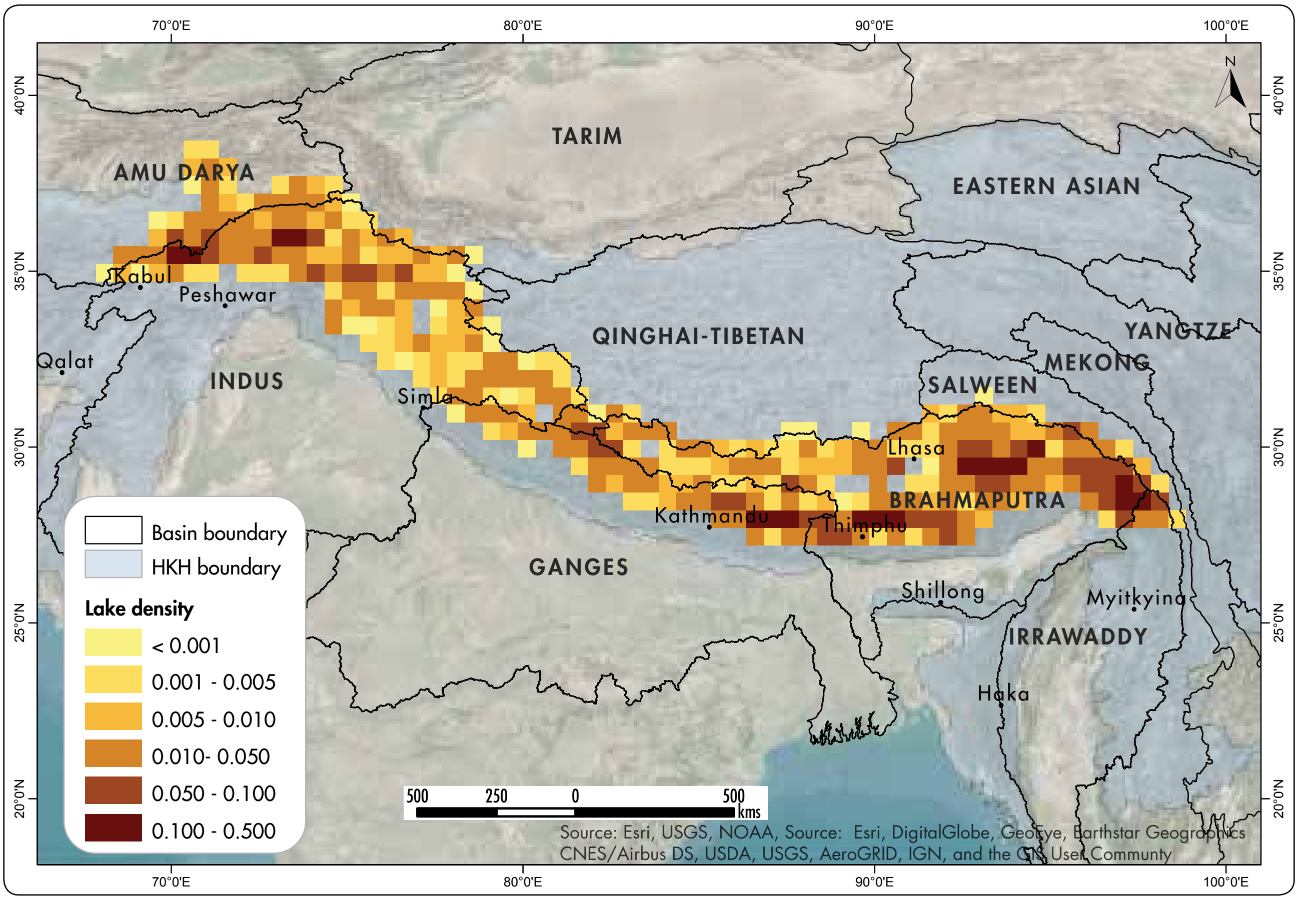
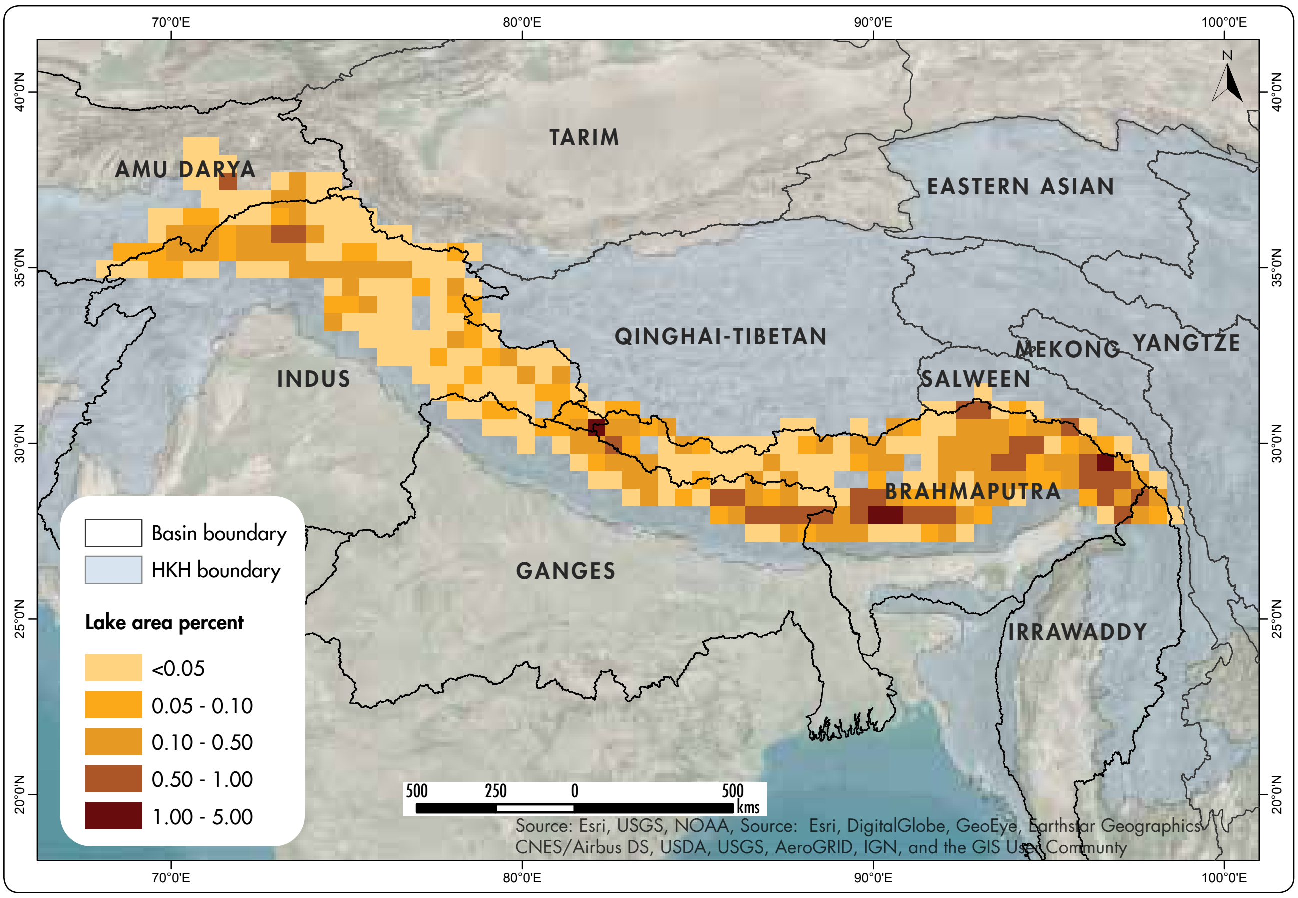


Figure 3.9: **Density of glacial lakes in terms of area**



Geographical Distance from the Glacier

The glacial lakes closer to the glaciers are mostly fed by glacial melt and continuously changing size. The lakes that lie far ahead of the glaciers may or may not be fed by glacial melt but are instead formed in the paleo-glaciation landforms and are mostly constant in size. The lakes are categorised into 10 classes in terms of distance from the glaciers. Lakes on the glaciers comprise 4.8% of the total number of lakes and are mostly ice-dammed. The size and number of these lakes change frequently depending on seasons and time, and supra-glacial lakes especially appear to merge with moraine-dammed lakes or may develop contemporaneously as composite forms. Lakes in contact with the glaciers are mostly moraine-dammed and comprise about 2.5% of all lakes. The size of these lakes changes rapidly due to melting of glaciers, and so need to be monitored. Figure 3.10 shows that the number and area of the lakes decrease with distance from the glaciers, while the number and area of the lakes increase closer to the glacier.

Figure 3.11 shows the distribution of different types of glacial lakes within distance of the glaciers. Mostly the lakes far away from the glaciers are bedrock-dammed and other types of lakes. Most of the moraine-dammed lakes are within 5 km of the glaciers. The highest number of moraine-dammed lakes are within 2 km of the glaciers.

Figure 3.10: **Number and area distribution in the distance from glacier (blue line = snout of glacier) in 200 m zone**

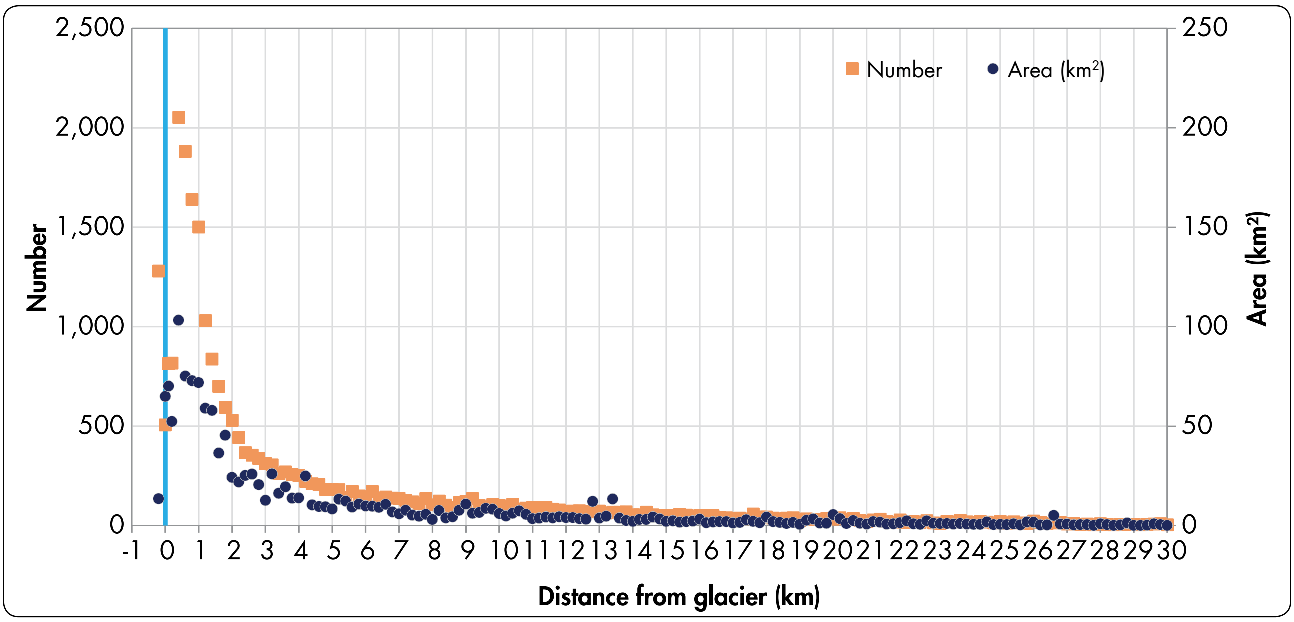
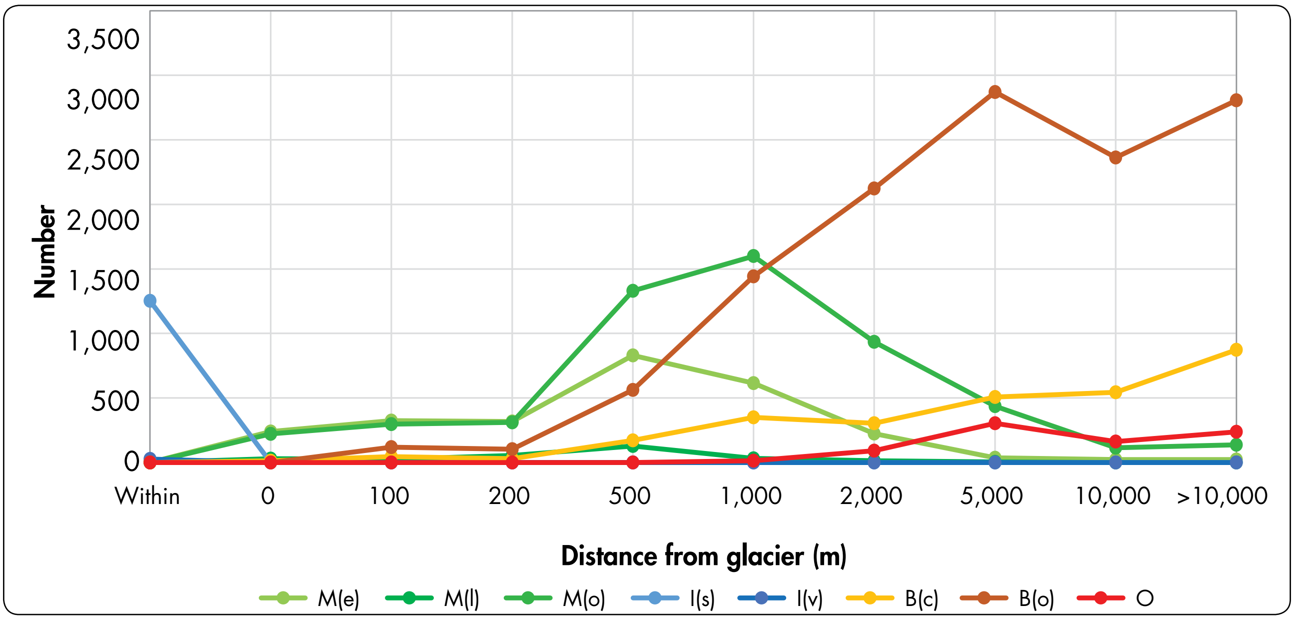


Figure 3.11: **Distribution of various types of lakes within the distance from the glaciers**

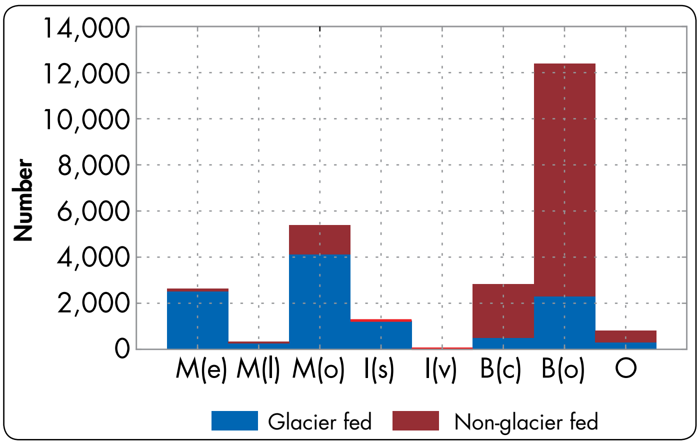


Glacier Fed and Non-Glacier Fed

Of all lakes in the HKH, 44% are fed by glaciers, of which 27% are moraine-dammed, 5% are ice-dammed, and 11% are bedrock-dammed (Table 3.6). Of the 56% that are non-glacier fed lakes — 49% are bedrock-dammed and 2% are other types. There is an inverse relationship between the percentage of area covered by glacier fed and non-glacier fed lakes in the HKH and the number of lakes. More than 53% of the total area of identified lakes are glacier fed whereas 47% are non-glacier fed.

This suggests that the average size of glacier fed lakes is larger than non-glacier fed lakes. The large number of bedrock-dammed lakes are non-glacier fed (Figure 3.12). Glacier fed lakes in the Amu Darya, Indus and Ganges River Basins are higher than non-glacier fed lakes while the Brahmaputra and Irrawaddy River Basins have more than double the number of non-glacier fed lakes. This also indicates that the large number of lakes mapped in the Brahmaputra and Irrawaddy River Basins are from paleo-glacial landforms and are mostly bedrock-dammed. So the percentage of non-glacier fed bedrock-dammed lakes is much higher than other types of glacier fed and non-glacier fed lakes in the region.

Figure 3.12: **Distribution on glacier fed and non-glacier fed lakes in the HKH**

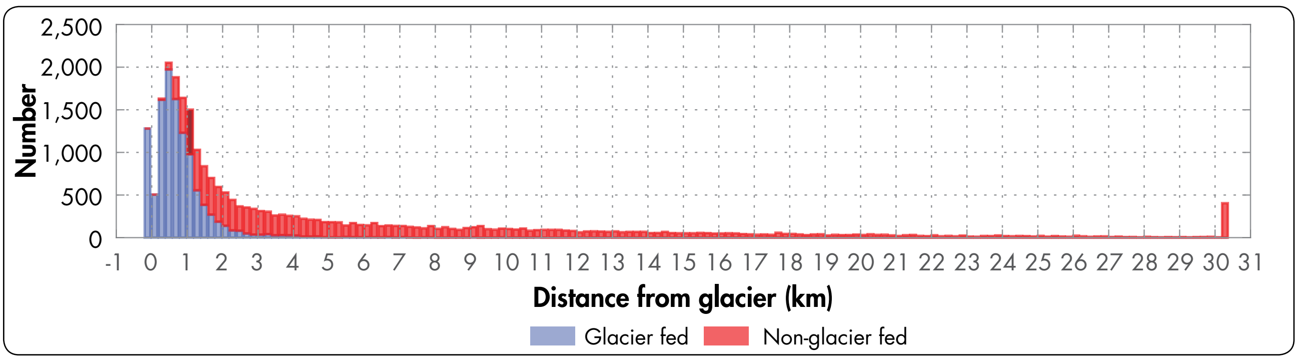


Mostly the glacier fed lakes lie within 2 km of the glaciers, and lakes beyond 2 km of the glaciers are mostly non-glacier fed (Figure 3.13). Almost 35% of lakes in the HKH lie within 2 km of the glaciers are glacier fed, 2% are in contact with glaciers, and 5% are ice-dammed lakes within the glaciers. 2% of total lakes within the distance from 2 km to 5 km of the glacier are glacier fed and very few glacier fed lakes are identified beyond 5 km. More than 42% of total lakes in HKH beyond 2 km and 13% of total lakes within 500 m to 2 km are non-glacier fed. Less than one percent of lakes within 500 m are identified as non-glacier fed lakes.

Table 3.6: **Glacier fed and non-glacier fed glacial lake distribution in different types of lakes**

Type			Number				Area (km²)			
			Glacier fed		Non-glacier fed		Glacier fed		Non-glacier fed	
			No.	%	No.	%	km²	%	km²	%
Moraine-dammed lake (M)	End-moraine	M(e)	2,519	9.83	115	0.45	305.68	21.17	8.79	0.61
	Lateral moraine	M(l)	281	1.1	9	0.04	20.67	1.43	1.17	0.08
	Others	M(o)	4,113	16.06	1,264	4.93	101.10	7.00	32.96	2.28
Ice-dammed lake (I)	Supra-glacial lake	I(s)	1,253	4.89	0	0	12.75	0.88	0	0
	Glacier ice-dammed lake	I(v)	27	0.11	0	0	0.80	0.06	0	0
Bedrock-dammed lake (B)	Cirque	B(c)	506	1.98	2336	9.12	59.36	4.11	179.96	12.46
	Others bedrock-dammed lake	B(o)	2,301	8.98	10,086	39.38	158.11	10.95	362.94	25.13
Others		O	305	1.19	499	1.95	110.99	7.68	88.91	6.16
Total			**11,305**	**44.14**	**14,309**	**55.86**	**769.45**	**53.28**	**674.73**	**46.72**

Figure 3.13: **Histogram showing the number of glacier fed and non-glacier fed glacial lakes within 100 m bin distance from the glacier in the HKH**



Status of Glacial Lakes in Major River Basins of the Hindu Kush Himalaya

Amu Darya River Basin

The Amu Darya River originates in Tajikistan and Kyrgyzstan in two headstreams, the Panj and Vakhsh Rivers. The river flows west-northwest into the Aral Sea and is one of the longest rivers in Central Asia. It forms a part of Afghanistan's border with Tajikistan, Uzbekistan, and Turkmenistan and a part of Uzbekistan's border with Turkmenistan. The part of the Amu Darya River Basin within the HKH lies entirely within Afghanistan covering a quarter of the total basin area.

The glacier and glacial lakes within the HKH of the Amu Darya Basin are distributed in three larger basins — the Wakhan, Kokcha, and Surkhab. Twelve tiles of Landsat cover the glaciated region of the basin. In total, 26 Landsat images were used to map the glacial lakes in the Amu Darya River Basin.

The glacial lakes lie between 38°19′37.2″ N and 35°3′50.4″ N latitude and 74°31′48′ E and 68°21′25.2″ E longitude. The distribution and characteristics of glacial lakes in each basin area are shown in Figure 4.1 and Table 4.1.

Figure 4.1: **Distribution of glacial lakes in Amu Darya Basin**

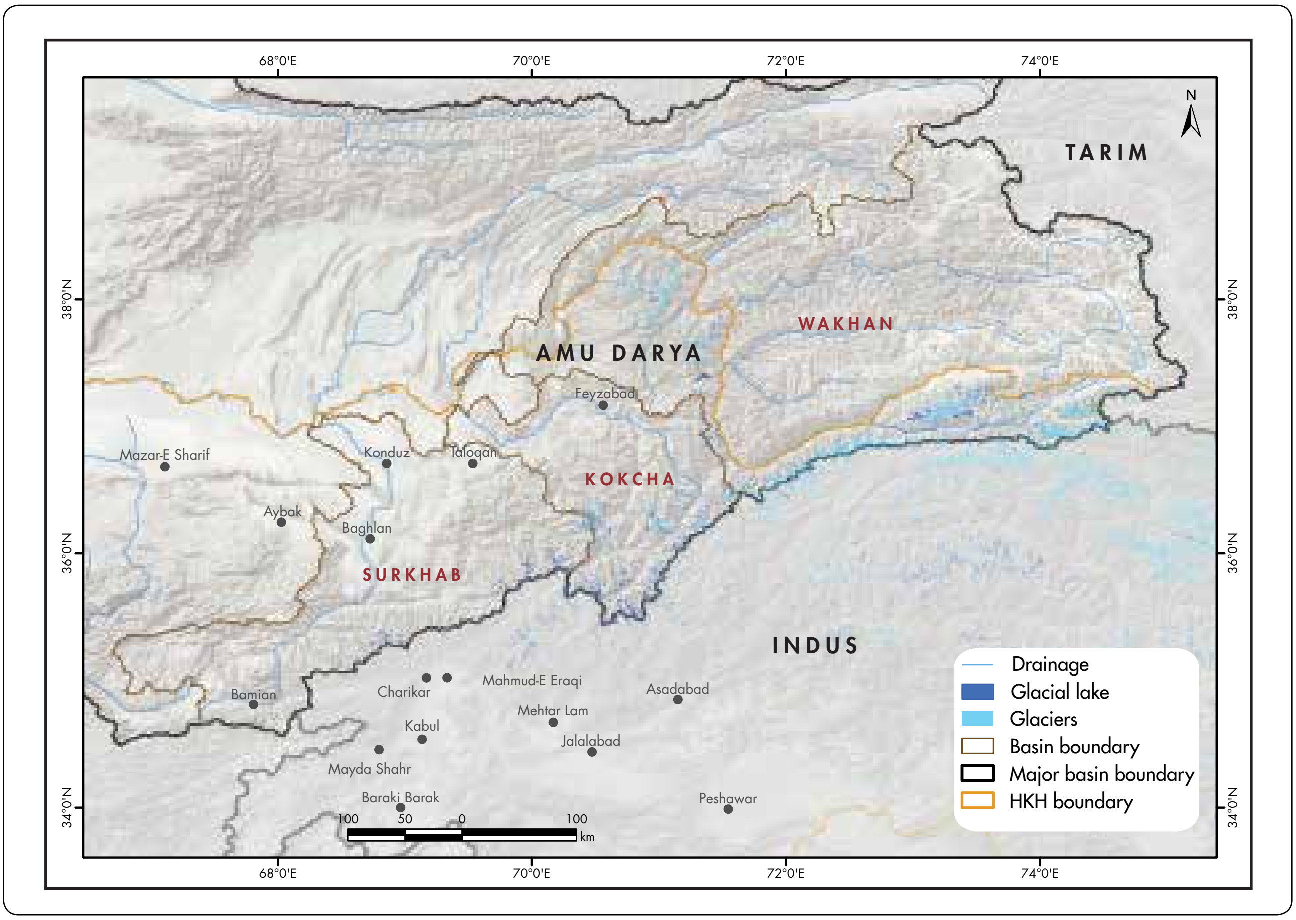


Table 4.1: **Number and area of different size category of glacial lakes in Amu Darya River Basin**

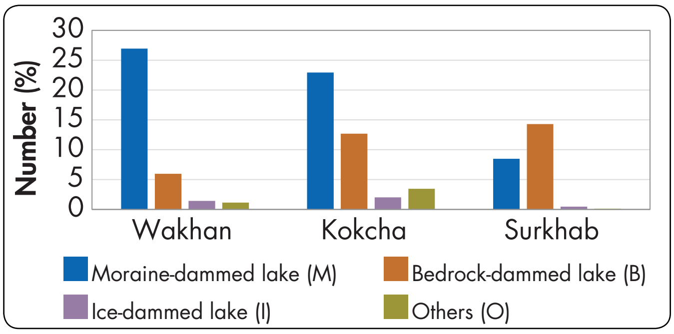
Basin			Wakhan		Kokcha		Surkhab		Total	
Type			Number	Area (km²)	Number	Area (km²)	Number	Area (km²)	Number	Area (km²)
Moraine-dammed lake (M)	End-moraine	M(e)	100	7.24	66	4.04	27	1.94	193	13.22
	Lateral moraine	M(l)	18	1.24	10	1.11	1	0	29	2.35
	Others	M(o)	279	4.7	262	3.95	97	2.17	638	10.82
Ice-dammed lake (I)	Supra-glacial lake	I(s)	20	0.14	30	0.18	7	0.03	57	0.35
	Glacier ice-dammed lake	I(v)	1	0.03	0	0	0	0	1	0.03
Bedrock-dammed (B)	Cirque	B(c)	13	0.33	21	1.79	22	1.48	56	3.6
	Others bedrock-dammed lake	B(o)	75	3.13	166	3.96	189	5.35	430	12.44
Others		O	17	16.51	51	6.59	2	0.18	70	23.28
Total			**523**	**33.32**	**606**	**21.78**	**345**	**11.87**	**1,474**	**66.09**

Number, area, and types

In total, Amu Darya River Basin has 1,474 glacial lakes — 606 in Kokcha , 523 in Wakhan, and 345 in Surkhab — with a total area of 67.09 km². The number of lakes is comparatively higher in Kokcha Basin than in Wakhan Basin but the area coverage is less, indicating that the lakes in Wakhan Basin are larger.

The numbers and area of various types of glacial lakes are summarized in Table 4.1. More than 58% of the lakes are moraine-dammed and 33% are bedrock-dammed. The average area of moraine-dammed lakes ranges from 0.017 to 0.072 km² and the average area of bedrock-dammed lakes ranges from 0.024 to 0.085 km². Wakhan Basin has more moraine-dammed lakes and Surkhab Basin has fewer, whereas the numbers of bedrock-dammed lakes are just opposite (Figure 4.2).

Figure 4.2: **Percentage distribution of various types of glacial lakes in each basin of Amu Darya River Basin**



Glacial lake size

The smallest and largest glacial lakes in Amu Darya River Basin are 0.003 km² and 15.09 km². The sizes of the lakes are categorised into seven classes. The highest number, almost 47% of total lakes, are class 2 (0.01 to <0.05 km²) covering just 22.4% of the total area of lakes (Table 4.2). The second highest number, almost 36.6% of total lakes, are class 1 (<0.01 km²) covering more than 5% of the total area. There are two larger-sized glacial lakes,

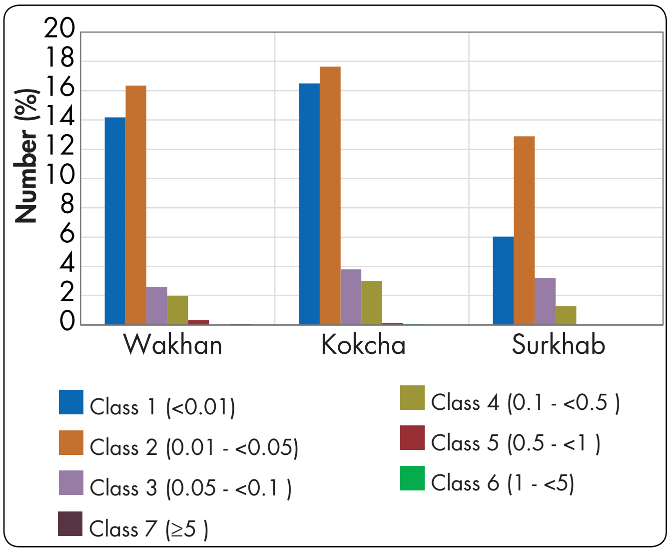
Table 4.2: **Number and area of different size categories of glacial lakes in Amu Darya River Basin**

Glacial lake size	Number	%	Area (km²)	%	Average size (km²)
Class 1 (<0.01)	541	36.55	3.31	5.01	0.006
Class 2 (0.01 - <0.05)	691	46.88	14.91	22.56	0.022
Class 3 (0.05 - <0.1)	141	9.57	9.57	14.48	0.068
Class 4 (0.1 - <0.5)	92	6.24	16.67	25.22	0.181
Class 5 (0.5 - <1)	7	0.47	5.4	8.17	0.771
Class 6 (1 - <5)	1	0.07	1.14	1.7	1.140
Class 7 (≥5)	1	0.07	15.09	22.48	15.090
Total	**1,474**	**100**	**66.09**	**100.00**	**0.045**

one class 6 (1 to <5 km²) and one class 7 (≥5 km²). Thus there is a high number of smaller-sized lakes and very few larger-sized lakes.

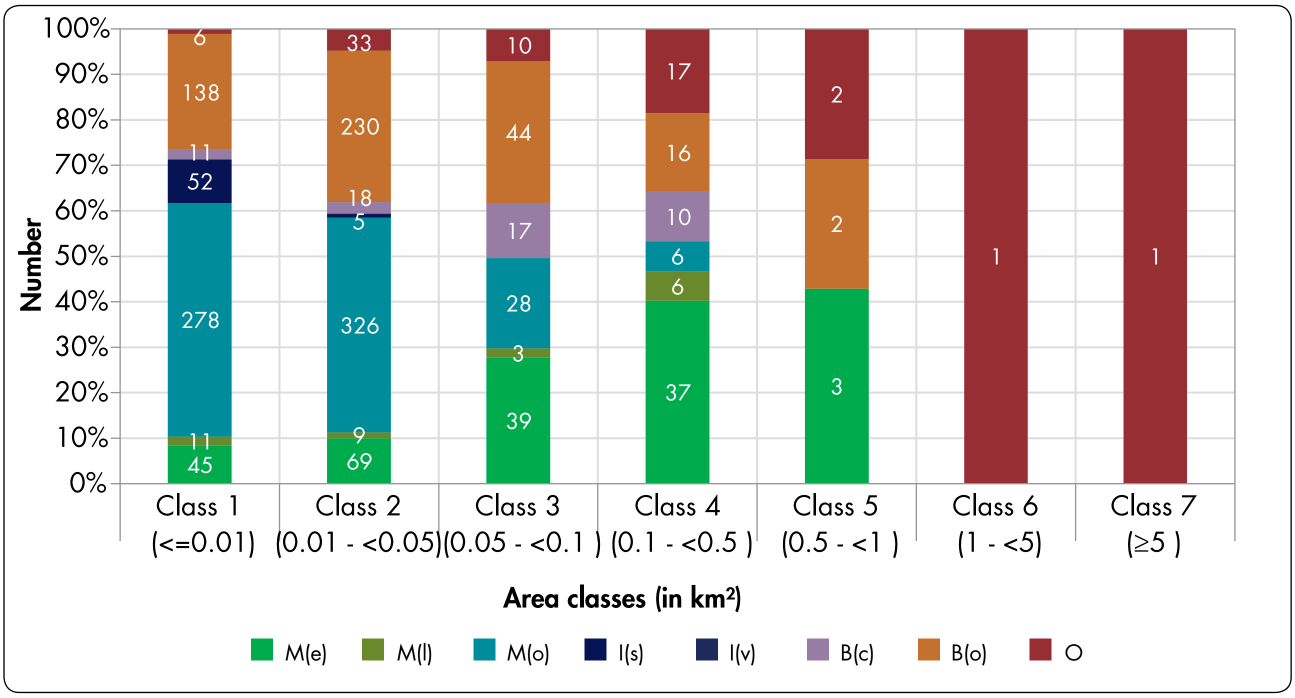
The basin consists of mostly smaller glacial lakes and almost 84% of the total glacial lakes are less than 0.05 km². Less than one percent of the lakes are larger than or equal to 0.5 km². Kokcha Basin has about 34% of total lakes in the Amu Darya River Basin of size <= 0.05 km² whereas Wakhan has about 31% and Surkhab has about 19% (Figure 4.3).

Figure 4.3: **Percentage distribution of different size classes in each basin of Amu Darya River Basin**



The percentage distribution of size versus types of glacial lakes shows that the larger lakes are mostly bedrock-dammed and other types of lakes whereas moraine-dammed lakes are mostly smaller, less than 0.5 km² (Figure 4.4). Almost 50% of total lakes of size <0.05 km² are moraine-dammed and 8% of total lakes of size 0.05 to <0.5 km² are moraine-dammed. Bedrock-dammed lakes of size <0.05 are almost 27% and size 0.05 to <0.5 km² are 6% of the total number lakes in the Amu Darya River Basin. Ice-dammed lakes are of size less than 0.05 km². Most of the other types of lakes are less than 0.5 km², with only four lakes greater than or equal to 0.5 km².

Figure 4.4: **Percentage of glacial lake size in different types of lakes in Amu Darya River Basin**



Altitudinal distribution

The lowest and highest elevation of glacial lakes mapped in the Amu Darya River Basin are 2,972 masl and 5,226 masl. The lowest elevation lake is in Wakhan Basin and the highest elevation lake is in Kokcha Basin. The distribution of lakes in various elevation zones is given in Table 4.3. The majority of lakes (about 87%) are within the elevation zone of 4,000 – <5,000 masl in which more than 53% are moraine-dammed and about 30% are glacier bedrock-dammed. Only one glacial lake is mapped at an elevation below 3,000 masl, which is classified as an other type of lake. Only about 10% and 3.5% of lakes are within the elevation zones of 3,000 – <4,000 masl and 5,000 – <6,000 masl, respectively. The proportion of moraine-dammed lakes is higher at higher elevation,

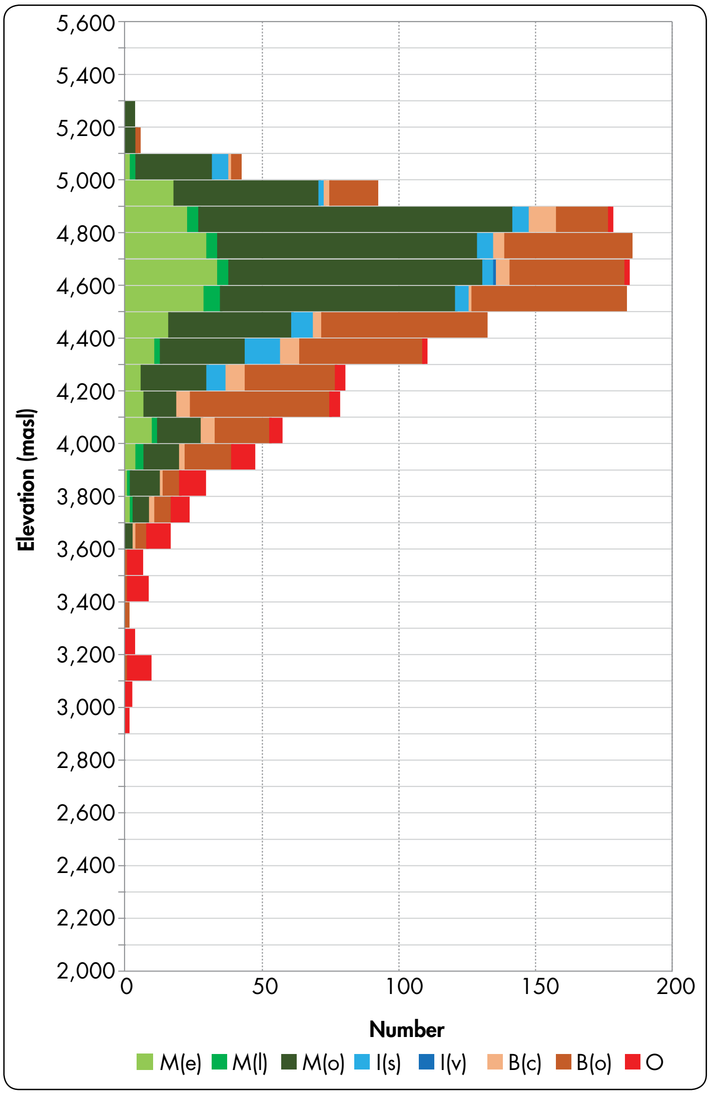
Table 4.3: **Distribution of different types of glacial lakes in elevation zones in Amu Darya River Basin**

Elevation zone			<3,000		3,000 – 4,000		4,000 – 5,000		5,000 – 6,000		Total	
Type			No.	%	No.	%	No.	%	No.	%	No.	%
Moraine-dammed lake (M)	End-moraine	M(e)	0	0	7	0.47	184	12.48	2	0.14	193	13.09
	Lateral moraine	M(l)	0	0	5	0.34	22	1.49	2	0.14	29	1.97
	Others	M(o)	0	0	33	2.24	570	38.67	35	2.37	638	43.28
Ice-dammed lake (I)	Supra-glacial lake	I(s)	0	0	0	0	51	3.46	6	0.41	57	3.87
	Glacier ice-dammed lake	I(v)	0	0	0	0	1	0.07	0	0	1	0.07
Bedrock-dammed lake (B)	Cirque	E(c)	0	0	6	0.41	49	3.32	1	0.07	56	3.8
	Others bedrock-dammed lake	E(o)	0	0	37	2.51	389	26.39	4	0.27	430	29.17
Others		O	1	0.07	56	3.8	13	0.88	0	0	70	4.75
Total			**1**	**0.47**	**144**	**9.77**	**1,279**	**86.77**	**50**	**3.39**	**1,474**	**100**

and mostly bedrock-dammed and others types of lakes are distributed below 3,600 masl (Figure 4.5).

The percentage distribution of various sizes of glacial lakes at 1,000 m interval elevation zones is shown in Figure 4.6. Smaller lakes of <=0.05 km^2 are distributed mostly at a higher elevation zone of 5,000 – <6,000 masl. Out of 50 lakes, 32 lakes are class 1 (<0.01 km^2), 16 are class 3 (0.01 – <0.05 km^2), and one each in class 3(0.05 – <0.1 km^2) and Class 4(0.1 – <0.5 km^2) are distributed at elevation zone of 5,000 – <6,000 masl. The highest concentration of lakes within the 4,000 – <5,000 masl elevation zone consists of more than 73% of total lakes of size <=0.05 km^2 and only five lakes are class 5 (0.5 – <1 km^2).

Figure 4.5: **Altitudinal distribution of number and types of lakes in Amu Darya River Basin**



Geographical distance from glacier

The distance of the glacial lake from the glacier is categorized into 10 classes (Table 4.4). 3.9% of the lakes in the basin lies within the glacier (ice-dammed lakes) which covers an area of 0.38 km^2, and the lakes in contact with the glacier are 5.4% of total glacial lakes in the basin. Mostly the lakes closer to the glaciers are fed by glacial melt whereas the lakes that lie far ahead of the glaciers may or may not be fed by glacial melt but instead are formed in the paleo-glaciation landforms. The highest number of lakes lie within 200 m to 5 km of the glacier. About 5.1% of the total lakes lie beyond 5 km. Figure 4.7 shows that the number of the lakes and area decreases with distance from the glaciers. Almost 95% of the lakes in the Basin are lies within the 5 km distance from the glaciers.

Figure 4.6: **Number of different sized glacial lakes in percent in different elevation zones in Amu Darya River Basin**

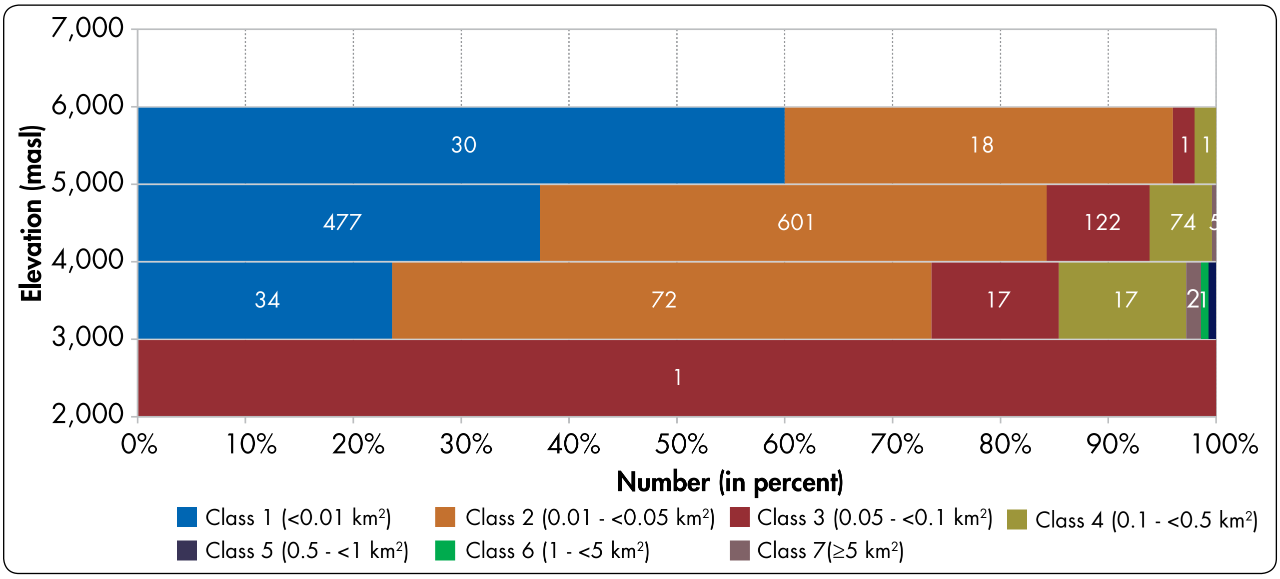


Table 4.4: **Distribution of glacial lakes and area in different distance from the glacier**

Distance from glaciers (m)	Number		Area	
	Count	%	km²	%
Within	58	3.9	0.38	0.6
Contact with	79	5.4	1.59	2.4
>0 – <100	139	9.4	4.11	6.2
100 – <200	99	6.7	1.68	2.5
200 – <500	257	17.4	6.65	10.1
500 – <1,000	375	25.4	14.47	21.9
1,000 – <2,000	249	16.9	11.72	17.7
2,000 – <5,000	142	9.6	23.20	35.1
5,000 – <10,000	49	3.3	1.47	2.2
≥ 10,000	27	1.8	0.82	1.2
Total	**1,474**	**100.0**	**66.09**	**100.0**

Figure 4.8 shows the distribution of different types of glacial lakes by distance from the glaciers. Mostly the lakes far away from the glaciers are bedrock-dammed and other types. Almost all the moraine-dammed lakes lie within 2 km of the glaciers.

Glacier fed and non-glacier fed

Glacial lake data are also classified into glacier fed and non-glacier fed based on the glacier inventory data. More than 77% of the total lakes in Amu Darya River Basin are fed by the glaciers of which more than 54% are moraine-dammed lakes (Table 4.5). Non-glacier fed lakes are higher in the number of bedrock-dammed lakes. Among 22.6% of the non-glacier fed lakes, 18% are bedrock-dammed. The number of non-glacier fed bedrock-dammed lakes is higher in Kokcha and Surkhab Basins whereas comparatively fewer non-glacier fed lakes are identified in Wakhan Basin (Figure 4.9). Wakhan Basin consists of a high concentration of glaciers, whereas glaciers in other two basins are relatively smaller and scattered. So a relatively higher percentage of the glacial lakes in Wakhan Basin are glacier fed.

More than 68% of total lakes in Amu Darya River Basin lie within 5 km of glaciers are glacier fed. And the lakes beyond 5 km of the glaciers are mostly non-glacier fed (Figure 4.10). Only 21% of the total lakes beyond 500 m distance from the glaciers and less than one percent within 500 m of glaciers are non-glacier fed.

Figure 4.7: **Number and area distribution of glacial lakes in the distance from glacier (blue line = snout of glacier) in Amu Darya River Basin**

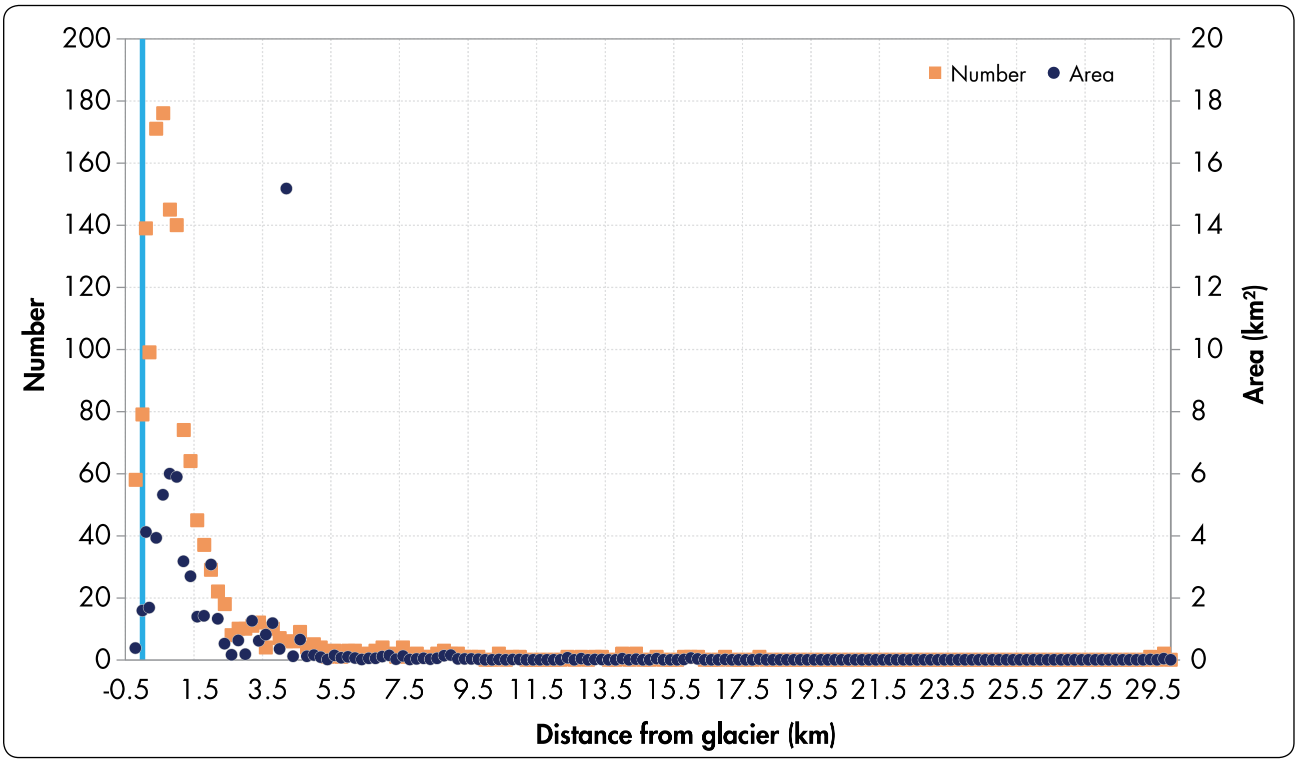


Figure 4.8: **Distribution of various types of lakes within the distance from the glaciers in Amu Darya River Basin**

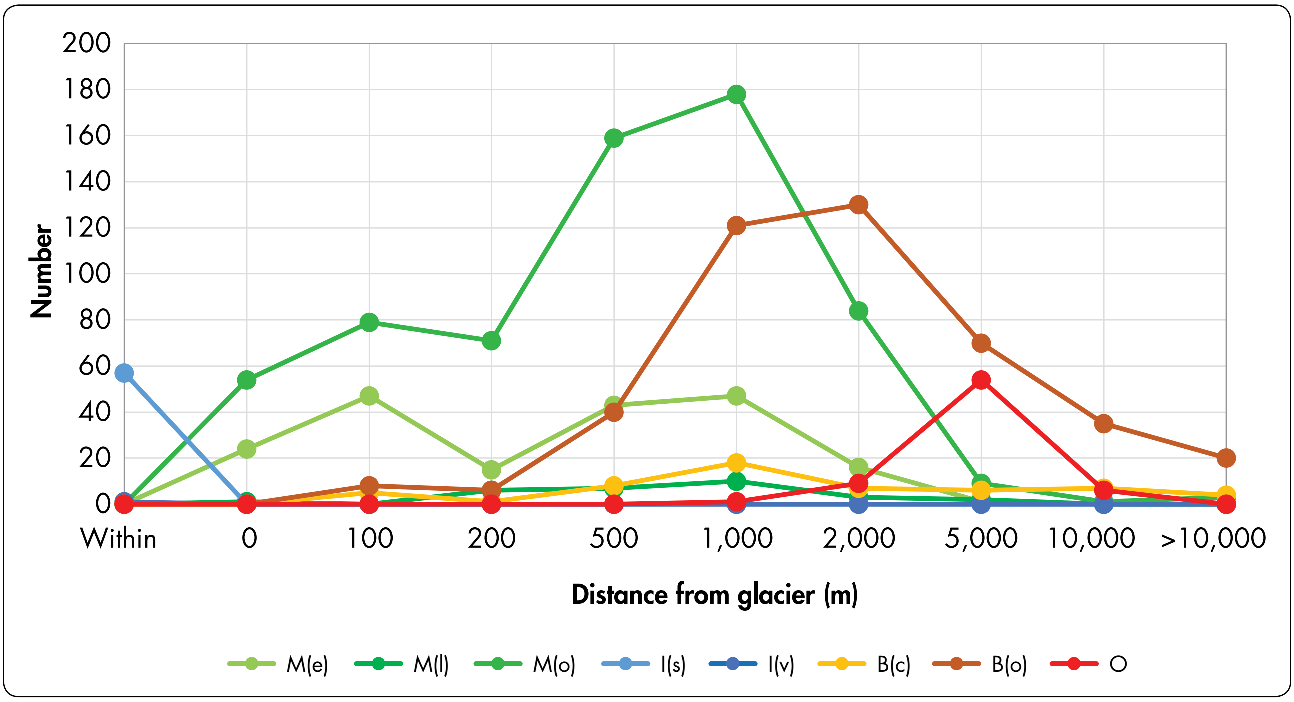


Table 4.5: **Glacier fed and non-glacier fed glacial lake distribution in Amu Darya River Basin**

Type			Number				Area (km²)			
			Glacier fed		Non-glacier fed		Glacier fed		Non-glacier fed	
			No.	%	No.	%	km²	%	km²	%
Moraine-dammed lake (M)	End-moraine	M(e)	190	12.89	3	0.2	13.15	19.9	0.06	0.1
	Lateral moraine	M(l)	28	1.9	1	0.07	2.34	3.55	0.004	0.01
	Others	M(o)	585	39.69	53	3.60	9.95	15.05	0.87	1.32
Ice-dammed lake (I)	Supra-glacial lake	I(s)	57	3.87	0	0	0.35	0.53	0	0
	Glacier ice-dammed lake	I(v)	1	0.07	0	0	0.03	0.05	0	0
Bedrock-dammed lake (B)	Cirque	B(c)	23	1.56	33	2.24	2.22	3.35	1.38	2.09
	Others bedrock-dammed lake	B(o)	193	13.09	237	16.08	7.25	10.96	5.20	7.87
Others		O	65	4.41	5	0.34	22.98	34.76	0.31	0.47
Total			**1,142**	**77.48**	**332**	**22.52**	**58.26**	**88.15**	**7.83**	**11.85**

Figure 4.9: **Distribution on glacier fed and non-glacier fed lakes in basins of the Amu Darya River Basin**

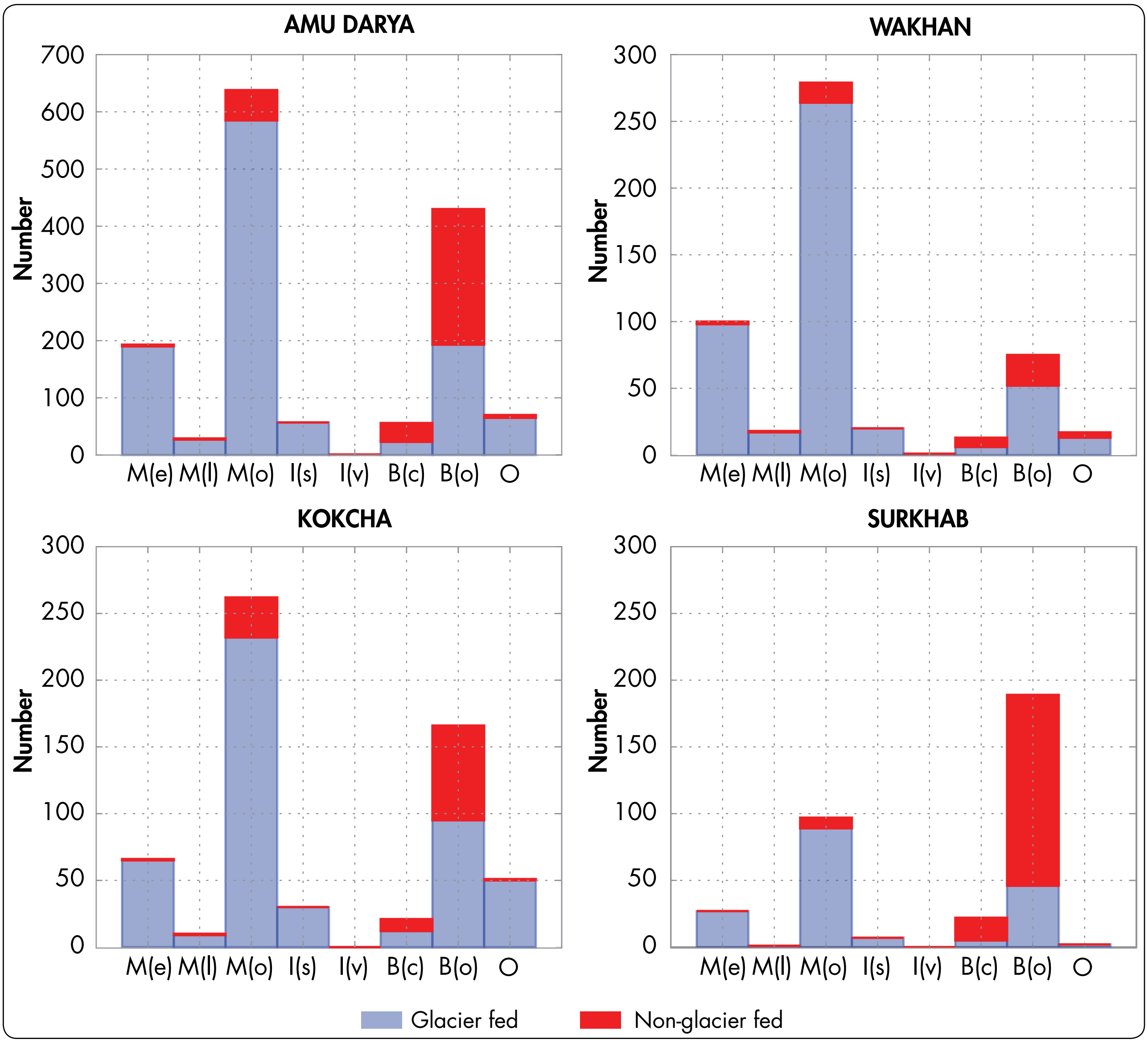
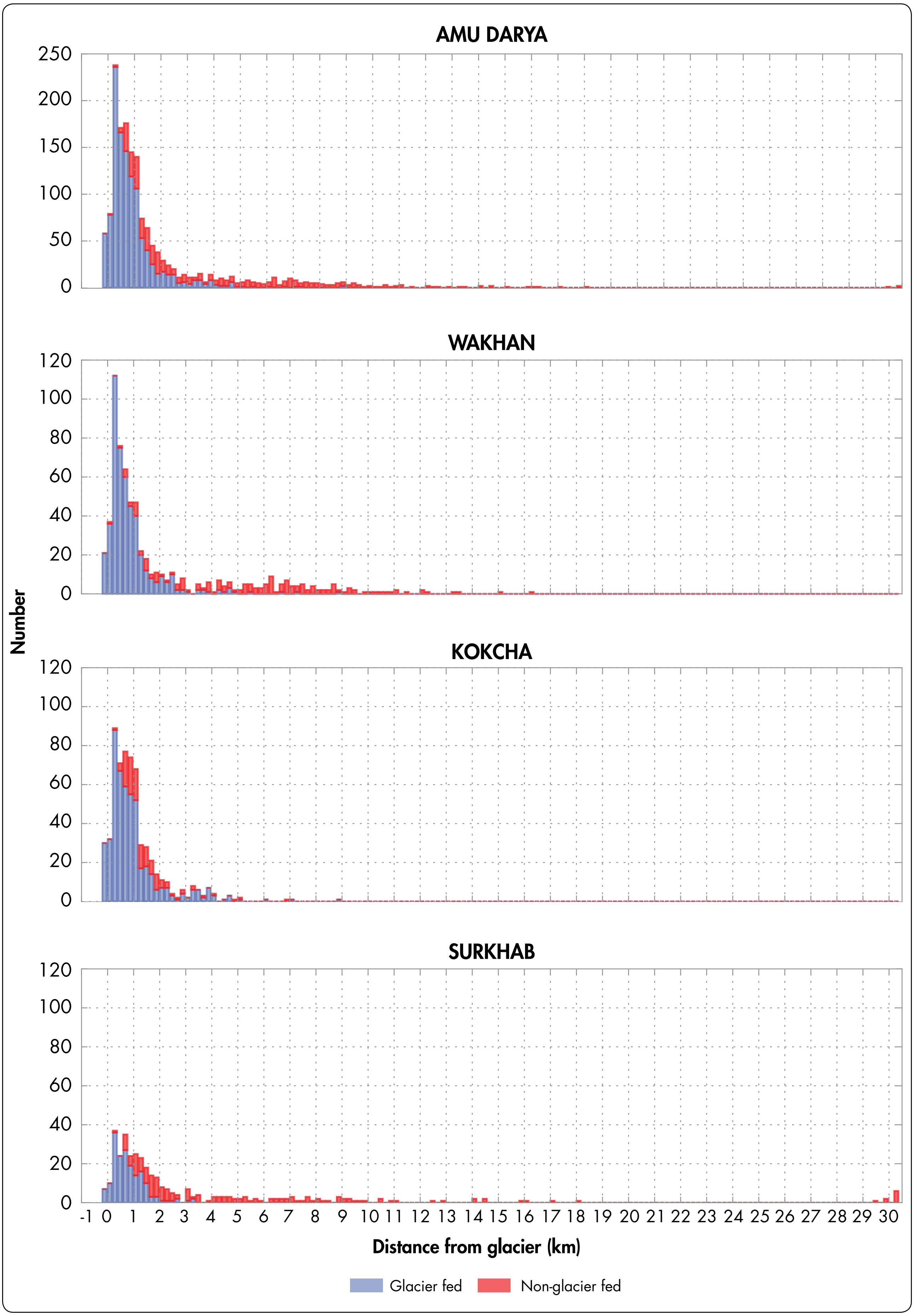


Figure 4.10: **Histogram showing the number of glacier fed and non-glacier fed glacial lakes within 100 m bin distance from the glacier in Amu Darya River Basin**



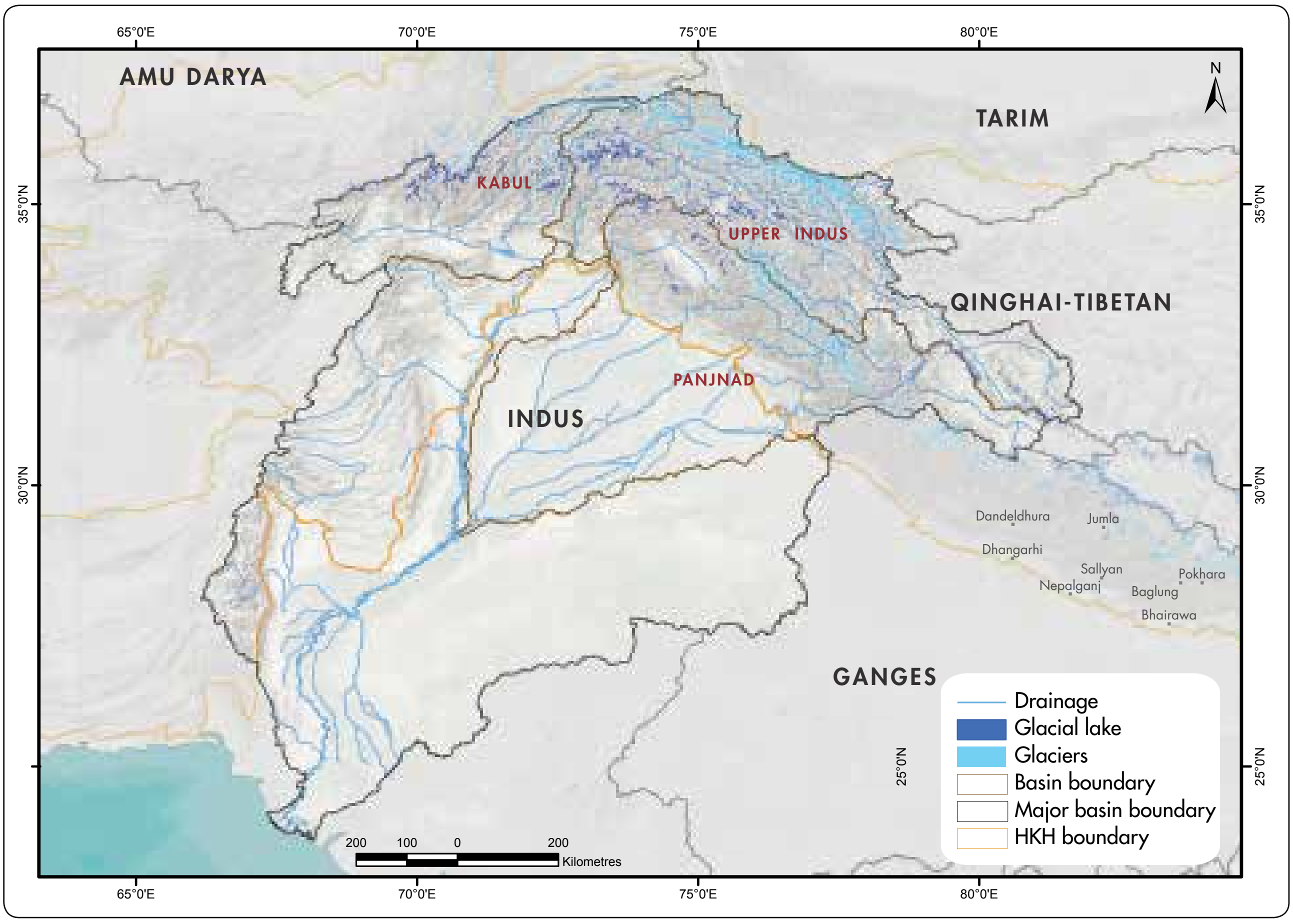
Indus River Basin

The Indus River is the main source of water in Pakistan. It originates from the Tibet Autonomous Region of China and flows first northwest then turns southwest at Gilgit in Pakistan. The main river of Indus flows through north to west of Pakistan and some major tributaries such as Sutlej, Ravi, Chenab, Beas, and Jhelum flow from India to Pakistan whereas Kabul River flows from Afghanistan to Pakistan.

Glacier and glacial lakes are mostly distributed in the northern upper reach of the basin. The glacial lakes are concentred between 36°57′25.2″ N and 30°30′57.6″ N latitude and 81°36′3.6′ E and 68°45′0″ E longitude in the basin. Thirty tiles of Landsat cover the glaciated region of the upper reach of the Indus Basin. In total, 63 Landsat images were used to map the glacial lakes in the Indus Basin.

The upper reach of the Indus Basin is divided into three basins: Kabul Basin flows from Afghanistan to Pakistan, Upper Indus Basin flows from China to Pakistan, and Panjnad Basin flows from China–India to Pakistan. The distribution of glacial lakes in these basins is shown in Figure 4.11 and details are given in Table 4.6.

Figure 4.11: **Distribution of glacial lakes in Indus River Basin**



Number, area, and types

In total, 5,689 glacial lakes covering an area of 260.56 km^2 were identified in the Indus Basin, in which 24.3%, 57.2%, and 18.5% are distributed in Kabul, Upper Indus, and Panjnad Basins, respectively. The number of lakes is higher in Kabul Basin compared to Panjnad Basin but the area coverage is less, indicating that the lakes in Panjnad Basin are larger. The distribution of number and area coverages by lakes in various glacial lake types in each basin is summarized in Table 4.6.

The percentage distribution of various types of glacial lakes in each basin is shown in Figure 4.12. Comparatively the number and area of bedrock-dammed lakes is higher than moraine-dammed lakes. In total, more than 52.5% of total lakes are bedrock-dammed, with 14.9%, 28%, and 9.7% in Kabul, Upper Indus, and Panjnad Basins, respectively. Of the total lakes, 33.8% are identified as moraine-dammed, with 6.2%, 20%, and 7.6% in Kabul, Upper Indus, and Panjnad Basins, respectively. Only 8% of total lakes are classified as ice-dammed lakes.

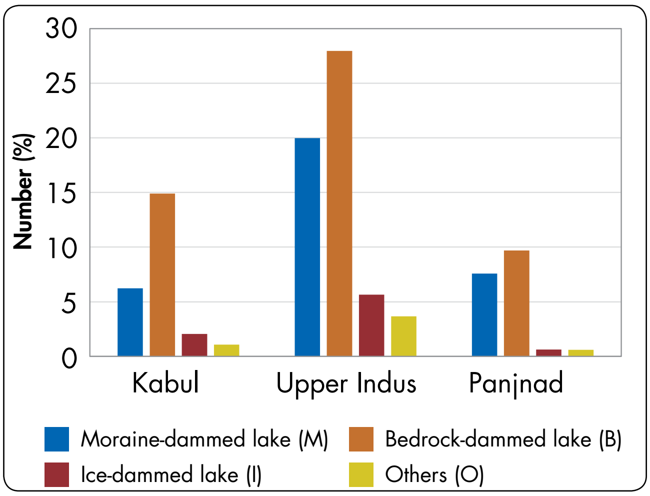
Table 4.6: **Number and area of different types of glacial lakes in Indus River Basin**

Basin			Kabul		Upper Indus		Panjnad		Total	
Type			Number	Area (km²)	Number	Area (km²)	Number	Area (km²)	Number	Area (km²)
Moraine-dammed lake (M)	End-moraine	M(e)	47	2.07	362	15.47	178	7.48	587	25.02
	Lateral moraine	M(l)	18	0.33	92	3.42	11	0.54	121	4.29
	Others	M(o)	290	7.54	683	23.61	242	7.92	1,215	39.07
Ice-dammed lake (I)	Supra-glacial lake	I(s)	117	0.90	310	3.55	34	0.30	461	4.75
	Glacier ice-dammed lake	I(v)	0	0.0	11	0.45	2	0.12	13	0.57
Bedrock-dammed lake (B)	Cirque	B(c)	124	11.24	157	15.14	97	14.45	378	40.83
	Others bedrock-dammed lake	B(o)	723	24.4	1,434	61.18	454	22.28	2,611	107.86
Others		O	61	6.02	208	23.12	34	9.03	303	38.17
Total			**1,380**	**54.5**	**3,257**	**145.94**	**1,052**	**62.12**	**5,689**	**260.56**

Glacial lake size

The smallest and largest glacial lakes in Indus Basin are 0.003 km² and 5.2 km². The largest one is in Panjnad Basin and is an other type lake. The highest number of lakes are class 2 (0.01 – <0.05 km²) consisting of more than 53% of total lakes covering 26.7% of the total glacial lake area. The second highest number of lakes are class 1 (<0.01 km²). The average lake size in the basin is 0.046 km² (Table 4.7).

Figure 4.12: **Percentage distribution of various types of glacial lakes in each basin of Indus River Basin**

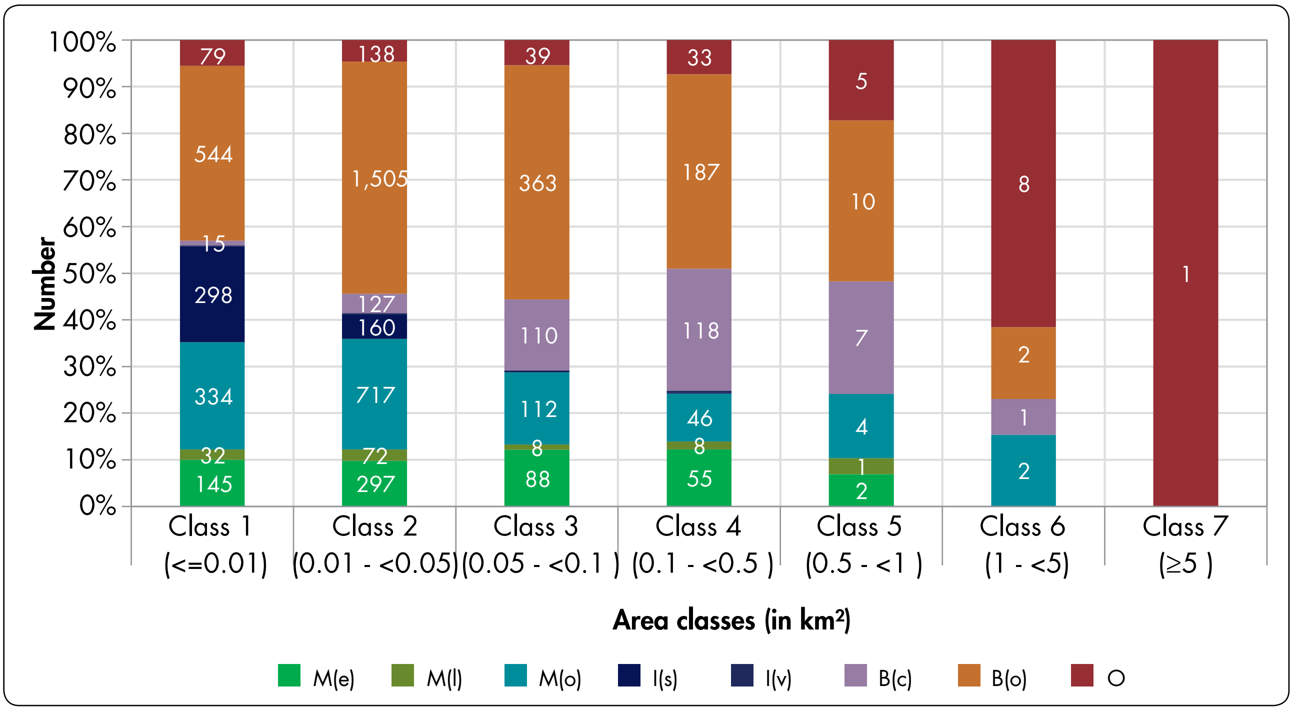


In all the glacial lake size classes, bedrock-dammed lakes are higher in number except in class 7 (≥5) which consists of only one lake of other type. Comparatively all types of lakes are higher in number in class 2 (0.01 – <0.05 km²) where more than 50% of total bedrock-dammed lakes are in the same class (Figure 4.13). Moraine-dammed lakes in class 1 and class 2 are 19% and 9% of lakes in the basin respectively. Only seven lakes in class 5 (0.5 – <1 km²) and two lakes in class 6 (1 – <5 km²) are identified as moraine-dammed.

Table 4.7: **Number and area of different size category of glacial lakes in Indus River Basin**

Glacial lake size	Number	%	Area (km²)	%	Average size (km²)
Class 1 (<0.01)	1,450	25.49	9.14	3.51	0.006
Class 2 (0.01 - <0.05)	3,023	53.14	69.51	26.68	0.023
Class 3 (0.05 - <0.1)	723	12.71	49.76	19.10	0.069
Class 4 (0.1 - <0.5)	450	7.91	83.79	32.16	0.186
Class 5 (0.5 - <1)	29	0.51	20.75	7.96	0.716
Class 6 (1 - <5)	13	0.23	22.38	8.59	1.722
Class 7 (≥5)	1	0.02	5.21	2.00	5.21
Total	**5,689**	**100.00**	**260.56**	**100**	**0.046**

Figure 4.13: **Percentage distribution of various types of glacial lakes within size classes of Indus River Basin**



Altitudinal distribution

The glacial lakes mapped in the basin are distributed between an elevation of 2,203 to 5,951 masl. The lowest elevation lake is an other type lake in the Gilgit Sub-basin. The distribution of number of glacial lakes in each 1,000 m elevation zone is given in Table 4.8. More than 65.7% of the lakes are distributed at an elevation zone of 4,000 – <5,000 masl in which about 41% are bedrock-dammed lakes and 18.6% are moraine-dammed lakes. About 14.8% and 19% of lakes lie in an elevation zone of 3,000 – <4,000 masl and 5,000 – <6,000 masl, respectively. Moraine-dammed lakes are comparatively higher in number at the higher elevation zone of 5,000 – <6,000 masl. All the lakes at lower elevation below 2,800 masl are bedrock-dammed and other types (Figure 4.14). Comparatively, the number of bedrock-dammed lakes is higher at elevation from 3,800 masl to 4,800 masl. Ice-dammed lakes were identified below 5,300 masl elevation and their numbers increased below 4,500 masl to 3,300 masl representing mostly supra-glacial lakes.

Table 4.8: **Distribution of lakes in each 1,000 m elevation zone in Indus River Basin**

Elevation zone			<3,000		3,000 – <4,000		4,000 – <5,000		5,000 – <6,000		Total	
Type			No.	%	No.	%	No.	%	No.	%	No.	%
Moraine-dammed lake (M)	End-moraine	M(e)	2	0.04	32	0.56	197	3.46	356	6.26	587	10.32
	Lateral moraine	M(l)	1	0.02	36	0.63	64	1.12	20	0.35	121	2.13
	Other morainedammed	M(o)	0	0	88	1.55	796	13.98	331	5.82	1,215	21.36
Ice-dammed lake (I)	Supra-glacial lake	I(s)	9	0.16	189	3.32	242	4.25	21	0.37	461	8.10
	Glacier ice-dammed lake	I(v)	0	0	0	0	5	0.09	8	0.14	13	0.23
	Other ice-dammed lake	I(o)	0	0	0	0	0	0	0	0	0	0
Bedrock-dammed lake (B)	Cirque	B(c)	0	0	84	1.48	267	4.69	27	0.47	378	6.64
	Others bedrock-dammed lake	B(o)	2	0.04	310	5.45	2,069	36.34	230	4.04	2,611	45.90
Others		O	14	0.25	100	1.76	101	1.77	88	1.55	303	5.33
Total			**28**	**0.49**	**839**	**14.74**	**3,741**	**65.71**	**1,081**	**19.00**	**5,689**	**100.0**

Figure 4.15 shows the percentage distribution of various sizes of lakes in each 1,000 m elevation zone. Twenty-eight lakes were identified at a lower elevation zone of 2,000 – <3,000 masl in which only two lakes lie below 2,500 masl of size classes 4 and 5. The highest number of lakes of size class 2 (0.01 – <0.05 km²) is about 36% and size class 1 (<0.01 km²) is 16.4% of total lakes lies at an elevation zone of 4,000 – <5,000 masl. The largest lake in this basin lies at an elevation of 4,670 masl.

Geographical distance from glacier

A large number of glacial lakes — more than 40% of the total lakes in the basin — are distributed within the distance of 500 m to 2 km from glaciers. Lakes area coverage is also more than 44% of total lake area in the basin. There are 474 lakes (8.3% of total lakes) within the glacier, which are ice-dammed lakes, and only 80 lakes are in contact with glaciers. More than 20% of the total lakes lie within a distance of up to 500 m from the glaciers. The detailed distribution of lakes with the distance of glaciers categorised into 10 classes is given in Table 4.9.

Figure 4.16 shows that the number of lakes and its area coverages decrease as the distance from glaciers increases. Mostly the number and area coverage is higher within the

Figure 4.14: **Altitudinal distribution of number and various types of lakes in Indus River Basin**

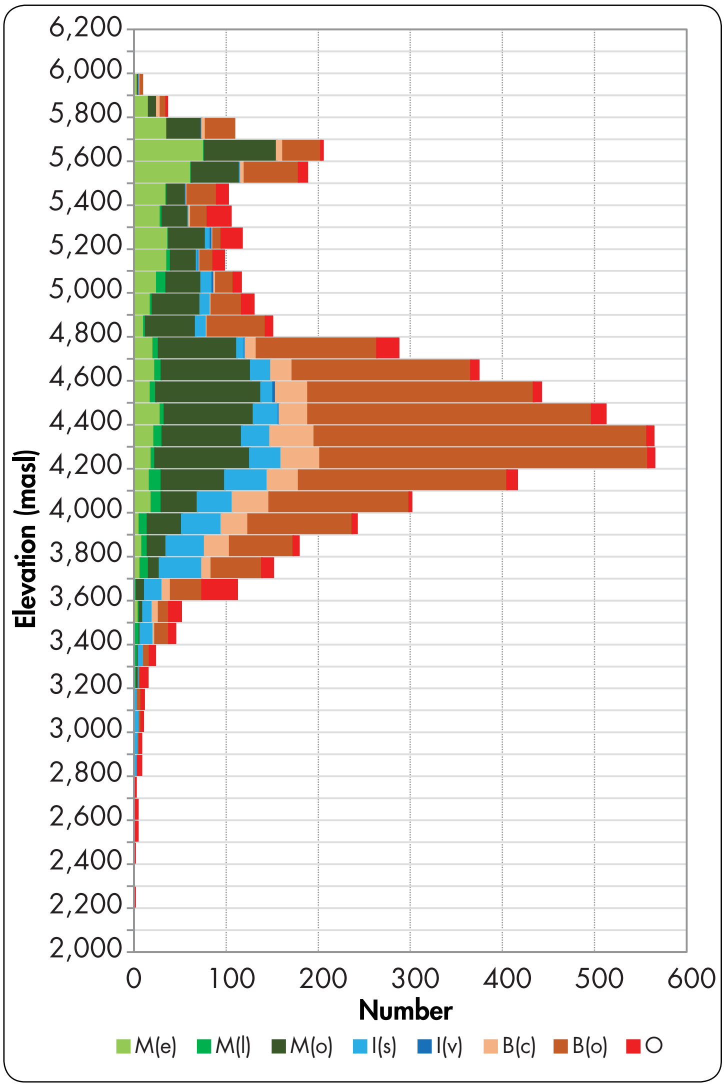
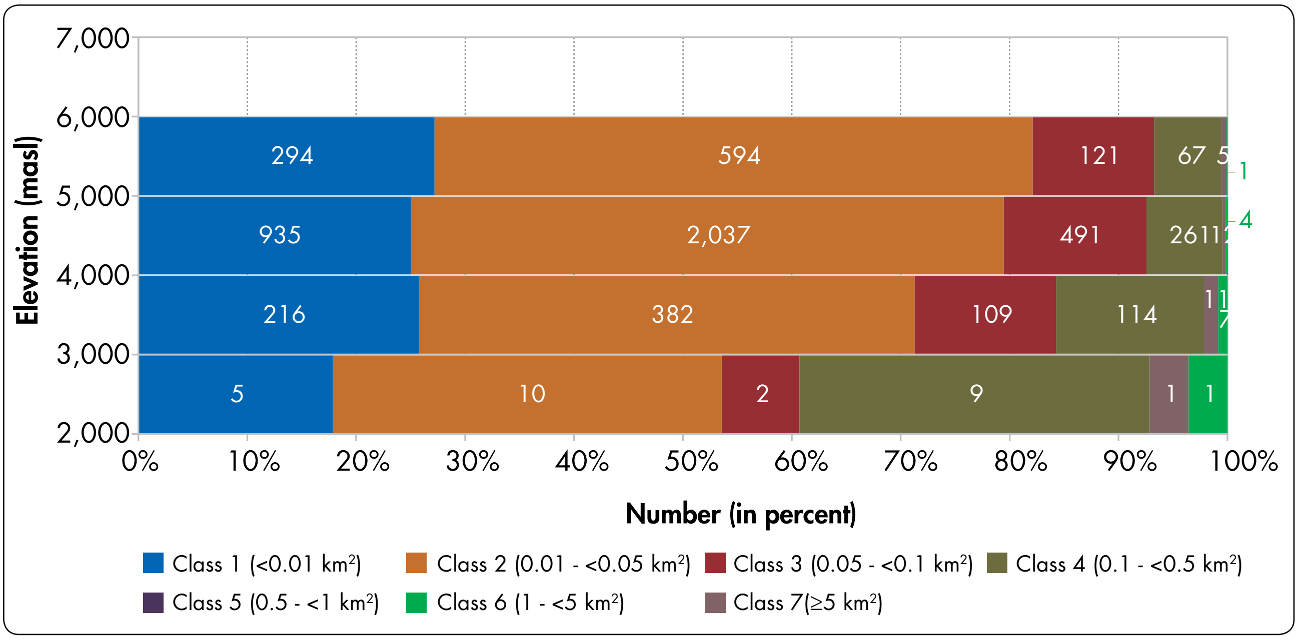


Figure 4.15: **Percentage distribution of different size of glacial lake within each 1,000 m elevation zone in Indus River Basin**



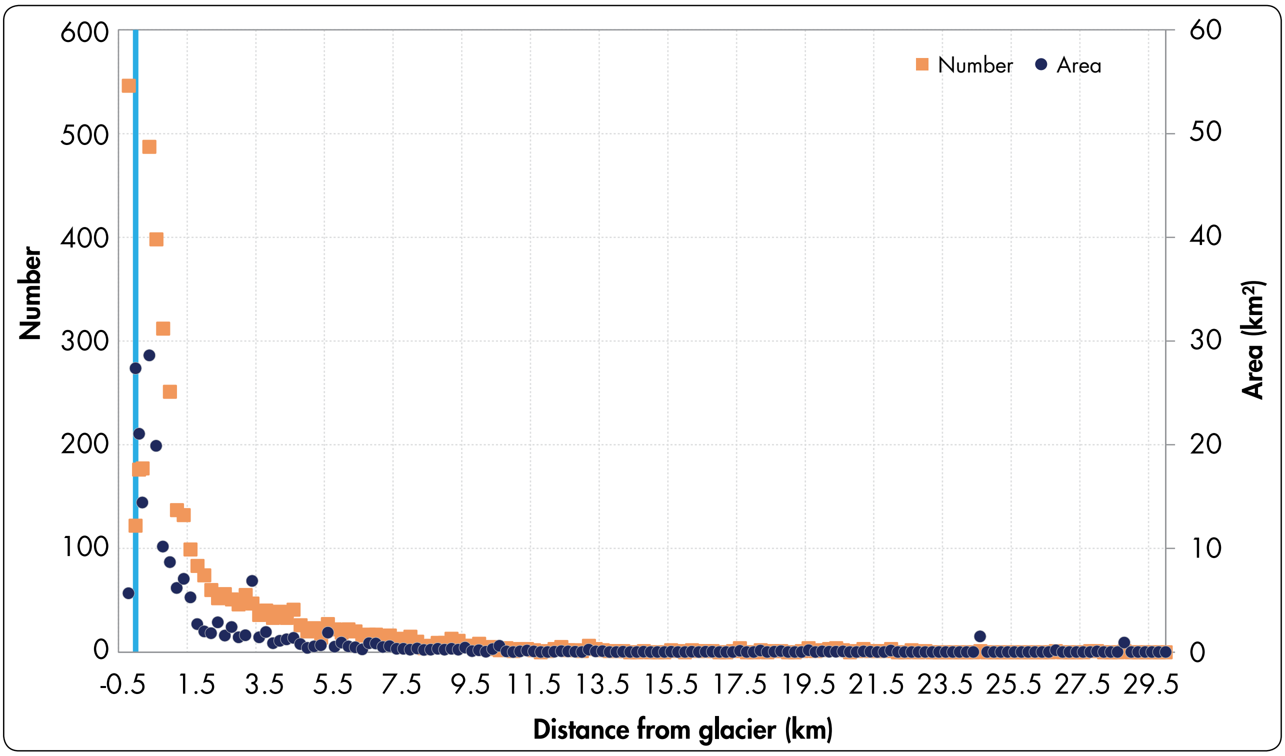
distance of 5 km from the glaciers. The lakes that lie closer to the glaciers are mostly fed by glacier melt and their size changes dynamically whereas lakes far away from the glacier may or may not be fed by glacier melts and their size does not change frequently. So the lakes closer to the glacier are very important for study not only in terms of water resources but also in terms of hazards. Many of the lakes closer to the glacier or basically in contact with the glaciers are growing very fast due to directly fed by glacier melt water into the lakes. Further study of these lakes is needed to identify the potential outburst.

Comparatively there are more bedrock-dammed lakes in this basin than moraine-dammed lakes but they lie mostly away from the glaciers, beyond 1 km, whereas moraine-dammed lakes are closer to the glacier with the highest concentration within 200 m to 2 km of the glaciers (Figure 4.17).

Table 4.9: **Distribution of glacial lakes and area in different distance from the glacier in Indus River Basin**

Distance from glaciers (m)	Number		Area	
	Count	%	km²	%
Within	474	8.3	5.31	2.0
Contact with	80	1.4	4.37	1.7
>0 – <100	189	3.3	9.68	3.7
100 – <200	219	3.8	6.44	2.5
200 – <500	748	13.1	26.94	10.3
500 – <1,000	1,177	20.7	55.56	21.3
1,000 – <2,000	1,142	20.1	58.91	22.6
2,000 – <5,000	911	16.0	44.09	16.9
5,000 – <10,000	421	7.4	30.45	11.7
≥10,000	328	5.8	18.80	7.2
Total	**5,689**	**100.0**	**260.55**	**100.0**

Figure 4.16: **Number and area distribution in the distance from glacier (blue line = snout of glacier) in Indus River Basin**



Glacier fed and non-glacier fed

Almost 54% of the total lakes in the Indus River Basin are fed by the glaciers in which more than 28% are moraine-dammed lakes (Table 4.10). Among 46.2% of the non-glacier fed lakes, more than 37.5% are bedrock-dammed lakes. The number of non-glacier fed bedrock-dammed lakes is higher in Upper Indus and Kabul Basins whereas fewer non-glacier fed lakes are identified in Panjnad Basin (Figure 4.18).

Figure 4.19 shows most of the glacier fed lakes are within the distance of 5 km of the glaciers and beyond 5 km distance from the glaciers are mostly non-glacier fed. More than 43.7% of total lakes in Indus River Basin lies within 5 km of the glaciers are glacier fed. Among 46.2% of total, almost 45.2% of lakes are beyond the 500 m distance from the glaciers (more than 45%) and 1% are within 500 m distance are non-glacier fed.

Figure 4.17: **Distribution of various types of lakes at distance from the glaciers in Indus River Basin**

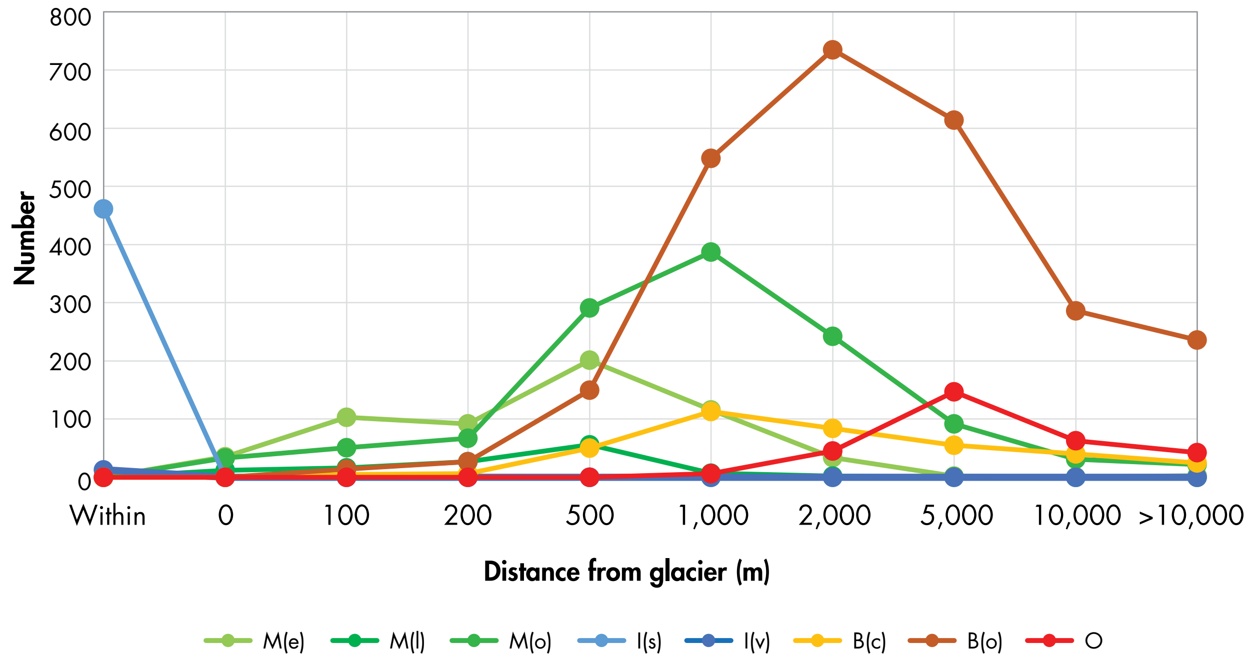


Table 4.10: **Glacier fed and non-glacier fed glacier lake distribution in different types of lakes**

Type			Number				Area (km²)			
			Glacier fed		Non-glacier fed		Glacier fed		Non-glacier fed	
			Count	%	Count	%	km²	%	km²	%
Moraine-dammed lake (M)	End-moraine	M(e)	574	10.09	13	0.23	24.65	9.46	0.37	0.14
	Lateral moraine	M(l)	120	2.11	1	0.02	4.24	1.63	0.03	0.01
	Other moraine-dammed	M(o)	910	16.00	305	5.36	29.24	11.22	9.83	3.77
Ice-dammed lake (I)	Supra-glacial lake	I(s)	461	8.1	0	0	4.75	1.82	0	0
	Glacier ice-dammed lake	I(v)	13	0.23	0	0	0.56	0.22	0	0
Bedrock-dammed lake (B)	Cirque	B(c)	130	2.29	248	4.36	19.08	7.32	21.75	8.35
	Others bedrock-dammed lake	B(o)	721	12.67	1,890	33.22	41.88	16.08	65.98	25.32
Others		O	131	2.3	172	3.00	23.26	8.93	14.90	5.72
Total			**3,060**	**53.79**	**2,629**	**46.21**	**147.67**	**56.68**	**112.86**	**43.32**

Figure 4.18: **Distribution on glacier fed and non-glacier fed lakes in basins of the Indus River Basin**

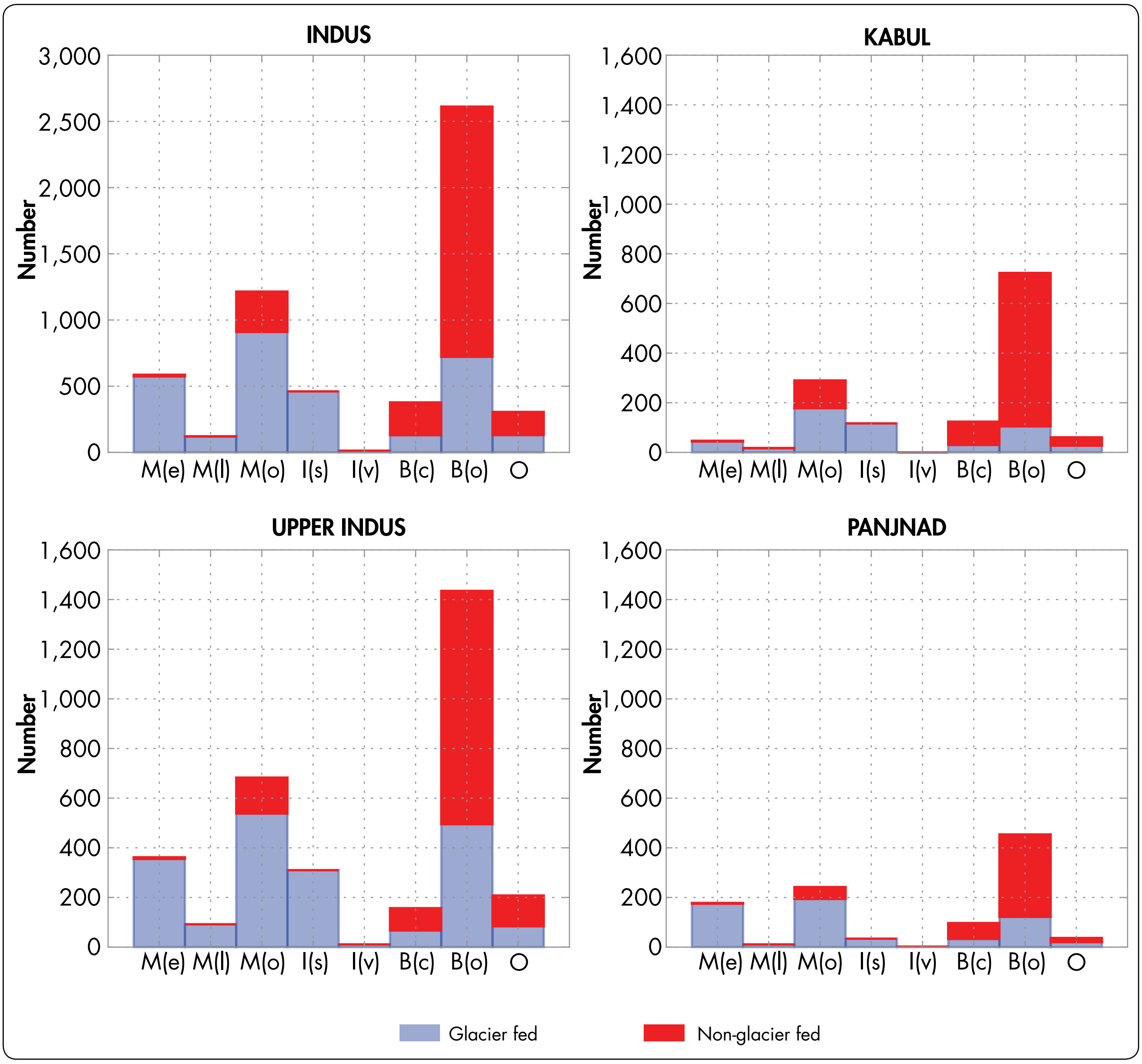
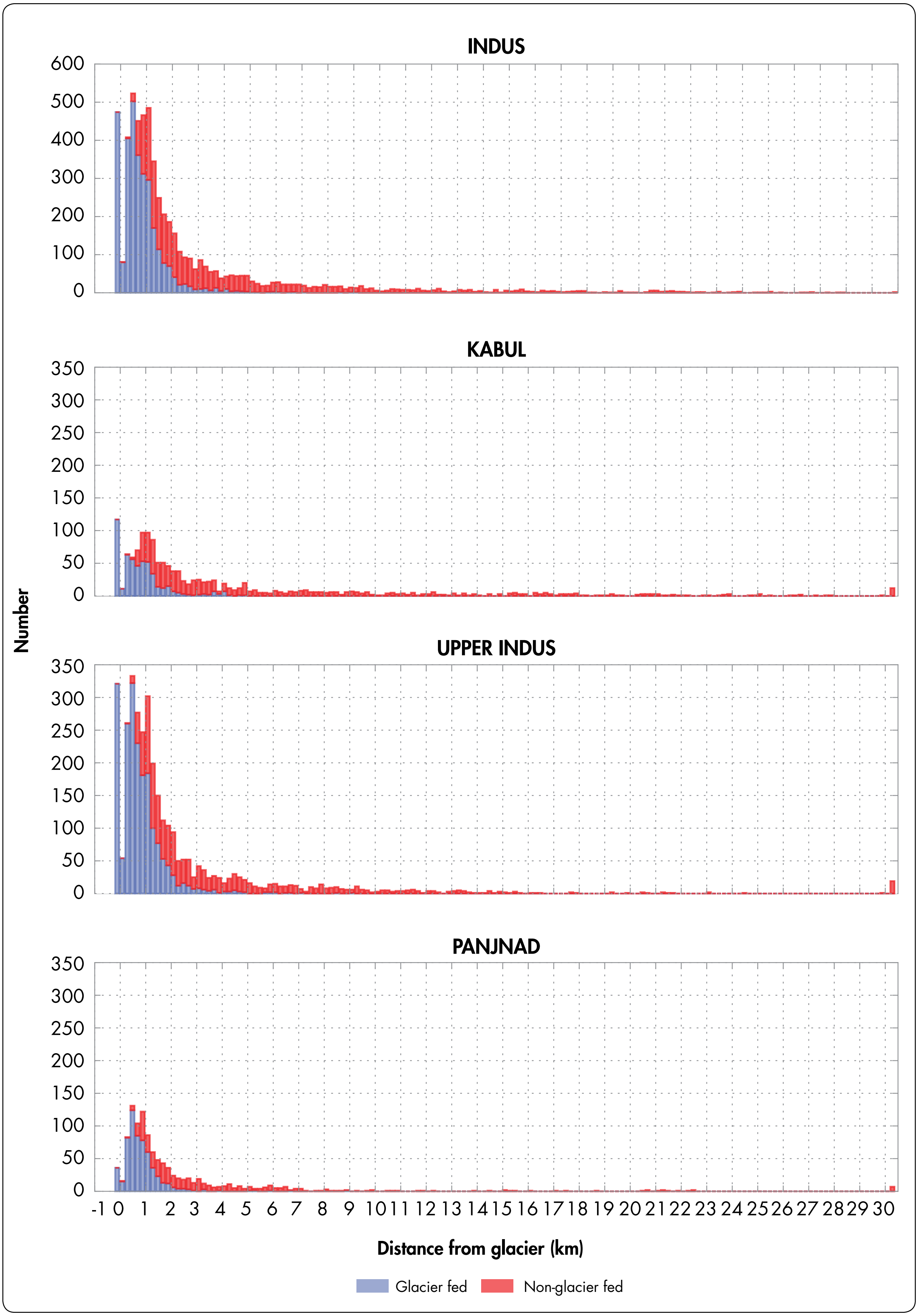


Figure 4.19: **Histogram showing the number of glacier fed and non-glacier fed glacial lakes within 100 m bin distance from the glacier in Indus River Basin**



Ganges River Basin

The Ganges (Ganga) River is one of the major rivers of the Indian subcontinent and is the major water resource for the peoples of India, China, Nepal, and Bangladesh. It forms at Devprayag at the confluence of the Bhagirathi and Alaknanda Rivers. The Bhagirathi River originates from Gaumukh (3,920 masl), the terminus of the Gangotri Glacier in Uttarakhand, India. The Alaknanda River, also known as the Vishnu Ganga, originates from the terminus of the Satopanth and Bhagirath Kharak Glaciers, which rise from Chaukhamba Mountain in Uttarakhand, India. Many major tributaries feed into the Alaknanda River, including the Dhauliganga, Nandakini, Pindar, Mandakini, and Bhagirathi. The confluences of these five major rivers with Alaknanda are known as Panch Prayag and all are considered sacred. Further down, the Ganges is joined by major tributaries from Nepal: the Karnali, Gandaki (Narayani), and Koshi Rivers.

Glacier and glacial lakes are mostly distributed in the northern upper reach of the basin, which is divided into five basins and 26 sub-basins. The largest tributaries of the Ganges are the Yamuna, Upper Ganga, Karnali (Ghagara in India) from western Nepal, Gandaki (Narayani) from central Nepal, and the Koshi from eastern Nepal.

Sixteen tiles of Landsat cover the glaciated region of the Ganges River Basin. In total, 79 Landsat images were used to map the glacial lakes in the basin.

The glacial lakes in the Ganges River Basin are distributed between 31°23′52.8″ N and 27°26′13.2″ N latitude and 88°43′12″ E and 78°5′16.8″ E longitude. The distribution of glacial lakes in the larger basins of the Ganges is shown in Figure 4.20 and details are given in Table 4.11.

Figure 4.20: **Distribution of glacial lakes in Ganges River Basin**

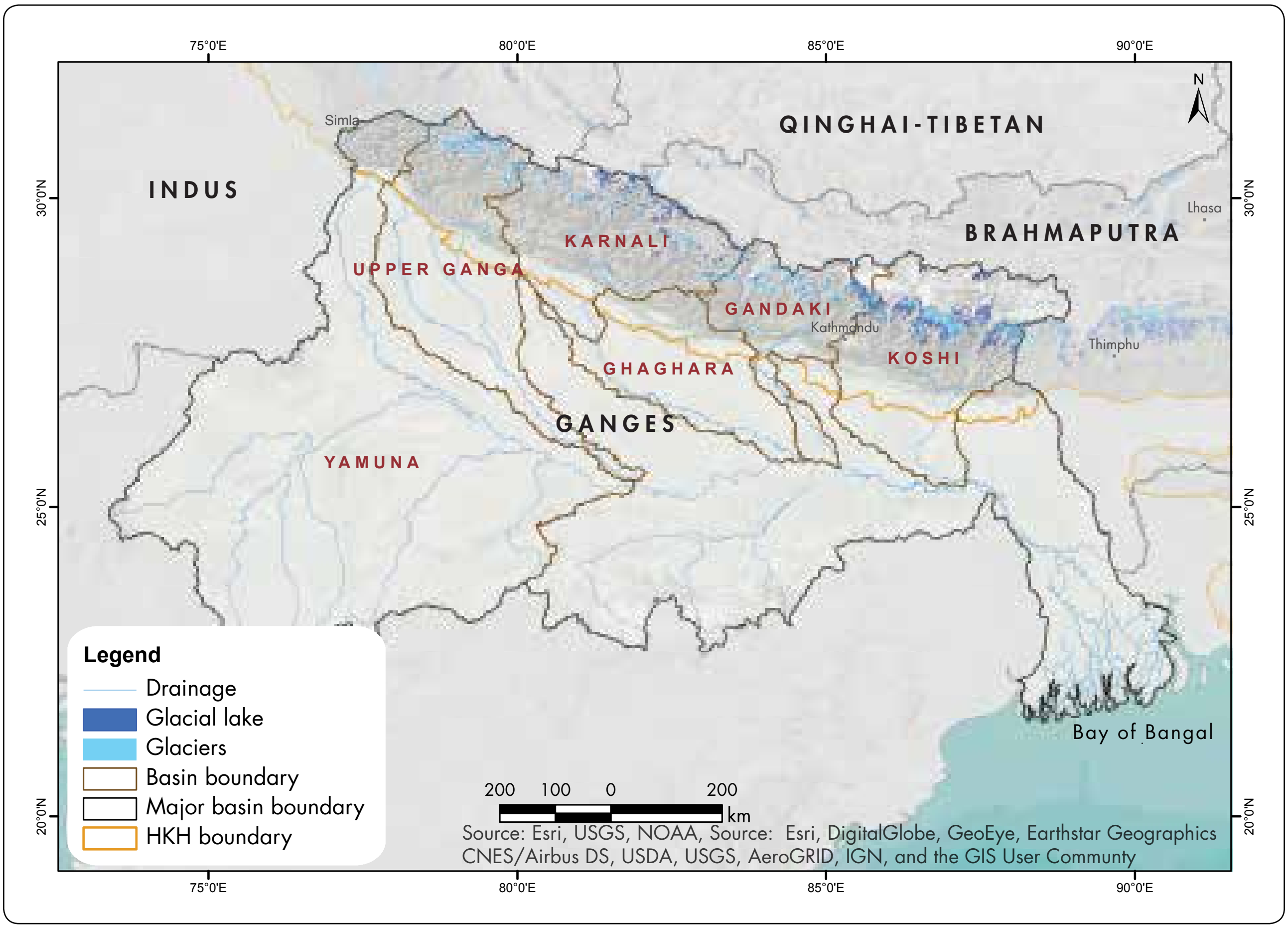


Table 4.11: **Number and area of different type of glacial lakes in Ganges River Basin**

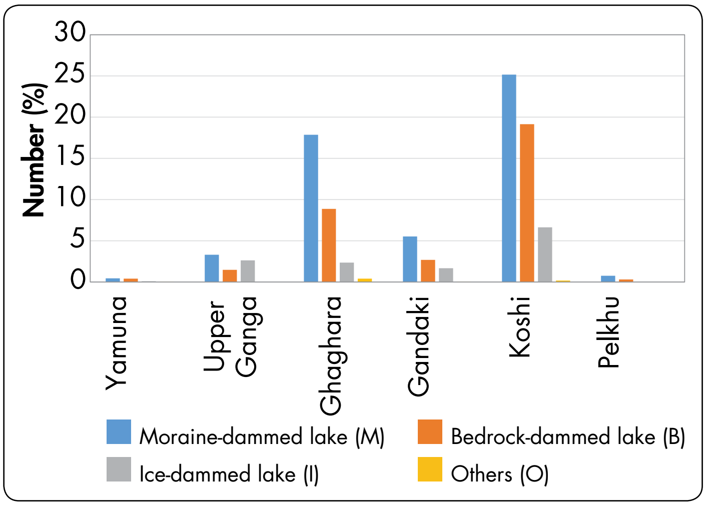
Basin			Yamuna		Upper Ganga		Ghaghara		Gandaki		Koshi		Pelkhu		Total	
Type			Number	Area (km^2)	Number	Area (km^2)	Number	Area (km^2)	Number	Area (km^2)	Number	Area (km^2)	Number	Area (km^2)	Number	Area (km^2)
Moraine-dammed lake (M)	End-moraine	M(e)	5	0.09	25	1.03	135	11.45	73	9.18	332	68.08	17	14.46	587	103.28
	Lateral moraine	M(l)	1	0.01	10	0.25	26	2.19	16	1.4	43	7.18	1	0.12	97	11.15
	Other morainedammed	M(o)	12	0.15	100	1.44	568	13.44	137	3.3	652	11.96	13	0.72	1,482	31.00
Ice-dammed lake (I)	Supra-glacial lake	I(s)	4	0.04	104	0.77	93	0.88	68	0.72	270	3.17	0	0	539	5.58
	Glacier ice-dammed lake	I(v)	0	0	3	0.06	3	0.03	0	0	1	0.01	0	0	7	0.1
Bedrock-dammed lake (B)	Cirque	B(c)	5	0.28	17	0.63	119	5.42	22	1.11	132	7.14	4	0.13	299	14.70
	Other bedrock-dammed lake	B(o)	12	0.29	43	1.0	243	5.91	88	2.03	650	24.44	9	0.69	1,045	34.35
Others		O	1	0.01	0	0	17	6.27	1	0.02	7	2.13	0	0	26	8.43
Total			**40**	**0.87**	**302**	**5.18**	**1,204**	**45.59**	**405**	**17.76**	**2,087**	**123.11**	**44**	**16.12**	**4,082**	**208.59**

Number, area, and types

In total, 4,082 lakes covering an area of 208.59 km^2 were mapped in the Ganges River Basin. The distribution of number, area, and types of lakes in five basins and one interior basin in Ganges are given in Table 4.11. The highest number of lakes, more than 51% of the total lakes in Ganges, are in Koshi Basin covering an area of 123.11 km^2. The second highest number of lakes, about 29.5% of total lakes, are in Ghaghara Basin. Only 40 lakes were mapped in the Yamuna Basin which covers only 0.87 km^2 indicating that the lakes are very small.

The percentage distribution of various types of glacial lakes in each basin is shown in Figure 4.21. Comparatively the number and area of moraine-dammed lakes are higher than bedrock-dammed, ice-dammed, and other type lakes in all the basins. More than 53.5% of total lakes are moraine-dammed — 25.3%, 17.8%, 5.5%, 3.3%, and 0.4% in Koshi, Ghaghara, Gandaki, Upper Ganga, and Yamuna Basins, respectively — and 33.5% are bedrock-dammed — 19.2%, 9%, 3%,1.5%, and 0.42% in Koshi, Ghaghara, Gandaki, Upper Ganga, and Yamuna Basins, respectively. Only 12.4% of total lakes are classified as ice-dammed lakes. The number and area of all types of lakes is highest in Koshi Basin.

Figure 4.21: **Percentage distribution of various types of glacial lakes in each basin of Ganges River Basin**



Glacial lake size

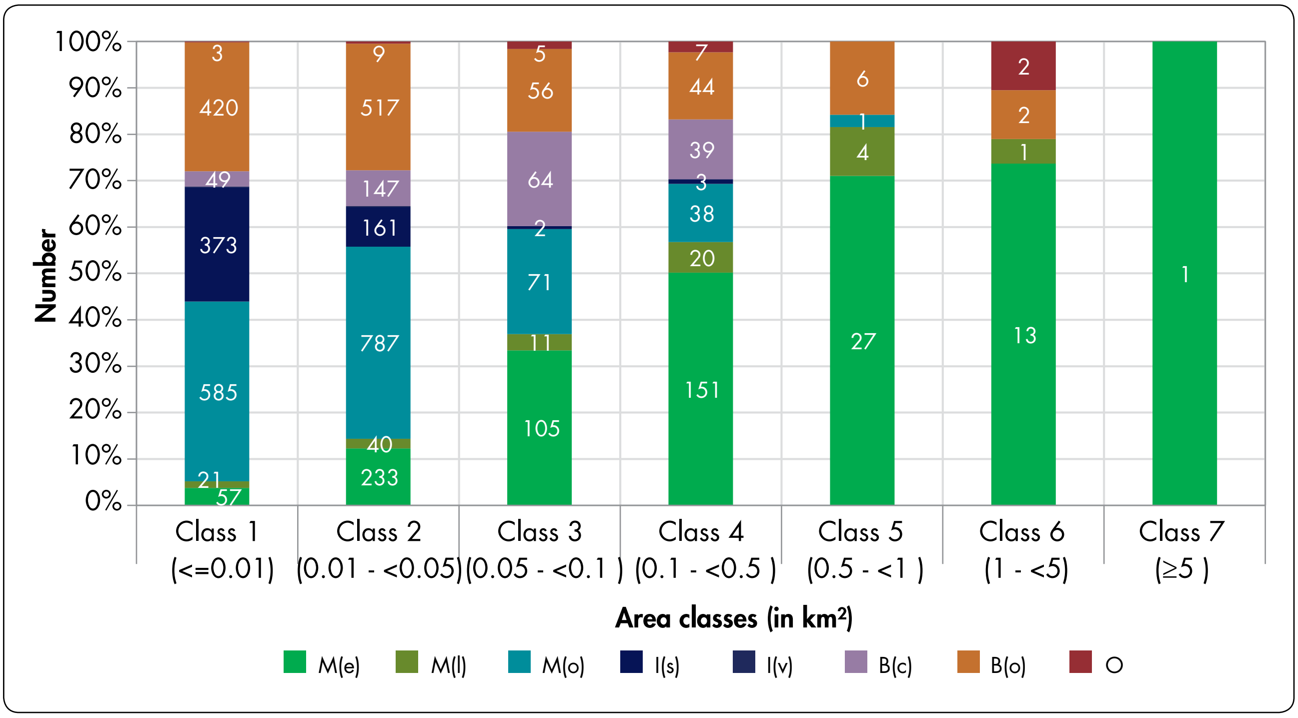
The smallest and largest glacial lakes in the Ganges River Basin are 0.003 km^2 and 5.35 km^2. The size of lakes are categorised into seven classes and distribution is given in Table 4.12. The largest lake is a moraine-dammed lake in Pelkhu Basin, which is the only class 7 lake (≥5 km^2). More than 83% of total lakes are <0.05 km^2 in which around 37% are class 1 (<0.01 km^2). Only 1.4% of lakes are size 0.5 – <5 km^2 and about 15% are of size 0.05 – <0.5 km^2. The number and area of the lakes in different size classes are inversely proportional. For smaller lakes the number is high and area is less whereas for larger lakes the number is less and area is high. The average size of each size class is less than 1 km^2 except in class 6 (1 – <5 km^2) and class 7 (≥5 km^2) in which the average size exceeded 2 km^2 and 5 km^2, respectively. The average size of lakes in the whole basin is just 0.051 km^2. Thus, the average size of glacial lakes in the Ganges River Basin is larger compared to the average size of the lakes in Amu Darya and Indus River Basins.

Figure 4.22 shows the percentage distribution of various types of glacial lakes within each size class. Number of Moraine-dammed lakes are higher in all size classes than bedrock-dammed lakes. The highest number of moraine-dammed lakes are class 2 (0.01 – <0.05 km^2), which is about 26% of the total number of lakes. The highest

Table 4.12: **Number and area of different size category of glacial lakes in Ganges River Basin**

Glacial lake size	Number	%	Area (km^2)	%	Average size (km^2)
Class 1 (<0.01)	1,510	36.99	9.31	4.46	0.006
Class 2 (0.01 - <0.05)	1,899	46.52	40.33	19.33	0.021
Class 3 (0.05 - <0.1)	314	7.69	22.07	10.58	0.070
Class 4 (0.1 - <0.5)	302	7.40	60.19	28.86	0.199
Class 5 (0.5 - <1)	38	0.93	28.12	13.48	0.740
Class 6 (1 - <5)	18	0.44	43.22	20.72	2.401
Class 7 (≥5)	1	0.02	5.35	2.56	5.350
Total	**4,082**	**100**	**208.59**	**100.00**	**0.051**

Figure 4.22: **Percentage distribution of various types of glacial lakes within size classes of Ganges River Basin**



number of bedrock-dammed lakes are of class 2 (0.01 – <0.05 km²), which is about 16.5% of total lakes. The highest number of ice-dammed lakes, about 9.2% of total number of lakes, are class 1 (<0.01 km²). Compared to other major river basins, Ganges River Basin consists of a larger number of moraine-dammed lakes.

Altitudinal distribution

The lowest and highest elevations of glacial lakes mapped in the Ganges River Basin are 2,462 masl and 6,190 masl. The lowest elevation lake is an other type lake in Gandaki Basin and the only lake mapped below 3,000 m, and the highest elevation is a bedrock-dammed lake in Koshi Basin and the only lake mapped above 6,000 m. The elevations of the remaining mapped lakes range between 3,200 masl and 6,000 masl. The distribution of the number of lakes in each 1,000 m elevation zone is given in Table 4.13. The highest number of lakes is identified at an elevation zone of 5,000 – <6,000 masl, which contains more than 57% of the total number of lakes in Ganges River Basin. Of the lakes within this zone, 36% are moraine-dammed, 15% are bedrock-

Table 4.13: **Distribution of lakes in each 1000 m elevation zone in Ganges River Basin**

Elevation zone			<3,000		3,000 – <4,000		4,000 – <5,000		5,000 –<6,000		6,000 – <7,000		Total	
Type			No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Moraine-dammed lake (M)	End-moraine	M(e)	0	0	5	0.12	181	4.43	401	9.82	0	0	587	14.38
	Lateral moraine	M(l)	0	0	0	0	59	1.45	38	0.93	0	0	97	2.38
	Other moraine-dammed	M(o)	0	0	12	0.29	439	10.75	1031	25.26	0	0	1,482	36.31
Ice-dammed lake (I)	Supra-glacial lake	I(s)	0	0	7	0.17	291	7.13	241	5.90	0	0	539	13.20
	Glacier ice-dammed lake	I(v)	0	0	0	0	2	0.05	5	0.12	0	0	7	0.17
Bedrock-dammed lake (B)	Cirque	B(c)	0	0	7	0.17	212	5.19	80	1.96	0	0	299	7.32
	Others bedrock-dammed lake	B(o)	0	0	12	0.29	498	12.20	534	13.08	1	0.02	1,045	25.60
Others		O	1	0.02	7	0.17	16	0.39	2	0.05	0	0	26	0.64
Total			**1**	**0.02**	**50**	**1.22**	**1,698**	**41.60**	**2,333**	**57.13**	**1**	**0.02**	**4,082**	**100**

dammed, and just 6% are ice-dammed. Almost 99% of the total lakes in the Ganges River Basin are within the elevation range 4,000 – <6,000 masl with the highest concentration between 4,900 masl to 5,600 masl (Figure 4.23). In this river basin, the proportion of moraine-dammed lakes is higher than bedrock-dammed lakes.

Figure 4.23: **Altitudinal distribution of number and various types of lakes in Ganges River Basin**

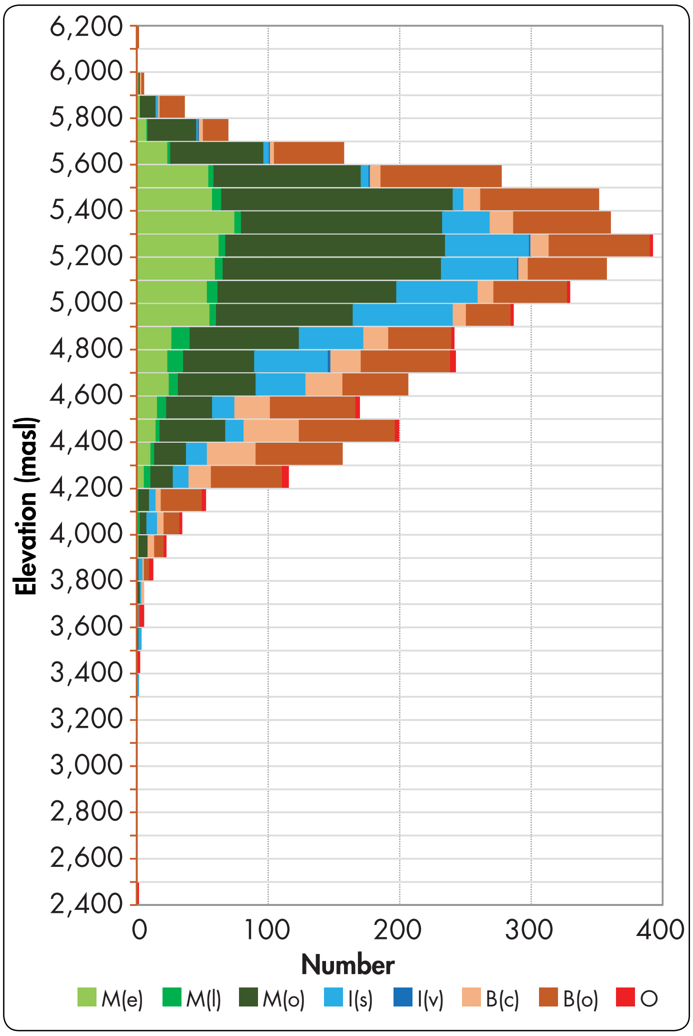


Figure 4.24 shows the distribution of various sizes of lakes in 1,000 m elevation zones. The single lake mapped at an elevation of 2,000 – <3,000 masl is class 2 (0.01 – <0.05 km²) and the single lake mapped at 6,000 – <7,000 masl is class 1 (<0.01 km²). Of all the other lakes, 26.63% and 19.34% of class 2 lakes (0.01 – <0.05 km²) are distributed at elevation zones of 5,000 – <6,000 masl and 4,000 – <5,000 masl, respectively. The second highest number, 20.95% and 15.62% of total lakes of class 1 (<0.01 km²), are distributed at elevation zones of 5,000 – <6,000 masl and 4,000 – <5,000 masl, respectively.

Geographical distance from glacier

The lakes within the glaciers (Ice-dammed) are higher in number compared to other River Basins. It consists of 546 numbers which is 13.4% of total number of lakes in the basin. Also the lakes in contact with the glaciers (160 in numbers) are second highest number compared to other River Basins. The highest number of lakes are concentrated within 200 m to 5 km of glaciers, almost 64% of total lakes lie within this zone. The detail distribution of number and area of lakes at distance from glaciers is given in Table 4.14. Figure 4.25 shows the distribution of lakes closer to the glacier is higher in number as well as area.

Figure 4.24: **Percentage distribution of different size of glacial lake within each 1000 m elevation zone**

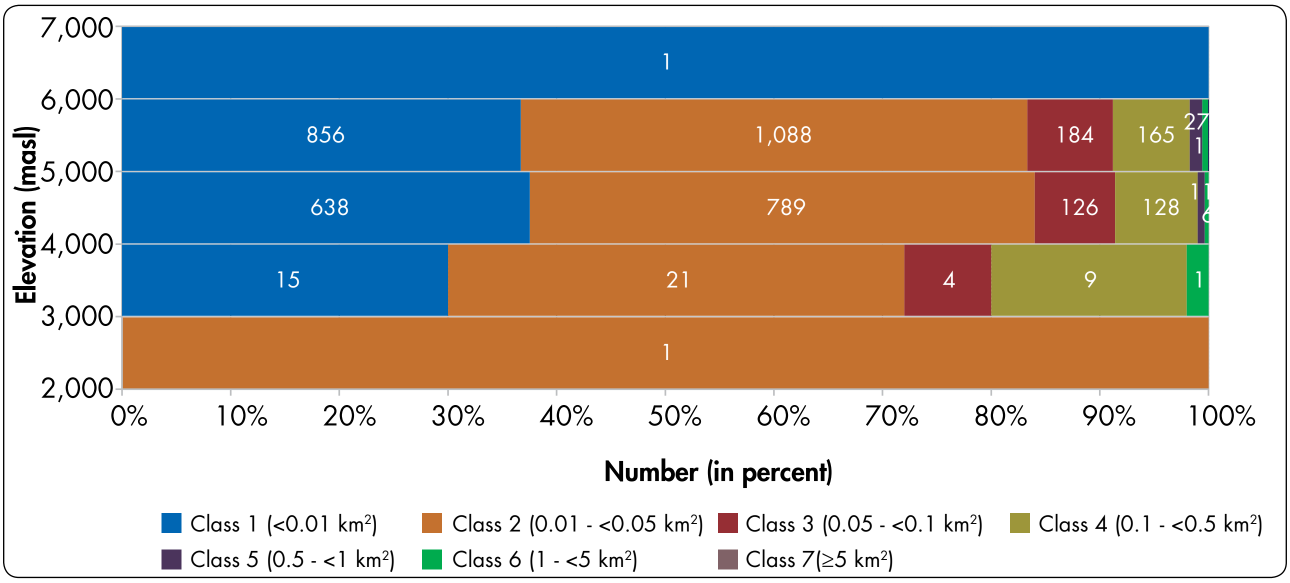
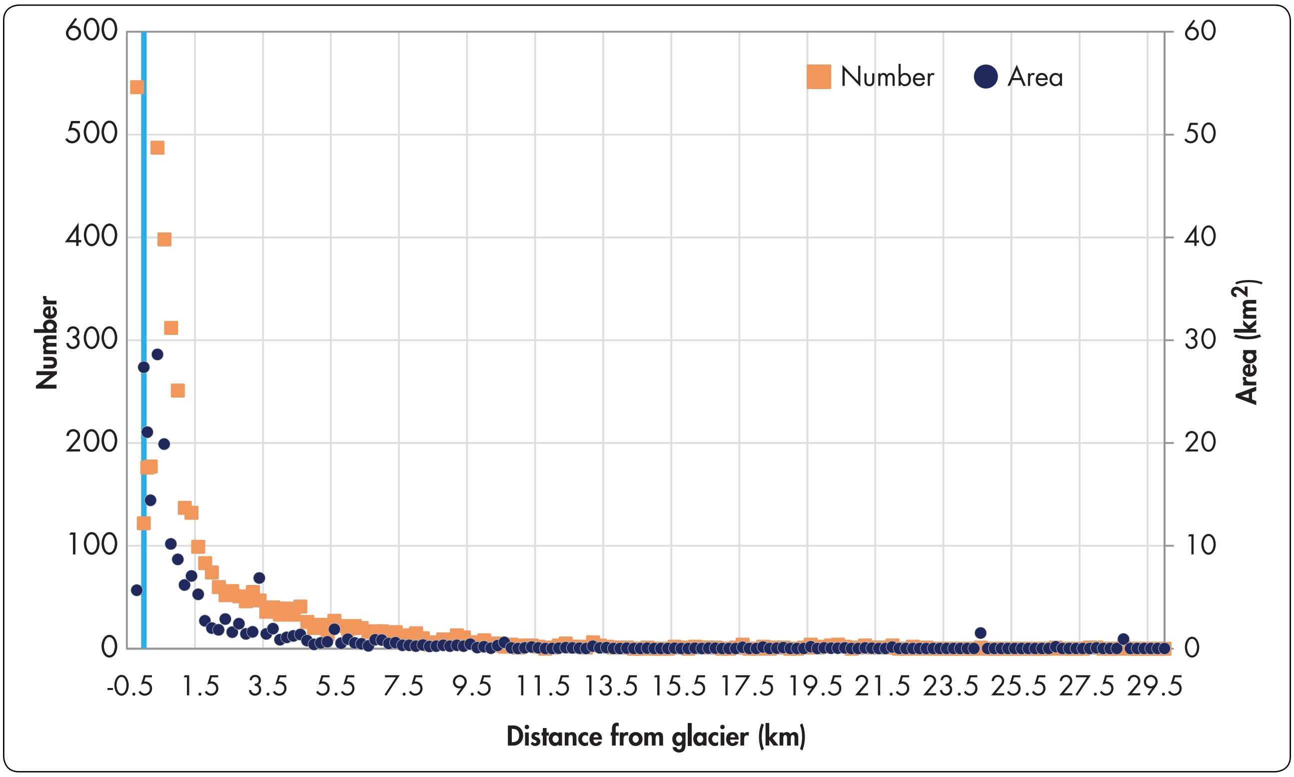


Table 4.14: **Distribution of glacial lake and area at distance from the glacier in Ganges River Basin**

Distance from glaciers (m)	Number		Area	
	Count	%	km²	%
Within	546	13.4	5.68	2.7
Contact with	122	3.0	27.35	13.1
>0 – <100	176	4.3	21.05	10.1
100 – <200	177	4.3	14.40	6.9
200 – <500	703	17.3	38.50	18.5
500 – <1,000	745	18.3	28.81	13.8
1,000 – <2,000	525	12.9	23.18	11.1
2,000 – <5,000	635	15.6	27.59	13.2
5,000 – <10,000	342	8.4	11.93	5.7
≥10,000	111	2.7	10.09	4.8
Total	**4,082**	**100.0**	**208.59**	**100.0**

Figure 4.25: **Number and total area distribution at the distance from glacier (blue line = snout of glacier) in 200 m zone**



Mostly the lakes away from the glaciers are bedrock-dammed and other types. The highest number of moraine-dammed lakes are concentrated within 5,000 m of the glacier (Figure 4.26).

Glacier fed and non-glacier fed

Almost 62% of the total lakes in Ganges River Basin are fed by the glaciers in which more than 41% are moraine-dammed lakes (Table 4.15). Non-glacier fed bedrock-dammed lakes are higher in number. Among 38% of the non-glacier fed lakes, more than 25.8% of the lakes are bedrock-dammed. The number of non-glacier fed bedrock-dammed lakes is higher in Koshi and Ghaghara Basins whereas comparatively fewer non-glacier fed lakes are identified in Upper Ganga Basin (Figure 4.27).

Figure 4.26: **Distribution of various types of lakes in the distance from the glaciers**

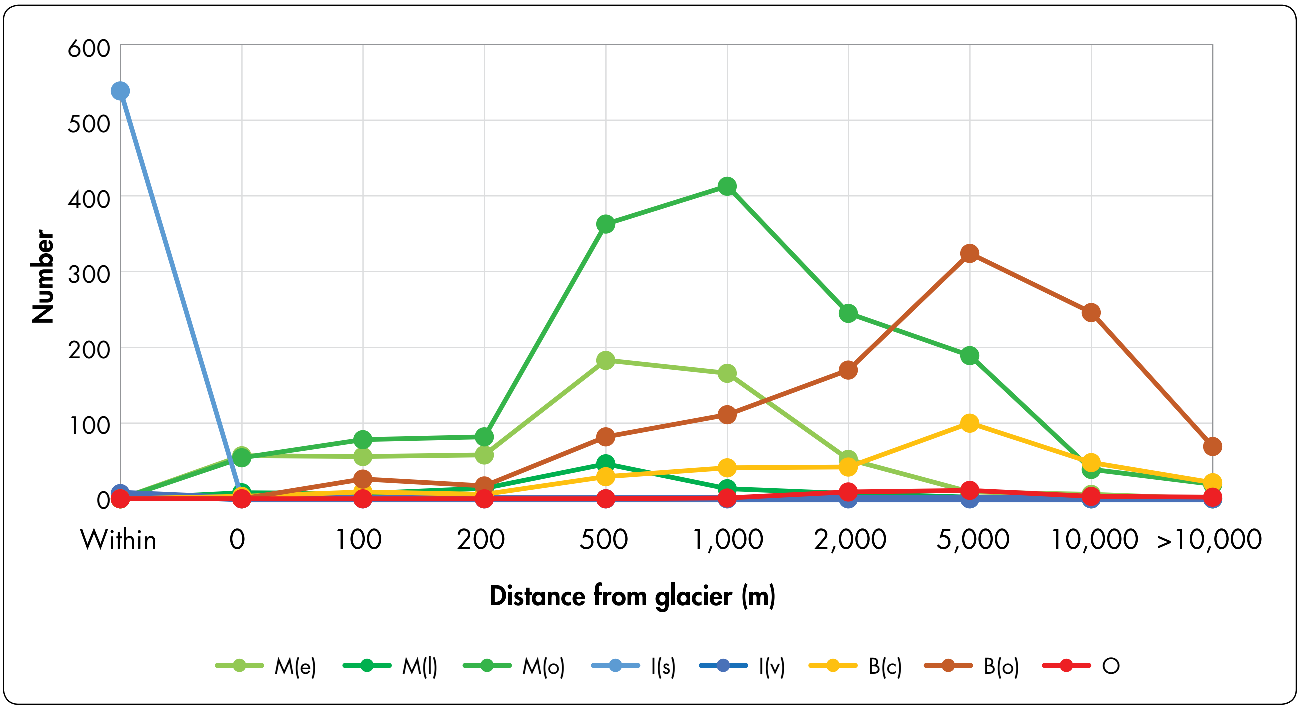


Table 4.15: **Glacier fed and non-glacier fed glacier lake distribution in different types of lakes**

Type			Number				Area (km²)			
			Glacier fed		Non-glacier fed		Glacier fed		Non-glacier fed	
			Count	%	Count	%	km²	%	km²	%
Moraine-dammed lake (M)	End-moraine	M(e)	549	13.45	38	0.93	99.96	47.92	3.32	1.59
	Lateral moraine	M(l)	92	2.25	5	0.12	10.59	5.08	0.56	0.27
	Other moraine-dammed	M(o)	1,036	25.38	446	10.93	20.58	9.87	10.42	5.00
Ice-dammed lake (I)	Supra-glacial lake	I(s)	539	13.20	0	0	5.58	2.68	0	0
	Glacier ice-dammed lake	I(v)	7	0.17	0	0	0.1	0.05	0	0
Bedrock-dammed lake (B)	Cirque	E(c)	70	1.71	229	5.61	3.72	1.79	10.98	5.26
	Others bedrock-dammed lake	E(o)	218	5.34	827	20.26	7.74	3.71	26.61	12.76
Others		O	16	0.39	10	0.24	7.88	3.78	0.55	0.26
Total			**2,527**	**61.91**	**1,555**	**38.09**	**156.15**	**74.86**	**52.44**	**25.14**

Figure 4.28 shows that most of the lakes within the distance of 2 km from the glaciers are glacier fed and beyond 2 km distance from the glaciers are non-glacier fed. More than 44% of total lakes in Ganges River Basin are within 2 km of the glaciers and 1.3% from 2 to 5 km distance from the glaciers are fed by glaciers. Only three lakes beyond 5 km from the glaciers are identified as glacier fed lakes. 38% of the lakes in the basin is non-glacier fed whereas more than 25% of total lakes are beyond 2 km from the glaciers.

Figure 4.27: **Distribution of glacier fed and non-glacier fed lakes in basins of the Ganges River Basin**

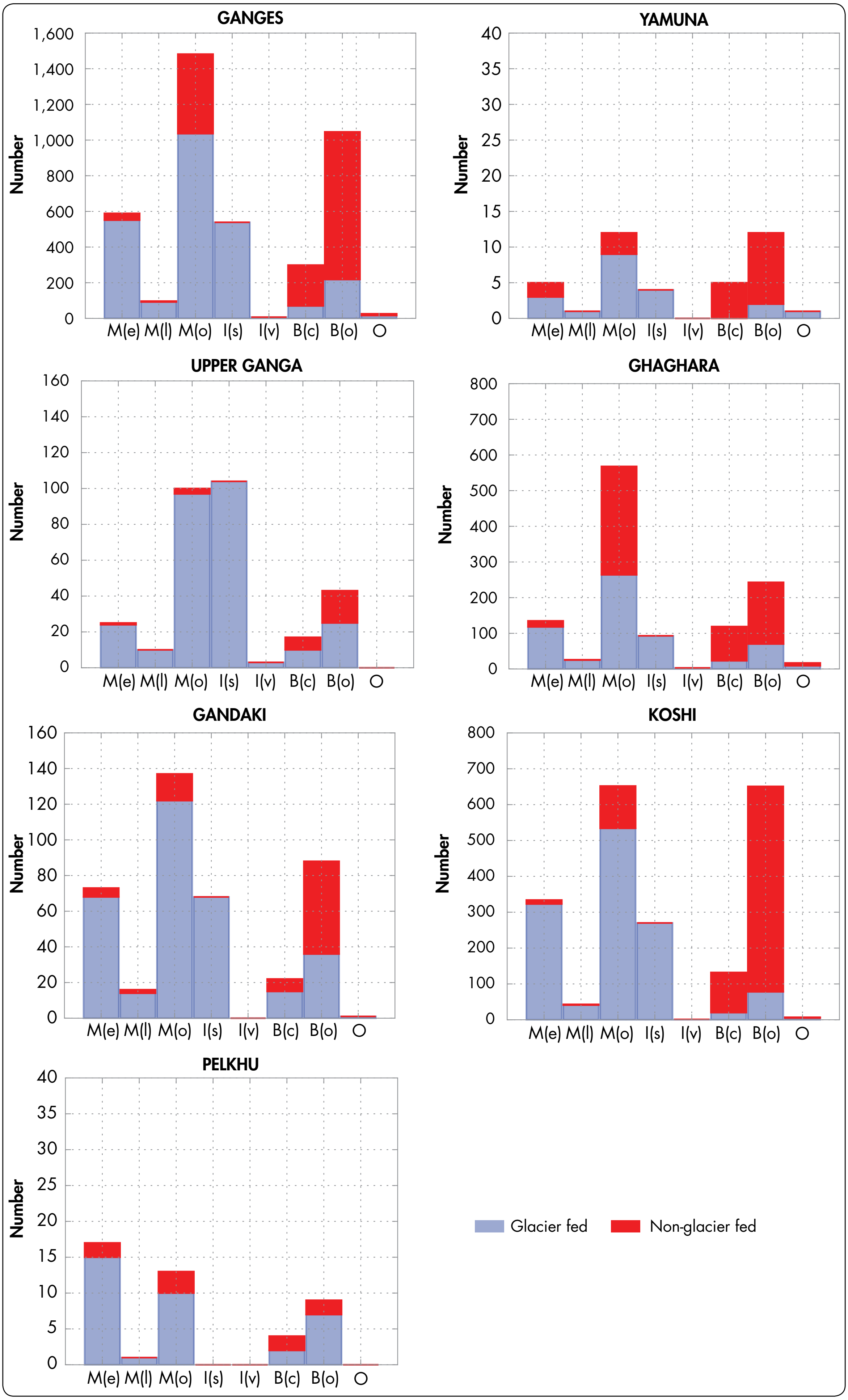
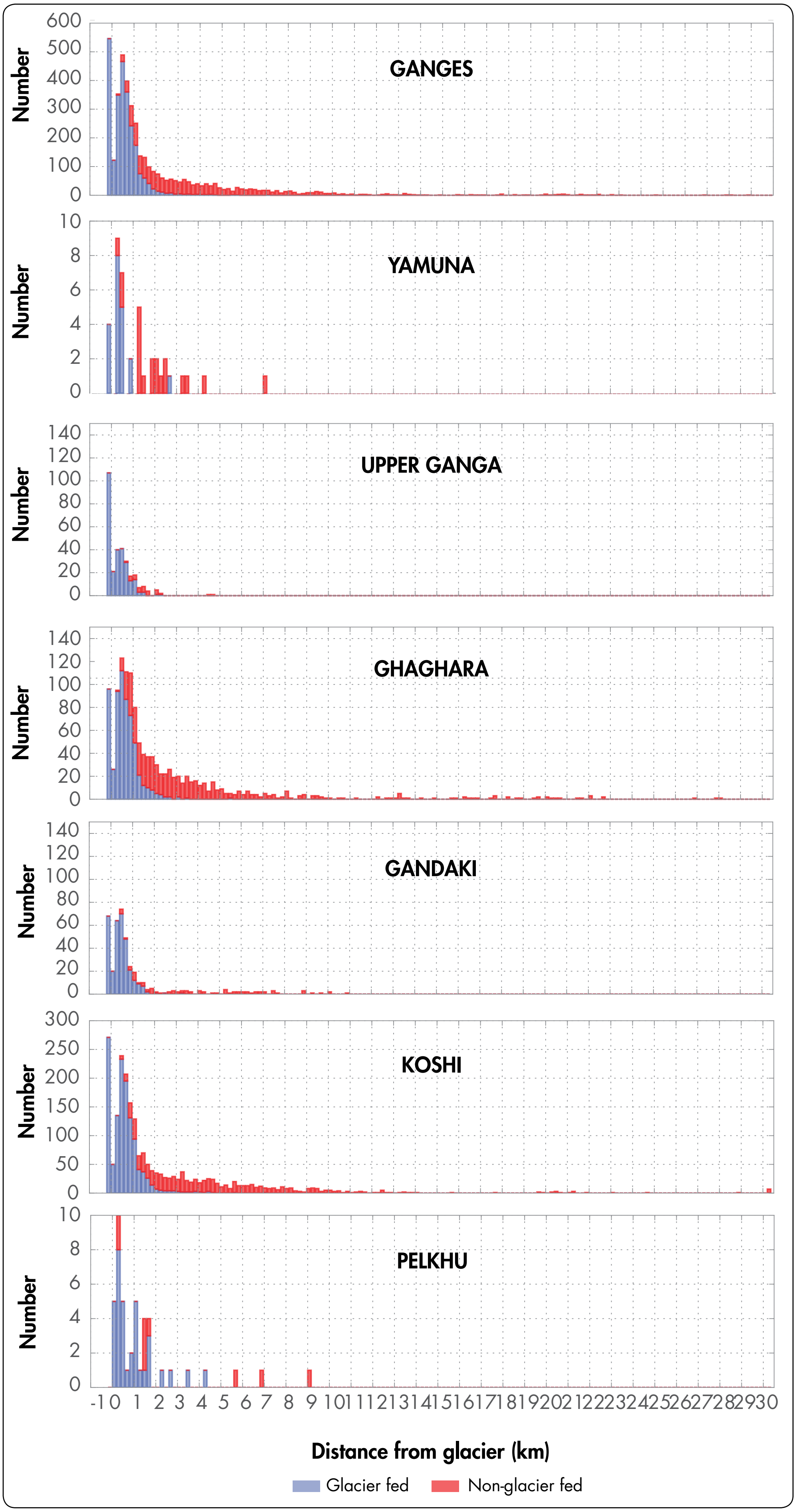


Figure 4.28: **Histogram showing the number of glacier fed and non-glacier fed glacial lakes within 100 m bin distance from the glaciers in Ganges River Basin**



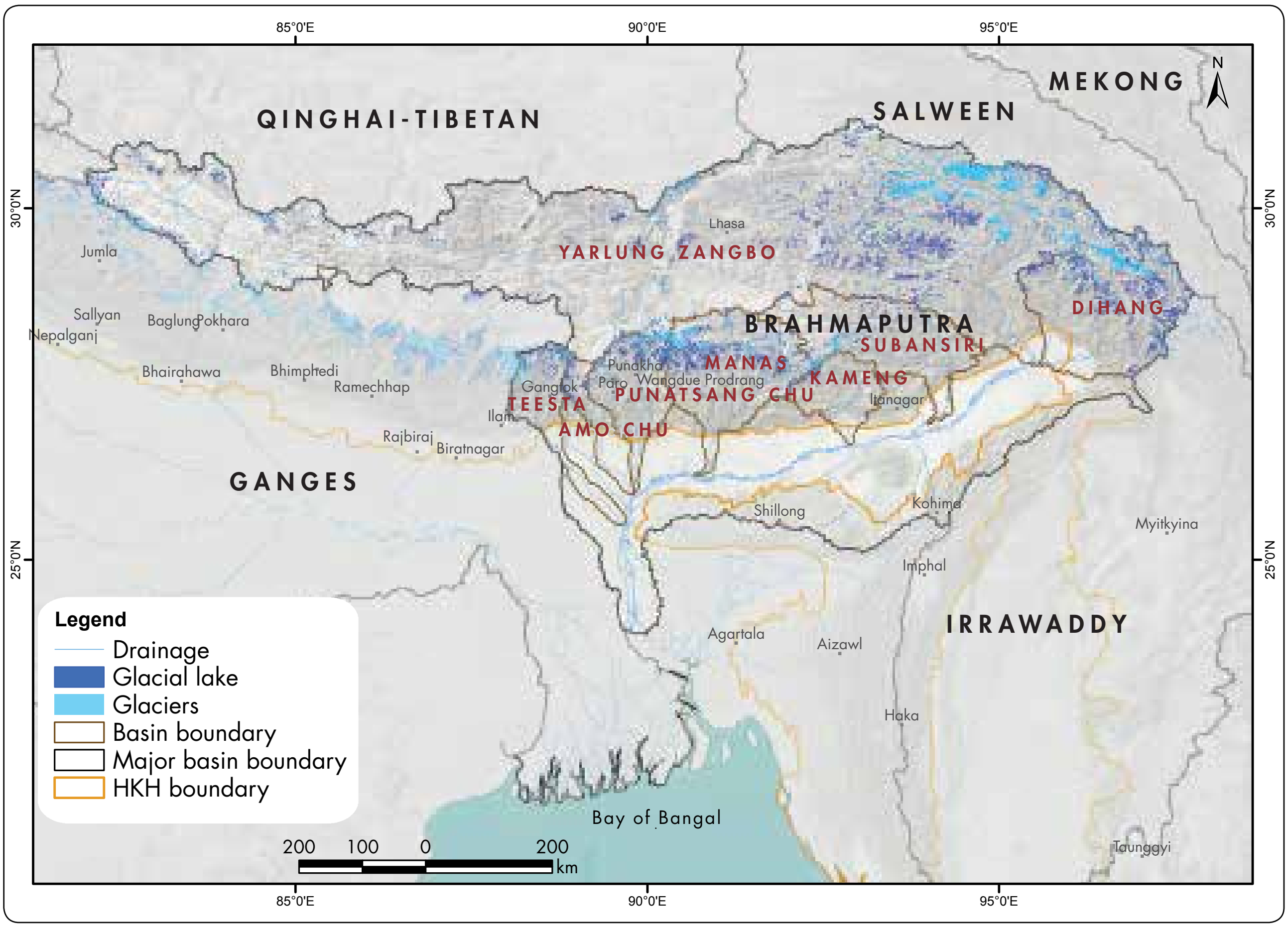
Brahmaputra River Basin

The Brahmaputra River is a transboundary river, originates from Angsi Glacier in southwestern Tibet and passes through the Tibet Autonomous Region of China towards the east. It flows across southern Tibet to break through the Himalaya in great gorges and enter into India at Namcha Barwa and bends to take a westerly path through the Indian states of Arunachal Pradesh and Assam, where it is joined by several tributaries such as the Subansiri and Kameng from Arunachal; Manas, Punatsang, and Amo from Bhutan; and the Tista from Sikkim, travelling further to its confluence with the Ganges River. The river has many names: Jamuna in Bengali, Dihang in Assamese, Tsangpo ('Purifier') in Tibetan, and Yarlung Zangbo Jiang in Chinese (Pinyin).

Thirty-two tiles of Landsat covers the glaciated region of Brahmaputra River Basin. In total, 133 Landsat images were used to map the glacial lakes in the basin.

The glacial lakes in the Brahmaputra River Basin are distributed between 31º16'19.2'' N and 27º14'20.4'' N latitude and 97º46'12'' E and 82º1'40.8'' E longitude. The distribution of glacier and glacial lakes is divided into eight larger basins and 26 sub-basins which is shown in Figure 4.29 and detailed in Table 4.16.

Figure 4.29: **Distribution of glacial lakes in Brahmaputra River Basin**



Number, area, and types

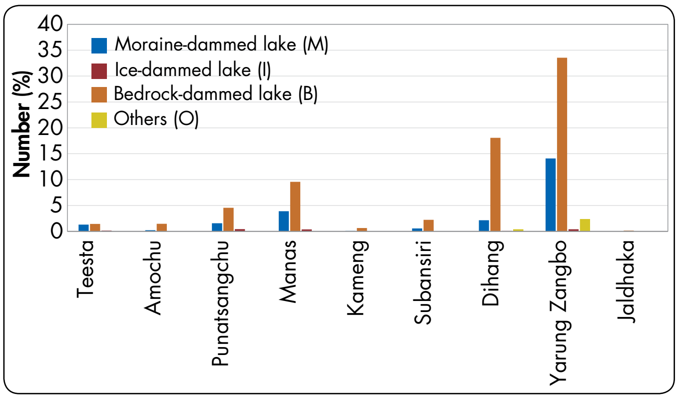
In total, 13,642 glacial lakes covering an area of 883.55 km^2 were mapped in the Brahmaputra River Basin. Table 4.16 shows the distribution of the number, area, and types of glacial lakes in the larger basins of the Brahmaputra River Basin. The highest number of lakes are in Yarlung Zangbo Basin which is more than 50% of the total lakes in the Brahmaputra covering an area of 521.4 km^2. The second highest number of lakes are in Dihang Basin (2,826 lakes) covering an area of 154.27 km^2.

Table 4.16: **Number and area of different types of glacial lakes in the larger basins of Brahmaputra River Basin**

Basin			Teesta		Amochu		Punatsangchu		Manas		Kameng		Subansiri		Dihang		Yarlung Zangbo		Jaldhaka		Total	
Type			No.	Area (km²)	No.	Area (km²)	No.	Area (km²)	No.	Area (km²)	No.	Area (km²)	No.	Area (km²)	No.	Area (km²)	No.	Area (km²)	No.	Area (km²)	No.	Area (km²)
Moraine-dammed lake (M)	End-moraine	M(e)	69	15.54	7	0.92	89	14.14	183	28.54	3	0.16	42	3.72	118	10.41	730	97.5	0	0	1,241	170.93
	Lateral moraine	M(l)	5	0.17	2	0.57	8	0.15	3	0.67	0	0	0	0	1	0.04	24	2.46	0	0	43	4.06
	Other moraine-dammed	M(o)	106	3.53	20	0.35	118	2.38	346	9.39	9	0.23	35	0.46	173	5.65	1166	29.50	0	0	1,973	51.48
Ice-dammed lake (I)	Supra-glacial lake	I(s)	21	0.22	3	0.01	58	0.93	53	0.47	0	0	0	0	10	0.11	51	0.34	0	0	196	2.08
	Glacier ice-dammed lake	I(v)	0	0	0	0	0	0	0	0	0	0	0	0	1	0.004	4	0.09	0	0	5	0.094
Bedrock-dammed lake (B)	Cirque	B(c)	65	4.56	67	4.41	176	15.37	331	26.54	26	1.32	59	5.11	479	56.5	772	59.63	1	0.03	1,976	173.47
	Others bedrock-dammed lake	B(o)	133	3.09	133	2.14	446	10.3	975	35.53	63	1.25	247	8.41	1,988	70.62	3,806	219.68	18	0.49	7,809	351.51
Others		O	2	0.2	0	0	0	0	7	5.77	0	0	7	0.79	56	10.95	327	112.2	0	0	399	129.91
Total			401	27.31	232	8.4	895	43.27	1,898	106.91	101	2.96	390	18.49	2,826	154.27	6,880	521.4	19	0.52	13,642	883.55

In this inventory the lakes formed in the landforms created by paleo-glaciation are also mapped so the large number of lakes in the basin are bedrock-dammed lakes. Almost 72% of the total lakes were mapped as bedrock-dammed lakes which covers 59% of total lake area mapped in the basin. A total of 3,258 lakes were mapped as moraine-dammed lakes, which is the highest number of moraine-dammed lakes compared to the other major river basins in HKH. Figure 4.30 shows the percentage distribution of various types of lake within each larger basin of the Brahmaputra River Basin. Bedrock-dammed lakes are higher in number in all the basins of the Brahmaputra. More than 33% of the total lakes in Brahmaputra are in Yarlung Zangbo Basin, 18% in Dihang Basin, and 9.5% in Manas Basin. The highest number of moraine-dammed lakes are also in Yarlung Zangbo Basin which is more than 14% of total lakes in the Brahmaputra River Basin. The second highest number of moraine-dammed lakes are in Manas Basin, which has about 4% total lakes, and Dihang Basin, which has more than 2% of total lakes. Ice-dammed lakes were mapped just about 1.5% of total lakes in the basin whereas Punatsangchu Basin has the highest number (58) of lakes followed by Yarlung Zangbo (55) and Manas (53). Out of 399 lakes identified as other types of lakes, 327 were in Yarlung Zangbo Basin.

Figure 4.30: **Percentage distribution of various types of glacial lakes in each sub-basin of Brahmaputra River Basin**



Glacial lake size

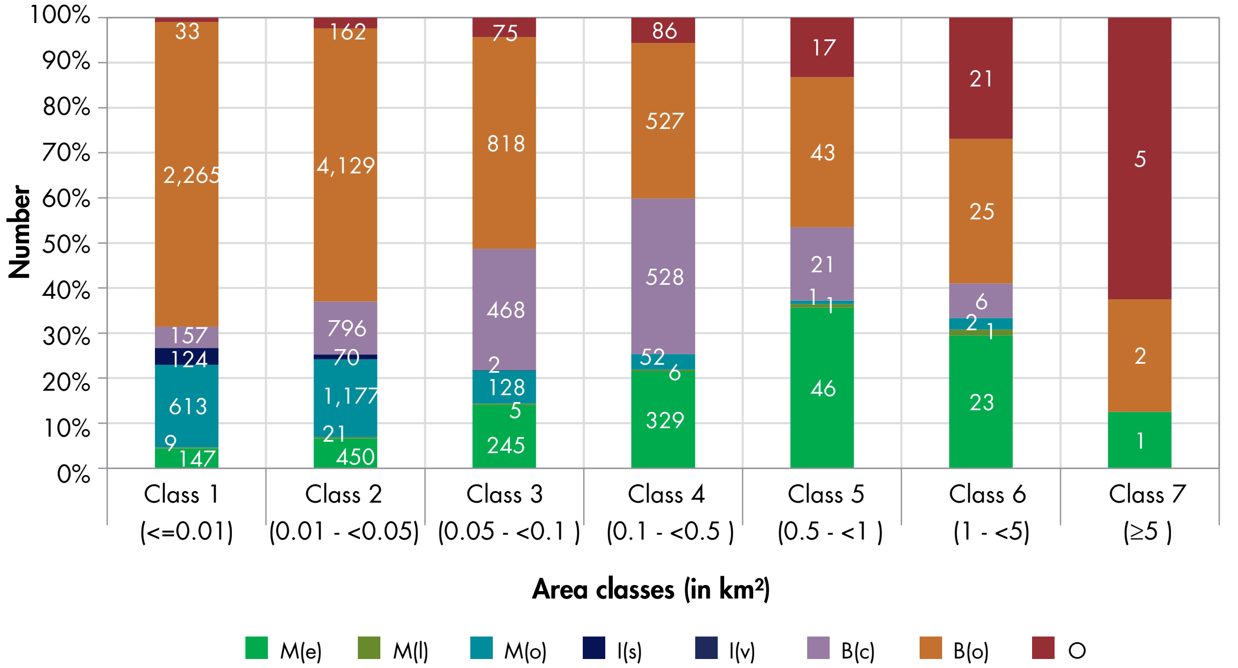
The smallest and largest lakes mapped in the Brahmaputra River Basin are 0.003 km² and 12.48 km². The largest lake is an other type lake and lies in Yarlung Zangbo Basin. The largest moraine-dammed lake is 5.6 km² and lies in Yarlung Zangbo Basin. The average size of lakes in Brahmaputra River Basin is 0.072 km². The detail distribution of various size classes is given in Table 4.17. Of total lakes in the Brahmaputra River Basin, the highest number of lakes, about 49.9%, are class 2 (0.01 – <0.05 km²) covering 17.7% of total lake area in the basin, and the second highest number, 24.55%, are class 1 (<0.01 km²). The number of lakes is higher in smaller-sized classes and lower in larger-sized classes whereas in the case of area it is the opposite.

The percentage distribution of various types of lakes within the size classes is shown in Figure 4.31. In all the size classes the proportion of bedrock-dammed lakes is higher. The highest number of bedrock-dammed as well as moraine-dammed lakes are class 2 (0.01 – <0.05 km²) which is 36.1% and 12% of the total lakes, respectively. There is only one class 7 (≥5 km²) moraine-dammed lake. The second highest number of bedrock-dammed and moraine-dammed lakes are class 1 (<0.01 km²) which is 17.7% and 5.64% of the total lakes in the basin, respectively. There are few ice-dammed lakes — just 1.47% of the total lakes mapped in the basin — with just 0.97%, 0.5%, and 0.01% of classes 1 (<0.01 km²), 2 (0.01 – <0.05 km²) and 3 (0.05 – <0.1 km²), respectively. The number of other type lakes are also highest in class 2 (0.01 – <0.05 km²).

Table 4.17: **Number and area of different size category of glacial lakes in Brahmaputra River Basin**

Glacial lake size	Number	%	Area (km²)	%	Average size (km²)
Class 1 (<0.01)	3,349	24.55	20.76	2.35	0.006
Class 2 (0.01 - <0.05)	6,809	49.91	156.36	17.7	0.023
Class 3 (0.05 - <0.1)	1,741	12.76	121.35	13.73	0.070
Class 4 (0.1 - <0.5)	1,528	11.2	294.85	33.37	0.193
Class 5 (0.5 - <1)	129	0.95	87.52	9.91	0.678
Class 6 (1 - <5)	78	0.57	139.51	15.79	1.789
Class 7 (≥5)	8	0.06	63.19	7.15	7.899
Total	**13,642**	**100**	**883.55**	**100.01**	**0.065**

Figure 4.31: **Percentage distribution of various types of glacial lakes within size classes of Brahmaputra River Basin**



Altitudinal distribution

The glacial lakes in the Brahmaputra River Basin are identified from elevation 2,459 masl to 6,081 masl. The lowest elevation lake is in the Dihang Basin and the highest in Yarlung Zangbo Basin. Both lakes are moraine-dammed. The distribution of number of lakes in each 100 m elevation zone is shown in Figure 4.32. Mostly the moraine-dammed lakes are distributed between elevations of 3,800 masl and 5,900 masl; very few are identified at lower elevation up to 2,400 masl. Comparatively this river basin consists of a higher percentage of bedrock-dammed lakes throughout each elevation zone. Only one lake is identified above 6,000 masl elevation and three lakes are below 2,500 masl. The distribution of lakes within each 1,000 m elevation zone is shown in Table 4.18. The highest concentration of lakes is in elevation zone of 4,000 – <5,000 masl which consists of more than 57.7% of total lakes in the Brahmaputra River Basin. About 35% of total lakes are at an elevation zone of 5,000 – <6,000 masl.

The distribution of various sizes of glacial lakes within 1,000 m elevation zones is shown in Figure 4.33. Only one glacial lake is identified

Figure 4.32: **Altitudinal distribution of number and various types of lakes in Brahmaputra River Basin**

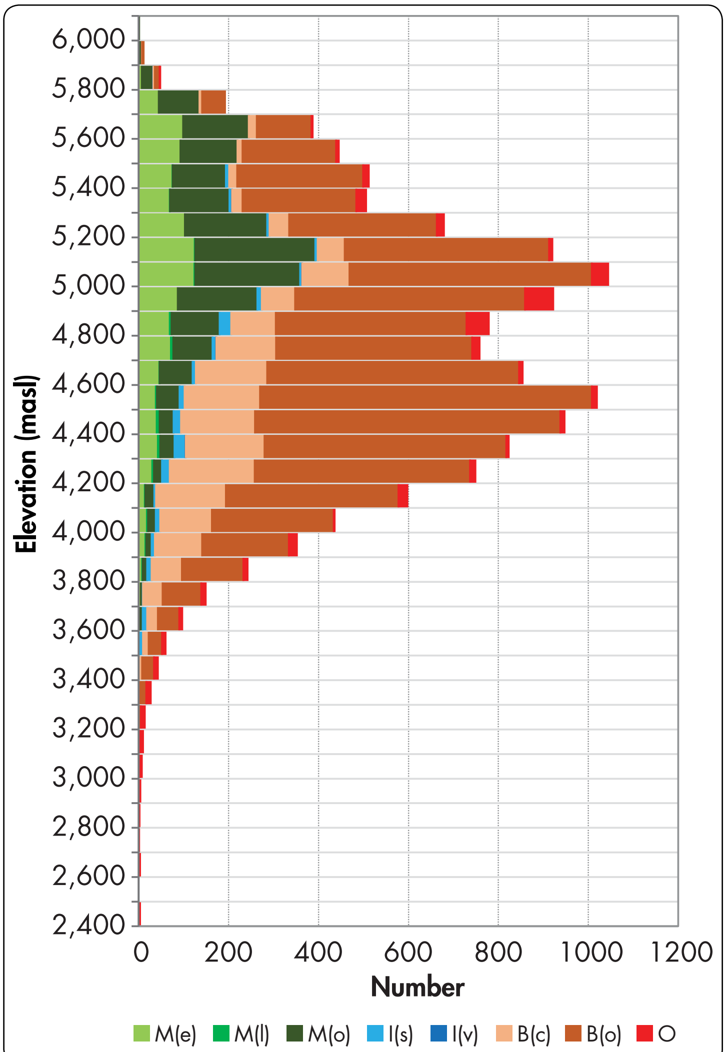
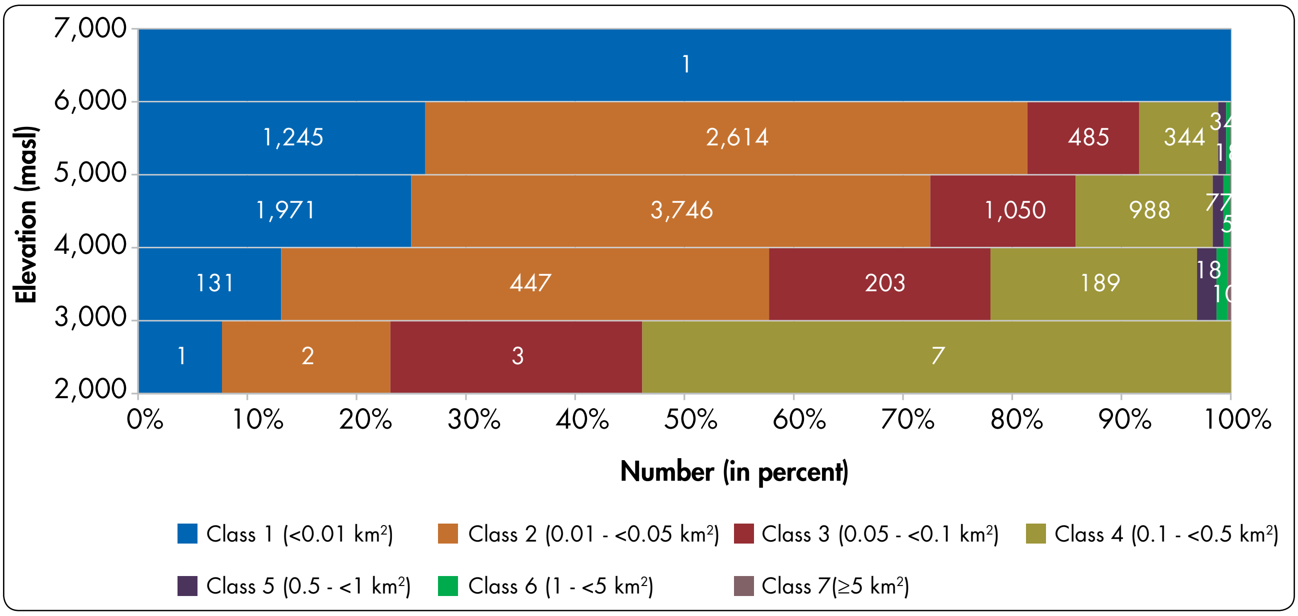


Table 4.18: **Distribution of lakes in each 1,000 m elevation zone in Brahmaputra River Basin**

Elevation zone			<3,000		3,000 – <4,000		4,000 – <5,000		5,000 – <6,000		6,000 – <7,000		Total	
Type			No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Moraine-dammed lake (M)	End-moraine	M(e)	5	0.04	38	0.28	457	3.35	741	5.43	0	0	1,241	9.1
	Lateral moraine	M(l)	0	0	5	0.04	33	0.24	5	0.04	0	0	43	0.32
	Other moraine-dammed	M(o)	0	0	34	0.25	612	4.49	1,326	9.72	1	0.01	1,973	14.47
Ice-dammed lake (I)	Supra-glacial lake	I(s)	0	0	37	0.27	133	0.97	26	0.19	0	0	196	1.43
	Glacier ice-dammed lake	I(v)	0	0	0	0	2	0.01	3	0.02	0	0	5	0.03
Bedrock-dammed lake (B)	Cirque	B(c)	0	0	255	1.87	1,432	10.5	289	2.12	0	0	1,976	14.49
	Others bedrock-dammed lake	B(o)	1	0.01	540	3.96	5,020	36.79	2,248	16.48	0	0	7,809	57.25
Others		O	7	0.05	92	0.67	196	1.44	104	0.76	0	0	399	2.92
Total			**13**	**0.1**	**1,001**	**7.34**	**7,885**	**57.79**	**4,744**	**34.76**	**1**	**0.01**	**13,642**	**100**

Figure 4.33: **Percentage distribution of different size of glacial lake within each 1,000 m elevation zone**



above the elevation 6,000 masl and the size is class 1 <0.01 km^2). The highest number of lakes in the basin are class 2 (0.01-0.05 km^2). About 27.5% of total lakes are class 2 (0.01-0.05 km^2) lies within the elevation zone of 4,000 – <5,000 masl and 19.2% of total lakes in the basin are class 2 (0.01-0.05 km^2) lies in elevation zone of 5,000 – <6,000 masl. The second highest number of lakes are class 1 (<0.01 km^2). More than 14.4% and 9% of total lakes in the basin are class 1 (<0.01 km^2) lies within elevation zone of 4,000 – <5,000 masl and 5,000 – <6,000 masl respectively. Out of 13 lakes within the elevation zone of 2,000 – <3,000 masl, seven lakes are class 2 (0.1 – 0.5 km^2), and six are of class 1 (<0.1 km^2).

Geographical distance from glacier

A large number of lakes were identified in the paleo-glaciation landform in the basin. Almost 25% of the total lakes in the basin lie more than 10 km from the glacier. These lakes are mostly formed in the paleo-glaciation landforms and mostly categorized as bedrock-dammed lakes. These lakes are also important water resources. The second highest number of lakes (17.5% of total number of lakes) are identified at a distance of 2,000 – <5,000 m from the glaciers. Of total lakes, 12.6% lie 1,000 – <2,000 m from the glacier but cover almost 14.5% of total area of mapped lakes. Only 201 lakes are mapped within the glacier as ice-dammed lakes and 222 lakes are in contact with glaciers. The distribution of number and area coverage of lakes mapped at distance from the glacier is given in

Figure 4.34: **Number and area distribution at the distance from glacier (blue line = snout of glacier) in 200 m zone**

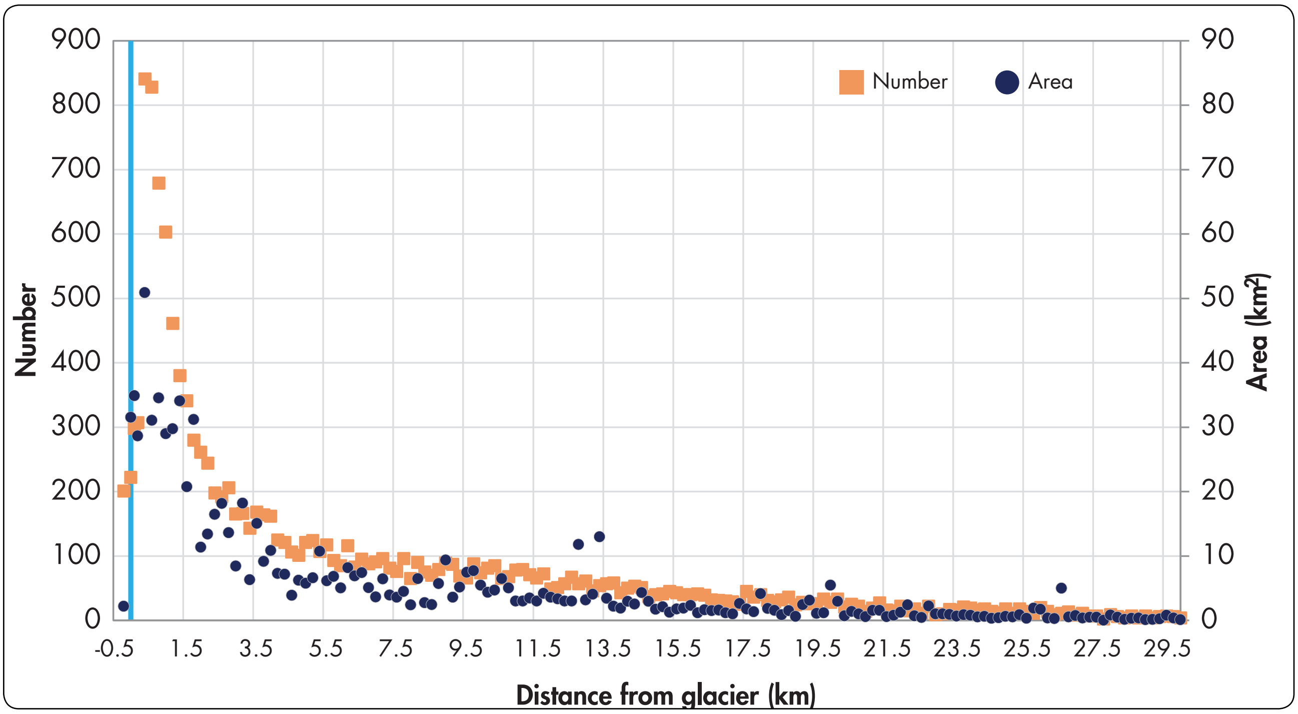


Table 4.19. Figure 4.34 shows the number and area of the lakes are decreases with distance from the glaciers.

The distribution of different types of lakes at the distance from the glaciers is shown in Figure 4.35. The number of bedrock-dammed lakes increases the distance from the glaciers. Moraine-dammed lakes are concentrated within 200 m to 5 km in which end-moraine-dammed lakes are concentrated at a distance below 2 km from glaciers.

Table 4.19: **Distribution of glacial lake and area at distance from the glacier in Brahmaputra River Basin**

Distance from glaciers (m)	Number		Area	
	Count	%	km²	%
Within	201	1.5	2.17	0.2
Contact with	222	1.6	31.52	3.6
>0 – <100	298	2.2	34.90	4.0
100 – <200	307	2.3	28.65	3.2
200 – <500	1,275	9.3	67.02	7.6
500 – <1,000	1,676	12.3	78.43	8.9
1,000 – <2,000	1,723	12.6	127.11	14.4
2,000 – <5,000	2,382	17.5	159.96	18.1
5,000 – <10,000	2,200	16.1	143.43	16.2
≥10,000	3,358	24.6	210.37	23.8
Total	**13,642**	**100.0**	**883.55**	**100.0**

Glacier fed and non-glacier fed

More than 32% of the total lakes in Brahmaputra River Basin are fed by the glaciers in which more than 20% are moraine-dammed lakes (Table 4.20). This basin consists of the highest number of non-glacier fed lakes (more than 67% of total lakes in basin), in which more than 61% of total lakes are bedrock-dammed lakes. Proportionally, non-glacier fed bedrock-dammed lake is higher than glacier fed moraine-dammed lakes. Also the number of non-glacier fed bedrock-dammed lakes is higher in all basins of the Brahmaputra River Basin (Figure 4.36). Comparatively, the number of non-glacier fed bedrock-dammed lakes is much higher in Dihang and Yarlung Zangbo Basins.

Most of the lakes within 2 km of the glaciers are glacier fed and beyond 5 km distance from the glaciers are mostly non-glacier fed (Figure 4.37). About 22.5% of total lakes in the River Basin lies within 2 km of glaciers and 1.5% lies within the distance of 2 to 5 km are glacier fed. More than 56% of the total lakes lies beyond 2 km from the glaciers are non-glacier fed lakes. Hence the proportion of non-glacier fed lakes increases with distance from the glacier. Less than 1% of lakes are within the distance of 500 m and between 500 m to 2 km 10.6% of total lakes are identified as non-glacier fed lakes. All the lakes identified in Kameng and Jaldhaka Basins are non-glacier fed lakes.

Figure 4.35: **Distribution of various types of lakes at the distance from the glaciers in Brahmaputra River Basin**

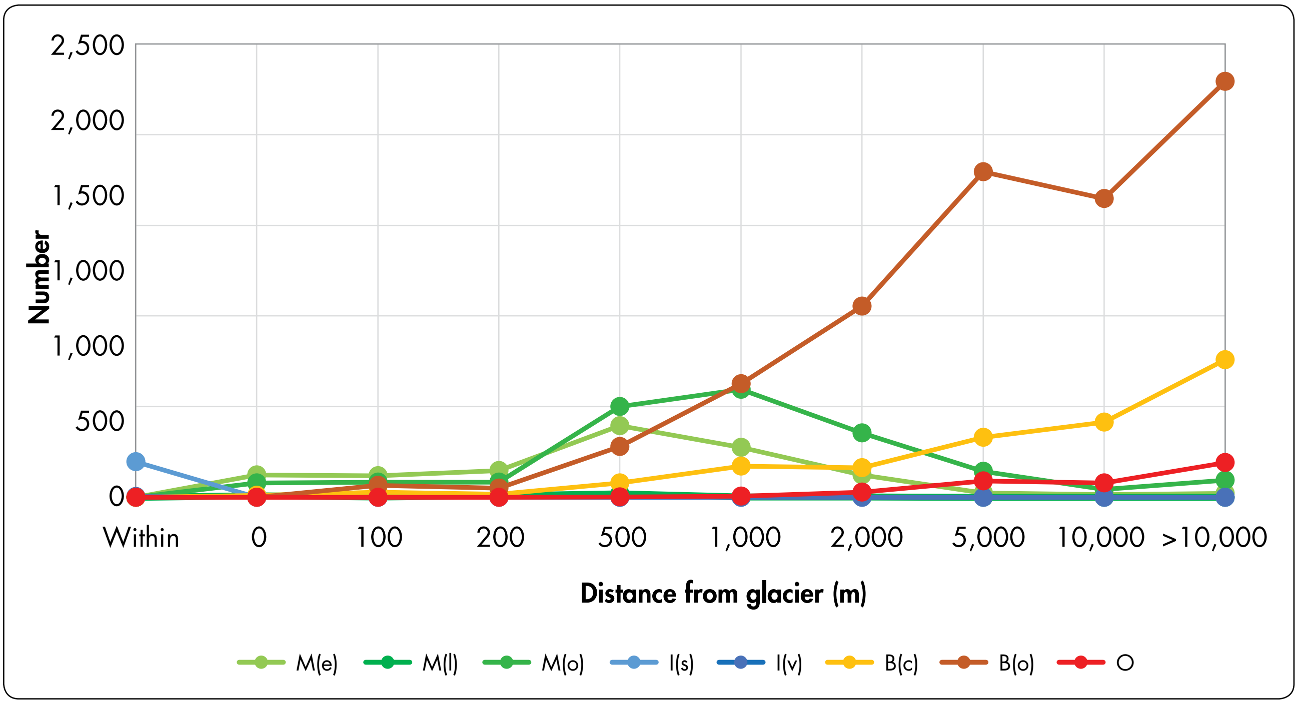


Table 4.20: **Glacier fed and non-glacier fed glacier lake distribution in different types of lakes**

Type			Number				Area (km²)			
			Glacier fed		Non-glacier fed		Glacier fed		Non-glacier fed	
			Count	%	Count	%	km²	%	km²	%
Moraine-dammed lake (M)	End-moraine	M(e)	1,181	8.66	60	0.44	165.90	18.78	5.04	0.57
	Lateral moraine	M(l)	41	0.30	2	0.01	3.49	0.40	0.57	0.06
	Others	M(o)	1,521	11.15	452	3.31	39.88	4.51	11.60	1.31
Ice-dammed lake (I)	Supra-glacial lake	I(s)	196	1.44	0	0	2.07	0.23	0	0
	Glacier ice-dammed lake	I(v)	5	0.04	0	0	0.1	0.01	0	0
Bedrock-dammed lake (B)	Cirque	B(c)	274	2.01	1,702	12.48	34.06	3.86	139.41	15.78
	Others bedrock-dammed lake	B(o)	1,121	8.22	6,688	49.03	97.31	11.01	254.21	28.77
Others		O	93	0.68	306	2.24	56.87	6.44	73.04	8.27
Total			**4,432**	**32.49**	**9,212**	**67.52**	**399.68**	**45.24**	**483.87**	**54.76**

Figure 4.36: **Distribution of glacier fed and non-glacier fed lakes in basins of the Brahmaputra River Basin**

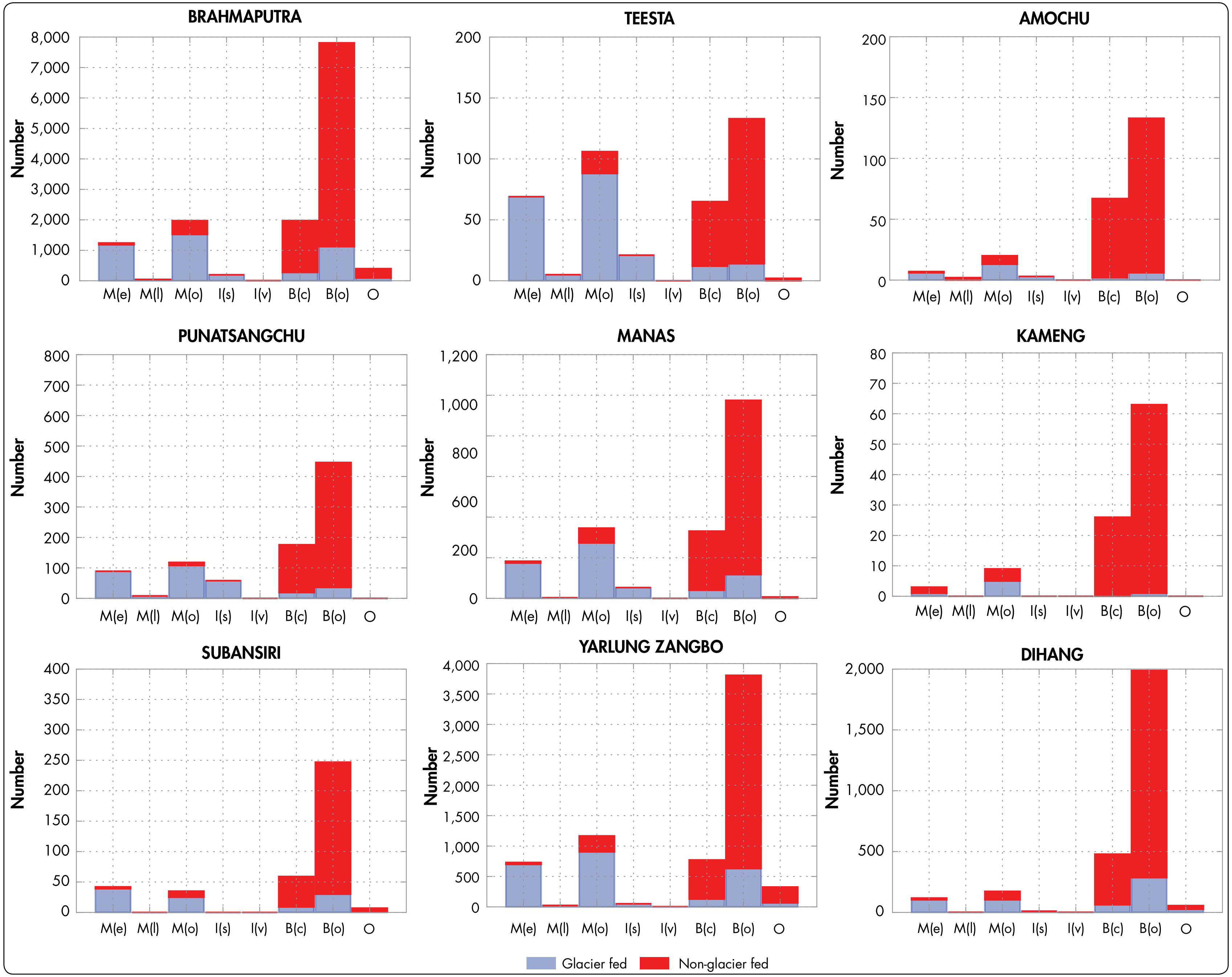
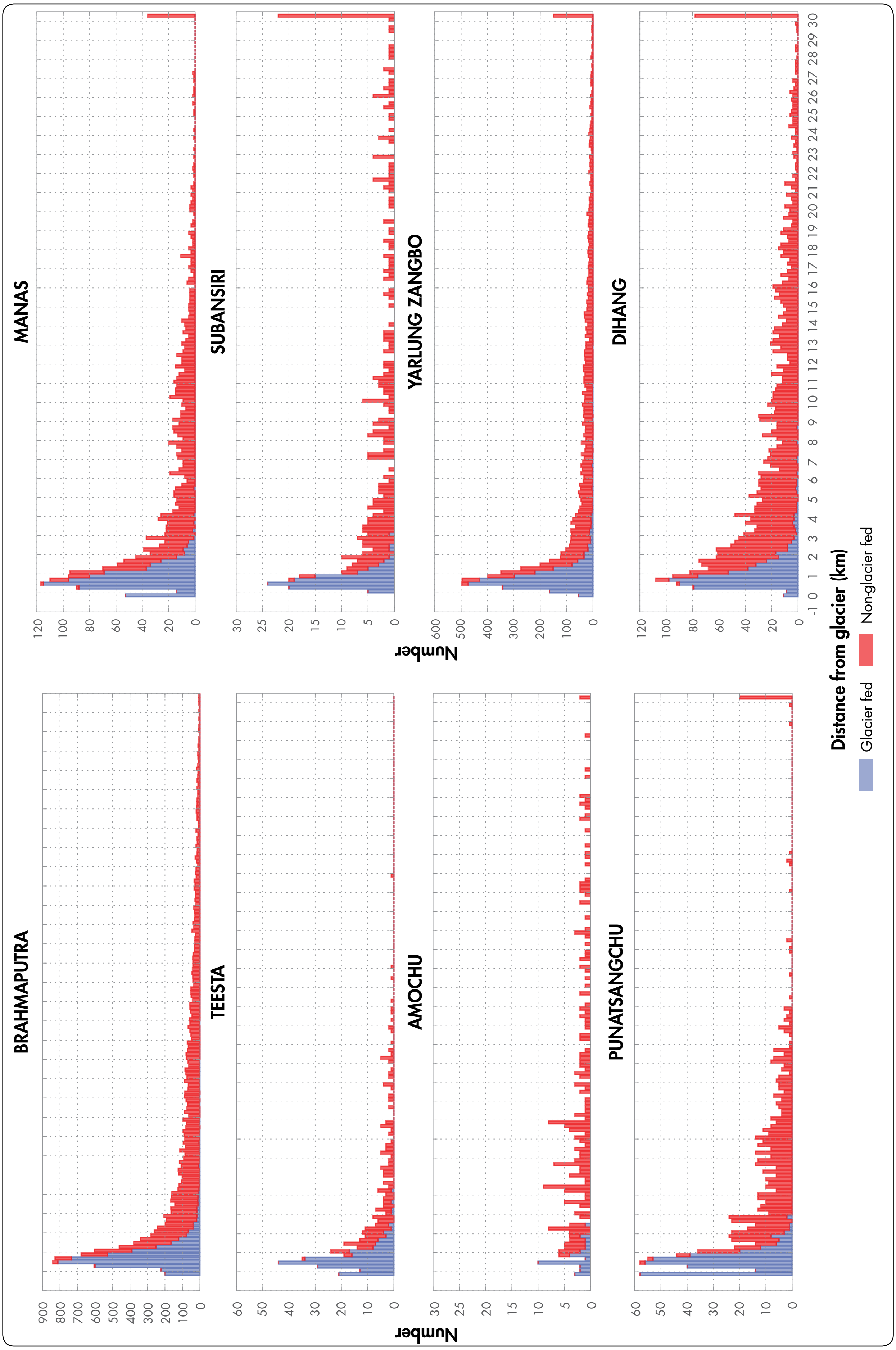


Figure 4.37: **Histogram showing the number of glacier fed and non-glacier fed glacial lakes within 100 m bin distance from the glacier in Brahmaputra River Basin**



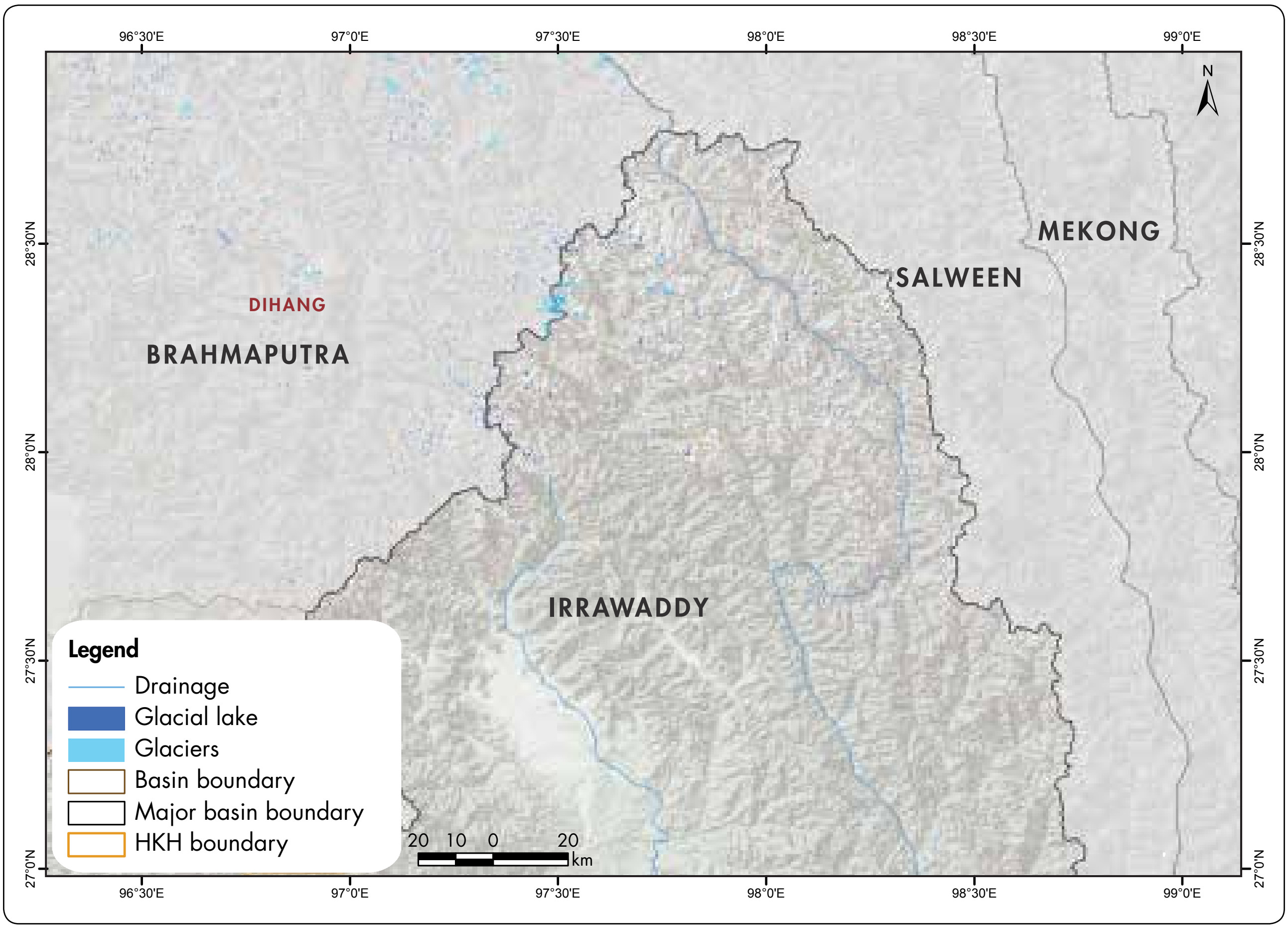
Irrawaddy River Basin

The Irrawaddy (Irawadi) is the principal river of Myanmar and fed by tributaries from Myanmar and China. The river forms in Kachin State at the confluence of the Mali and NMai Rivers north of Myitkyina. The western branch of the Mali River originates north of Putao from the end of the southern Himalaya, and is called Nam Kiu locally. The easternmost branch of the NMai River originates in the Languela Glacier north of Putao in China. The area has a mainly tropical climate; the watershed area is covered by clouds and fog most of the time and perennial ice and snow are only found in a limited area. The Irrawaddy flows through the country from north to south bisecting the centre and empties through a nine-armed delta into the Andaman Sea. The NMai River is not navigable because of the strong current, whereas the smaller western river, the Mali, is navigable despite having a few rapids. The Chindwin River is the largest tributary of the Irrawaddy. It flows 840 km before joining the Irrawaddy River close to Mandalay.

The glacier and glacial lakes are distributed mainly in the northern part of the Irrawaddy River Basin in the watershed of the NMai River. Only three scenes of Landsat covers the glaciated region of the basin. A total of five Landsat images were used to map the glacial lakes in the basin.

The glacial lakes in the Irrawaddy River Basin are distributed between 28º45′28.8′′ N and 27º39′39.6′′ N latitude and 98º25′22.8′′ E and 96º57′39.6′′ E longitude. The distribution of glacier and glacial lakes is shown in Figure 4.38.

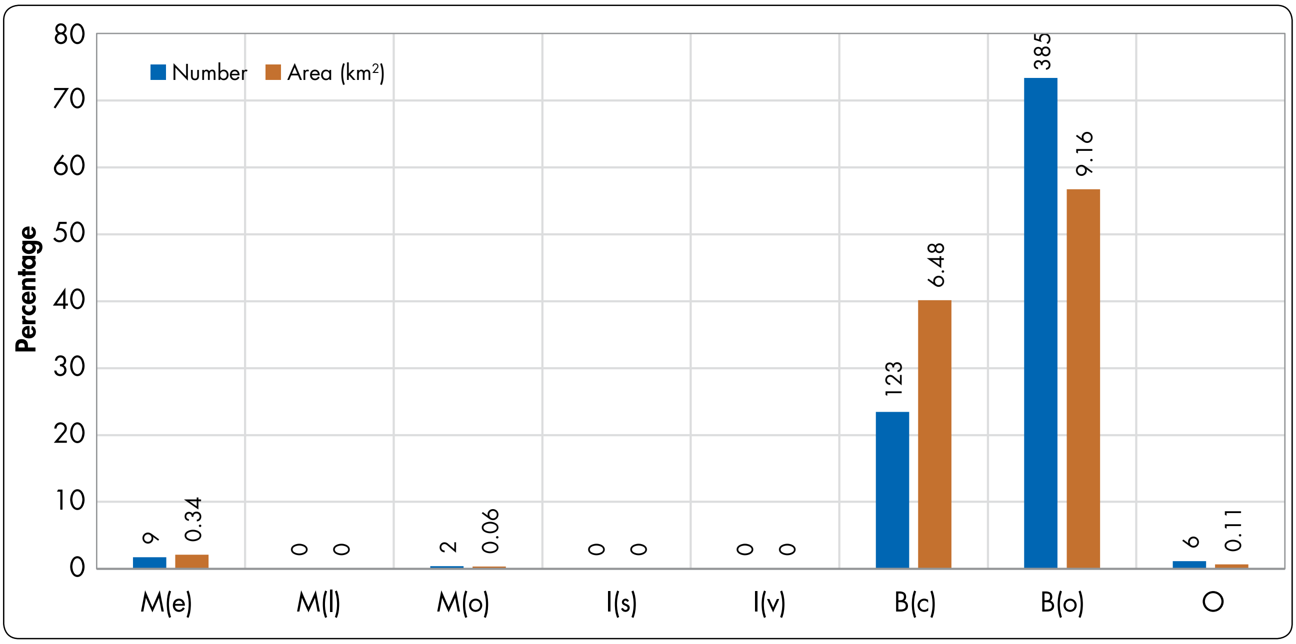
Figure 4.38: **Distribution of glacial lakes in Irrawaddy River Basin**



Number, area, and types

In total, 525 lakes were identified in the Irrawaddy River Basin covering 16.16 km² area, which is only 2% of total lakes mapped in the HKH. The distribution of various types of lakes in the basin is shown in Figure 4.39. Only

Figure 4.39: **Percentage distribution various types of glacial lakes in Irrawaddy River Basin**



11 lakes were identified as moraine-dammed lakes covering an area of 0.4 km² in which nine are end-moraine-dammed and two are other moraine-dammed. Almost 96.8% of the lakes mapped in this basin are bedrock-dammed which covers an area of 15.64 km² and just six lakes are other type lakes.

Glacial lake size

The largest glacial lake mapped in the Irrawaddy River Basin is 0.496 km² of bedrock-dammed lakes. The distribution of number and area of each size classes of lakes in the basin is given in Table 4.21. Overall the average size of the lakes in the basin is 0.031 km². The highest number of lakes, 52.76%, are class 2 (0.01 - <0.05 km²) and the second highest number, 32.95%, are class 1 (<0.01 km²). Just 27 lakes in the basin are class 4 (0.1 – <0.5 km²) with an average size of 0.193 km².

Table 4.21: **Number and area of different size category of glacial lakes in Irrawaddy River Basin**

Glacial lake size	No.	%	Area (km²)	%	Average size (km²)
Class 1 (<0.01)	173	32.95	1.11	6.87	0.006
Class 2 (0.01 - <0.05)	277	52.76	6.31	39.05	0.023
Class 3 (0.05 - <0.1)	48	9.14	3.53	21.84	0.074
Class 4 (0.1 - <0.5)	27	5.14	5.21	32.24	0.193
Total	**525**	**100**	**16.16**	**100**	**0.031**

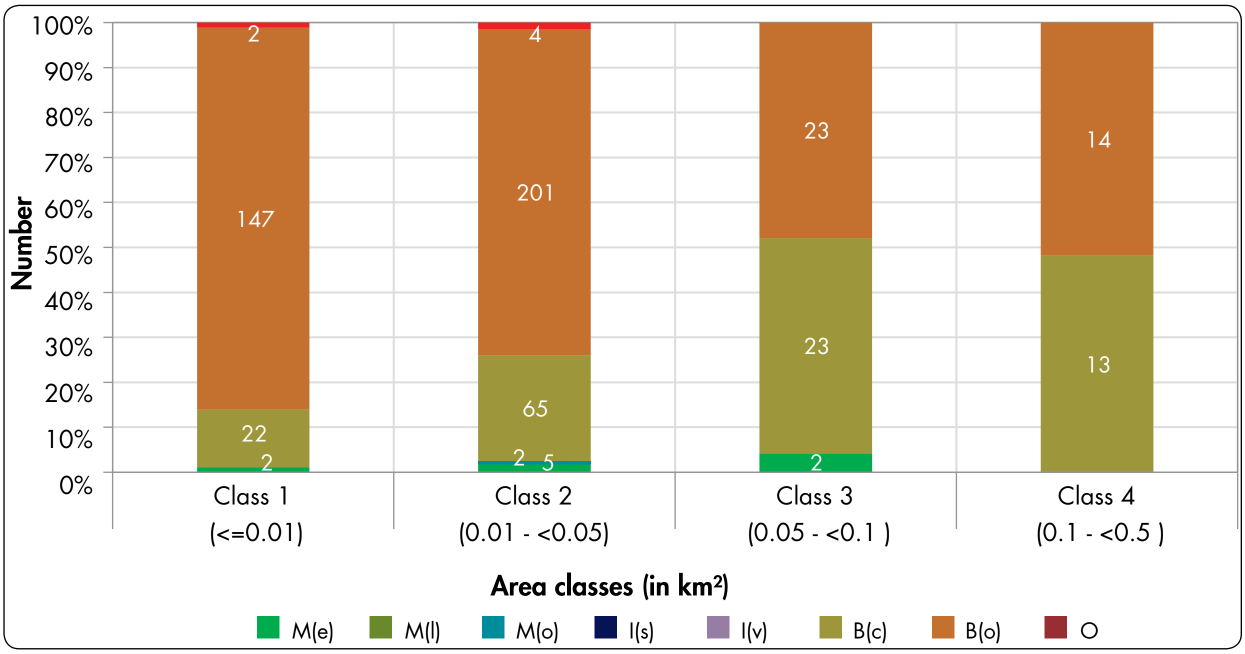
About 56.7% and 32.2% of the total lakes in the basin are class 2 (0.01 - <0.05 km²) and class 1 <0.01 km²) respectively. These lakes were classified as bedrock-dammed lakes. Out of 11 moraine-dammed lakes seven are class 2 (0.01 – <0.05 km²), two are class 1 <0.01 km²), and two are class 3 (0.05 – <0.1 km²). The distribution of various types of glacial lakes within different size classes is shown in Figure 4.40.

Altitudinal distribution

The glacial lakes in the Irrawaddy River Basin are distributed between 3,461 and 5,050 masl (Figure 4.41). The lowest and highest elevation of mapped lakes are bedrock-dammed lakes at 3,461 masl and 5,045 masl. The highest concentration, more than 83% of total lakes in the basin, are within the elevation ranges from 4,000 masl to 4,700 masl (Figure 4.41). Only 9% and 7% of total lakes in the basin are below 4,000 masl and above 4,700 masl.

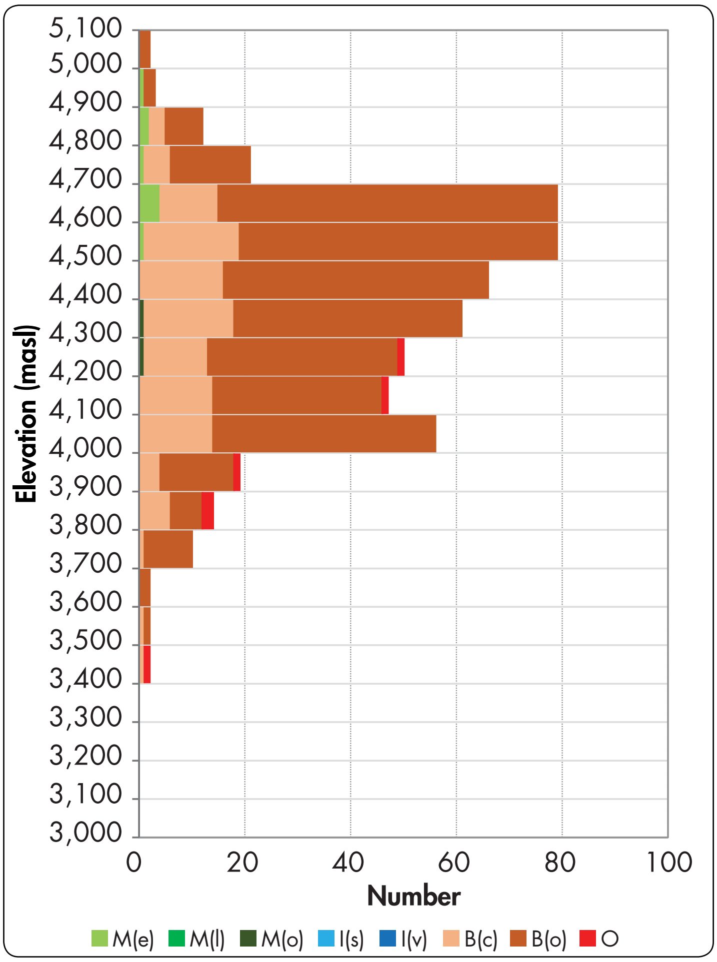
All the moraine-dammed lakes mapped in the basin lie within the elevation of 4,000 to <5,000 masl. Out of 96.8% of total lakes in the basin identified as bedrock-dammed lakes, more than 87.8% of the total lakes are within 4,000 to <5,000 masl, 8.5% are in below 4,000 masl and only two bedrock-dammed lakes are above 5,000 masl. The detail distribution is given in Table 4.22.

Figure 4.40: **Percentage distribution of various types of glacial lakes within size classes of Irrawaddy River Basin**



The distribution of glacial lake size within 1,000 m elevation zone are shown in Figure 4.42. More than 46.7% of lakes are class 2 (0.01 – <0.05 km^2) and 30.5% of lakes are class 1 (< 0.01 km^2) lies within the elevation zone of 4,000 – <5,000 masl. 8.2% and 5% of the total lakes in the basin are of class 3 (0.05 – <0.1 km^2) and class 4 (0.1 – 0.5 km^2) respectively lies in the elevation zone of 4,000 – <5,000 masl.

Figure 4.41: **Altitudinal distribution of number and various types of lakes in Irrawaddy River Basin**



Geographical distance from glacier

This basin mostly consists of mountain-type glaciers, with no supra-glacier and other ice-dammed lakes or lakes in contact with the glaciers. Only 128 lakes are identified within the distance of 5,000 m from the glaciers, and only one of these lies within 100 m. More than 75% of the mapped lakes lie beyond 5,000 m of the glaciers in the basin. Most of these lakes are bedrock-dammed lakes. The detail distribution of the lakes and area at distance from the glacier is given in Table 4.23 and type categorization is shown in Figure 4.43.

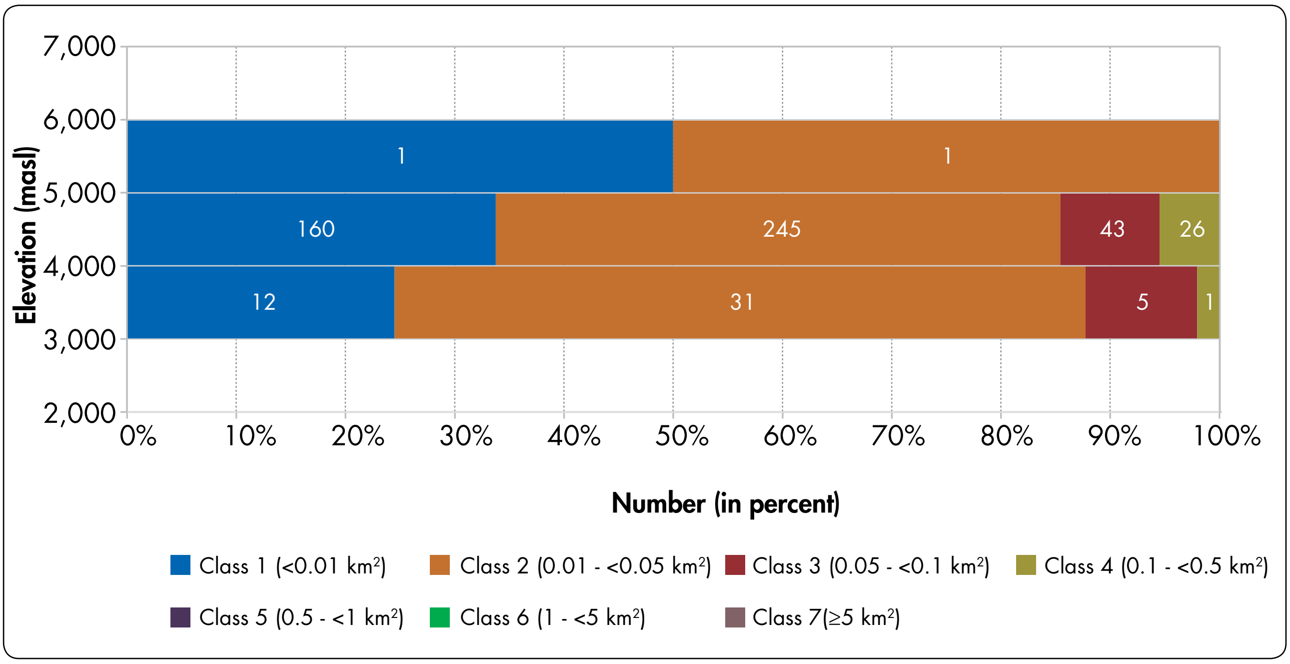
Glacier fed and non-glacier fed

Only 29 lakes (5.5% of the total lakes) in Irrawaddy River Basin are fed by the glaciers in which nine are moraine-dammed lakes and 20 are bedrock-dammed lakes (Table 4.24). This basin consists of the highest number of non-glacier fed lakes (more than 94.5% of

Table 4.22: **Distribution of lakes in each 1,000 m elevation zone in Irrawaddy River Basin**

Elevation zone			3,000 – <4,000		4,000 – <5,000		5,000 – <6,000		Total	
Type			No.	%	No.	%	No.	%	No.	%
Moraine-dammed lake (M)	End-moraine	M(e)	0	0	9	1.71	0	0	9	1.71
	Lateral moraine	M(l)	0	0	0	0	0	0	0	0
	Others	M(o)	0	0	2	0.38	0	0	2	0.38
Bedrock-dammed lake (B)	Cirque	B(c)	13	2.48	110	20.95	0	0	123	23.43
	Others bedrock-dammed lake	B(o)	32	6.1	351	66.86	2	0.38	385	73.34
Others		O	4	0.76	2	0.38	0	0	6	1.14
Total			**49**	**9.33**	**474**	**90.3**	**2**	**0.38**	**525**	**100**

Figure 4.42: **Percentage distribution of different size of glacial lake within each 1,000 m elevation zone**



total lakes in basin), in which almost 93% of total lakes are bedrock-dammed. Other type of lakes identified in the basin are not fed by the glacier and only two moraine-dammed lakes are not fed by glacier (Figure 4.44).

Mostly the glacier fed lakes are within the distance of 2 km of glaciers and beyond 2 km of glaciers are non-glacier fed (Figure 4.45). Only 28 lakes (5.3% of total lakes) lies within the distance of 2 km of glaciers are glacier fed.

Table 4.23: **Distribution of glacial lake and area at distance from the glacier in Irrawaddy River Basin**

Distance from glaciers (m)	Number		Area	
	Count	%	km²	%
Within	0	0.0	0	0.0
Contact with	0	0.0	0	0.0
>0 – <100	1	0.2	0.11	0.7
100 – <200	2	0.4	0.09	0.6
200 – <500	5	1.0	0.09	0.6
500 – <1,000	19	3.6	0.65	4.0
1,000 – <2,000	34	6.5	1.55	9.6
2,000 – <5,000	67	12.8	2.12	13.1
5,000 – <10,000	161	30.7	5.11	31.7
≥10,000	236	45.0	6.43	39.8
Total	**525**	**100.0**	**16.16**	**100.0**

Table 4.24: **Glacier fed and non-glacier fed glacier lake distribution in different types of lakes**

Type			Number				Area (km²)			
			Glacier fed		Non-glacier fed		Glacier fed		Non-glacier fed	
			Count	%	Count	%	km²	%	km²	%
Moraine-dammed lake (M)	End-moraine	M(e)	8	1.52	1	0.19	0.34	2.09	0.005	0.03
	Lateral moraine	M(l)	0	0	0	0	0	0	0	0
	Others	M(o)	1	0.19	1	0.19	0.04	0.26	0.02	0.12
Bedrock-dammed lake (B)	Cirque	B(c)	5	0.95	119	22.62	0.20	1.26	6.28	38.88
	Others bedrock-dammed **lake**	B(o)	15	2.85	370	70.34	0.94	5.84	8.22	50.85
Others		O	0	0	6	1.14	0	0	0.11	0.67
Total			**29**	**5.51**	**497**	**94.49**	**1.53**	**9.44**	**14.63**	**90.56**

Figure 4.43: **Distribution of various types of lakes at the distance from the glaciers in Irrawaddy River Basin**

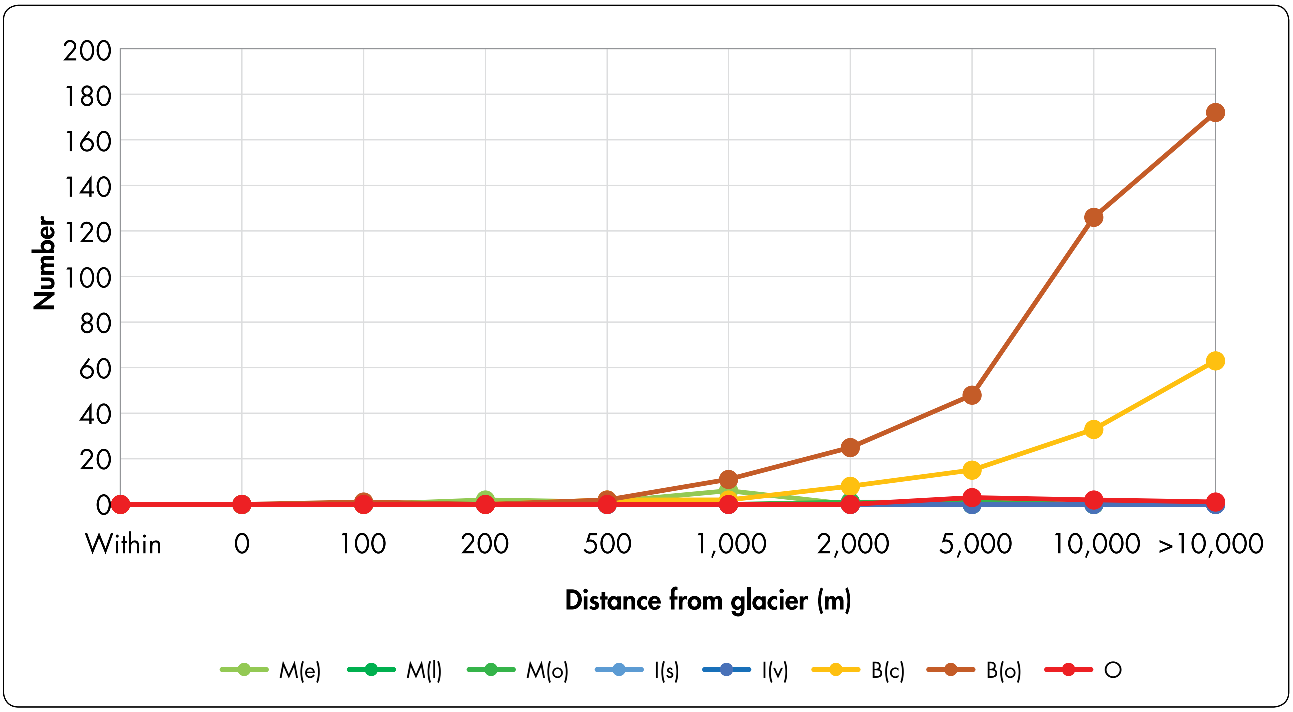


Figure 4.44: **Distribution of glacier fed and non-glacier fed lakes in basins of the Irrawaddy River Basin**

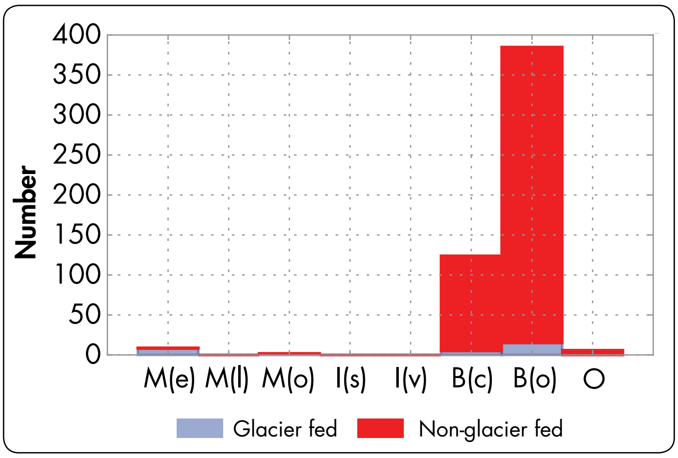
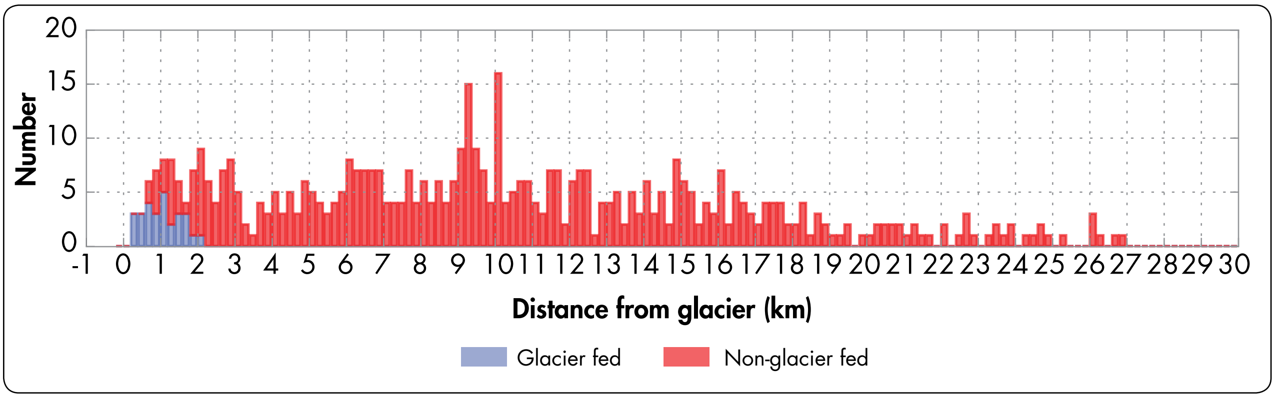


Figure 4.45: **Histogram showing the number of glacier fed and non-glacier fed glacial lakes within 100 m bin distance from the glacier in Irrawaddy River Basin**



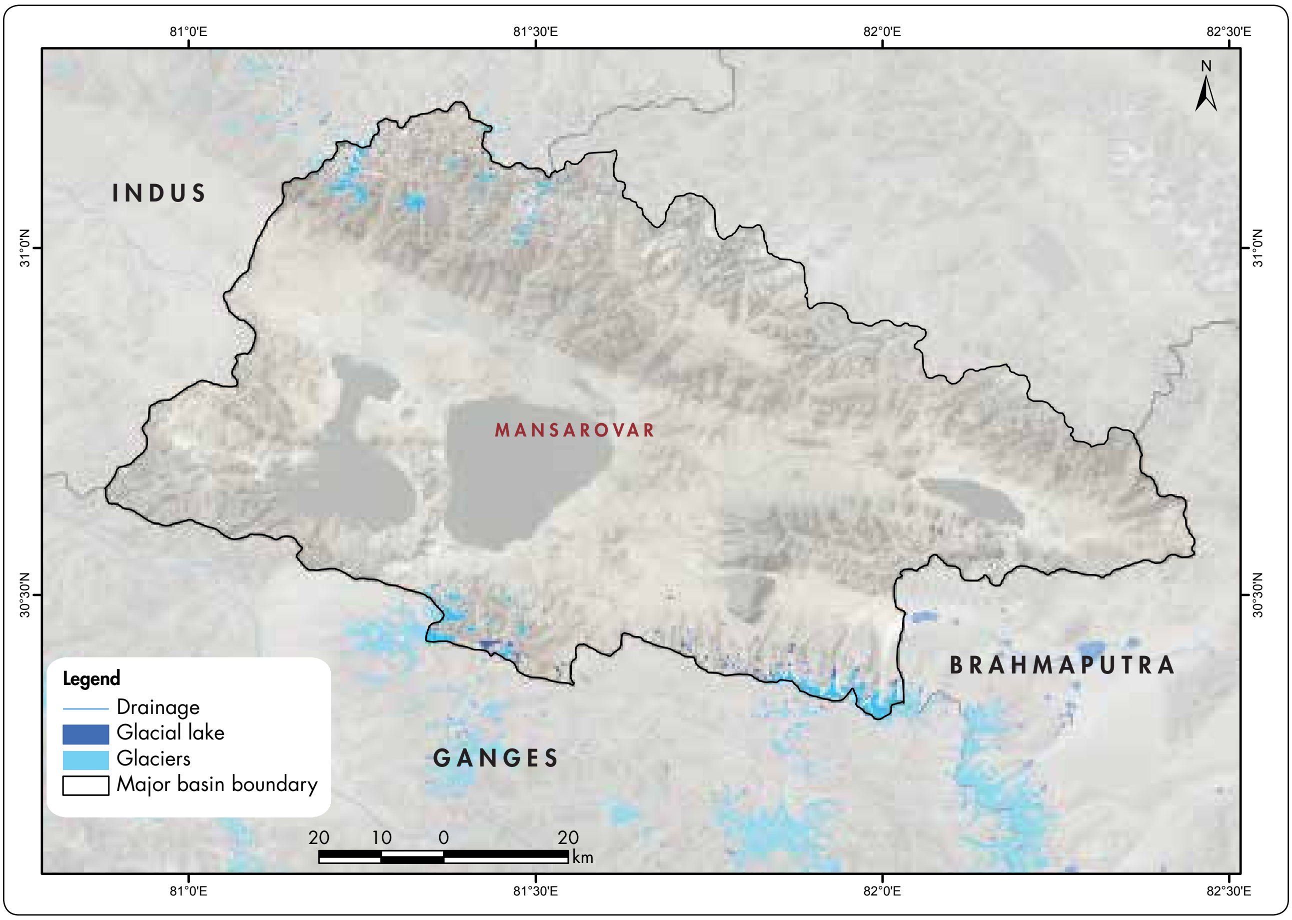
Mansarovar Interior Basin

Mansarovar Lake is a freshwater lake that lies above 4,590 masl in the Tibetan Autonomous Region of China. It is relatively rounded in shape and connected to nearby Rakshastal Lake to the west by the natural Ganga Chhu Channel. It is to the south of Mount Kailash. The source of water is from the glaciers in the surrounding peaks and overflows into Rakshastal Lake which is a saltwater endorheic lake. It is near the origin of the major rivers of southern Asia – Brahmaputra in the east, Ganges in the south, and Indus in the west. Mansarovar Lake is a pilgrimage site for religious people from India, Nepal, and neighbouring countries. It is believed that bathing and drinking its water cleanses all sins so every year many Hindu people visit this lake to take ceremonial baths.

The glacier and glacial lakes in the surrounding peaks are the sources of water in the lakes. The two scenes of Landsat cover the whole interior basin of Mansarovar Lake.

The glacial lakes in the Mansarovar Interior Basin are distributed between 31º10′51.6′′ N and 30º21′7.2′′ N latitude and 82º10′48′′ E and 81º11′45.6′′ E longitude. The distribution of glacier and glacial lakes is shown in Figure 4.46.

Figure 4.46: **Distribution of glacial lakes in Mansarovar Interior Basin**



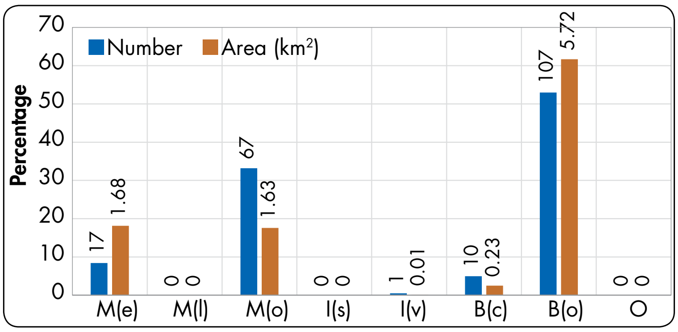
Number, area, and types

In total, 202 lakes were identified in this interior basin covering an area of about 9.3 km^2, which is less than 1% of total lakes mapped in the HKH. The distribution of various types of lakes in the basin is shown in Figure 4.47. More than 41.6% of total lakes in the basin were identified as moraine-dammed lakes covering an area of 3.31 km^2. More than 57.9% of the lakes mapped in the basin are of bedrock-dammed, which covers an area of 5.9 km^2, and just a single lake is ice-dammed.

Glacial lake size

The largest glacial lake mapped in the basin is 1.912 km² and is bedrock-dammed. The distribution of number and area of each size class of lakes in the basin is given in Table 4.25. The average size of the lakes in the basin is 0.046 km². The highest number of lakes are class 2 (0.01 - <0.05 km²), at 54.5% of total lakes in the basin, and the second highest number are class 1 (<0.01 km²), at (24.7.7% of total lakes in the basin. All the lakes mapped in the basin are smaller than 0.5 km² except one lake which is greater than 1 km².

Figure 4.47: **Percentage distribution of various types of glacial lakes in Mansarovar Interior Basin**

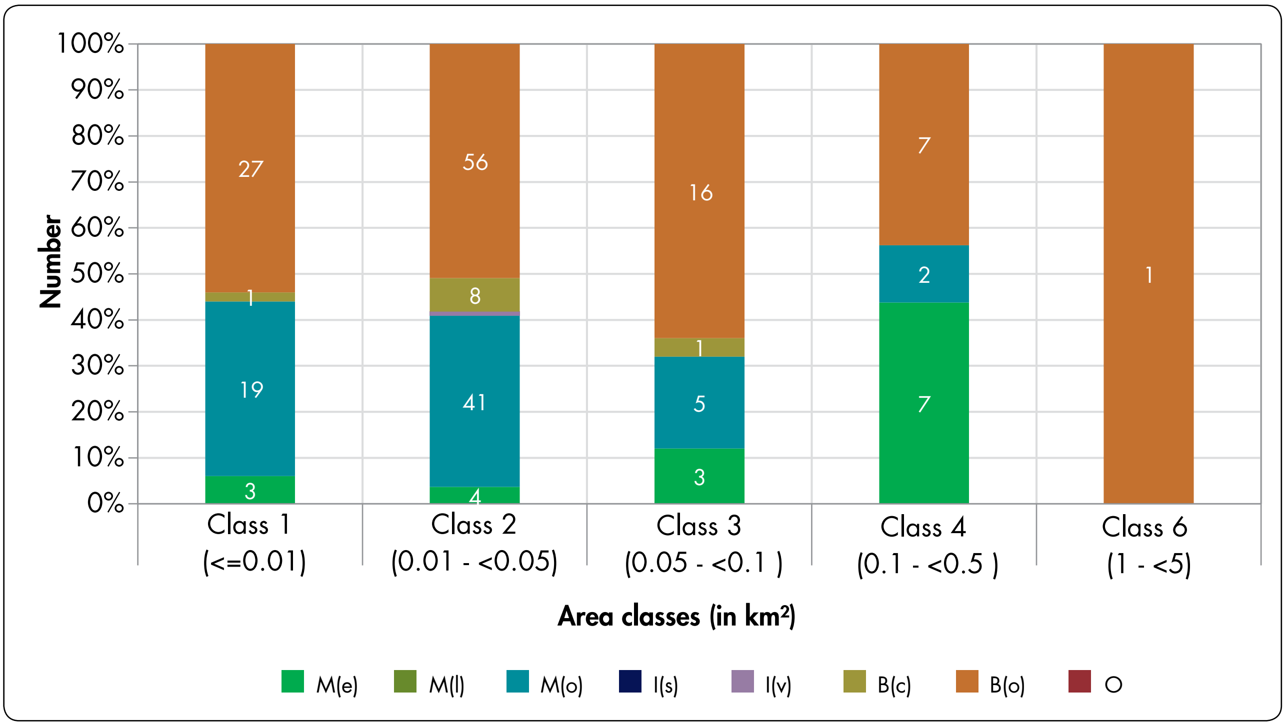


The bedrock-dammed lakes of about 31.7% and 14% of the total lakes in the basin are class 2 (0.01 - <0.05 km²) and Class 1 (<0.01 km²) respectively. Moraine-dammed lakes of 22.3% of total lakes are class 2 (0.01- <0.05 km²) and 10.9% of total lakes in the basin are class 1 (<0.01 km²). Only one lake identified as ice-dammed lakes is class 2 (0.01 – <0.05 km²). The distribution of various type of glacial lakes within different size classes is shown in Figure 4.48.

Table 4.25: **Number and area of different size category of glacial lakes in Mansarovar Interior Basin**

Glacial lake size	No.	%	Area (km²)	%	Average size (km²)
Class 1 (<0.01)	50	24.75	0.33	3.99	0.007
Class 2 (0.01 - <0.05)	110	54.46	2.46	26.43	0.022
Class 3 (0.05 - <0.1)	25	12.38	1.75	19.42	0.072
Class 4 (0.1 - <0.5)	16	7.92	2.78	29.99	0.174
Class 5 (0.5 - <1)	0	0	0	0	0
Class 6 (1 - <5)	1	0.5	1.91	20.6	1.91
Total	**202**	**100**	**9.27**	**100**	**0.046**

Figure 4.48: **Percentage distribution of various types of glacial lakes within size classes of Mansarovar Interior Basin**



Altitudinal distribution

The glacial lakes in the Mansarovar Interior Basin are distributed between 4,800 to 6,100 masl (Figure 4.49). The lowest elevation of mapped lakes are bedrock-dammed lakes at 4,816 masl and highest elevation are moraine-dammed lakes at 5,045 masl. The highest concentration of lakes are within the elevation ranges from 5,400 masl to 5,700 masl, which consists of more than 66.3% of total lakes in the basin. Below 5,400 masl, it covers 24.3% of total lakes, and only 9.5% (19 lakes) of total lakes in the basin are above 5,700 masl.

All the moraine-dammed lakes mapped in the basin lie within the elevation of 5,200 to 6,000 masl except two lakes at elevation above 6,000 masl. More than 54.5% of the total lakes are bedrock-dammed lakes lies at 5,000 – <6,000 masl elevation zone. Below 5,000 masl, only 3.5% of total lakes are bedrock-dammed lakes. The detail distribution is given in Table 4.26.

The glacial lake size in 1,000 m elevation zone distribution is shown in Figure 4.50. Almost 50.5% of lakes are class 2 (0.01 – <0.05 km²) and 24.3% of lakes are class 1 (<0.01 km²) lies within the elevation zone of 5,000 – <6,000 masl. Only seven lakes are class 2 (0.01 –< 0.05 km²) lies within elevation zone of 4,000 – <5,000 masl.

Figure 4.49: **Altitudinal distribution of number and various types of lakes in Mansarovar Interior Basin**

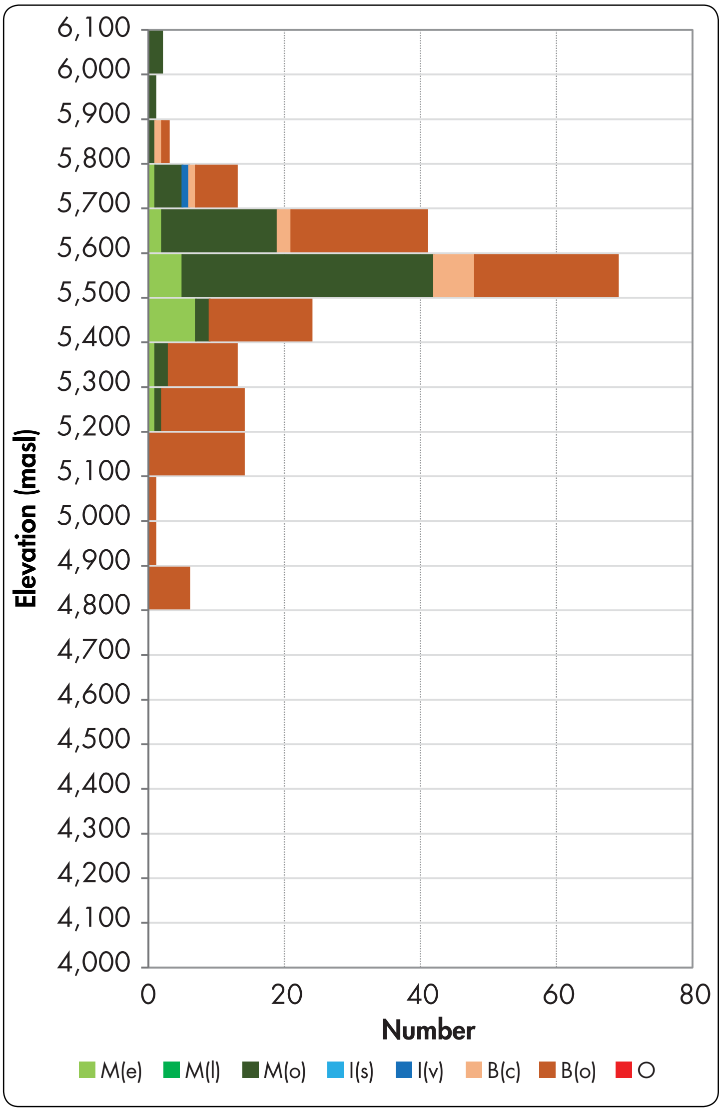
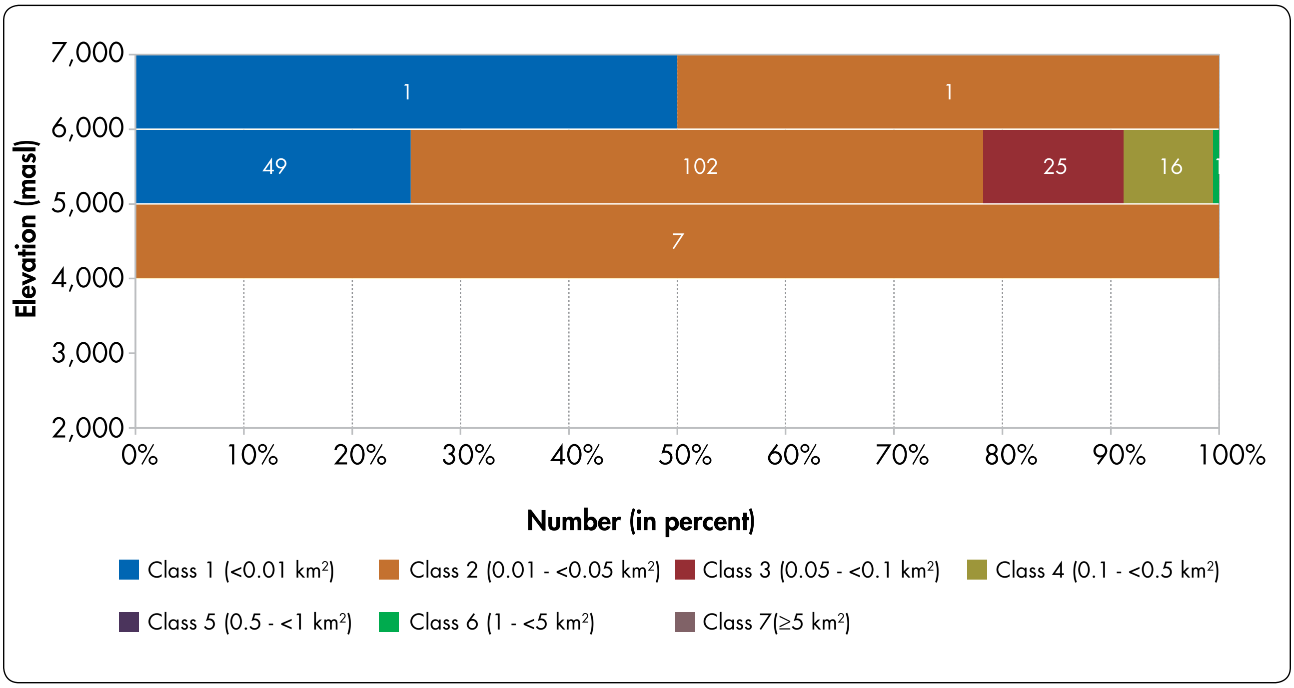


Table 4.26: **Distribution of lakes in each 1,000 m elevation zone in Mansarovar Interior Basin**

Elevation zone			4,000 – <5,000		5,000 – <6,000		6,000 – <7,000		Total	
Type			No.	%	No.	%	No.	%	No.	%
Moraine-dammed lake (M)	End-moraine	M(e)	0	0	17	8.42	0	0	17	8.42
	Lateral moraine	M(l)	0	0	0	0	0	0	0	0
	Other moraine-dammed	M(o)	0	0	65	32.18	2	0.99	67	33.17
Ice-dammed lake (I)	Supra-glacial lake	I(s)	0	0	0	0	0	0	0	0
	Glacier ice-dammed lake	I(v)	0	0	1	0.5	0	0	1	0.5
Bedrock-dammed lake (B)	Cirque	B(c)	0	0	10	4.95	0	0	10	4.95
	Others bedrock-dammed lake	B(o)	7	3.47	100	49.5	0	0	107	52.97
Others		O	0	0	0	0	0	0	0	0
Total			**7**	**3.47**	**193**	**95.54**	**2**	**0.99**	**202**	**100**

Figure 4.50: **Percentage distribution of different size of glacial lakes within each 1000 m elevation zone**



Geographical distance from glacier

The only lake identified within the glacier is 0.012 km² and the two lakes in contact with the glacier snout covers an area of 0.1 km². More than 78% of total lakes lie within the distance of 5,000 m from the glaciers in which only 11 lakes are within 100 m. The detail distribution of number and area coverage is given in Table 4.27.

Figure 4.51 shows the distribution of different types of lakes at the distance of the glacier. Almost all the moraine-dammed lakes are within 5,000 m of the glaciers. Mostly the bedrock-dammed lakes are distributed beyond 5,000 m of the glacier. The highest concentration of glacial lakes is within the 200 m to 5,000 m distance of glacier. More than 31% of the lakes are moraine-dammed lies within 200 m to 5,000 m distance of glacier. Mostly the end-moraine-dammed lakes are closer to the glacier, up to 1,000 m, whereas other moraine-dammed lakes are up to 5,000 m from the glaciers.

Table 4.27: **Distribution of glacial lake and area at distance from the glacier in Mansarovar Interior Basin**

Distance from glaciers (m)	Number		Area	
	Count	%	km²	%
Within	1	0.5	0.01	0.1
Contact with	2	1.0	0.10	1.1
>0 – <100	11	5.4	0.33	3.5
100 – <200	13	6.4	1.1	11.8
200 – <500	34	16.8	1.05	11.3
500 – <1,000	58	28.7	3.34	36.0
1,000 – <2,000	20	9.9	0.51	5.5
2,000 – <5,000	22	10.9	1.26	13.6
5,000 – <10,000	23	11.4	0.86	9.3
>10,000	18	8.9	0.72	7.8
Total	**202**	**100.0**	**9.28**	**100.0**

Glacier fed and non-glacier fed

More than 57.4% of the total lakes in the basin are fed by the glaciers in which more than 38% are moraine-dammed and 18.8% are bedrock-dammed (Table 4.28). About 42.6% of total lakes in the basin are non-glacier fed, in which more than 39% of total lakes are bedrock-dammed. Only seven moraine-dammed lakes are non-glacier fed (Figure 4.52).

Mostly the glacier fed lakes are within the distance of 2 km of glaciers and beyond 2 km of glaciers are non-glacier fed (Figure 4.53). Almost 56% of total lakes lies within the distance of 2 km of glaciers are glacier fed and 29.7% of the total lakes lies beyond the 2 km of glaciers are non-glacier fed.

Figure 4.51: **Distribution of various types of lakes at the distance from the glaciers in Mansarovar Interior Basin**

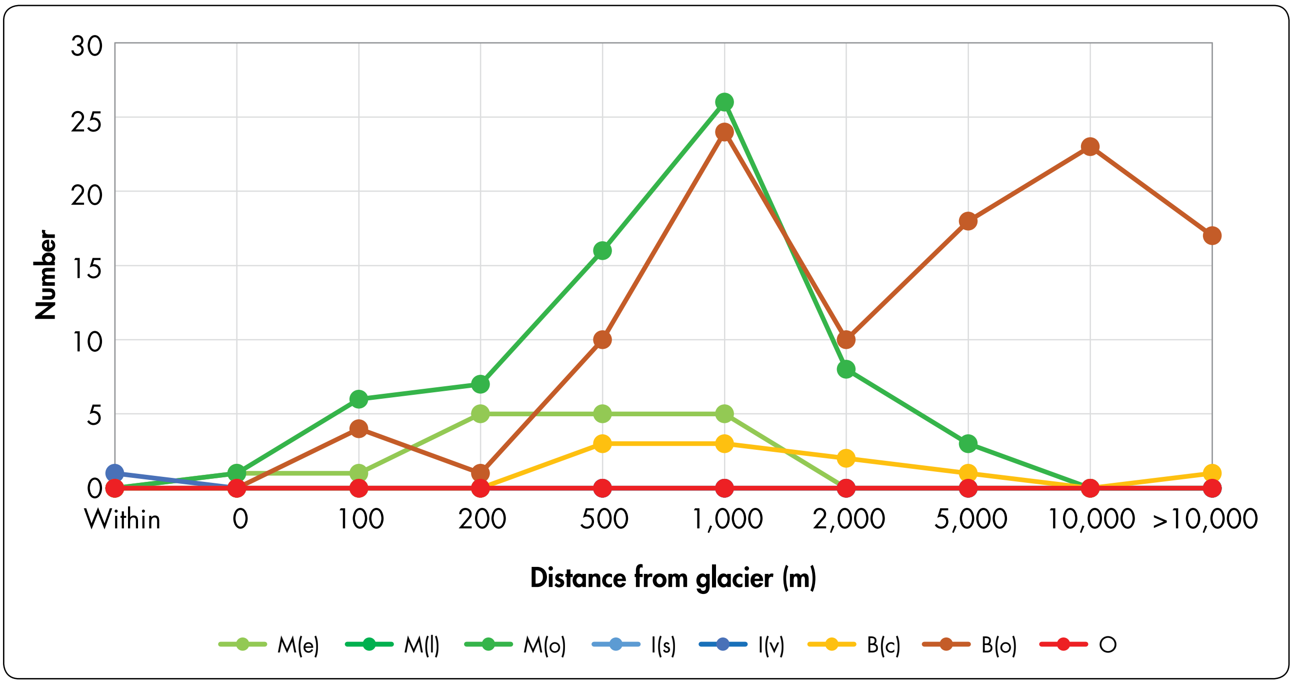


Table 4.28: **Glacier fed and non-glacier fed glacier lake distribution in different types of lakes**

Type			Number				Area (km²)			
			Glacier fed		Non-glacier fed		Glacier fed		Non-glacier fed	
			Count	%	Count	%	km²	%	km²	%
Moraine-dammed lake (M)	End-moraine	M(e)	17	8.42	0	0	1.682	18.15	0	0
	Lateral moraine	M(l)	0	0	0	0	0	0	0	0
	Others	M(o)	60	29.7	7	3.47	1.41	15.21	0.217	2.34
Ice-dammed lake (I)	Supra-glacial lake	I(s)	0	0	0	0	0	0	0	0
	Glacier ice-dammed lake	I(v)	1	0.5	0	0	0.01	0.13	0	0
Bedrock-dammed lake (B)	Cirque	B(c)	5	2.48	5	2.48	0.07	0.78	0.154	1.66
	Others bedrock-dammed lake	B(o)	33	16.34	74	36.63	2.92	32.28	2.729	29.45
Others		O	0	0	0	0	0	0	0	0
Total			**116**	**57.43**	**86**	**42.57**	**6.17**	**66.55**	**3.1**	**33.45**

Figure 4.52: **Distribution of glacier fed and non-glacier fed lakes in basins of the Mansarovar Interior Basin**

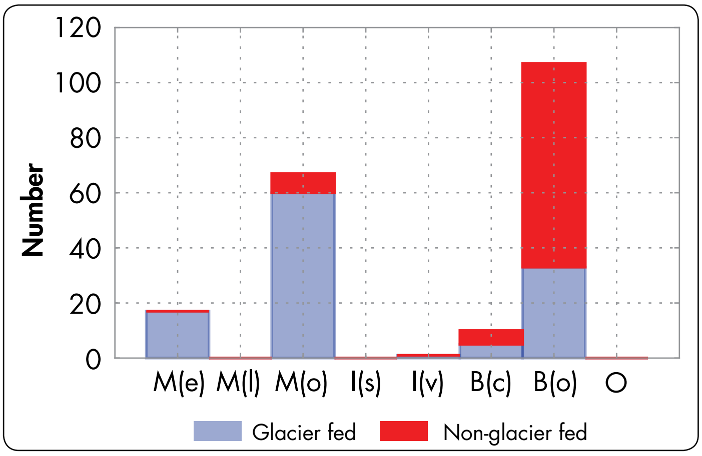
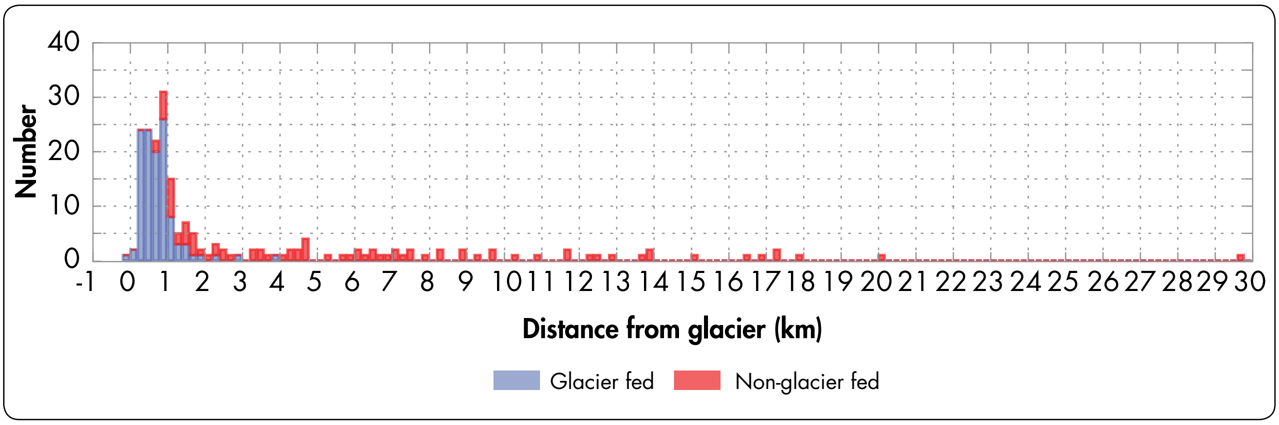


Figure 4.53: **Histogram showing the number of glacier fed and non-glacier fed glacial lakes within 100m bin distance from the glacier in Mansarovar Interior Basin**



Summary and Conclusions

The Hindu Kush Himalaya (HKH) contains the world's greatest areal extent and volume of ice outside the polar regions. Glaciers, snow, and permafrost as well as most other components of the cryosphere have undergone significant changes during recent decades, related to climatic forcing. One of the impacts of glacier recession is the formation of glacial lakes. Accelerated glacier retreat during the past few decades has resulted in the rapid accumulation of melt water resulting in the development of pro-glacial lakes by damming of meltwater or expansion and merging of already existing glacial lakes. Expansion or formation of new lakes at the margin of many shrinking glaciers has increased the risk of glacial lake outburst floods (GLOFs). Information about them is important for assessing regional water resources, hazard management applications, and climate change impact studies. This study provides the comprehensive data of glacial lakes representation of a base year 2005 +/-2 years in five major river basins — Amu Darya, Indus, Ganges, Brahmaputra, and Indus, including Mansarovar Interior Basin — of the HKH. This inventory includes all the water bodies in front of and on or beside a glacier or in the lowland formed by paleo-glaciation.

A total of 25,614 glacial lakes covering an area of 1,444 km^2 were identified. Brahmaputra River Basin (53.3% of total lakes) has the highest number of glacial lakes followed by Indus (22%), Ganges (16%), Amu Darya (5.8%), and Irrawaddy (2%) River Basins. This inventory also includes all the glacial lakes in the paleo-glaciation landforms, so the majority of glacial lakes are bedrock-dammed lakes. Nearly one-third of all the glacial lakes in the region are moraine-dammed lakes. The number of moraine-dammed lakes is higher in Amu Darya and Ganges River. The area coverages of moraine-dammed lake in Ganges River Basin is higher than in Amu Darya River Basin. But the proportion of bedrock-dammed lakes is higher in Brahmaputra and Irrawaddy River Basin. About 5% of total lakes are identified as ice-dammed lakes. The size and number of these lakes are changing frequently depending on seasons and time.

The majority of lakes are small in size and an inverse relationship between the number and area of glacial lakes is found. The largest glacial lake in the HKH is 15.1 km^2, which lies in the Amu Darya River Basin and is an other type of lake. Almost 79% of lakes mapped in the HKH are less than 0.05 km^2. More than 83% of the lakes in each basins - Irrawaddy, Ganges, and Amu Darya River Basins - are of size less than 0.05 km^2, whereas in other River Basins has less than 80%. Only 11 lakes are larger than 5 km^2, one each in Amu Darya, Indus, and Ganges, and eight in Brahmaputra. The average size of the lakes in the region is 0.056 km^2. The average size of other types of glacial lakes are comparatively bigger than moraine-dammed and ice-dammed lakes, indicating that the size of the other types of glacial lakes are larger. The average size of lakes in Brahmaputra and Ganges River Basins are 0.065 and 0.051 km^2, respectively, whereas the average size in other river basins ranges from 0.045 to 0.046, except in Irrawaddy River Basin which averages size is 0.031 km^2. This indicates that overall the lakes in Brahmaputra and Ganges are larger than in other River Basins.

The glacial lakes in the HKH are distributed at elevations from 2,200 masl to 6,200 masl. The lowest elevation of glacial lake mapped in this inventory is 2,203 masl in the Indus Basin and the highest elevation is 6,190 masl in the Ganges River Basin. The majority of glacial lakes are located in elevation zones of 4,000–5,000 m followed by 5,000–6,000 m. The lowest elevations of glacial lakes mapped in the major river basins are 2,971 masl in Amu Darya, 2,203 masl in Indus, 2,462 masl in Ganges, 2,459 masl in Brahmaputra, 3,461 masl in Irrawaddy, and 4,800 masl in Mansarovar Interior Basin.

The lake density both in terms of number and area is much higher in the eastern part of the HKH with much more concentration towards the east of central Nepal. It is low in the central part of the HKH and increases somewhat to the western part of the HKH. The number of lakes and lake area decrease with distance from the glaciers and increase closer to the glacier. Overall, number and area coverage is higher within 5 km of the glaciers. Mostly the lakes beyond 5 km of the glacier are bedrock-dammed lakes and other type lakes. The proportion of moraine-dammed lakes is higher closer to the glaciers.

Mostly the glacial lakes closer to the glacier, within a distance of 2 km, are directly fed by the glacier melt, whereas the lakes farther away from the glaciers are non-glacier fed and mostly fed by snowmelt and precipitation. The proportion of non-glacier fed is much higher for bedrock-dammed and other types of lakes. Very few moraine-dammed lakes are identified as non-glacier fed. The non-glacier fed bedrock-dammed lakes in the Brahmaputra River Basin are much higher in number compared to other River Basins. The number of non-glacier fed lakes are less in the Amu Darya and Ganges River Basins. Glacier fed lakes in the Amu Darya and Ganges River Basins comprise 77% and 61%, respectively, of all the lakes in those basins, whereas glacier-fed lakes makeup less than 60% of all lakes in the remaining river basins. Many lakes close to glaciers or in contact with glaciers will vary in size due to seasonal variations in melt water, which escalates the threat of outburst. Further study of these lakes is warranted. Lakes further away from glaciers are mostly in paleo-glaciation landforms and classified as bedrock-dammed lake. These lakes are mostly fed by snowmelt and precipitation. The study of these lakes is important in terms of water resource.

Although remote sensing made the processes for mapping and monitoring of glacial lakes quicker in the larger scale with development of new advance tools and technology, it is challenging to apply an automatic method to capture the glacial lakes throughout the HKH due to inconsistent and not analogous climatic conditions in the region. So we have adopted automatic image processing wherever the image quality is good with less cloud cover and the least amount of snow cover and also used a manual visual interpretation method for cross-checking as well as in the area mostly covered by snow and partially covered by cloud with comparing multiple time series images. This inventory used the same time span images used for glacier inventory so that the data can be interlinked for analysis. Hence the inventory is based on Landsat images (Landsat TM and ETM+) of years 2005±2. Also for the quality of the data only the glacial lakes bigger than 0.003 km^2 were mapped and past glacial lake inventories data, wherever available, and high resolution images in Google Earth environment were used for verification. Once the final glacial lake polygons were generated, the attributes of the glacial lake were generated in ArcGIS.

Further work in developing time series data on glacial lakes, identification of critical lakes, numerical simulation of outburst flood, and downstream vulnerability assessment are needed for further understanding of the dynamics of glacial lakes and the risks associated with outburst floods.

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