RESEARCH REPORT

Inventory of glacial lakes and identification of potentially dangerous glacial lakes in the Koshi, Gandaki, and Karnali river basins of Nepal, the Tibet Autonomous Region of China, and India

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RESEARCH REPORT

Inventory of glacial lakes and identification of potentially dangerous glacial lakes in the Koshi, Gandaki, and Karnali river basins of Nepal, the Tibet Autonomous Region of China, and India

Authors

Samjwal Ratna Bajracharya, Sudan Bikash Maharjan, Finu Shrestha, Tenzing Chogyal Sherpa, Nisha Wagle, and Arun Bhakta Shrestha

Contents

Most Himalayan glaciers are rapidly melting and shrinking, concurrent with the warming climate. The rapid shrinking and retreating of glaciers not only impacts water resources and hydrological processes, but also influences the formation and expansion of glacial lakes, increasing the risk of GLOFs. Therefore, systematic and regular assessment of glaciers and glacial lakes, and identification of potentially dangerous glacial lakes, and ranking of their hazard levels are useful in designing GLOF risk management and reduction strategies.

Nepal consists of three major river basins – Koshi, Gandaki, and Karnali (including Mahakali), all of which are major tributaries of the Ganges. These river basins are transboundary, straddling the Tibet Autonomous Region (TAR) of China (upper section), Nepal (upper and middle sections), and India (largely the lower section, barring the western middle section of the Kali River).

The glacial lakes presented in this study consist of water bodies that are proximal to present glaciers as well as those located in lowland areas that were covered by glaciers in the past. This section covers detailed methods on mapping and monitoring of glacial lakes, identification of potentially dangerous glacial lakes, and ranking of these lakes using remote sensing and geospatial techniques.

Glacial lakes in the Koshi, Gandaki, and Karnali river basins are found on the upper reaches at altitudes above 3000 metres. This section provide detailed information on glacial lakes in the Koshi, Gandaki, and Karnali basins including spatial distribution, size, type, altitudinal distribution, and linkages to glaciers.

The stability of a lake depends on its physical characteristics, the damming materials, and the characteristics of surrounding features. This section provides detailed information on lake stability and the processes applied in identifying potentially dangerous glacial lakes, in the Koshi, Gandaki, and Karnali river basins.

GLOFs are a crucial problem for people living in the mountains, which develop at high altitudes and can extend for long distances, gravely damaging downstream infrastructure. The identification of potentially dangerous glacial lakes will help design GLOF risk management and reduction strategies.

Na, a village near Tsho Rolpa glacial lake in Rolwaling Valley, Nepal.

Abbreviations and acronyms

ALOS	Advanced Land Observing Satellite
ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer
B (c)	Cirque lake
B (o)	Other bedrock-dammed lake
co	Compressed and old dam
DEM	Digital elevation model
dl	Dam length
dm	Distance to source glacier
DMS	Degree minute second
ds	Dam slope
ETM+	Enhanced Thematic Mapper Plus
GCF	Green Climate Fund
GCM	Global climate model
GIS	Geographic information system
GL	Glacial lakes
GLIMS	Global Land Ice Measurements from Space
GLOBE	Global Land One km-Base Elevation Project
GLOF	Glacial lake outburst flood
GloVis	USGS Global Visualization Viewer
HKH	Hindu Kush Himalaya
I	Ice-dammed lake
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Intergovernmental Panel on Climate Change
I (s)	Supraglacial lake
I (v)	Lakes dammed by tributary valley glaciers
LIGG	Lanzhou Institute of Glaciology and Geocryology
M	Moraine-dammed lake
M (e)	End moraine-dammed lake
M (l)	Lateral moraine-dammed lake
M (o)	Other moraine-dammed lake
NAP	National Adaptation Plan, Nepal
NASA	National Aeronautics and Space Administration
nc	No crest
NCVST	Nepal Climate Vulnerability Study Team
NDC	Nationally Determined Contributions
NDWI	Normalized Difference Water Index
NEA	Nepal Electricity Authority
NIR	Near infrared
NSIDC	National Snow and Ice Data Center
O	Other glacial lakes
OLI	Operational Land Imager
PDGL	Potentially dangerous glacial lake
RCM	Regional Climate Model
RS	Remote sensing
sm	Slope of source glacier
Spot	Satellite Pour l'Observation de la Terre
SRTM	Shuttle Radar Topography Mission
TAR	Tibet Autonomous Region
UNDP	United Nations Development Programme
WECS	Water and Energy Commission Secretariat

Foreword

Glaciers and glacial lakes are major sources of freshwater in the Himalaya. They play a significant role in local and regional hydrology, and in maintaining ecosystem services in the high mountain areas and downstream. Himalayan glaciers are vulnerable to global climate change, and have been melting at an unprecedented rate since the mid-20th century, impacting flow regimes in major associated river basins. The shrinking, thinning, and retreating of glaciers not only impacts water resources and river flows, but also leads to the formation of new lakes as well as the expansion of existing glacial lakes, increasing the risk of glacial lake outburst floods (GLOFs).

GLOFs, which are caused by a sudden release of water from glacial lakes that have breached their moraine dams, are a prominent water-induced hazard in Nepal and other mountainous countries. Historically, GLOFs have had catastrophic consequences in Nepal, leading to a loss of lives and livestock, and damages to multi-million dollar infrastructure projects and transportation routes through the direct impacts of flooding and cascading impacts such as landslides, erosion, and sedimentation in river valleys. Often, such damages are irreparable for years or even decades, with huge costs to the economy and impacts on downstream populations. Twenty-six GLOF events have been recorded in Nepal, and 11 of these have had transboundary impacts. Recorded information on GLOF events shows an increment in the frequency and magnitude of these disasters in recent decades. If climate change continues at its present pace, rates of glacier mass loss and shrinkage, and the formation and expansion of glacial lakes will increase further, which could escalate the occurrence of GLOFs and other glacial hazards and impact the availability of water resources.

In view of these rapid changes in glacier environments and increased risk to lives due to the expansion of settlements and infrastructure along rivers, regular monitoring, periodic mapping, and hazard assessment of glacial lakes are required to ensure GLOF risk management and planning, and the implementation of risk reduction strategies.

Since 1986, ICIMOD and its partners have been involved in preparing and updating a database of glacial lakes and the identification of potentially dangerous glacial lakes in the Hindu Kush Himalayan region. These research initiatives have helped identify the most critical glacial lakes in the region for the implementation of mitigation measures and installation of early warning systems. Such measures have enabled the Nepal government to lower water levels in two of its largest and most critical glacial lakes, both considered high-risk. More recently, ICIMOD and the United Nations Development Programme (UNDP) Nepal have worked together to prepare an updated comprehensive glacial lake inventory of three major transboundary basins – the Koshi, Gandaki, and Karnali (including Mahakali) – which cover parts of China and Nepal, and a small portion of India.

The present report provides an update on the status and changes in the number and area of glacial lakes in the three basins along with a detailed methodology for the identification of critical glacial lakes in remote and inaccessible mountain terrain using remote sensing tools and technologies. It also identifies a number of potentially dangerous glacial lakes in the basins and categorizes them into four hazard levels.

This research has made an important contribution to the identification of potentially dangerous glacial lakes in three major basins of Nepal, on the basis of which regular monitoring of these lakes with on-site verification by experts can be made, and early warning systems can be deployed in highly prioritized dangerous glacial lakes. Based on the information made available, hazard assessment and mitigation work could be implemented to secure the lives and livelihoods of mountain and downstream communities. Short-, medium-, and long-term strategic plans and legal frameworks can be developed to manage GLOF hazards and inform regulations for the construction of hydropower plants.

ICIMOD is grateful to UNDP-Nepal for this opportunity to support the Government of Nepal. We thank the authors and many contributors for their generous support and contributions to the report.

David Molden, PhD
Director General, ICIMOD

Foreword

Nepal has, in recent years, given top priority to mitigating the impacts of climate change. This has involved a systemic risk mitigation approach, including adjustment of its development policies and plans to align with climate imperatives. Nepal's key economic sectors – agriculture, hydropower, and tourism – are particularly vulnerable to climate change. Climate disasters can wreak devastation on these sectors, damaging infrastructure and property worth millions of dollars, ruining livelihoods. In 2019, the Ministry of Home Affairs reported that on average, Nepal loses 333 lives and property worth over USD17.24 million (NPR 2,099 Million) each year to extreme climate events.

Glacial lake outburst floods (GLOFs) are among the high-impact climate hazards caused by rising temperatures in high altitude areas. Rising temperatures cause glaciers to melt and glacial lakes to form. Nepal has experienced 26 GLOF events since 1977, of which 14 originated in Nepal. These floods have caused immense damage to infrastructure –hydropower, roads, and bridges, for instance – and to economic lifelines, such as agriculture and biodiversity.

In 2016, in collaboration with the Government of Nepal, UNDP helped to reduce the risk of GLOFs at Imja glacial lake. The estimated monetary value of elements exposed to GLOF risk at Imja was USD 35.5 million (NPR 4,323 million). Similarly, the elements exposed to GLOF risk at Thulagi glacial lake are valued at USD 415.35 million (NPR 50,581 million). UNDP plans to work with the Government of Nepal and other stakeholders to reduce this risk. Just one GLOF event has the potential to reverse many of Nepal's development gains, including its progress towards the Sustainable Development Goals.

I would like to thank the Government of Nepal for entrusting UNDP with the vital role of helping to mitigate the risks of GLOFs and other climate-induced disasters. Our successful experience in reducing GLOF risks at the Imja Lake and at Tsho Rolpa has given us the confidence to move on to the next phase of risk mitigation at four other potentially dangerous glacial lakes: Dona/Thulagi in the Gandaki basin, the Lower Barun glacial lake, and Lumding Tsho and Chamlang North (Hongu II) in the Koshi basin.

Our engagement in GLOF risk mitigation made it clear that an updated inventory of glacial lakes and a fresh analysis of their threat levels is a fundamental requirement. This body of knowledge is necessary not only to address imminent risks to the downstream population, but also to build strategies for long-term community resilience, which, in turn, contribute to the 2030 Agenda for Sustainable Development.

We are thankful to ICIMOD for its cooperation and technical support in successfully completing this study and jointly bringing its findings to a wider audience. This publication fills critical knowledge gaps in the areas of risks associated with glacial lakes in Nepal.

The report is being published at the right time. I am certain it will inform the ongoing revision of the Nationally Determined Contributions (NDC) and National Adaptation Plan (NAP) formulation processes, particularly in validating Nepal's risk profile and recommending medium- to long-term adaptation actions. The analysis is also expected to help realize the policy commitments enshrined in Nepal's Climate Change Policy (2019) and National Disaster Risk Reduction Policy and Strategic Action Plan (2018).

Now, as the world battles the COVID-19 pandemic, climate change remains a major issue of our times. While it is yet to be determined if this pandemic is in any way related to climate change, any combination of crises will certainly complicate matters. The pandemic's impacts are likely to increase existing vulnerabilities to climate change, and this calls for a strategy to develop the resilience of communities to a range of shocks.

We reiterate our earnest support to the Government of Nepal's comprehensive approach to building resilience and its commitment to making Nepal a safer and more resilient nation by 2030.

Ayshanie Medagangoda-Labé
Resident Representative
United Nations Development Programme

Lumding Tsho, a glacial lake in the Dudh Koshi basin, Nepal.

Key findings

Glacial lakes equal to or larger than 0.003 km^2 were mapped for 2015, based on Landsat images and using remote sensing tools and techniques, for the Koshi, Gandaki, and Karnali basins of Nepal, the Tibet Autonomous Region (TAR) of China, and India. The study found 3,624 glacial lakes located in the three basins, of which 2,070 lakes are in Nepal, 1,509 lakes in the TAR, China, and 45 lakes in India. As many as 1,410 lakes are larger than or equal to 0.02 km^2, which are considered large enough to cause a glacial lake outburst flood (GLOF). Lakes associated with a large, retreating glacier and steeply sloping landforms in their surroundings are susceptible to a GLOF.

Forty-seven glacial lakes were identified as potentially dangerous glacial lakes (PDGLs) based on the following criteria: (i) characteristics of the lakes and their dams; (ii) the activity of the source glacier; and (iii) morphology of the surroundings. Other factors, such as extreme climatic conditions, seismic activity, and human interference on or around the lake and on the dam, are not considered.

Of the 47 PDGLs identified, 42 are located in the Koshi basin, three in the Gandaki basin, and two lakes in the Karnali basin. With respect to political boundaries, 25 PDGLs are in the territory of the TAR, China, 21 are located in Nepal, and one PDGL is in India. The number of PDGLs in Nepal identified by this study is the same as a previous exercise in 2011. However, only 13 of them are the same PDGLs identified previously; eight PDGLs have been deleted from the earlier list and eight new PDGLs added.

The physical parameters of the lakes, dams, and surroundings were considered to categorize the PDGLs into three ranks, depending on their hazard level. The critical lakes are classed under Rank I. These have a greater possibility of expansion, are dammed by loose moraine material, and could experience snow and/or ice avalanches and landslides in their surroundings that may impact the lake and the dam. A slight rise in the water levels of these lakes or a reduction in the strength of their dams could cause a breach. This warrants the immediate implementation of potential measures for GLOF mitigation. The lakes classed under ranks II and III have the potential to grow, and hence need close and regular monitoring. Of the 47 lakes reviewed, 31 lakes were classed under Rank I, 12 lakes in Rank II, and 4 lakes under Rank III.

Further detailed information regarding socioeconomic parameters such as settlements, bridges, roads, hydropower projects and distance from them, agricultural land, and other infrastructure along river valleys downstream need to be investigated, and linked with the GLOF simulation model output in order to identify the risk levels and prioritization of these lakes for GLOF risk reduction.

The water levels of four Rank I lakes had been lowered in the past to reduce the risk of GLOFs. The water level of Tsho Rolpa in Nepal was lowered by more than 3 metres in 2000, and of Imja Tsho, also in Nepal, by 3.4 metres in 2016. Similarly, the water levels of two lakes in the TAR, China, GL088066E27933N and GL088075E27946N, had also been lowered, but the details are not known.

Glacial lake inventories should be updated periodically, and potentially dangerous glacial lakes (PDGLs) monitored regularly. Detailed field assessments should be undertaken to enable risk assessments – particularly of high-ranked PDGLs – for new development projects and to reduce the vulnerability of mountain people and settlements downstream.

Dudh Khola as seen from Ponkar Glacier.

Acknowledgements

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We are indebted to the Department of Hydrology and Meteorology, Government of Nepal for their detailed review of the report. Special thanks go to the report's external and internal reviewer's – David Rounce, University of Alaska, Fairbanks, and Samuel Inglis, Cryosphere Outreach Analyst, ICIMOD.

A majority of the data used in our research was sourced from landsat satellite images, Shuttle Radar Topography Mission (SRTM), and the ALOS PALSAR digital elevation model. We are deeply indebted to the data providers — NASA, the United States Geological Survey (USGS), the Alaska Satellite Facility, NASA's Jet Propulsion Laboratory (JPL), and the Consultative Group on International Agricultural Research (CGIAR).

We wish to express our gratitude to our colleagues in the Cryosphere Initiative, Geospatial Solutions theme, and the Mountain Environment Regional Information Systems (MENRIS) programme for their support and cooperation, which were essential to the successful completion of our work.

The calving of ice from the Tarkading Glacier into the Tsho Rolpa glacial lake.

SECTION 1

Introduction

The cryosphere (glaciers, snow, river ice, lake ice, sea ice, and permafrost) is an integral part of the global climate system, and has important linkages with a number of ecosystem and socioeconomic benefits. However, it has been changing rapidly in recent decades; the changes vary, depending on the spatial and temporal scale at which they are examined. Most Himalayan glaciers have been rapidly melting and shrinking since the 1980s (Bajracharya et al. 2014a), concurrent with a warming climate (Bhambri & Bolch 2009; Bolch et al. 2012; Yao et al. 2012). Glacial loss and shrinkage not only affect water resources and hydrological processes, but also influence the formation and expansion of glacial lakes (Yao et al. 2010).

The International Centre for Integrated Mountain Development (ICIMOD) has been involved in the tabulation of glacial lake inventories and the identification of potentially dangerous glacial lakes (PDGLs) since 1986 (Ives 1986). ICIMOD, in collaboration with partners in different countries, embarked on the preparation of an inventory of glaciers and glacial lakes, and the identification of potential sites for glacial lake outburst floods (GLOFs) in the Hindu Kush Himalayan (HKH) region. A glacial lake inventory for Nepal and Bhutan was started in 1999 (Mool et al. 2001a, 2001b), and inventories for selected basins in China, India, and Pakistan were started in 2002 (ICIMOD 2011).

In 2011, a comprehensive study undertaken by ICIMOD outlined the status of glaciers in the HKH region (Bajracharya & Shrestha 2011). To understand the changes in glacier area and extent, ICIMOD mapped glaciers in Nepal, Bhutan, and some selected basins of other parts of the HKH region, from the 1980s, 1990, 2000, and 2010, based on satellite images. Analysis of the time series data revealed that the glaciers had lost almost a quarter of their total area over the 30 year period (Bajracharya et al. 2014b, 2014c, 2015). Moreover, total glacial area had decreased by 24% in Nepal between 1977 and 2010, while the number of glacial lakes had increased by 11% (Bajracharya et al. 2014b). The rapid melting and recession of many Himalayan glaciers due to climate change is leading to the formation of new glacial lakes.

At the same time, the enlargement of existing lakes is increasing the risk that their surrounding moraines will become destabilized (Jimenez Cisneros et al. 2014; Cruz et al. 2007; IPCC 2007; Rosenzweig et al. 2007). The moraines are mostly composed of loose debris and are susceptible to GLOFs (Randhawa et al. 2005). GLOFs from moraine-dammed glacial lakes have been assessed and modelled in several previous studies (Osti et al. 2013; Wang et al. 2012; Westoby et al. 2014). Several investigations of changes in glacial lakes have also been conducted in the Himalayas, and heterogeneous areal expansions with regional differences have been reported (Bajracharya 2011; Bolch et al. 2008; Gardelle et al. 2011; Li & Sheng 2012; Mool et al. 2001a).

GLOFs are a crucial problem that countries and people in the Himalayan region face (Ageta et al. 2000). Himalayan GLOFs develop at high altitudes and can extend for long distances, gravely damaging downstream infrastructure (Chen et al. 2007; Liu et al. 2014; Osti & Egashira 2009). GLOFs that have occurred previously in the Himalayas demonstrate that they constitute a serious threat to socioeconomic and developmental endeavours (Rai 2005; Wang et al. 2014; Worni et al. 2013). Some GLOFs have been associated with transboundary impacts as well (Ives et al. 2010; Reynolds 1998; Xu et al. 1989; Yamada & Sharma 1993).

Over 50 GLOF events have been reported in the HKH region; however, records are available only for some areas of China, Nepal, Pakistan, and Bhutan (Che et al. 2014; LIGG/WECS/NEA 1988). Many more such events may have occurred but remain undocumented or unrecorded (Ives et al. 2010). An increase in the frequency of GLOF events in the Himalayas has been reported over 1940–2000, although the trend has been considered statistically insignificant (Bajracharya 2009; Richardson & Reynolds 2000). Nepal had experienced 26 recorded GLOFs, in which significant damage and loss of life was reported. For instance, both the Dig Tsho GLOF of 1985 and the (Sabai Tsho) Tampokhari GLOF in 1998 caused a considerable loss of life, property, and infrastructure, and severely affected the livelihoods of people living in downstream areas (Bajracharya & Mool 2009; Bajracharya et al. 2008; Dwivedi et al. 2000; Vuichard & Zimmermann 1987).

Although GLOFs are not a recent phenomenon, they started drawing considerable attention from scientists after the 1980s, as the risks from potential GLOFs increased (Chen et al. 2013; Liu & Sharma 1988; Vuichard & Zimmermann 1986, 1987; WECS 1987; Xu 1988). About 1.6 million people live downstream within 3 km of moraine-dammed lakes in Nepal, and may be at risk from these natural hazards (Ghimire 2004). The settlements, roads, bridges, hydropower projects, and other infrastructure built along the river valleys have intensified GLOFs risk. The number of people likely to be affected by the loss of resources from GLOFs are about 96,767 for Imja Lake, 141,911 for Tsho Rolpa Lake, and 165,068 for Thulagi Lake (ICIMOD 2011).

However, the risk of GLOFs can be reduced through the implementation of appropriate mitigation and adaptation measures (Bajracharya 2009). To achieve this, an updated and standardized glacial lake inventory should be conducted periodically, ideally at least every five years, in order to analyse the spatial distribution and temporal development of glacial lakes; a GLOF hazard assessment produced; and plans made for the mitigation of identified, potential GLOF risks. In addition, adequate information should be made available to the public in varied languages to help them understand GLOFs and the risks they pose to people's lives and infrastructure.

In order to support the Green Climate Fund (GCF) project proposal formulated by UNDP—Nepal, a comprehensive mapping and assessment of glacial lakes in Nepal, as well as basins in the TAR of China, and India (which drain into Nepal) was conducted for 2000 and 2015. It was done using remote sensing (RS) and geographic information system (GIS) tools. Varied physical criteria were used to sort the PDGLs into three ranks, depending on their hazard level.

Gangapurna glacier and glacial lake in Manang Valley, Nepal.

SECTION 2

Study area

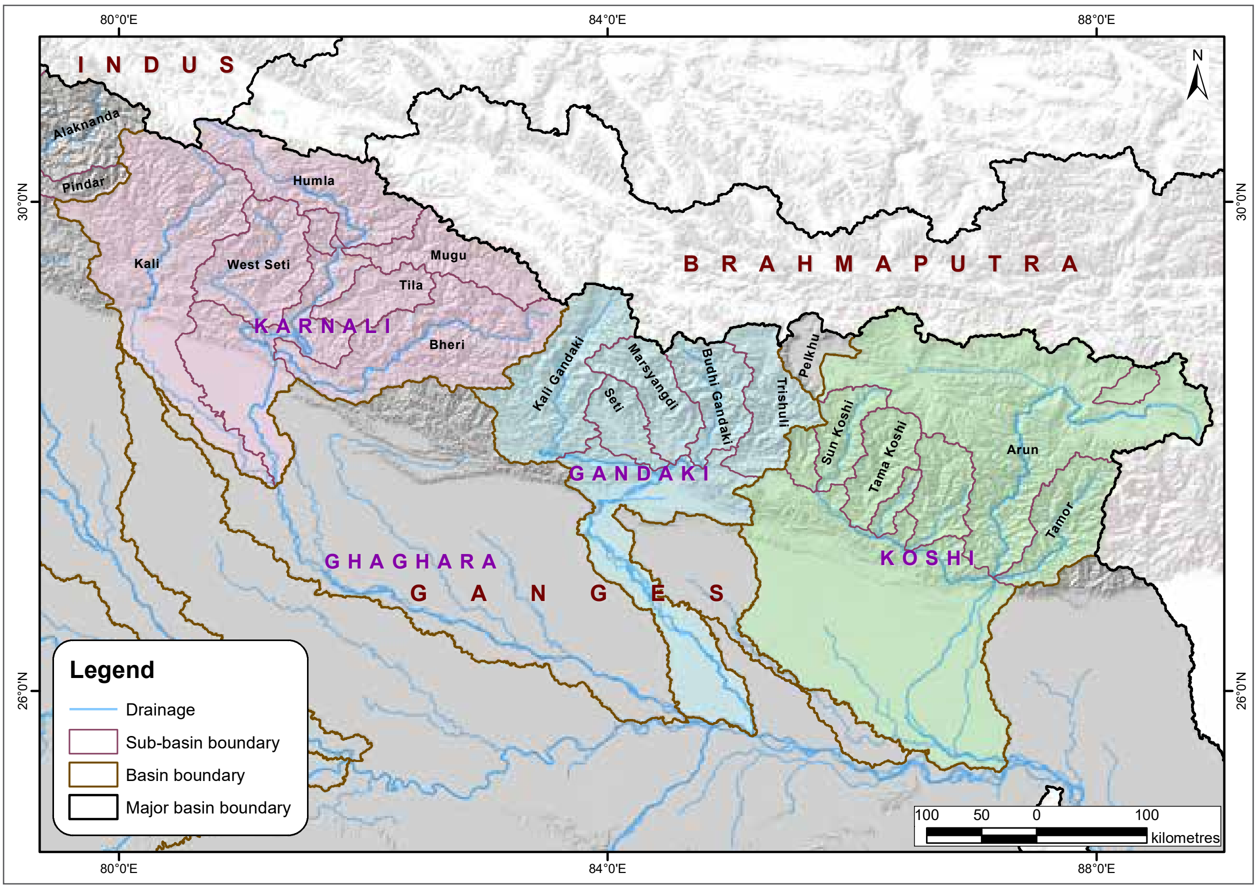
The present study area lies within the river basins of the Koshi, Gandaki, and Karnali, all of which are major tributaries of the Ganges. The catchments of these river basins are transboundary, straddling the Tibet Autonomous Region (TAR) of China (upper section), Nepal (upper and middle sections), and India (largely the lower section, barring the western middle section of the Kali River). Some of the tributaries have their source in the TAR, China, before flowing through Nepal to finally merge with the Ganges River in India (Figure 2.1).

The major tributaries of the Koshi are the Tamor, the Arun (Pumqu River in China), the Dudh Koshi, the Tama Koshi (the Rongxer in China), the Likhu, the Sun Koshi (the Poiqu in China), and the Indrawati. The Gandaki is fed by the Trishuli, Budhi Gandaki, Seti, Marsyangdi, and the Kali Gandaki. A portion of the upper sections of the Budhi Gandaki and Trishuli rivers lie in the TAR, China. The Karnali River of western Nepal is also known as Ghaghara in India. The main tributaries of the Karnali are the Mahakali (Kali), Bheri, Humla Karnali, Mugu Karnali, Kawari, West Seti, and Tila. Some tributaries of the upper Humla River have their source in China and the catchment of the upper Kali River spans Nepal, India, and China.

The glaciers and glacial lakes are distributed only in the upper and middle sections of the river basins. Hence, the study area is almost entirely confined to Nepal and the TAR, China, except for a small section in India (Table 2.1). Consequently, the glaciers and glacial lakes covered in India by this study are small in number. Relevant information from India has been presented in the text or tables where appropriate.

The overall catchment areas of the Koshi, Gandaki, and Karnali basins are 88,593 km^2, 44,658 km^2, and 131,747 km^2 respectively. Approximately 44.5%, 71.9%, and 51.5% of the total catchment areas of the Koshi, Gandaki, and Karnali respectively, lie in Nepal. Similarly, about 33.2%, 9.7% and 2.3% of the catchment areas of these three rivers lie in the TAR, China. And though 22.2%, 18.3%, and 46.2% of the catchment areas of the Koshi, Gandaki and Karnali respectively lie in India, much of them are in the lower section of the basins except for a small portion of the Kali River (Table 2.1).

FIGURE 2.1 **STUDY AREA IN THE KOSHI, GANDAKI, AND KARNALI BASINS IN NEPAL, THE TAR OF CHINA, AND INDIA**



Disclaimer: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

Ponkar Lake is a lateral moraine-dammed glacial lake.

TABLE 2.1 CATCHMENT AREAS OF THE KARNALI, GANDAKI, AND KOSHI BASINS IN NEPAL, THE TAR OF CHINA, AND INDIA

Basin	Sub-basin	Nepal	TAR, China	India	Total
		Area (km²)			
Koshi	Indrawati	1,229	0	0	1,229
	Sun Koshi	1,399	1,967	0	3,367
	Tama Koshi	2,688	1,442	0	4,130
	Likhu	1,051	0	0	1,051
	Dudh Koshi	4,065	0	0	4,065
	Arun	5,146	26,041	0	31,187
	Tamor	6,056	0	0	6,056
	Trunk Koshi	17,820	0	19,687	37,507
	Subtotal	**39,454**	**29,450**	**19,687**	**88,591**
Gandaki	Kali Gandaki	10,382	20	0	10,402
	Seti	2,947	0	0	2,947
	Marsyangdi	4,787	0	0	4,787
	Budi Gandaki	3,626	1,358	0	4,984
	Trishuli	2,782	2,975	0	5,757
	Trunk Gandaki	7,592	0	8,187	15,779
	Subtotal	**32,116**	**4,353**	**8,187**	**44,656**
Karnali	Kali	6,456	0	13,978	20,434
	West Seti	7,379	0	0	7,379
	Humla	5,984	3,010	0	8,994
	Kawari	822	0	0	822
	Mugu	5,374	0	0	5,374
	Tila	3,329	0	0	3,329
	Bheri	13,683	6	0	13,689
	Trunk Karnali	24,838	0	46,888	71,726
	Subtotal	**67,865**	**3,016**	**60,866**	**131,747**
Total		**139,435**	**36,819**	**88,740**	**264,994**

Imja Lake is a typical example of a moraine-dammed lake that has developed from a supraglacial lake.

SECTION 3

Approach and methodology

The glacial lake inventory presented in this study consists of water bodies that are proximal to present glaciers as well as those located in lowland areas that were covered by glaciers in the past. Glacial lakes are generally formed by the blocking of glacier meltwater. Glacier meltwater may be blocked by glacier ice, moraine, bedrock, landslides, and alluvial fans. Glacier meltwater may also exist beneath glaciers (subglacial lakes) or within them (englacial lakes), but these are usually not visible in aerial/optical images, and their detection is challenging as it requires field-based methods to acquire the necessary information. Thus, subglacial and englacial lakes are not included in this inventory because they cannot be mapped from aerial/optical satellite images.

The last glacial lake inventory of Nepal and adjacent regions before this one was conducted between 2003 and 2007, using Landsat Enhanced Thematic Mapper Plus (ETM+) satellite images (Maharjan et al. 2018). However, in the context of climate change and global warming in the region, glaciers are shrinking and retreating rapidly, resulting in large changes in the status of glacial lakes (Bajracharya et al. 2007).

Knowledge of glacial lakes and related disaster risks is important to reduce the risk of GLOFs to lower riparian communities. To understand the latest status of the glacial lakes, we use Landsat images to produce an updated inventory of glacial lakes of 2000 and 2015, verified with high resolution satellite images available on Google Earth. 5m and 12m digital elevation models (DEMs) were used to examine the geometric properties of the lakes in Nepal, and the TAR of China and India, respectively.

3.1 Data sources

3.1.1 Landsat OLI

Landsat satellite images have been widely used to map the extent of glaciers and glacial lakes globally due to their spatial resolution and accessibility (Bolch et al. 2011). Landsat images have been used in this study due to their consistent spatial coverage of the region, high spatial resolution, and free accessibility through the GLOVIS web portal (http://glovis.usgs.gov). We have used the Landsat Operational Land Imager (OLI) to prepare the glacial lake inventory of the region for 2015. The OLI, built by Ball Aerospace, measures the visible, near-infrared, and shortwave infrared portions of the spectrum. Its images have 15-metre panchromatic and 30-metre multispectral spatial resolutions, along a 185 km-wide swath. The images cover wide areas of the Earth, while retaining sufficient resolution to distinguish features such as glaciers, glacial lakes, urban centres, farms, forests, and other objects. OLI is more reliable than ETM+ and provides improved performance. In addition, the use of satellite images of higher spatial resolution has been emphasized in this study.

The OLI images acquired, covering the region during 2015–2018, were used for mapping glacial lakes. Mostly, images from 2015 were used to map the glacial lakes. Images from the other years were used for cross-checking wherever there were shadows or other features that hindered clarity of the images. Images from different years, and derived from different sensors, were also used to verify the existence of the mapped lakes. Images taken between September and December were used primarily, because there is a lesser likelihood of snow or cloud cover during this period compared to other months of the year.

3.1.2 Digital elevation models

Topographic information of the lakes and adjacent areas was used to identify and categorize the lakes, and to establish a ranking of PDGLs. A digital elevation model (DEM) can be used to extract topographic parameters of glacial lakes, associated glaciers, moraines, and adjacent areas. It can be defined as a regular gridded matrix representation of the continuous variation of relief over space and is a digital model of the land surface. The primary requirements of any DEM are that it should have the desired accuracy and resolution, and be devoid of data errors.

The steady and widespread application of DEMs can be further attributed to their easy integration within a GIS environment. Before 2000, base elevation models depicting a global coverage were available with a 1-km resolution, for example, GTOPO-30 (Global 30-Arc-Second Elevation Data Set) and GLOBE (Global Land One-km Base Elevation Project). However, in the last decade, more advanced global DEMs with higher spatial resolutions – such as the Shuttle Radar Topography Mission (SRTM) (version 4, C-Band DEM of 3 arc-second, 90 m resolution, or 1/1,200th of a degree latitude or longitude), and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (version 2, 30 m resolution) – have become available. Apart from these freely available DEM datasets, stereo images from a number of satellites (for example, Cartosat 1, Landsat 7 ETM+, QuickBird, IKONOS, SPOT, and ASTER sensors, among others) have also been used to create DEMs using various software applications for examining landscapes. High-resolution images are capable of providing more accurate surface information.

For this study, we used an SRTM DEM for mapping glacial lakes. The Advanced Land Observing Satellite (ALOS) DEMs of a 5 m resolution for Nepal, and a 12 m resolution for the TAR of China and India were used to generate attributes of the lakes and dams for identifying PDGLs and dam break modelling.

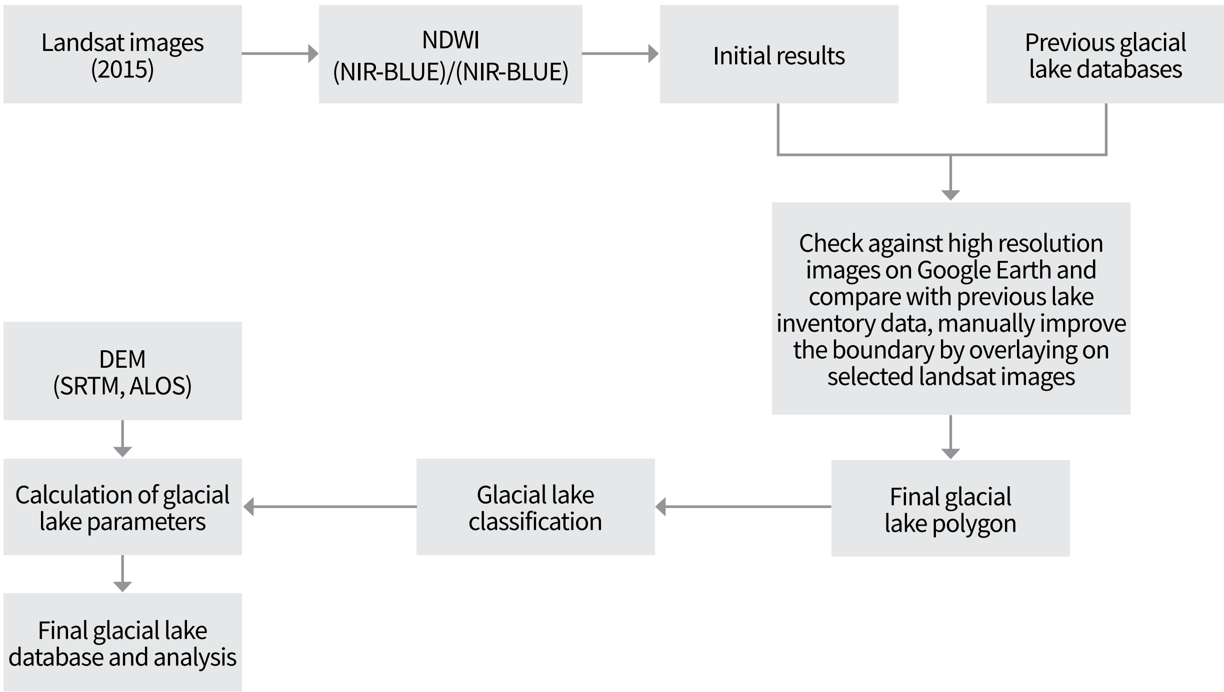
3.2 Mapping method

A number of remote sensing methods have been developed for generating glacial lake inventories (Huggel et al. 2002, 2006; Ives et al. 2010; Kääb, 2000; Mool et al. 2001a, 2001b). We adopted the method used by Maharjan et al. (2018) for generating this inventory of glacial lakes. The Normalized Difference Water Index (NDWI) method (see Eq 1), adopted in this study, provides an automatic way to detect water bodies, including glacial lakes, on the basis of Landsat 8 OLI images. The entire process is summarized in Figure 3.1.

The ratio images of the Normalized Difference Water Index (NDWI) are created by an arithmetic calculation of Band 4 near infrared (NIR) and Band 1 (Blue) of the Landsat images. The NDWI threshold value is applied to classify the glacial lakes in the images. A NDWI threshold value of –0.6 to –0.9, as adopted by Huggel et al. (2002), was used to prepare the inventory of glacial lakes. Although this automatic classification method can speed up the detection of glacial lakes, it cannot be applied to the whole region due to uncertainties created by atmospheric and physical processes. For example, if lakes are frozen or covered with snow, or if cloud cover or shadows obstruct the taking of the image, they cannot be detected using this automatic classification method. In such cases, a manual delineation method has been applied to map the lakes.

The mapped glacial lakes were checked and validated, and modified if necessary, by overlaying the Landsat images over previous inventory datasets, wherever available (Mool et al. 2001a, 2001b; Mool & Bajracharya

FIGURE 3.1 **REMOTE SENSING-BASED GLACIAL LAKE INVENTORY PROCESS ADOPTED**



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

2003). Through this, any misclassification of lakes was corrected, and missing lakes added manually. Further, the mapped lakes were overlaid with high resolution images, if available in the Google Earth environment, for validation.

Generally, pixels in the raster images do not give homogenous reflectance, and represent only one object, unless the imaging is perfectly aligned in a single object. And so, at least four pixels are required to map the exact boundary of the object (lake) 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. Hence, a glacial lake area of 0.003 km^2 (or about 32,292 sq. feet) is the threshold for lake size that has been applied for mapping in the present glacial lake inventory.

3.3 Dealing with uncertainties and limitations

The uncertainties, or accuracy, in mapping glacial lakes or glaciers from the satellite images used depend, typically, on the spatial resolution of the images used, seasonal/temporal snow cover, the presence of shadow, and the contrast between the glacial lakes' pixels and those of the surroundings (Bajracharya et al. 2014c; DeBeer & Sharp 2007). Landsat images with the least snow cover and cloud cover were selected for mapping, in order to increase the quality of the automatic mapping approach, and reduce the manual correction of the boundary. The lake data was overlaid on the high-resolution images on Google Earth and also cross-checked with the previous inventory data wherever available, in order to validate and improve the accuracy of mapped lakes from the automatic approach.

Additionally, the glacial lake data was thoroughly checked by overlaying the Landsat images used for automatic mapping on the high-resolution images from Google Earth. Any mismatches in the boundaries of the lakes due to 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 was affected by various other types of obscurities, which are mostly dependent on the image resolution. The uncertainty of the glacial lake boundary could not be greater than half the image resolution (that is, ±15 m in the TM, ETM+, and OLI) (Bajracharya et al. 2014c). Hence, the uncertainty of the glacial lake boundary was estimated by variation of the area bounded by the lake polygon, which is calculated by the 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:

$$\text{Root mean square error (RMSE)} = \sqrt{\frac{\sum_{i=1}^{n}(a - \hat{a})^2}{n}} \quad \text{.....................2}$$

where a is the area of the glacial lake from the total pixel bounded by the glacial lake polygon, and â is the area of the glacial lake from the total pixel bounded by the 15-m buffer of the glacial lake boundary. The total uncertainty of the glacial lake area is ±2%. This uncertainty was also observed in mapping the glacial lakes and glaciers of the HKH region (Bajracharya et al. 2014c; Maharjan et al. 2018). Depending on the scale of mapping of the glacial lakes, the 30-m resolution of the Landsat images is satisfactory enough to map lake boundaries. The accuracy will be higher in the high spatial resolution images. Field verification is necessary to confirm this information before mitigation measures are considered.

3.4 Attributes of glacial lakes

Once the final glacial lake polygons were generated, the attributes of the glacial lake were generated using the architecture geographic information system, ArcGIS. Each lake polygon is given a unique ID containing the longitude and latitude of the centroid of the polygon, in the same way that the Global Land Ice Measurement from Space (GLIMS) ID is developed for glaciers by the National Snow and Ice Data Center (NSIDC), Colorado. The GLIMS ID consists of 14 letters (for instance, GxxxxxxEyyyyyN) for glaciers, and 15 letters (GLxxxxxxEyyyyyN) for glacial lakes, where G stands for Global, E for East, N for North, 5y for 3-digit degree decimal latitude, and 6x for 3-digit degree decimal longitude.

This is for the first time that lake IDs are being used in a lake inventory study (Maharjan et al. 2018; Shrestha et al. 2017). The initial letter 'G' in the GLIMS ID has been replaced by 'GL', representing 'glacial lake'. Other parameters such as slope and elevation were calculated automatically in ArcGIS using the DEM. A morphological classification of the glacial lakes was done by manually overlaying the high-resolution lake images with terrain data from Google Earth. The lakes were classified as moraine-dammed, ice-dammed, or bedrock-dammed (Table 3.1).

TABLE 3.1 CLASSIFICATION OF GLACIAL LAKES

	Glacial lake type	Code	Definition
Moraine-dammed (M)	End moraine-dammed lake	M(e)	Lake dammed by end (terminal) moraines. The lake's water usually touches the walls of the side moraines, and is typically held back by the end moraine but not necessarily in contact with the glacier. Glacier ice may be present at the bottom of the lake (defined in some other classifications as an advanced form of a supraglacial lake)
	Lateral moraine-dammed lake	M(l)	Lake dammed by lateral moraines (in the tributary valley, trunk valley, or between the lateral moraine and the valley wall, or at the junction of two moraines). The lake is held back by the outside wall of a lateral moraine, that is, away from the former glacial path
	Other moraine-dammed lake	M(o)	Lake dammed by other moraines (includes kettle lakes and thermokarst lakes)
Ice-dammed	Ice-dammed lake	I	Lake dammed by glacier ice (including lakes on the surface of a glacier), or by glaciers in the tributary/ trunk valley, or between the glacier's margin and the valley wall, or at the junction of two glaciers
	Supraglacial lake	I(s)	Body of water (ponds or lakes) on the surface of a glacier
	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's margin and valley wall
Bedrock-dammed	Bedrock-dammed lake	B	Body of water that forms as a result of earlier glacial erosion. The lake accumulates in depressions after the glacier has retreated or melted away
	Cirque lake	B(c)	A small pond occupying a cirque
	Other glacier erosion lake	B(o)	Body of water occupying depressions formed by glacial erosion. These are usually located on the mid-slope of hills, but not necessarily in a cirque
Other blocked lakes		O	Lakes formed in a glaciated valley and fed by glacier melt, but the damming material is not directly part of the glacial process, for example, debris flow, alluvial, or landslide-blocked lakes

Note: Modified from ICIMOD (2011)

The Albers equal area conic projection is used to calculate the area of the glacial lake. The unit of area adopted is square kilometres (km^2). A detailed list of glacial lake attributes is given in Table 3.2.

3.5 Identification of potentially dangerous glacial lakes

The step-by-step approach to identifying critical or potentially dangerous glacial lakes, developed by ICIMOD (ICIMOD 2011; Mool et al. 2001a, 2001b), has previously been applied to the Koshi basin (Shrestha et al. 2017), and is used in this study with some modifications (Figure 3.2).

The stability of a lake depends on its characteristics and damming material. The dam should have sufficient strength to hold the lake water to be considered stable. If it does not, it may be breached in an outburst flood. Different features of the lakes and dams were analysed in detail using remote sensing to assess the stability of each lake. However, even stable lakes may burst their dams, due to the activity of the source glacier and landslides in its vicinity that may impact the lake and/or the dam. Hence, the physical condition of the source glacier and the surroundings of the lake and dam are also considered in this study. Other triggering factors, including earthquakes, extreme climatic events, and unsafe anthropogenic intervention could also cause a breach in a dam, but their potential impact could not be evaluated.

The criteria to identify PDGLs discussed in Mool et al. (2001a, 2001b), Bajracharya et al. (2007), and ICIMOD (2011) are considered in this study, along with some additional criteria such as the area of the lake, the elevation difference (the height of the moraine), and the length of the dam.

The step-by-step filtering approach, using remote sensing data, was applied to identify the PDGLs: at the first level of filtering, the characteristics of the lake such as its size, type, expansion rate, etc were considered. The second level of filtering considered the characteristics of the dam, including its physical properties and condition. Levels 3 and 4 include the characteristics of the source glaciers and features of the areas surrounding the dam and lake that could impact them. The updated step-by-step approach is elaborated below:

3.5.1 Different levels of criteria applied

CHARACTERISTICS OF THE LAKE

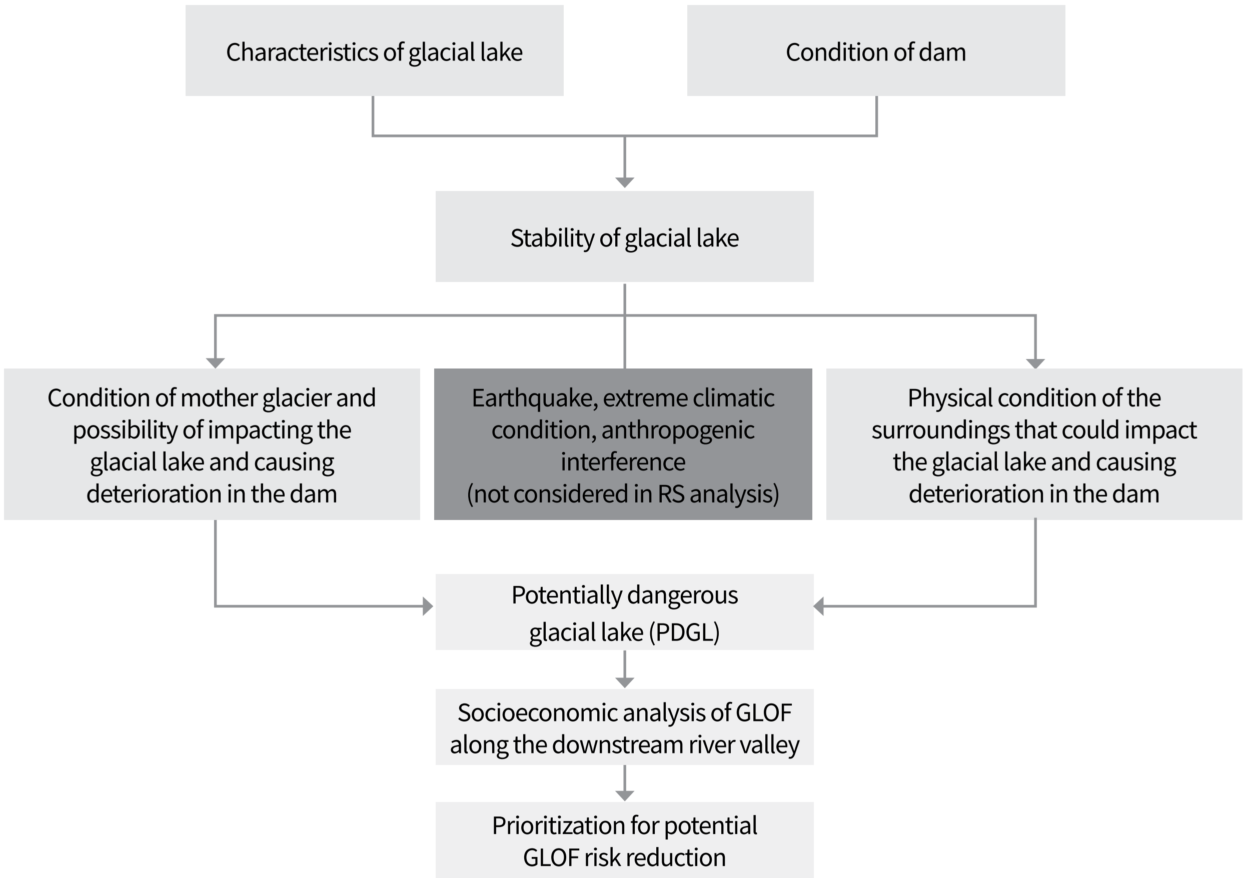
The mapping of glacial lakes carried out in this study includes all lakes equal to or greater than 0.003 km^2. If the lakes are larger than 0.02 km^2, and located on a steep slope, an outburst may cause serious damage, especially in highly populated areas with extensive infrastructure downstream (Bajracharya and Mool, 2005). The expansion rates of lakes equal to or larger than 0.02 km^2 were analysed to estimate the possible increase in the volume of water. The following criteria were used to analyse the stability of the lakes:

- Size of the lake size and rate of expansion;
- Increase in the water level, or in the volume of water;
- Presence of cascading lakes; and
- Intermittent activity of supraglacial lakes.

TABLE 3.2 FIELDS AND FORMATS OF GLACIAL LAKE ATTRIBUTES

S. No.	Field name	Type	Format	Description
1	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
2	Basin name	string	Text	Name of the drainage basin based on maps and the literature
3	Sub-basin name	string	Text	Name of the drainage sub-basin based on maps and the literature
4	Longitude	string	DMS	Longitude of the centre of the glacial lake
5	Latitude	string	DMS	Latitude of the centre of the glacial lake
6	Altitude	integer	Metres above mean sea level (masl)	Water level of the glacial lake. Extracted from DEMs (SRTM and ALOS)
7	Area	float	km^2	Area of the glacial lake, based on the Albers equal area conic projection
8	Gl_type	string	Text	Type of glacial lake

FIGURE 3.2 **IDENTIFICATION OF POTENTIALLY DANGEROUS GLACIAL LAKES AND PRIORITIZATION FOR GLOF RISK REDUCTION**



Rapid changes in lake area and the lake's potential to grow in the near future due to the size of its catchment, the presence of cascading lakes, and the chances that supraglacial lakes may merge were assessed. An expansion in lake area indicates an increase in the volume of water, which can adversely affect the stability of the dam and hence increase the risk of an outburst.

Varied morphological landforms, created by glacial processes, on which glacial lakes are formed, also influence the stability of a lake. Lakes on glacial erosional surfaces, mostly dammed by bedrock, are safer than lakes formed behind huge moraines deposited by glaciers or those dammed by glacier ice. A morphological classification of the lakes was done by visual interpretation based on Maharjan et al (2018). Moraine-dammed lakes larger than 0.02 km^2 that could expand, and their rate of expansion, are considered for selecting the PDGLs from the inventory datasets.

CHARACTERISTICS OF THE DAM

The condition of the dam is an important parameter to consider in assessing how stable a lake is. Dams formed by loose or unconsolidated moraine materials are susceptible to rupture. Lakes with narrow crested moraines have a relatively high outburst potential, compared to those with moraines having a wide crest. Thus, lakes with thinner moraine crests may be associated with GLOFs. Due to erosion and landslides, these moraine crests are usually angular and narrow at the top. This makes them vulnerable to any surge wave generated by ice or snow avalanches, ultimately triggering a GLOF. How steep the slopes of the moraine are also determines the likelihood of a lake outburst.

The main characteristics of a dam that can impact its stability, relevant for this study, are:

- Type of damming material;
- Width of the crest;
- Slope of the dam wall;
- Elevation difference of the moraine (height of the dam);
- Length of the dam;
- Erosional activity or presence of landslides around the dam;
- Presence (or absence) of drainage outflow;

- Whether the dam has been breached and then got closed in the past, and the lake got filled with water again;
- Seepage through the dam's walls; and
- Existence and stability of ice cores and/or permafrost within the dam.

Data pertaining to some of these physical parameters, such as dam crest, and length, width, and slope of the dam wall are generated via remote sensing and GIS techniques using high-resolution satellite images and available DEMs. These parameters are calculated, based on the profile lines drawn manually over the high-resolution images on Google Earth. Other parameters are visually interpreted from the high-resolution images available on Google Earth. As it is difficult to identify the type of damming material from satellite images, we only categorized the damming material as fine or coarse in comparison to each other, by analysing the images and using information from previous reports. The presence of small ponds on the dam and changes in features indicates the existence of ice cores and/or permafrost within the dam. These can be observed from repetitive Landsat images and high-resolution images available on Google Earth.

CHARACTERISTICS OF THE SOURCE GLACIER

The potential of a lake to burst its flanks and cause damage downstream is heightened if the lakes are associated with a glacier. If the lake is in contact with a glacier retreating on a gentle slope, there is the possibility that the lake expands. On the other hand, if the glacier has crevasses and is on a steep slope, masses of ice may detach from the glacier and fall into the lake. Falling chunks of ice can disturb the stability of the dam and/or the lake. Even stable lakes in such an environment can be considered potentially dangerous and become a candidate for monitoring. The main characteristics that can be relevant to the condition of the glacier are:

- Condition of the source glacier(s);
- Distance between the glacial lake and the source glacier(s);
- Steepness of the glacier tongue;
- Debris cover on the lower glacier tongue;
- Presence of crevasses and ponds on the glacier's surface;
- Calving of ice from the glacier's snout; and
- Icebergs breaking off the glacier terminus and floating into the lake

The size of the associated glacier and its changes also have a bearing on the existing glacial lakes. A rapid retreat or advance of an associated glacier can directly impact the expansion of existing lakes and the rise in water levels, or create new lakes, which could create the risk of a breach.

Some of these characteristics, including the presence of crevasses and ponds on the glacier's surface, the calving of ice, the presence of icebergs, and potential icebergs breaking off, were identified and analysed by examining repeated Landsat images and high-resolution satellite images available on Google Earth. Other important parameters, such as the distance and slope between the glacier and the lake, were calculated by generating flow lines between each glacier and lake using DEM and higher-resolution image analysis. The steepness of the glacier's tongue was calculated considering a certain distance (generally 50–200 metres) from the glacier's snout, depending on the surface characteristics of the glaciers such as the presence of crevasses on the surface and a steep slope near the terminus.

PHYSICAL CONDITIONS OF THE SURROUNDINGS

The physical factors that can destabilize a lake and trigger its outburst can be identified using remote sensing of the lake's and the dam's surroundings. The factors considered in this study are:

- Hanging glaciers being in contact with or very close to the lake;
- Potential rockfall or rock slide (mass movements) sites around the lake;
- The presence of large snow avalanche sites immediately above the lake; and
- The sudden advance of a glacier towards a lower tributary or the main glacier which has a well-developed frontal lake.

OTHER FACTORS

Some other, unseen factors that can destabilize a lake and/or dam to trigger lake outbursts are outside the scope of the remote sensing techniques used in this study. The following triggering factors have not been considered:

- Earthquakes, which can generate waves in the lake, and can also destabilize the moraine, resulting in the deterioration and collapse of the dam;

- Extreme climatic events, such as excessive and continuous precipitation on the lake, dam, and around the catchment area; and
- Inappropriate anthropogenic interference on the lake and dam that may destabilize the containing walls.

The first two factors are unpredictable. However, there is a need to increase stakeholder awareness about the dangers associated with the identified lakes and to desist from any potentially hazardous activity in the lake itself.

To summarize, a glacial lake's stability depends directly on the physical condition of the lake and the dam. Other factors that may significantly impact its stability include the activity of the source glacier and the stability of the surroundings. This study considers data regarding lake characteristics, dam properties, source glacier characteristics, and the physical conditions of the area surrounding the lakes to identify potentially dangerous glacial lakes in the study area.

3.6 Ranking of potentially dangerous glacial lakes

Potentially dangerous glacial lakes were identified and their hazard levels ranked based on the physical characteristics of the lakes and morphology of the dams, source glaciers, and their surroundings, following the criteria outlined in Section 3.5 (for more details, see subsection 5.2). Not all PDGLs pose the same level of risk to communities and infrastructure in the river basins.

3.7 Climate change: Trends, scenarios, and its impact on glaciers and glacial lakes in Nepal

3.7.1 Climate change trends in Nepal

Nepal is among those countries most vulnerable to climate change, the impacts of which have been observed in several sectors such as water, agriculture, and biodiversity, and the cryosphere. Glacier retreat, temperature increases, erratic rainfall, and an increase in the frequency and intensity of extreme climatic events are some impacts of climate change in the country (Karki et al. 2009). Glacier retreat, for instance, was found to be 10–60 m per year in the Everest region (Bajracharya et al. 2009). Also among the major signs of climate change are increased glacier ice melt, and the formation and expansion of glacial lakes with the occurrence of GLOF events.

Temperature is one of the important climatic variables responsible for glacier melt. Several studies have reported an increase in temperatures in Nepal over the past few decades. Shrestha et al. (1999) reported continuous and consistent warming after the mid–1970s in the Nepalese Himalaya, with an average warming of 0.06 degrees Celsius (°C)/year over 1971–1994. The warming was more pronounced in winters and at higher altitudes. Likewise, increasing trends in the maximum and minimum temperatures, by 0.05°C/year and 0.03°C/year respectively, was observed over the period 1996–2005, with a higher increase in the northern part of the country (PAN 2009). Baidya et al. (2008) also reported an increase in temperature extremes, with an increasing number of warm days and nights and a decreasing number of cool days and nights in the mountainous region from 1971–2006. A study of climate change in specific regions found an average temperature rise of 1.7°C in the Langtang valley and 1°C in the Imja valley, over 1988–2008 (Bajracharya et al. 2014a). All the studies reported a significant warming in the Higher Himalaya, reflecting the sensitivity of mountain glaciers to climate change.

The Department of Hydrology and Meteorology (DHM) recently conducted a comprehensive study of climate change between 1971 and 2014 in Nepal to provide information for the National Adaptation Plan (NAP) process. It found that the trend in annual maximum temperature in Nepal was significantly positive, at 0.056°C/yr over 1971–2014, a value very similar to that in Shrestha et al. (1999) for 1971–1994. It also revealed a greater warming rate of 0.086°C/year in the Higher Himalaya over that period (DHM 2017).

Climate projections based on global and regional climate models also indicate a continuous warming trend in the future. Agrawala et al. (2003) projected a significant and consistent increase in mean temperature, by 1.2°C, 1.7°C, and 3°C by 2030, 2050, and 2100 respectively, with a more prominent increase during the winter months than over summer. The Nepal Climate Vulnerability Study Team also projected an increase in annual mean temperature, by 1.4°C, 2.8°C, and 4.7 °C by 2030, 2060, and 2090 respectively (NCVST 2009). A recent study suggests an increase in annual mean temperature by 0.9°C–1.1°C during 2016–2045, and 1.3°C–1.8°C during 2036–2065 as compared to a 1981–2010 baseline, with more frequent and severe extreme climatic events (MoFE 2019). The recent HKH Assessment report also specifies that the warming in HKH region will likely be at least 0.3°C higher even if the global warming is kept to 1.5°C by the end of 21st century and even more pronounced in mountain ranges (Wester et. al. 2019)

Unlike temperature, trends in past precipitation are less clear. A large spatial variation in rainfall patterns was observed over a period of 30 years (1976–2005) (PAN 2009). Likewise, Shrestha et al. (2000) reported that no distinct long-term trends in precipitation were observed over 1966–1997, with significant annual and decadal variations. However, Baidya et al. (2008) reported an increasing trend in both the total and heavy precipitation in Nepal over 1971–2006, with more weather-related extreme events such as floods and landslides. This result was similar to DHM (2017).

IMPACTS ON GLACIERS AND GLACIAL LAKES

The receding of glaciers worldwide is clear evidence of a changing global climate since the mid-19th century, as glaciers are sensitive to rising temperatures (UNEP & WGMS 2008). Studies suggest that climate change will have more a severe impact at higher elevations in Nepal, and in particular on glaciers and glacial lakes. Glaciers are a vital source of freshwater in major rivers of the country (Shrestha & Aryal 2010), sustaining the lives and livelihoods of millions of people living downstream. However, the increased warming at higher altitudes indicated above has accentuated rapid glacier melt and reduced glacier mass and area, leading to multiple hazards such as floods, avalanches, and GLOFs. As already indicated, these pose a significant risk to human settlements and infrastructure. Higher glacier melt will initially increase river flows, but in the long run, a decreased snow/ice mass will reduce the flows. The precipitation record of the DHM from 1971 to 2014 shows a decrease of 1.46 millimetres (mm) per year in the Higher Himalaya in Nepal (DHM 2017). In addition, warming will reduce precipitation in the form of snow, thus, reducing the volume of snow.

The *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC) mentioned that the mass budget of Himalayan glaciers has decreased over the last five decades. It projects a continuous loss of glacier mass through the 21st century (Jimenez Cisneros et al. 2014). A 2017 study on High Mountain Asia (HMA) glacier mass balance shows that the loss of glacier mass between 2000 and 2016 in Nepal was higher than the total mass loss in the entire HMA (Brun et al. 2017). Likewise, a consistent warming of HMA at a higher rate than the global average and a reduction in glacier mass is reported (Wester et. al. 2019; Kraaijenbrink et al. 2017; Xu et al. 2009). Mountains are sensitive to increased temperatures and extreme changes in altitude over small distances (Karki et al. 2009).

Glacial lakes tend to grow in response to higher glacier melt. This can increase the hydrostatic pressure, which can cause structurally weak and unstable dams to breach suddenly. This can result in a sudden, high discharge of debris and water in a few hours, causing catastrophic floods.

Notable glacier retreat and glacial lake expansion have been reported in recent decades in Nepal, most likely due to increasing temperatures (Agrawala et al. 2003; Bajracharya et al. 2014b), which can severely impact downstream communities. It has been estimated that a 1°C rise in temperature will cause alpine glaciers worldwide to shrink by as much as 40% in area and more than 50% in volume as compared to 1850 (CSE 2002; IPCC 2001). Measurements indicate that Himalayan glaciers have been retreating at an increased rate since 1970 (Bajracharya et al. 2006). Glacier areas in Nepal and Bhutan decreased by 24% and 23% respectively in the 33 years between 1977 and 2010 (Bajracharya et al. 2014a, 2014b). Chapagain et al. (2010) reported glacier retreat, in the range 11–14 m/yr, of two western glaciers in the Manaslu conservation area from 1962–2008. Trakarding glacier (on the southwestern slope of Manaslu Himal) retreated at 66 m/yr between 1957–2000. Imja glacier showed the highest rate of retreat among Nepal's glaciers, of 74 m/yr over 2001–2006 (Bajracharya et al. 2007).

In addition, numerous GLOF events have been recorded in Nepal. A 2011 study by ICIMOD reported 24 GLOF events in the past, 14 of which had occurred in Nepal, while 10 were caused by overspills due to flood surges across the China (TAR)–Nepal border (ICIMOD 2011). GLOFs that have occurred since the 1980s are listed in Table 3.3. The most significant GLOF occurred in 1985 of the Dig Tsho glacial lake in eastern Nepal (Vuichard & Zimmermann 1986, 1987). Dig Tsho is a glacial lake dammed by the end moraine of the Langmoche glacier in the western section of Sagarmatha National Park (ICIMOD 2011).

The GLOF resulted in an estimated economic loss of US$ 1.5 million, destroyed infrastructure including the Namche hydropower plant (Horstmann 2004; Mool et al. 2001a), and caused a few casualties. Before that, in 1977, a GLOF was recorded in Dudh Koshi, causing 2–3 casualties (Agrawala et al. 2003). GLOFs can also have transboundary effects. The Zhangzangbo–cho (Ciremacho Lake) in the TAR, China, was breached in July 1981 and destroyed the Friendship Bridge on the China–Nepal highway, and the intake dam of the Sun Koshi hydropower station, causing serious economic losses in Nepal. Damages were estimated US$ 3 million at the time (Mool et al. 2001).

TABLE 3.3 GLOF EVENTS SINCE THE 1980s THAT HAVE CAUSED DAMAGE IN NEPAL

S. No.	Date	River basin	Location
1.	23 June1980	Tamor	Nagma Pokhari
2.	11 July 1981	Bhote Koshi	Cirenmacho Lake, Zhangzangbo Valley
3.	4 August 1985	Dudh Koshi	Dig Tsho
4.	12 July 1991	Tama Koshi	Chubung
5.	3 September 1998	Dudh Koshi	Sabai Tsho (Tam Pokhari)
6.	15 August 2003	Madi	Kabache Lake
7.	8 August 2004	Madi	Kabache Lake
8.	5 July 2016	Bhote Koshi	TAR, China
9.	20 April 2017	Barun Valley	Near Lower Barun

The 2017 GLOF event near the Lower Barun has left a lasting impact in the Barun Valley.

Thungali Lake is expanding, raising the possibility of landslides and snow avalanches from its side walls.

SECTION 4

Status of glacial lakes

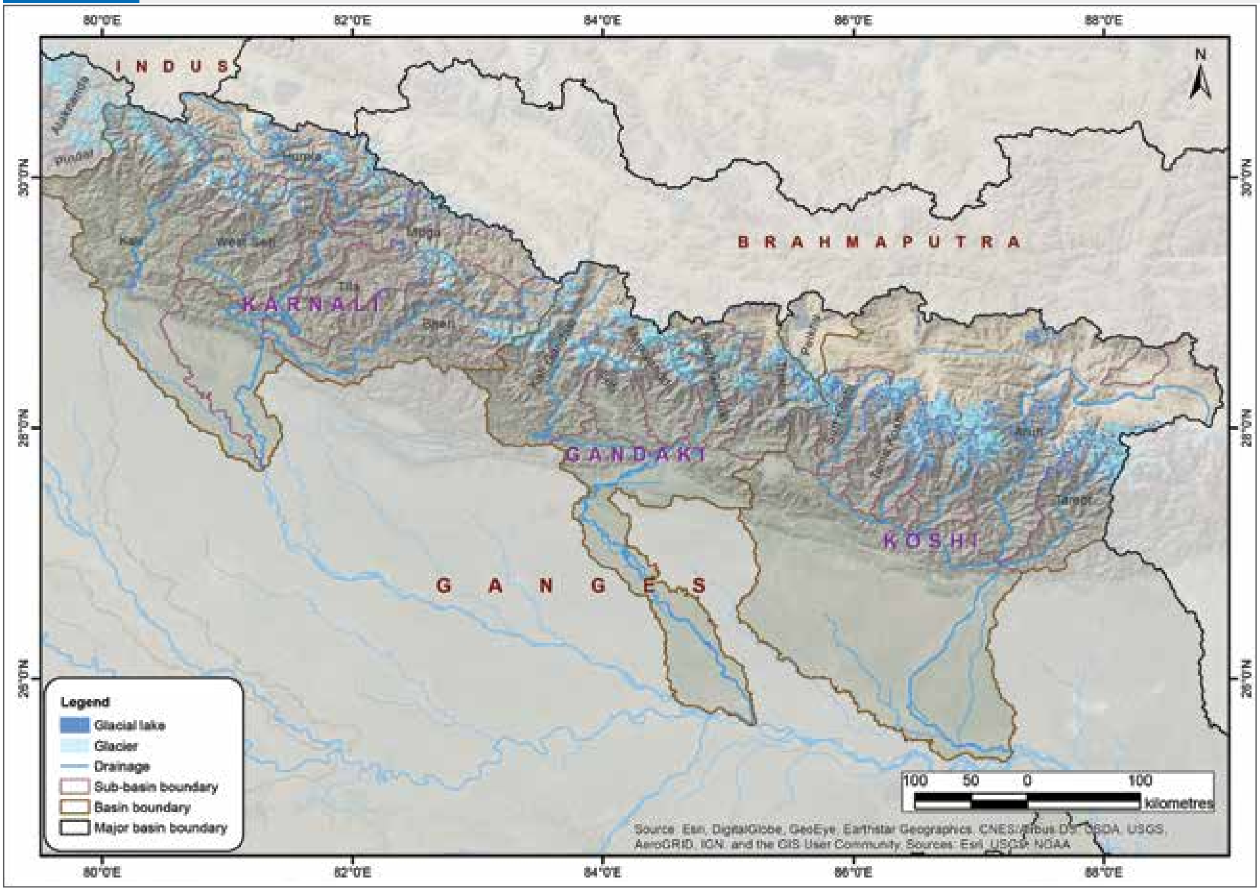
Glacial lakes equal to or larger than 0.003 km^2 were mapped from Landsat satellite images of 2015, for the Koshi, Gandaki, and Karnali basins of Nepal, the TAR of China, and India (Figure 4.1). Some were taken in 2014 and 2016. A unique identity (GLIMS ID) was assigned to each glacial lake present in the study area. The slope, elevation, and topographic features of individual glacial lakes were calculated from the 5 m resolution ALOS DEM for Nepal and 12 m resolution PALSAR DEM for the TAR of China and India, using ArcGIS. The lakes were analysed based on their size. Each lake was identified and classified into bedrock-dammed, moraine-dammed, ice-dammed, and other lake classes. The altitudinal distribution of the lakes was analysed using the DEMs and lake boundaries in ArcGIS. The distance to the source glacier was measured manually only for moraine-dammed lakes equal to or larger than 0.02 km^2.

4.1 Number and area of glacial lakes

A total of 3,624 glacial lakes was mapped in the Koshi, Gandaki, and Karnali basins of Nepal, the TAR of China, and India. The distribution of the glacial lakes in these three basins is shown in Figure 4.1. The Koshi basin had the largest number of glacial lakes (2,064), followed by the Karnali basin (1,128) and the Gandaki basin (432) (Figure 4.2). Their distribution and area are presented at the sub-basin level in Table 4.1.

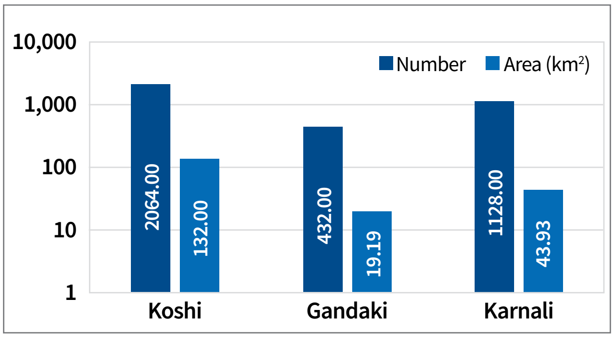
The Arun sub-basin of the Koshi basin had the highest number of, and total area covered by, glacial lakes among the sub-basins in the study area. This sub-basin contributes more than a quarter of the total number of lakes and over one-third by total lake area in the inventory. The Humla sub-basin of the Karnali basin contributes the second-highest number of glacial lakes and is the third-highest in terms of lake area. The Sun Koshi sub-basin of the Koshi basin consists of only 181 lakes, but it is the second-highest in terms of total glacial lake area, and the highest in terms of average lake area. This is because the Sun Koshi sub-basin has

FIGURE 4.1 **DISTRIBUTION OF GLACIAL LAKES IN THE KOSHI, GANDAKI, AND KARNALI BASINS OF NEPAL, THE TAR OF CHINA, AND INDIA**



Disclaimer: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

FIGURE 4.2 **NUMBER AND AREA OF GLACIAL LAKES IN THE KOSHI, GANDAKI, AND KARNALI BASINS**



the highest proportion of large lakes in the study area. The Tamor, Dudh Koshi, and Tama Koshi sub-basins each contribute between 7%–10% of the total number of glacial lakes, and between 4%–8% of the total lake area. The other sub-basins account for less than 5% of the total number of lakes and total lake area in the study region. Very few glacial lakes exist in the Likhu, Indrawati, Seti, and Kawari sub-basins.

Glacial lakes in the study area occupy a combined area of 195.12 km^2 (Table 4.1). Of this, ~132 km^2 (67.65%) falls in the Koshi basin, 19.18 km^2 (9.83%) in the Gandaki basin, and 43.94 km^2 (22.51%) in the Karnali basin (Figure 4.2). The average mean area of the glacial lakes within each sub-basin ranges from 0.01 km^2 in the Indrawati sub-basin to 0.12 km^2 in the Sun Koshi sub-basin, both in the Koshi basin. The average mean area of the glacial lakes is 0.06 km^2 in the Koshi basin and 0.04 km^2 in the Karnali and Gandaki basins. The overall average mean area of the glacial lakes in the study area is 0.05 km^2.

4.2 Types of glacial lakes

Glacial lakes are often formed as the result of a glacier's retreat, a process that may leave behind large deposits of debris. Lakes may be formed either within a part of the eroded landform (such as bedrock-dammed lakes) or behind a dam formed by moraines, ice, and/or landslide debris. The lakes in this inventory were classified based on the damming material, such as moraine-dammed (M), ice-dammed (I), bedrock-dammed (B), and others (O), including debris flow, alluvial, or landslide dams. Moraine-dammed lakes

TABLE 4.1 NUMBER AND AREA OF GLACIAL LAKES IN SUB-BASINS OF THE KOSHI, GANDAKI, AND KARNALI (2015)

Basin	Sub-basin	Number		Area		
		Count	%	km²	%	Average (km²)
Koshi	Tamor	283	7.81	9.12	4.68	0.03
	Arun	909	25.08	68.58	35.15	0.08
	Dudh Koshi	355	9.80	16.92	8.67	0.05
	Likhu	17	0.47	0.41	0.21	0.02
	Tama Koshi	307	8.47	14.68	7.52	0.05
	Sun Koshi	181	4.99	22.13	11.34	0.12
	Indrawati	12	0.33	0.16	0.08	0.01
	Sub-total	**2,064**	**56.95**	**132.00**	**67.65**	**0.06**
Gandaki	Trishuli	242	6.68	8.19	4.20	0.03
	Budhi Gandaki	49	1.35	1.58	0.81	0.03
	Marsyangdi	59	1.63	6.22	3.19	0.11
	Seti	4	0.11	0.15	0.08	0.04
	Kali Gandaki	78	2.15	3.05	1.56	0.04
	Sub-total	**432**	**11.92**	**19.19**	**9.83**	**0.04**
Karnali	Bheri	164	4.53	9.20	4.72	0.06
	Tila	82	2.26	4.11	2.11	0.05
	Mugu	239	6.59	6.22	3.19	0.03
	Kawari	28	0.77	1.04	0.53	0.04
	West Seti	51	1.41	1.43	0.73	0.03
	Humla	498	13.74	20.21	10.36	0.04
	Kali	63	1.74	1.53	0.78	0.02
	Karnali	3	0.08	0.19	0.10	0.06
	Sub-total	**1,128**	**31.13**	**43.93**	**22.51**	**0.04**
Total		**3,624**	**100.00**	**195.12**	**100.00**	**0.05**

are further categorized into end moraine (e), lateral moraine (l) and other moraine (o) lakes. Similarly, ice-dammed lakes are further classified into supraglacial (s) and valley (v) types. Bedrock-dammed lakes are split into cirque (c) and other erosional landforms (o) (Table 3.1).

Moraine-dammed lakes comprise a majority of the glacial lakes in all three basins of the study area (Table 4.2). In general, their moraines consist of loose, coarse material with little cementing content. This composition makes it easy for them to erode, and thus lakes with moraines comprising this material are vulnerable to GLOFs.

Moraine-dammed lakes constitute about 55% of the total number of lakes (2,003), followed by bedrock-dammed lakes (1,255, or 35%) and ice-dammed lakes (339, 9.4%), with others merely 27 (0.7%). Among the moraine-dammed lakes, end moraine-dammed lakes comprise 28.6% (573), lateral moraine-dammed lakes 4.1% (82), and other moraine-dammed lakes 67.3% (1,348). Among the ice-dammed lakes, supraglacial lakes comprise 99.4% (337) and glacier ice-dammed lakes only 0.6% (2). Among bedrock-dammed lakes,

FIGURE 4.3 PERCENTAGE OF THE DIFFERENT TYPES OF GLACIAL LAKES IN THE KOSHI, GANDAKI, AND KARNALI BASINS

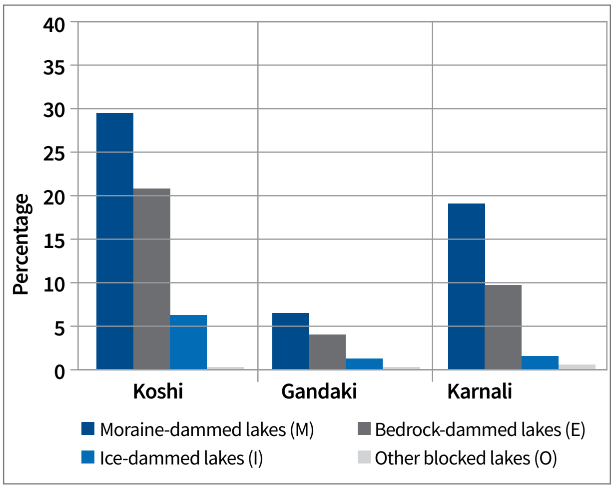


TABLE 4.2 NUMBER AND AREA OF GLACIAL LAKES BY TYPE (2015)

Major basin		Koshi		Gandaki		Karnali		Total	
Type		No.	Area (km^2)	No.	Area (km^2)	No.	Area (km^2)	No.	Area (km^2)
Moraine-dammed lake (M)	M (e)	359	74.98	75	9.94	139	11.72	573	96.64
	M (l)	37	7.48	20	1.45	25	1.92	82	10.85
	M (o)	669	12.85	143	3.46	536	12.53	1348	28.84
Sub-total		**1,065**	**95.31**	**238**	**14.85**	**700**	**26.17**	**2,003**	**136.33**
Ice-dammed lake (I)	I (s)	234	3.36	46	0.37	57	0.45	337	4.18
	I (v)	0	0	0	0	2	0.04	2	0.04
Sub-total		**234**	**3.36**	**46**	**0.37**	**59**	**0.49**	**339**	**4.22**
Bedrock-dammed/erosion lake (B)	B (c)	131	7.04	31	1.34	118	5.42	280	13.80
	B (o)	625	24.06	116	2.56	234	5.69	975	32.31
Sub-total		**756**	**31.10**	**147**	**3.90**	**352**	**11.11**	**1,255**	**46.11**
Other blocked lakes	O	9	2.26	1	0.1	17	6.14	27	8.50
Total		**2,064**	**132.03**	**432**	**19.22**	**1128**	**43.91**	**3,624**	**195.16**

Notes: M(e)—end moraine (e); M(l)—lateral moraine; M(o)—other moraine; I(s)— supraglacial; I(v)—valley (v); B(c)—cirque (c); B(o)—other erosional landforms.

cirque glacial lakes constitute about 22.3% (280) of the subtotal, whereas other erosional glacial lakes comprise ~77.6% (975). The distribution of lake types within each basin is shown in Figure 4.3.

The distribution of different glacial lake types for each sub-basin is given in Table 4.3. The total number and area of moraine-dammed lakes are comparatively higher than bedrock-dammed, ice-dammed, and other types of lakes across all of the basins. The Arun sub-basin has the highest number of moraine-dammed lakes, followed by the Humla sub-basin of the Karnali basin. The Dudh Koshi and Tama Koshi sub-basins of the Koshi basin have more than 200 moraine-dammed lakes, and more than a hundred moraine-dammed lakes are located in the Tamor, Sun Koshi, Trishuli, and Mugu sub-basins each. The Gandaki basin has fewer moraine-dammed lakes than the Koshi and Karnali basins.

The ice-dammed lakes in this inventory are mostly supraglacial lakes, which tend to be dynamic in nature, appearing and disappearing periodically, depending on the glacier's melt rates. The growth and merging of supraglacial lakes are characteristic of this class of lakes, and they ultimately convert into moraine-dammed lakes. Imja Tsho and Tsho Rolpa are typical examples of moraine-dammed lakes that have developed from supraglacial lakes (Bajracharya et al. 2007). This type of lake is more vulnerable to GLOFs.

If supraglacial lakes do not merge, there is a high possibility that they may disappear over time. The Dudh Koshi sub-basin comprises the highest number of ice-dammed lakes.

Bedrock-dammed lakes are the most stable type of lakes. They have a lower probability of GLOF occurrence, compared with the other two types. However, ice, snow, or debris falling in these lakes may trigger flash floods, causing the water to overflow the bedrock sill. There is little possibility of a breach of the bedrock dam by foreign masses landing on the dam or in the lake.

4.3 Classification by size

The glacial lakes mapped in this study were categorized into seven classes, by size: Class 1 (< 0.02 km^2), Class 2 (≥0.02–0.05 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).

Class 1 lakes are the most common (2,214) and constitute 61% of the total inventory (Table 4.4). However, being small, these lakes cover only 20.25 km^2 overall, merely 10.38% of the total lake area. Their average size is merely 0.01 km^2. Class 1 glacial lakes are not analysed further for the identification of potentially dangerous glacial lakes.

TABLE 4.3 NUMBER AND AREA OF GLACIAL LAKES BY TYPE IN THE DIFFERENT SUB-BASINS OF THE KOSHI, GANDAKI, AND KARNALI (2015)

Basin	Sub-basin	Number									Area (km²)								
		Moraine-dammed lake (M)			Ice-dammed lake (I)		Bedrock-dammed lake (B)		Other	Total	Moraine-dammed lake (M)			Ice-dammed lake (I)		Bedrock-dammed lake (B)		Other blocked lakes	Total
		M(e)	M(l)	M(o)	I(s)	I(v)	B(c)	B(o)	O		M(e)	M(l)	M(o)	I(s)	I(v)	B(c)	B(o)	O	
Koshi	Tamor	37	9	78	36	0	34	87	2	283	3.00	0.17	1.50	0.38	0.00	2.03	1.60	0.46	9.14
	Arun	167	4	218	39	0	64	411	6	909	36.80	0.23	4.64	0.98	0.00	3.78	20.36	1.79	68.58
	Dudh Koshi	64	17	134	103	0	4	32	1	355	9.77	3.04	2.22	1.40	0.00	0.17	0.31	0.01	16.92
	Likhu	2	0	8	0	0	3	4	0	17	0.15	0.00	0.11	0.00	0.00	0.10	0.05	0.00	0.41
	Tama Koshi	55	2	162	38	0	14	36	0	307	9.31	1.19	2.80	0.30	0.00	0.53	0.56	0.00	14.69
	Sun Koshi	34	5	64	18	0	11	49	0	181	15.95	2.85	1.50	0.30	0.00	0.41	1.12	0.00	22.13
	Indrawati	0	0	5	0	0	1	6	0	12	0.00	0.00	0.08	0.00	0.00	0.02	0.06	0.00	0.16
	Sub-total	**359**	**37**	**669**	**234**	**0**	**131**	**625**	**9**	**2,064**	**74.98**	**7.48**	**12.85**	**3.36**	**0.00**	**7.04**	**24.06**	**2.26**	**132.03**
Gandaki	Trishuli	34	13	62	35	0	18	80	0	242	3.13	0.49	1.80	0.29	0.00	0.97	1.52	0.00	8.20
	Budhi Gandaki	11	2	18	8	0	6	4	0	49	0.76	0.12	0.28	0.06	0.00	0.10	0.27	0.00	1.59
	Marsyangdi	14	3	23	3	0	4	12	0	59	4.09	0.37	0.61	0.02	0.00	0.15	0.19	0.00	6.24
	Seti	0	0	0	0	0	0	3	1	4	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.10	0.15
	Kali Gandaki	16	2	40	0	0	3	17	0	78	1.15	0.47	0.77	0.00	0.00	0.12	0.53	0.00	3.04
	Sub-total	**75**	**20**	**143**	**46**	**0**	**31**	**116**	**1**	**432**	**9.94**	**1.45**	**3.46**	**0.37**	**0.00**	**1.34**	**2.56**	**0.10**	**19.22**
Karnali	Bheri	21	1	56	3	0	16	65	2	164	1.44	0.01	1.07	0.02	0.00	0.73	0.98	4.96	9.21
	Tila	2	0	20	2	0	24	32	2	82	0.51	0.00	1.32	0.01	0.00	1.50	0.54	0.23	4.11
	Mugu	29	0	127	7	0	31	40	5	239	1.91	0.00	2.37	0.10	0.00	1.03	0.65	0.16	6.22
	Kawari	5	0	10	0	0	6	7	0	28	0.50	0.00	0.21	0.00	0.00	0.27	0.06	0.00	1.04
	West Seti	9	3	22	9	0	4	3	1	51	0.84	0.14	0.24	0.08	0.00	0.10	0.01	0.004	1.41
	Humla	61	16	285	22	2	31	74	7	498	6.10	1.63	6.77	0.16	0.04	1.53	3.18	0.79	20.20
	Kali	12	5	16	14	0	3	13	0	63	0.42	0.14	0.55	0.08	0.00	0.07	0.27	0.00	1.53
	Karnali	0	0	0	0	0	3	0	0	3	0.00	0.00	0.00	0.00	0.00	0.19	0.00	0.00	0.19
	Sub-total	**139**	**25**	**536**	**57**	**2**	**118**	**234**	**17**	**1,128**	**11.72**	**1.92**	**12.53**	**0.45**	**0.04**	**5.42**	**5.69**	**6.14**	**43.91**
Total		**573**	**82**	**1,348**	**337**	**2**	**280**	**975**	**27**	**3,624**	**96.64**	**10.85**	**28.84**	**4.18**	**0.04**	**13.80**	**32.31**	**8.50**	**195.16**

TABLE 4.4	NUMBER AND AREA OF GLACIAL LAKES BY SIZE CLASS IN THE KOSHI, GANDAKI, AND KARNALI BASINS (2015)

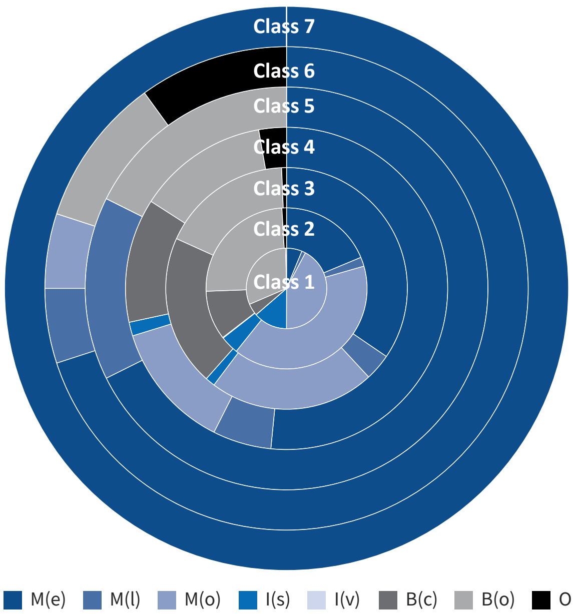
Class	Koshi			Gandaki			Karnali			Total		
	Number	Area (km²)		Number	Area (km²)		Number	Area (km²)		Number	Area (km²)	
		Total	Avg.		Total	Avg.		Total	Avg.		Total	Avg.
1	1,239	11.04	0.01	261	2.46	0.01	714	6.75	0.01	2,214	20.25	0.01
2	433	13.35	0.03	95	2.94	0.03	231	7.19	0.03	759	23.48	0.03
3	181	12.54	0.07	38	2.65	0.07	88	6.40	0.07	307	21.59	0.07
4	163	35.24	0.22	36	6.84	0.19	90	16.27	0.18	289	58.34	0.20
5	29	21.24	0.73	1	0.92	0.92	4	2.40	0.60	34	24.56	0.72
6	18	33.19	1.84	1	3.38	3.38	1	4.92	4.92	20	41.50	2.08
7	1	5.41	5.41	0	0.00	0	0	0.00	0	1	5.41	5.41
Total	**2,064**	**132.01**	**0.06**	**432**	**19.19**	**0.04**	**1,128**	**43.93**	**0.04**	**3,624**	**195.13**	**0.05**

Class 2 lakes are the second-highest in number (759), and constitute about 21% of the total lake area. The number of glacial lakes decreases with increasing size (and class number). However, although Class 4 lakes are ranked fourth in number, they have the largest total area among the glacial lakes. Only one Class 7 lake is present in the inventory with an area of 5.41 km².

Table 4.4 shows the distribution of glacial lake numbers and their area in different size classes within the basins. The Koshi basin has the highest number of lakes in all classes. The largest glacial lake is also in the Koshi basin. There is an inverse relationship between the number and area of lakes according to the size classes. Similar observations have also been made in the Pumqu (Arun) basin (Che et al. 2014) and the Poiqu (Bhote Koshi) basin (Wang et al. 2014), with large numbers of small lakes belonging to Class 1 and Class 2.

Table 4.5 displays the proportional distribution of lakes by size of the different types of glacial lakes. A considerable number of lakes consist of other moraine, other bedrock dammed, and end moraine-dammed glacial lake types. The end moraine-dammed lakes are higher in all size classes of the lakes except in classes 1 and 2 (Figure 4.4). Forty-five moraine-dammed lakes are larger than 0.5 km²; of these, 21 lakes are larger than 1 km². Most of the larger lakes are moraine-dammed lakes, although some of them are blocked lakes (Table 4.5). The risk levels of the larger glacial lakes dammed by ice or moraines are high. The expansion of supraglacial lakes near the terminus of a glacier due to the melting of the glacier increases the risk level.

FIGURE 4.4 NUMBER OF GLACIAL LAKES BY SIZE CLASS AND LAKE TYPE IN THE KOSHI, GANDAKI, AND KARNALI BASINS (2015)



4.4 Altitudinal distribution

The glacial lakes covered in this report are found between 3,400–6,100 masl (Table 4.6). The highest elevation of debris-covered glaciers in the Nepalese Himalayas is roughly 6,000 masl (Bajracharya et al. 2014b). Above this altitude, the landforms are steep and mostly exist in a frozen state, which implies that no permanent/perennial lakes can exist there. Figure 4.5 displays the distribution of glacial lakes in 100-m elevation zones. One glacial lake is at 2,400 masl., in the Seti River sub-basin of the Gandaki basin.

TABLE 4.5 NUMBER OF GLACIAL LAKES BY SIZE CLASS AND LAKE TYPE (2015)

Class	Size (km²)	Types of lake								Total
		M (e)	M (l)	M (o)	I (s)	I (v)	B (c)	B (o)	O	
Class 1	<0.02	138	34	936	301	1	108	688	8	2,214
Class 2	≥0.02–0.05	142	14	305	28	1	75	187	7	759
Class 3	≥0.05–0.1	106	11	68	4	0	62	54	2	307
Class 4	≥0.1–0.5	149	17	38	4	0	35	38	8	289
Class 5	≥0.5–1.0	23	5	0	0	0	0	6	0	34
Class 6	≥1.0–5.0	14	1	1	0	0	0	2	2	20
Class 7	≥5.0	1	0	0	0	0	0	0	0	1
Total		**573**	**82**	**1,348**	**337**	**2**	**280**	**975**	**27**	**3,624**

TABLE 4.6 DISTRIBUTION OF TYPES OF GLACIAL LAKES AT DIFFERENT ELEVATION ZONES (masl)

Elevation zone		3,000–4,000		4,000–5,000		5,000–6,000		6,000–7,000		Total	
Type		Number	%	Number	%	Number	%	Number	%	Number	%
M	M(e)	7	15.56	180	12.33	386	18.26	0	0	573	15.81
	M(l)	0	0	43	2.95	37	1.75	2	50	82	2.26
	M(o)	6	13.33	387	26.51	953	45.08	1	25	1,347	37.17
I	I(s)	7	15.56	178	12.19	152	7.19	0	0	337	9.3
	I(v)	0	0	0	0	2	0.09	0	0	2	0.06
	I(o)	0	0	0	0	0	0	0	0	0	0
B	B(c)	7	15.56	202	13.84	72	3.41	0	0	281	7.75
	B(o)	12	26.67	452	30.96	510	24.12	1	25	975	26.9
Others	O	6	13.33	18	1.23	2	0.09	0	0	26	0.75
Total	**Number**	**45**		**1,460**		**2,114**		**4**		**3,623**	
	%	**1.24**		**40.29**		**58.33**		**0.11**			**100**

Note: Only one glacial lake is below 3,000 masl.

It was formed due to the melting of glacier ice from an avalanche; the rest are above 3,400 masl. The majority of glacial lakes (58.3%) is located at elevations between 5,000–6,000 masl. About 40.3% of the total number of lakes are located between 4,000–5,000 masl. Hence, about 99% of the glacial lakes mapped are to be found between 4,000–6,000 masl.

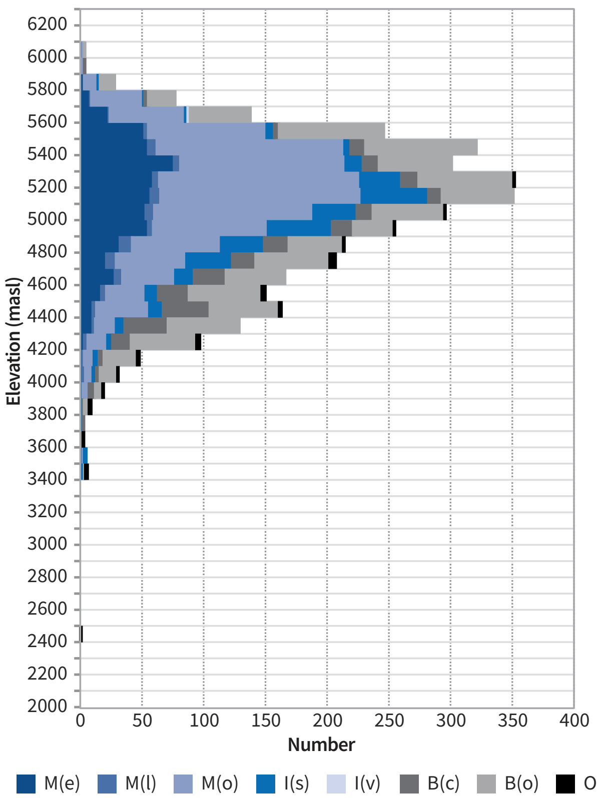
Similar altitudinal differences in the distribution of glacial lakes have been reported in the Himalayas in other studies (Nie et al. 2013; Wang et al. 2014). For example, in the Poiqu basin, Wang et al. (2014) showed that glacial lakes are distributed within the altitudinal range of 4,420–5,860 masl., with the majority of the lakes (76%) situated at elevations above 5,000 masl. The altitudinal distribution of the lakes shown in Figure 4.5 clearly demonstrates that a large proportion of the moraine-dammed lakes are at higher elevations, whereas erosional and 'others' types of glacial lakes exist lower down.

Figure 4.6 indicates that the percentage of small glacial lakes (<0.02 km²) is high in all the altitudinal zones except the one below 2,500 masl. However, the percentage of large glacial lakes (>0.1 km²) is comparatively higher in the altitudinal zone between 3,500–5,500 masl.

4.5 Geographical distance from the source glacier

The distance of glacial lakes from their source glacier(s) is another important factor in the stability of lakes. Lakes that are more than 10 km from their source glacier(s) are not considered glacial lakes as the latter are defined by their contact with, or proximity to their source glacier.

FIGURE 4.5 ALTITUDINAL DISTRIBUTION OF NUMBER AND TYPES OF LAKES



Changing glacier melt and retreat are closely associated with changes in the glacial lake environment. Lakes located within the glaciers are typically supraglacial lakes and constitute about 11% of the lakes in the Koshi basin, 10% in the Gandaki, and 5% in the Karnali basin (Table 4.7). Lakes in contact with a glacier are mostly moraine-dammed. They constitute about 6% of the lakes in Koshi, 13% in the Gandaki basins, and more than 5% in the Karnali basin. Lakes at a distance of less than 500 m comprise 20%, 34%, and 19% of the lakes in Koshi, Gandaki, and Karnali basins respectively. For lakes more than 500 m away from their source glacier(s), the latter's distance makes them less of a factor in the stability of the lakes and dams.

Figure 4.7 shows the distribution of the number and size of the glacial lakes in relation to their distance from source glaciers. The number and size of the lakes decreases with an increase in their distance from the glaciers. Lakes closer to a glacier are higher in number and tend to be larger in size. Lakes farther away from glaciers tend to be mostly erosional/bedrock-dammed lakes, or belong to the category 'Others'. Most of the moraine-dammed lakes are within 5 km of the glaciers. The highest number of moraine-dammed lakes is within 2 km of the glaciers.

FIGURE 4.6 NUMBER OF GLACIAL LAKES BY SIZE CLASS IN DIFFERENT ELEVATION BANDS

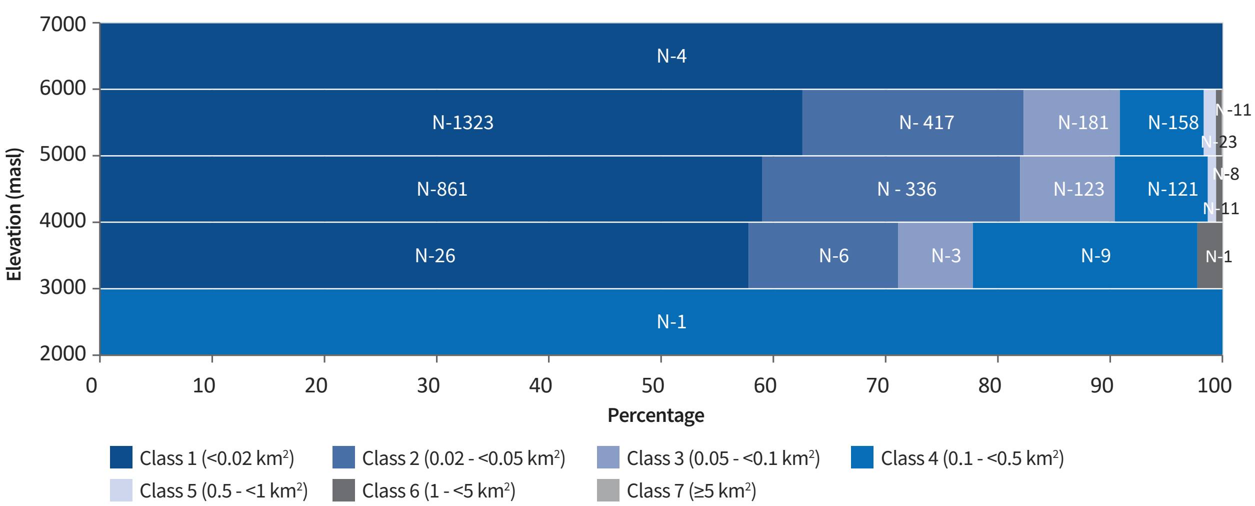
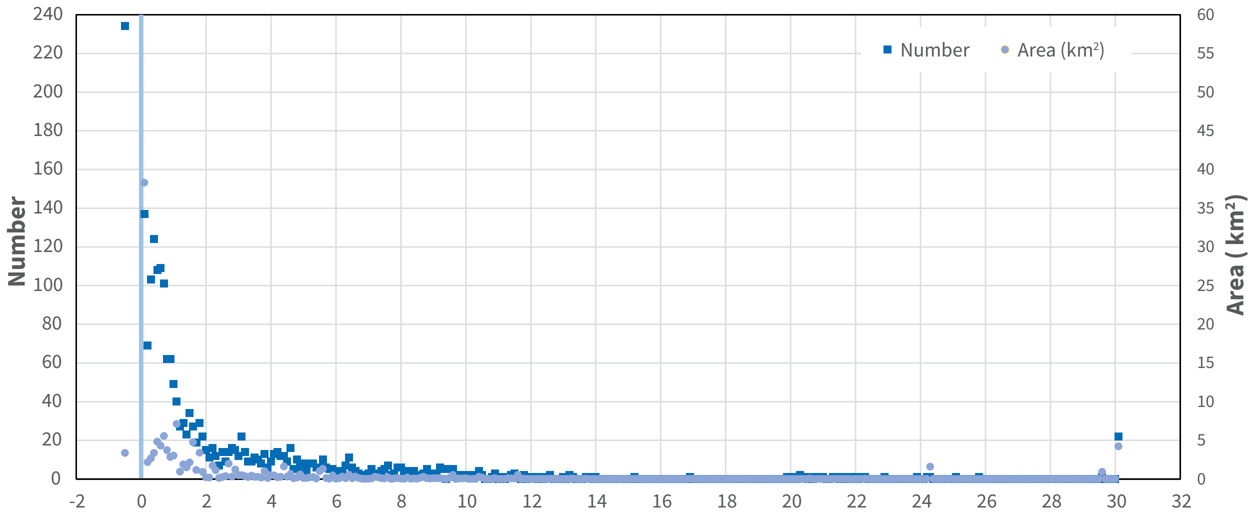


TABLE 4.7 DISTRIBUTION OF THE NUMBER AND AREA OF GLACIAL LAKES BY THEIR DISTANCE FROM SOURCE GLACIERS

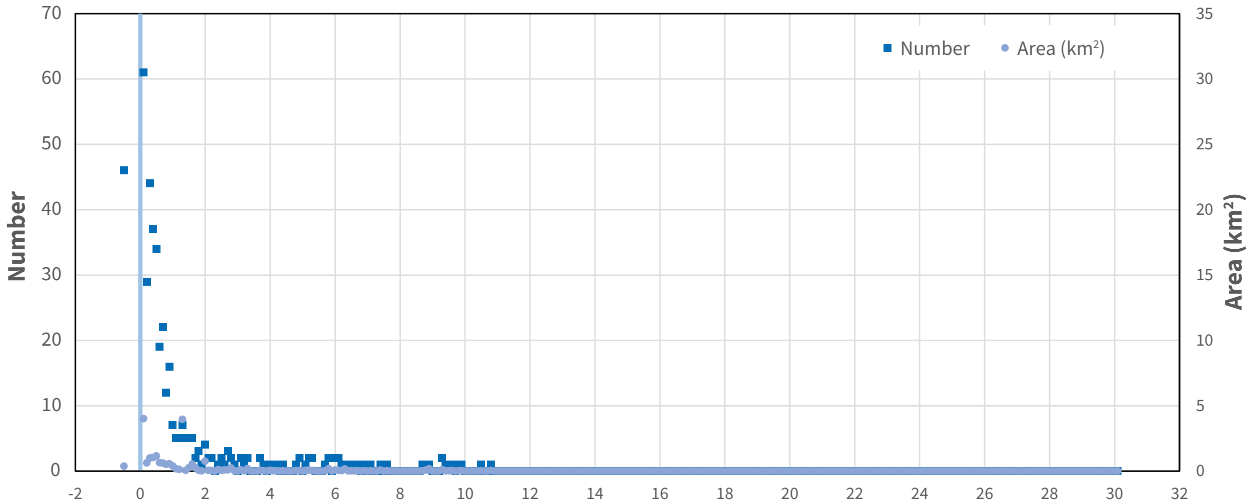
Distance from source glaciers (m)	Koshi				Gandaki				Karnali			
	Number	%	Area (km²)	%	Number	%	Area (km²)	%	Number	%	Area (km²)	%
Within	234	11.3	3.36	2.5	46	10.6	0.36	1.9	57	5.1	0.46	1.1
Contact with	124	6.0	37.45	28.4	57	13.2	3.96	20.7	58	5.1	4.09	9.3
>0–<100	13	0.6	0.84	0.6	4	0.9	0.03	0.2	8	0.7	0.39	0.9
100–<200	69	3.3	2.19	1.7	29	6.7	0.61	3.2	40	3.5	0.83	1.9
200–<500	335	16.2	10.87	8.2	115	26.6	3.17	16.5	169	15.0	4.56	10.4
500–<1,000	383	18.6	19.50	14.8	76	17.6	2.68	13.9	238	21.1	9.22	21.0
1,000–<2,000	265	12.8	24.07	18.2	42	9.7	6.06	31.6	190	16.8	7.30	16.6
2,000–<5,000	342	16.6	16.28	12.3	29	6.7	1.09	5.7	210	18.6	10.93	24.9
5,000–<10,000	214	10.4	8.67	6.6	32	7.4	1.20	6.3	77	6.8	2.68	6.1
≥10,000	85	4.1	8.79	6.7	2	0.5	0.03	0.1	81	7.2	3.48	7.9
Total	**2,064**	**100**	**132.01**	**100**	**432**	**100**	**19.19**	**100**	**1,128**	**100**	**43.93**	**100**

Hongu 2 glacial lake, Nepal.

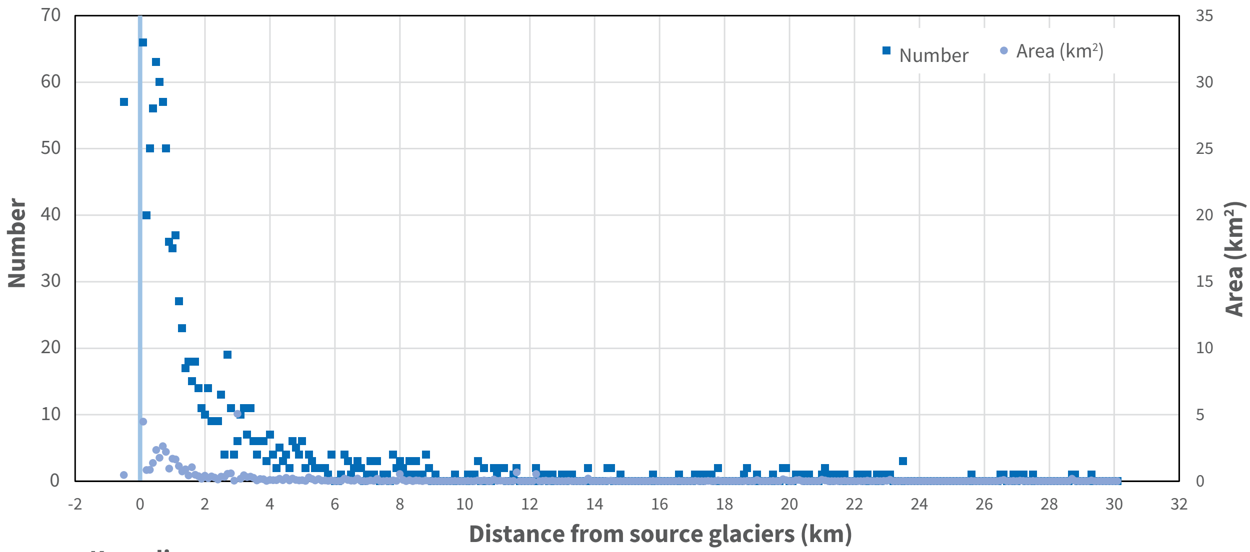
FIGURE 4.7 **DISTRIBUTION OF THE NUMBER AND SIZE OF THE GLACIAL LAKES IN RELATION TO THEIR DISTANCE FROM THE SOURCE GLACIER IN THE (A) KOSHI, (B) GANDAKI, AND (C) KARNALI BASINS**



a. Koshi



b. Gandaki



c. Karnali

Note: The blue line signifies the snout of the glacier.

The Lower Barun Lake is located in the upper reaches of the Barun River.

SECTION 5

Potentially dangerous glacial lakes in the Koshi, Gandaki, and Karnali basins

5.1 Parameters for lake stability

5.1.1 Characteristics of the lakes

Changes in the glacial lakes mirror changes in their source glaciers. In the 33-year period between 1977 and 2010, glaciers in Nepal have decreased by almost a quarter of their initial area (Bajracharya et al. 2014). Accordingly, for example, the number of glacial lakes in the Koshi basin has increased from 1,160 in 1977 to 2,168 in 2010; their total area has increased from 94.4 km^2 to 127.6 km^2 over this period (Shrestha et al. 2017). The number of lakes has increased by 86.9%, and the total lake area by 35.1%.

ICIMOD mapped the glacial lakes for 2000 and 2015 and compared this inventory against existing data gathered in 2005 (Maharjan et al. 2018) to produce an assessment of the changes that have taken place (Table 5.1). The number of glacial lakes in the Koshi basin decreased from 2,119 in 2000 to 2,087 in 2005 and to 2,064 in 2015. In contrast, the number of glacial lakes has increased in the Gandaki basin, from 377 in 2000 to 405 in 2005, and 432 in 2015. The increase in the number of glacial lakes is indicative of the rapid melting of glaciers and formation of new lakes, particularly those dammed by glacier ice and moraines. The glacial lakes in the Karnali basin increased from 1,105 in 2000 to 1,204 in 2005 but decreased to 1,128 in 2015. This decrease in the number of glacial lakes in the Karnali, or the falling numbers in some years in the Koshi basin, are not indicative of a loss of glacial lakes, as this pattern is produced by the merging of lakes with neighbouring glacial lakes. As a result, the total area of the glacial lakes has increased, from 179.56 km^2 in 2000 to 186.44 km^2 in 2005 and to 195.39 km^2 in 2015.

Additionally, the threshold value chosen for the distance to the glacier between the 2005 inventory and the present study is slightly different. Hence the number of glacial lakes in the Koshi and Karnali basins identified in 2005 was slightly higher than in

TABLE 5.1 NUMBER AND TOTAL AREA OF GLACIAL LAKES IN THE THREE BASINS, 2000, 2005, AND 2015

Basin	2000		2005		2015±1year		Difference (2000 to 2015)			
	Number	Area (km²)	Number	Area (km²)	Number	Area (km²)	Number	%	Area (km²)	%
Koshi	2,119	118.42	2,087	123.10	2,064	132.27	- 55	- 2.60	13.9	11.70
Gandaki	377	17.76	405	17.75	432	19.19	55	14.59	1.4	8.07
Karnali	1,105	43.38	1,204	45.60	1,128	43.93	23	2.08	0.6	1.27
Total	**3,601**	**179.56**	**3,696**	**186.44**	**3,624**	**195.39**	**23**	**0.64**	**15.8**	**8.82**

Note: The 2005 data is from Maharjan et al. (2018).

2015. However, the total lake area increased by 12% in the Koshi basin, 8% in the Gandaki basin, and 1.27% in the Karnali basin between 2000 and 2015. The number of supraglacial lakes in the Koshi basin is high; the merging of supraglacial lakes reduces the number of lakes but the overall lake area has increased.

This study has identified about 1,410 glacial lakes that have an area equal to or larger than 0.02 km². In comparison to 2000, the number of lakes of this size increased in all the three basins by 2015 (Table 5.2). By 2015, this number had increased by 69 in the Koshi basin, 31 in the Gandaki basin, and 38 in the Karnali basin.

a further 516 lakes – including supraglacial lakes (36), valley lakes (1), blocked lakes (bedrock-dammed lakes) (287+172=459) (Table 4.5), and other blocked lakes (19) – are also excluded from the PDGL analysis because the main dam of these lakes are bedrocks with thin layers of moraine and hence more stable than moraine-dammed lakes. Hence a total of 2,729 lakes are now excluded, and 895 lakes remain to identify the PDGLs for level 2 analysis.

Analysis for PDGL (Level 1) = Total lakes (Level 0) – Class 1 – I(s+v) – B(c+o) – O = 895 .... (1)

TABLE 5.2 NUMBER AND AREA OF GLACIAL LAKES EQUAL TO OR LARGER THAN 0.02 KM², 2000 AND 2015

Basin	2000		2015		Difference	
	Number	Area (km²)	Number	Area (km²)	Number	Area (km²)
Koshi	771	106.64	825	120.97	69	14.85
Gandaki	140	13.97	171	16.73	31	2.76
Karnali	381	32.67	414	37.18	38	4.8
Total	**1,292**	**153.28**	**1,410**	**175.69**	**138**	**22.41**

The increase in lake area is associated with a corresponding increase in the risk of GLOFs. All lakes with an area equal to or larger than 0.02 km² are analysed further to understand the stability of the lakes and their dams. Lakes upstream and downstream of these lakes are also examined as these may impact lake stability.

An enlargement in the lake's area increases the potential energy of the reservoir, while a decrease in the dam area reduces the dam's strength, both of which potentially increase the chances of a breach. The types and sizes of glacial lakes are given in Table 4.5. About 2,214 lakes, being smaller than 0.02 km², are excluded from the analysis of PDGLs. In the next step,

The number of glacial lakes derived from Level 1 (Equation 1) is further analysed incorporating the characteristics of the dams of the respective glacial lakes.

5.1.2 Characteristics of the dams

The flow of glacier meltwater can be obstructed by rocky terrain, glacier ice, loose moraine, and landslides, to form a lake. The obstructing features constitute a natural dam. A more rapid glacier melt results in either an increase in surface run-off, or an expansion of the lake. The rapid melting of the glacier and a consequent expansion of the lake will either increase the potential energy of the reservoir and discharge of lake water, which would impact the dam, or its waters would flow over the dam.

The condition of the dam is important in determining the stability of a lake. Most lakes close to a glacier's snout are dammed by loose moraine material. When lake waters flow over thin and loose moraines, these structures could easily erode, resulting in a GLOF. Lakes enclosed by narrow crest moraines have a higher potential for an outburst compared to lakes with wide crest dams. Due to erosion and transportation, dam crests are usually angular and narrow at the top. Any surge wave generated by ice or snow avalanches may ultimately trigger a GLOF. The steepness of the slope of the moraine wall also determines the likelihood of an outburst from a lake. Ice-dammed and moraine-dammed lakes are particularly susceptible to instability. Ice-dammed lakes in the study area are mostly supra-glacial lakes, and a majority of them are smaller than their thresholds. Some prominent sized supra-glacial lakes have been considered as having been formed by a cascading effect for the purpose of analysis. Bedrock-dammed lakes are more stable than lakes with other types of natural dams, as the stability of other dammed lakes depends on the characteristics of dammed features.

The main characteristics of the dams were analysed for glacial lakes equal to or larger than 0.02 km^2. The main features and characteristics of dam stability include: (1) no dam crest (nc) – the volume of inflow and outflow of the lake being equal; (2) compressed and old dam material (co), which is more stable than loose debris; (3) its length is greater than 200m (dl), which reduces the erosional capacity of overflow; and (4) the outer slope of the dam is less than 20 degrees (ds) – a lower gradient will have less erosional capacity. Based on these parameters, eight lakes identified as PDGLs in 2011 (Table 5.3) were removed from the PDGL list in this study.

Lakes with dams that have characteristics of no crest (nc), compressed and old dam material (co), dam length being greater than 500 m (dl), and their outer slope being less than 20 degrees (ds) are assumed to be stable and hence 600 lakes are subtracted from Level 1 for further analysis in the identification of PDGLs. A total of 295 lakes remain for the analysis of Level 3.

Analysis for PDGL (Level 2) = Level 1–nc–co–dl–ds = 295 (2)

TABLE 5.3 POTENTIALLY DANGEROUS GLACIAL LAKES FROM 2011 DISCOUNTED IN THE PRESENT LIST

S. No.	Lake ID/Name	Valley	Description
1	kotam_gl_0135/ Nagma Pokhari	Tamor	Outburst in 1980. Confined outflow through the moraine and debris for almost 1,700 m, and only then does the water drop at a steep slope. No further GLOF is expected
2	kodud_gl_0193/ Tam Pokhari	Dudh Koshi	Outburst in 1998. Presence of a confined channel wider than 45 m. Water flows through the moraine and debris for almost 1,450 m, and only then flows into the river valley. No further GLOF is expected
3	gakal_gl_0004	Kaligandaki	Blocked by debris, possibly from an earlier landslide. Wide and confined lake outlet present at the side of the dam. No further GLOF is expected
4	koaru_gl_0012/ Barun Pokhari	Arun	Evidence of a GLOF in the past. The river valley is full of alluvial fan with a gentle slope for about 300 m. No damming, compact debris downstream. Little chance of huge ice avalanches to create a GLOF
5	gabud_gl_0009/ Birendratal	Budhigandaki	The lake is in contact with a retreating glacier. Compact debris downstream, in contact with the retreating glacier. In case of a glacier topple, there's only the possibility of an overflow of splashing water. No GLOF is expected
6	koaru_gl_0016	Arun	No damming glacial, erosional land feature; compact debris downstream; fed by lake at the glacier snout; dam length of about 1,500 m, then landslide and steep slope. No GLOF is expected
7	gakal_gl_0008	Kaligandaki	On medial moraine, old and compact moraine; confined surface flow. Distance to its source glacier is about 1 km; no chances of an ice fall, landslide or any other means for the moraine to break
8	gakal_gl_0022	Kaligandaki	Lake has been formed in the river valley with a clear outlet; no chance of an ice fall, landslide or any other triggers for a GLOF

5.1.3 Characteristics of the source glaciers

While the characteristics of a glacial lake and dam determine whether a lake is considered to be stable, a lake's stability may also be disturbed by its source glacier. This may occur either due to the rapid melting of glacier ice, resulting in the rapid growth of the glacial lake, or by the toppling/collapse of a large mass of glacier ice that disturbs the flow of the lake or damages its dam, causing it to breach. For lakes in direct contact with their source glacier, steep slopes and large differences in elevation between the lake and the glacier may allow large masses of ice to fall into the lake, creating a huge wave that may rupture the dam. This process is considered potentially dangerous, and glacial lakes that exhibit these properties become candidates for being identified as PDGLs that need to be monitored. Information about the condition of hanging glaciers, the distance to lakes, the steepness of glacier tongues, debris cover on lower glacier tongues, the presence of crevasses and ponds on the glacier's surface, the possibility of toppling/collapsing ice from glacier fronts, and icebergs breaking off the glacier's terminus and floating into the lake are also examined in this study to identify PDGLs.

Lakes situated more than 500 m from the glacier terminus (dm), and those with source glaciers with surface slopes less than 45 degrees (sm) are assumed to be stable and are removed from further detailed analysis.

5.1.4 Physical condition of the surroundings

The stability of the surroundings of the glacial lake and dam are important additional factors that may destabilize them (discussed in section 3.5). Much of the study area is located at a high altitude, at which snow/ice avalanches and landslides commonly occur. These phenomena can disturb a lake or a dam significantly enough to trigger a GLOF. Of the 295 lakes indicated above, a total of 243 lakes were deemed safe, from both the source glacier and the surroundings (S). It leaves us with 52 lakes, which were analysed for level 4.

Analysis for PDGL (Level 3) = Level 2–dm–sm–(S) = 52 (4)

These 52 glacial lakes were thoroughly rechecked against the high-resolution satellite images available on Google Earth. By comparing the various surrounding features that could impact the lakes and dams, 47 glacial lakes were identified as potentially dangerous and selected for potential GLOF risk reduction (Figure 5.1 and Table 5.4).

5.2 Identification and ranking of potentially dangerous glacial lakes

In this study, a remote sensing approach combined with a geographic information system was used to identify potentially dangerous glacial lakes within the large population of lakes in the study area. First, the small lakes (<0.02 km^2) were excluded. The

FIGURE 5.1 IDENTIFICATION OF POTENTIALLY DANGEROUS GLACIAL LAKES BASED ON THE CHARACTERISTICS OF THE LAKES, DAMS, AND SURROUNDING FEATURES, INCLUDING THE SOURCE GLACIERS

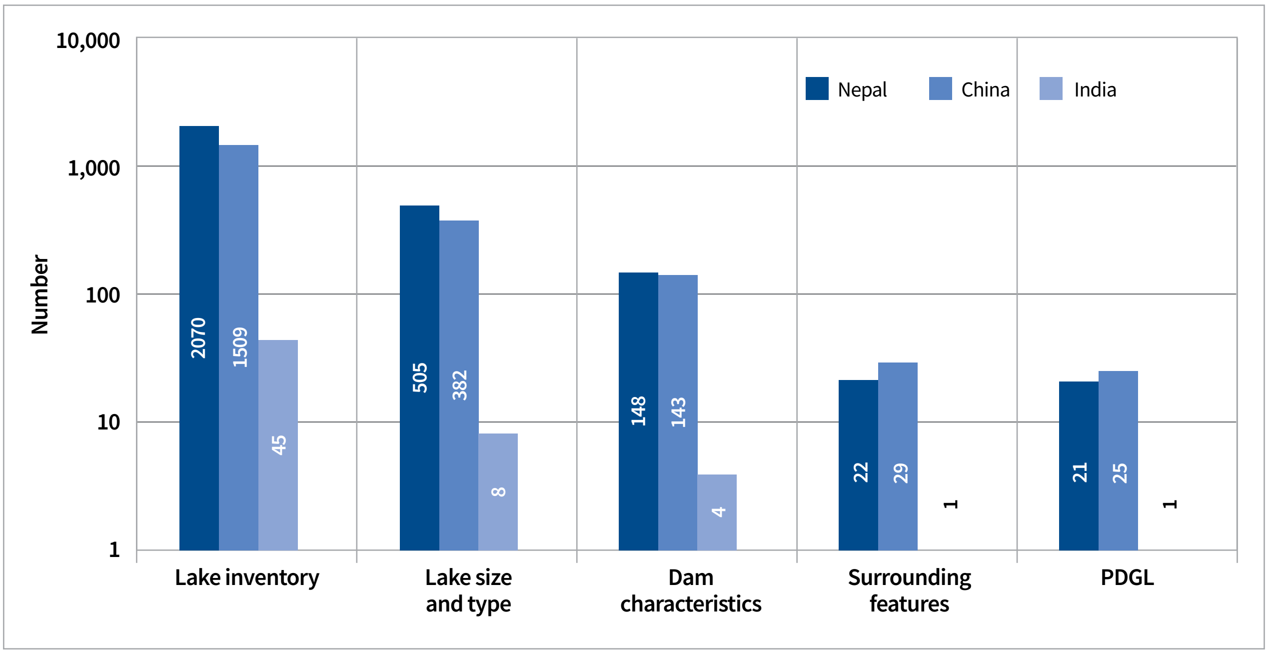


TABLE 5.4 IDENTIFICATION OF POTENTIALLY DANGEROUS GLACIAL LAKES BASED ON CHARACTERISTICS OF THE LAKES, DAMS, AND SURROUNDING FEATURES, INCLUDING THE SOURCE GLACIERS

Country	Basin	Lake inventory	Lake size and type	Characteristics of the dams	Source glaciers and surrounding features	PDGLs
		Level 0	Level 1	Level 2	Level 3	Level 4
Nepal	Koshi	834	199	91	19	18
	Gandaki	255	65	18	2	2
	Karnali	981	241	39	1	1
	Sub-total	2,070	505	148	22	21
China	Koshi	1,230	308	123	28	24
	Gandaki	177	52	17	1	1
	Karnali	102	22	3	0	0
	Sub-total	1,509	382	143	29	25
India	Koshi	0	0	0	0	0
	Gandaki	0	0	0	0	0
	Karnali	45	8	4	1	1
	Sub-total	45	8	4	1	1
Total		**3,624**	**895**	**295**	**52**	**47**

remaining lakes were then evaluated using a range of geomorphological and physical criteria, which assessed factors relating to the lake, the dam, the source glacier, and the surrounding area to identify the PDGLs.

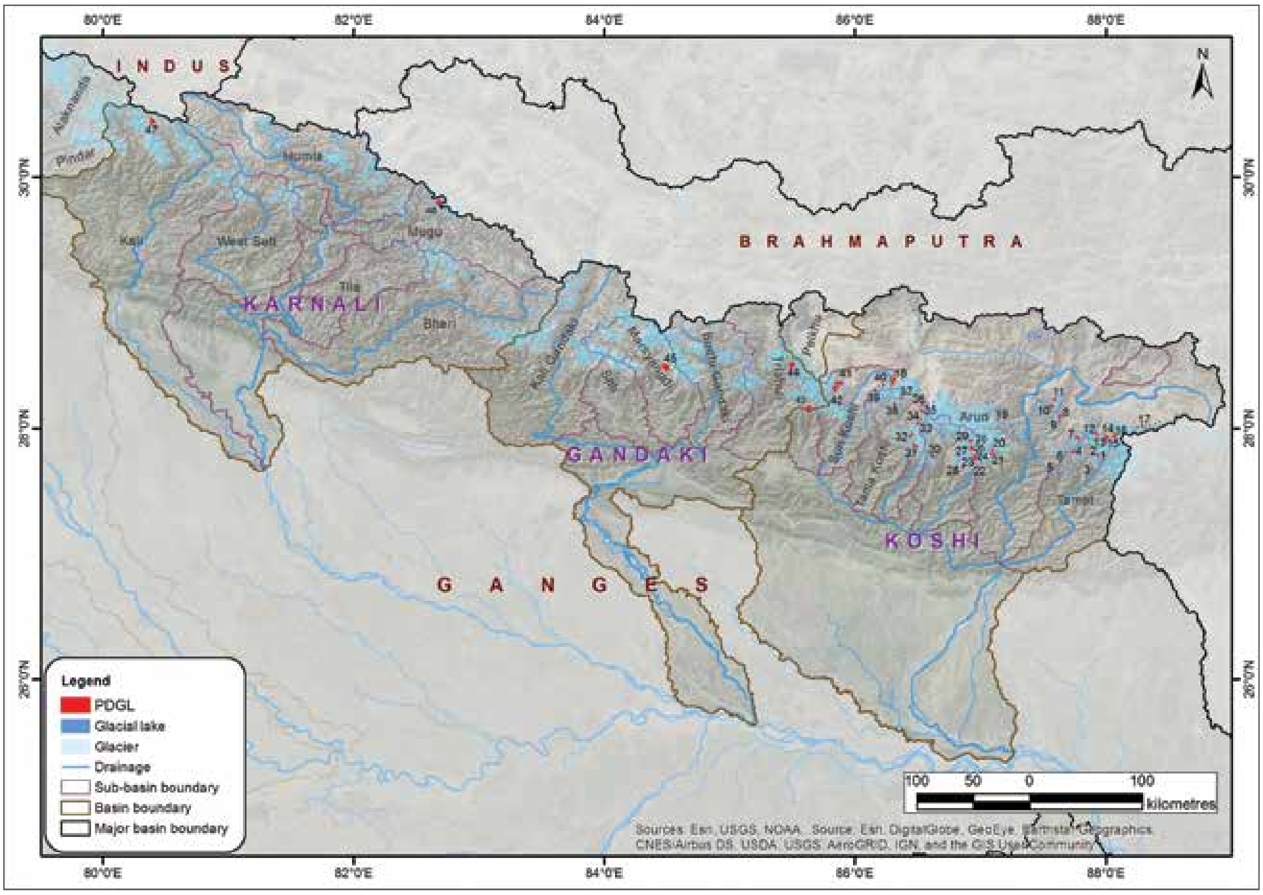
Out of 3,624 lakes mapped, 1,410 lakes are equal to or larger than 0.02 km^2. This is considered large enough to cause damage downstream were the lake to rupture. This potential is heightened if the lakes are associated with a large and retreating glacier. Of the 1,410 lakes, 1,358 lakes were removed, based on the damming condition, the activity of the source glaciers, and their surroundings. The remaining 52 lakes were analysed further to identify potentially dangerous glacial lakes. Eventually, 47 glacial lakes were identified as potentially dangerous. These include 42 lakes in the Koshi, 3 in the Gandaki, and 2 in the Karnali basins (Figure 5.2). Of these, 25 PDGLs are in the TAR, China, and flow across the border into Nepal, 21 PDGLs are situated in Nepal, and one is located in India. Table 5.5 shows the PDGLs by river basin, sub-basin, and country, and Table 5.6 provides a list of the 47 PDGLs, including a ranking of their danger levels.

The PDGLs were ranked to determine the priority for potential GLOF risk reduction. A precise ranking was not possible. Outbursts can occur that have no precedent, especially in view of the current atmospheric warming discussed in Section 3.7. It is

TABLE 5.5 SUMMARY OF POTENTIALLY DANGEROUS GLACIAL LAKES IN THE KOSHI, GANDAKI, AND KARNALI BASINS OF NEPAL, THE TAR OF CHINA, AND INDIA

Basin	Sub-basin	Nepal	TAR, China	India	Total
Koshi	Tamor	4	—	—	42
	Arun	4	13	—	
	Dudh Koshi	9	—	—	
	Tama Koshi	1	7	—	
	Sun Koshi	—	4	—	
Gandaki	Trishuli	1	1	—	3
	Marsyangdi	1	—	—	
Karnali	Kali	—	—	1	2
	Humla	1	—	—	
Total		**21**	**25**	**1**	**47**

FIGURE 5.2 LOCATION OF POTENTIALLY DANGEROUS GLACIAL LAKES IN THE KOSHI, GANDAKI, AND KARNALI BASINS IN NEPAL, THE TAR OF CHINA, AND INDIA



Disclaimer: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

S. No.	Lake ID	S. No.	Lake ID	S. No.	Lake ID	S. No.	Lake ID	S. No.	Lake ID
1	GL087945E27781N	11	GL087591E28229N	21	GL087092E27798N	31	GL086476E27861N	41	GL085870E28360N
2	GL087934E27790N	12	GL087930E27949N	22	GL086977E27711N	32	GL086447E27946N	42	GL085838E28322N
3	GL087893E27694N	13	GL088002E27928N	23	GL086958E27755N	33	GL086500E28033N	43	GL085630E28162N
4	GL087749E27816N	14	GL088019E27928N	24	GL086957E27783N	34	GL086520E28073N	44	GL085494E28508N
5	GL087596E27705N	15	GL088066E27933N	25	GL086935E27838N	35	GL086530E28135N	45	GL084485E28488N
6	GL087632E27729N	16	GL088075E27946N	26	GL086928E27850N	36	GL086532E28185N	46	GL082673E29802N
7	GL087771E27926N	17	GL088288E28017N	27	GL086917E27832N	37	GL086371E28238N	47	GL080387E30445N
8	GL087636E28093N	18	GL086304E28374N	28	GL086858E27687N	38	GL086314E28194N		
9	GL087626E28052N	19	GL087134E28069N	29	GL086925E27898N	39	GL086157E28303N		
10	GL087563E28178N	20	GL087095E27829N	30	GL086612E27779N	40	GL086225E28346N		

TABLE 5.6	RANKING OF POTENTIALLY DANGEROUS GLACIAL LAKES IN THE KOSHI, GANDAKI, AND KARNALI BASINS OF NEPAL, THE TAR OF CHINA, AND INDIA

S. No.	Lake ID/Name	Rank	Description	River basin	Country	PDGL identified in (year)
1	GL087945E27781N	I	Dam is not long (<400 m) and the crest width less than 20 m; steep side slope and chances of landslide; source glacier hanging	Tamor	Nepal	
2	GL087934E27790N	III	Lake close to the dam end but has confined outlet; hanging glacier; side wall at a steep slope	Tamor	Nepal	
3	GL087893E27694N	III	Shallow lake at steep slope; short dam length; hanging mother glacier	Tamor	Nepal	
4	GL087749E27816N	I	Glacier in contact; dam not long; possibilities of avalanches; landslide on outer slope of the dam	Tamor	Nepal	
5	GL087596E27705N	I	Lake expanding; cascading lake overflow may trigger an outburst; dam width not large; erosion at end moraine	Arun	Nepal	
6	GL087632E27729N	III	Lake outlet close to end of moraine (2 m); dam at a high gradient	Arun	Nepal	
7	GL087771E27926N	I	Possibilities of lake expansion; calving source glacier; lake outlet near the dam end; steep side wall	Arun	China	
8	GL087636E28093N	I	Possibilities of lake expansion; lake outlet near the dam end; marking of outlet drainage; seepage at the bottom of the dam; steep outward slope of dam; steep side wall	Arun	China	
9	GL087626E28052N	I	Possibility of lake expansion; lake outlet near the dam end; no clear outlet drainage; seepage at the bottom of the dam; steep and eroded side wall with landslide and blocks of rock; hanging source glacier	Arun	China	
10	GL087563E28178N	III	Large, expanding lake; no distinct lake outlet and surface run-off appears after 500 m down the slope; steep wall on one side	Arun	China	
11	GL087591E28229N	II	Large lake at the extreme end of the moraine; dry outlet channel for almost 370 m, after which the river flow begins; old and compact moraine; hanging source glacier	Arun	China	
12	GL087930E27949N	I	Possibility of small lakes merging; dam width not large, calving source glacier; steep side slope with the possibility of snow avalanches and landslides	Arun	China	
13	GL088002E27928N	I	Large lake fed by many tributary glaciers; old and dry lake outlet channel of about 40 m, after which major seepage appears; calving source glacier; PDGL GL088019E27928N is in the tributary valley	Arun	China	
14	GL088019E27928N	I	Possibility of lake expansion; lake outlet at the end of the dam; couple of overflow channels; moraine seems old and compact; calving source glacier	Arun	China	
15	GL088066E27933N	I	Lake water lowered in the past; compaction done at end-moraine dam; calving glacier; possibility of lake expansion; short dam length	Arun	China	
16	GL088075E27946N	I	Lake water lowered in the past; lake expanding at both ends; dead ice on the end moraine; large source glaciers; large PDGL (GL088066E27933N) at valley to the left may damage the lake	Arun	China	
17	GL088288E28017N	II	Lake close to dam end but confined; wide outlet channel; compact and old moraine; calving source glacier at a steep slope; high gradient of moraine	Arun	China	

S. No.	Lake ID/Name	Rank	Description	River basin	Country	PDGL identified in (year)
18	GL086304E28374N	II	Possibility of ice fall from source glacier; large lake; old moraine	Arun	China	
19	GL087134E28069N	I	Possibility of lake expansion; lake outlet almost at dam end, minor overflow but much seepage; possibility of landslides on the side wall	Arun	China	
20	GL087095E27829N	II	Hanging lake connected with the retreating glacier; landslide at the side wall	Arun	Nepal	
21	GL087092E27798N Lower Barun	I	Possibility of lake expansion; calving source glacier; chances of landslides and ice avalanches at the wall to the right of the lake; one lake and two small lakes in the upper catchment	Arun	Nepal	2001 and 2011
22	GL086977E27711N	I	Lake expanding towards the glacier; short dam length and steep, calving source glacier; high chances of ice toppling and avalanches	Dudh	Nepal	
23	GL086958E27755N Chamlang	II	Hanging glaciers; high chance of ice avalanches; lake formation near the end moraine; ice underneath the dam; small ponds on the dam, but the dam is more than 500 m long, extending up to the main river valley	Dudh	Nepal	2011
24	GL086957E27783N Hongu 2	I	Hanging glacier; chances of avalanches; short dam length; steep slope with many erosional features	Dudh	Nepal	2011
25	GL086935E27838N Hongu1	I	Lake expanding towards the retreating glacier snout; hanging lakes on both sides of the valley; lake outlet close to the dam end; many cascading lakes in the lower old moraine. PDGL GL086928E27850N is in the hanging valley	Dudh	Nepal	2011
26	GL086928E27850N	I	Lake outlet near the dam end; dam's outer slope is steep; cascading lake upstream; chances of landslide and ice avalanches upstream; may also affect lake number GL086935E27838N	Dudh	Nepal	
27	GL086917E27832N	I	Close to source glacier; short dam length and steep side slope with erosional features; ice underneath the dam	Dudh	Nepal	
28	GL086858E27687N	I	Few metres of freeboard; steep slope of outer dam; hanging source glacier; chances of landslides and ice avalanches from the headwater and from valley to the true right	Dudh	Nepal	
29	GL086925E27898N Imja Tsho	I	Lake water lowered by 4 m in 2016; lake expansion reduced; ice underneath end moraine; merging of supraglacial pond	Dudh	Nepal	2001 and 2011
30	GL086612E27779N Lumding	I	Lake expanding rapidly, in contact with calving glacier; three hanging lakes in the side valley; continuous dam slope	Dudh	Nepal	2011
31	GL086476E27861N Tsho Rolpa	I	Lake water lowered in 2000; expanding rapidly with the retreat of calving source glacier; steep moraine; side moraine is thin and in danger; hanging lake in tributary glacier	Tama	Nepal	2001 and 2011
32	GL086447E27946N	I	Lake expanding with possibility of merging with supraglacial ponds; evidence of small supralake outburst at end moraine; dead ice at the end moraine; fed by three glaciers; calving at source glacier	Tama	China	
33	GL086500E28033N	II	Lake expanding; calving source glacier; additional small lake at end moraine; steep slope at end moraine; large hanging glacial lake in the side valley	Tama	China	

S. No.	Lake ID/Name	Rank	Description	River basin	Country	PDGL identified in (year)
34	GL086520E28073N	I	Lake extension is close to end moraine; hanging source glacier; erosional features at left valley wall	Tama	China	
35	GL086530E28135N	II	Pond and ice in end moraine; confined outlet with gentle slope; hanging lake in the tributary valley; steep and calving source glacier	Tama	China	
36	GL086532E28185N	I	Lake snout at the end of the dam; possibility of expansion; calving source glacier and crevasses near the lake	Tama	China	
37	GL086371E28238N	I	Lake expanding in contact with long cascading glacier; no freeboard; short inward dam length; supraglacial lake in the side valley	Tama	China	
38	GL086314E28194N	I	Lake extension is close to end moraine; hanging source glacier with steep slope; hanging lake at the side valley	Tama	China	
39	GL086157E28303N	I	Lake extension up to end moraine; crevasse on the hanging source glacier; possibility of ice avalanches	Sun	China	
40	GL086225E28346N	II	Lake expanding on calving source glacier; short dam length but clear outlet in the lake	Sun	China	
41	GL085870E28360N Ganxico	II	Large expanding lake; small outlet; gentle dam; possibility of ice in end moraine; possibility of landslides and ice avalanches from side slope	Sun	China	
42	GL085838E28322N Lumichimi	II	Fast-growing lake; steep source glacier; short end moraine; narrow lake outlet	Sun	China	
43	GL085630E28162N	I	Lake at extreme end of dam; chances of landslides from the wall to the right, and of ice avalanches from the hanging source glacier	Trishuli	Nepal	
44	GL085494E28508N	II	Lake expanding towards the debris-covered glacier; hanging moraine; steep outer dam slope; chances of snow and ice avalanches; length of moraine is about 100 m	Trishuli	China	
45	GL084485E28488N Thulagi	I	Large lake, expanding on the debris-covered source glacier; possibility of landslides and snow avalanches from the side walls; evidence of subsidence of old and compact end moraine	Marsyangdi	Nepal	2001 and 2011
46	GL082673E29802N	II	Shallow lake but close to the crest; overhanging boulder protecting erosion of the dam; hanging source glacier with many crevasses	Mugu	Nepal	
47	GL080387E30445N	I	Lake close to top dam end; chances of lake expanding due to debris-covered source glacier; steep outer dam slope; chances of landslide upstream	Kali	India	

important to remember this limitation. Also, many of the GLOFs that have occurred have effectively altered the retaining end moraines to the extent that the likelihood of subsequent outbursts in the same locality is minimal. Another consideration is that potential outbursts tentatively identified in areas remote from human habitation and activity ought not to be prioritized. Finally, reliable determination of the degree of a glacial lake's instability, in most cases, require detailed glaciological and geotechnical field investigation (Ives et al. 2010).

The key physical parameters applied in the ranking of danger levels were: the distance between the lake outlet and the dam crest; the lake's enlargement over time; changes in the boundary conditions of the associated glaciers (frontal retreat); and the distance between the lake and the glacier, that is, whether the two are in contact, close, or less than 500 m apart. Lakes farther than 500 m from their associated glaciers were not considered potentially dangerous. The factors determining the stability of the dam included their height, width, and steepness. The risks from surroundings of the lake area included factors such as possible rockslides or debris slides, hanging glaciers, and potential avalanche paths. The danger levels of the PDGLs are categorized into three ranks, with Rank I being the highest:

Rank I – Large lake and possibility of expansion due to the calving of glaciers; lake close to the loose moraine end; no overflow through the moraine; steep outlet slope; hanging source glacier; chances of snow and/or ice avalanches and landslides in the surroundings impacting the lake and dam.

Rank II – Confined lake outlet; lake outlet close to compact and old end-moraine; hanging lake; distinct seepage at the bottom of end-moraine dam; gentle outward slope of moraine.

Rank III –Confined lake outlet; gentle outward slope of the dam; large lake but shallow depth; moraine more than 200 m wide; old and compact moraine.

Based on this, of the 47 lakes reviewed, 31 lakes were classified as belonging to Rank I, 12 lakes as Rank II, and four lakes as Rank III (Table 5.6). As mentioned, the water levels of four lakes (belonging to Rank I) had earlier been lowered, by more than 3m in Tsho Rolpa and 3.4 m in Imja Tsho, both in Nepal, and of two lakes, GL088066E27933N and GL088075E27946N, in the TAR, China.

The construction of an artificial open channel helped lower the water level in Imja Lake by 3.4 metres.

SECTION 6

Conclusions

Altogether, 3,624 glacial lakes equal to or larger than 0.003 km^2 were mapped from the Koshi, Gandaki, and Karnali river basins of Nepal, the Tibet Autonomous Region (TAR), China, and India, based on Landsat OLI images of 2015, and using remote sensing and geographic information systems. Of these, 1,410 lakes are equal to or larger than 0.02 km^2, which are considered large enough to cause serious damage downstream if they burst. The potential for damage would be heightened if they are associated with a large and retreating source glacier.

A total of 1,358 lakes that are either erosional or of a valley type, without a crest on their damming material, or which flow directly through their moraine with a low gradient, were removed from the analysis. A longitudinal profile, from lake outlet to dam end, of 52 lakes was plotted to understand their dam length, slope of the damming material, and dam crest. Based on the above criteria, a total of 47 lakes in the study area were identified as potentially dangerous glacial lakes (PDGLs).

Of the 47 PDGLs, 42 lakes are in the Koshi basin, three are in the Gandaki basin, and two are in the Karnali basin. Twenty-five PDGLs are in the territory of the TAR, China and 21 lakes in Nepal; one PDGL is in India. Altogether, 21 PDGLs were identified in Nepal in 2011, and from this study as well, but the present PDGL list contains 13 lakes from the old list, and eight newly identified ones.

These 47 PDGLs were ranked based on physical parameters and hazard levels – 31 belong to Rank I, 12 lakes to Rank II, and four lakes to Rank III. Water levels had earlier been lowered in four lakes to reduce the risk of GLOFs — Tsho Rolpa and Imja Tsho in Nepal, and GL088066E27933N and GL088075E27946N in the TAR, China.

The findings of the number of glacial lakes, the identification of potentially dangerous glacial lakes, and the ranking of the PDGLs will be useful in designing GLOF risk management and reduction strategies in Nepal. Further detailed investigation regarding socioeconomic parameters – such as settlements, bridges, roads, hydropower projects and distance from them, agricultural land, and other infrastructure along river valleys downstream – linked to GLOF simulation output will help to identify the potential risk levels and prioritization of these PDGLs for GLOF risk reduction. Validation of remote sensing data with field observations is necessary to implement any kind of formal risk reduction decision. It is hoped that the findings of this study will serve as a resource guide and provide material to assess GLOF hazards in Nepal, socioeconomic vulnerabilities, and GLOF impacts downstream.

An automatic weather station at the Yala Glacier base camp (5,058 masl).

Tsho Rolpa glacial lake as seen from the Tarkading Glacier terminus.

SECTION 6

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About ICIMOD

The International Centre for Integrated Mountain Development (ICIMOD), is a regional knowledge development and learning centre serving the eight regional member countries of the Hindu Kush 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.

About UNDP

The United Nations Development Programme (UNDP) works in about 170 countries and territories, helping to achieve the eradication of poverty, and the reduction of inequalities and exclusion. We help countries to develop policies, leadership skills, partnering abilities, institutional capabilities and build resilience in order to sustain development results.

In Nepal, UNDP works together with the people and the Government Nepal, international development partners and the private sector in helping the country achieve the Sustainable Development Goals (SDGs), particularly focusing on three key areas: inclusive economic growth, democratic governance, rule of law and human rights and resilience, disaster risk reduction and climate change. UNDP works in coordination with other UN agencies in Nepal, and its activities are guided by its Country Programme Document (2018-2022) agreed with the Government of Nepal under the broader United Nations Development Assistance Framework (UNDAF) 2018–2022.

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