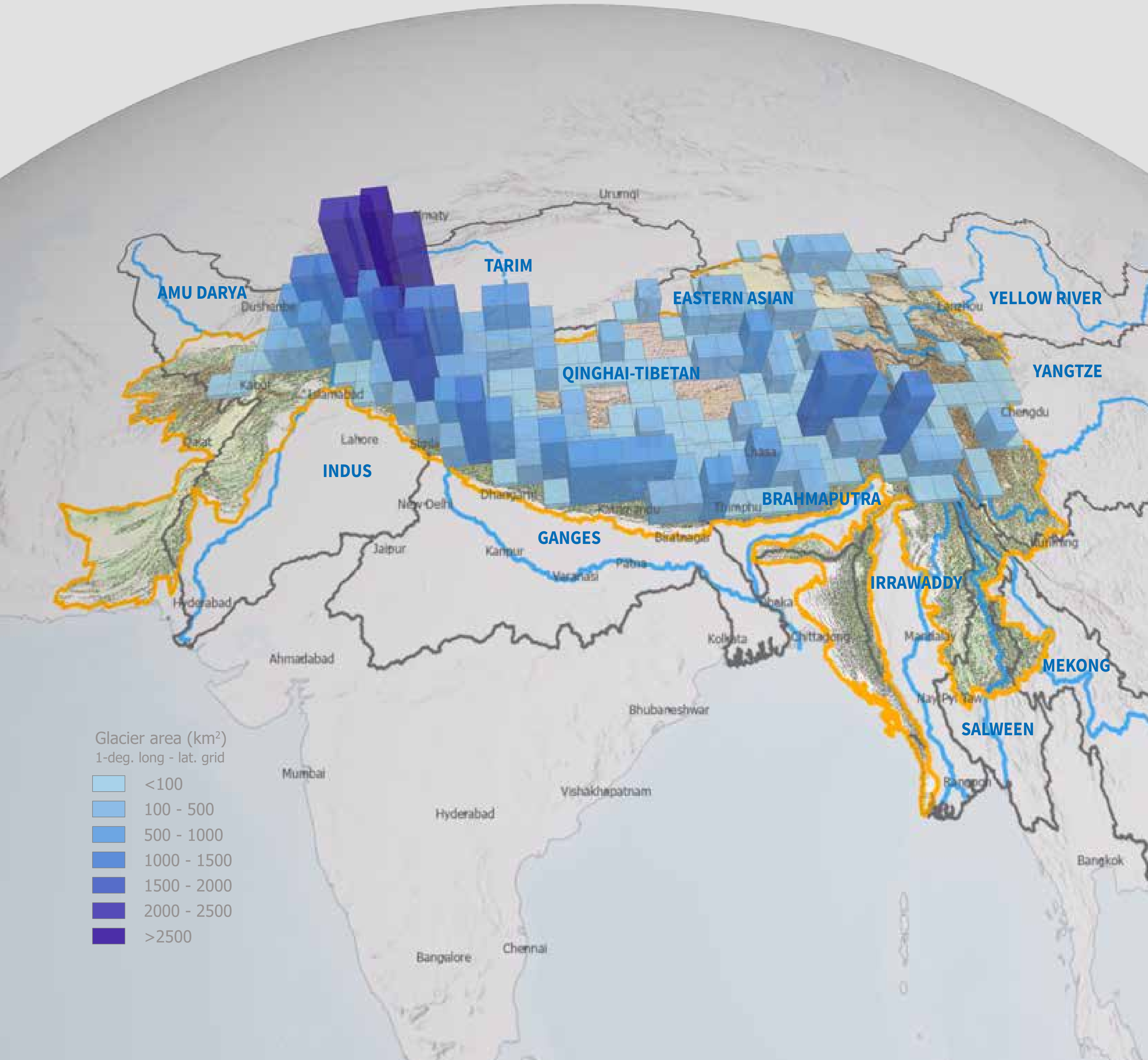
ICIMOD

RESEARCH REPORT

Changing dynamics of glaciers in the Hindu Kush Himalayan region

from 1990 to 2020



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Decadal glacier changes dataset
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RESEARCH REPORT

Changing dynamics of glaciers in the Hindu Kush Himalayan region from 1990 to 2020

Authors

Sudan Bikash Maharjan and Tenzing Chogyal Sherpa

International Centre for Integrated Mountain Development (ICIMOD)
2026

DUDH KHOLA ORIGINATED FROM PONKAR GLACIER IN THE GANDAKI BASIN, NEPAL

Foreword

This decadal glacier inventory of the Hindu Kush Himalaya (HKH), from 1990 to 2020, provides a comprehensive and scientifically robust assessment of the glacier dynamics across the region over the years of accelerating global warming. Higher-quality time-series glacier datasets illustrate the regionally differentiated pattern of glacier shrinkage in response to climate, topography, and local environmental conditions across the region.

This document is not merely a catalogue of ice. It is a record of changes measured and analysed to show where we stand today in terms of our glacier-fed water reserves, and how rapidly they are being lost. At a time when evidence-based decisions on water security, disaster risk, and climate adaptation are the urgent need of the hour, this inventory offers the much-needed evidence that demands policy attention.

For decades, ICIMOD and its regional partners have monitored and mapped glaciers and made these findings publicly accessible, often on an annual basis. This comprehensive decadal documentation of changes in HKH glaciers, however, goes beyond observation. It underscores the growing urgency of both mitigating and adapting to the impacts of glacier change.

The findings show that between 1990 and 2020, glaciers across the HKH experienced a 12% reduction in total area and a 9% decline in estimated ice reserves. The rate of loss accelerated markedly after 2010, particularly in the eastern and central HKH, where smaller glaciers have been most affected. The most substantial losses occurred in these eastern and central parts of the region.

The Ganges and Brahmaputra River basins, home to the largest glacier areas after the Indus River basin, experienced the greatest total area loss over the past three decades, with reductions of approximately 21% and 16%, respectively. Percentage losses are even more severe in the eastern basins, including the Yellow, Yangtze, and Salween River basins, which lost approximately 22%, 23%, and 33% of their glacier area over past three decades, respectively.

Large glaciers play a critical role as natural water storage. Glaciers exceeding 10 square kilometres (km^2) account for nearly 40% of the region's total glacier area and estimated ice reserves and play a disproportionate role in sustaining dry-season river flows. These glaciers are now under increasing stress from rising temperatures, with implications that extend far beyond the high mountains.

Glaciers may sit high in the Himalaya, but their influence runs deep into our rivers, our cities, and our economies. The changes documented here translate directly into growing uncertainty for water availability, increasing exposure to hazards such as glacial lake outburst floods (GLOFs), avalanches, landslides, and debris flows, and mounting risks for downstream communities and infrastructure, thereby reinforcing the inextricably linked future of food, water, energy and livelihood security in the overall region with the future of the glaciers in the high mountains.

Therefore, this inventory equips decisionmakers with the evidence needed to move from awareness to action, and to act before the remaining margin for choice narrows further. The dataset supports advanced modelling of water availability, basin-scale climate adaptation planning, disaster risk reduction, and transboundary water cooperation. It also offers a valuable resource for training automated monitoring systems using satellite imagery and artificial intelligence, enabling more continuous and responsive tracking of glacier change.

We believe that this report will serve as a timely reference for scientists, practitioners, policymakers, and academics seeking to understand glacier changes in HKH. It will strengthen our understanding of this highly sensitive region in the context of accelerating climate change, highlighting the need for continued monitoring, collaborative research, and informed decision-making.

We thank all the authors and contributors for their invaluable input and generous support in producing this timely and insightful long-term analysis of glaciers in the HKH.

Pema Gyamtsho, PhD
Director General, ICIMOD

KHUMBU GLACIER IN EVEREST REGION

Acknowledgement

The report builds upon previous glacier inventories of the Hindu Kush Himalaya (HKH) region published by the International Centre for Integrated Mountain Development (ICIMOD). It includes updated datasets, and addresses gaps in earlier published data. The report is the result of collaboration among several professionals from various organisations, particularly in preparation of the dataset.

The authors acknowledge the contributions of Finu Shrestha, Remote sensing and Geo-information Analyst at ICIMOD; Abhijit Vaidya, Reeju Shrestha, and Yathartha Dhungel, former Research Associates at ICIMOD; and Samjwal Ratna Bajracharya, former Remote Sensing Specialist at ICIMOD, for their essential support during the initial phase of the work.

We also extend our thanks to Esmat Joya, Mohammad Murtaza Rahimi, Mahboobullah Bariz, Abdul Ghayoor Shokory, and Khanagha Muzafari, former associates at the General Directorate of Water Resources (GDWR), National Water Affairs Regulation Authority (NWARA), Afghanistan, for their invaluable help in preparing the glacier datasets for Afghanistan.

Our special thanks also goes Kabi Raj Paudyal and Ramita Bajracharya from the Central Department of Geology, Mamata Sayami and Subash Acharya from the Department of Geology at Tri-Chandra Multiple College, and Anita Tuitui and Earina Sthapit from the Central Department of Hydrology and Meteorology – all at the Tribhuvan University- for their contributions in mapping glaciers in the Kailash area and the Ganges and Brahmaputra River basins.

This study has been conducted by the Cryosphere Intervention team within the Strategic Group on Climate and Environmental Risks at ICIMOD. We extend our sincere thanks to both the former and current intervention managers, Miriam Jackson and Mohd Farooq Azam, respectively, to Neera Shrestha Pradhan, Lead of the Action Area on Cryosphere and Water, and Qianggong Zhang, Head of the Strategic Group on Climate and Environmental Risks, for their continuous guidance, support and encouragement.

Additionally, we are profoundly indebted to Arun Bhakta Shrestha, Senior Advisor and former Head of the Strategic Group on Climate and Environmental Risks, for guiding us throughout the entire process of the documentation. His remarkable guidance and suggestions have been crucial for the successful achievement of this work.

We are also grateful to our colleagues in the Action Area on Cryosphere and Water at ICIMOD for their direct and indirect support that was essential to the success of this work.

For this research, we relied heavily on the Landsat imagery and the Shuttle Radar Topography Mission (SRTM) digital elevation model data. We are deeply thankful to the data providers, namely the Jet Propulsion Laboratory (JPL) of the National Aeronautics and Space Administration (NASA), the United States Geological Survey (USGS), and the Consultative Group for International Agricultural Research (CGIAR).

Lastly, we would also like to express our heartfelt thanks to the external reviewers for their valuable comments and feedback.

Executive summary

This report provides a comprehensive analysis of glacier dynamics in the Hindu Kush Himalaya (HKH) region, spanning three decades, from 1990 to 2020. It introduces the first-ever comprehensive database on the status and decadal changes in glaciers across the region. It serves as a valuable resource for understanding cryospheric changes, provides a robust foundation for glacio-hydrological and climate modelling and supports data driven decision making for regional water resource planning.

The database was created using a systematic semi-automatic method integrating object-based image classification with rigorous manual validation and correction. This approach ensures high accuracy and reliability, as it resolves uncertainties caused by terrain shadowing and low contrast between glaciers and their surrounding terrain. Alongside that, extensive cross-checking with global and regional glacier inventories has also significantly enhanced the reliability of the database.

Based on the Landsat imagery of 2020, the study has mapped 63,761 glaciers across the HKH region, covering an area of 55,782.02 square kilometres (km^2) and containing approximately 5,735.79 cubic kilometres (km^3) of estimated ice reserves. Spatially, the glaciers (both in numbers and area) are largely concentrated in the southern and western parts of HKH. The Indus River basin, located in the western part, has 41% of the total number of glaciers and 44% of total glacierised area in the HKH, followed by the the Brahmaputra (with 20% of glaciers and 17% of glacierised area) and the Ganges River basin (holding 13% of glaciers and 13% of the glacierised area in the region) in the southern part of the HKH.

In terms of mountain ranges, the Karakoram range, covering nearly 18% of the total area of the HKH region, is situated in the western part of the region and stands out as the most heavily glaciated range of the region housing 14.2% of all glaciers and 26.3% of total glacier area. It has 18 of the 25 largest glaciers in the HKH, each spanning at least 100 km^2, with nine of these exceeding 200 km^2 in area. The Himalaya range in the southern part of the HKH region, on the other hand, contains 38% of the glaciers covering 35% of the total glacierised area in the region.

The database also provides valuable insights into the spatial patterns related to the glacier characteristics, particularly in terms of size, type and topography. The analysis shows an inverse relationship between the number of glaciers and their area distribution across different glacier size classes. The smaller sized glaciers of ≤0.5 km^2 dominate in glacier number (74%) but encompass only around 13% of the total glacier area and 3% of estimated ice reserves. In contrast, the glaciers of ≥10 km^2 contribute to only 1% of the total glacier numbers but occupy substantial glacier area (39%) and estimated ice reserves (40%) in the HKH, emphasising the role of these large glaciers in sustaining regional water resources.

Glacier distribution and retreat patterns are further influenced by terrain characteristics, such as elevation, slope, and aspect. Overall, in the HKH, glaciers are highly concentrated between 4,500 – 6,000 metres above the sea level (masl), accounting for over 78% of the total glacierised area. However, this elevation range varies significantly across basins and mountain sub-regions. In the western basins, such as the Amu Darya and the Indus River basins, the highest concentration of glacierised area lies between 5,000 and 5,500 masl, accounting for 46% and 31% of the respective glacierised area within the basins. Moving eastward, this concentration shifts upward to 5,500 – 6,000 masl in the central - Ganges Basin (35%) and the Qinghai-Tibetan Interior basin (64%). It then drops back to 5,000 – 5,500 masl in the eastern basins - Brahmaputra (35%), Salween (55%), and Mekong (75%) River basins. The lowest mapped glacier snout is from the Indus River basin (or Karakoram Mountain range) at an elevation below 2,400 masl, while highest glacier crown elevation is in the Ganges River basin (or central Himalaya) at above 8,800 masl on the northern slope of the Mount Everest.

The analysis of mean slope and aspect indicates a distinct control of slope and aspect on the distribution of glaciers in the region. Around 69% of the total number of glaciers and 86% of the total glacier area, exhibit mean slopes between 10 and 30 degrees (°), which is the most favourable for snow accumulation and glacier formulation. Thus, most of the larger valley and basin type glaciers, including debris covered glaciers, fall within this slope range. In contrast, smaller and less numerous glaciers, such as cirque, niche, and apron types glaciers, are generally located on the steeper slopes exceeding 30°, where snow retention and ice stability are more limited.

Aspect wise, 59% of the glaciers, covering 53% of the total glacier area, with 44% of the estimated ice reserves, predominantly oriented towards the northern (N), northeastern (NE), and northwestern (NW) aspects. These aspects receive comparatively less solar radiation, which provide more favourable conditions for snow accumulation and ice formation. Although glaciers on the eastern, southeastern, and southern aspects are relatively less in number, they tend to be larger in size (with an average area generally exceeding 1 km^2 across all three aspects), most likely due to specific local topographic or climatic conditions supporting their formation and preservations. This spatial pattern is consistent across most major river basins and sub-mountain ranges within the region.

The multidecadal database also provides valuable insights into the spatial-temporal patterns and trends in glacier change, as well as the influence of various factors including slope, area sizes, and glacier type,on glacier behaviour.

Decadal changes from 1990 to 2020 show that glaciers across the HKH region have undergone consistent retreat, with a 12% reduction in total glacier area and a 9% decline in estimated ice reserves.

The most pronounced acceleration in glacier shrinkage occurred between 2010 and 2020, especially in the eastern and central parts of the region, where the smaller glaciers have been the most affected. Glaciers smaller than 0.5 km^2 area have shown an increasing trend in number across all basins and sub-mountain ranges, despite continued reductions in their total area. This reflects both the fragmentation of larger glaciers into smaller units and the rapid shrinkage of these smaller glaciers, with some disappearing entirely or reducing below the mapped area threshold. Although larger glaciers have retreated at a comparatively slower rate, they too are experiencing significant area loss in absolute terms due to rising temperatures.

Geographically, the most substantial glacier losses occurred in the southern latitudes (27° N – 30° N) and eastern longitudes (100° E – 104° E), particularly within the Hengduan Shan and Eastern Tibetan Mountains, where glacier areas have decreased by up to 33% and 22%, respectively, over the past three decades (1990 – 2020). In contrast, the Karakoram (with only a 0.9% reduction in glacier area) demonstrated exceptional glacier stability, while the Kunlun Shan (with 0.07% area loss in western Kunlun and 6% in eastern Kunlun) experienced minimal losses. These spatial patterns are also reflected in the major river basins: the Indus River basin lost 6% of its glacier area, while the Ganges and the Brahmaputra River basins experienced reductions of 21% and 16%, respectively. Despite hosting the most extensive glaciers in the region, including some of the region's largest glaciers, these basins also experienced the most significant glacier area losses over all three decades since 1990. The most severe reduction occurred in the Salween River basin, which lost nearly 33% of its glacier area over the study period. Similar trends of glacier area decline were observed in other eastern basins, with the Yangtze River basin losing over 23% and the Yellow River basin over 22% of their respective glacier areas.

Glacier retreat also exhibits distinct spatial patterns influenced by terrain characteristics, especially elevation, mean aspects and slope characteristics. In the last three decades since the 1990, the greatest absolute area losses in the HKH region have been generally concentrated at 5,000 – 5,500 masl, with almost all the major basins and sub-mountain ranges in the region facing it. The substantial area losses, nearly 15% each over the past three decades, have also been observed in adjacent elevation ranges of 4,500 – 5,000 masl and 5,500 – 6,000 masl. Glaciers in these elevation ranges, particularly those below 5,500 masl, have experienced accelerated thinning and retreating due to their proximity to the equilibrium line altitude (ELA), making them highly sensitive to rising temperatures and shifts in precipitation patterns. Lower-elevation glaciers, particularly those below 4,500 masl, have shown higher proportional retreat rates and greater fragmentation, while glaciers above 6,000 masl have exhibited comparatively lower rates of area loss, benefiting from colder conditions, majorly locating in accumulation zone and reduced melt.

The orientation of glaciers across different aspects plays a crucial role in influencing glacier retreat. Glaciers facing northern, northeastern, and northwestern aspects, receive less solar radiation and benefit from cooler microclimates, thereby experiencing relatively lower retreat rates compared to the glaciers oriented towards the southern, southeastern, and eastern, where higher solar insolation accelerates melting. Relatively smaller in number, the glaciers oriented towards the northeastern, eastern and southeastern aspects have exhibited faster and more extensive shrinkage.

Slopes of the glaciers also significantly affect glacier dynamics. Glaciers with gentle to moderate mean slopes (10° – 30°), which account for 86% of the total glacierised area and include many of the larger glaciers, have experienced considerable area loss, but generally retreat at slower rates than glaciers on steeper slopes (>30°). Steeper glaciers generally smaller cirque, aprons, and niche types are more susceptible to rapid ice loss due to reduced snow accumulation efficiency, thinner ice contains and rapid melt.

Observed changes in glacier number and area across different slopes and aspect classes partly reflect the effects of glacier shrinkage and fragmentation. As glaciers diminish and fragment into smaller ones, their shape, orientation, and mean slope often change, leading to reclassification into different slope and aspect classes. Despite these shifts in classification, the overall glacier area across all classes has consistently decreased over time. Overall, the interaction of elevation, aspect, and slope strongly governs the spatial variability of glacier retreat across the HKH region, with elevation below 5,500 masl; southern, southeastern and eastern aspects, and steeper glaciers being the most susceptible to ongoing climatic changes.

These findings underscore the alarming rate of glacier retreat in the HKH region and its far-reaching implications for water resources, ecosystems, and the livelihoods of downstream communities. As glacier retreat accelerates, the region confronts escalating challenges, particularly in ensuring water availability during dry seasons and risks from its associated hazards such as glacial lake outburst floods (GLOFs), avalanches, landslides, and debris flows.

The dataset could also serve as a valuable resource for training automated monitoring systems that utilise satellite imagery and Machine learning/ Deep learning/artificial intelligence (AI). These advancements will allow for continuous and accurate tracking of glacier changes. Furthermore, this comprehensive database is vital for modelling water availability, formulating basin-specific climate adaptation strategies, and fostering transboundary water cooperation, especially in areas where glacier meltwater plays a crucial role in water security.

Lastly, this research not only provides essential insights into the ongoing changes in the HKH glaciers but also offers a scientifically robust foundation for informed decision-making in water resource management, and disaster risk reduction in the region.

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GLACIER AND ICEFALL FORMATIONS ON THE SLOPES OF MOUNT EVEREST AND SURROUNDING SLOPES IN THE CENTRAL HIMALAYA

SECTION I

Introduction

Perched among the world's highest peaks, the glaciers of the Hindu Kush Himalaya (HKH) form part of the largest concentration of snow and ice outside the polar realms, a region that has rightly earned the title "Third Pole" (Qiu, 2008; Yao et al., 2012; Wester et al., 2019). As slowly moving masses of snow and ice, glaciers are essential indicators of climate change, with their retreat and advancement depicting one of the most visual representations of climate change (Haeberli et al., 2017; Hock and Huss., 2021). Spanning over 4.2 million km² area, the HKH region is home to the large number of glaciers that plays a crucial role in an interconnected cryo-geo-ecological system for sustaining life. These glaciers serve as the one of the major sources for Asia's most extensive river basins, which support nearly two billion people, both directly and indirectly (Immerzeel et al., 2010, 2020; Wester et al., 2019; Viviroli et al., 2020). While the direct contribution of glacier melt varies across the basins, it generally increases as we move upstream into the High Mountain areas (Lutz et al. 2014). However, glaciers play a more crucial role in stabilizing and regulating continuous river flow particularly during the drier seasons, and their significance is even greater in arid and semi regions. (Kaser et al. 2010). Owing to this influence and connectivity with essential hydrological and ecological systems, this region is also referred to as the "Water Tower of Asia."

However, climate change now poses a significant threat to these glaciers in the HKH region. Studies indicate that the region has been warming at an average rate of 0.2 °C per decade over the last fifty years (Wester et al., 2019). Alongside that, increasing evidence on elevation-dependent warming in the region, specifically from the Tibetan Plateau, highlights the region's heightened vulnerability to rising temperatures (Mountain Research Initiative EDW Working Group, 2015; Palazzi et al., 2019; Wester et al., 2019). This would mean that, even if the global mean annual surface air temperature is limited to 1.5 °C above the pre-industrial period, the HKH is still projected to warm by 1.80 ± 0.40 °C (Wester et al., 2019). Given that most glaciers in HKH are located at high mountains, this would mean that they are particularly susceptible to these temperature increases. At the same time, snow cover has also been showing a clearly negative trend across the HKH since the early 21st century (Ackroyd et al., 2021; Bormann et al., 2018; Desinayak et al., 2022). The number of snow cover days has also declined across most mountain regions in the HKH at an average rate of five days per decade (ICIMOD, 2023), likely due to the increasing conversion of solid precipitation to liquid as temperatures rise (Hock et al., 2019). This reduction in snowfall, coupled with rising temperatures, has severe implications for the glacier's mass balance, which is the balance between the amount of accumulation and the ablation of snow/ice experienced by the glacier. This sensitivity to climatic conditions is why glaciers are invaluable natural indicators or proxies of climate change (Haeberli & Hoelzle, 1995).

Concurrent to this, studies have shown that the glaciers in HKH have been losing mass 65% higher in the recent decades than in comparison to the previous decades (ICIMOD, 2023). Projections also show that even within optimistic emission scenarios, these glaciers are still on track to lose around 30% - 40% of their mass by the end of this century and in higher emission scenarios, the situation looks much graver, as they could lose 60 - 80% of their mass, with many of these glaciers disappearing completely as well (ICIMOD, 2023). As these glaciers continue to melt, they contribute to the formation and expansion of glacial lakes. This process increases the risk of glacial lake outburst floods, one of the most significant hazards in the HKH.

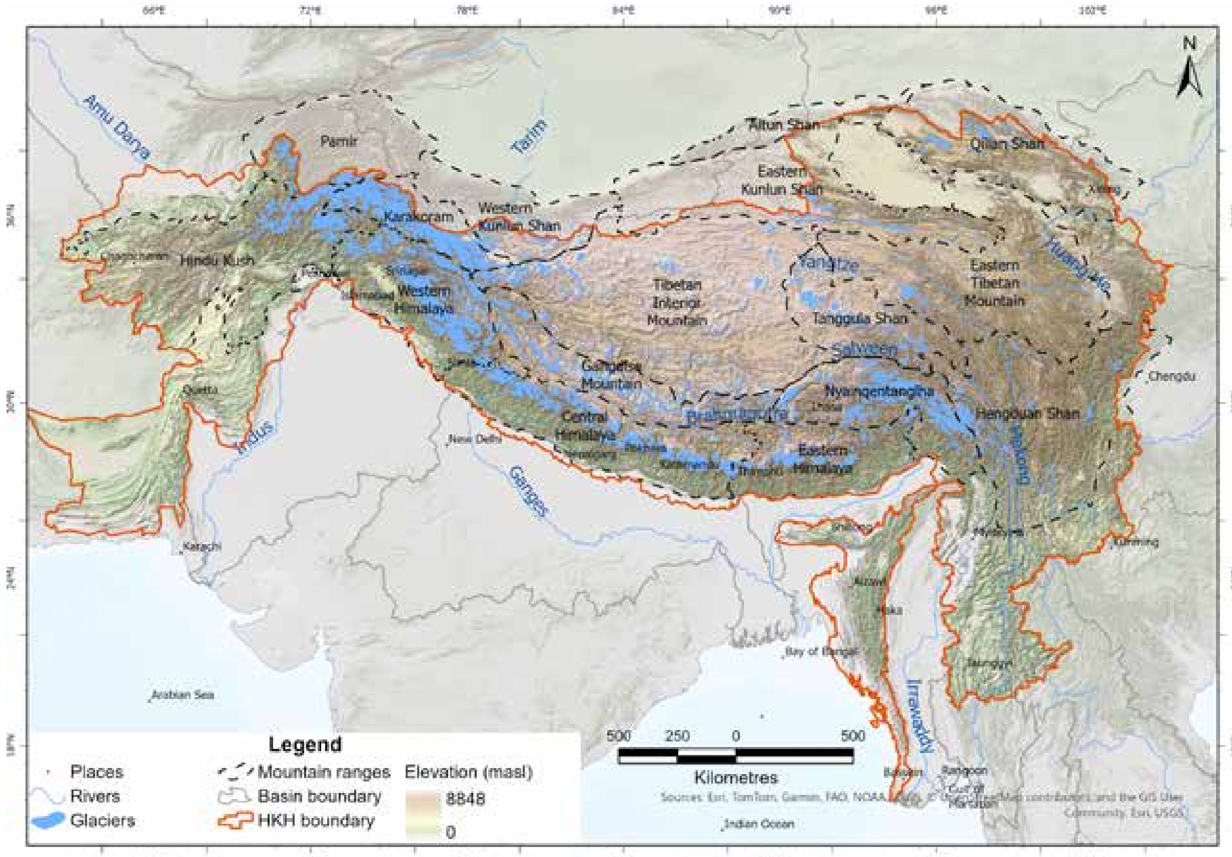
A comprehensive inventory of glacial lakes in the HKH including the lakes formed in the paleo-glacial landforms across five major river basins – Amu Darya, Indus, Ganges, Brahmaputra and Irrawaddy, and based on 2005 Landsat imagery, identified over 25,000 glacial lakes (Maharjan et. al, 2018). More broadly, in High Mountain Asia (HMA), a study using 2018 Landsat imagery and considering glacial lakes within a 10 km distance of current glacier extents identified over 30,000 glacial lakes (Wang et al. 2020). Notably, more than 53% of these glacial lakes are located within the five major basins of the HKH region. These studies indicate that both their number and surface area vary depending on the methods, datasets and timeframes used and continue to increase in response to accelerating glacier melt (Shugar et al., 2020). GLOFs have already caused devastating damage across the region, making them one of the most direct and severe consequences of accelerated glacier melt.

Despite the growing research on these glaciers, significant uncertainties still remain due to a lack of field-based observations. Less than 1% of glaciers in the HKH have long term measurements (Azam et al., 2018; ICIMOD, 2023). However, given the vast number and inaccessibility of glaciers in the region, direct monitoring of each glacier is impractical. To bridge this data gap, remote sensing techniques have played a crucial role in advancing our understanding of the state of glaciers and their mass loss in the region. Most of the existing information on HKH glaciers has been derived from satellite-based remote sensing methods, significantly enhancing our ability to assess glacier changes over time. However, to fully comprehend these changes, there remains a need for more detailed data on spatial variability, glacier boundary changes, surface area fluctuations, retreat rates, and interdecadal trends. This is where glacier inventories become indispensable.

Glacier inventories have evolved into essential datasets for regional glacier mass balance assessments and hydrological modeling (Shean et al., 2020; Haeberli, 2011). The practice of glacier monitoring began as early as 1894, initially focusing on tracking frontal changes. This concept of a standardised global glacier inventory, measuring parameters such as glacier length, area, volume and mass, was first proposed during the international Geophysical Year (IGY) in 1957–58. However, significant development was in progress after the establishment of the World Glacier Inventory (WGI) in the 1970s. Following its assessment by the World Glacier Monitoring Service (WGMS) in 1989, glacier database development became more structured and included historical glacier fluctuation records dating back to the 19th century (Haeberli et al., 1989).

Beyond providing critical baseline information, they also serve as foundational datasets for glacier modelling and geodetic studies, helping to demarcate glacier boundaries and accurate understand their changes (Bajracharya & Shrestha, 2011; Bajracharya et al. 2011a; Paul et al., 2004; Bolch et al., 2010). They are also integral to glacio-hydrological models that quantify meltwater contributions within catchments and basins. In 1995, the Global Land Ice Measurements from Space (GLIMS) initiative started to compile more structured digital glaciers database generated based on remote sensing and geospatial methods and techniques. Since then, various global and regional efforts such as the Randolph Glacier Inventory (RGI), the Glacier Area Mapping for Discharge from the Asian Mountains (GAMDAM), the Chinese Glacier Inventory and from ICIMOD have emerged to generated and consolidate digital glacier datasets. With the growing availability of high-resolution satellite imagery and advancements in remote sensing and geospatial techniques, it has become increasingly feasible to systematically generate such inventories at both regional and global scales (Bajracharya and Shrestha 2011; Bajracharya et al. 2011a; Ye et al., 2017). However, these most existing datasets generally provide only one-time snapshots information on glacier extents, derived across wide time span from 1990s to 2013, using diverse methods and levels of accuracy.

FIGURE 1.1 **MAP OF THE HINDU KUSH HIMALAYA (HKH) REGION SHOWING MOUNTAIN RANGES AND MAJOR RIVER BASINS, INCLUDING THE DISTRIBUTION OF GLACIERS.**

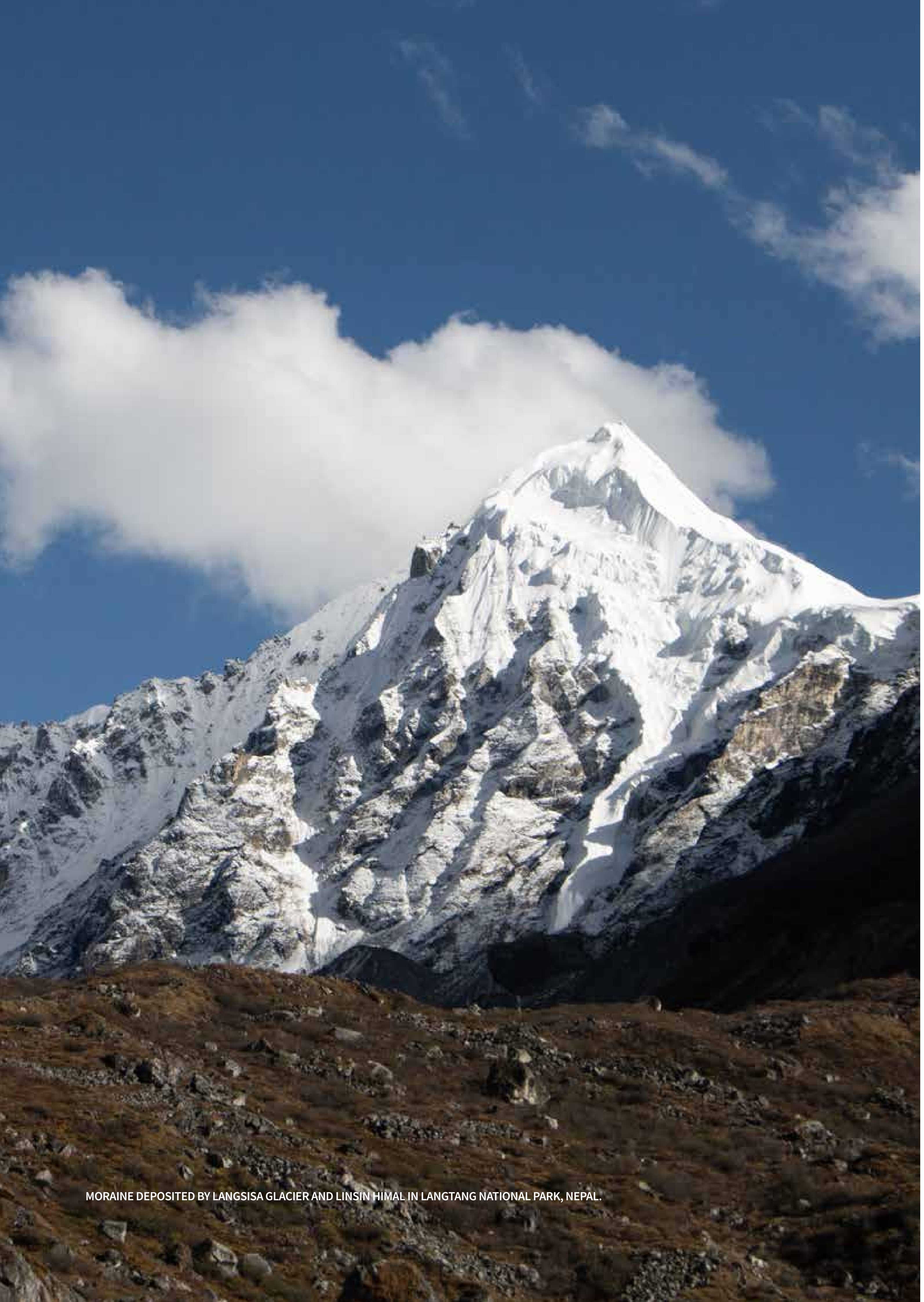


However, due to the dynamic nature of glaciers, continuous monitoring is essential to capture their behaviour and response to changing climatic conditions. Developing glacier inventories at a regional scale and at high temporal resolutions remain a challenging task. Till date various research and initiatives have developed the glacier dataset of the HKH regions and serve as a key reference for cryospheric studies. These datasets are limited to certain specific areas, basins, sub-basins or small catchments of the HKH region. However, further efforts are essential to refine and expand these inventories across multiple time scales, ensuring comprehensive coverage of the entire HKH region.

This required the use of systematic and consistent methodologies and data sources within narrow and well-defined time spans to accurately capture multidecadal changes within individual glacier boundaries. In 2011, ICIMOD had already published glacier inventories of the HKH region with the development of systematic semi-automatic object-based image classification method based on Landsat satellite images of 2005 ± 3 years (Bajracharya & Shrestha, 2011). Following that, ICIMOD then consistently developed and published multidecadal glacier datasets to quantify decadal changes of the glaciers in Nepal, Bhutan, Afghanistan, and some selected basins and transboundary landscapes in the HKH regions, considering narrow time spans (± one years of base year) of Landsat imageries from 1980s to 2020 (Bajracharya et al 2014a, b, c,2015; Maharjan et al 2021a, b, 2024). These assessments revealed loss of glacier area of almost one fourth of its total in 30 years. However, the glacier data generated from the Landsat MSS images (60m resolution) of 1980s, with limited choice in the availability of the images and produced high errors in comparison to other decades. Hence the analysis was restricted to glacier data from the 1990s to date.

Therefore, multiyear glacier inventories emerge as the desired ideal dataset allowing us to quantify changes in glacier parameters such as glacier length and area (Paul et al. 2004; Shangguan et al. 2007; Wu et. al. 2018; Bolch et al. 2010; Bhambri et al. 2011). These changes provide an indirect, time-delayed, and filtered signal representation of climate-related changes (Haeberli and Hoelzle 1995), which can be subsequently correlated with the mass balance of the glacier and ultimately to changing climate. Hence, the present study has been undertaken to develop and refine multidecadal glacier change datasets for the entire HKH region, with the aim of understanding the magnitude and patterns of glacier change across the region. To ensure systematic and consistent data, this effort incorporates already established methodologies and integrates new platforms, such as Google Earth Engine, for cloud-based data processing. This report provides comprehensive insights into the current status of glaciers in the HKH region, including decadal changes since the 1990s across sub-basins, major basins, mountain ranges, and overall changes throughout the region. Figure 1.1 illustrates the extent of the HKH region, highlighting its major basins and the sub-mountain ranges covered in this report. The following chapters detail the methodologies used for mapping and provide an in-depth analysis of glacier status and decadal changes across the entire HKH region since the 1990s.

INSTALLATION OF NEW STAKE AND MEASUREMENT DURING FIELD MONITORING EXPEDITION IN YALA GLACIER (MAY 2025).



MORAINE DEPOSITED BY LANGSISA GLACIER AND LINSIN HIMAL IN LANGTANG NATIONAL PARK, NEPAL.

SECTION I I

Data and methods

In the past, information regarding glacier extents was primarily derived from topographical maps created using aerial photographs and limited ground observations, typically at a scale of 1:50,000. However, with the advancements in satellite imagery, the evolution of Global Positioning System (GPS) technology, and the development of Remote Sensing and Geographic Information System (GIS) based tools and technology, the field of glacier mapping and monitoring has witnessed a significant transformation and growth (Gao and Liu, 2001). This convergence of technological progress marked a pivotal milestone in the history of glacier mapping, allowing data from diverse sources to seamlessly integrate and contribute to the GIS framework.

These approaches range from entirely manual delineation to automated algorithms that leverage multispectral characteristics of snow and ice. For the scope of this study, a semi-automated approach has been adopted, which combines elements of automated algorithms with manual intervention methods to refine the glacier outline. This approach strikes a balance between the efficiency offered by automated processes and the accuracy and validation associated with manual interpretations. Nevertheless, it's important to note that manual delineations can exhibit variation based on the interpreter's perception of a glacier. Therefore, it is crucial to establish a clear understanding of how glaciers are defined.

In this context, our study adheres to the standard definition provided by the Global Land Ice Measurements from Space (GLIMS), in collaboration with the World Glacier Monitoring Service (WGMS). The definition, adapted from UNESCO guidelines and tailored for satellite-based mapping, characterises a glacier as follows: 'A glacier or perennial snow mass, identified by a single GLIMS glacier ID, consists of a body of ice and snow that is observed at the end of the melt season, or, in the case of tropical glaciers, after transient snow melts. This includes, at a minimum, all tributaries and connected feeders that contribute ice to the main glacier, plus all debris-covered parts of it. Excluded is all exposed ground, including nunataks. An ice shelf shall be considered as a separate glacier.' (Raup and Khalsa, 2010)

Adhering to this definition, widely used automated algorithms (Paul 2002; Racoviteanu 2009; Bolch et al., 2008; Bajracharya & Shrestha, 2011; Bajracharya et al., 2014a, b), particularly effective for mapping clean ice, are initially implemented. Subsequently, these results are subject to manual adjustments as needed within the confines of the provided definition. In cases involving debris-covered glaciers, numerous classification methods have been developed; however, most of them still require consistent manual intervention and refinement, especially in the glacier's frontal part. Consequently, most of the debris-covered glaciers in this study have undergone manual intervention especially on snout and shadow area. Although the debris-covered portions have been incorporated within the glacier area, they have not been separated into distinct feature categories.

Following this methodology, glaciers have been systematically mapped for four distinct decades (1990, 2000, 2010, and 2020) within the Hindu Kush Himalaya (HKH) region. The primary data sources for the delineation and inventory of these glaciers comprise Landsat images and digital elevation models, which are freely accessible for download from the United States Geological Survey (USGS) website.

2.1 Satellite images

Satellite imagery forms the fundamental keystone of the mapping approach, with the selection and processing of these images playing a crucial role in shaping the final output. The earliest available satellite image encompassing the HKH region dates to the 1970s, captured by the US Earth Resources Technology Satellite (ERTS), later renamed as Landsat-1. In contemporary times, a constellation of satellites orbits and continuously monitors Earth, offering progressively enhanced spatial, spectral, and temporal resolutions. This satellite network has facilitated the creation of several glacier inventories over time.

One of the initial mapping endeavours was undertaken by the United States Geological Survey (USGS), which employed Landsat Multispectral Scanner (MSS) data for glacier mapping. After this, numerous other inventories and mapping have been undertaken harnessing various satellite resources, including ASTER, SPOT, as well as high-resolution imagery like Sentinel, Planet, and Worldview. When striving for a multidecadal glacier inventory, maintaining consistency of data sources is paramount, and it's here that the Landsat satellite series plays a critical role.

The Landsat satellite series represents the longest-standing enterprise dedicated to acquiring Earth's satellite imagery. Its medium-resolution images have consistently demonstrated their reliability in glacier mapping since the earliest mapping endeavours. Furthermore, the more recent iterations of the Landsat satellite series offer spectral resolution on par with newer satellite imagery, rendering this series an optimal choice for assessing multidecadal glacier change assessment. Consequently, this study utilises the time series data of Landsat imagery to ensure consistency in data sources, with standardised spatial, radiometric and temporal resolutions.

Access to these images is facilitated through USGS Landsat website (http://landsat.usgs.gov/) and USGS GLOVIS portal (http://glovis.usgs.gov/), which contains an archive spanning 40+ years, encompassing nearly comprehensive global coverage data captured by the Landsat series satellites.

One of the key factors influencing the effectiveness and reliability of glacier outlines lies in the careful selection of Landsat images. Optimal images are those with minimal cloud cover and snow cover, and every effort is made to select such images whenever feasible. Cloud cover and snow cover are notably significant sources of error during automated processing. Therefore, excluding these elements in the initial stages greatly enhances efficiency and expedites the process. If the preferred image is unavailable, images from up to one or two years before and after the target year are also considered.

In this study, more than 139 tiles of Landsat cover all the glaciers in the HKH region and in total more than 6,000 Landsat imageries of 1990, 2000, 2010, and 2020 have been employed for mapping glaciers across the entire region. Efforts were made to select images with minimal snow cover and as little cloud interference as possible to ensure rapid and accurate glacier delineation.

2.2 Digital Elevation Models (DEM)

There are several DEMs available worldwide with high spatial resolution and coverage. For this study, we utilised the Void-filled Global Digital Elevation Model (GDEM) from NASA's Shuttle Radar Topography Mission (SRTM), based on its widespread use in glacier research and proven vertical accuracy (Frey and Paul, 2012; Bolch et al., 2005; Khasanov, 2020; Santillan and Santillan, 2016). The SRTM DEM, with a spatial resolution of 90 metres, was used to derive topographic parameters such as elevation, hypsometric information, and flow direction. Alongside glacier parameters, they are particularly useful in delineating ice divides and for ortho-rectifying satellite imagery. Besides that, when combined with multidecadal glacier outlines, they are useful in determining surface elevation changes in the glacier (e.g. Surazakov and Aizen, 2006; Larsen et al., 2007; Racoviteanu et al., 2007; Schiefer et al., 2007; Paul and Haeberli, 2008), which provide the representative changes or shifting of glacier snout over time. Other derivative components from the DEM are the slope and aspect, which are also very important parameters in identifying glaciers and generating glacier attributes.

2.3 Glacier mapping

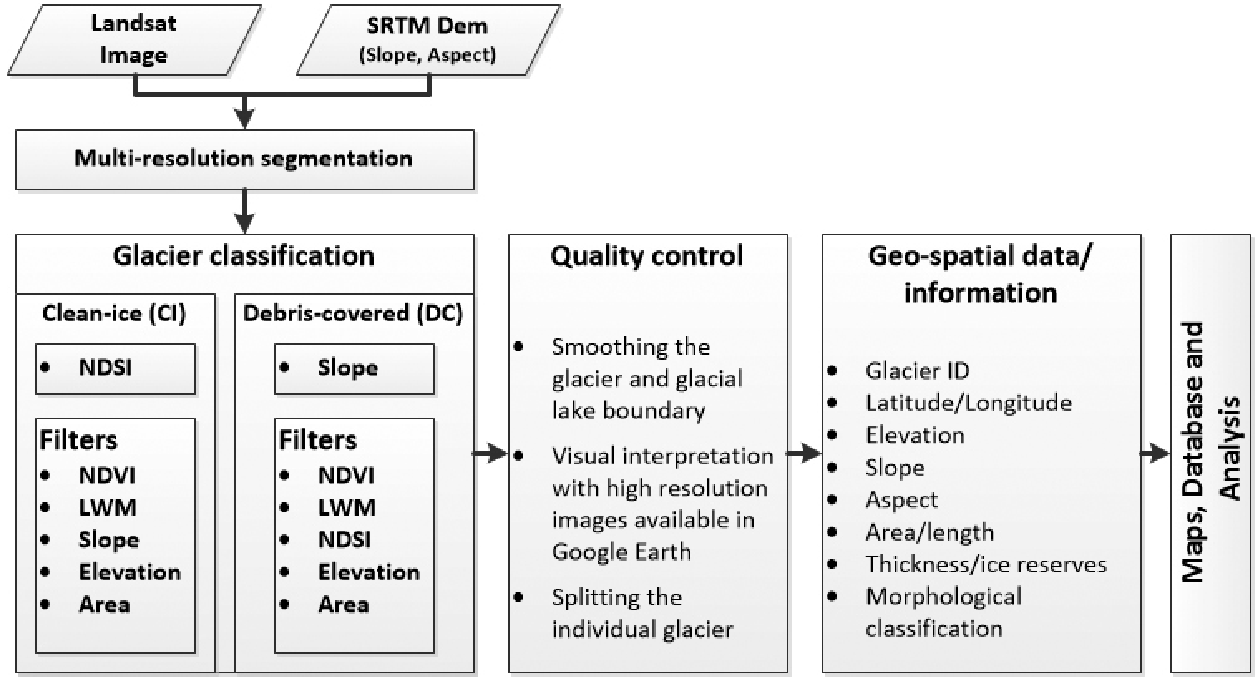
The present study adopted a semi-automatic object-based image classification method like the previous ICIMOD inventories (Bajracharya & Shrestha, 2011; Bajracharya et al., 2011a, 2014a, 2018; Maharjan et al. 2021a,b, 2024), This technique, involving automated multispectral classification of optical satellites imagery coupled with digital elevation model (DEM), is a widely accepted procedure (Frey et al, 2012; Frey and Paul, 2012; Bhambri and Bolch, 2009; Bolch et al., 2010a,b; Paul and Kaab, 2005; Paul and Andreassen, 2009; Racoviteanu et al., 2009). Firstly, the Landsat image tile is segmented using multi-resolution segmentation to create and image objects based upon homogeneous characteristics of spectral values, shape, relation to neighbouring objects and texture. The image objects represent clusters of pixels exhibiting similar features and qualities. The scale factor is determined to precisely align the boundaries of image objects with those of glacier boundaries depicted in the images. These image objects are then classified using rulesets/algorithms that comprise a various number of standard indices, developed from distinctive spectral signatures and disparities. The ruleset relies on the mean values of the defined objects rather than pixel values. The overall comprehensive classification process with distinct rulesets for Clean-ice (CI) and debris-covered (DC) glacier is exhibited in Figure 2.1 and Figure 2.2.

A pivotal part in the methodology involves formulating the rulesets or algorithms for classification of CI and DC glaciers. Initially, clean-ice glaciers were classified utilising widely used spectral indices - Normalized Difference Snow Index (NDSI). Although, this index is renowned for its capacity to differentiate snow and ice from other features due to their distinct reflectivity and absorption characteristics in visible and SWIR wavelengths (Dozier, 1989; Rees, 2006). It requires calibration to separate seasonal snow from glaciers or perennial snow masses which is done by employing appropriate threshold values determined through iterative refinement processes based on the specific scene and region. Additional indices such as normalised difference vegetative index for vegetation masking, land and water mask for masking water bodies, mean hue for shadow removal, contribute to improvement in classification. Additionally, a slope threshold above 60, elevation and area threshold criteria are subsequently applied for further refinement.

The classification of DC glaciers is rather complex due to the spectral resemblance with adjacent moraines and landforms. DC glacier classification is applied on the remaining objects after the CI glacier classification. This process employs mean slope or Normalized Difference Vegetation Index (NDVI), selected through subjective evaluation for each satellite image. The classification process also encompasses other features like vegetation, bedrock, and shadows which are subsequently filtered out using various criteria such as LWM, Slope (>25), and elevation (above 6,000 and below 3,000 masl depending upon the locality). Despite these filters, the generated outlines may not fully capture DC glaciers, hence manual intervention (checking and refining) is necessary with cross-checking on available high-resolution imageries from Google Earth. The manual refinement considers the presence of exposed ice cliffs and stream outlets to accurately delineate the terminus of the DC glaciers.

Upon generation of both CI and DC glacier outlines, they are integrated into a single polygon layer and some manual intervention was done in shadow, seasonal snow cover area, turbid/frozen proglacial lakes and especially the boundary of DC glaciers and its terminus by overlaying on corresponding Landsat images and cross-checking on high-resolution images in Google Earth. The final glacier polygon was generated by smoothing automatically to remove the zigzag boundary formed due to pixel size of the images and subsequently separating to individual glaciers based on hydrological catchments integrated with DEM and overlying satellite images (Bajracharya and Shrestha, 2011; Maharjan et al., 2018; Bajracharya et al., 2017).

FIGURE 2.1 **FLOW CHART OF THE METHODOLOGY TO MAP GLACIERS (BASE LAYER).**
(MODIFIED BAJRACHARYA AND SHRESTHA, 2011 AND BAJRACHARYA ET AL, 2014A, B)

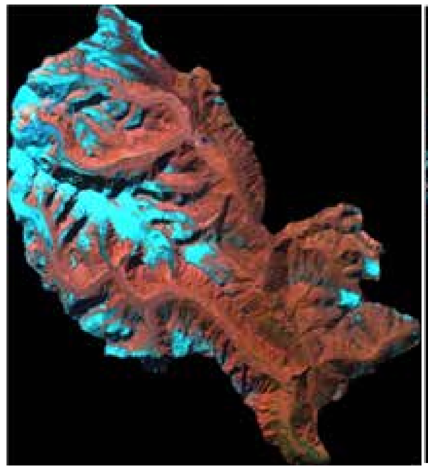


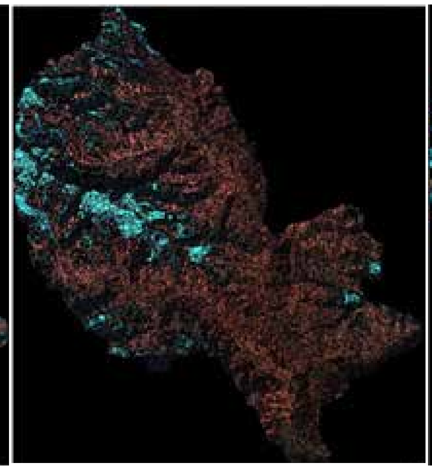
This process has been executed to generate the base glacier layer. Here we utilised the previously prepared glacier boundaries employing the same method (Bajracharya and Shrestha, 2011, Bajracharya et al, 2014a,b; Maharjan et al, 2021a,b, 2024) as a base layer. In case where the previous dataset did not encompass, we employed this procedure to prepare the base layers. For other time periods, the glacier datasets were manually prepared by superimposing the final base layer glacier boundaries into corresponding images of different time frames (eg., 1990, 2000 and so forth). This manual process was implemented to minimise processing time and discrepancies in the overlapping boundaries within the comprehensive dataset across all-time series.

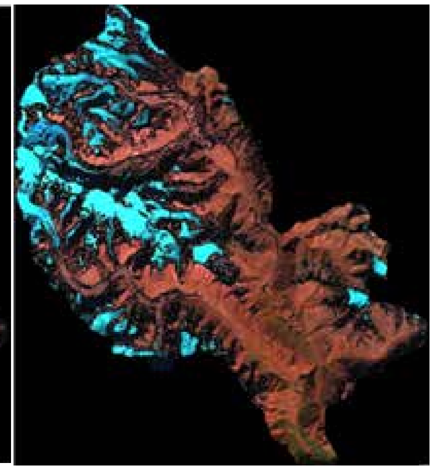
Additionally, we leverage recent technological advancements to access and process satellite images. The code and tool have been developed on the Google Earth Engine platform to handle large volumes of Landsat images, particularly for selecting high-quality ones. We have also created a mapping tool within Earth Engine, which has been applied to regions with excellent image quality, such as in the Tibetan region. However, selecting high-quality images is challenging, especially in the eastern Himalayas, where we used a compilation of series of Landsat images for the year, applying a cloud and medium filter and downloading the composite for manual mapping.

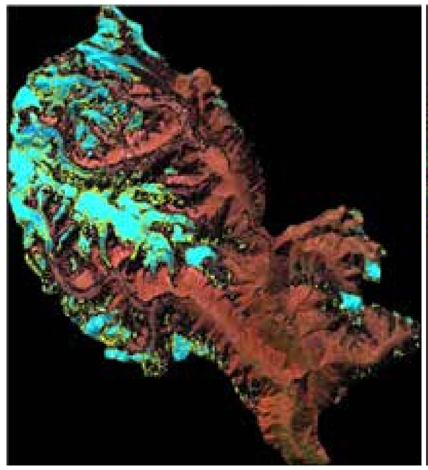
Further the final glacier outlines have been prepared by calculating the glacier ID (GLIMS ID) and other attributes like elevation (minimum, mean and maximum elevation bounded by the glacier boundary in the DEM) , slope (mean slope bounded by glacier boundary of the slope raster generated from the DEM), aspect (mean aspect derived as the average of cosine and sine values bounded by the glacier boundary), and hypsometry were derived by summarising DEM values for each glacier. Ice reserves were estimated using an empirical relation between glacier area and average ice thickness. The entire process of data management and post classification was conducted in GIS environments (ArcGIS). A comprehensive detail method on delineation of glaciers and generating attributes are accessible in previous ICIMOD's published reports (Bajracharya & Shrestha, 2011; Bajracharya et al, 2017; Maharjan et al., 2017).

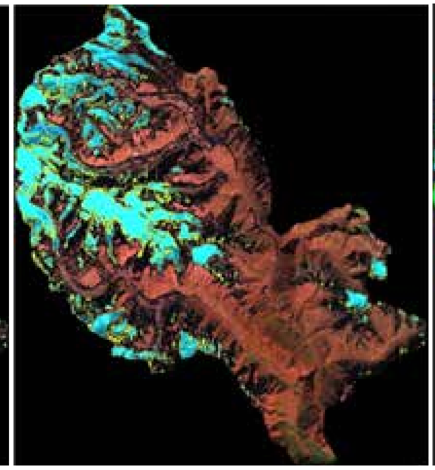
FIGURE 2.2 **EXAMPLES OF STEP-BY-STEP PROCESS OF PREPARING BASE GLACIER DATASETS.**
(MODIFIED BAJRACHARYA & SHRESTHA, 2011)

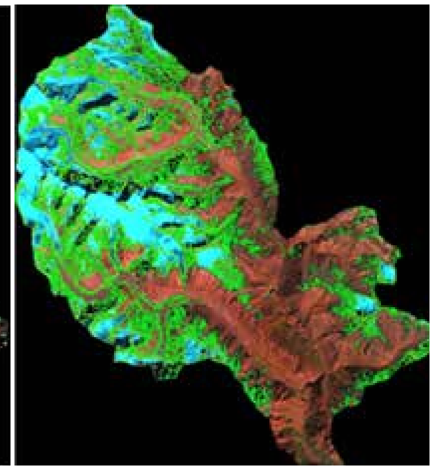

Importing Landsat images with nominal snow cover and no cloud cover.

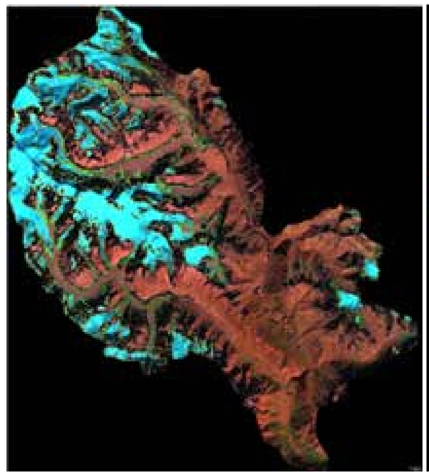

Generating image objects (black polygon) based on homogeneity of spectral values and shape properties.

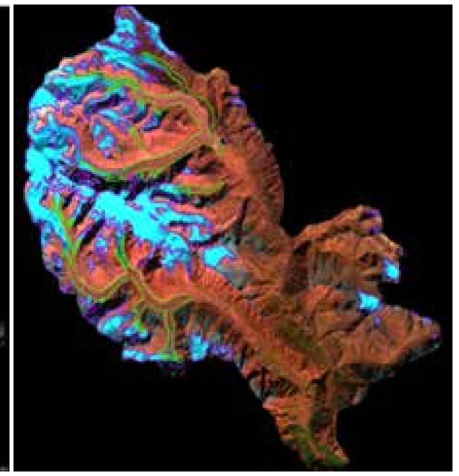

Modifying image objects depending on various spectral indices threshold (NDSI, NDVI and slope).


Classifying image objects as clean ice by applying NDSI threshold.


Filtering in clean-ice class for removing non-ice image objects by applying various parameters such as NDVI, LWM, slope, elevation, brightness etc.


Classify debris-covered glaciers from remaining unclassified image objects using mean slope value of image objects.


Filtering in debris-covered class for removing mis-classified image objects by utilising various parameters such as NDVI, LWM, NDSI, elevation, area and so on.


Final product after smoothing and manual corrections.

2.4 Uncertainty

The accuracy of defining glacier boundaries typically hinged on factors such as the image quality utilised, the interpretations made by individuals, and the contrast between the glacier and its surrounding features (Stokes et al., 2013; DeBeer & Sharp, 2007; Bajracharya et al., 2014b). In this study, efforts were made to use images with minimal to no snow cover and minimal cloud cover for mapping purposes, aiming to generate precise boundaries through automated procedures. Manual adjustments were performed to account for shadows, seasonal snow cover, and cases of low contrast between glacier boundaries and adjacent terrain, especially in debris covers and snout of the glaciers. This was achieved by overlaying corresponding images and conducting visual cross-checks with high-resolution imagery from Google Earth.

Another significant challenge across the decadal datasets was ensuring consistency in glacier boundary delineation. To address this, semi-automatically derived glacier boundaries from 2010 and/or 2020 were superimposed onto representative satellite images from 1990, 2000, 2010, and 2020. The outlines of the respective times were then manually adjusted and corrected to align accurately with the imagery. This manual refinement process substantially improved the accuracy of glacier boundaries across all time periods. As a result, the remaining positional uncertainty of glacier outlines constrained with respect to the image resolutions, which is dependent on a maximum of half the image resolution.

Consequently, the uncertainty associated with glacier boundaries was quantified by calculating the root mean square of each glacier's area from the polygon representing the glacier and the number of pixels enclosed by the glacier boundary, incorporating a buffer equal to half the image resolution increment (Bajracharya et al., 2014b). Overall, the uncertainty in glacier area for each time ranges from 2% to 3% of the total area, aligning closely with previously reported estimates (Bolch et al., 2010; Frey et al, 2012; Bajracharya et al., 2014b, Maharjan et. al., 2021, 2024).

PREPARATION OF BATHYMETRY SURVEY IN THE TSHO ROLPA GLACIAL LAKE, ROWALLING VALLEY, NEPAL

KUNJ GLACIER AND GLACIAL LAKE IN HINDU KUSH MOUNTAIN RANGE, PANJSHIR, AFGHANISTAN

NAVIGATING STAKE LOCATION IN THE YALA GLACIER DURING CAPACITY BUILDING TRAINING ON MAY 2025

SECTION III

Status and decadal changes of glaciers in the HKH region

The glaciers in the HKH have been experiencing significant ice loss over the past decades (Kadota et al., 1997; Fujita et al., 2001; Bolch et al., 2008). Studies have found that this rate of ice loss has increased rapidly in recent decades with the average rate of ice loss twice as much in the 21st century compared to the end of the 20th (Maurer, 2019). Most of these glaciers have been facing a general retreat except for the Karakoram region, where the glaciers may have increased mass or remained relatively stable over the last decade, which has been termed as the Karakoram Anomaly (Gardelle et al., 2012, 2013; Hewitt, 2005, 2011; Kaab et al., 2012). Most of these studies have applied geodetic methods by including glacier extents from the regional glacier inventories like Randolph Glacier Inventory, GAMDAM Glacier Inventory Chinese Glacier Inventory or ICIMOD's inventory itself. But, in order to understand such contrasted patterns of mass changes, it is essential to accurately map these glaciers at a multi annual scale in order to comprehend the magnitude of surface area changes in the glaciers as a result of retreat, surge or advancement and sequentially validate or bound the model forecasts according to these area changes. Therefore, a repeat glacier inventory was prepared for the years 1990, 2000, 2010, and 2020 using consistent data sources and methods.

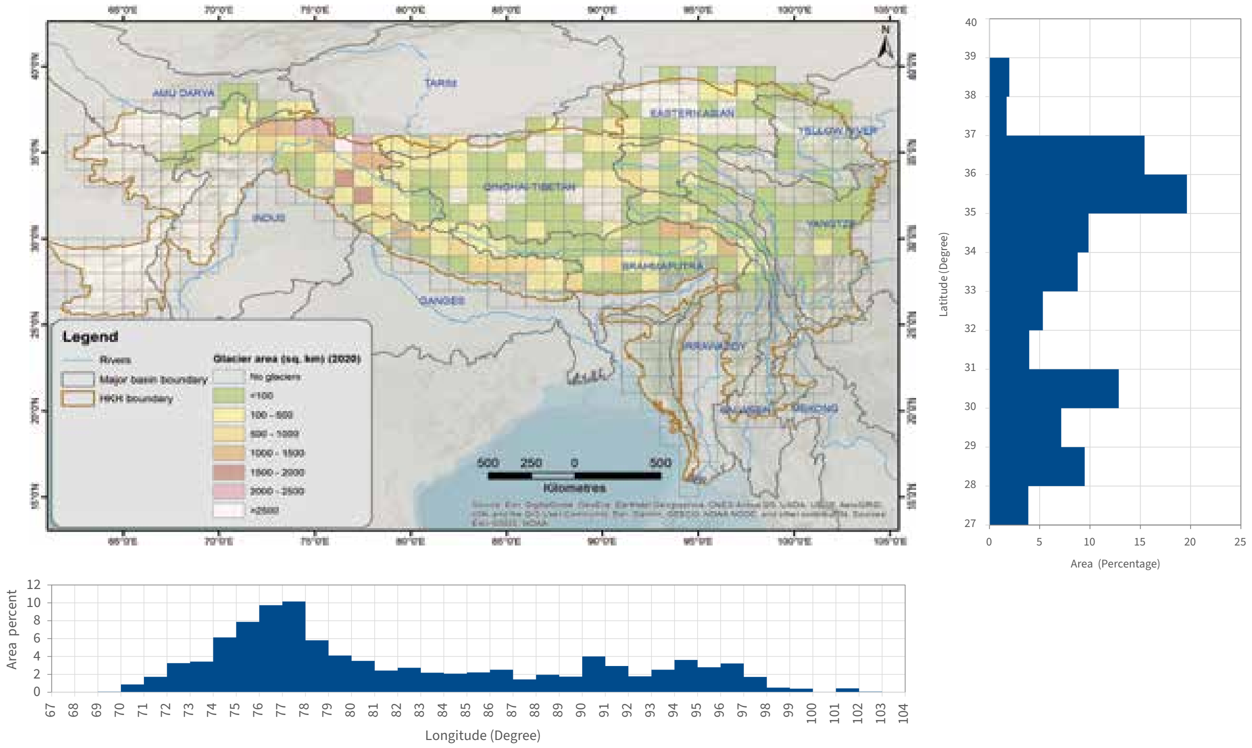
Glacier distribution in 2020

A total of 63,761 glaciers encompassing a total area of 55,782.02 km^2 and estimated ice reserves of 5,735.79 km^3 have been identified and mapped using Landsat images of 2020 year. These glaciers stretch out between 27.0° N and 39.3° N latitude and 67.6° E and 103.9° E longitude ranging from an elevation of 2,309 masl to 8,811 masl.

Figure 3.1 exhibits a glacier area distribution pattern across each one degree latitude and longitude grid within the region, indicating variations in geographical conditions and climatic influences along the latitudinal and longitudinal axis. The distribution pattern indicates the higher concentration of glacier area in mid-latitudes around 30°N – 37°N (almost 76% of the total glacier area in the region) with the peak area observed in the 35°N to 36° N latitudes covering almost 20% of the total glacier area in the region. A notable decrease in glacier area distribution observed beyond 37°N latitude, which covers only about 4% of the total glacier area in the region.

The mid-longitudes west to east distribution shows a notable peak in glacier area observed between 74°E – 79°E, 90°E – 91°E and 94°E – 95°E longitude consisting of the glacier area higher than 2,000 km^2.

FIGURE 3.1 GLACIER AREA COVERAGES ACROSS EACH ONE-DEGREE LONGITUDE AND LATITUDE GRID.



These zones consist of more than 51% of the glacier area in the region. This concentration suggests that certain longitudinal zones within the region are more conducive to glacier formation and preservation, likely due to factors such as altitude, topography, and climatic conditions.

However, there is variability in glacier area coverage across different longitudinal zones, with some ranges showing relatively less area coverage. For instance, the glacier area coverage comparatively reduced between 68°E to 70°E and 99°E to 104°E longitude. Also, there are some no glacier grids between the higher concentrated longitudinal zones. This variability underscores the complex interplay of geographical factors influencing glacier formation and distribution within the region. Moreover, the decline in glacier area coverage towards the eastern and western extremes of the region reflects a decrease in suitable conditions of glacier formation, which underscores the sensitivity of glaciers to regional climatic variations and highlights the importance of understanding localised environmental factors in assessing glacier dynamics and their implications for water resource management and climate adaptation in the region.

It also suggests that local geological and climatic conditions play a significant role in determining the extent and distribution of glaciers along the longitudinal and latitudinal axis.

The glaciers in the region vary in size, ranging from 0.02 to 1,008 km^2. They are classified into five distinct categories based on their surface area coverage: Class 1 (≤ 0.5 km^2), Class 2 (0.51 to 1.00 km^2), Class 3 (1.01 to 5.00 km^2), Class 4 (5.01 to 10.00 km^2), and Class 5 (≥ 10.00 km^2). The distribution of glaciers, their areas, and estimated ice reserves according to these classes in the HKH region is depicted in the Figure 3.2, with detailed information available in the accompanying Table 3.1.

Nearly three-quarters of the glaciers in the region belong to the smallest size class (less than 0.5 km^2). Despite their numerical dominance, these glaciers contribute only 13% to the total glacier area in the region. Conversely, the total glacier area is predominantly occupied by Class 5 glaciers (greater than or equal to 10 km^2), which account for 39% of the region's total glacier area. Although only 1% of glaciers fall into this category, their substantial size results in a significant contribution to the overall

FIGURE 3.2 GLACIER NUMBER, AREA, AND ESTIMATED ICE RESERVES CATEGORISED BY SIZE CLASSES (TOP), ALONG WITH THEIR DISTRIBUTION ACROSS DIFFERENT MEAN SLOPE (LEFT BOTTOM) AND ASPECT (RIGHT BOTTOM) CLASSES.

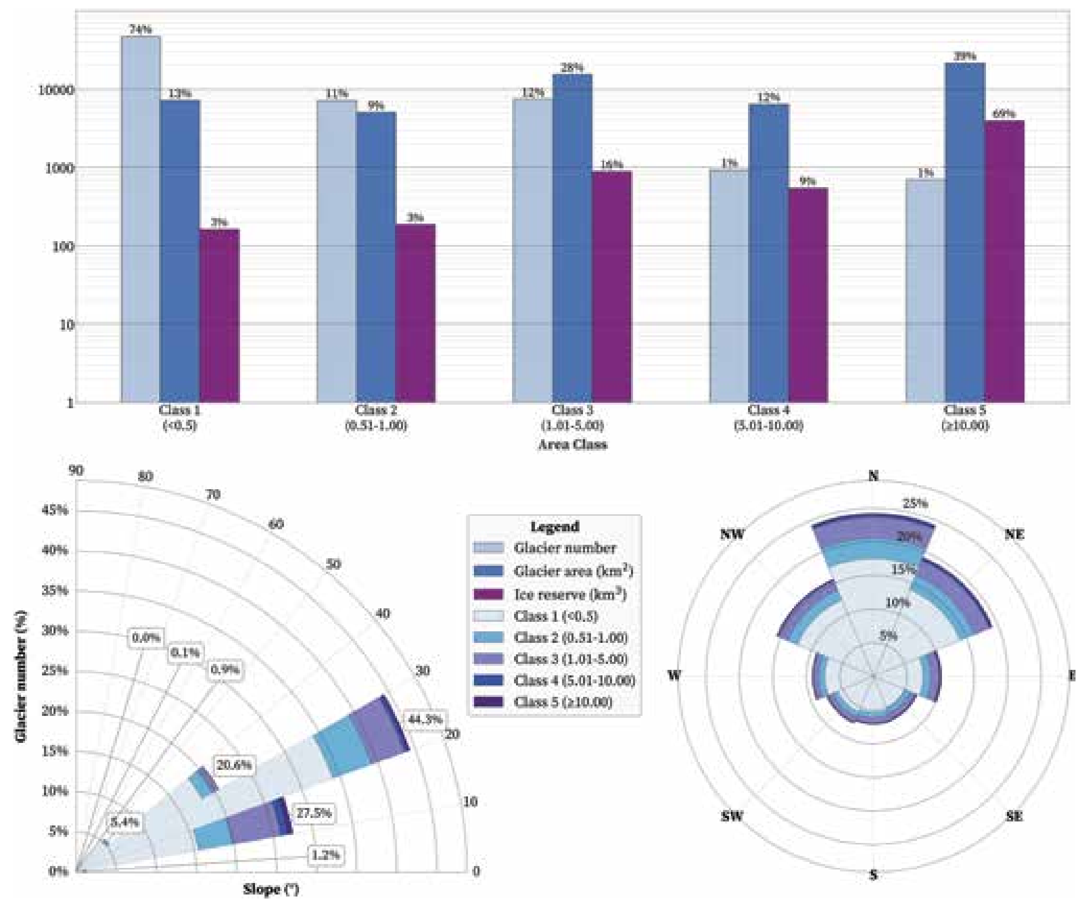


TABLE 3.1 DISTRIBUTION OF GLACIER NUMBER, AREA, AND ESTIMATED ICE RESERVES BY GLACIER SIZE CLASSES IN THE HINDU KUSH HIMALAYA (2020).

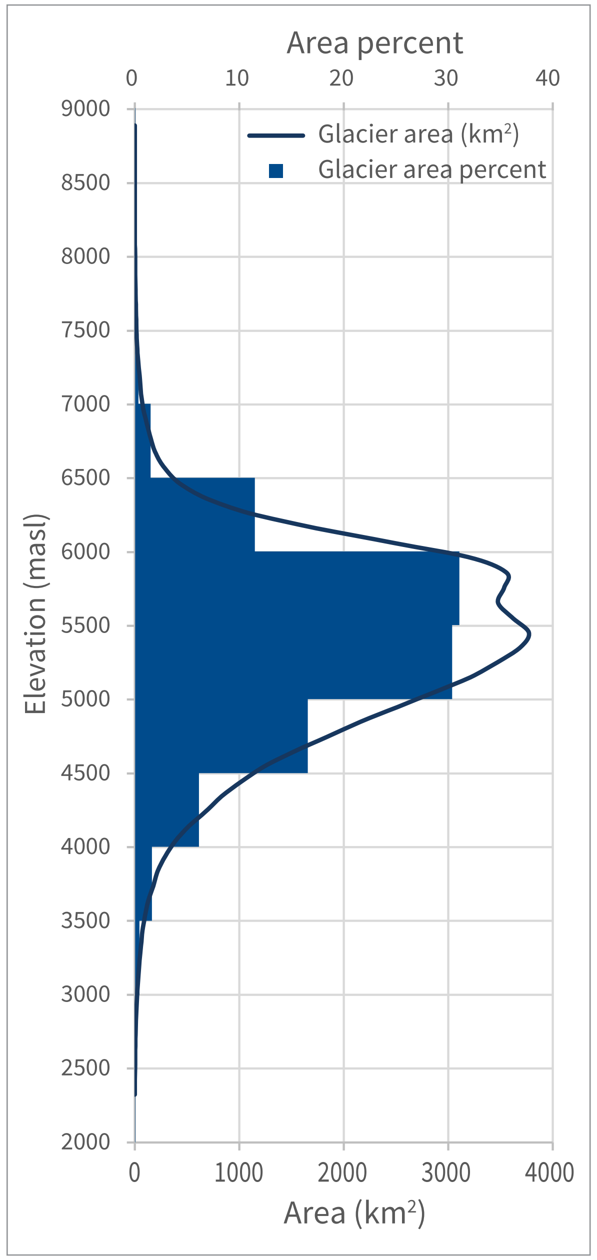
Area classes	Number		Area		Estimated ice reserves		Mean area per glacier
	count	%	km²	%	km³	%	km²
Class 1 (< 0.5 km²)	47,452	74	7,199.80	13	1,404.14	24	0.15
Class 2 (0.51 – 1.00 km²)	7,193	11	5,047.79	9	407.25	7	0.70
Class 3 (1.01 – 5.00 km²)	7,478	12	15,508.80	28	1,168.05	20	2.07
Class 4 (5.01 – 10.00 km²)	936	1	6,428.00	12	444.38	8	6.87
Class 5 (≥10.00 km²)	702	1	21,597.63	39	2,311.98	40	30.77
Total	**63,761**	**100**	**55,782.02**	**100**	**5,735.79**	**100**	**0.87**

glacier area. Correspondingly, they also hold most of the estimated ice reserves in the region (40%).

Based on these statistics, the average area per glacier across the entire region is calculated to be 0.9 km², whereas for the largest size class, it is 30.7 km².

The distribution of glacier areas in the HKH region shows a clear dependence on elevation (Figure 3.3). It is distributed from 2,300 masl to 8,800 masl elevation with lowest in the Karakoram range and highest elevation in central Himalaya. Glaciers are scarce at lower elevations below 3,500 masl with minimal coverage less than 0.5% of the total glacier area in the region. As the elevation increases above 3,500 masl, the glacier area starts to increase significantly. The most substantial glacier coverage is found in the elevation range between 5,000 – 6,000 masl covering more than 61% of total glacier area in the region, peaking at 5,300 – 5,400 masl constituting almost 7% of the total glacier area. Beyond 6,000 masl, the glacier areas start to decline sharply, and at elevations above 7,000 masl, the glacier coverage becomes minimal which is less than 0.5% of the total glacier area in the region. This distribution suggests that glaciers are most sustainable and prevalent in the mid-to-high elevation range of 4,000 – 6,000 masl in the HKH region.

FIGURE 3.3 **ELEVATION DEPENDENT GLACIER AREA DISTRIBUTION OF THE HKH REGION.**



In general, the presence and distribution of glaciers are influenced by the slope and orientation (aspect) of the terrain. Glaciers form and persist in the area where snow accumulation surpasses the rates of melting and sublimation. To understand the topographic characteristics of glacier distribution in the region, the slope and aspect of the individual glaciers were analysed based on these parameters generated by using Global SRTM DEM. The mean slope of the glaciers has been divided into six different classes. Lower slope angles are more prominent for glacier formation and preservation as they promote snow accumulation. More than 70% of glaciers have a mean slope of less than 30°, and it covers more than 91% of total glacier area and more than 96% of estimated ice reserves in the region. Glaciers with average slope less than 10° represent a small fraction, comprising 1% of the total number, yet covering 5% of the total glacier area and holding 7.1% of the total estimated ice reserves. Glaciers with slopes between 10°- 20° constitute the largest portion, representing 23% of the total number and occupying 50% of the total glacier area, with a significant 60.4% of the total estimated ice reserves. As slope angles increase, the number and area of glaciers decrease, along with their contribution to ice reserves. Glaciers with slopes greater than 60°, while minimal in number and area, collectively hold less than 0.002% of the total ice reserves. Overall, the distribution shows that glaciers on steeper slopes have smaller average areas compared to those on gentler slopes, indicating that larger glaciers are found on gentle slopes, while steeper slopes are characterised by much smaller glaciers. The detailed distribution is provided in the Figure 3.2 and Table 3.2.

TABLE 3.2 **DISTRIBUTION OF GLACIER NUMBER, AREA, AND ESTIMATED ICE RESERVES BY MEAN SLOPE CLASS IN THE HINDU KUSH HIMALAYA (2020).**

Slope classes	Glacier number		Glacier area		Estimated ice reserves		Mean area per glacier
	Number	%	km²	%	km³	%	km²
<10	483	1	2,843.95	5	410.13	7.2	5.89
10 - 20	14,800	23	27,969.29	50	3,463.83	60.4	1.89
20-30	29,141	46	19,985.57	36	1,664.31	29.0	0.69
30-40	14,544	23	4,167.64	7	174.15	3.0	0.29
40-50	3,999	6	719.13	1	21.15	0.4	0.18
50-60	707	1	89.84	0.2	2.11	0.04	0.13
>60	87	0.1	6.59	0.01	0.11	0.002	0.08
Total	**63,761**	**100%**	**55,782.02**	**100%**	**5,735.79**	**100.0**	**0.87**

A comparative analysis of glacier status in the region has been conducted based on their aspects. The mean aspect for each glacier was calculated by computing the mean sine and cosine of each pixel within the glacier's boundaries, using the SRTM DEM (Paul et al., 2009 and 2010). These mean aspect values were then grouped into eight aspect classes for the analysis. A graphical representation of glaciers across different aspects is shown in the Figure 3.2 and Table 3.3. The analysis reveals that northern aspects host the highest number of glaciers, accounting for 24% of the total glacier number, and cover the largest glacier area, representing over 22% of the total glacier area in HKH. The northeast (NE) aspect follows, contributing 19% to both the glacier number and area coverage, while the northwestern (NW) aspect represents 16% of the glacier number and 12% of the total area in the region.

In comparison, the southern aspects – south, southeast, and southwest – contain fewer glaciers, each contributing 7% to 8% to the total glacier number and covering 7% to 9% of the total glacier area in the HKH. The southeastern aspect has the least number of glaciers, while the southwestern has the smallest area coverage. Eastern-facing glaciers (E), while comprising nearly 10% of the total glacier count, are larger on average area and hold the highest estimated ice reserves per glacier. This is likely due to favourable snow accumulation conditions, especially influenced by monsoon precipitation. The eastern aspect covers almost 15% of the total glacier area in the HKH.

TABLE 3.3 **DISTRIBUTION OF GLACIER NUMBER, AREA, AND ESTIMATED ICE RESERVES BY MEAN ASPECT CLASS IN THE HINDU KUSH HIMALAYA (2020).**

Aspect classes	Number		Area		Estimated ice reserves		Mean area per glacier
	Count	%	km²	%	km³	%	km²
N	15,476	24%	12,453.32	22.3	981.58	17.11	0.80
NE	12,224	19%	10,382.86	19	846.40	15	0.85
E	6,426	10%	8,225.58	15	1,298.06	23	1.28
SE	4,471	7%	4,735.35	8	483.48	8	1.06
S	4,549	7%	4,901.51	9	632.34	11	1.08
SW	4,810	8%	4,050.95	7	366.20	6	0.84
W	5,830	9%	4,093.68	7	406.28	7	0.70
NW	9,975	16%	6,938.78	12	721.45	13	0.70
Total	**63,761**	**100%**	**55,782.02**	**100%**	**5,735.79**	**100%**	**0.87**

The distribution also shows that northern, northwestern, and western-facing glaciers have the smallest mean area per glacier, reflecting their higher number of smaller glaciers, often located in high-altitude, narrow valleys. In contrast, the southern aspects – southern and southeastern (S and SE), despite having fewer glaciers, tend to host moderately larger glaciers compared to the northern, northwestern, and western-facing slopes, due to higher elevation and more favourable climatic conditions. This distribution suggests that northern slopes are more favourable for glacier formation due to reduced solar exposure and colder temperatures, which help preserve glaciers, while southern-facing slopes, receiving more direct sunlight, are more prone to melting.

Decadal changes of glaciers from 1990s to 2020

Glaciers in the HKH region have been retreating rapidly over the past few decades (Bolch et al. 2008; Fujita et al, 2001; Kadota et al, 1997). This trend is a significant concern due to its impact on water resources, ecosystems, and local communities. The evidence of the glacier retreat and shrunk from some parts of the region such as Afghanistan, Bhutan, and Nepal have been have been presented before based on 30-year period satellite images. This research shows almost a quarter of the glacier area has decreased within 1980s to 2010. (Bajracharya et al. 2014a, 2014b, 2014c, Maharjan et al, 2021a, b). The present study follows the same consistent method and presented here the detail change of glacier area throughout the HKH region from 1990s to 2020.

The decadal glacier changes datasets from the 1990s to 2020 of the whole HKH region indicate that the number of glaciers decreased by 2% and their area shrank by about 12% over this 30-year period. Notably, the rate of reduction in both number and area was higher in the most recent decade, with a 2% decrease in number and approximately a 5% decrease in area between 2010 and 2020, compared to previous two decades starting from 1990. Interestingly, there was a slight increase (0.3%) in the number of glaciers in the first decade (1990–2000), likely due to glacier fragmentation. However, the area consistently decreased throughout the decades. Fluctuations in glacier numbers alone do not accurately reflect glacier health. Changes in glacier areas over time provide a clearer picture of glacier retreat, advancement, or shrinkage. The Table 3.4 and Figure 3.4 below show the details of glacier number, area and estimated ice reserves changes in each decade of the HKH region.

Figure 3.5 shows the glacier area change percentage between 1990 to 2020 in each one degree longitudinal and latitudinal grid in the HKH region. The latitude bands from 27°N to 40°N show consistent decreases in glacier area. The greatest glacier area decrease percentage occurred between 29°N – 30°N and 27°N – 28°N, both the bands experiencing more than 20% of glacier area loss. Other significant glacier area losses were observed in latitude bands 28°N – 29°N and 31°N – 32°N, with glacier area losses exceeding 18%. The largest glacier area concentrations, found in latitude bands 35°N – 36°N and 36°N – 37°N, experienced smaller glacier area losses of less than 5% each.

Similarly, the largest percentage of area decreases occurred in the longitudinal bands of 102°E – 103°E and 100°E – 101°E, both having area loss of more than 45%. Other nodal area loss percentages were found in the adjacent longitudinal bands of 103°E – 104°E, 99°E – 100°E and 68°E – 69°E, with area losses ranging from 32% to 36%. The longitudinal bands with the largest glacier area concentrations, 76°E – 77°E and 77°E – 78°E, experienced relatively less area loss ranging between 5% and 6%.

TABLE 3.4 DECADAL CHANGES IN GLACIER NUMBER, AREA, AND ESTIMATED ICE RESERVES IN THE HINDU KUSH HIMALAYA (1990–2020).

Glacier	Year				Percentage change			
	1990	2000	2010	2020	1990–2000	2000–2010	2010–2020	1990–2020
Number	65,188	65,394	64,885	63,761	0.3	-0.8	-1.7	-2.2
Area (km^2)	63,121.52	61,099.24	58,676.32	55,782.02	-3.2	-4	-4.9	-11.6
Estimated ice reserves (km^3)	6,293.24	6,163.04	5966.62	5,735.79	-2.1	-3.2	-3.9	-8.9

FIGURE 3.4 DECADAL CHANGES OF GLACIER NUMBER AND AREA FROM 1990S TO 2020 IN THE HKH REGION.

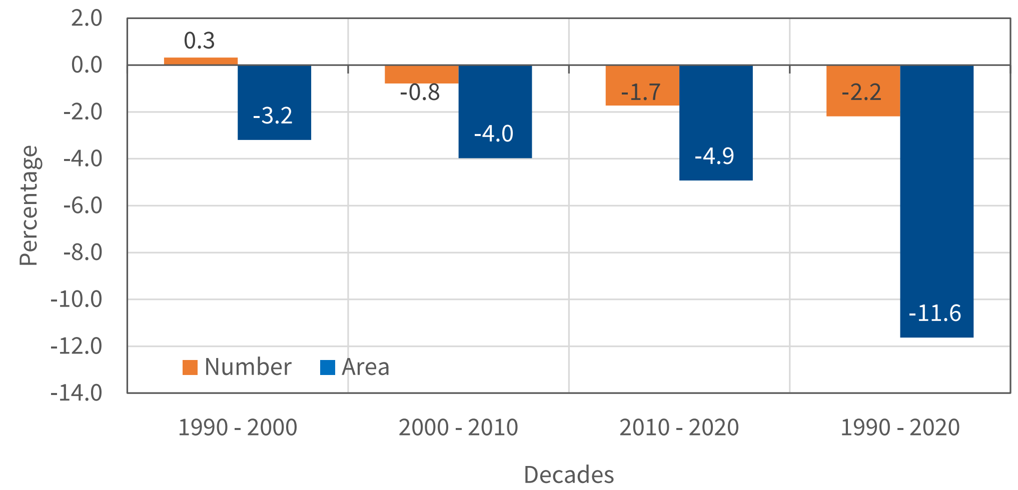
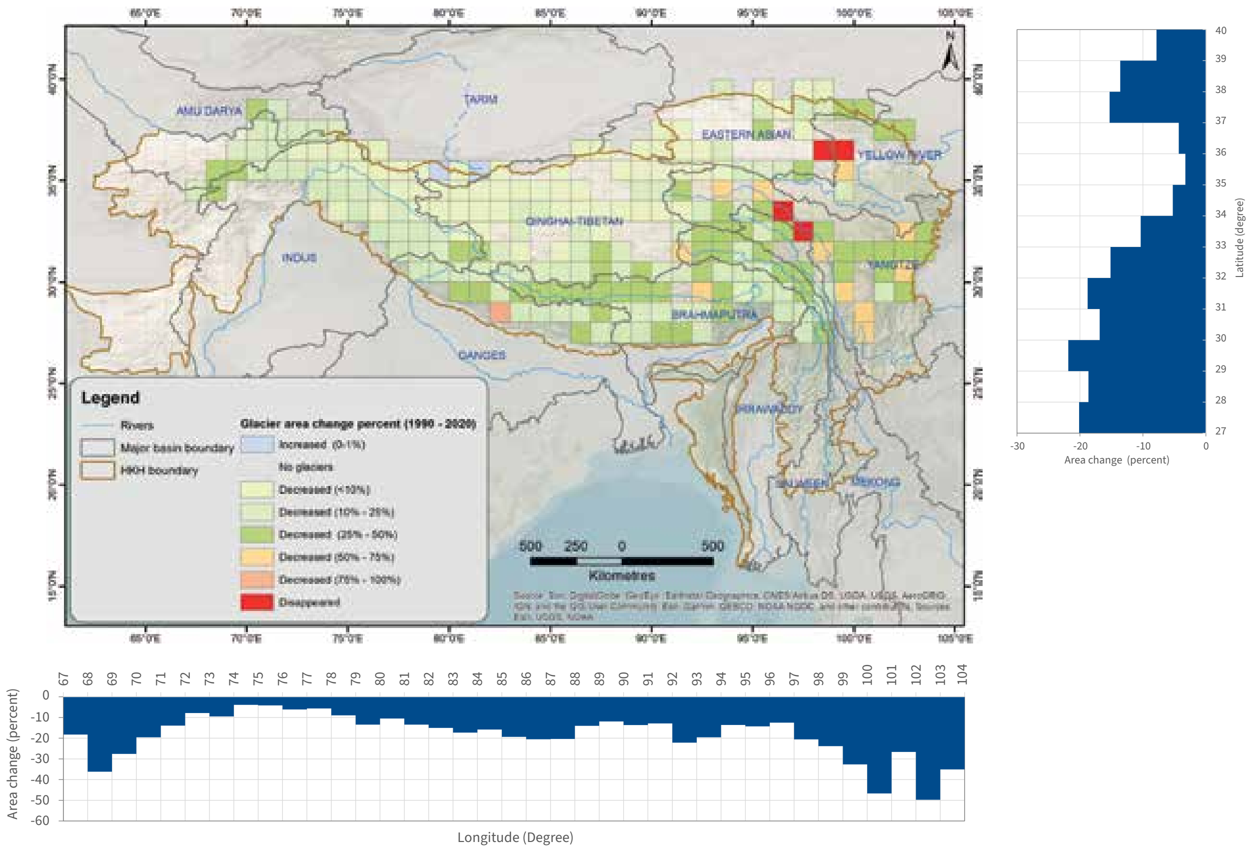


FIGURE 3.5 GLACIER AREA CHANGE PERCENTAGE ACROSS EACH ONE-DEGREE LONGITUDE AND LATITUDE GRIDS.



These observations reveal that while the rate and extent of the loss of the glacier area varied within each latitudinal and longitudinal band, the most substantial percentage of loss occured in the region with smaller glacier area distributions. Overall, the glacier area loss percentages were higher in the eastern part of the region, where the glacier area distribution is smaller compared to western and central parts of the HKH region. Latitudinally, the glacier area loss percentages were higher in the lower latitudes (southern parts) than in higher latitudes (northern parts) of the region.

The size of a glacier plays a crucial role in determining its melt rate and stability. Smaller glaciers are more vulnerable to climate change and tend to melt faster than larger ones (Lee et al., 2021; Yao et al., 2012). This is primarily due to their higher surface-area-to-volume ratio, reduced thickness, and limited accumulation zones, often positioned below the equilibrium line altitude (ELA). As a result, they have less snow cover, and as melting progresses, the increasing exposure of glacier ice accelerates melt rates due to a reduction in surface albedo. To analyse glacier changes based on size, glaciers are categorised into five different classes according to their area across all time periods. Figure 3.6 depicts the percentage changes in glacier number and area within various size classes over each of the past three decades in the HKH region.

Overall, both the number and area of glaciers in the HKH region have been consistently declining in all the size classes throughout each decade except the number of smaller sized glaciers of area less than 0.5 km^2 has increased. But its increase rate has declined in recent decades. Whereas the area of this class has experienced a steady decrease across the three decades, with a higher rate of 4.3% reduction in recent decades. Class 2 glaciers (0.51-1.00 km^2) show the most significant reductions in both number and area in all decades, with a substantial decline of 8.3 % in number and 8.6% of area in recent decades of 2010 to 2020. While other larger size glaciers also decline consistently in both number and area in all decades, the rate of reduction declines with increasing size classes. Largest size classes show the least percentage reduction in both number and area compared to reduction in other area classes.

The data reveals a consistent decline in both the number and area of glaciers across all size classes, with smaller glaciers experiencing the most significant reductions. The increase in the number of the smallest glaciers, along with their accelerating area loss, can be attributed to the fragmentation and shrinkage of larger glaciers. Additionally, the rising rate of area reduction suggests that some of the smallest glaciers are losing area below a threshold or disappearing entirely, as they are more vulnerable to rising temperatures. While larger glaciers remain relatively more stable, they are also undergoing gradual decline. These trends highlight the pressing need for climate action to mitigate the impacts of glacier retreat in the region.

The elevation dependent glacier area changes shown in Table 3.5 and Figure 3.7 indicate that the glacier area in all the elevation zones have decreased, with the most prominent glacier area loss observed at an elevation range from 4,500 to 6,000 masl. The area loss percentage is highest at elevation ranges

FIGURE 3.6 INTERDECADAL GLACIER NUMBER AND AREA CHANGE PERCENTAGE IN VARIOUS GLACIER AREA SIZE CLASSES.

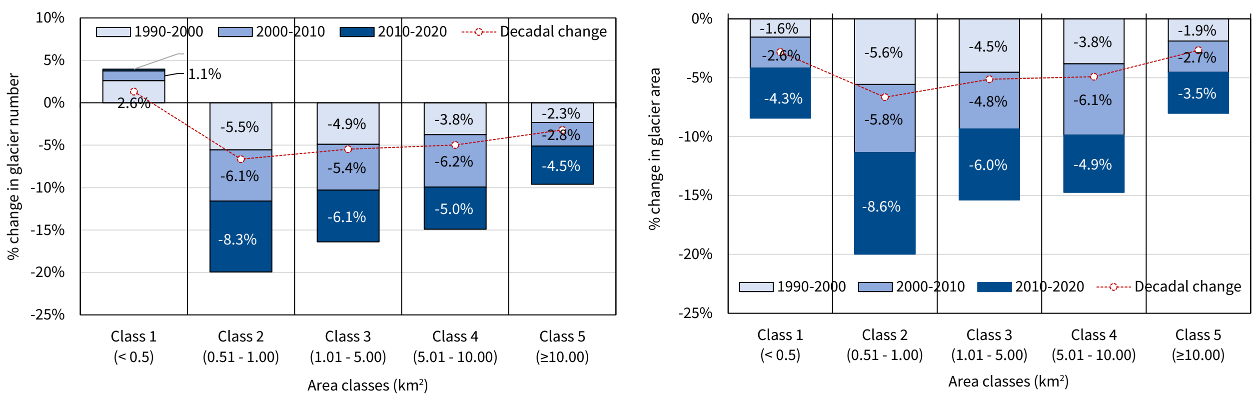


FIGURE 3.7 DISTRIBUTION AND CHANGES IN GLACIER AREA AT VARIOUS ELEVATION RANGES FROM 1990 TO 2020 IN THE HKH REGION.

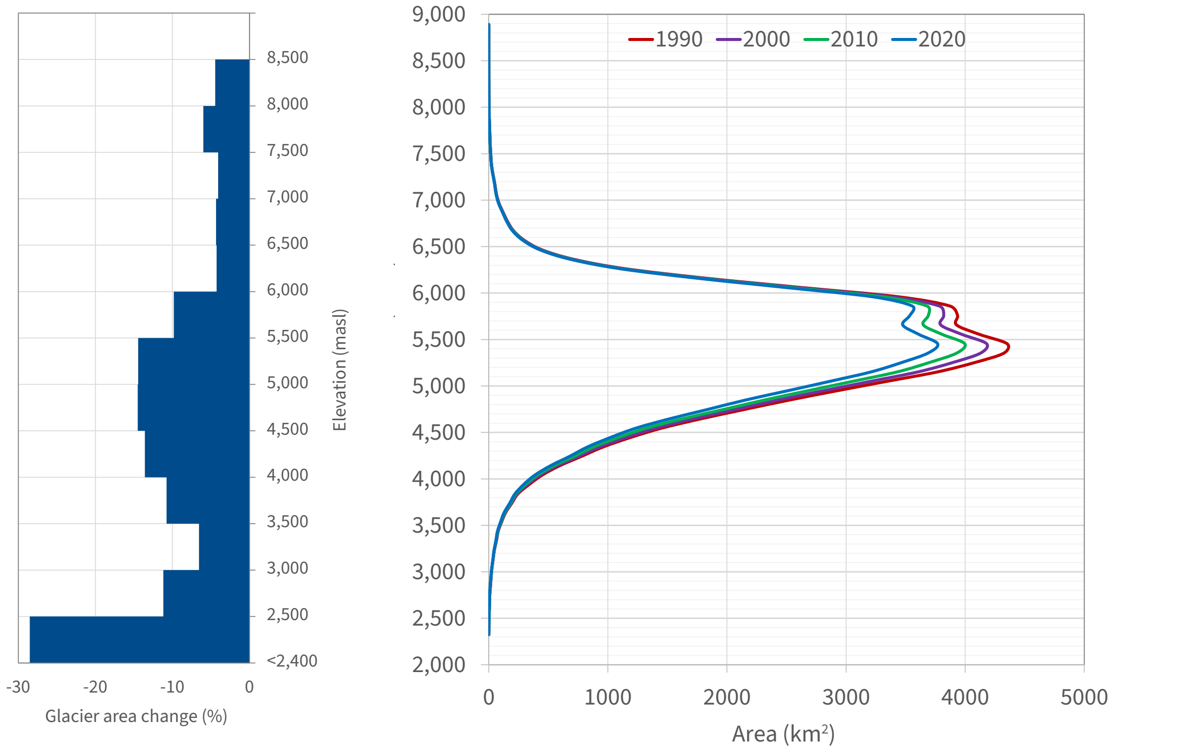


TABLE 3.5 GLACIER AREA DISTRIBUTION AND DECADAL CHANGES ACROSS ELEVATION RANGES IN THE HINDU KUSH HIMALAYA (1990–2020).

Elevation ranges (masl)	Area (km^2)				Rate of change (%)				Change in area per decade (%)
	1990	2000	2010	2020	1990–2000	2000–2010	2010–2020	1990–2020	
<2,500	1.224	1.216	0.891	0.875	-0.6	-26.7	-1.8	-28.5	-9.7
2,500–3,000	46.199	46.616	42.727	41.032	0.9	-8.3	-4.0	-11.2	-3.8
3,000–3,500	250.794	248.468	242.287	234.402	-0.9	-2.5	-3.3	-6.5	-2.2
3,500–4,000	1024.976	998.507	958.350	914.703	-2.6	-4.0	-4.6	-10.8	-3.7
4,000–4,500	3,971.508	3,842.983	3,644.330	3,432.878	-3.2	-5.2	-5.8	-13.6	-4.7
4,500–5,000	10,835.899	10,437.896	9,923.650	9,264.365	-3.7	-4.9	-6.6	-14.5	-5.1
5,000–5,500	19,877.334	19,026.010	18,122.211	17,006.592	-4.3	-4.8	-6.2	-14.4	-5.1
5,500–6,000	19,296.202	18,754.584	18,137.670	17,402.611	-2.8	-3.3	-4.1	-9.8	-3.4
6,000–6,500	6,712.471	6,646.296	6,533.253	6,427.522	-1.0	-1.7	-1.6	-4.2	-1.4
6,500–7,000	874.186	867.271	849.621	836.379	-0.8	-2.0	-1.6	-4.3	-1.5
7,000–7,500	190.820	189.794	184.104	183.068	-0.5	-3.0	-0.6	-4.1	-1.4
7,500 – 8,000	36.058	35.691	33.618	33.898	-1.0	-5.8	0.8	-6.0	-2.0
8,000 – 8,500	3.483	3.541	3.241	3.328	1.7	-8.5	2.7	-4.4	-1.4
>8,500	0.365	0.365	0.365	0.365	0.0	0.0	0.0	0.0	0.0
Total	**63,121.52**	**61,099.24**	**58,676.32**	**55,782.02**	**-3.2**	**-4.0**	**-4.9**	**-11.6**	**-4.0**

from 4,000 to 5,500 masl which is 13.6% to 14.5% over 30 years from 1990 to 2020 (Table 3.5). The loss percentage at this elevation range was significant and consistent throughout all decades with a higher rate in recent decades. The percentage of area loss has been gradual and steady in the elevation ranges of 3,500 – 4,000 masl and 5,500 – 6,000 masl. At an average of 3% – 4.5% per decade, the total loss has been around 10% – 11% over the 30-year period. Above 6,500 masl, the glacier area loss is considerably less. While the loss rate slows down, it remains notable with some (minor) variations. This could be due to the seasonal snow accumulation or permanent snow deposition and melting.

Whereas the rate of area loss below 3,500 masl elevation is the maximum, but the (absolute) level of area loss is considerably less. The area loss below 3,500 masl also indicates the retreat of the glacier terminus and upward shifting of glacier elevation. This is also evidenced by the changes in the minimum elevation of glaciers, which shifted upward by 25m, between 1990 and 2020. This upward shift in minimum elevation varies across basins, sub-basins, and mountain ranges.

As glacier surface area decreases, the mean slope of glaciers also changes. The Figure 3.8 illustrates the changes in both glacier number and area across different mean slope classes over three decades (1990 – 2020). The most significant reductions in both number and area occurred in slope ranges between 20° and 30°, indicating that glaciers in these mid-slope ranges are particularly vulnerable. Overall, this category experienced the highest decline in glacier numbers (around 9%) and area loss (nearly 12%), emphasising its high sensitivity to climate change.

Similarly, substantial area loss was observed in glaciers within the 10 – 20° and 30 – 40° slope classes, further reinforcing the trend that mid-range slope glaciers are more susceptible to melting. In contrast, glaciers of gentler mean slopes (<10° and 10 – 20°) and steeper mean slopes (>60°) showed an increase in number, likely due to the fragmentation of larger glaciers into smaller ones. However, this increase does not represent actual glacier growth, as these fragmented glaciers remain highly prone to further melting.

Additionally, the increase in glacier numbers within the 10 – 20° slope range, despite the loss in total glacier area, along with the simultaneous decline in both number and area in the adjacent 20 – 30° slope class, indicates a shift in the mean slope of glaciers. This trend suggests that as glaciers lose area and become fragmented, their distribution changes, leading to an apparent increase in glacier number within certain slope ranges. These findings highlight the dynamic response of glaciers to climate change and the ongoing transformation of glacier morphology.

FIGURE 3.8 **GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES.**

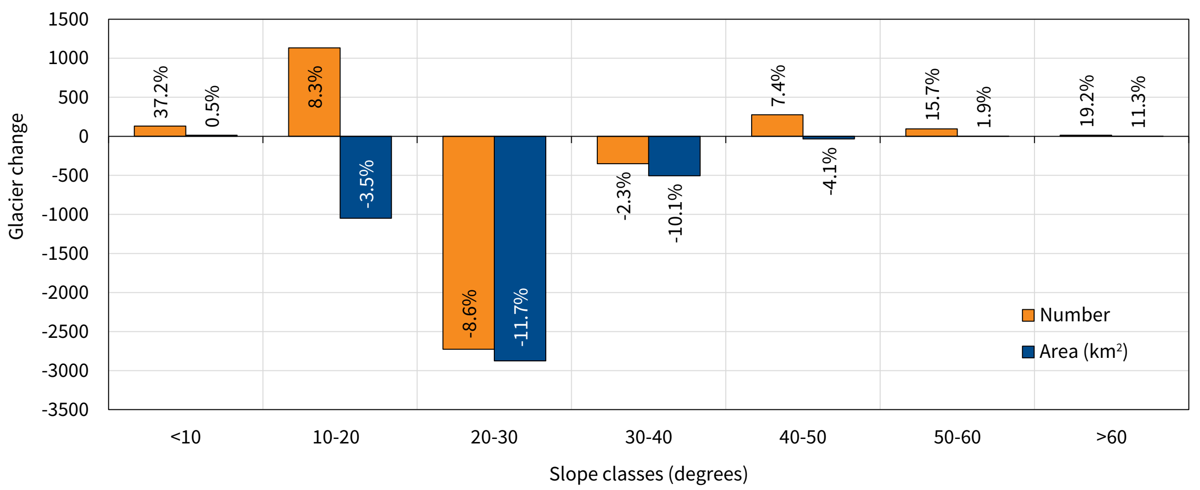
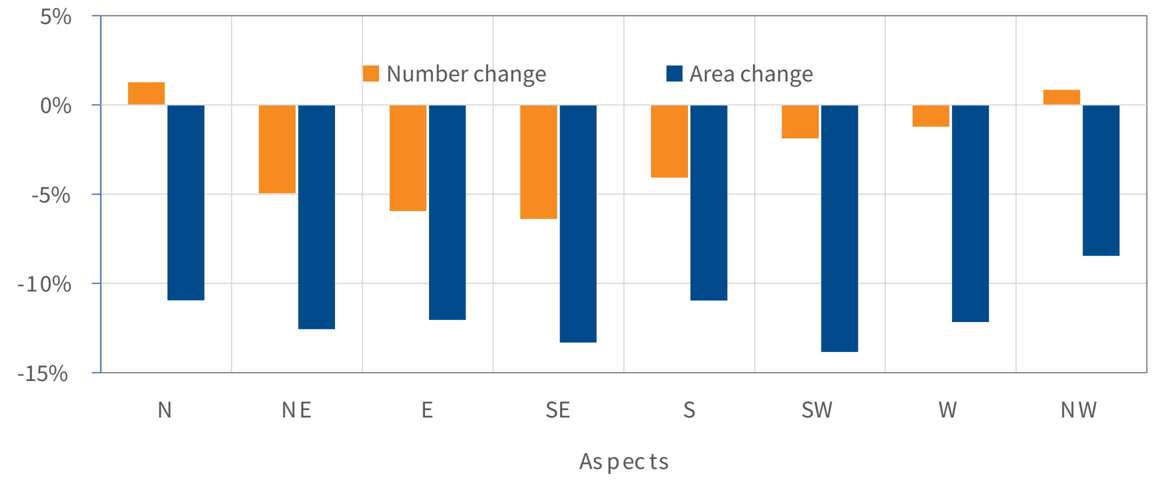


FIGURE 3.9 **GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES.**



The decadal glacier changes across different mean aspects reveal varying retreat rates (Figure 3.9). The northeastern, eastern, and southeastern aspects have experienced the most significant losses in both numbers and areas over the past three decades. The northeastern aspect recorded the largest glacier number loss (about 5%) and a nearly 13% reduction in area, making it as the area one of the most affected aspects. Similarly, the eastern aspect has lost around 6% of its glaciers, with an area decline exceeding 12%. The southeastern aspect, on the other hand, has experienced over a 13% area reduction, the second highest percentage loss among all aspects. These aspects, which receive more direct sunlight and higher radiation, are retreating at a faster rate due to accelerated melting.

The southwestern and western aspects also show significant glacier retreat, with the southwestern having the highest percentage loss in area (about 14%), followed by western (over 12%). Though the number of glaciers lost in these areas is lower than in the northeastern and southeastern, their area loss is considerable. This suggests that while fewer glaciers may be disappearing completely, those that remain are shrinking at an alarming rate. The southern aspect, similarly, has seen 4% of glacier losses and about 11% of area decline, indicating substantial glacial shrinkage.

In contrast, northern and northwestern aspects show the increases in number over the previous two decades and slight decreases in recent decade from 2010 to 2020, with an overall increase by about 0.3% to 0.4% over three decades. However, the glacier area in both aspects remains significant loss by about 8.5% in northwestern aspect and 11% in northern aspect over three decades. This increase in number could be due to alteration of mean aspects of the glacier from other aspects with shrinkage of glaciers and due to fragmentation of larger glaciers.

Overall, the trend suggests that the northeastern, eastern, southeastern, and southwestern aspects glaciers are the most vulnerable, experiencing the highest glacier losses in both number and area. Northwestern is the most stable aspect, showing the lowest rate of area loss among other aspects. The northern aspect, despite some glacier number increases, has the largest total area loss, indicating significant fragmentation and shrinkage of larger glaciers.

FIELD EXPEDITION ON YALA GLACIER, LANGTANG VALLEY, NEPAL .

SECTION IV

Status and decadal changes of glaciers in the HKH mountain ranges

A mountain range is a series of mountains that have a similar shape, structure, and alignment, formed through the same geological process, usually an orogeny. These ranges are often segmented by various geological and geomorphological features and structures. The HKH region, as the youngest mountain system in the world, is composed of multiple mountain ranges that play a vital role in shaping climatic patterns, supporting diverse ecosystems and providing essential resources for human life and livelihoods. Mountain ranges act as climatic barriers, influencing weather patterns by blocking or redirecting winds and precipitation. The presence of glaciers within these mountain systems signifies the large storage of frozen water and gradually releasing through seasonal melting ensures the continuous flow in the larger river systems, sustaining agriculture, hydropower and drinking water supplies for billions of people living downstream.

To provide a detailed assessment and highlight a regional overview of glacier distribution and changes across the various mountain ranges of the HKH region, glaciers have been categorised into 16 distinct mountain ranges. These classifications are based on updated boundaries that consider both geographical and climatological characteristics, as accessed from the HKH Assessment Reports (Wester et al, 2019).

Table 4.1 provides detailed insights into the mountain ranges within the Hindu Kush Himalaya (HKH) region, covering aspects such as geographical extent, elevation ranges, glacier statistics, and highest peaks. The geographical extent and elevation ranges vary significantly across mountain ranges, with Tibetan Interior being the largest and Hengduan Shan being a second largest area coverage within the HKH and Altun Shan covers the smallest portion of the HKH. Elevation ranges are also diverse, with the central Himalaya housing Mount Everest, the highest peak at 8,848.86 masl, while the eastern Himalaya includes elevations as low as 85 masl.

Glacier distribution highlights notable differences in the number, area, and size. The western Himalaya has the highest number of glaciers (12,575), accounting for 19.73% of the total glaciers in the HKH region. Karakoram stands out with the largest glacier area and representing 26.27% of the total glacier area and has an average glacier size of 1.62 km^2 indicating the larger glacier size. Majorly the three mountain regions, Karakoram, western and central Himalaya together, constitute the largest share of glaciers and glacier area in the region with each having higher than 14% of both glaciers and glacier area. Rest of the other mountain ranges cover less than 8% of both the number and area under glaciers, with the only exception being Nyainqêntanglha (eastern part of the HKH) which consists of around 11% of area and about 12.5 % of the total number of glaciers in the HKH. In contrast, Altun Shan (northern end of the HKH boundary) has the fewest glaciers (9) and the smallest glacier area (7 km^2), making up only 0.01% of the total glacier area with an average glacier size of 0.78 km^2.

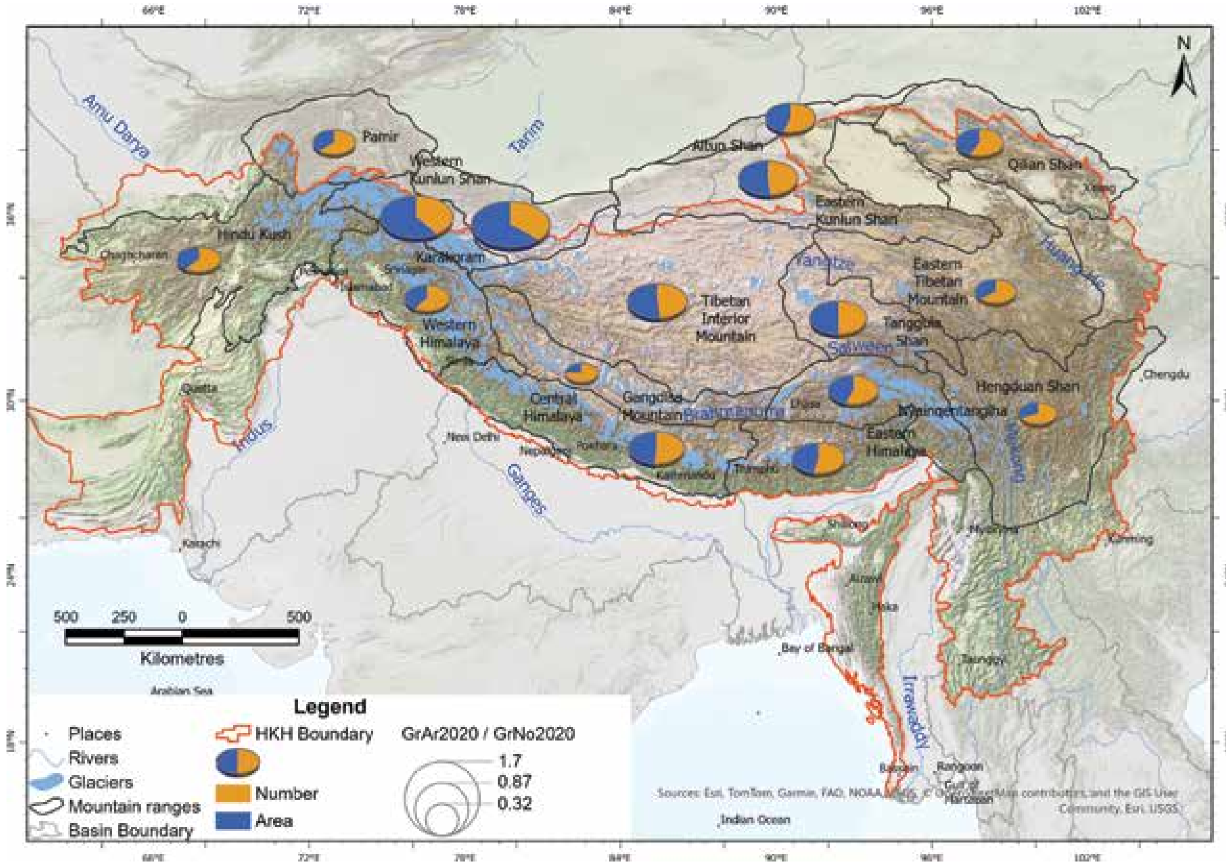
TABLE 4.1 GLACIER DISTRIBUTION AND TOPOGRAPHIC CHARACTERISTICS OF THE MOUNTAIN RANGES WITHIN THE HINDU KUSH HIMALAYA (HKH).

Mountain sub-regions	Total area (km^2) with in HKH	Extent (Longititude/ Latitude- degrees)	Elevation ranges (masl)	Glacier (2020)						
				Number	Number (%)	Area (km^2)	Area (%)	Elevation range (masl)	Average size (km^2)	Largest glacier (km^2)
Hindu Kush	32,9143.1	62.419 E - 74.653 E 31.614N - 37.226 N	300 – 7,708	5,071	7.95	3,001.59	5.38	3,036 – 7,553	0.59	99.79
Karakoram	63,474.6	72.443 E - 79.706 E 34.135N - 37.136 N	1,246 – 8,611	9,067	14.22	14,653.28	26.27	2,329 – 8,570	1.62	1007.86
Western Himalaya	186,678.1	72.777E - 80.370E 30.784N - 35.852N	244 – 8,126	12,575	19.73	7,878.44	14.12	2,413 – 8,039	0.63	113.17
Central Himalaya	253,278.6	76.998E - 89.275E 26.658N - 31.450N	107 – 8846.86	8,722	13.68	8,184.81	14.67	3,436 – 8,811	0.94	125.8
Eastern Himalaya	164,543.2	87.989E - 95.449E 26.701N - 29.892N	85 – 8,452	3,401	5.33	2,886.34	5.17	3,032 – 8,091	0.85	81.55
Gangdise Mountains	154,883.5	78.657E - 90.186E 29.115N - 33.763N	3,362 – 7,031	3,514	5.51	1,135.65	2.04	5,322 – 6,991	0.32	19.91
Nyainqêntanglha	172,220.6	89.590E - 97.881E 27.249N - 31.509N	179 – 7,093	7,961	12.5	6,079.60	10.9	2,607 – 7,094	0.76	166.74
Hengduan Shan	354,249.9	95.350E - 104.257E 25.615N - 32.693N	352 – 7,556	2, 239	3.51	985.86	1.77	2,979 – 7,145	0.44	23.76
Tanggula Shan	145,065.7	90.075E - 97.348E 30.835N - 35.160N	3,160 – 6,575	1,697	2.66	1,702.91	3.05	4,270 – 6,573	1.00	50.63
Tibetan Interior Mountains	516,813.4	78.101E - 92.127E 29.939N - 36.033N	3,574 – 6,751	3,413	5.35	3,702.51	6.64	5,030 – 6,757	1.09	50.84
Eastern Tibetan Mountains	333,122.4	91.411E - 102.613E 30.953N - 37.430N	2,296 – 6,253	580	0.91	299.17	0.54	4,510 – 6,254	0.52	20.02
Qilian Shan	135,966.6	93.708E - 102.902E 35.838N - 39.305N	1,725 – 5,767	1,490	2.34	1,016.87	1.82	3,929 – 5,762	0.68	19.53
Eastern Kunlun Shan	134,879.9	84.406E - 98.674E 34.786N - 38.994N	2,657 – 6,941	1,288	2.02	1,397.40	2.51	4,650 – 6,804	1.9	95.04
Western Kunlun Shan	35,836.3	78.226E - 82.848E 34.446N - 35.982N	4,220 – 7,131	1,012	1.59	1,897.94	3.4	5,195 – 7,126	1.88	234.51
Pamir	23,095.4	69.938E - 74.900E 36.548N - 38.489N	575 – 6,277	1,710	2.68	952.65	1.71	3,554 – 6,229	0.56	17.76
Altun Shan	6,297.5	90.612E - 94.334E 38.609N - 39.319N	2,719 – 5,821	9	0.01	7.01	0.01	4,870 – 5,761	0.78	2.65

Figure 4.1 shows the distribution of the glaciers and glacier area within each mountain ranges of the HKH. It clearly depicts that the proportion of area is higher than the number of glaciers in Karakoram, central Himalya, western and eastern Kunlun Shan and Tibetan Interior Mountain ranges, indicating that these regions have considerably larger sized glaciers in the region.

Figure 4.2 and Table 4.2 provide a comprehensive view of glacier changes across various mountain ranges from 1990 to 2020. The database shows significant trends in glacier area fluctuations. The Hindu Kush, Karakoram and western Himalaya show the minor fluctuations in glacier number but in overall glacier areas declined moderately with decrease of about 11%, 1.7% and 12% respectively. Conversely, the central and eastern Himalaya showed both the number and area of glaciers decrease significantly, with declines of about 21% and about 17% in area, reflecting substantial glacier retreat. The Gangdise Mountain and Hengduan Shan exhibited similar patterns of glacier area reduction, with declines of about 24% and 33%, respectively, suggesting accelerated glacial loss. In contrast, the Tibetan Interior Mountain showed a slight loss in

FIGURE 4.1 PROPORTIONAL DISTRIBUTION OF GLACIER NUMBER AND AREA ACROSS THE MOUNTAIN RANGES IN THE HKH REGION.



glacier area by 4.4%, while other regions like the Eastern Tibetan Mountain and Pamir experienced notable decreases in both glacier number and area, with declines of more than 22% and 16% in area, respectively.

Over each decade, most regions experienced a consistent decline in glacier area, indicating a widespread glacier retreat and a pervasive impact of climate change on high-altitude environments. In 1990 – 2000, the glacier changes show mixed trends with some regions showing minor decreases while others experienced more pronounced declines. The glaciers in Karakoram and western Kunlun Shan shows stable and minor decreases in glacier area and others like the Hindu Kush and Himalayas experience notable decreases in glacier area.

The decade of 2000 to 2010 is marked as a period of continued pattern of moderate to significant decreases in glacier area across many ranges. The western Himalaya, eastern Tibetan mountain, Qilian Shan, Tanggula Shan shows the continued pattern of area decrease whereas Hengduan Shan show pronounced decrease of glacier area by 12% during the decade, highlighting accelerated ice loss.

By the 2010s, the pace of glacier retreat intensified further across most mountain ranges. Many of the mountain ranges such as Hindu Kush, central Himalaya and Gangdise Mountain shows continued decline in glacier area, with majority (11 out of 16) of mountain ranges experiencing glacier area reductions exceeding 5% over the decade. Notably, the Hengduan Shan consistently exhibited substantial glacier area loss, with a cumulative decline of nearly 16% from 2010 to 2020 alone.

Overall, these trends underscore the profound impact of climate change on mountain glaciers. The trend of glacier area retreat shows increasing in recent decades. This dataset provides compelling evidence on ongoing changes in the mountain environment. Further detailed information on distribution and changes in each mountain range is provided in below sections.

FIGURE 4.2 INTERDECADAL CHANGE IN GLACIER AREA ACROSS SUB-MOUNTAIN RANGES IN THE HKH REGION.

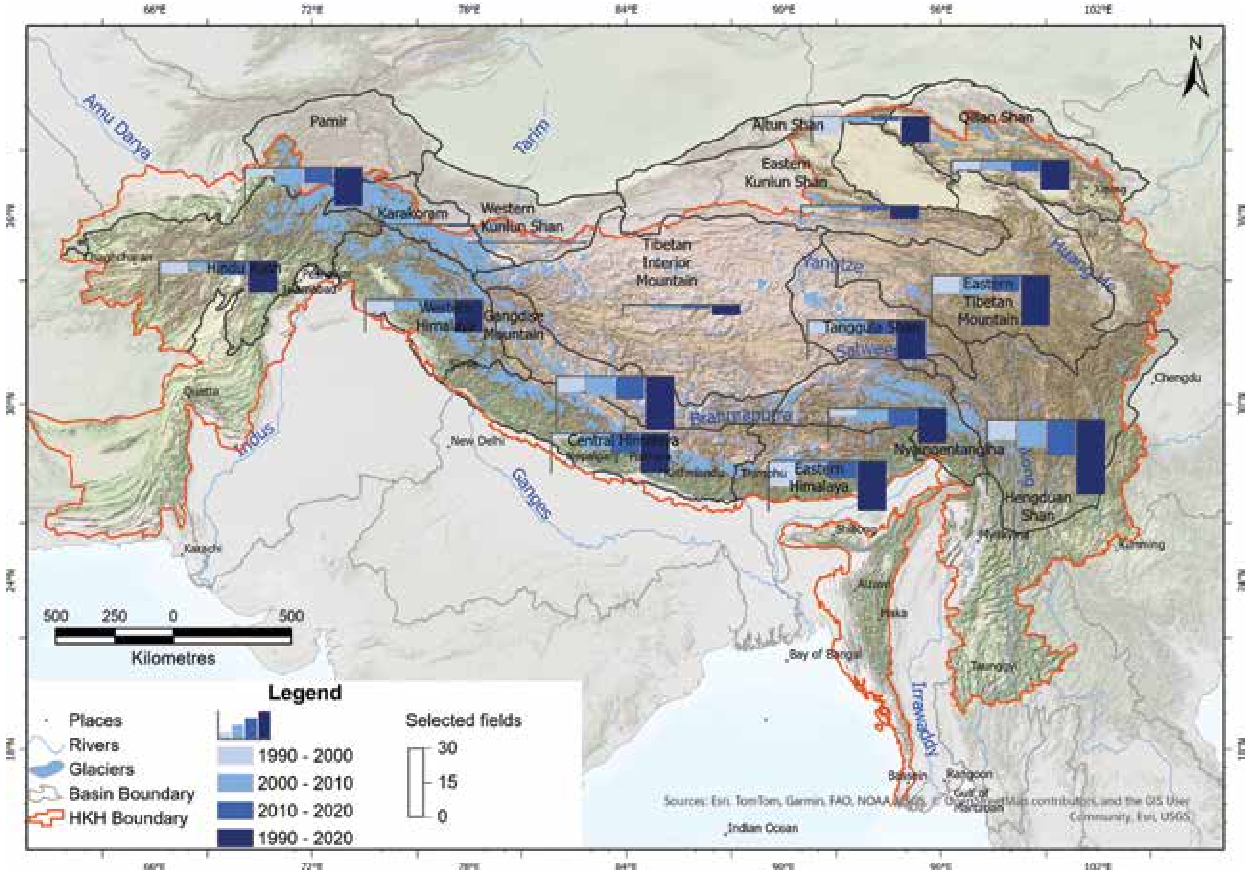


TABLE 4.2 DECADAL CHANGES IN GLACIER NUMBER AND AREA ACROSS MOUNTAIN RANGES IN THE HINDU KUSH HIMALAYA (1990–2020).

SN	Mountain ranges	Glacier number				Glacier area (km²)				Percentage change in glacier numbers (Area)			
		1990	2000	2010	2020	1990	2000	2010	2020	1990 – 2000	2000 – 2010	2010 – 2020	1990 – 2020
1.	Hindu Kush	5,084	5,068	5,083	5,071	3,366.98	3,297.95	3,192.73	3,001.59	-0.3 (-2.1)	0.3 (-3.2)	-0.2 (-6.0)	-0.3 (-10.9)
2.	Karakoram	9,044	9,022	9,076	9,067	14,901.47	14,853.74	14,754.28	14,653.28	-0.2 (-0.3)	0.6 (-0.7)	-0.1 (-0.7)	0.3 (-1.7)
3.	Western Himalaya	12,492	12,529	12,616	12,577	8,964.83	8,671.58	8,316.79	7,878.44	0.3 (-3.3)	0.7 (-4.1)	-0.3 (-5.3)	0.7 (-12.1)
4.	Central Himalaya	8,634	8,863	8,770	8,722	10,317.51	9,650.77	8,956.11	8,184.81	2.7 (-6.5)	-1.1 (-7.2)	-0.6 (-8.6)	1.0 (-20.7)
5.	Eastern Himalaya	3,557	3,684	3,601	3,401	3,463.04	3,278.81	3,131.80	2,886.34	3.6 (-5.3)	-2.3 (-4.5)	-5.6 (-7.8)	-4.4 (-16.7)
6.	Gangdise	3,637	3,645	3,638	3,514	1,484.38	1,381.01	1,262.74	1,135.65	0.2 (-7)	-0.2 (-8.6)	-3.4 (-10.1)	-3.4 (-23.5)
7.	Nyainqêntanglha	8,377	8,379	8,241	7,971	7,145.03	6,926.03	6,559.57	6,079.60	0.0 (-3.1)	-1.7 (-5.3)	-3.3 (-7.3)	-4.9 (-14.9)
8.	Hengduan Shan	2,636	2,595	2,461	2,239	1,465.74	1,334.99	1,173.02	985.86	-1.6 (-8.9)	-5.2 (-12.1)	-9.0 (-16.0)	-15.1 (-32.7)
9.	Tanggula Shan	1,996	1,938	1,798	1,697	2,053.65	1,945.97	1,819.32	1,702.91	-2.9 (-5.2)	-7.2 (-6.5)	-5.6 (-6.4)	-15.0 (-17.1)
10.	Tibetan Interior	3,413	3,396	3,418	3,413	3,871.68	3,826.87	3,759.80	3,702.51	-0.5 (-1.2)	0.7 (-1.8)	-0.2 (-1.5)	0.0 (-4.4)
11.	Eastern Tibetan	695	654	607	580	383.81	353.00	322.93	299.17	-5.9 (-8.0)	-7.2 (-8.5)	-4.5 (-7.4)	-16.6 (-22.1)
12.	Qilian Shan	1,551	1,541	1,518	1,490	1,171.76	1,118.16	1,071.40	1,016.87	-0.6 (-4.6)	-1.5 (-4.2)	-1.8 (-5.1)	-3.9 (-13.2)
13.	Eastern Kunlun Shan	1,311	1,301	1,295	1,288	1,484.94	1,452.12	1,426.77	1,397.40	-0.8 (-2.2)	-0.5 (-1.8)	-0.5 (-2.1)	-1.8 (-5.9)
14.	Western Kunlun Shan	1,012	1,015	1,014	1,012	1,899.24	1,901.85	1,902.67	1,897.94	0.3 (0.1)	-0.1 (0.04)	-0.2 (-0.3)	0.0 (-0.1)
15.	Pamir	1,740	1,755	1,740	1,710	1,139.54	1,099.08	1,019.26	952.65	0.9 (-3.6)	-0.9 (-7.3)	-1.7 (-6.5)	-1.7 (-16.4)
16.	Altun Shan	9	9	9	9	7.93	7.31	7.14	7.01	0.0 (-7.8)	0.0 (-2.2)	0.0 (-2.0)	0.0(-11.6)

4.1 Hindu Kush

This mountain range forms the western section of the HKH region. It stretches across Afghanistan from its central part and reaching into northern Pakistan and Tajikistan. The upper ends on the north, it fortifies the Pamir Mountains, near the point where the frontiers of Afghanistan, China, and Pakistan, the formidable Karakoram Range, creating a formidable natural boundary. Towards its southern end, it connects harmoniously with the Spin Ghar Range, uniting with the meandering Kabul River. Figure 4.3 shows the distribution of glaciers and extent of the Hindu Kush Mountain range within the HKH region.

Glacier distribution in 2020

As of 2020, a total of 5,071 glaciers were mapped, covering an area of 3,001.59 km² and estimated ice reserves of 222.2 km³. This is almost 8% and 5.4% of total number of glacier and glacier area in the HKH region. The size of the glaciers in this mountain range is comparatively smaller, with an average size of 0.6 km². It spans from latitude 34.575° N to 36.969° N and longitude 67.631° E to 74.311° E.

The size of the glaciers ranges from 0.02 to 99.8 km². Figure 4.4 provides a comprehensive overview of the different area class distribution of glaciers in the Hindu Kush Mountain range. Most of the glaciers (79%) are smaller in size, each covering less than 0.5 km² (Class 1). Despite their high number, these glaciers only cover 19% of the total glacier area and contain 6% of the total estimated ice reserves. In contrast, the larger glaciers with area greater than or equal to 10 km² are few (1%) but they occupy a significant portion of total glacier area (28%) and hold the majority of the estimated ice reserves (54%). The mid-sized glaciers ranging from 1 to 5 km² (Class 3) contribute substantially to total glacier area (32%) and estimated ice reserves (24%), though they constitute only 9% of the total glaciers in the Hindu Kush Mountain range. The average glacier area varies significantly across different size classes, with the smallest glacier size class averaging 0.1 km² to largest glacier size class averaging 24.3 km². Overall, the distribution shows inverse distribution in glacier number and area (Figure 4.4).

FIGURE 4.3 MAP SHOWING THE GLACIER DISTRIBUTION AND EXTENT OF THE HINDU KUSH MOUNTAIN RANGE IN THE HKH.

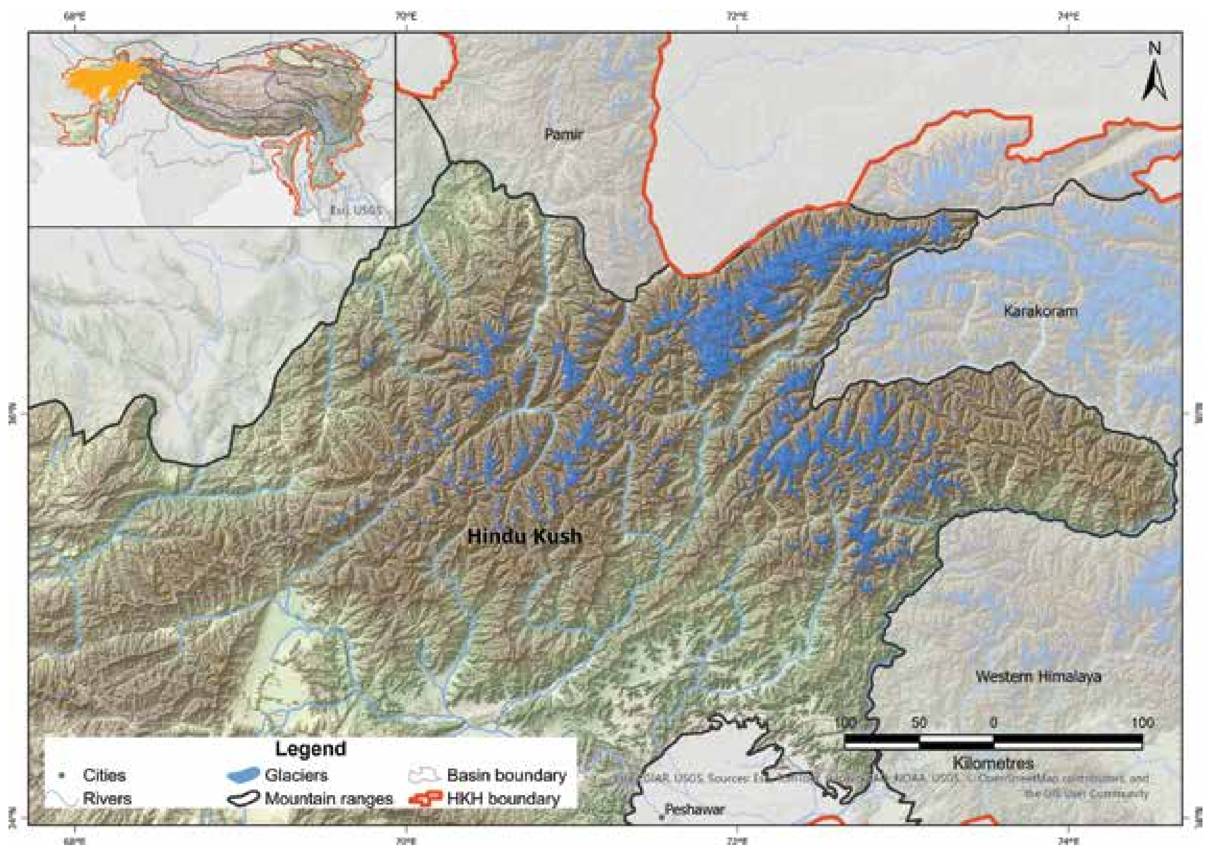
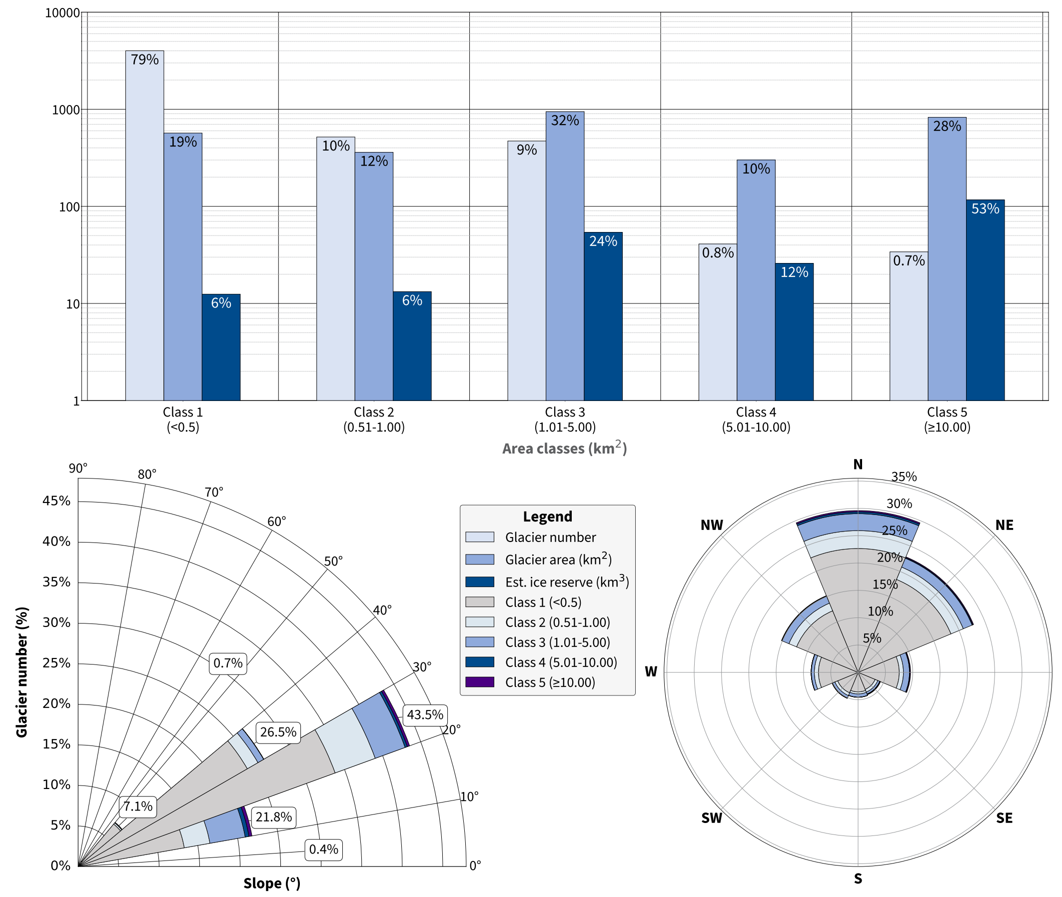


FIGURE 4.4 **GLACIER NUMBER, AREA AND ESTIMATED ICE RESERVES BY GLACIER AREA SIZE-CLASS AND DISTRIBUTION OF GLACIERS BY MEAN SLOPE AND ASPECTS IN THE HINDU KUSH MOUNTAIN RANGE.**

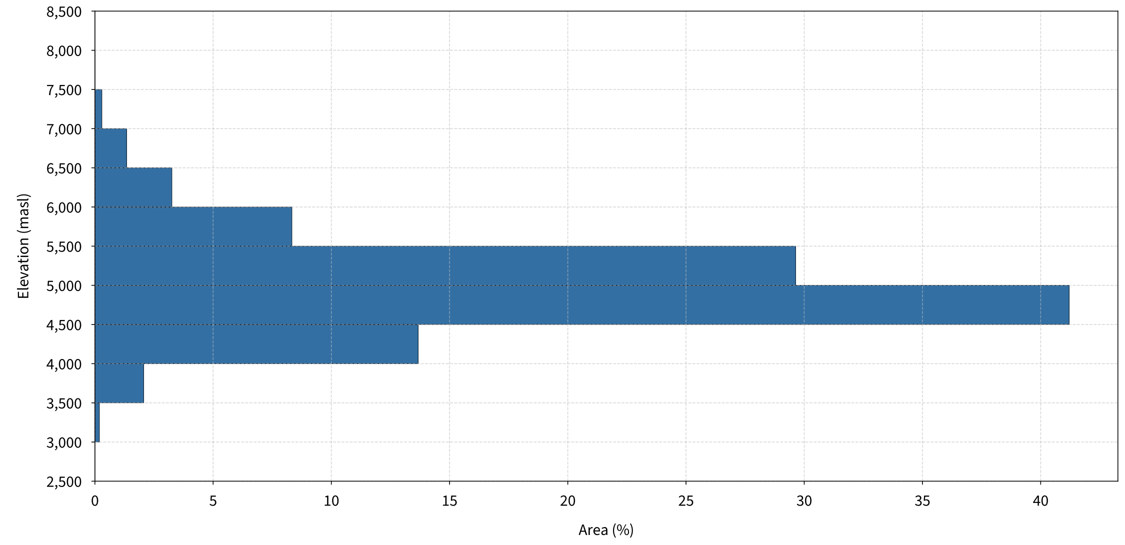


The glaciers in this mountain range are located at elevations ranging from 3,000 to 7,553 masl. Almost 93% of the overall glacier area lies between 4,000 and 6,000 masl with significant portion (more than 41%) being concentrated between 4,500 to 5,000 masl. The glacier area coverage below 4,000 is just 2.3% and above 6,000 masl is about 4.9% of the total glacier area in this mountain range. The largest glacier in the region lies at an elevation between 3,672 and 7,343 masl. The elevation wise distribution of glacier area is shown in Figure 4.5.

Further to understand the topographic characteristics of the glaciers, the glaciers are categorised into six different slope classes and eight aspects considering the mean values of each individual glacier's slope and aspect (Figure 4.4). The majority of glaciers are concentrated in the slope ranges of 10° – 20° and 20° – 30°, accounting for 62% of the total number of glaciers in the mountain range. These slope ranges also dominate in terms of total area and total estimated ice reserves, with the slope class of 10° – 20° alone comprising 41% and 49% of the total area and estimated ice reserves in the mountain range respectively. In contrast, the steeper slope ranges host fewer glaciers and contribute less to overall glacier area and estimated ice reserves. For instance, the slope range 30° – 40° contains 28% of the glaciers, but they only contribute 11% and 5% of the total glacier area and estimated ice reserves respectively. Glaciers on very steep slopes, such as the 50° – 60° and >60° classes, are rare, comprising just 1% and 0.02% of the total glacier number, respectively. This pattern indicates that the lower to moderate slopes are more favourable for glacier formation and stability in the region.

The size verses slope ranges of glaciers also show the slope ranges of 10° – 20° and 20°– 30° dominance in hosting substantial glaciers in terms of glacier numbers, area and estimate ice reserves. Large glaciers greater than 5 km² primarily occupying in 10° – 20° and 20° – 30° slope classes, with notably

FIGURE 4.5 **ELEVATION WISE DISTRICBUTION OF GLACIER AREA IN THE HINDU-KUSH MOUNTAIN RANGE.**



higher percentage of glacier number, area and estimated ice reserves in the 10° – 20° slopes. The smaller (<0.5 km²) and moderate sized (0.5 – 1.0 and 1.0 – 5.0 km²) also dominated in the slope class ranges from 10° – 20° and 20° – 30° with higher percentage of number and area distribution is in 20° – 30° slope. This distribution suggests that the geomorphological and climatic conditions associated with moderate slopes (10° – 30°) are more favourable for glacier sustenance, reflecting the intricate interplay between topography and glaciation processes in the region.

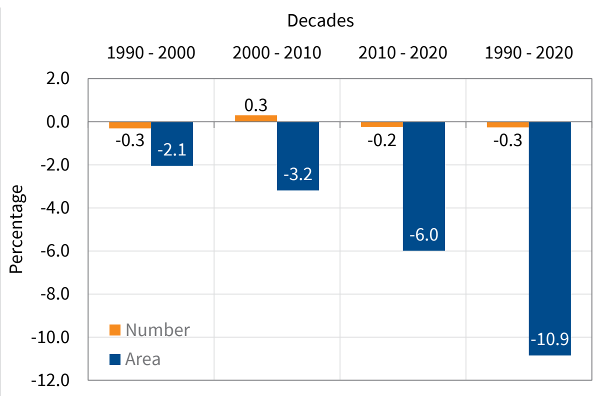
In terms of mean aspects of the glaciers, the northern (N) and northeastern (NE) aspects dominate glacier coverage in this mountain range, with the northern aspect containing nearly 30% of the total glaciers and the largest glacier area, accounting for almost 32% of the total glacier area in the Hindu Kush (Figure 4.4). Additionally, this aspect holds over 28% of the total estimated ice reserves, making it the most significant in terms of glacial storage. The northeastern aspect follows closely, hosting 23% of the glaciers, covering 24% of the glacier area, and contributing 28% to the total estimated ice reserves. The predominance of glaciers in these aspects suggests that reduced direct sunlight exposure and lower radiation levels play a crucial role in glacier preservation.

In comparison, the eastern (E) and western (W) aspects have a relatively similar number of glaciers, with a slightly higher number in the eastern aspect. However, the eastern aspect has a significantly larger glacier area and estimated ice reserves, nearly three times higher than in the western aspect. The eastern aspect hosts 10% of the total glaciers, covering 14% of the glacier area and containing 19% of the total estimated ice reserves. This is further emphasised by the highest average glacier size in the region, at 0.84 km² per glacier, indicating the presence of larger individual glaciers in this aspect.

The southeastern (SE), southern (S), and southwestern (SW) aspects exhibit a relatively equal number of glaciers, each containing between 4% to 5% of the total glacier count. The glacier area in these aspects is also similar, ranging from 4% to 6% of the total glacier area, with the southeastern aspect having a slightly higher share (6%). These aspects, which are more exposed to direct sunlight, are expected to experience higher melting rates, impacting glacier stability.

In contrast, the northwestern (NW) aspect shows moderate glacier distribution, containing 15% of the total glaciers, but covering only 13% of the total glacier area and contributing 10% to the total estimated ice reserves. This suggests that although the northwestern aspect has a higher number of glaciers, they tend to be smaller in size compared to those in the northern and northeastern aspects, which is also indicated by lower average area per glacier of 0.49 km².

FIGURE 4.6 DECADAL CHANGES OF GLACIER NUMBERS AND AREAS IN THE HINDU KUSH MOUNTAIN RANGE.



Overall, the northern and northeastern aspects remain the primary glacier cover zones, holding the largest glacier area and estimated ice reserves. The eastern and southeastern aspects contain relatively larger glaciers compared to other orientations, while the southern, southwestern and western aspects have lower glacier presence and reduced estimated ice reserves, making them more vulnerable to glacial retreat. The northwestern aspect, despite hosting a significant number of glaciers, lags in terms of total area coverage and estimated ice reserves, highlighting the impact of aspect orientation on glacier distribution.

Decadal glacier changes from 1990 to 2020

The glaciers in the Hindu Kush Mountain range experienced a collective reduction in number, area and estimated ice reserves over the past 30 years from 1990s to 2020. Specifically, there was an about 0.3% decrease in number and an almost 11% glacier area loss during this period (Figure 4.6). Similar percentage of glacier area retreat is observed in previously published report on decadal glacier areas changes in Afghanistan (Maharjan et al, 2021). It is also observed that the glacier area loss percentage has increased from 2% in 1990s – 2000 to about 6% in the recent decade of 2010 – 2020. Whereas the decrease in glacier numbers was notably higher in the earlier decade of 1990 – 2000 and has only marginally increased during 2000 – 2010. This could be due to the disappearance and retreat of smaller glaciers and fragmentation of larger ones.

In terms of glacier size classes, there was a consistent negative trend in glacier number and area across all size classes (Figure 4.7). Smaller glaciers Class 1 (< 0.5 km^2) were the exception, showing an increase in number by 4.4% despite experiencing a 6.6% reduction in area. The increases in number occurred consistently over the three decades, with a 0.5% rise from 1990 to 2000, 1.9% from 2000 to 2010, and 2.0% from 2010 to 2020. Conversely, the area of these smaller glaciers decreased in all decades, with a 1.1% reduction in 1990 -2000, 0.3% from 2000 to 2010 and a more significant retreat of 5% in recent decades from 2010 to 2020. This trend of increasing numbers suggests the fragmentation of larger glaciers into smaller ones as they lose mass and the decrease in glacier area indicates a disappearance or shrinking below the area threshold.

Conversely, larger glaciers experienced substantial declines in number and area, with the most significant reductions observed in glaciers sized Class 2 (0.5 – 1.00 km^2) and Class 3 (1 – 5 km^2) with reduction of both glacier number and area by about 16% and 14% respectively. This rate of change in the glacier area is also related to the increasing number of smaller glaciers. As the area of larger glaciers reduces, portions of them may fragment or shrink into smaller glaciers, contributing to the rise in the number of glaciers in the smaller size category. The Class 4 (5 – 10 km^2) class experienced a 12.8% reduction in number and 10% reduction in area, while the largest glaciers Class 5 (≥10 km^2) shows an 8.1% decrease in number and 7.4% of area decrease.

The decadal rate also shows same pattern of the reduction in number and area across each size classes, with higher rate in mid-sized glaciers (0.5 – 1 km^2, 1 – 5 km^2 and 5 – 10 km^2) and increasing rate of number in smallest sized one (<0.5 km^2). Figure 4.7 illustrates a broad retreat of glaciers of all sizes, with mid-sized (Class 2, 3 and 4) glaciers experiencing the steepest declines.

The analysis of glacier area changes shows the consistent decline across different elevation zones from 1990 to 2020 (Figure 4.8). The rate of change accelerated over time, especially in the last decade, indicating increasing environmental pressures. The lowest elevation zone (3,000 – 4,500 masl), experienced the most significant losses, with the 3,000 – 3,500 masl range shrinking by 19.2%, indicating a rapid retreat. The decadal change rates for this range also show increasing severity, with a -6.8% change per decade. However, the absolute area changes are less compared to the elevation range above 4,500 masl to 5,500 masl. The lowest elevation of glaciers also clearly indicates the shifting of glacier snouts from 3,019 masl to 3,036 masl, indicating the retreat of glacier area completely below 3,036 masl.

In contrast, the area percentage loss at elevation ranges from 4,500 – 5,500 masl showed steady decline, with notable acceleration between 2010 and 2020, indicating the increasing trend of glacier area loss. But in terms of absolute area loss, this elevation range constitutes the most impacted areas, losing almost 265 km^2 of glacier area over the last three decades. The elevation range of 4,500 – 5,000 masl experienced the largest absolute area decrease, losing 193.63 km^2 over the 30-year period (Table 4.3).

The higher elevation ranges above 6,000 masl experienced minimal changes, indicating greater stability, though they may still be vulnerable to long-term climatic effects. The elevation range 7,500 – 8,000 masl remained unchanged. Overall, the data highlights a clear pattern of increasing area loss, especially in lower and mid-elevation zones, pointing to the significant impact of climate change over the past three decades.

FIGURE 4.7 INTER DECADAL CHANGES OF GLACIER NUMBER AND AREA ACROSS SIZE CLASS IN THE HINDU KUSH MOUNTAIN RANGE.

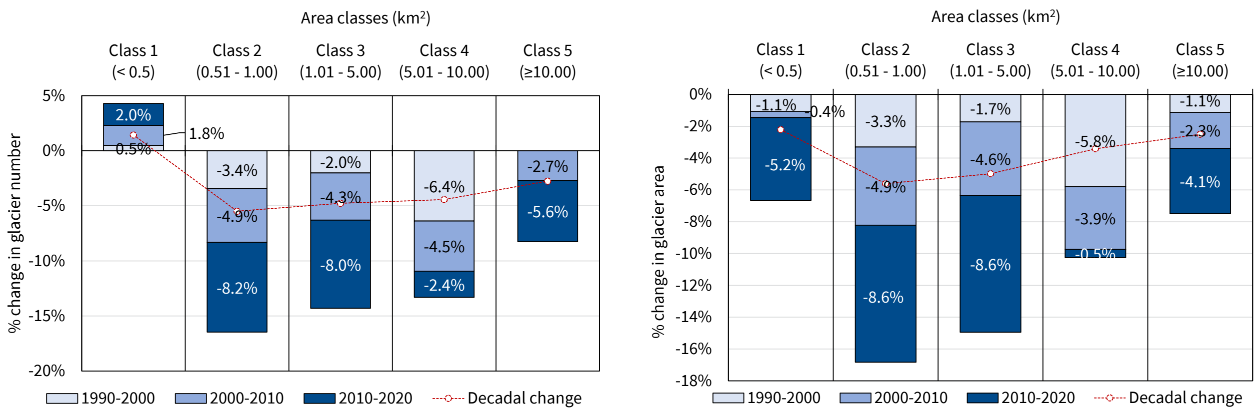


FIGURE 4.8 CHANGE IN GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE HINDU KUSH MOUNTAIN RANGE.

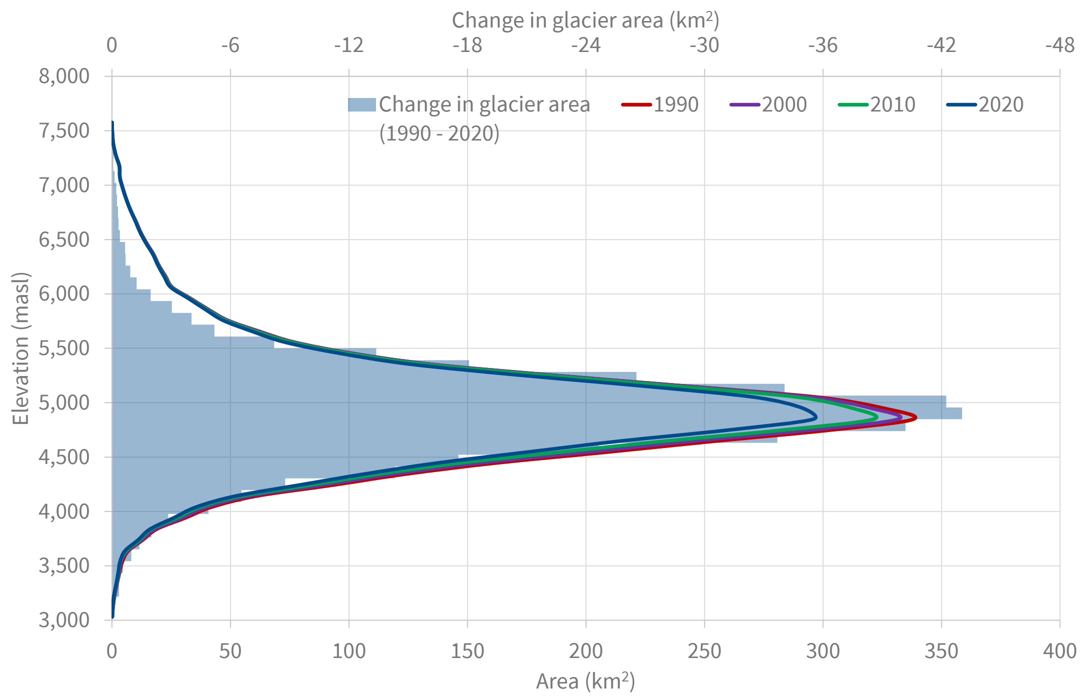
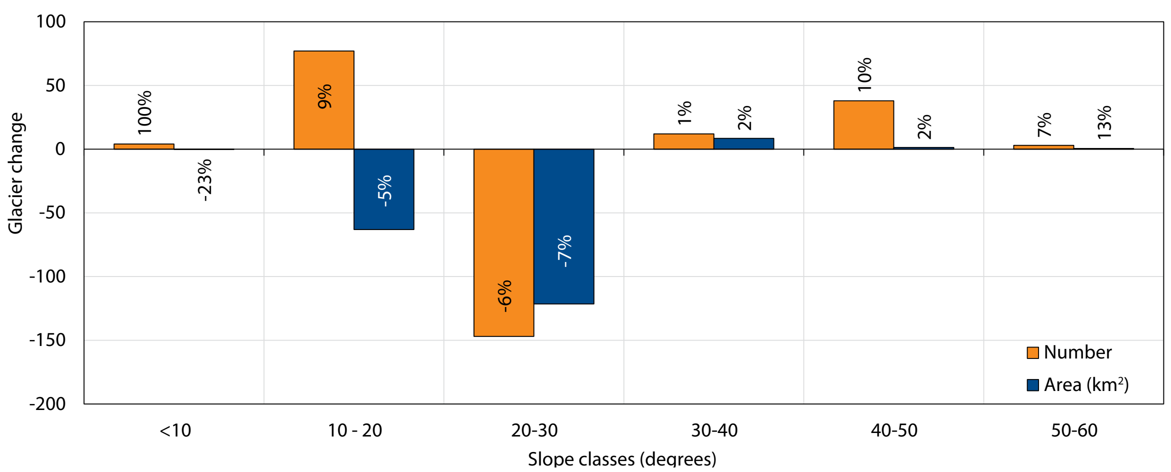


TABLE 4.3	GLACIER AREA DISTRIBUTION AND RATE OF CHANGE ACROSS 500M ELEVATION RANGES FROM 1990 TO 2020 IN THE HINDU KUSH MOUNTAIN RANGE.

Elevation range (masl)	Area (km²)				Decadal change in area (%)				Interdecadal rate of change (%)
	1990	2000	2010	2020	1990–2000	2000–2010	2010–2020	1990–2020	
3,000 - 3,500	7.16	6.76	6.30	5.79	-5.6	-6.7	-8.2	-19.2	-6.8
3,500 - 4,000	74.05	70.42	65.39	61.93	-4.9	-7.1	-5.3	-16.4	-5.8
4,000 - 4,500	482.33	460.32	435.18	410.35	-4.6	-5.5	-5.7	-14.9	-5.2
4,500 - 5,000	1,430.45	1,392.31	1,339.27	1,236.82	-2.7	-3.8	-7.6	-13.5	-4.7
5,000 - 5,500	961.26	958.16	941.54	889.56	-0.3	-1.7	-5.5	-7.5	-2.5
5,500 - 6,000	261.44	260.69	256.90	250.16	-0.3	-1.5	-2.6	-4.3	-1.5
6,000 - 6,500	100.22	99.70	98.81	97.79	-0.5	-0.9	-1.0	-2.4	-0.8
6,500 - 7,000	41.01	40.56	40.39	40.24	-1.1	-0.4	-0.4	-1.9	-0.6
7,000 - 7,500	9.04	9.00	8.91	8.90	-0.4	-1.1	0.0	-1.5	-0.5
7,500 - 8,000	0.04	0.04	0.04	0.04	-2.4	2.5	0.0	0.0	0.0
Total	3,366.98	3,297.95	3,192.73	3,001.59	-2.1	-3.2	-6.0	-10.9	-3.7

FIGURE 4.9 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES IN THE HINDU KUSH MOUNTAIN RANGE.



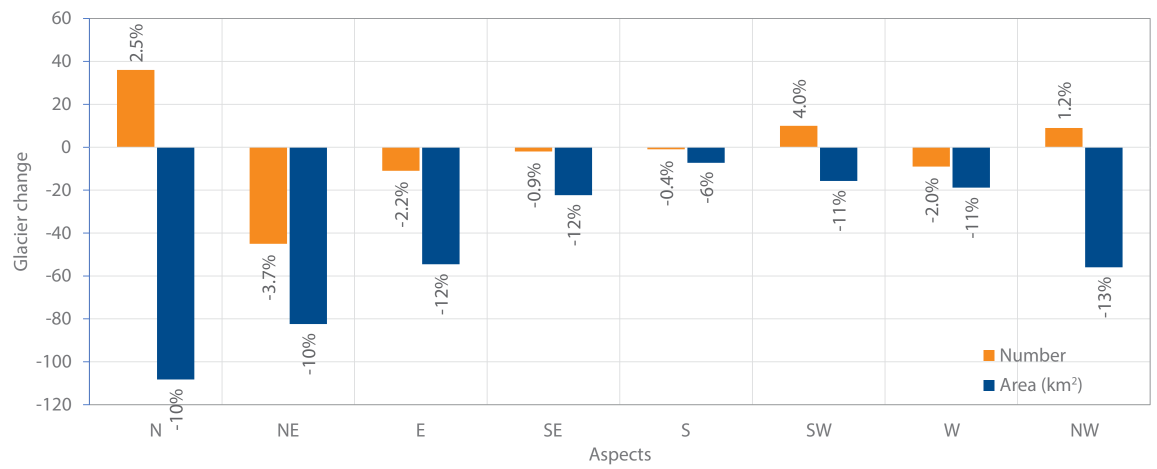
The analysis of glacier changes across various mean slope classes reveals both dynamic shifts and concerning trends. The most dramatic number and area loss is observed in the 20° – 30° slope class, which showed 6% of number and 7% of area loss within three decades (Figure 4.9).

Interestingly, the <10° and 10–20° classes, despite gaining in number, experienced notable area shrinkage, which further supports the trend of glacier fragmentation or the retreat of larger ice masses. Meanwhile, the distribution and changes of number and area in steeper slopes (above 50°) showed minimal, likely due to their high-altitude, colder environments that buffer against climate-induced melt. Overall, the observed patterns across slope classes reflect widespread glacier retreat and fragmentation, often resulting in shifts in average slope as larger glaciers disintegrate. This is evidenced by the increasing number of glaciers in both lower and higher slope classes, accompanied by a consistent decrease in area, indicating both retreat and restructuring of glacier mass over time.

The aspect-wise analysis of glacier change in the Hindu Kush mountains reveals notable spatial differences in glacier dynamics (Figure 4.10). Glaciers facing northern (N) aspect showed the most prominent increase in number by 36 glaciers over three decades, equivalent to a 2.5% increase, despite a substantial area loss of 108.26 km² (–10.2%). Conversely, glaciers with a northeastern (NE) aspect experienced the most significant numerical loss, decreasing by 45 glaciers (–3.7%), alongside an area reduction of 82.40 km² (–10.39%), highlighting vulnerability despite relatively favourable solar exposure.

AUTOMATIC WEATHER STATION AT RIKHA SAMBA GLACIER, HIDDEN VALLEY, MUSTANG, NEPAL

FIGURE 4.10 GLACIER NUMBER AND AREA CHANGES ACROSS VARIOUS MEAN ASPECTS OVER THREE DECADES IN HINDU-KUSH MOUNTAIN RANGE.



Eastern aspect glaciers (E) showed a mixed trend, although glacier numbers slightly decreased by 11 glaciers (–2.21%), they experienced substantial area loss of 54.55 km², which is equivalent to about 12% loss, implying retreat of larger ice masses. A similar pattern is seen for southeastern (SE) aspect, with a minor decline of glacier count but significant area loss by 22.32 km² (11.86% loss), reflecting heightened sensitivity to exposure in solar radiation. Interestingly, southern (S) aspect showed relative stability in glacier number with losing one glacier and modest area loss of –7.27 km², equal to (6.34% loss) over three decades.

Southwestern (SW) and northwestern (NW) aspects present contrasting dynamics. While SW-facing glaciers increased in number by 10 (3.98%), they still saw a notable area decline of 15.75 km² (–11.11%). Northwestern aspect glaciers also gained nine glaciers but exhibited one of the highest area losses of about –56 km², which is about 13% of area loss over three decades, indicating the gain in number doesn't equate to glacier stability. Western aspect (W) showed a consistent decrease in both number and area. Overall, while the glacier number slightly decreases and increases across various mean aspects of the glaciers, the consistent and severe area loss across all aspects emphasised the predominance of glacier shrinkage and fragmentation regardless of orientation. However, the variation in magnitude of glacier area loss suggests that solar exposure and microclimatic conditions linked to aspect play critical roles in glacier response to climate change.

MAJESTIC DRANG-DRUNG GLACIER, ONE OF THE LARGEST GLACIERS IN THE ZANSKAR VALLEY, LADAKH, WESTERN HIMALAYA

4.2 Karakoram

The Karakoram Mountain range form the north-western section of the HKH region. It is extended from the Wakhan corridor of Afghanistan in north-west and occupies a major part of Gilgit-Baltistan region of Pakistan then extending into the Ladakh, India and Aksai chin region of China at south and eastern part. The Indus, Gilgit, and Shyok Rivers form the entire southern boundary of the Karakoram Mountain range and separate it from the northwestern edge of the Himalayan range. It forms the second highest mountain range consisting of world's second highest mountain peak, K2 (8,611 masl). The mountain range has a length of about 500 km and a width of about 240 km. The average elevation of the Karakoram Mountain range is about 6,100 m and overall, there are four peaks with elevations higher than 8,000 m and about 18 peaks that have an elevation of more than 7,500 m. The topography of the mountain ranges is characterised by long slopes, craggy peaks and taluses. The southern slopes of the Karakoram ranges are long and steep, while its northern slopes are comparatively short and steep. Figure 4.11 shows the spatial distribution of glaciers and extent of the Karakoram Mountain range within the HKH region.

The mountain range is the most heavily glaciated region in the HKH region, consisting of six out of eight longest glaciers in the world whose length is greater than 50 km. Some of the longest glaciers are the Siachen Glacier (~85.9 km), Biafo Glacier (72.9 km), Baltoro Glacier (65.4 km long), Batura Glacier (59.2 km), Hispar Glacier (57.16 km), Chogo Lungma Glacier (47.5 km) and Kondus Glacier (42.3 km).

Glacier distribution in 2020

The Karakoram Mountain range stands out as the most heavily glaciated region within the HKH region. A dataset based on 2020 Landsat images reveals that glaciers cover nearly 18% of the total area of this mountain range. A detailed analysis identified 9,067 glaciers, collectively spanning 14,653.28 km^2, with an estimated ice reserve of 2,508 km^3. These numbers represent over 14% of the total number and 26.3% of the total area of glaciers in the HKH region.

FIGURE 4.11 MAP SHOWING THE GLACIER DISTRIBUTION AND EXTENT OF THE KARAKORAM MOUNTAIN RANGE IN THE HKH.

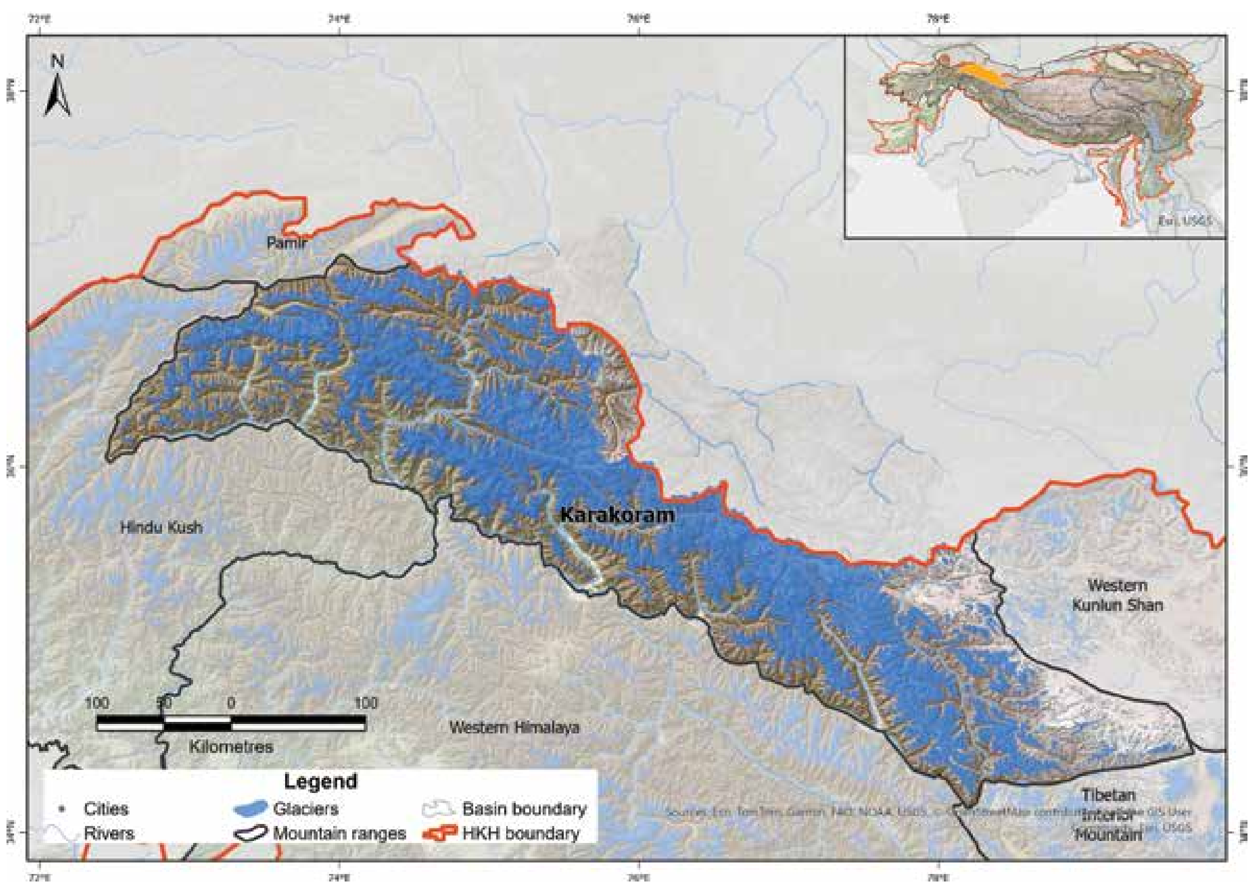
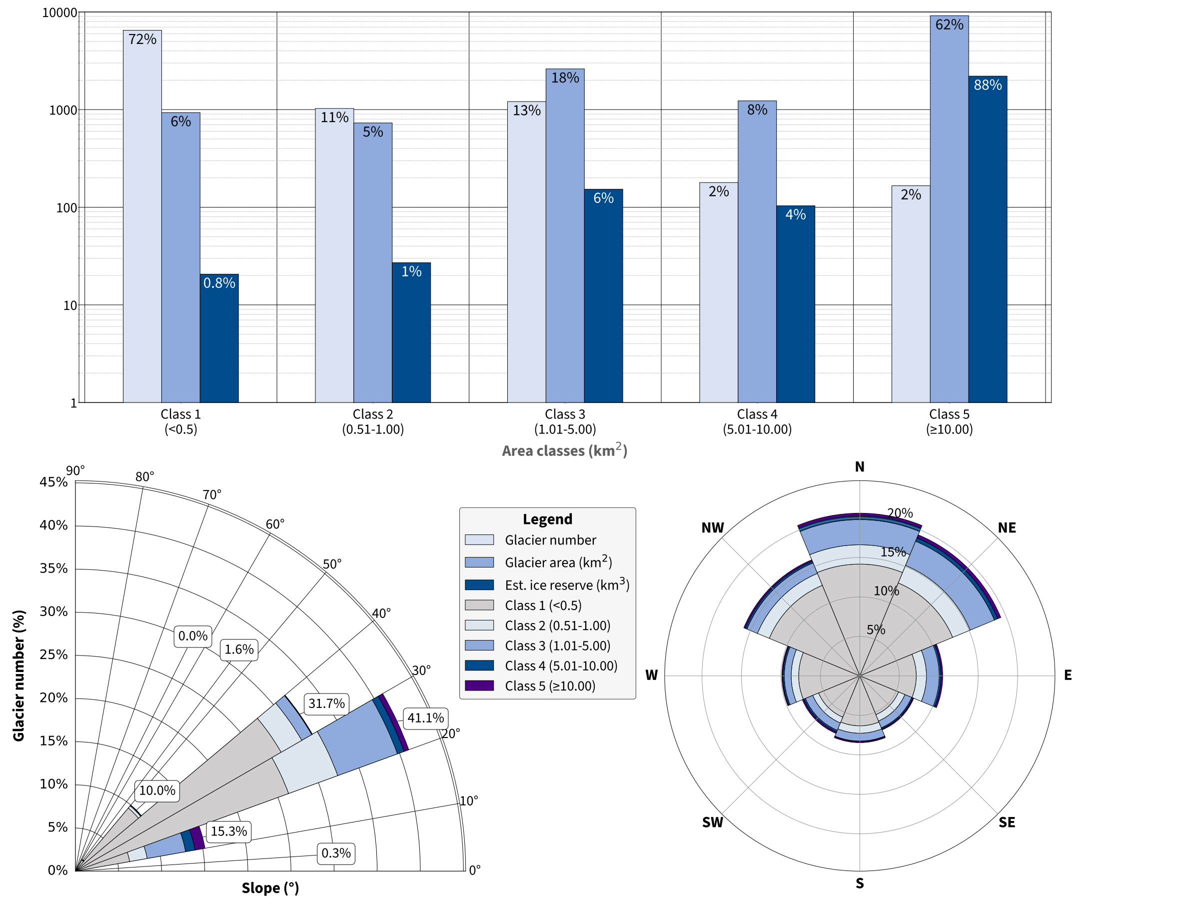


FIGURE 4.12 GLACIER NUMBER, AREA AND ESTIMATED ICE RESERVES BY AREA SIZE CLASS AND ITS DISTRIBUTION ACROSS MEAN SLOPE AND ASPECTS IN THE KARAKORAM MOUNTAIN RANGE.



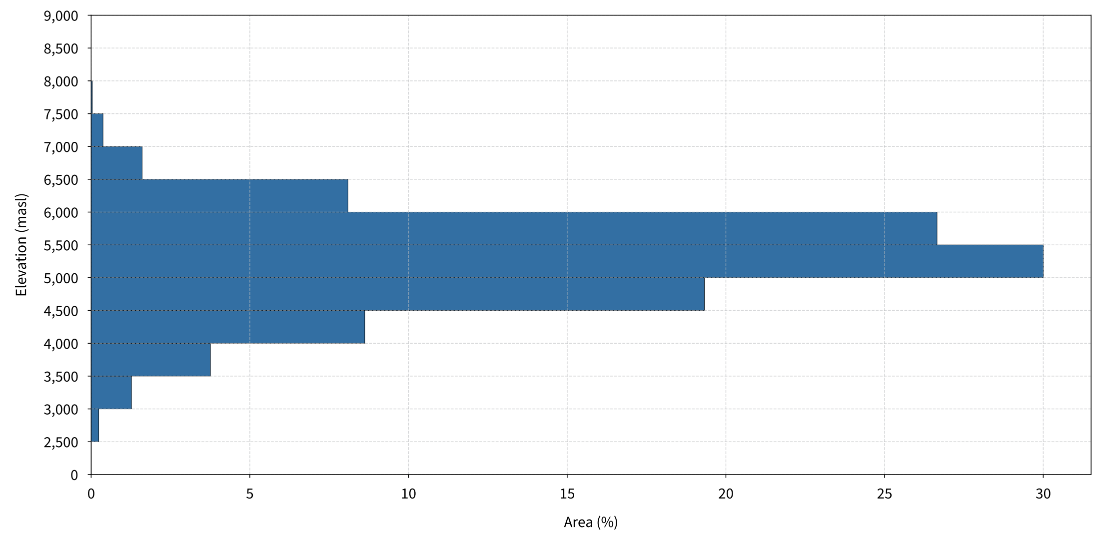
Among these glaciers, the Siachen Glacier, the largest in the HKH region, covers approximately 1,008 km². The average size of glaciers in the Karakoram is notably larger compared to other mountain ranges in the HKH, underscoring the significant presence of large glaciers. Moreover, the Karakoram has 18 of the 25 largest glaciers in the HKH, each covering an area greater than or equal to 100 km², with nine of them exceeding 200 km² in area.

The glaciers in this mountain range vary significantly in size, spanning from the smallest to the largest in the HKH region (Figure 4.12). The smallest glaciers, classified as Class 1 (<0.5 km²), comprise approximately 71% of the total number of glaciers in this range. Despite their abundance, they cover only 6% of the total glacier area and represent just 1% of the estimated ice reserves of the mountain range. In contrast, the largest glaciers, classified as Class 5 (≥10.00 km²), are fewer in number (166 glaciers, 1%), yet they dominate more than 62% of the total glacier area and hold over 88% of the total estimated ice reserves. Even the 18 largest glaciers, each greater than 100 km², collectively cover more than one-third (almost 36%) of the total glacier area in the mountain range.

The mid-sized glaciers, categorised as Class 3 (1 to 5 km²), constitute the second highest number of glaciers and contribute a significant 18% to the total glacier area. Class 2 and Class 4 glaciers, which are smaller and larger than Class 3 respectively, account for 11% and 2% of the total number of glaciers, and 5% and 8% of the glacier area within this mountain range.

The glaciers in this mountain range stretch from 2,329 to 8,570 masl elevation, which is the lowest and second highest elevation of the glaciers in the HKH region. The distribution of glacier area by elevation reveals that the majority of glacier area (76%) is concentrated at an elevation range from 4,500 to 6,000 masl, with the highest coverage (30%) at an elevation range from 5,000 to 5,500 masl and 19% and 27% coverages at below (4,500 – 5,000 masl) and above (5,500 – 6,000 masl) of this elevation zone (Figure 4.13).

FIGURE 4.13 GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN THE KARAKORAM MOUNTAIN RANGE.



Glaciers at lower elevations (below 4,000 masl) are relatively less abundant and the area coverage percentage steadily decreases as elevation decreases. This decline reflects the diminishing suitability for glacier formation at lower altitudes where temperatures are generally warmer and less conducive to sustained ice accumulation. A similar pattern of sharp decreasing glacier area coverage percentage beyond 6,000 masl is observed, with just 2% of the glacier area distributed above 6,500 masl elevation. This decline in glacier area distribution is likely due to the steeper terrain conditions, where limited accumulation zones restrict the formation and existence of glacier ice.

Further, the glacier distribution by various mean slope classes reveals that the slope range of 10° - 20° dominated the number of glaciers (at 12%) covering more than half (55%) of the total glacier area in the Karakoram Mountain range. These glaciers also hold the majority (69%) of estimated ice reserves. The second highest contribution is from slope range of 20° – 30° having 40% of the total number of glaciers with 37% of the total glacier area in this mountain range (Figure 4.12). This dominance underscores the importance of moderate slopes in supporting large, voluminous glaciers crucial for hydrological stability and water resources in the Karakoram.

In contrast, higher slope categories (>30°) host more numerous but smaller glaciers. For instance, slopes ranging from 30°– 40° contain 34% of the total glaciers that cover just 7% of total glacier area coverage. The mean slopes above 50° show the minimal contribution to the number of glaciers, glacier area, and (minimum) estimated ice reserves. The mean area per glacier also decreases as slope steepness increases, indicating a trend towards much smaller, more fragmented glaciers on steeper terrain.

The slope verses glacier sized distribution also indicates that the smaller glaciers are more widely distributed across all the slope classes from 10° to 60° slopes, while larger glaciers are concentrated on gentle slopes of 10° to 30° and dominated the total glacierised area. The largest glacier sized Class 5 majorly dominating area coverage of 44% and 18% in 10° – 20° and 20° – 30° slopes respectively. The smaller glacier sized Class 1 dominated in numbers by the same slope classes consisting of 25% and 29% of the total glaciers but its area coverage is considerably less by 0.4% and 2.4% respectively.

In terms of the mean aspect of the glaciers, the northern aspect hosts the largest number of glaciers comprising nearly 21% of the total glaciers and covering about 17% of the total glacier area in the mountain ranges. In contrast, the southern aspects are most prominent in terms of glacier area, covering 18% of the total area and holding 29% of the total estimated ice reserves. While both the southeastern and northeastern aspects contribute significantly to area coverage, each accounting for 15% of the total glacier area, the southeastern aspect has considerably fewer glaciers - less than half of the number in the northeastern aspects. This indicates that glaciers in the southeastern aspect are considerably larger. Notably, both the southeastern and southern aspects are distinguished by their larger average sizes, each exceeding larger than 3.2 km².

The western and eastern aspects each account for approximately 10% of the total number of glaciers and 8% of the total glacier area in the mountain range, with a slightly larger glacier distribution in the western aspect. In comparison, the southwestern aspect covers the same 8% of the total glacier area but has fewer glaciers than in eastern and western aspects, suggesting larger sized glacier distribution than in eastern and western aspects.

Finally, the northwestern aspect encompasses a considerable number of glaciers (16%) and covers nearly 12% of the total glacier area, with an average glacier size of 1.24 km².

Decadal glacier changes from 1990 to 2020

Compared to other mountain ranges, changes in glaciers within this range have been relatively insignificant in both number and area. From 1990 to 2020, the number of glaciers slightly increased, while the total glacier area decreased by only 1.7%, suggesting a stable glacier system. However, examining decadal trends reveals a slight acceleration in the rate of area reduction: from 0.32% between 1990 and 2000 to 0.68% between 2010 and 2020 (Figure 4.14).

Figure 4.15 shows the percentage change in glacier number and area across various glacier area size classes , including the average rate of change per decade, from 1990 to 2020. The number of Class 1 (<0.5 km²) glaciers has increased significantly by 132 reflecting a 2.1% rise over the three decades. However, the total glacier area in this class has decreased by 2.2%, indicating the fragmentation of larger glaciers and shrinkage of glaciers. The rate of increase in number and decrease in glacier areas occur consistently with a higher rate of increase in glacier number (by 1.6%) in the 2000 -2010 period, despite less lower rate of decrease in the glacier area.

In all other glacier size classes, there has been a consistent decline in both the number and area of the glaciers. The Class 2 (0.5 – 1 km²) and Class 3 (1 – 5 km²) glaciers saw the same rate of decrease in glacier numbers , while their total area diminished by 4.2% and 3% respectively over the past three decades. The Class 3 glaciers are under the most significant absolute reduction in both numbers and area. The rate of decline in the glacier area for both of these glacier size-classes has accelerated in recent decades, particularly between 2010 – 2020, vis-à-vis between 1990 – 2000.

Among the different size classes, Class 4 (5 – 10 km²) glaciers have experienced the highest percentage reduction in both numbers and glacier area, while in the largest glacier category of Class 5 (≥10 km²), only one glacier has been lost, with its area decreasing by nearly 40 km² over the same period. Initially, from 1990 to 2000 the glacier area in this class has increased, but it sharply declined in subsequent decades, possibly due to accelerated glacier retreat.

The changes in glacier area across different elevation zones are illustrated in Figure 4.16 and detailed in the Table 4.4. Notably, the most significant glacier reductions occurred below 5,500 masl, while glaciers at higher elevations, particularly above 6,000 masl, remained relatively stable.

FIGURE 4.14 DECADAL CHANGES OF GLACIER NUMBERS AND AREAS IN THE KARAKORUM MOUNTAIN RANGE.

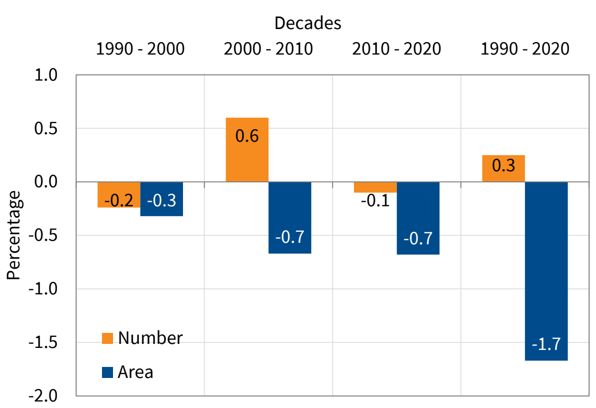


FIGURE 4.15 GLACIER NUMBER AND AREA CHANGES ACROSS SIZE CLASSES OVER THREE DECADES INCLUDING MEAN DECADAL CHANGE RATE IN THE KARAKORAM MOUNTAIN RANGE.

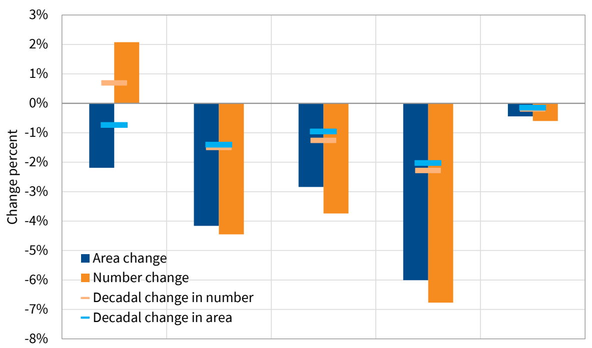


FIGURE 4.16 CHANGE IN GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN THE KARAKORAM MOUNTAIN RANGE FROM 1990 TO 2020.

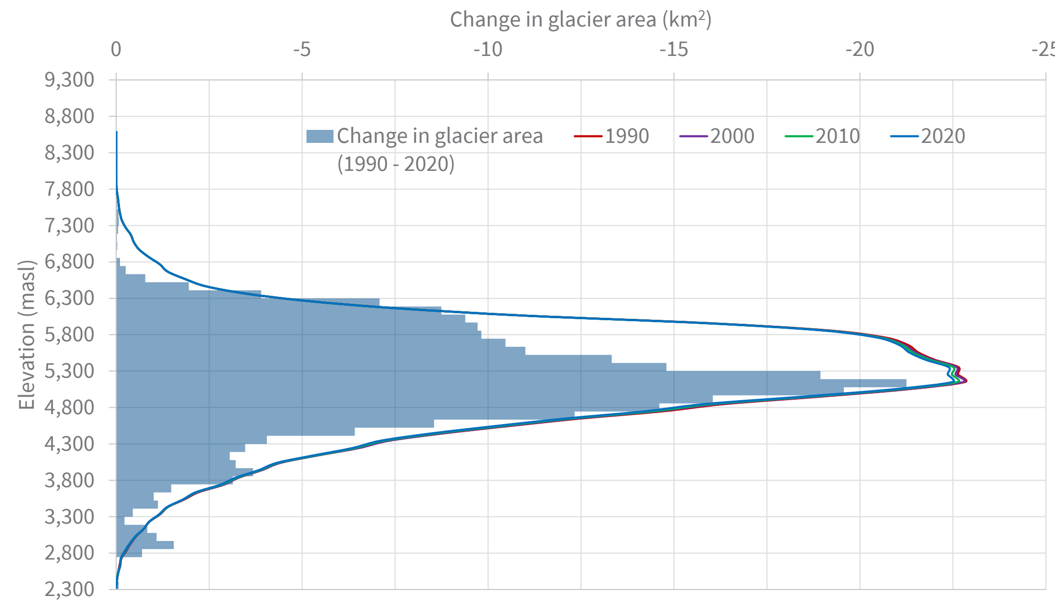


FIGURE 4.4 GLACIER AREA DISTRIBUTION AND PERCENTAGE CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN KARAKORAM MOUNTAIN RANGE.

Elevation range	Area (km²)				Decadal change in area (%)				Interdecadal rate of change (%)
	1990	2000	2010	2020	1990–2000	2000–2010	2010–2020	1990–2020	
<2,500	0.92	1.08	0.80	0.81	17.7	-25.6	1.0	-11.6	-2.3
2,500 – 3,000	37.50	38.22	35.70	35.00	1.9	-6.6	-1.9	-6.7	-2.2
3,000 – 3,500	190.36	189.85	188.48	186.72	-0.3	-0.7	-0.9	-1.9	-0.6
3,500 – 4,000	565.77	564.27	557.26	551.19	-0.3	-1.2	-1.1	-2.6	-0.9
4,000 – 4,500	1,298.12	1,299.45	1,280.19	1,263.25	0.1	-1.5	-1.3	-2.7	-0.9
4,500 – 5,000	2,921.98	2,900.32	2,867.13	2,831.46	-0.7	-1.1	-1.2	-3.1	-1.0
5,000 – 5,500	4,456.69	4,446.88	4,422.41	4,397.10	-0.2	-0.6	-0.6	-1.3	-0.4
5,500 – 6,000	3,944.67	3,930.36	3,918.98	3,905.69	-0.4	-0.3	-0.3	-1.0	-0.3
6,000 – 6,500	1,188.86	1,186.84	1,186.81	1,185.74	-0.2	0.0	-0.1	-0.3	-0.1
6,500 – 7,000	235.65	235.53	235.58	235.41	-0.1	0.0	-0.1	-0.1	0.0
7,000 – 7,500	54.97	54.97	54.95	54.92	0.0	0.0	0.0	-0.1	0.0
7,500 – 8,000	5.61	5.61	5.61	5.61	0.0	0.0	0.0	0.0	0.0
8,000 – 8,500	0.31	0.31	0.31	0.31	0.0	0.0	0.0	0.0	0.0
>8,500	**0.06**	**0.06**	**0.06**	**0.06**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Total	14,901.47	14,853.74	14,754.28	14,653.28	-0.3	-0.7	-0.7	-1.7	-0.6

In the lower elevation zones (below 3,000 masl), there was a substantial glacier area loss over the past three decades. Although there was a slight increase in glacier area from 1990 to 2000, this was followed by significant reductions in subsequent decades. Overall, the glacier area decreased by 11.6% below 2,500 masl and 6.7% between 2,500 and 3,000 masl, with decadal change rates averaging -2.3% and –2.2%, respectively.

The most pronounced absolute glacier area loss occurred between 3,500 and 6,000 masl, peaking between 4,000 and 5,000 masl. Over the three decades from 1990 to 2020, the area loss percentage was consistent across 500 metre elevation zones from 3,500 to 5,000 masl, ranging from 2.6% to 3.1%, with an increasing trend observed in the recent decades. The decadal average area loss in these zones ranged from 0.9% to 1%.

Above 5,000 masl, glaciers experienced minimal changes, with a 1.3% area loss in the 5,000 to 5,500 masl elevation over three decades. Glaciers above 6,000 masl showed negligible changes, indicating that higher elevation zones have remained relatively stable. This stability contrasts with the more pronounced retreat observed at lower elevations, highlighting the greater sensitivity of glaciers to climatic variations at lower altitudes. These trends suggest that glaciers at lower elevations are more vulnerable to climate change, while those at higher elevations remain more stable, likely due to cooler temperatures and less impact from recent climatic changes.

Glacier number and area changes vary significantly across different mean slope classes over three decades. As glaciers retreat and shrink, they often fragment into smaller glaciers, altering their mean slopes.

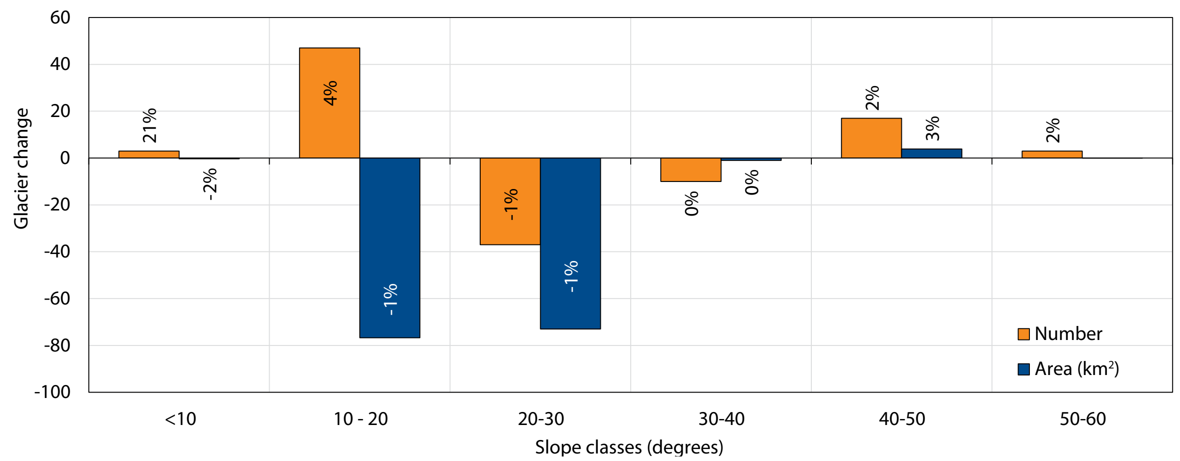
The overall distribution of changes in glacier number and area for each slope class is illustrated in the Figure 4.17. It shows that the most substantial reductions occurred in the 20° – 30° slope class, with a decrease of 37 glaciers and a loss of 73 km^2 in glacier area. A similar loss of glacier area (76.7 km^2) is observed in the 10° – 20° slope class, despite an increase in the number of glaciers within this range. This increase may be due to changes in mean slope resulting from glacier shrinkage and fragmentation, as the mean slope was calculated from the average slope values of all pixels within each glacier boundary.

In higher slope classes, changing trends are mixed. The 30° – 40° slope class experienced an overall reduction in glacier number and a slight decrease in glacier area by 36.34 km^2. In even steeper slopes, the number and area of glaciers generally increased, although the increase in number and area are considerably less. This increase is primarily due to the shrinkage and fragmentation of the glaciers into smaller sizes, and most of the glaciers in these higher slope classes are smaller, as shown in the glacier size versus slope class figures above.

Over the past three decades, glacier number and area changes across various aspects in the Karakoram have shown significant variability, reflecting a complex interplay of surging, advancing, retreating, and fragmentation processes. The northern, southeastern, and northwestern aspects exhibited the most notable increases in glacier numbers (Figure 4.18). The northern aspect showed an increase of 36 glaciers (~2%), while the southeastern and northwestern aspects each gained 11 glaciers. However, despite the increase in number, the northern and northwestern aspects experienced area losses of approximately 2% and 1%, respectively indicating the fragmentation of larger glaciers into smaller ones. Conversely, southeastern glaciers not only increased in number but also exhibited a slight area gain of 3.3%, suggesting glacier surging or advancing behaviour.

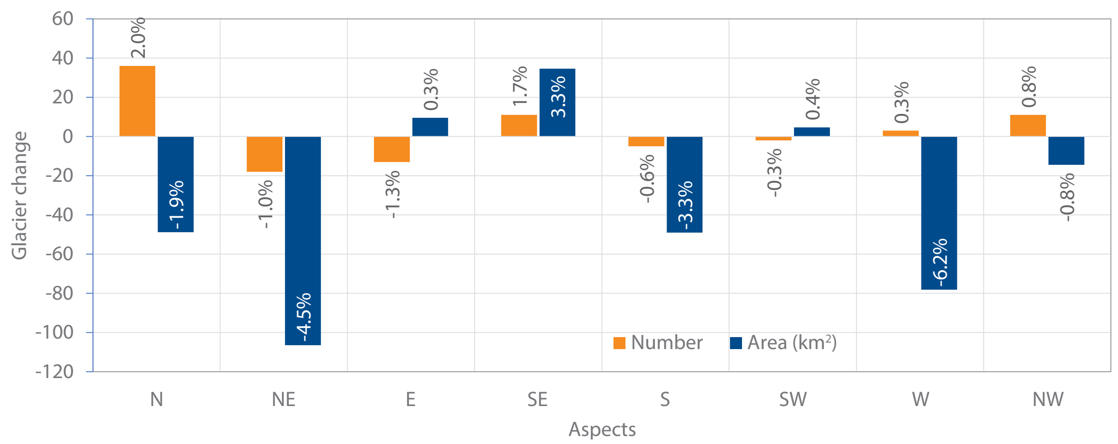
In contrast, the northeastern and eastern aspects experienced the most pronounced glacier losses. The northeastern aspect lost 18 glaciers and nearly 4.5% of its glacier area, while the eastern aspect saw a reduction of 13 glaciers, accompanied by a marginal net area loss of only 0.3%, implying the disappearance of smaller glaciers.

FIGURE 4.17 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES IN THE KARAKORAM MOUNTAIN RANGE.



PONKAR GLACIAL LAKE ON THE LEFT LATERAL SIDE OF THE PONKAR GLACIER IN MANANG DISTRICT, NEPAL.

FIGURE 4.18 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES IN KARAKORAM MOUNTAIN RANGE.



Other aspects displayed mixed patterns. The southern aspect experienced modest declines in both glacier number (by 0.6%) and area (by 3.3%). Southwestern glaciers remained relatively stable, with a slight decrease in number but a small area gain of 0.4%. Glaciers on the western aspect increased in number by three but lost a substantial 6.2% of their total area, indicating significant retreat of larger glaciers.

GLACIER NEAR TO THE MANANG VILLAGE, NEPAL

4.3 Himalayas – Western, Central and Eastern

The Himalayas, the world's youngest, tallest, and the most densely populated mountain range, stretches over 2,400 kilometres across five countries: Bhutan, China, India, Nepal, and Pakistan. It is home to the planet's highest peaks, including Mount Everest, which rises to 8,848.86 masl. The range forms a natural barrier between the Tibetan Plateau to the north and the plains of the Indian subcontinent to the south.

This mountain range features breathtaking landscapes characterised by towering snow-covered peaks, deep valleys, and vast glaciers. These natural features support diverse ecosystems and serve as vital water sources for three of Asia's major river systems: the Indus, Ganges, and Brahmaputra, which sustain millions of people living downstream.

The Himalayas are divided into three major sections: western, central, and eastern Himalayas. The western Himalaya stretch from the Indus River in Pakistan across northern India, including regions such as Jammu and Kashmir and Himachal Pradesh, primarily covering the eastern part of the Indus River basin. The central Himalaya extend from the Yamuna River basin boundary in the west to the Koshi River in the east, encompassing Uttarakhand in India and Nepal. This section primarily covers the Ganges River basin and includes the world's highest peaks, such as Mount Everest, Kanchenjunga, Lhotse, and Makalu. The eastern Himalaya stretch from the Tista River basin through Bhutan and the Indian state of Arunachal Pradesh to the Brahmaputra or Yarlung Zangbo River. This section predominantly covers the western part of the Brahmaputra River and is rich in biodiversity, dense forests, and unique wildlife. Figure 4.19 shows the spatial distribution of glaciers and the extent of each sub-mountain ranges in the Himalayas.

FIGURE 4.19 MAP SHOWING THE GLACIER DISTRIBUTION AND EXTENT OF THE HIMALAYAS IN THE HKH.

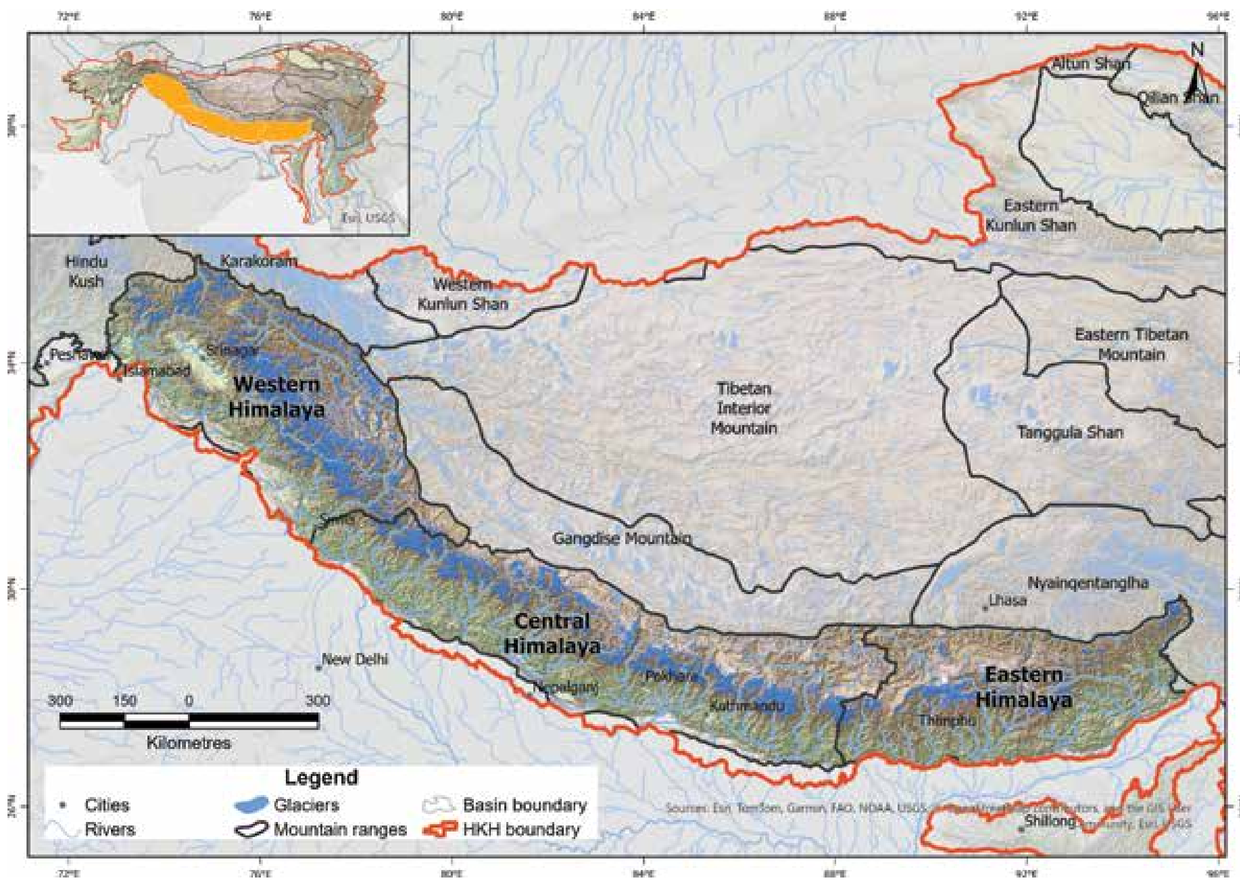
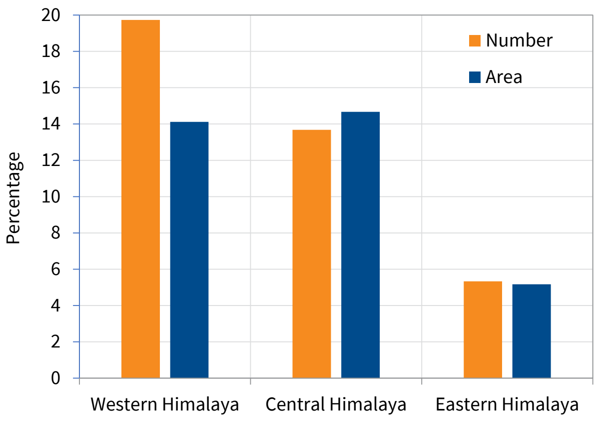


FIGURE 4.20 GLACIER NUMBER AND AREA PERCENT DISTRIBUTION IN THE SUB-MOUNTAIN RANGE OF THE HIMALAYAS.



Glacier distribution in 2020

The Himalayas hold the highest number and largest glacier area coverage, accounting for approximately 39% of the glaciers and 35% of the glacier area within the HKH region. The distribution of glaciers across each three major sections of the Himalayas show significant variations in both number and area. The western Himalaya has the largest number of glaciers, consisting of approx. 20% of glacier in the HKH. The central Himalaya followed as third after Karakoram, containing about 13.7% of the total glaciers in the HKH. Whereas in glacier area coverage, western Himalaya (14.1%) covers slightly less than central Himalaya (14.7%). The eastern Himalaya consists of almost equal percentage of glacier number (5.3%) and area (5.2%) in the HKH. The percentage distribution pattern is shown in the Figure 4.20 and detailed number and area distribution are given in Table 4.1.

The size of the glaciers ranges from 0.02 to 125.8 km², with the largest glacier, Gangotri, located in the central Himalaya. The second and third largest glacier, covering 113.2 km² and 83.7 km², are in the western Himalaya, while the fourth-largest glacier, spanning 81.6 km², is in the eastern Himalaya. The size distribution pattern of glaciers in these mountain sections shows significant regional differences (Figure 4.21 and Figure 4.22). The western Himalaya has the highest number of glaciers but a relatively smaller mean area per glacier. The central Himalaya, while having fewer glaciers, covers a large total glacier area and contains more estimated ice reserves, especially in the larger glaciers. The eastern Himalaya has the fewest glaciers and the smaller total glacier area, but a substantial portion of the estimated ice reserves are held in its larger glaciers.

The western Himalaya consists of the highest number of smaller glaciers Class 1 (<0.5 km²), which is 40% of the total glaciers in the Himalayas, However, these glaciers contribute only 7% of the total glacier area. This pattern continues toward east, with the central and eastern Himalayas having progressively fewer small glaciers (25% and 10% respectively) and a smaller contribution 5% and 2% of the total glacier area in the Himalaya respectively.

In contrast, the distribution of largest glaciers of Class 5 (>=10 km²) reverse the trend. The central Himalaya reign supreme, holding the most extensive glaciers covering 15% of total glaciers area by 130 glaciers. The western Himalaya comes in second with 90 glaciers and 11% of the total area, while the eastern Himalayas have 48 larger glaciers covering only 5% of the total glacier area.

FIGURE 4.21 DISTRIBUTION OF GLACIER NUMBERS IN EACH AREA SIZE CLASSES OF SUB-MOUNTAIN RANGES OF THE HIMALAYAS.

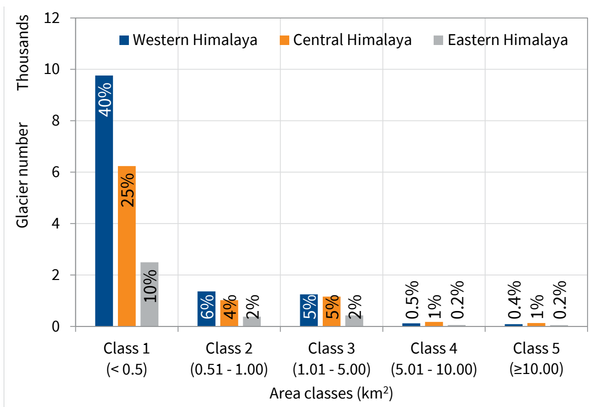
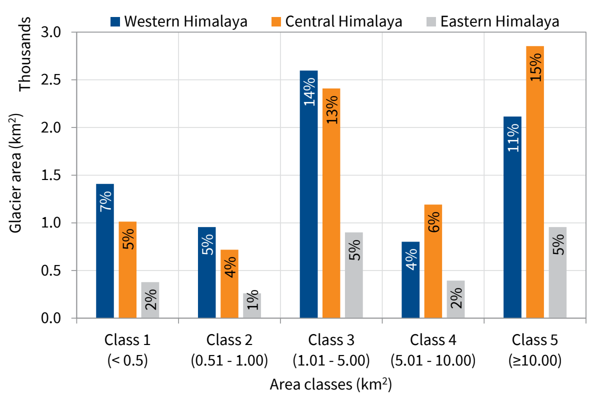


FIGURE 4.22 DISTRIBUTION OF GLACIER AREA IN EACH AREA SIZE CLASSES OF SUB-MOUNTAIN RANGES OF THE HIMALAYAS.



The mid-sized glaciers of Class 3 have a higher percentage of glacier area coverage compared to other classes. The western Himalaya lead with 14% of total glacier area coverage and followed by the central and eastern Himalaya with area coverage of 13% and 5% of the total area respectively. However, their numbers remain less than 5% each of total numbers within the Himalaya. Overall, all these mountain sections show inverse relation on glacier number and area distribution indicating higher glacier number in smaller size and higher glacier area coverage by larger sized glaciers.

The elevation range of Himalayan glaciers is immense, spanning from a low of 2,400 masl at the western Himalaya all the way up to 8,811 masl close to highest peak at central Himalaya.

The majority of Himalayan glaciers are concentrated in the elevation range of 4,500 masl to 6,500 masl, with nearly one-third (33%) of the total area covered falling within the 5,000 – 5,500 masl elevation band. There is a slight variation in glacier distribution from the western to the central and eastern Himalaya (Figure 4.23 and Table 4.5).

In the western Himalaya, glaciers are prominently found between 3,500 masl and 6,500 masl. The area increases significantly from 3,500 – 4,000 masl, covering approximately 145 km², to a peak area coverage of about 2,948 km² within the 5,000 – 5,500 masl elevation range. It then gradually decreases to approximately 259 km² in the 6,000 – 6,500 masl elevation band. Above 6,500 masl, glacier coverage decreases considerably, constituting less than 0.5% of the total glacier area. Below 3,500 masl, the area coverage is very little, covering only 0.2% of the total glacier area.

In the central Himalaya, glaciers are primarily concentrated between 4,500 and 6,500 masl, with the highest area coverage amounting to 37% of the total glacier area found in the 5,500 – 6,000 masl elevation range. At elevations of 5,000 – 5,500 masl, glaciers cover more than 29% of the total area, while at 6,000 – 6,500 masl, they account for approximately 17% of the total glacier area. Below 4,500 masl and above 6,500 masl, glacier coverage decreases significantly, constituting less than 3% and 6% of the total glacier area in these respective sections.

Similarly, in the eastern Himalaya, glacier distribution follows a similar pattern to that of the central Himalayas. The highest concentration, comprising approximately 37% of the total glacier area in this section, occurs within the elevation range of 5,000-5,500 masl. Furthermore, 39.3% and 16.8% of the total glacier area in this section are distributed between 4,500 – 5,000 masl and 5,500 – 6,000 masl, respectively. Below 4,500 masl and above 6,500 masl, glacier coverage diminishes considerably, constituting 2.7% and 5.2% of the total area, respectively.

FIGURE 4.23 GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN THE HIMALAYAS.

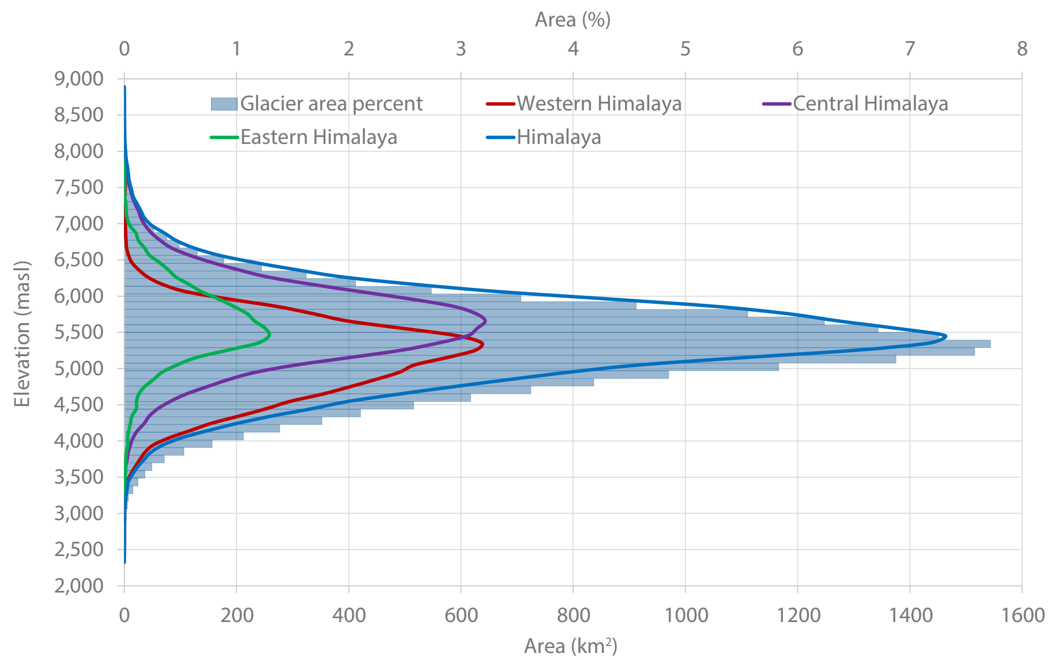


TABLE 4.5 GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN EACH SUB-MOUNTAIN RANGE OF HIMALAYAS.

Elevation range (masl)	Area (km²)				Area percentage			
	Western	Central	Eastern	Himalayas	Western	Central	Eastern	Himalayas
<2,500	0.06			0.06	0.001			0.00
2,500 – 3,000	1.36			1.36	0.02			0.01
3,000 – 3,500	14.75	0.45	2.10	17.30	0.19	0.01	0.07	0.09
3,500 – 4,000	144.38	26.05	16.01	186.43	1.83	0.32	0.55	0.98
4,000 – 4,500	808.25	178.38	59.81	1,046.44	10.26	2.18	2.07	5.52
4,500 – 5,000	1,988.87	759.55	203.30	2,951.72	25.24	9.28	7.04	15.58
5,000 – 5,500	2,947.56	2,375.07	903.25	6,225.88	37.41	29.02	31.29	32.85
5,500 – 6,000	1,686.44	2,996.03	1,065.02	5,747.49	21.41	36.60	36.92	30.33
6,000 – 6,500	259.22	1,372.18	486.27	2,117.66	3.29	16.77	16.84	11.18
6,500 – 7,000	18.86	350.12	136.71	505.69	0.24	4.28	4.74	2.67
7,000 – 7,500	5.27	100.39	12.33	117.98	0.07	1.23	0.43	0.62
7,500 – 8,000	3.39	23.36	1.49	28.25	0.04	0.29	0.05	0.15
8,000 – 8,500	0.03	2.95	0.04	3.02	0.00	0.04	0.00	0.02
>8,500		0.30		0.30		0.00		0.00
Total	7,878.444	8,183.731	2,887.411	18,949.59	100.00	100.00	100.00	100.00

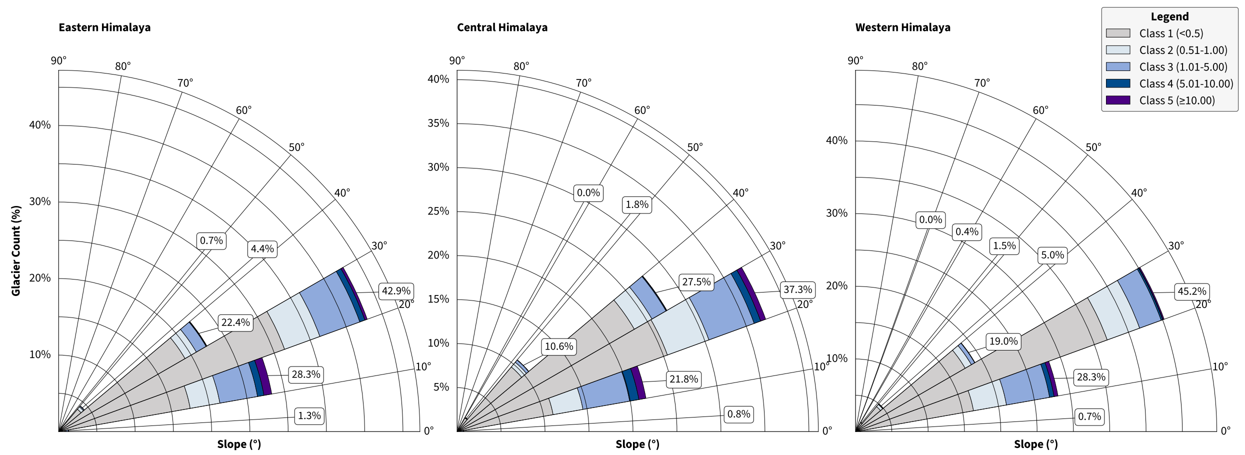
In terms of percentage, the elevation-wise distribution of glaciers shows higher concentrations in each elevation zone of the eastern Himalaya compared to the central and western Himalaya. However, in terms of total area coverage within each elevation zone, the central and western Himalayas exhibit significantly larger glacier areas. In the western Himalaya, there is substantial area coverage between 4,000 and 6,000 masl, while the central Himalaya maintain significant coverage above 6,000 masl as well, with about 16.8% of the total area coverage at 6,000 – 6,500 masl. Similarly, the eastern Himalaya also shows a comparable proportion of total glacier area coverage at elevations above 6,000 masl.

Across the three sections of the Himalayas, the distribution of glaciers varies significantly with slope classes. In the western Himalaya, glaciers are predominantly found on slopes ranging between 10° to 30° (Figure 4.24). The 20° – 30° slope class has the highest number of glaciers, making up 47% of the total glaciers in this section, while the 10° – 20° slope class covers the largest area, accounting for 55% of the total glacier area. The mean area per glacier in the 10° – 20° slope range is about 1.5 square kilometres, indicating larger-sized glaciers. On slopes steeper than 30°, the number, area, and estimated ice reserves of glaciers decrease considerably. Glaciers on the steepest slopes (>60°) have the least presence, comprising only 0.5% of the total glaciers and covering a mere 0.06% of the glacier area, indicating significantly smaller glaciers.

In the central Himalaya, 38% of the total number of glaciers are found on slopes ranging from 20° - 30°, covering 44% of the total glacier area. This indicates that the 20° – 30 ° slope range has the largest glacier distribution in this section. The 10° – 20° slope range follows, comprising 18% of the total glaciers and covering 40% of the total glacier area. With a mean glacier area of 2.03 km², this slope range exhibits a larger glacier distribution. Glaciers on slopes less than 10° are rare, comprising only 0.47% of the total number and 1% of total area coverage. As the slope increases beyond 30°, the number, area and estimated ice reserves diminish.

Similar to the elevation distribution, the mean slope-wise distribution of glaciers in the eastern Himalaya follows the pattern of the central Himalaya. The 20° – 30° slope range has the highest concentration, with 44% of the total glaciers covering 40% of the total glacier area. Meanwhile, the 10° – 20° slope range accounts for 24% of the total glaciers but covers 48% of the total glacier area, indicating a distribution of larger glaciers. Glaciers on slopes steeper than 30° are fewer and cover smaller areas, with a notable decline in the steepest slopes where no glaciers are present on slopes greater than 60°.

FIGURE 4.24 GLACIER NUMBER DISTRIBUTION IN VARIOUS MEAN SLOPE CLASSES IN SUB-MOUNTAIN RANGES OF THE HIMALAYAS.



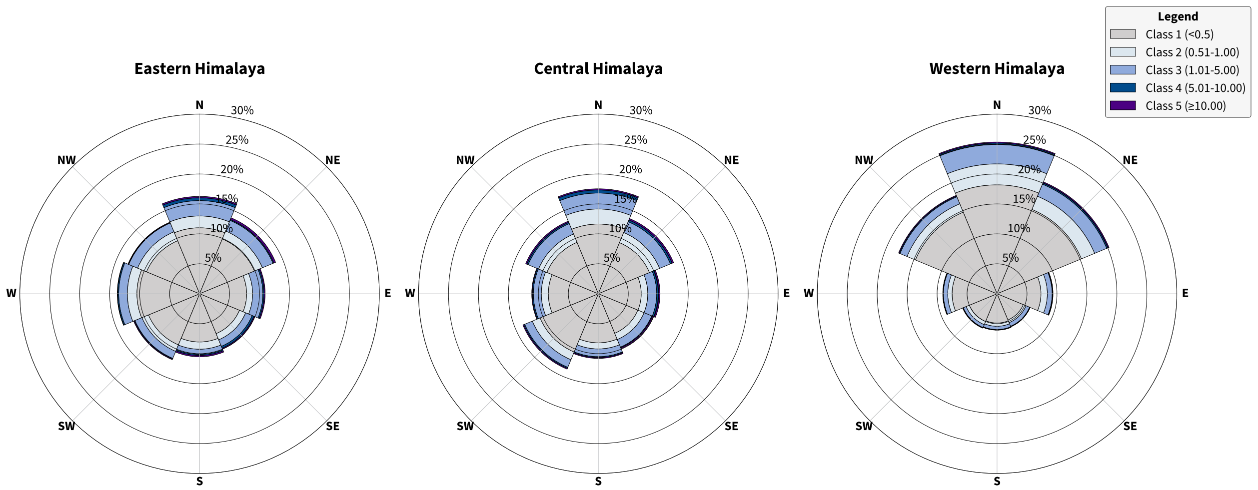
The analysis of glacier size versus mean slope shows that smaller glaciers of Class 1 (<0.5 km²) are distributed across all slope classes in all three sections of the Himalayas, with a higher concentration in the 10° to 30° slope classes. Specifically, 51%, 34%, and 46% of Class 1 glaciers are found in this slope range in the western, central, and eastern Himalayas, respectively. Despite their prevalence, these glaciers cover only about 13%, 6.5%, and 9% of the total area in each region. The distribution of these small glaciers significantly decreases with an increasing slope, becoming rare on slopes greater than 60°. In the western Himalaya, a few Class 1 glaciers are found on slopes over 60°, but none are identified in the central and eastern Himalayas.

Larger glaciers of Classes 4 and 5 are primarily concentrated in the 10° to 30° slope range. In the western Himalaya, Class 5 glaciers dominate the 10° to 20° slope class, comprising over 21% of the total glacier area in this region. The central Himalaya's larger glaciers are more evenly distributed across the moderate slopes of 10° to 20° and 20° to 30°, covering approximately 18% and 17% of the total area, respectively, with a slight preference for the 10° to 20° slope range. A similar pattern is observed in the eastern Himalaya, where the number and area of larger glaciers are higher in the 10° to 20° slope class compared to the 20° to 30° slope range.

The mean aspect of the glaciers in the Himalayas consistently shows higher concentrations and larger glacier area in northern, northeastern and northwestern aspects which collectively account for about 54% of the total glacier and 56.3% of the total glacier area in the Himalayas (Figure 4.25). The mean areas per glaciers in these aspect in all three subregions has relatively higher than other aspects, indicating larger glacier distribution.

Glaciers in the western Himalaya are the most numerous in northern, northeastern and northwestern aspects, hosting majority of the glaciers, collectively accounting for approximately 63.3% of the total glacier in this sub region. These aspects also dominate in glacier area and estimated ice reserves, contributing around 67.8% of the total glacier area and 69.7% of the total estimated ice reserves. Among these aspects, the northern aspects consist of higher percentage consisting of more than one-fourth of the glaciers, area coverage and estimated ice reserves in this sub-mountain region. The mean glacier sizes also suggest the relatively larger glacier distribution, with northern and northeastern aspects having particularly substantial glacier presence. In contrast, southern, southeastern and southwestern aspects represent a smaller share of glaciers in terms of number, area and estimated ice reserves. Collectively they contributes 18% of total glaciers and around 17% of the glacier area and estimated ice reserves in this sub-mountain range. Notably, southern and southeastern glaciers are smaller and fewer, likely due to longer exposure to solar radiation unfavourable for formation and stability of the glaciers. However, the southwestern aspect exhibiting the similar mean glacier size of 0.73 km², indicating the larger size glacier distribution. The eastern and western aspects hold similar number of glaciers and their area coverage with slightly higher percentages of area coverage in eastern aspects.

FIGURE 4.25 GLACIER NUMBER DISTRIBUTION IN VARIOUS MEAN ASPECTS IN SUB-MOUNTAIN RANGES OF THE HIMALAYAS.



The central Himalaya exhibits a similar distribution pattern, with the northern and northeastern aspects holding the highest glacier number, area, and estimated ice reserves. These aspects also feature larger glacier sizes, as reflected by a mean glacier area exceeding 1 km², indicating the dominance of sizable glaciers. The northwestern aspect also plays a significant role, accounting for 13% of the glaciers, 14% of the total area, and 7% of the estimated ice reserves, underscoring its importance in the region's glaciation.

In contrast, the southern, southeastern, and southwestern aspects each contribute approximately 10% of the total glacier area. Among these, the southwestern aspect stands out with the highest glacier number (14%), suggesting a higher density of smaller glaciers, further supported by a lower mean glacier area of 0.71 km². The eastern and western aspects show similar glacier numbers, making up 10% and 11% of the total, respectively. However, the eastern aspect contributes a larger share of glacier area (13%), compared to just 9% in the west, indicating larger average glacier sizes in the east - reinforced by the highest mean glacier area of 1.2 km² across the central Himalaya.

Similarly, the eastern Himalaya also displays the same pattern of glacier distribution across various aspects, with the northern and northeastern aspects dominating in terms of glacier number, area, and estimated ice reserves. Together, these two aspects account for approximately one-third of the total glaciers and more than one-third of the total glacier area and estimated ice reserves in this sub-mountain range, underscoring their glaciological significance. The northwestern aspect also hosts a considerable share of glaciers, making up 13% of the total number, similar to the northeastern aspect. However, its glacier area is significantly smaller, covering only 9% of the total, which points to a predominance of smaller-sized glaciers, as reflected in the mean glacier size of 0.59 km².

The southern, southeastern, and southwestern aspects each contribute a relatively similar share of glacier area - ranging from 10% to 11%, with the southwestern aspect slightly lower. Interestingly, their glacier number distribution contrasts with this pattern: the southwestern aspect has the highest glacier count (12%), while the southeastern has the lowest (10%), indicating the presence of more numerous but smaller glaciers in the southwestern. The eastern and western aspects also play important roles in glacier distribution. The western aspect has a slightly higher glacier count (14%) but a lower area share (9%), whereas the eastern aspect has fewer glaciers (11%) but a higher area coverage (12%), reflecting the presence of larger glaciers on eastern slopes.

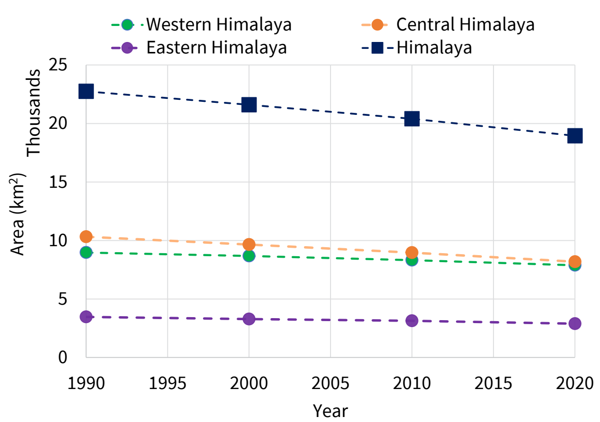
Overall, the western Himalaya is characterised by a large number of fragmented glaciers, the central Himalaya by balanced distribution in both number and area with larger glaciers sizes, and the eastern Himalaya by fewer glaciers but significantly larger ones. Aspects wise, northern and northeastern aspects consistently support the largest number, area and estimated ice reserves across all three sub-mountain ranges in Himalayas.

Decadal glacier changes from 1990 to 2020

Over the past three decades, the Himalayas has experienced notable changes in glacier numbers and area across the three sub-regions. Overall, there was a slight increase in the number of glaciers, rising from 24,683 in 1990 to 24,700 in 2020. However, the total glacier area decreased significantly from 22,745.39 km² to 18,949.58 km², representing a total reduction of about 17% of the total glacier area in the Himalayas. The trend across the entire Himalayas shows a consistent decline in glacier area, despite variations in glacier numbers and changes across the western to eastern Himalaya (Figure 4.26).

In the western Himalaya, the total number of glaciers increased slightly by 0.7% over the three decades. This growth was evident with increases of 0.3% from 1990 to 2000 and 0.7% from 2000 to 2010, followed by a minor decline of 0.31% in the most recent decade from 2010 to 2020. Despite this modest increase in glacier numbers, the glacier area consistently decreased, with a reduction of 3.3% in the first decade (1990-2000) growing to 5.3% in the last decade (2010-2020), resulting in an overall decline of over 12% from 1990 to 2020.

FIGURE 4.26 DECADAL DISTRIBUTION AND TRENDS OF GLACIER AREA IN THE SUB-MOUNTAIN RANGES OF THE HIMALAYAS.



In the central Himalaya, the number of glaciers also increased by 1% over the same period. This increase was observed primarily in the early decades (1990-2000), followed by a decrease in the subsequent decades. In contrast, the glacier area in this region has steadily declined throughout all decades, with the most significant losses occurring between 2010 and 2020. Compared to the western and eastern Himalayas, the central Himalaya experienced a higher rate of glacier retreat, with an overall reduction of nearly 21% in glacier area from 1990 to 2020.

Similarly, the eastern Himalaya also experienced an increase in numbers of glaciers by approximately 3.6% from 1990 to 2000. However, this was followed by a decline of about 2.3% from 2000 to 2010 and a further decrease of roughly 5.6% from 2010 to 2020, resulting in an overall reduction of around 4.4% in glacier numbers. Meanwhile, the glacier area consistently decreased, with losses of 5.3% in the initial decade and more than 7.8% in the most recent decade (2010-2020). Over the entire three decades, the eastern Himalaya experienced a substantial reduction of approximately 16.7% in glacier areas. The detailed distribution of the glacier number and area in each time interval and its change percentage are provided in the Table 4.6.

The changes in glaciers across different size classes reveal remarkable differences within each class and in each sub-range. Overall, in the Himalayas range, the number of the smallest size Class 1 (<0.5 km²) increased by approximately 9.5%, with a consistent rise across each decade. In contrast, larger size classes experienced significant declines in both number and area. Specifically, Class 2 glaciers had the largest reduction in number, with declines of nearly 22.5%, while the largest glaciers of Class 5 had decreased by 13% of glacier number

TABLE 4.6 DECADAL CHANGES IN GLACIER NUMBER AND AREA ACROSS SUB-MOUNTAIN RANGES OF THE HIMALAYAS.

Mountain range	Number				Area				Number (Area) change percent			
	1990	2000	2010	2020	1990	2000	2010	2020	1990 - 2000	2000 - 2010	2010 - 2020	1990 - 2020
Western Himalaya	12,492	12,529	12,616	12,577	8,964.83	8,671.58	8,316.79	7,878.44	0.3 (-3.27)	0.69 (-4.09)	-0.31 (-5.27)	0.68 (-12.12)
Central Himalaya	8,634	8,863	8,770	8,722	10,317.51	9,650.77	8,956.11	8,184.81	2.65 (-6.46)	-1.05 (-7.2)	-0.55 (-8.61)	1.02 (-20.67)
Eastern Himalaya	3,557	3,684	3,601	3,401	3,463.04	3,278.81	3,131.80	2,886.34	3.57 (-5.32)	-2.25 (-4.48)	-5.55 (-7.84)	-4.39 (-16.65)
Himalaya	**24,683**	**25,076**	**24,987**	**24,700**	**22,745.39**	**21,601.16**	**20,404.71**	**18,949.58**	**1.59 (-5.03)**	**-0.35 (-5.54)**	**-1.15 (-7.13)**	**0.07 (-16.69)**

over three decades. Despite the increasing number of smaller glaciers, the area of glaciers across all classes has consistently decreased throughout all decades. The glacier area has been shrunk by about 6% in smallest glaciers of Class 1 (<0.5 km²), Class 2 (0.5-1.0 km²) has the greatest percentage reduction of 22.7% followed by a 21.7% reduction in Class 4 (5-10 km²), and the largest glaciers in Class 5 shrank by 15.61% over the three decades. This trend of shrinking glacier area, particularly pronounced in recent decade (2010 – 2020), highlights a substantial reduction in glacier area despite a slight increase in the number of smaller glaciers, suggesting fragmentation of larger glaciers.

The pattern of increasing smaller glacier numbers and shrinking glacier areas is evident across the Himalayas (Figure 4.27 and Figure 4.28). In the western Himalaya, the smallest-sized glaciers in Class 1 showed a steady increase in number, rising by nearly 2% to 3% each decade and resulting in a total increase of 7% over three decades. However, the glacier area declined consistently, with mid-sized glaciers of Class 2 to Class 4 showing significant reductions of 17.5% to 14.4% over thirty-year period. The largest and smallest-sized glaciers of Class 5 and Class 1 were reduced by more than 9% and almost 6% of glacier areas over three decades respectively.

The central Himalaya experienced even more pronounced changes in both number and area across different size classes. The smallest glaciers of Class 1 (<0.5 km²) had a notable increase in glacier number, rising by 15.4% over three decades. This increase in number was most pronounced in the 1990-2000 period, with a 9.6% increase, followed by smaller increments of 1.9% in 2000 -2010 and 3.4% in 2010-2020. Conversely, larger glacier classes had substantial decreases in both number and area throughout all decades. Class 2 glaciers had the greatest reductions, with more than 26% decrease in both number and area. Class 3 and 4 also showed significant decreases, with a reduction of approximately 20.6% and 23.5% respectively in both number and area. The largest glaciers of Class 5 had a reduction in number by about 19% and its area shrank by about 22% over the thirty-year period.

The eastern Himalaya displayed the most pronounced overall decline. The smallest glaciers in Class 1 were an overall increase of number by 5.3%, with the most notable increase of 8.7% in the decade from 1990 to 2000. However, this was reversed in the subsequent decades, with a decrease of glacier number by 0.6% in 2000 to 2010 and a further decline of 2.6% in recent decade of 2010 to 2020. The number of all mid- and larger-sized glaciers were reduced more remarkably. Similarly, the glacier area also experienced a continuous decline over all decades and in each glacier, size classes, with overall losses ranging from 8.8% in smallest glacier to greatest area losses in Class 2 and Class 4 classes and the largest glaciers Class 5 loss by almost 8.3% over three decades. Notably, the rate of loss in the glacier area was higher in the recent decade (2010 – 2020) compared to earlier periods.

Comparatively, the western Himalaya showed a relatively stable number of glaciers with a notable decline in glacier area, while the central Himalaya experienced a notable increase in glacier numbers but substantial reductions in glacier area, especially among larger glaciers. The eastern Himalaya exhibited the most significant overall declines in both glacier numbers and area, with a pronounced reduction across all size classes.

The analysis of glacier area changes from 1990 to 2020 across various elevation ranges shows a significant reduction in all ranges, though the extent and rate of decrease varies. At elevations below 2,500 masl, glacier area decreased dramatically by approximately 53%. However, in absolute terms, this loss is less than that observed in mid-elevation ranges, such as 4,000 to 6,000 masl. Additionally, the lowest glacier elevation shifted from 2,389 masl in 1990 to 2,413 masl in 2020.

Glacier area loss increases with elevation from 3,000 masl to 6,000 masl, with the most significant reduction, nearly 20% occurring in the 5,000 to 5,500 masl range over the three decades. This elevation range experienced the highest concentration as well as the highest area losses compared to other zones. Adjoining ranges, including 4,500 to 5,000 masl and 5,500 to 6,000 masl, also experienced substantial reductions of 21% and 15%, respectively (Table 4.7).

Above 6,000 masl, the proportion of area loss decreases, with a loss of about 9% in the 6,000 to 6,500 masl range, narrowing to around 5% in the 8,000 to 8,500 masl elevation range. Despite this reduction, the absolute changes are relatively minor compared to those below 6,000 masl, indicating greater stability in glacier coverage at these higher elevations.

FIGURE 4.27 PERCENTAGE CHANGES OF GLACIER NUMBERS WITH RESPECT TO SIZE CLASSES OVER THREE DECADES IN SUB-MOUNTAIN RANGES OF THE HIMALAYAS.

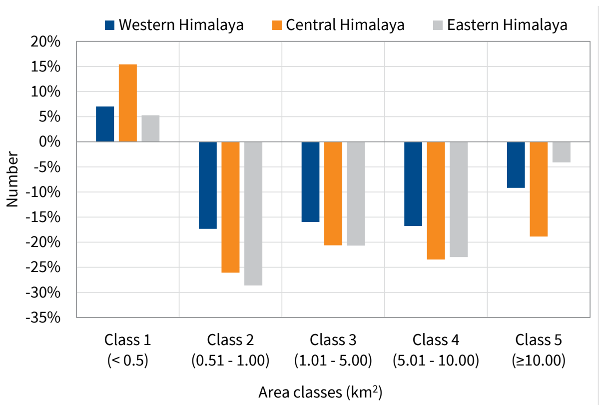


FIGURE 4.28 GLACIER AREA PERCENTAGE CHANGES WITH RESPECT TO SIZE CLASSES OVER THREE DECADES IN SUB-MOUNTAIN RANGES OF THE HIMALAYAS.

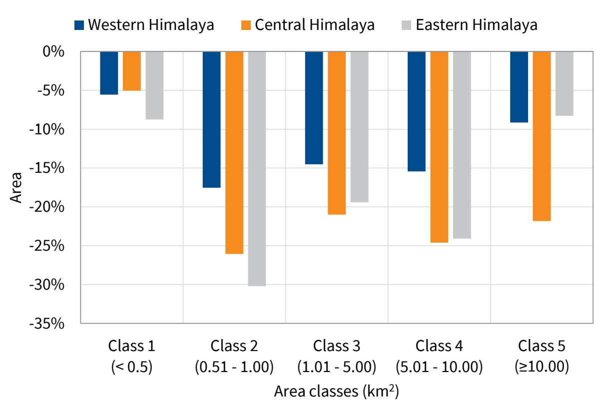


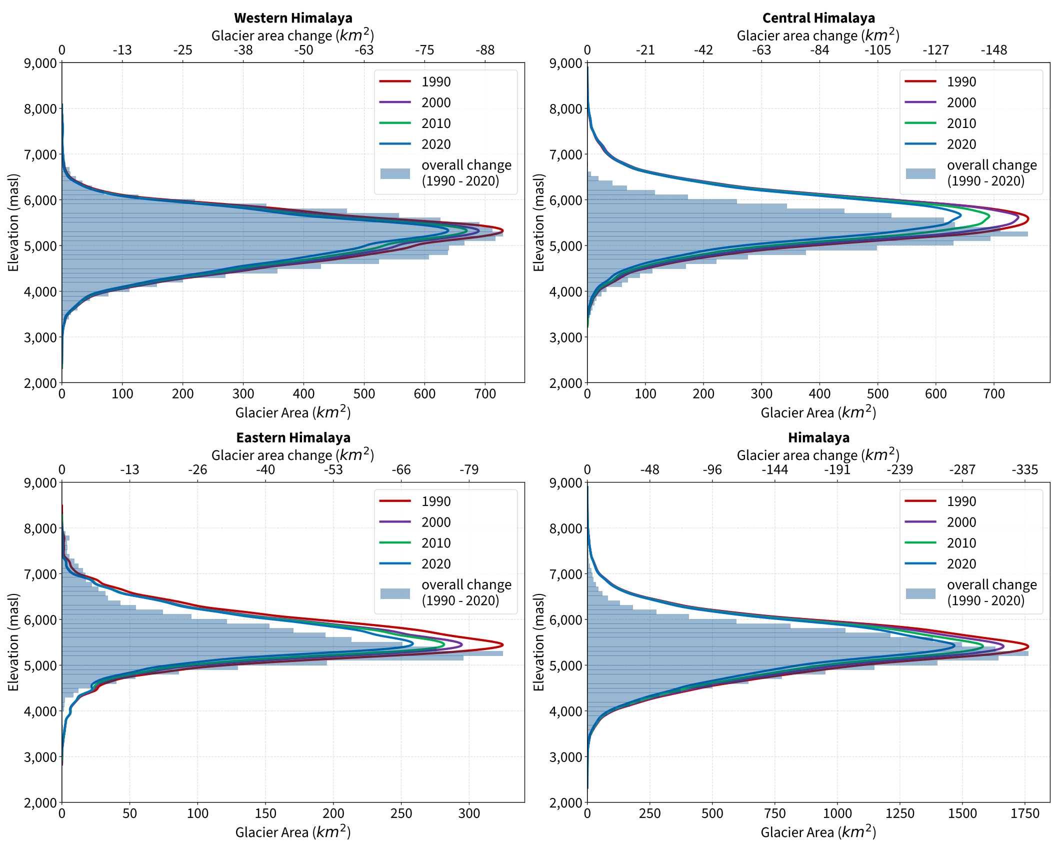
TABLE 4.7 GLACIER AREA DISTRIBUTION AND PERCENTAGE CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN SUB-MOUNTAIN RANGES OF THE HIMALAYAS.

Elevation ranges (masl)	Area (km²)				Area change - km² (change percent)			
	1990	2000	2010	2020	1990 - 2000	2000 - 2010	2010 - 2020	1990 - 2020
<2,500	0.14	0.14	0.09	0.06	0 (0.0%)	-0.05 (-35.5%)	-0.02 (-27%)	-0.07 (-52.9%)
2,500 – 3,000	1.59	1.61	1.34	1.36	0.02 (1.5%)	-0.27 (-16.6%)	0.02 (1.3%)	-0.23 (-14.3%)
3,000 – 3,500	22.39	22.14	20.39	17.30	-0.25 (-1.1%)	-1.76 (-7.9%)	-3.09 (-15.1%)	-5.09 (-22.7%)
3,500 – 4,000	225.50	218.53	204.00	186.43	-6.96 (-3.1%)	-14.53 (-6.6%)	-17.57 (-8.6%)	-39.07 (-17.3%)
4,000 – 4,500	1,268.21	1,217.91	1,138.41	1,046.44	-50.31 (-4.0%)	-79.50 (-6.5%)	-91.97 (-8.1%)	-221.77 (-17.5%)
4,500 – 5,000	3,724.56	3,499.19	3,259.61	2,951.72	-225.36 (-6.1%)	-239.59 (-6.8%)	-307.89 (-9.4%)	-772.84 (-20.7%)
5,000 – 5,500	7,753.69	7,253.54	6,817.65	6,225.88	-500.15 (-6.5%)	-435.88 (-6.0%)	-591.78 (-8.7%)	-1,527.81 (-19.7%)
5,500 – 6,000	6,720.44	6,415.22	6,102.34	5,747.49	-305.22 (-4.5%)	-312.88 (-4.9%)	-354.84 (-5.8%)	-972.95 (-14.5%)
6,000 – 6,500	2,327.80	2,279.49	2,192.69	2,117.66	-48.31 (-2.1%)	-86.80 (-3.8%)	-75.02 (-3.4%)	-210.13 (-9%)
6,500 – 7,000	541.65	535.25	518.02	505.69	-6.39 (-1.2%)	-17.24 (-3.2%)	-12.32 (-2.4%)	-35.96 (-6.6%)
7,000 – 7,500	125.54	124.56	118.98	117.98	-0.98 (-0.8%)	-5.59 (-4.5%)	-0.99 (-0.8%)	-7.56 (-6.0%)
7,500 – 8,000	30.41	30.04	27.96	28.25	-0.37 (-1.2%)	-2.08 (-6.9%)	0.28 (1.0%)	-2.16 (-7.1%)
8,000 – 8,500	3.17	3.23	2.93	3.02	0.06 (1.8%)	-0.3 (-9.3%)	0.09 (3.0%)	-0.16 (-4.9%)
>8,500	0.30	0.30	0.30	0.30	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Total	**22,745.38**	**21,601.16**	**20,404.70**	**18,949.59**	**-1,144.22 (-5.0%)**	**-1,196.39 (-5.5%)**	**-1,455.11 (-7.1%)**	**-3,795.79 (-16.7%)**

A similar pattern of glacier area loss has been observed across all Himalayan subregions – western, central, and eastern (Figure 4.29). In the western Himalaya, the lowest elevation glaciers below 2,500 masl were reported. Within this subregion, a 5.6% reduction in glacier area was noted between 2,500 and 3,000 masl over three decades. The proportion of area loss increased with elevation from 3,000 masl to 6,000 masl across all decades. For elevations between 3,000 and 5,000 masl, the percentage of area loss ranged from approximately 14% to 15% within each 500-metre elevation zone. Notably, the absolute area change was significantly higher in the 4,500 – 5,000 masl range. The greatest area loss occurred in the 5,000 – 5,500 masl range, with an 11% reduction over the three decades. The rate of area loss decreased slightly in the 5,500 – 6,000 masl elevation, and above 6,000 masl, the loss rate diminished significantly, indicating greater stability at higher elevations. Overall, the western Himalaya exhibits a consistent trend of glacier area reduction across all decades, with a more pronounced loss in recent decades (2010 to 2020) and more substantial reductions in below 6,000 masl elevation.

In the central Himalaya, glaciers were only reported above 3,200 masl in all decades. The glacier area loss in the lower elevation from 3,000 to 3,500 masl was modest compared to higher elevation, with a total loss less than 2 km^2 over the three decades. However, this loss rate is comparatively high when expressed as a percentage. The absolute area losses become more pronounced in the higher elevation up to 6,000 masl. The most considerable amount of area loss was observed in the elevation range from 4,500 masl to 5,500 masl, with loss of the highest area of about 838.6 km^2 from 5,000 – 5,500 masl. Compared to the percentage loss in this range is relatively lower than in lower elevation. The higher elevation above 5,500 masl to 6,500 masl also showed the significant amount of area loss, with an around 614 km^2 in 5,500 – 6,000 and 167 km^2 in 6,000 – 6,500 masl. Despite these significant amounts of area loss, the percentage change is less dramatic than in lower elevation range. Overall, the central Himalaya demonstrates a clear trend of glacier retreat, with the most significant loss occurring at elevation ranges of 4,500 masl to 6,500 masl over all decades and the trend toward greater stability at higher altitudes. The rate of loss has accelerated in recent decades, particularly noticeable in the elevation below 6,000 masl.

FIGURE 4.29 **DECADAL GLACIER AREA DISTRIBUTION AND CHANGES ACROSS ELEVATION RANGES IN SUB-MOUNTAIN RANGES OF THE HIMALAYAS.**

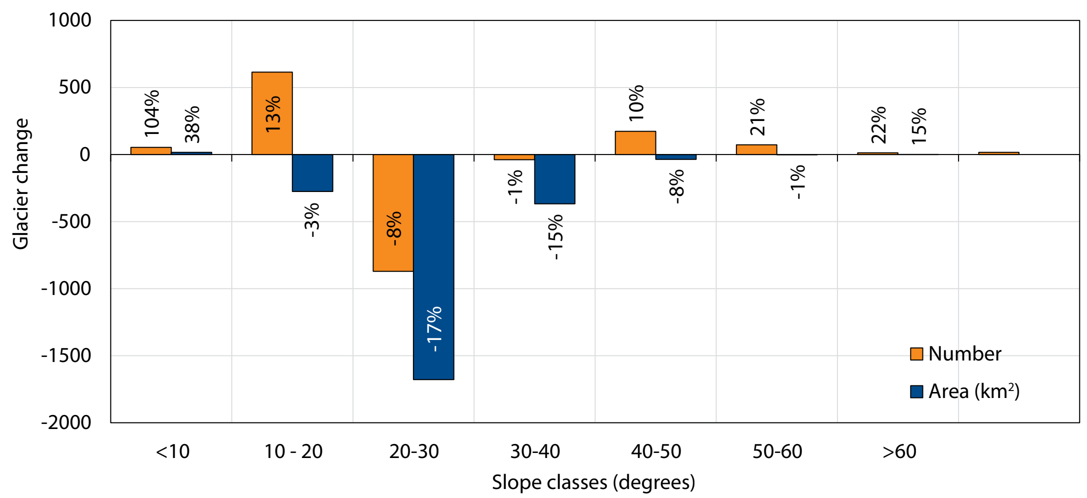


In the eastern Himalaya, glacier area changes from 1990 to 2020 reveal a clear trend of increasing retreat. Glaciers in this range have consistently been found at elevations above 2,800 masl across all decades. Glaciers at lower elevation, below 3,000 masl, showed notable reduction, with a total loss of less than 1 km^2. This is also reflected in the shifting of the lowest glacier snout from 2,553 masl in 1990 to 3,032 masl in 2020. Glaciers at elevation between 3,000 to 4,000 masl have seen a relatively modest area loss. There was negligible loss in the early decades from 1990 to 2000, but the rate of loss increased in following decades, indicating a gradual but consistent retreat. Above 4,000 masl, area loss becomes more pronounced with increasing elevation. The most severe loss occurred between 5,000 masl to 5,500 masl, where glaciers lost over 26% of their area over three decades. A similar percentage of area loss was observed between 4,500 masl to 5,000 masl, but the total area loss was less, approximately less than one-fourth of that lost between 5,000 masl to 5,500 masl. In contrast, glaciers between 5,500 masl to 6,000 masl experienced only half of the area loss compared to those between 5,000 masl to 5,500 masl, with a total loss percentage of just 12.2% over three decades. Above 6,000 masl, area loss has decreased, showing smaller and less extreme reductions compared to lower elevations. Overall, the eastern Himalaya shows significant variability in glacier area loss across different elevation ranges, with most dramatic reductions occurring in the elevation range between 4,500 masl to 6,000 masl.

Glacier changes have varied significantly across different mean slope classes over the past three decades. The mean slope of glaciers varies with their retreat, shrinkage, and fragmentation, as it is calculated based on the average slope of each pixel within the glacier's spatial extent. Overall, glacier numbers generally increased in lower slope (<10°) and steeper slope (>60°) classes, with notable rises 52 glaciers in 1990 to 106 glaciers in 2020 at slope less than 10° and 58 to 71 glaciers from 1990 to 2020 in steeper slope class (>60°). In contrast, glacier numbers decreased in the middle slope classes, particularly 20° – 30°, which showed an 8% decline. The overall glacier area, however, showed reductions across most of the slope classes. The most notable decreases were observed in slope classes of 20° – 30° and 30° – 40°, with reductions of 17% and 15% respectively. Despite the increase in glacier numbers in some slope classes, the total glacier area across the Himalayas has decreased, reflecting a trend of shrinking glacier mass and potentially altered glacier distributions over time (Figure 4.30).

Figure 4.31 and Figure 4.32 shows the glacier number and changes across various slope classes in each sub-section of the Himalayas. In the western Himalaya, the glacier number decreased significantly in the

FIGURE 4.30 **GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES IN THE HIMALAYAS.**



20° – 30° slope class, with a total loss of 5% glaciers over 1990-2020. This class also showed the largest area reduction of 11% from 1990 to 2020. Conversely, the <10° slope class showed a modest increase in glaciers number (15) but experienced a slight area loss of -0.44 km^2 . The 30° – 40° and 40° – 50 ° slope classes had smaller changes in glacier number but still faced area losses, with total reductions of 9% and 8% of the area from 1990 to 2020, respectively. Overall, the western Himalaya saw substantial glacier area loss, particularly in 10° – 50° slope classes.

In the central Himalaya, changes in glacier numbers and areas reflect a more pronounced decline in 20° – 40° slope classes. The most significant reduction of number and area was observed in 20° – 30° slope class, with a total decrease of 350 glaciers and an area loss by 20% from 1990 to 2020. The 30° – 40° class also saw a notable decrease in glaciers (59) and a significant area reduction. However, the <10° slope class demonstrated an increase in the number of glaciers (28) and a minor area gain of 9.65 square kilometres. Overall, the central Himalaya witnessed severe glacier losses in mid to high slope classes, contributing to the total area loss of -1,361.40 km^2 over three decades.

In the eastern Himalaya, the glacier changes also reveal distinct patterns. The 20° – 30° slope class saw a dramatic decrease of 218 glaciers and an area loss of -268.47 km^2. The 30° – 40 ° class experienced a decrease in glacier numbers (15) and an area loss of -34.51 square kilometres. The <10° slope class, in contrast, had a modest increase in glaciers (11) and a small area loss of -7.76 km^2. The 40° – 50° slope class showed a slight overall increase in glacier number (10) and a minor area gain of 0.62 km^2. The eastern Himalaya displayed significant glacier losses in mid-

FIGURE 4.31 **GLACIER NUMBER CHANGES ACROSS MEAN SLOPE CLASSES IN THE SUB-MOUNTAIN RANGE OF THE HIMALAYAS.**

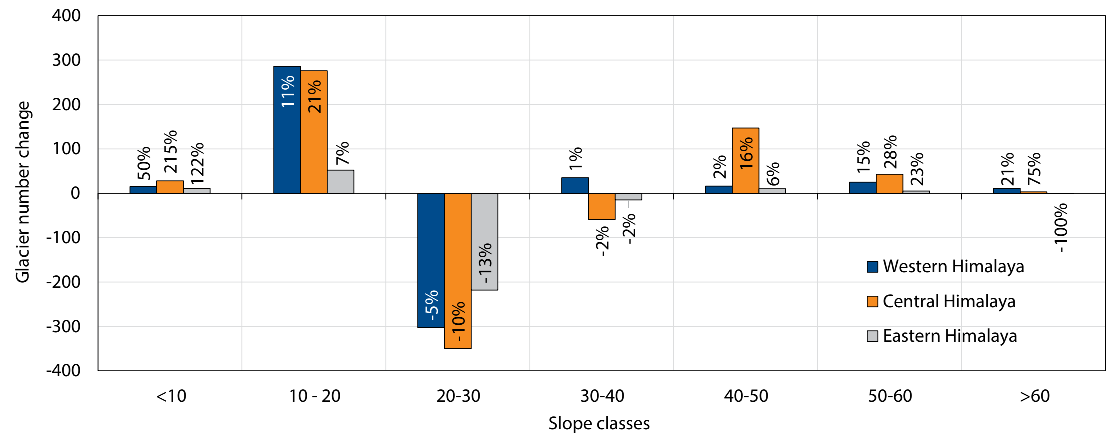
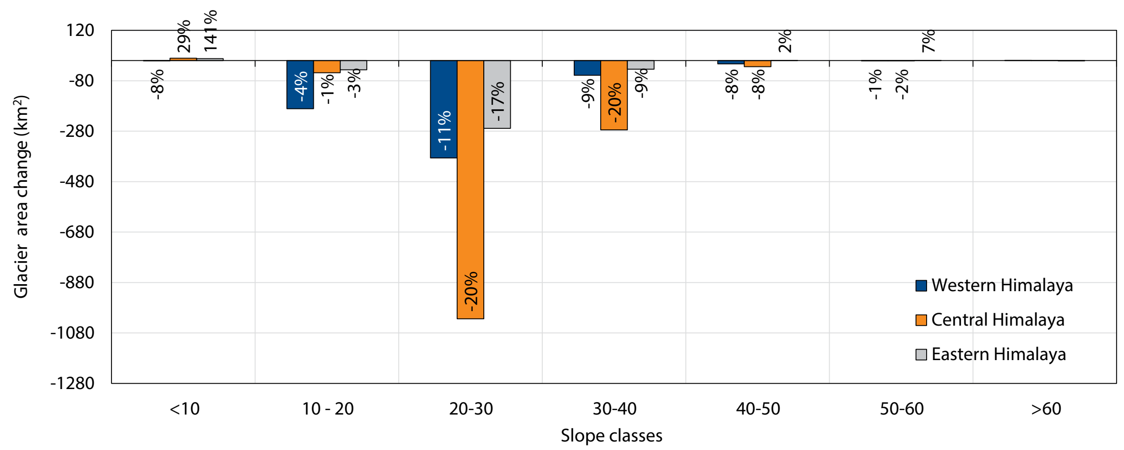


FIGURE 4.32 **GLACIER AREA CHANGES ACROSS MEAN SLOPE CLASSES IN THE SUB-MOUNTAIN RANGE OF THE HIMALAYAS.**



slope classes and a more stable trend in higher slopes, with a total area loss of -331.24 km^2 over three decades.

Overall, the analysis highlights that while all sub-regions experienced glacier losses, the western and central Himalayas faced more severe declines, especially in mid-slope classes. The eastern Himalaya, while also experiencing significant losses, showed a more variable pattern with some areas showing stability.

Glacier changes across different mean aspects revealed a distinct and consistent pattern throughout the sub-Himalayan ranges and the entire Himalayas (Figure 4.33 and Figure 4.34). In all three regions – western, central, and eastern Himalayas – the northern and northwestern aspects consistently showed an increase in glacier numbers across each decade, with the northern aspect exhibiting the most significant gain. Despite these increases in number, glacier areas in all sub-Himalayan ranges and the entire Himalaya declined markedly over the same period. This trend was especially pronounced in the central Himalaya, where glacier area decreased by more than 18% on northern aspect and 13% on northwestern aspect, even as glacier numbers rose by 6% and 8%, respectively, over the past three decades. The eastern and western Himalayas also experienced notable glacier area losses, over 14% and 11% on northern aspects, and 8% and 12% on northwestern aspects, respectively. However, in terms of the increase in glacier number, the eastern Himalaya had a significantly smaller rise compared to the western and central Himalayas.

In contrast, the northeastern aspect exhibited a different pattern, with both glacier number and area decreasing consistently across all sub-Himalayan ranges over the decades. Over the past

FIGURE 4.33 **GLACIER NUMBER CHANGES ACROSS MEAN ASPECTS IN THE SUB-MOUNTAIN RANGE OF THE HIMALAYAS.**

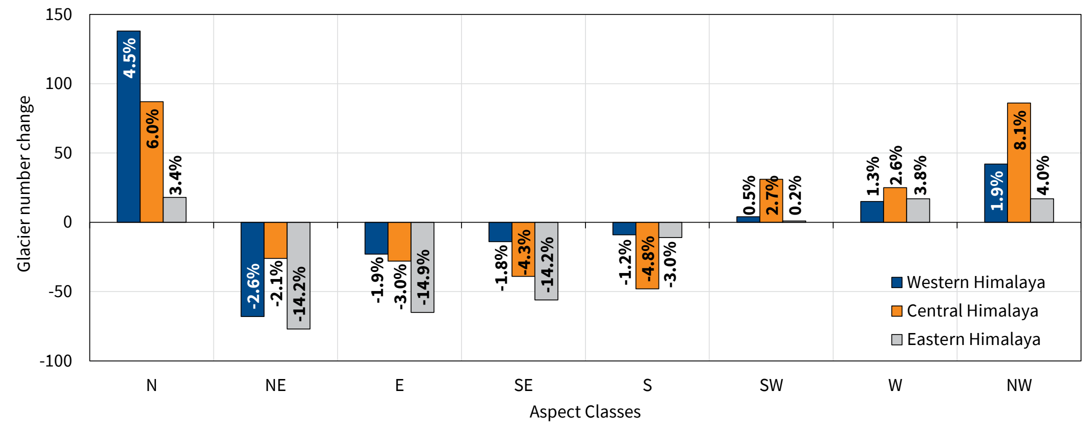
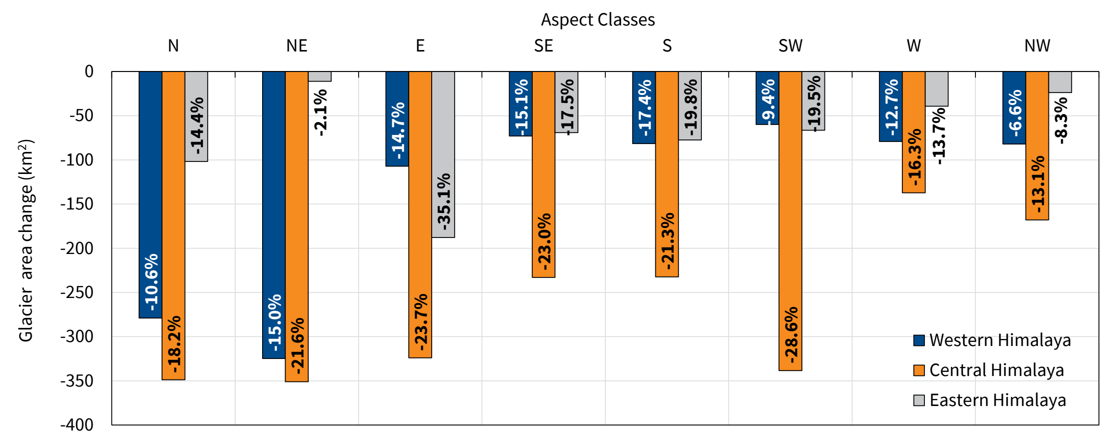


FIGURE 4.34 **GLACIER AREA CHANGES ACROSS MEAN ASPECTS IN THE SUB-MOUNTAIN RANGE OF THE HIMALAYAS.**



DISCHARGE MEASUREMENT AT RIKHA SAMBA GLACIER OUTLET IN HIDDEN VALLEY, MUSTANG, NEPAL

three decades, the western and central Himalayas recorded the highest absolute glacier area losses in the northeastern aspect – approximately 324 km² (a 15% decrease) and 351 km² (a 22% decrease), respectively. Meanwhile, the eastern Himalaya experienced only a modest 2% loss in glacier area on this aspect, despite a slightly higher decline in glacier numbers compared to the western and central Himalaya.

Similarly, the southern and southeastern aspects followed the same declining pattern as the northeastern aspect across all three sub-Himalayan ranges, but with comparatively smaller losses in both glacier number and area. The central Himalaya again recorded the most significant proportional losses, with glacier number declining by 4 – 5% and glacier area by 21– 23% in both aspects over the three decades. In the western Himalaya, glacier area declined by 15 – 17%, while glacier number fell by 1.2 – 1.8%, with higher area loss in the southern aspect and greater number loss in the southeastern aspect. The eastern Himalaya showed a 17% and 20% area loss and a 14% and 3% decrease in glacier number in the southeastern and southern aspects, respectively, over the same period.

The southwestern and western aspects exhibited similar change patterns as the northern aspects across all sub-Himalayan ranges, with an overall increase in glacier number across the decades, although some fluctuations were observed in individual decades. Meanwhile, the glacier area continued to decline steadily. Among the three sub-Himalayan ranges, the central Himalaya region experienced the highest area losses, almost 29% in the southwestern aspect and 16.3% in the western aspect over the past three decades. The western and eastern Himalaya also had significant area losses, ranging from 9% to about 13% in the western Himalaya and approximately 19.5% and 14% in the eastern Himalaya for the southwestern and western aspects, respectively.

The eastern aspect followed a pattern similar to the northeastern aspect, with both the number of glaciers and glacier area declining in all decades. In the central Himalaya, a higher proportion of glacier area - nearly 24% - was lost, despite a decrease of only 28 glaciers over three decades. However, the eastern Himalaya experienced a proportionally greater loss in glacier number, with a decrease of 65 glaciers and 188 km² of glacier area.

Overall, the trends underscore a pervasive and significant glacier retreat throughout the Himalayas, with eastern, southeastern and southern aspects showing the most pronounced impacts, likely due to increased insolation and warming, while northern northwestern and western aspects, despite increases in number, continue to experience considerable area loss, suggesting shrinkages and fragmentation of the glaciers alters the mean aspects of the individual glaciers. Among the three sub-Himalayan ranges, the central Himalaya had the most significant proportions of glacier area loss over all the aspects than in other two sub-Himalayan ranges.

4.4 Gangdise Mountain

The Gangdise Mountain range spans the southwestern region of Tibetan Autonomous Region in China, running parallel to the Himalayas in a northwest to southeast direction. This range serves as the dividing line between the inland water system of the high-altitude northern Tibetan plateau and the Indian ocean water system in the south. The Gangdise means lord of the mountains in Tibetan.

Gangdise Mountain range stretches approximately 1,100 kilometres with an average elevation of around 6,000 masl. Although the highest peak is Mt. Loinbo Kangri (Lunpo Gangri) which reached up to 7,095 masl, Mt. Kailash is the most famous holy peak standing at the north of the Manasarover lake with reaching up to 6,656 masl. The boundary of this mountain ranges from Pengong tso in the northwest to the Namutso in the northeast. The southern boundary passes along the Yarlung Zango at Shigatse. Figure 4.35 showing the glacier distribution and extent of the Gangdise Mountain range.

Glacier distribution in 2020

Based on the Landsat images from 2020, The Gangdise mountain range hosts 3,514 glaciers covering an area of 1,135.65 km², with an estimated ice reserve of 50 km³. These figures account for over 5.5% of the total number and 2% of the total glacier area in the HKH region. Despite covering only about 0.7% of the total area of the mountain range, the Gangdise range features glaciers averaging size of 0.3 km², including the largest ones reaching about 20 km². This suggests that the range predominantly consists of smaller glaciers compared to other mountain ranges in the region.

The glacier size class distribution shows that the majority of glaciers in this mountain range are small, with 86% having an area of less than 0.5 km² (Class 1) (Figure 4.36). However, the total area covered by this smaller size glaciers (Class 1) are equivalent to the mid-sized glacier Class 3 (1 to 5 km²), covering 36% each of total glacier area in the mountain ranges. In terms of number,

FIGURE 4.35 MAP SHOWING THE GLACIER DISTRIBUTION AND EXTENT OF THE GANGDISE MOUNTAIN RANGE IN THE HKH.

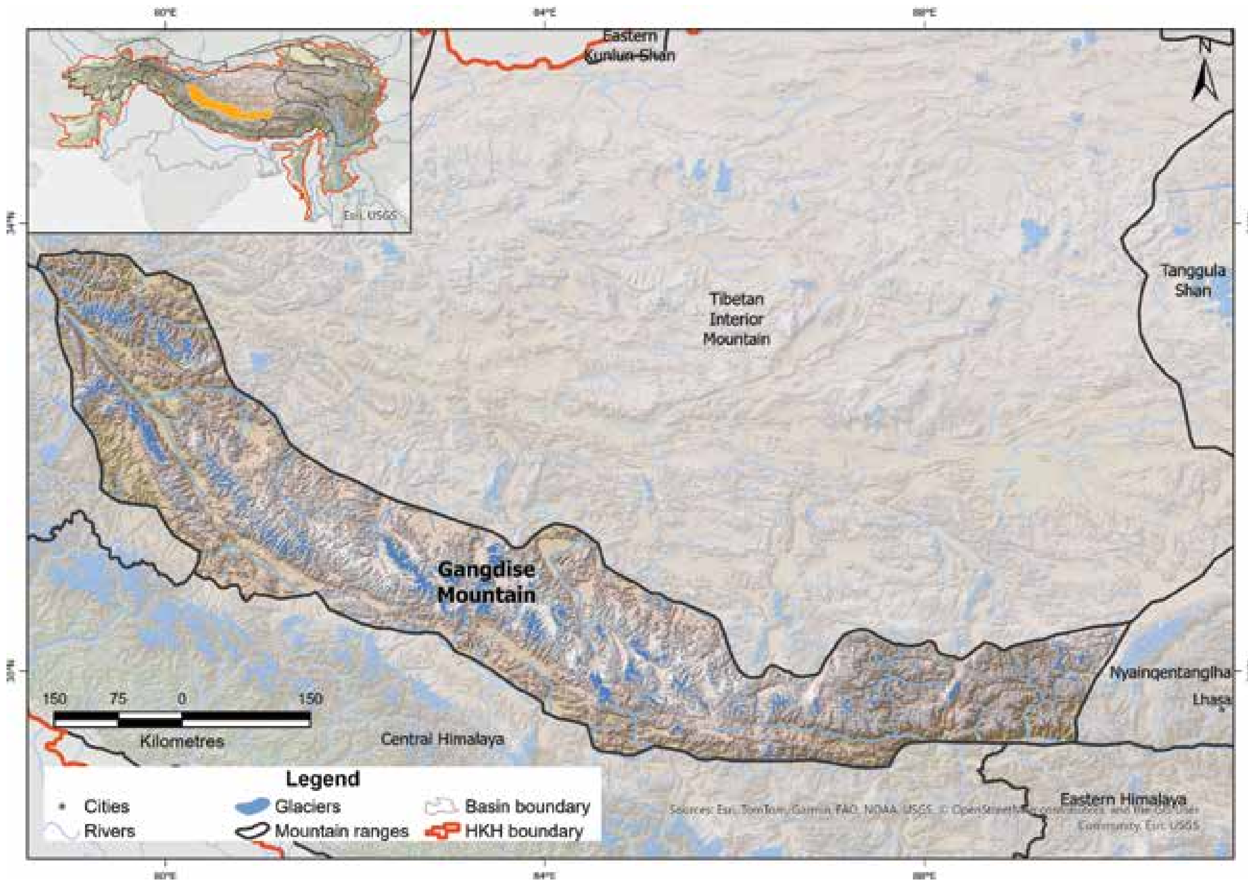
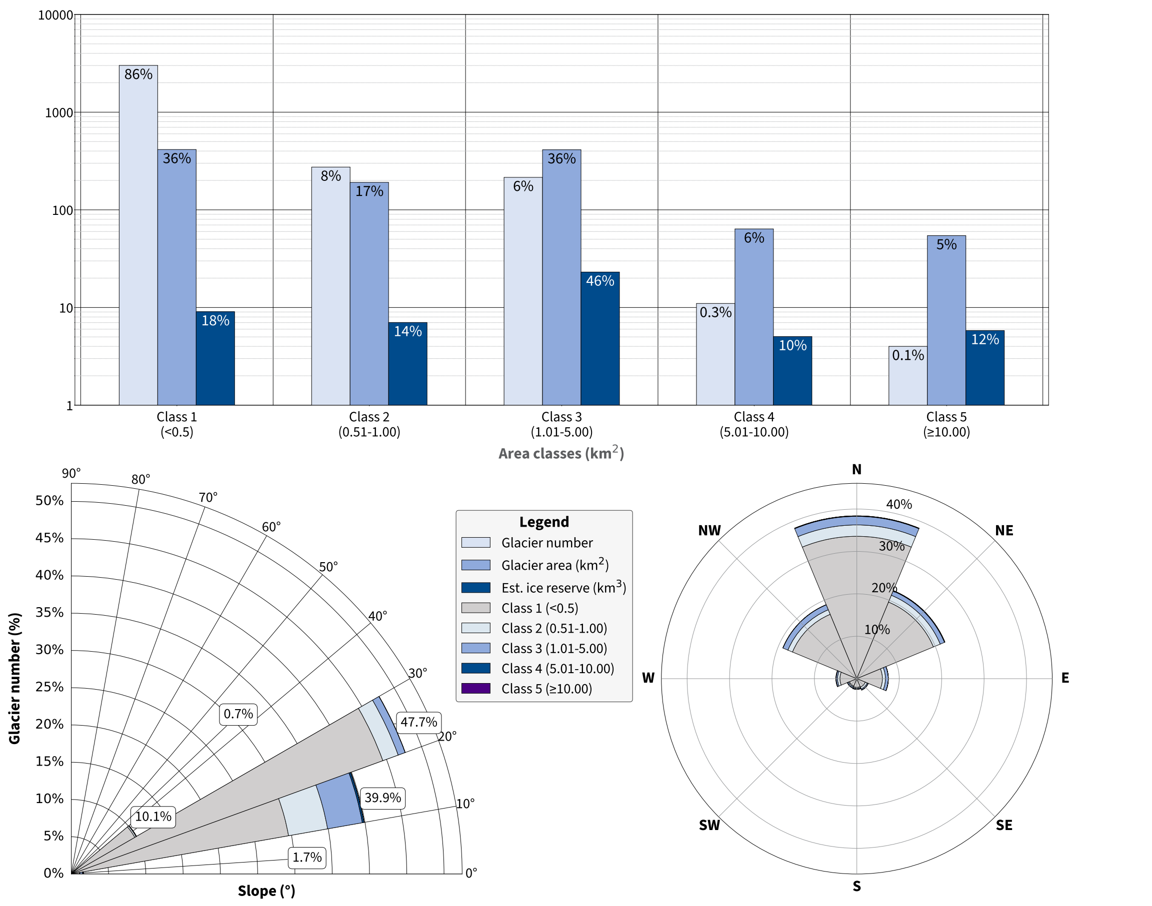


FIGURE 4.36 **GLACIER NUMBER, AREA AND ESTIMATED ICE RESERVES BY AREA SIZE CLASS (TOP) AND ITS DISTRIBUTION ACROSS MEAN SLOPE (BOTTOM LEFT) AND ASPECTS (BOTTOM RIGHT) IN THE GANGDISE MOUNTAIN RANGE.**

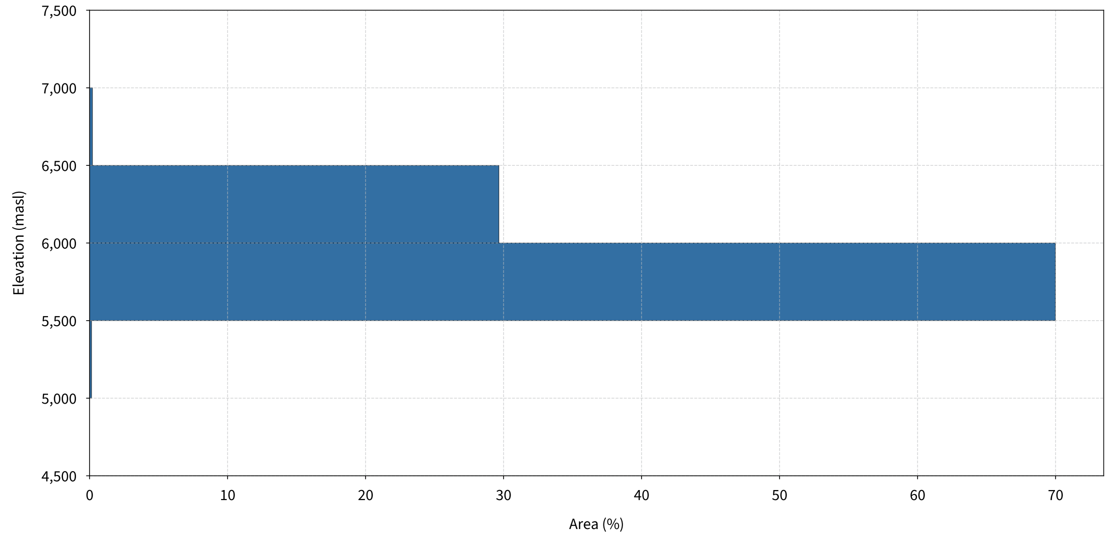


Class 3 constitutes a smaller portion with only 6% of total glacier number in the range. The glaciers of sizes greater than 5 km² are very less in number, only 15 in total, of which 4 exceed 10 km², collectively covering 11% of total area and 22% of the total estimated ice reserves. This distribution underscores the predominance of smaller glaciers in the Gangdise Mountain, highlighting their collective contribution to regional hydrology and the sensitivity of these diverse ice formations to environmental changes. Understanding these patterns is crucial for assessing the mountain range's role in water resource management and its vulnerability to ongoing climate dynamics.

The glaciers in this mountain range are distributed in narrow elevation zone from 5,300 masl to 7,000 masl elevation. The distribution of glacier areas across elevation zone illustrates a significant concentration between 5,500 to 6,000 masl, encompassing nearly 70% of the total glacier area (Figure 4.37). Within this range, the narrow band from 5,800 to 6,000 masl alone accounts for more than half (50.6%) of the total glacier area in this mountain range. Glaciers above 6,000 masl constitute a significant portion as well, particularly between 6,000 and 6,100 masl. Conversely, glacier coverage decreases significantly at higher elevations beyond 6,200 masl, reflecting the challenging conditions for sustained glacier formation and growth could be due to steeper topography. Understanding these elevation-dependent variations is crucial for assessing glacier dynamics and their response to climatic changes within the Gangdise Mountain.

The glacier distribution is also significantly influenced by the slope of the terrain. The classification of glaciers based on its mean slope highlights the significant variation of its distribution, with more than half (52%) of the total glaciers are found on moderate slopes (20 – 30) covering 32% of the total glacier area and holding 21% of the total estimated ice reserves (Figure 4.36). Glaciers on slightly gentler slopes (10° – 20°) also account for a significant portion, with 34% of the glaciers,

FIGURE 4.37 **GLACIER AREA PERCENTAGE DISTRIBUTION ACROSS ELEVATION RANGES IN THE GANGDISE MOUNTAIN RANGE.**



covering 59% of the glacier area, and holding the largest portion of estimated ice reserves (68%). Glaciers on the gentlest slopes (<10°) are fewer but larger in size, covering 5% of the area and holding 9% of the estimated ice reserves. As the slope increases beyond 30°, the number, area, and estimated ice reserves of glaciers decreases significantly. Steep slopes (30° – 40°) host 13% of the glaciers, covering 5% of the total area and holding 2% of the total estimated ice reserves. Very steep slopes (40° – 50°) have a minimal glacier presence, with only 1% of glaciers covering 0.22% of the area and holding less than 0.1% of the estimated ice reserves. No glaciers were mapped beyond the mean slope of 50°. The mean glacier area across different slope classes is higher on gentle slopes, reaching 1.7 km² for slopes less than 10°, and decreases significantly with increasing slope, dropping to 0.08 km² in the 40°– 50° range, indicating smaller glaciers in steeper terrain. This distribution clearly shows the higher and larger glaciers distribution mostly on the gentle and moderate slope up to 30° indicating the favourable conditions of glacier formation and stability, while steeper slopes pose challenges for glacier persistence due to increased ice movement and melting rates as well as stability of snow accumulation.

The slope verses glacier-sized distribution also shows the smaller glaciers are predominantly found in slopes of 10°– 30°, with significant concentration on slopes 20° – 30°. As the size increases, their number and distribution become more limited, with larger glaciers of Class 5 (≥ 5.01 km²) primarily found on gentler slopes (< 20°). This pattern suggests that while smaller glaciers can exist on a variety of slopes, larger glaciers are more stable and sustainable on gentler slopes.

The orientation of glaciers in eight different aspects reveals that the northern aspect is the most dominant, accounting for nearly 36% of the total glacier area and 31% of the total estimated ice reserves (Figure 4.36). This is followed by northeastern, which covers 21% of the area, and northwestern covering 15% of the total area. The southern, southeastern and southwestern aspects show similar distributions in terms of glacier numbers, with a slightly higher percentage in the southeastern aspect. In terms of area, all these three aspects each covering 4% of the area, with a marginally larger area in southeastern aspect. The western and eastern aspects each cover about 8% of the total area, with the eastern aspect showing slightly larger absolute area. However, the eastern aspect has a higher number of glaciers, while the western aspect holds larger estimated ice reserves, as evidenced by the average glacier size of 0.5 km² in the western aspect compared to 0.36 km² in the eastern aspect. This also suggests that the glaciers in the western aspect were bigger in size than in the eastern aspect. Overall, this distribution of glaciers in various aspects highlights that the northern, northeastern and northwestern aspects favour larger and more numerous glaciers in this mountain range.

Decadal glacier changes from 1990 to 2020

Similar to neighbouring mountain ranges, the Gangdise mountain range has experienced a significant decline in both number and area of glaciers over the past three decades, with a total reduction of approximately 3.4% in number and nearly 23.5% of area. While the number of glaciers increased slightly by 0.2% from 1990 to 2000 period, it has steadily decreased by about 0.2% from 2000 to 2010 and by 3.4% in the most recent decade. Conversely, glacier area has decreased throughout all decades, with the rate of loss accelerating in recent decade – from around 7% loss in early 1990s to more than 10% loss in recent decade from 2010 to 2020 (Figure 4.38).

Changes across various glacier size classes reveal significant reductions in both number and area for most classes, except for the largest size Class 5 (≥10 km²). This class did not experience any change in the number of glaciers but lost a modest area of about 6.1% over the past three decades. The most pronounced reductions were observed in the mid-sized classes, particularly from Class 2 to Class 4 (Figure 4.39). Class 2 glaciers experienced the most substantial decline in glacier number, with reduction of 142 (34.1%), while Class 3 glaciers have the highest area loss by 111 km² – which is more than 21% of the glacier retreat over the three decades. Although Class 4 showed the highest percentage of glacier retreat, Class 2 had the greatest absolute area loss.

Interestingly, the smallest glacier Class 1 initially showed an increase in the number of glaciers during the first two decades (1990 – 2010). This increase likely indicates that the shrinkage and fragmentation of larger glaciers have contributed to the formation of smaller glaciers. However, this trend reversed in the most recent decade (2010 – 2020), with a 2.1% decrease in the number of smallest glaciers. The glacier area in this class has been retreated throughout all time periods, with total reductions of 15.3% over the three decades. Overall, the rate of the glacier area retreat was higher in the most recent decade (2010 to 2020) compared to earlier decades (1990 – 2010).

Glacier area changes across different elevation ranges reveal a clear trend of retreat over the past three decades. The most significant retreat was observed at elevation range from 5,500 masl to 6,000 masl, with a total area loss of 27.5% over the three decades (Figure 4.40). Within this range, the greatest proportion of area loss was observed between 5,700 and 5,900 masl across all decades. Adjacent elevation zones, specifically from 5,600 to 5,700 masl and 5,900 to 6,000 masl, also experienced substantial glacier retreat compared to the areas below 5,600 masl and above 6,000 masl. Although the absolute glacier area loss diminished at elevations below 5,600 masl and above 6,000 masl, the rate of percentage change was higher in the lower elevations and less significant in the higher elevations. Across all elevation ranges, the rate of glacier area loss increased in the recent decade (2010 – 2020) compared to the earlier decades (1990 – 2010). Details of these changes by elevation range are given in Table 4.8 and illustrated in the Figure 4.40.

The distribution of glaciers across different mean slope classes from 1990 to 2020 reveals that the 20° – 30° slope class experienced the most significant losses in both glacier number and area (Figure 4.41). Over the three-decades, this class lost 257 glaciers, representing a 13% reduction, along with a substantial area loss of 128.76 km², amounting to a 24% decrease in total glacier area.

FIGURE 4.38 DECADAL CHANGES OF GLACIER NUMBERS AND AREAS IN THE GANGDISE MOUNTAIN RANGE.

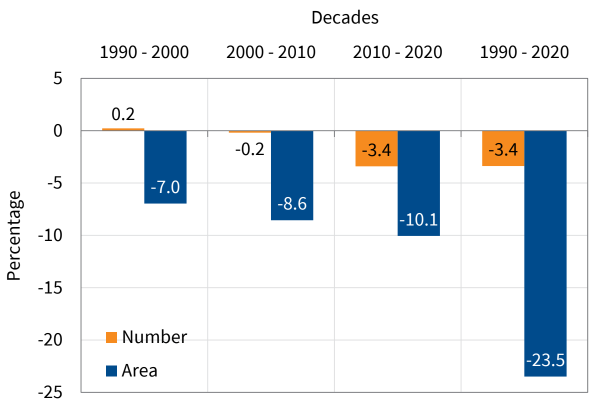


FIGURE 4.39 GLACIER NUMBER AND AREA CHANGES ACROSS VARIOUS SIZE CLASSES OVER THREE DECADES INCLUDING MEAN DECADAL CHANGE RATE IN THE GANGDISE MOUNTAIN RANGE.

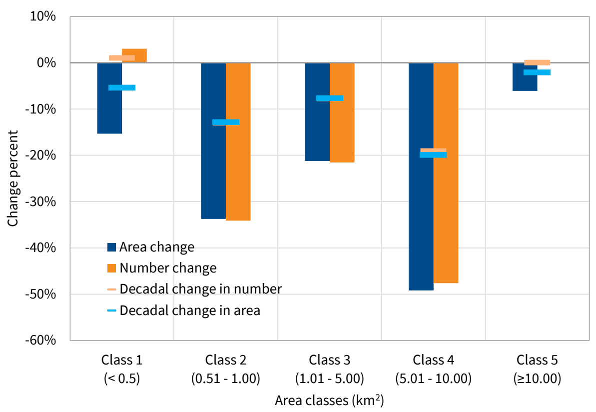


FIGURE 4.40 GLACIER AREA DISTRIBUTION AND CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE GANGDISE MOUNTAIN RANGE.

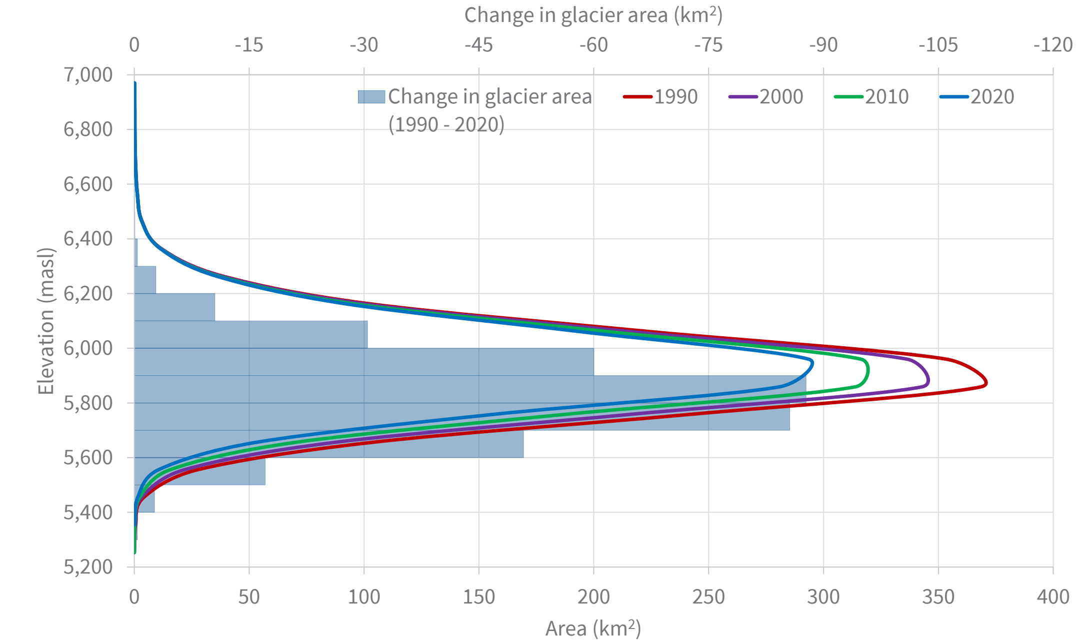
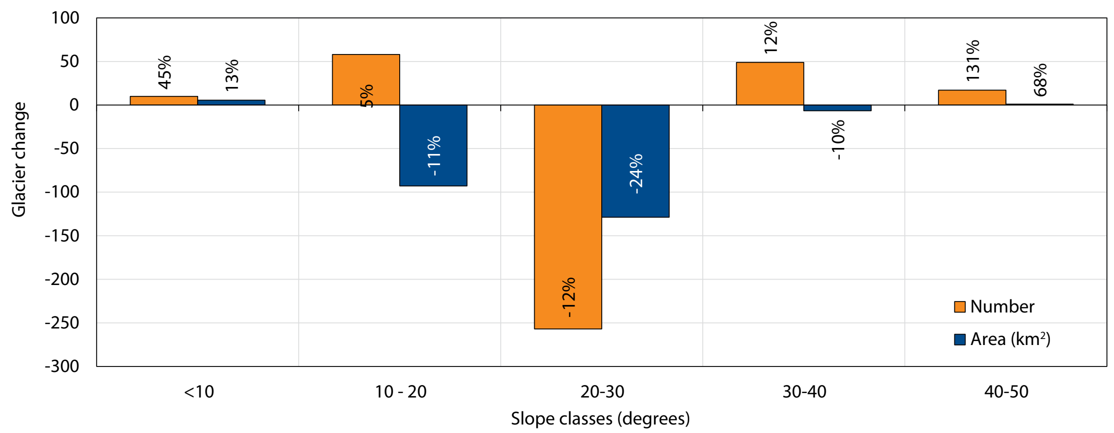


TABLE 4.8 GLACIER AREA DISTRIBUTION AND PERCENTAGE CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE GANGDISE MOUNTAIN RANGE.

Elevation Range	Area (km²)				Change percentage				Decadal change rate (percent)
	1990	2000	2010	2020	1990–2000	2000–2010	2010–2020	1990–2020	
5,000–5,500	4.73	3.57	2.54	1.64	-24.6	-28.8	-35.7	-65.4	-29.7
5,500–6,000	1096.06	1005.22	904.18	794.82	-8.3	-10.1	-12.1	-27.5	-10.2
6,000–6,500	381.09	369.75	353.60	336.82	-3	-4.4	-4.7	-11.6	-4.0
6,500–7,000	2.50	2.48	2.41	2.37	-0.9	-2.6	-1.8	-5.2	-1.8
Total	1,484.38	1,381.01	1,262.74	1,135.65	-7.0	-8.6	-10.1	-23.5	-8.6

FIGURE 4.41 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES IN THE GANGDISE MOUNTAIN RANGE.



In contrast, other slope classes recorded an increase in glacier numbers but a simultaneous reduction in area, suggesting a trend toward glacier fragmentation and shifting mean slopes as glacier area shrink. In the 30°– 40° slope class, 49 glaciers increased, but experienced a 10% area loss, indicating a complex interplay of new or fragmented glaciers contributing to the number but not offsetting the overall loss in glacier area. The 10° – 20° slope class faced the second-highest area loss, with an 11% reduction, despite an increase in glacier numbers – further supporting the trend of fragmentation and downsizing.

Meanwhile, slope classes below 10° and between 40° – 50° displayed relatively minor changes, with slight increases in both number and area. However, the changes were minimal and did not significantly alter overall glacial trends. Notably, the rate of glacier area loss intensified during the last decade (2010–2020) across all slope classes, emphasising an accelerated pattern of glacier retreat in recent years, regardless of slope steepness.

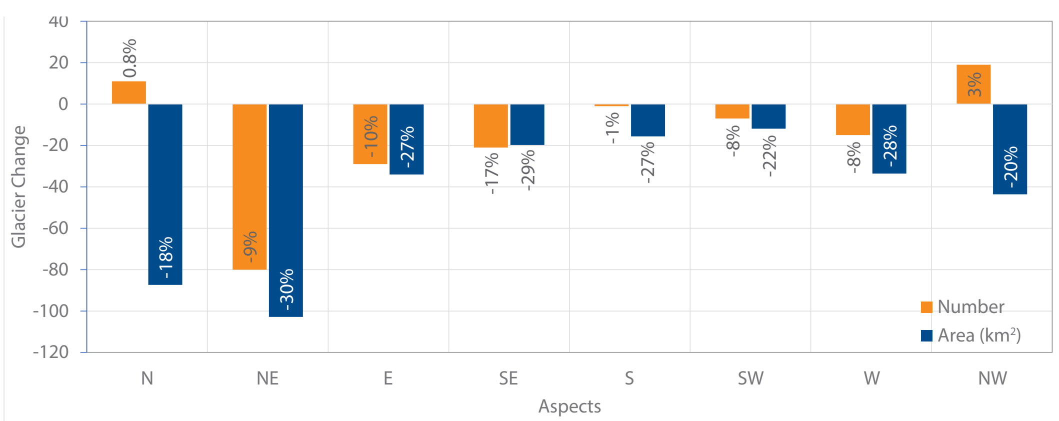
The distribution of glaciers into various mean aspects between 1990 to 2020 reveal a distinct pattern of its number and area changes (Figure 4.42). The northern, northeastern and northwestern aspects show a mixed pattern of glacier changes. The number of glaciers in northern and northwestern aspects shows increases in the earlier two decades and a steep decrease in glacier numbers in recent decade with overall increases of 11% and 19%. While northeastern aspect shows consistent decreases over each decade, with overall loss of 9.2% of glacier number in three decades. Despite this fluctuation in glacier number, the glacier area was consistently shrinking across all three aspects, with the largest area loss by almost 30% over three decades in northeastern aspect. northwestern and northern aspects also show considerable amount of area loss of about 20% and 18% respectively.

In contrast, the southern, southeastern, and southwestern aspects showed more consistent and pronounced glacier recession across all decades. Glacier numbers dropped in each aspect, with southeastern and southern aspects losing about 17% and 1% of glaciers respectively. The southwestern aspect experienced an 8% drop in glacier numbers over the three decades. More importantly, the area loss was extensive, with southeastern and southern losing 29% and 27% respectively, while southwestern lost 22% over three decades.

The remaining eastern and western aspects also showed glacier retreat but with moderate characteristics compared to the other aspects. In the eastern aspect, the number of glaciers dropped by 10%, while in the western aspect, the decline was 15%. In terms of area, both aspects lost around 33 – 34 km², with eastern aspect losing 26.7% and western aspect losing 27.7% of glacier area. Though significant, these losses were somewhat less severe than those in the southern aspects, but more than those on northern aspect.

Overall, the southern aspect glaciers showed the most uniform and aggressive retreat in both number and area. The northern aspect glaciers exhibited more variability, with some gains in numbers offset by substantial area losses. Similarly, the eastern and western aspects showed steady decline. This increase in number could be influenced by the alteration on mean aspect with shrinkage of glaciers.

FIGURE 4.42 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES IN THE GANGDISE MOUNTAIN RANGE.



4.5 Nyainqêntanglha Mountain

The Nyainqêntanglha mountain range, also known as Nyenchen Tanglha, is situated in the southeastern section of the HKH region and forms the southern part of the Tibetan Autonomous Region in southwestern China. This range spans approximately 700 kilometers, extending from the Namtso Lake region in the west to the Brahmaputra River in the east, between longitudes 89.590°E and 97.881°E and latitudes 27.249°N and 31.509°N. The Nyainqêntanglha range runs parallel to the eastern Himalaya to the south. Its elevation ranges from 179 masl to 7,162 masl, with the highest peak, Mount Nyainqêntanglha, reaching an altitude of 7,162 masl. Figure 4.43 showing the glacier distribution and extent of the Nyainqêntanglha Mountain range.

Glacier distribution in 2020

This mountain range consists of 7,961 glaciers, covering an area of 6,079.6 km², with estimated ice reserves of 496 km³ based on Landsat images of 2020 (Table 4.1). These glaciers cover 3.5% of the total land area of the mountain range and about 11% of the total glacier area in the HKH region. The glaciers are relatively large, with a mean glacier area of 0.8 km². Additionally, the range includes two of the 25 largest glaciers in the HKH region, each exceeding 100 km², with the largest glacier measuring 166.74 km².

The glacier size class distribution in the Nyainqêntanglha mountain range is diverse, with a higher percentage of smaller glaciers and significant area coverage by mid and larger-sized glaciers. Nearly 72% of the glaciers are smaller than 0.5 km², covering only 15% of the total glacier area and holding 4% of the estimated ice reserves (Figure 4.44). Mid-sized glaciers (1.0 – 5.00 km²) account for 12% of the glacier number but cover the largest glacier area, representing 31% and holding 22% of the total estimated ice reserves. The largest glaciers (>10.00 km²) are the fewest, comprising only 1% of the total number, yet they cover 30% of the total glacier area and hold a substantial 56% of the estimated ice reserves. Overall, the distribution demonstrates an inverse relationship between glacier number and area: many small glaciers

FIGURE 4.43 MAP SHOWING THE GLACIER DISTRIBUTION AND EXTENT OF THE NYAINQÊNTANGLHA MOUNTAIN RANGE IN THE HKH.

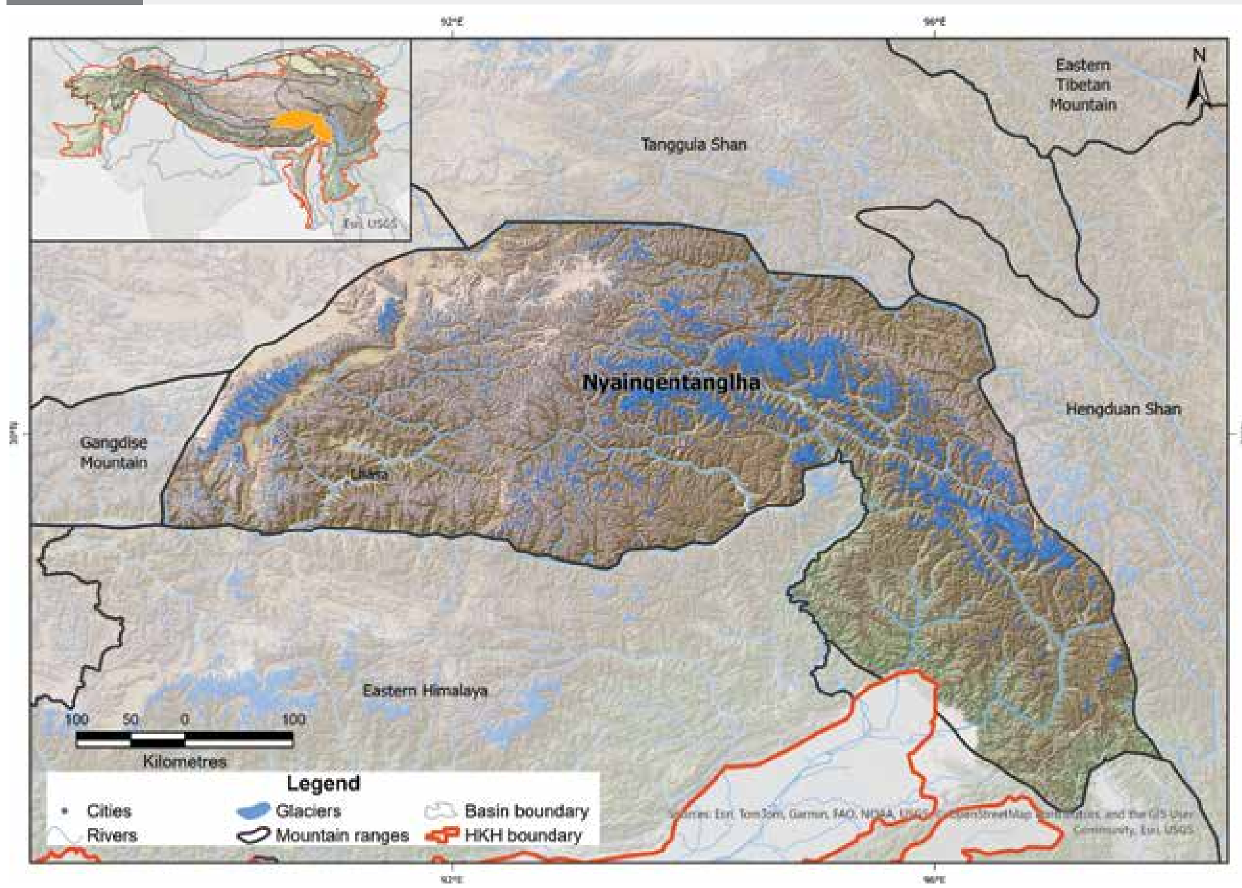
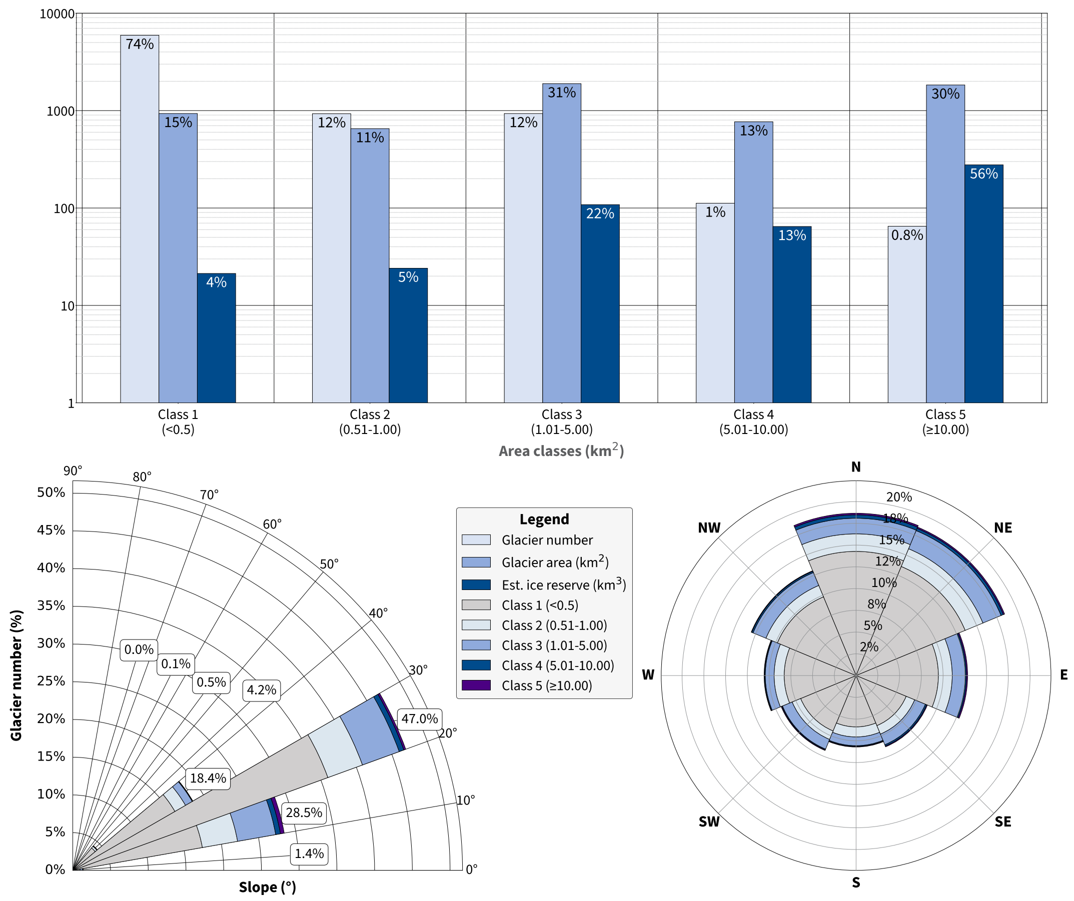


FIGURE 4.44 **GLACIER NUMBER, AREA AND ESTIMATED ICE RESERVES BY AREA SIZE CLASS** (TOP) **AND ITS DISTRIBUTION ACROSS MEAN SLOPES** (BOTTOM LEFT) **AND ASPECTS** (BOTTOM RIGHT) **IN THE NYAINQÊNTANGLHA MOUNTAIN RANGE.**



contribute a minor portion of the total area, while a few large glaciers account for a significant portion of the glacier coverage.

The glaciers in this mountain range span a wide range of elevations from 2,600 masl to 7,100 masl. Their distribution reveals a distinct pattern, with a higher concentration between 4,500 masl and 6,000 masl, covering more than 87% of the total glacier area in the range (Figure 4.45). Outside this optimal elevation range, both lower and higher elevations show a significantly decreasing trend in glacier presence.

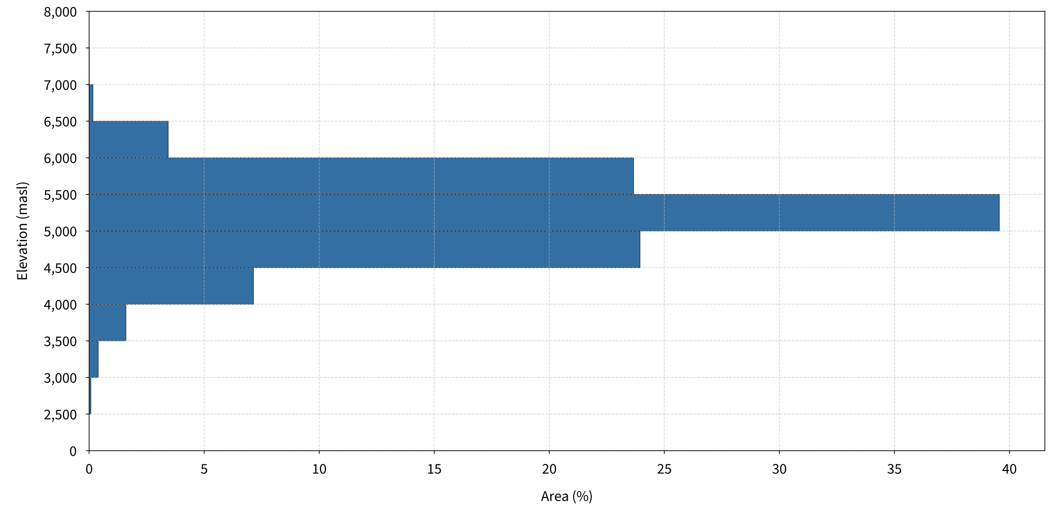
At elevations below 3,000 masl, glaciers are almost non-existent, covering just 0.08% of the total glacier area. As the elevation increases, glacier area coverage gradually rises from 3,000 to 4,500 masl, ranging from 0.4% to 7% of the total glacier area in each 500 metre elevation zone. Beyond 4,500 masl up to 6,000 masl, the area distribution increases significantly, with each 500 metre zone accounting for more than 23% of the total glacier area. The highest concentration, almost 40% of the total glacier area, is found between 5,000 and 5,500 masl.

Above 6,000 masl, the glacier area decreases considerably, with the lowest coverage being just 0.6 km² above 7,000 masl and 10 km² in the 6,500 to 7,000 masl elevation range.

Similar to other mountain ranges, the distribution of glaciers in various mean slope classes in the Nyainqêntanglha mountain range reveals a clear pattern: glaciers are most prevalent on slopes between 10° and 30° (Figure 4.44). These slopes host nearly 73% of the total glaciers, which cover about 88% of the total glacier area and hold 93% of the estimated ice reserves. Glaciers in the 30°– 40° slope class constitute 20.6% of the total glaciers, covering 9.4% of the glacier area and containing 5.3% of the estimated ice reserves.

In steeper slope classes, glaciers become increasingly rare. Only about 6% of the total glaciers are found on slopes above 40°, covering just 1.4% of the total glacier area. The average size of glaciers in these steeper classes ranges from 0.1 to 0.19 km²,

FIGURE 4.45 **GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN THE NYAINQÊNTANGLHA MOUNTAIN RANGE.**



indicating smaller glacier distribution. In contrast, glaciers on slopes ranging from 0° to 30° have larger average sizes, ranging from 0.7 to 1.43 km², indicating a more significant glacier distribution on these slope classes.

The glacier size classes versus mean slope class distribution indicates that a significant number of glaciers across all size classes are concentrated within the 10° – 30° slope range. Smaller glaciers (Class 1, <0.5 km²) dominate in number, particularly in the 10° – 20° and 20° – 30° slope classes, comprising 55% and 49% of the total glaciers, respectively. However, these small glaciers account for only 15% of the total glacier area. Larger glaciers (Classes 4 and 5) are fewer in number but cover substantial areas. Glaciers of Class 4 (5.01 – 10.00 km²) are mostly found on 10° – 20° and 20° – 30° slopes, while those in size Class 5 (≥10.00 km²) are predominantly located on 10° – 20° slopes, contributing significantly to the total glacier area (20%). This highlights that glaciers are predominantly found on slopes ranging from 10° – 30°, with larger glaciers dominating in the gentler slopes of 10° – 20°.

In terms of mean aspect, glaciers facing northern and northeastern aspects are the most prominent, each accounting for over 18% of the total glacier number (Figure 4.44). Collectively, they cover more than one-third (36.5%) of the total glacier area in the mountain range and hold around one-third (33%) of the total estimated ice reserves, making them the most significant contributors in terms of both extent and estimated ice reserves.

In contrast, glaciers facing southern, southeastern, and southwestern aspects are the least prominent, each representing roughly 8–9% of the total glacier number. Among them, the southeastern aspect stands out slightly higher area coverages, covering about 11% of the total glacier area, while the southern and southwestern aspects contribute only 7% and 8%, respectively. These aspects also contain the least estimated ice reserves, each making up just 5% of the total.

Eastern facing glaciers are also substantial, comprising 13% of the total number, yet contributing the highest glacier area (19%) and the largest amount of estimated ice reserves (29%) among all aspects. Western and northwestern aspects also host a significant number of glaciers, accounting for 11% and 13% of the total, respectively. However, their area coverage varies significantly, the western aspect has the lowest area (7%) and estimated ice reserves (5%), whereas northwestern aspects contribute a considerable amount of glacier area (12%) and estimated ice reserves (10%).

When it comes to mean glacier size, eastern aspects lead with the largest average glacier area, exceeding 1 km², indicating the presence of larger glaciers. The southeastern aspect also supports relatively large glaciers distribution, with a mean glacier size of 0.96 km². Northern, northeastern, and northwestern aspects have moderate-sized glaciers, with average sizes ranging from 0.67 to 0.75 km². In contrast, the western aspect has the smallest mean glacier size at 0.53 km², reflecting the presence of smaller and more fragmented glaciers.

Decadal glacier changes from 1990 to 2020

Over the past three decades this mountain range has experienced notable changes in glaciers' number and area. Initially the glacier number increased by 2 from 1990 to 2000 and later it decreased significantly by 135 in 2000 to 2010 and 269 in 2010 to 2020, resulting in a net reduction by 4.9% over three decades. In terms of glacier area, there was a consistent and significant decline over the same period with an increasing rate of area loss. Between 1990 and 2000, the area lost more than 3%. The loss rate was accelerated in the next decade (2000 – 2010), with a further reduction of 5.3%. The most recent decade (2010 – 2020) continued this trend, with a substantial area loss of 7.3%. Overall, almost 15% of the total area was lost from 1990 to 2020. Therefore, the glacier number in this mountain range showed some fluctuation but the overall trend in the glacier area showed a substantial decline trend, with the most significant losses occurring in the most recent decade (Figure 4.46).

FIGURE 4.46 DECADAL CHANGES OF GLACIER NUMBER AND AREA IN THE NYAINQÊNTANGLHA MOUNTAIN RANGE.

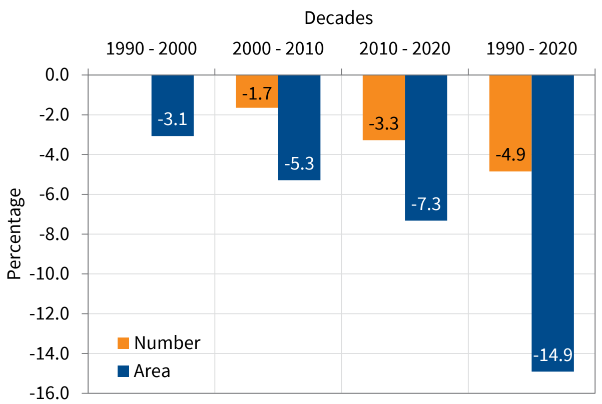
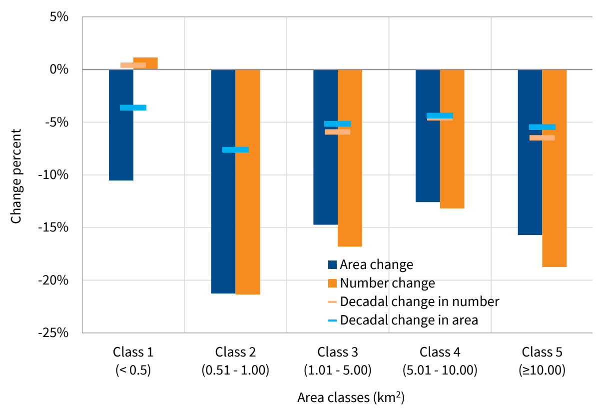


FIGURE 4.47 GLACIER NUMBER AND AREA CHANGES ACROSS SIZE CLASSES OVER THREE DECADES INCLUDING MEAN DECADAL CHANGE RATE IN THE NYAINQÊNTANGLHA MOUNTAIN RANGE.



Across all glacier size classes, both the number and area of glaciers have consistently decreased over the past three decades. The exception is the smallest size class (<0.5 km²), which had a slight increase in the number by 1.2% over all time period (1990 -2020). However, this class experienced a substantial area loss of 10.5% over the same period.

The most notable reduction in glacier numbers occurred in Class 2 (0.51 – 1.00 km²), with a net decrease of 21% from 1990 to 2020 (Figure 4.47). This class also suffered the second highest loss in the glacier area. The Class 3 (1.01 – 5.00 km²) glaciers experienced the greatest area loss, nearly 15% over three decades, along with a significant reduction in glacier numbers, approximately 17%. Despite the substantial number reduction in Class 2 (0.51 – 1.00 km²) glaciers and area reduction of those in the Class 3 (1.01 – 5.00 km²), the rate of decline in both glacier number and area has been consistently higher in the size Class 2 across all decades, with an accelerating trend oberserved especially in the most recent decade (2010 – 2020).

In contrast, the larger glacier size classes, such as Class 4 (5.01 – 10.00 km²) and Class 5 (≥10.00 km²), showed fewer reductions in glacier numbers, with net decreases of 17 and 15 glaciers, respectively, from 1990 to 2020. Despite this, these larger classes experienced significant area losses across all decades, highlighting a continued trend of retreat even in the larger glaciers. The area loss percentage in Class 4 (5.01 – 10.00 km²) glacier varied from 3% to 6% across the decades, culminating in a total reduction of 12.6%. Similarly in the largest Class 5, the area loss percentage varied from about 2% to 12% over the decades, resulting in a total loss of about 16%. Therefore, the present dataset showed a pronounced glacier retreat across all size classes, with the most prominent area losses occurring in the largest glaciers. The rate of area loss has steadily increased, reflecting a severe and accelerating trend of glacier retreat.

The lowest glacier snout in this mountain range, initially mapped at 2,469 masl elevation in 1990, had retreated to 2,607 masl by 2020, indicating significant glacier retreat. Over the past three decades, glacier area changes across different elevation ranges in this mountain range reveal a clear trend of decline, with variations in the rate of retreat based on elevation. The most pronounced

FIGURE 4.48 GLACIER AREA DISTRIBUTION AND CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE NYAINQÊNTANGLHA MOUNTAIN RANGE.

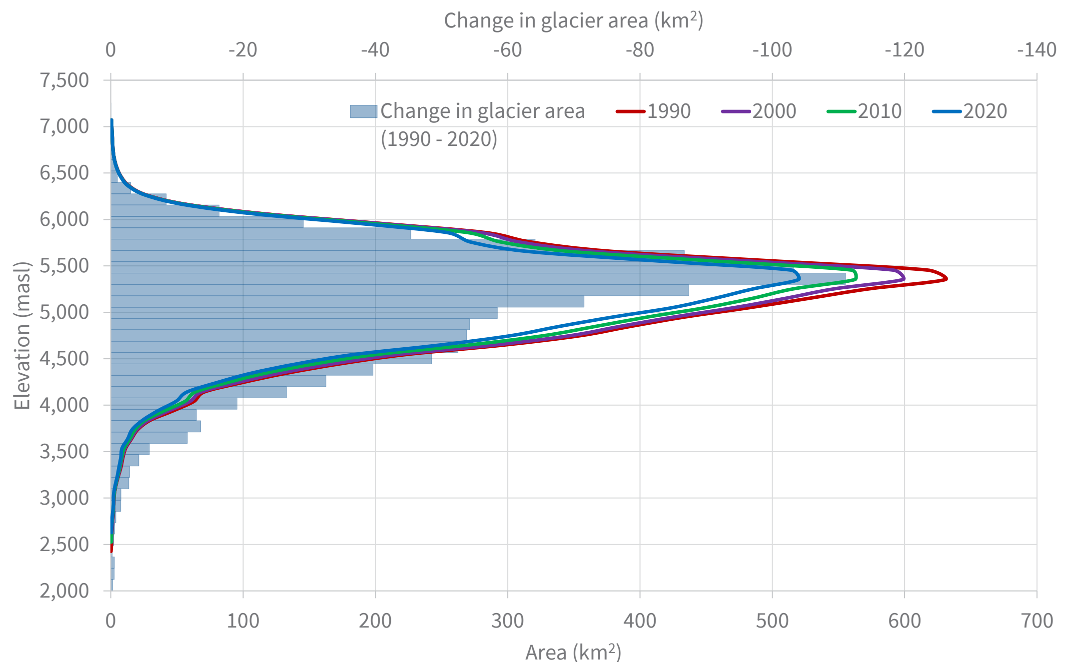


TABLE 4.9 GLACIER AREA DISTRIBUTION AND PERCENTAGE CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE NYAINQÊNTANGLHA MOUNTAIN RANGE.

Elevation ranges (masl)	Area (km²)				Area change (%)			
	1990	2000	2010	2020	1990 – 2000	2000 – 2010	2010 – 2020	1990 – 2020
<2,500	0.17							
2,500 – 3,000	6.85	6.51	5.56	4.64	-5.0	-14.6	-16.5	-32.3
3,000 – 3,500	28.89	27.78	26.35	24.01	-3.8	-5.2	-8.9	-16.9
3,500 – 4,000	124.48	118.62	109.67	97.34	-4.7	-7.5	-11.2	-21.8
4,000 – 4,500	538.46	519.36	479.97	434.42	-3.5	-7.6	-9.5	-19.3
4,500 – 5,000	1,701.97	1,666.15	1,573.53	1,455.67	-2.1	-5.6	-7.5	-14.5
5,000 – 5,500	2,832.83	2,722.60	2,579.16	2,405.13	-3.9	-5.3	-6.7	-15.1
5,500 – 6,000	1,678.20	1,633.13	1,559.12	1,438.81	-2.7	-4.5	-7.7	-14.3
6,000 – 6,500	222.10	220.75	215.36	208.90	-0.6	-2.4	-3.0	-5.9
6,500 – 7,000	10.52	10.53	10.24	10.09	0.1	-2.7	-1.5	-4.1
7,000 – 7,500	0.57	0.57	0.57	0.57	0.0	0.0	0.0	0.0
Total	7,145.03	6,926.03	6,559.57	6,079.60	-3.1	-5.3	-7.3	-14.9

glacier area loss was observed between 4,000 masl to 6,000 masl elevation range, with the greatest absolute area loss was observed in 5,000 masl to 5,500 masl elevation over all time periods (Figure 4.48 and Table 4.9). Although, the proportion of area loss diminishes both above and below this elevation range, the rate of loss percentage is higher at lower elevations below 4,000 masl and lower at higher elevations above 6,000 masl.

At lower elevation below 3,000 masl, it lost 32.4% of glaciers from 1990 to 2020. This reduction occurred steadily, with a loss of 5.1% in the initial decade from 1990 – 2000, accelerating to 16.5% in the most recent decade (2010 – 2020). Similarly, the elevation ranges from 3,000 masl to 3,500 masl experienced a total decline of 17% over the same period, with notable losses of 4% and 8.8% in the earlier and later decades, respectively.

The proportion of loss increases above 4,000 masl and attains its peak at elevation ranges from 5,000 masl to 5,500 masl, with total area loss percentage of 15.2% at this elevation range from 1990 to 2020. The area loss slightly diminishes at elevation 5,500 masl to 6,000 masl with loss of 14.4% in three decades. But beyond 6,000 masl, the loss rate diminishes significantly from 6% at elevation 6,000 masl to 6,500 masl to almost no changes above 7,000 masl over all decades. Therefore, this mountain range had more severe glacier area loss in elevations below 6,000 masl and reductions are more gradual at higher elevations.

Glacier changes have varied across different mean slope classes, reflecting diverse patterns in both glacier numbers and areas. In the slope class with a mean slope of <10°, glacier numbers increased by 19% overall from 1990 to 2020, with a rising trend in each decade. However, this increase in glacier numbers was accompanied by an 11% decrease in total glacier area, indicating that while more glaciers appeared, individual glaciers are shrinking.

Similarly, the 10° – 20° slope class showed a notable increase of 188 glaciers (11%) between 1990 and 2020. However, this was accompanied by a 5% reduction in the glacier area, with the most significant decline occurring in the most recent decade. The 20° – 30° slope class experienced the most pronounced decreases, with a 13% reduction in glacier numbers and an 11% reduction in glacier area over three decades (Figure 4.49). This class saw substantial area losses, particularly in the last decade, highlighting a trend of both shrinking numbers and reduced sizes.

The 30° – 40° slope class also showed decreases in both glacier numbers and area over the three decades, but the reductions were less pronounced compared to the 20° – 30° slope class. While slope classes steeper than 40° experienced increases in both glacier numbers and area, these changes were relatively minor. Overall, the increase in glaciers' numbers in slope classes is influenced by the changes of mean slope class with shrinking and

FIGURE 4.49 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES IN THE NYAINQÊNTANGLHA MOUNTAIN RANGE.

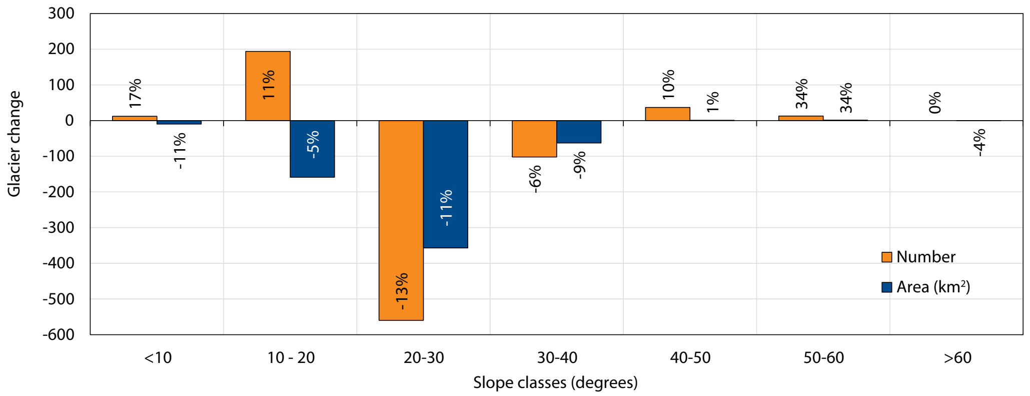
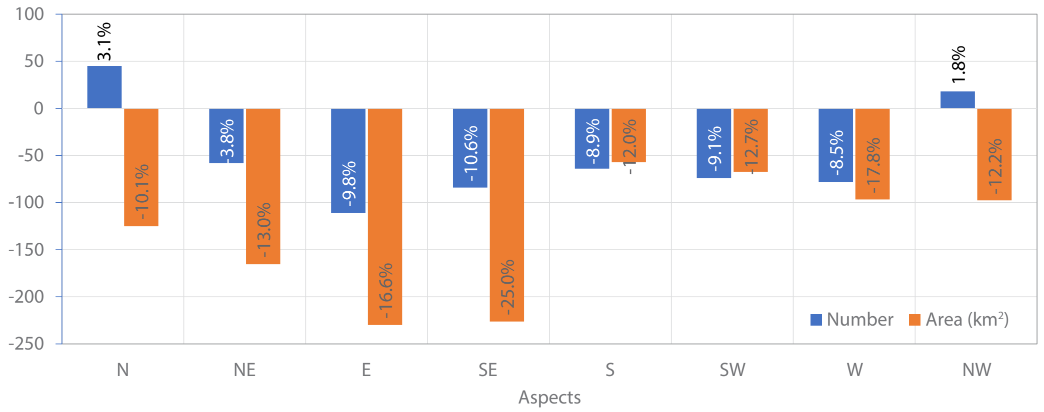


FIGURE 4.50 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES IN THE NYAINQÊNTANGLHA MOUNTAIN RANGE.



AUTOMATIC WEATHER STATION AT KYANGJING, LANGTANG VALLEY, NEPAL

fragmentation of glaciers, which also influenced in the significant reduction of glacier area in some of the mean slope classes.

The glacier changes across various mean aspects reveals a significant retreat trend over the past three decades. Glaciers on northern, northeastern, and northwestern aspects demonstrated relatively better resilience in terms of number. The northern and northwestern aspects even experienced a net gain in glacier number over the three decades, increasing by 45 and 18 glaciers respectively. However, this was accompanied by substantial area losses, over 10% in northern and nearly 12.3% in northwestern glaciers (Figure 4.50). The northeastern aspect, while experiencing a moderate loss of glacier numbers (58 glaciers), showed higher area loss of more than 13% over three decades.

In contrast, glaciers in the southern, southeastern, and southwestern aspects were the most adversely affected. All three showed significant declines in both number and area. The southeastern aspect experienced the steepest loss in the glacier area of 25%, along with a 10.6% drop in glacier number.

The southern aspect lost about 9% of glaciers and about 12% of the glacier area, while the southwestern aspect showed a reduction of more than 9% of glaciers and about 13% of the area over three decades. These trends point to a consistent and accelerating retreat of glaciers on south facing slopes, which are more exposed to solar radiation and warming.

The eastern and western aspects also exhibited clear signs of glacier degradation. Eastern aspect glaciers experienced the highest area loss of almost 16.6% with a significant reduction in glacier number by 9.8%. The western aspect showed a similar trend, losing about 8.5% of glaciers and nearly 18% of the glacier area. These declines reflect the vulnerability of glaciers on these slopes, likely influenced by climatic and topographic factors.

Over three decades, the most recent decade (2010 – 2020) showed the fastest rate of area loss, indicating that glacier retreat has accelerated in recent years across all aspect classes, underscores the growing impact of climate change on high-mountain cryospheric systems.

4.6 Hengduan Shan

The Hengduan Shan extends from the Tibetan Plateau in the north to the southeastern parts of China, spanning approximately 750 kilometres in a north-south direction. This range separates the lowlands of northern Myanmar from the lowlands of the Sichuan Basin in China. Three of the ten major river systems in the HKH region, Salween, Mekong, and Yangtze, flow parallel through this mountain range, carving deep valleys and gorges into the rugged terrain. The elevation in Hengduan Shan ranges from 350 masl to its highest peak, Gongga Shan, which stands at 7,556 masl. It covers an area of 354,250 km² within HKH Region. Figure 4.51 showing the glacier distribution and extent of the Hengduan Shan.

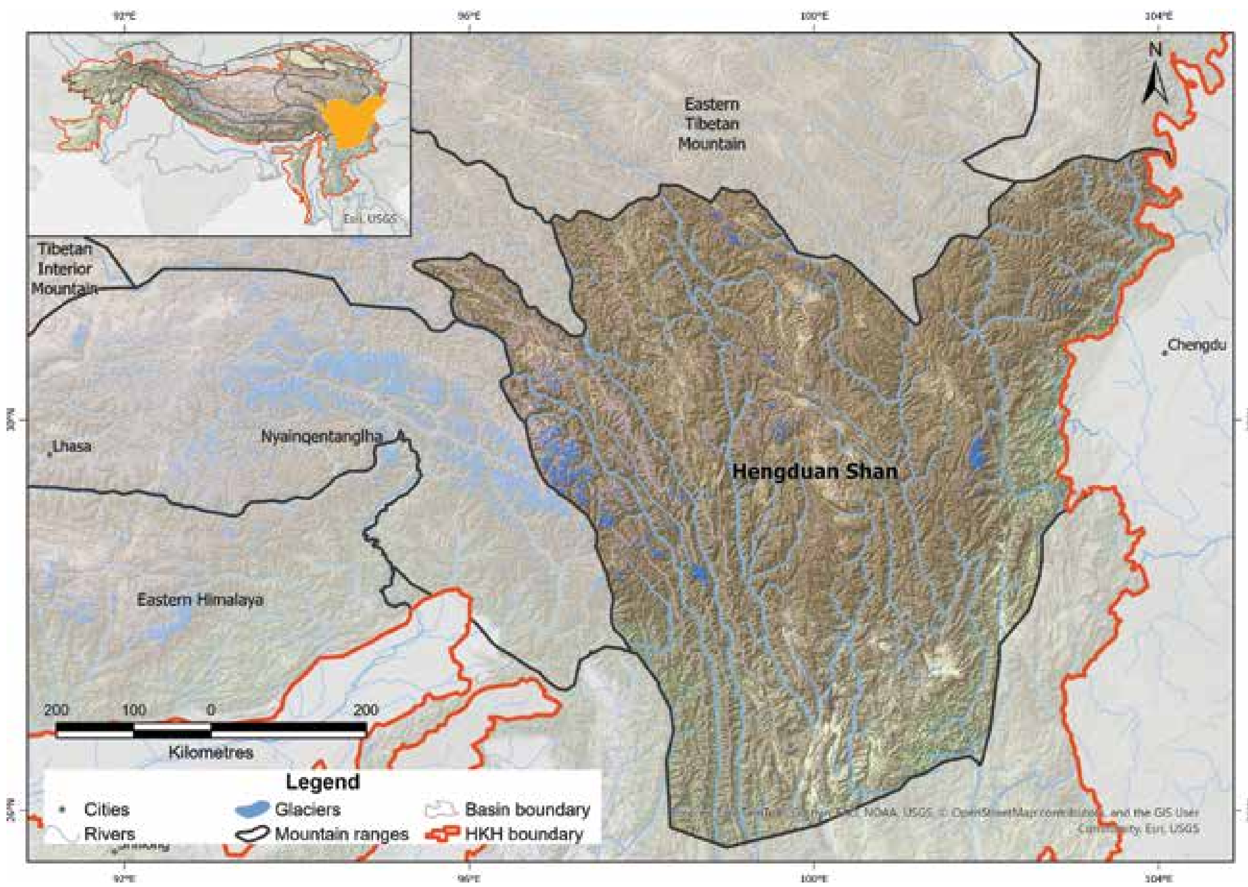
Glacier distribution in 2020

A total of 2,239 glaciers, covering an area of 985.86 km² and containing an estimated ice reserve of 52 km³, were mapped in this mountain range using Landsat images from 2020 (Table 4.1). These figures represent 3.5% of the total number of glaciers and 1.8% of the total glacier area in the HKH region. Glaciers in this mountain range cover only about 0.2% of their total area. The average glacier size is just 0.44 km², indicating a predominance of relatively smaller glaciers.

The size of the glaciers ranges from 0.2 km² to 23.76 km². Analysing the distribution of glaciers by size reveals that the majority are smaller, with most being less than 0.5 km². Over 80% of the glaciers fall into this smallest size Class 1, covering 28% of the total glacier area in the mountain range (Figure 4.52). Class 3 glaciers contribute the largest share of the total glacier area (34%) and estimated ice reserves (35%). Although larger glaciers are fewer in number, they cover a significant area and hold substantial estimated ice reserves. Classes 4 and 5 comprise only 22 glaciers, yet account for 10% and 12% of the total glacier area and hold 16% and 26% of the total estimated ice reserves, respectively.

The glacier distribution in the Hengduan Shan varies significantly across different elevation zones from 2,970 masl to 7,150 masl. The most substantial glacier coverage occurs between 4,500 masl and

FIGURE 4.51 MAP SHOWING THE GLACIER DISTRIBUTION AND EXTENT OF THE HENGDUAN SHAN IN THE HKH.



6,000 masl, with more than 62% of the total glacier area concentrated between 5,000 masl and 5,500 masl (Figure 4.53). Beyond this range, glacier area coverage begins to decline. From 5,500 masl to 6,000 masl, glaciers account for more than 21% of the total glacier area, which is still significant but less dominant. As elevation increases further, the coverage decreases significantly to 2.5% between 6,000 masl and 6,500 masl, and even smaller percentages at higher elevations, with less than 1% of the total glacier area.

A similar pattern is observed at lower elevations below 5,000 masl, where glacier coverage decreases significantly from 11% of the total glacier area between 4,500 masl and 5,000 masl to 1.6% between 4,000 masl and 4,500 masl, and is nearly non-existent below 3,000 masl, covering just 0.024 km^2. Overall, this indicates that glaciers in this mountain range are most abundant at elevations between 4,500 masl and 6,000 masl.

Further the glacier distribution by various mean slope classes shows the majority of the glaciers are distributed in slope range classes of 10° – 20° and 20° – 30° collectively more than 78% glaciers, more than 84% of the total glacier area and almost 87% of total estimated ice reserves (Figure 4.52).

Further analysis of glacier distribution by slope classes reveals that the majority of glaciers are found in the 10° – 20° and 20° – 30° ranges. Together, these classes consist of over 78% of the total glaciers, more than 84% of the total glacier area, and almost 87% of the total estimated ice reserves. The 20° – 30° slope range has the highest number of glaciers, covering 39% of the total glacier area. However, the largest portion of the glacier area, over 45%, and nearly 47% of the estimated ice reserves are concentrated in the 10° – 20° slope range, which contains almost one-third of the glaciers. At slopes of less than 10°, there are only 22 glaciers, which contribute just 3% of the total glacier area. However, with an average size of 1.36 km^2, this suggests a distribution of larger-sized glaciers.

The number of glaciers and their area contributions decrease on slopes steeper than 30°. In the 30° – 40° slope range, glaciers make up almost 17% of the total number and contribute nearly 12% of the total glacier area, with an average size of 0.3 km^2, indicating smaller glacier distribution. Glaciers on slopes steeper than 40° are considerably fewer in number, and their area contribution is negligible.

FIGURE 4.52 **GLACIER NUMBER, AREA AND ESTIMATED ICE RESERVES BY AREA SIZE CLASS** (TOP) **AND ITS DISTRIBUTION ACROSS MEAN SLOPES** (BOTTOM LEFT) **AND ASPECTS** (BOTTOM RIGHT) **IN THE HENGDUAN SHAN.**

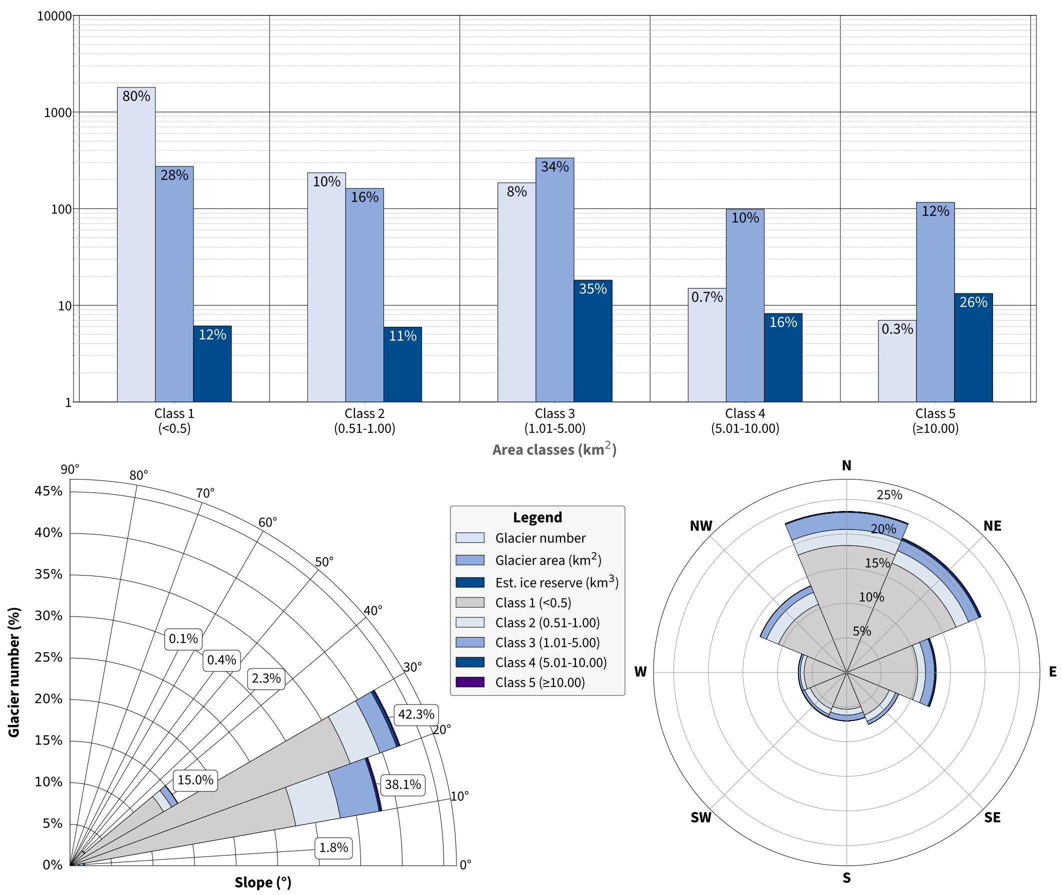
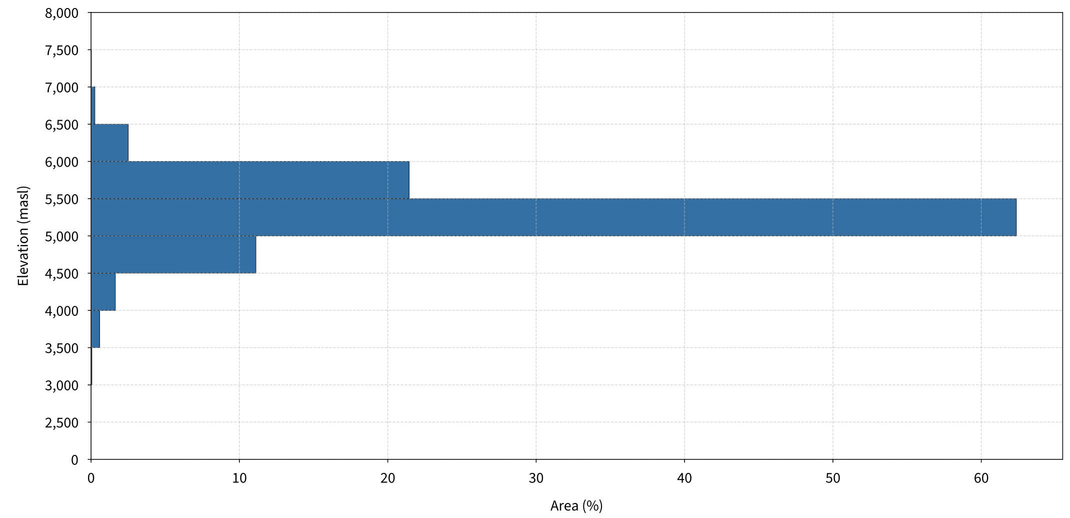


FIGURE 4.53 **GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN THE HENGDUAN SHAN.**



The distribution of glacier size classes relative to slope classes highlights a predominance of smaller glaciers, notably those under 0.5 km^2 (Class 1), spread across all slope categories, with a greater concentration on slopes ranging from 10° – 20° and 20° – 30°. As glacier size increases, their distribution becomes more focused, primarily on slopes between 10° and 30°. The largest glaciers, classified as Class 5 (≥10.00 km^2) and numbering only seven, covering 12% of the total area, are situated within the slope range of 10° – 30°.

The analysis of glacier distribution across eight aspect classes reveals distinct patterns in glacier number, area and estimate ice reserves. The northern, northeastern, and northwestern aspects are prominent, hosting the highest number of glaciers and the largest total glacier area and estimated ice reserves (Figure 4.52). Collectively, these aspects account for 58% of the total glacier number, 57% of the total glacier area, and 53% of the total estimated ice reserves in the mountain range.

The eastern and southeastern aspects also contain a considerable number of glaciers, each comprising 13% and 8% of the total glacier number respectively. The eastern aspect is particularly significant, covering 20% of the total glacier area, while the southeastern aspect covers only 8% of the total glacier area. This indicates a comparatively higher concentration of glacier areas in the eastern aspect than in southeastern aspect.

The southern, southwestern and western aspects each contain 7% of the total glacier numbers. However, their area distribution varies, with the southern aspect having the largest area coverage of 7%, while other aspects, southwestern and western have 6% and 4% respectively.

Additionally, the mean area per glacier varies across the aspect classes, highlighting different densities and sizes of glaciers. The eastern aspect stands out with the largest mean area per glacier at 0.68 km^2, indicating larger glaciers compared to other aspects. In contrast, the western aspect has the smallest mean area per glacier at 0.27 km^2, indicating smaller glaciers compared to other aspects.

Decadal glacier changes from 1990 to 2020

This mountain range experienced the highest percentages of both number and area loss over three decades compared to other ranges. From 1990 to 2020, the glacier number decreased by nearly 15%, and the area shrank by almost 33%. The rate of loss for both numbers and area increased over time, with the rate of decline rising from 1.6% and nearly 9% in the early decade (1990 and 2000), to 9% and almost 16% in most recent decade (2010 to 2020) respectively. The average decadal rate of glacier area retreat was 12.3%, while the number decreased by 5.2% (Figure 4.54).

The distribution and changes analysis of glaciers over various area size classes shows that a pronounced reduction of both number and area in all size classes throughout all decades. The most significant reductions were observed in smallest

FIGURE 4.54 DECADAL CHANGES OF GLACIER NUMBER AND AREA IN THE HENGDUAN SHAN.

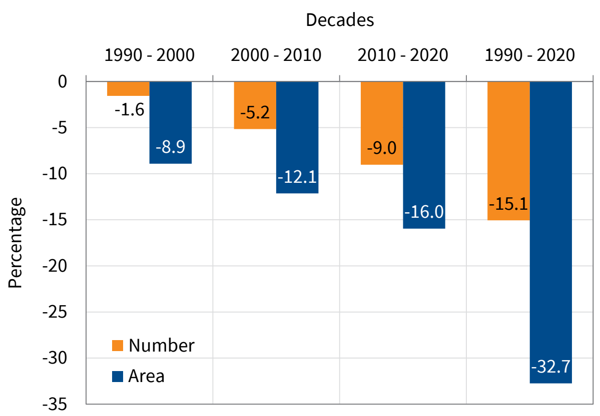
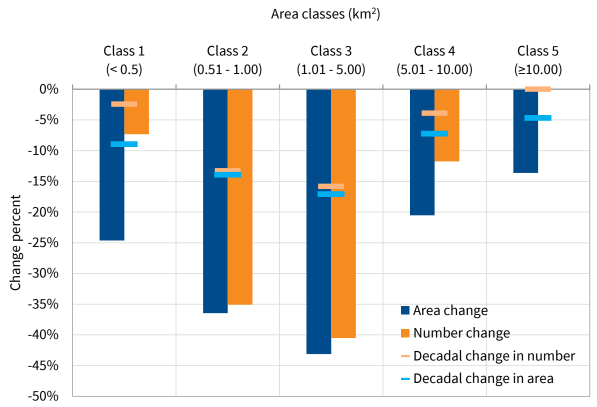


FIGURE 4.55 GLACIER NUMBER AND AREA CHANGES ACROSS SIZE CLASSES OVER THREE DECADES INCLUDING MEAN DECADAL CHANGE RATE IN THE HENGDUAN SHAN.



sized Class 1 (< 0.5 km²) to mid-sized glaciers of Class 2 (0.51 – 1.00 km²) in all decades, with accelerated rates of loss in the most recent decade (2010-2020). The smallest glacier Class 1 (< 0.5 km²) showed an initial increase in numbers, but this was followed by a sharp decline, leading to a total decrease of 142 glacier. Concurrently, the area of these glaciers shrank by 24.5% within three decades, reflecting a substantial acceleration in the loss rate, especially in the most recent decade (2010 – 2020).

Both Class 2 (0.51 – 1.00 km²) and Class 3 (1.01 to 5.00 km²) show the most significant reductions in both glacier numbers and area across all decades, with the most pronounced decrease occurring in the recent decade (Figure 4.55). Both classes experienced a comparable decrease in the number of glaciers, with net area losses of 36% for Class 2 and 43% for Class 3 from 1990 to 2020.

Larger glaciers of Class 4 (5.01 – 10.00 km²) and Class 5 (≥ 10.00 km²) have experienced a moderate decrease in area but a stable number. However, the area of these glaciers decreased significantly by 25.61 km² and 18.3 km² respectively over three decades.

In this mountain range, the lowest glacier snout was recorded at 2,870 masl in 1990. By 2020, this snout had shifted upward to 2,979 masl, indicating a glacier retreat by 109 metres over the past three decades. This is also noted by consistent glacier area reduction over all decades in different elevation ranges, with severe reduction in glacier area in lower and mid elevations. The details of glacier area distribution across various elevation range from 1990 to 2020 including its change percentage is provided in Table 4.10.

From 1990 to 2020, the elevation below 3,000 masl lost an area by 0.23 km² which represents over 90% of their total area in 1990. Similarly, glaciers between 3,000 and 3,500 masl experience a reduction of 1.38 km², or 70% of the total glacier area in 1990. The proportion of area loss increases with elevation up to 5,500 masl, after which it decreases significantly in higher elevation.

The greatest area loss occurred between 5,000 masl to 5,500 masl elevation range, with a reduction of 34.2% of the glacier area from 1990 to 2020 (Figure 4.56). The adjacent lower elevation range of 4,500 to 5,000 masl also experienced a notable decrease, with a 46% loss over three decades. Area loss rates have varied across decades, with the most rapid decline occulting from 2010 to 2020. Concurrently, at higher elevation above 6,000 masl, glaciers exhibit the smallest reduction in area and almost negligible loss above 7,000.

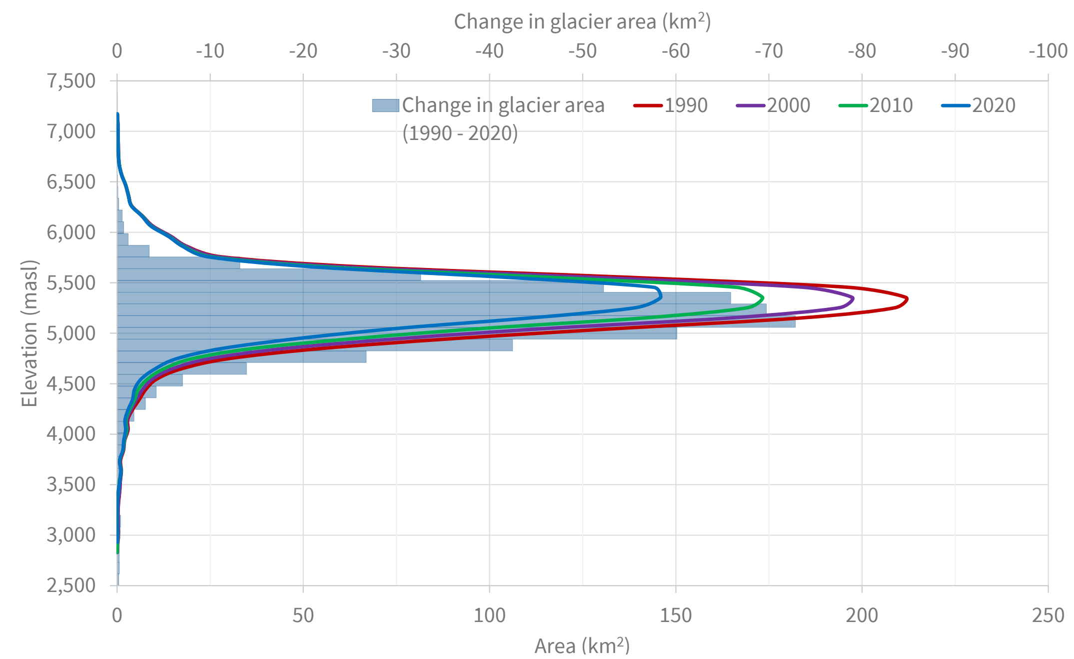
Overall, this highlights the most severe reduction of glacier area from lower and mid elevation ranges below 5,500 masl and less pronounced at higher elevations above 6,000 masl. The variability in loss rates in each elevation ranges over all decades underscores how elevation and time influences glacier vulnerability to temperature increases.

The mean slopes of individual glaciers have changed due to shrinkage and fragmentation over time. Analysis of glaciers by their mean slopes reveals that the most substantial declines in both number and area occurred in the 20° – 30° and 30° – 40° slope classes across all decades (Figure 4.57). Specifically, the 20° – 30° slope class experienced a 22% reduction in glacier numbers and a 28% loss in glacier area over three decades. Similarly, the 30° – 40° slope class had a 31% decrease in glacier numbers and a 27% loss in area.

TABLE 4.10 GLACIER AREA DISTRIBUTION AND PERCENTAGE CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN HENGDUAN SHAN.

Elevation ranges (masl)	Area (km²)				Area change (%)			
	1990	2000	2010	2020	1990 - 2000	2000 - 2010	2010 - 2020	1990 - 2020
2,500 – 3,000	0.25	0.27	0.12	0.02	6.8	-54.9	-80.2	-90.4
3,000 – 3,500	1.98	1.92	0.75	0.59	-2.9	-60.8	-21.3	-70.01
3,500 – 4,000	6.71	6.29	5.89	5.70	-6.2	-6.3	-3.0	-14.8
4,000 – 4,500	23.63	21.31	18.73	16.19	-9.8	-12.1	-13.4	-31.3
4,500 – 5,000	204.21	171.02	141.55	109.59	-16.3	-17.2	-22.4	-46.2
5,000 – 5,500	937.13	857.46	749.61	614.85	-8.5	-12.6	-17.8	-34.2
5,500 – 6,000	263.01	247.96	228.17	211.33	-5.7	-8.0	-7.2	-19.5
6,000 – 6,500	25.68	25.73	25.16	24.74	0.2	-2.2	-1.5	-3.4
6,500 – 7,000	2.83	2.76	2.76	2.57	-2.6	0.0	-6.5	-8.9
7,000 – 7,500	0.32	0.28	0.28	0.28	-13.0	0.0	0.4	-12.7
Total	1,465.74	1,334.99	1,173.02	985.86	-8.9	-12.1	-15.8	-32.6

FIGURE 4.56 CHANGE IN GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE HENGDUAN SHAN.



In contrast, the gentler slope classes of <10° and 10° – 20° exhibited increases in the number of glaciers throughout the entire period. The slope class of <10° showed a notable increase of 14 glaciers, while the 10° – 20° class added 75 glaciers from 1990 to 2020. Despite these increases in glacier numbers, the 10° – 20° slope class experienced a consistent decrease in glacier area, ranging from 5% in 1990 – 2000 to 13% in 2010 – 2020, resulting in an overall net loss of 9% over three decades. Conversely, the slope class <10° showed an increasing trend in glacier area during 2000 – 2010 and 2010 – 2020, with an overall increase of 4.24 km² from 1990 to 2020. However, this increase is comparatively modest compared to the more significant reductions observed in the steeper slope ranges.

Unlike the moderate and gentle slope ranges below 40°, the steeper slope ranges above 40° exhibited a mixed trend, with minimal changes in both glacier number and area. This indicates that while steeper slopes experienced some fluctuations, the overall impact on glacier number and area changes in these mean slope ranges was minor compared to the more pronounced changes in lower slope classes.

The glacier changes across different mean aspects in the Hengduan Shan from 1990 to 2020 reveal

FIGURE 4.57 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES IN THE HENGDUAN SHAN MOUNTAIN RANGE.

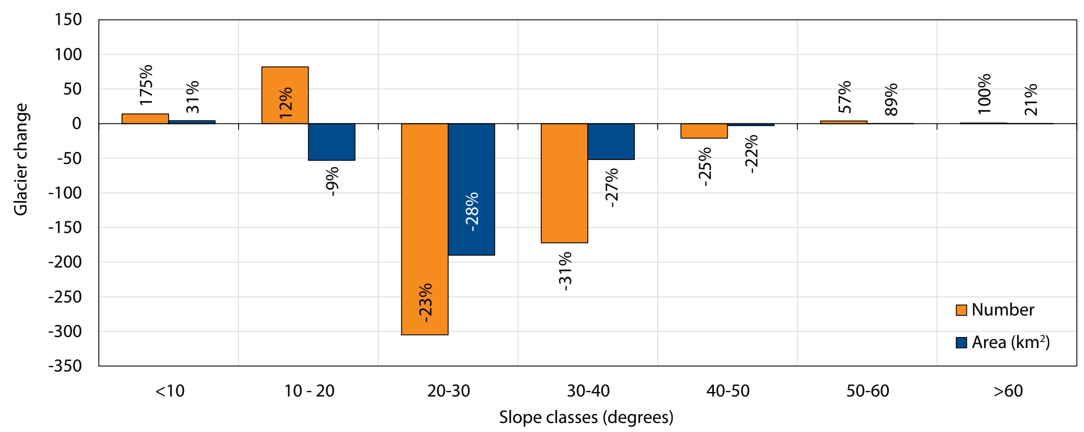
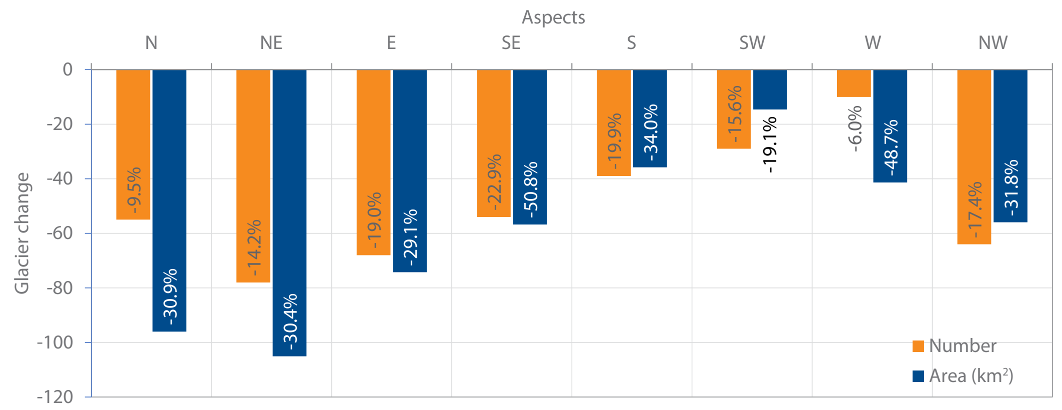


FIGURE 4.58 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES IN THE HENGDUAN SHAN MOUNTAIN RANGE.



distinct spatial patterns of retreat. The northern, northeastern and northwestern aspects experienced substantial glacier retreat in both number and area. A total of 197 glaciers were lost across these aspects, with northeastern and northwestern aspects glaciers showing the most pronounced losses in the 2000s and 2010s. In percentage terms, glacier numbers dropped by 9.5% in the northern aspect, 14.2% in the northeastern aspect, and 17.4% in the northwestern aspect. Glacier area losses were also significant, each aspect lost about 30% and 32% of the glacier area over three decades, with most significant area loss in northeastern aspect (Figure 4.58).

The southern, southeastern and southwestern aspects exhibited an even more intense retreat in terms of percentage loss. However, the distribution and changes in terms of absolute area loss was comparatively less than northern facing aspects. Together, these aspects lost 122 glaciers, with southeastern aspect alone accounting for 54 of those losses. The percentage decline in glacier number ranged from 15.6% in the southwestern to 22.9% in southeastern aspects. Area losses were similarly significant, with the southeastern aspect showing the most dramatic area shrinkage by over 50.8% over three decades. followed by 34.0% in the southern and 19.1% in the southwestern aspects. These figures underscore the stronger sensitivity of southern-facing glaciers, particularly those facing southeastern.

The eastern and western aspects showed a mixed pattern. Eastern aspect suffered a major loss in number by 19% and area by 29.1% over three decades. In contrast, the western aspect had a smaller numerical decline of 6% but experienced a surprisingly high area loss of 48.7%. However, in terms of absolute area, this loss is slightly less than the eastern aspect. This suggests that while western glaciers were fewer in number and relatively less amount of area coverages than in eastern glaciers, their individual sizes diminished substantially, indicating an overall shrinkage of glacier mass.

4.7 Tanggula Shan

The Tanggula Mountains, also known as Tanggula Shan or Tanggula Range, are a significant mountain range in the Tibetan Plateau. They form a natural boundary between the Tibetan Plateau to the south and the Qaidam Basin to the north. This mountain ranges covers the headwaters of three major basins Yangtze, Mekong and Salween. They are in the western part of China, primarily within the Tibet Autonomous Region and Qinghai Province. The Tanggula Shan are known for their high elevation, with peaks over 6,000 masl (19,685 feet). The highest peak in the range is Geladandong, which stands at 6,621 masl (21,722 feet) and is the highest mountain in Qinghai Province. Geographically, the Tanggula Shan act as a climatic barrier, influencing the weather patterns and precipitation distribution in the region. They also mark the boundary between different ecological zones, with lush vegetation to the south and more arid landscapes to the north. Figure 4.59 shows the extent of this mountain area and the glacier distribution within it.

Glacier distribution in 2020

As of 2020, the Tanggula Shan in the HKH region comprises 2.7% of the total number of glaciers and covers 3% of the total glacier area. This includes 1,697 glaciers spanning an area of 1,703 km² and estimated ice reserves of 137.5 km³ (Table 4.1). The largest glacier in this mountain range is 50.6 km². The average size of the glaciers is greater than 1 km² indicating the glacier area is larger compared to Hengduan Shan.

The distribution of glaciers across various size classes in this mountain range highlights distinct patterns and contributions (Figure 4.60). The range is characterised by a significant number of smaller glaciers of Class 1 (<0.5km²), comprising 71% of the total glacier number. Despite their numerical dominance, these small glaciers collectively cover only 13% of the total glacier area and contribute just 4% to the total estimated ice reserves.

Moving to larger size classes, the analysis shows that Class 2 (0.5 to 1 km²) and Class 3 (1 to 5 km²) have relatively equal numbers of glaciers, but

FIGURE 4.59 MAP SHOWING THE GLACIER DISTRIBUTION AND EXTENT OF THE TANGGULA SHAN IN THE HKH.

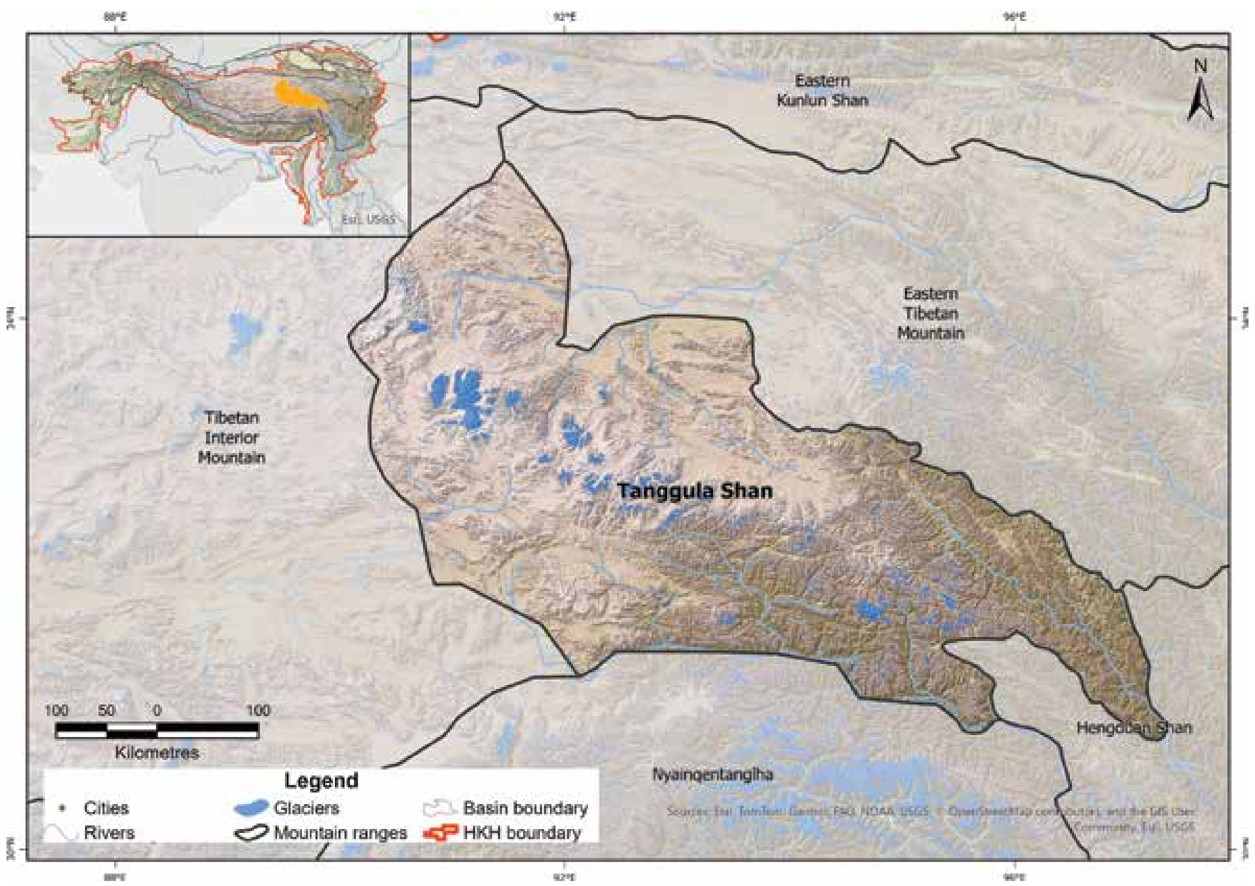
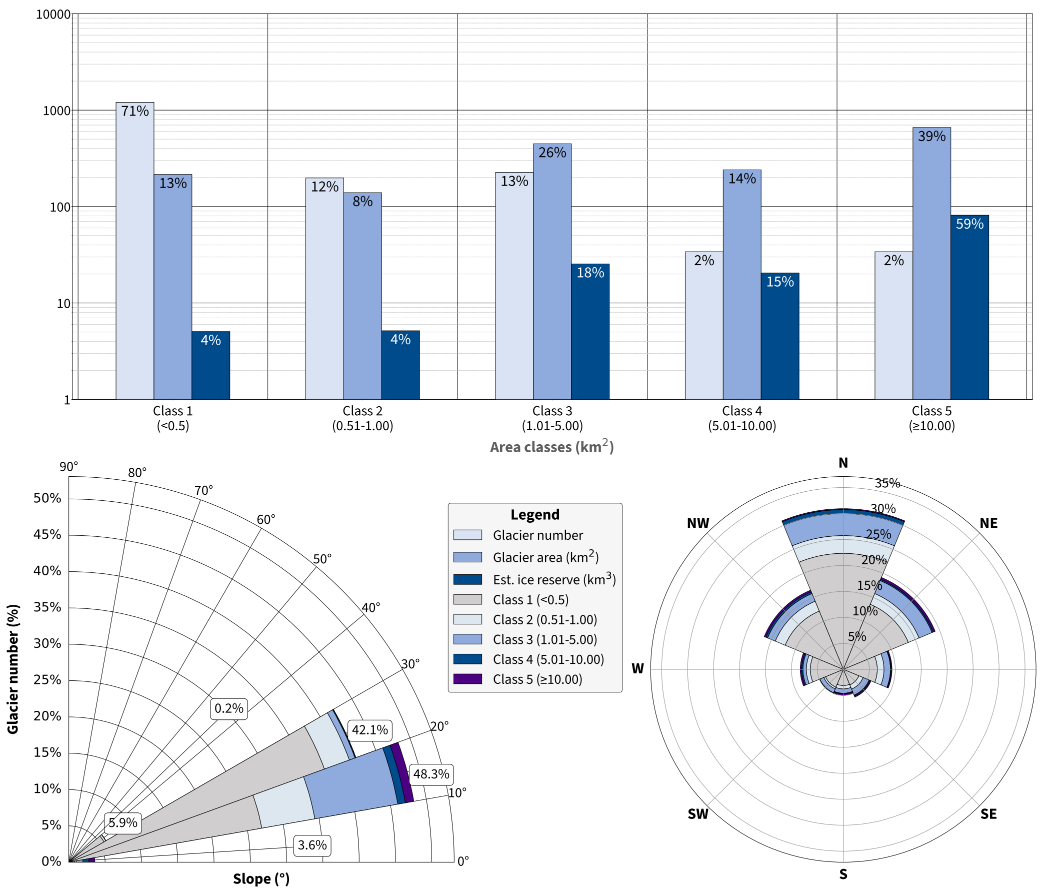


FIGURE 4.60 **GLACIER NUMBER, AREA AND ESTIMATED ICE RESERVES BY AREA SIZE CLASS** (TOP) **AND ITS DISTRIBUTION ACROSS MEAN SLOPES** (BOTTOM LEFT) **AND ASPECTS** (BOTTOM RIGHT) **IN THE TANGGULA SHAN.**



Class 3 contains three times the glacier area and estimated ice reserves compared to Class 2. Class 3 glaciers cover 26% of the total glacier area and contribute 18% to the estimated ice reserves, while Class 2 covers only 8% of the total glacier area and contributes 4% to the total estimated ice reserves.

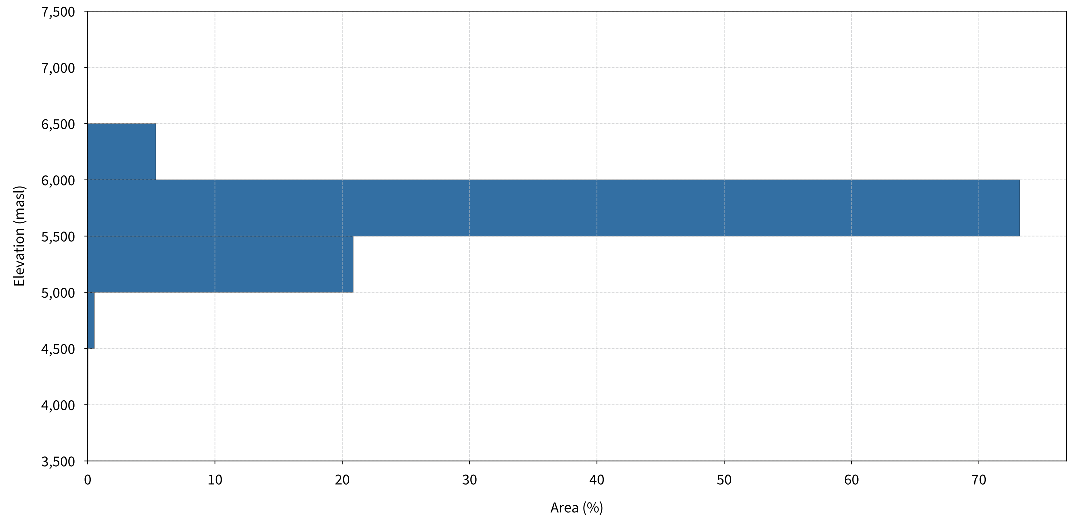
Similarly, for the largest glaciers in Class 4 (5 to 10 km²) and Class 5 (≥10 km²), both classes have the same number of glaciers, but Class 5 glaciers cover nearly three times the area and hold approximately three times the estimated ice reserves compared to Class 4. Class 5 glaciers encompass more than 39% of the total glacier area and contribute 59% to the estimated ice reserves in the mountain range. The mean area per glacier in these larger classes is notably higher at 7.1 km² for Class 4 and 19.4 km² for Class 5, indicating a significant contribution of glacier area by larger glaciers compared to other size classes. Overall, the smaller glaciers dominate in number, but larger glaciers play a critical role in terms of both area coverage and estimated ice reserves in this mountain range.

The glaciers in this mountain range are distributed within a narrow elevation range from 4,200 masl to 6,600 masl (Figure 4.61). The distribution of glacier area across each 500 m elevation zone reveals that below 5,000 masl, glaciers occupy a relatively small portion, accounting for about 0.6% of the total glacier area in the mountain range.

The most substantial area of glacier coverage is observed between 5,500 and 6,000 masl, encompassing more than 73% of the total glacier area in the region. The elevation range of 5,000 to 5,500 masl also comprises a significant area, covering approximately 21% of the total glacier area. In contrast, the glacier area decreases significantly beyond 6,000 masl. Between 6,000 and 6,500 masl, glaciers cover only 5.4% of the total area, and above this elevation, the coverage is negligible.

In terms of the mean slopes of the glaciers, the glaciers in the Tanggula Shan Mountain ranges are distributed within the slope ranges from 0° – 50°. The distribution across various slope classes reveals distinct patterns

FIGURE 4.61 **GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN THE TANGGULA SHAN.**



in glacier characteristics. Gentle slopes below 10° accommodate a smaller percentage of glaciers (around 2%), yet they cover a significant area, comprising nearly 17% of the total glacier area. These larger glaciers average approximately 8.2 km² each.

Moderate slope ranges between 10° to 20° and 20° to 30° host the majority of glaciers, collectively accounting for almost 91% of the total glaciers in the mountain range, with the highest number found in the 20° to 30° slope range (Figure 4.60). Between these two slope ranges, the 10° to 20° slope range covers nearly 70% of the total glacier area and 73% of the total estimated ice reserves in the mountain ranges. In contrast, the 20° to 30° slope range comprises approximately 12.5% of the total area and 5% of the estimated ice reserves. The larger average size of glaciers in the 10° to 20° slope range indicates the presence of larger glaciers on gentler slopes.

Beyond the slope range of 30°, the number, area and estimated ice reserves decrease significantly, reflecting the challenges posed by steeper terrain for glacier development. Slopes exceeding 40° have minimal glacier presence, underscoring the limitations of rugged environments for glacier formation.

A comparison of the distribution of glaciers across slope range verses glacier size reveals that the larger glaciers of Class 4 and 5 are predominantly located in gentle slopes less than 20°. Conversely, smaller glaciers of Class 1 (<0.5 km²) are distributed across slope ranges from 0° – 50° with majority in 10° – 30° slope. Steeper slopes, specifically those ranging from 30° – 40° and higher, contain fewer glaciers of smaller size of Class 1 (0.5 km²) with minimal area coverage. This suggests that glacier occurrence is limited in the steeper slope due to the challenging conditions for the existence of snow and ice on the steep slopes.

The distribution of glaciers across various aspects in this mountain range reveals distinct patterns in size and abundance. The northern quadrants, encompassing the northern, northeastern and northwestern aspects, are particularly dominant, hosting larger and more numerous glaciers compared to the southern quadrants – southern, southwestern, and southeastern aspects (Figure 4.60).

Specifically, the northern aspect alone account for nearly 31% of the total glaciers, covering 24.4% of the total glacier area and 22% of the estimated ice reserves. The northeastern and northwestern aspects also hold notable number of glaciers, containing 19% and 16% of total glaciers respectively, and covering 18% and 13% of the total glacier area. The mean area per glacier in these northern quadrant aspects ranges from 0.79 to 0.94 km², suggesting a relatively smaller glaciers compared to the glaciers in other aspects.

In contrast, the southern, southeastern and southwestern aspects consists of relatively equal number of glaciers each holding around 5 to 6% of the total glaciers, which are significantly three to four times less than in northern quadrant aspects. Similarly in terms of area coverage, these southern quadrant aspects cover 7% to 10% of the total glacier area in the mountain range, with higher percentage in the southern aspect. These area coverages are half to two times less than in northern quadrant aspects. However, the mean area per glaciers in these aspects showed higher, ranges from 1.4 km² to 1.95 km², indicating the significantly larger size glacier distribution than in northern quadrant aspects.

The eastern and western aspects, with approximately 9% and 8% of the total number of glaciers respectively, show similar area coverage to the southern quadrants, with 9% and 10% of the total glacier area. However, the mean glacier area in these aspects is slightly smaller than in the southern quadrant aspects, reflecting a comparatively smaller glacier size distribution.

Decadal glacier changes from 1990 to 2020

The decadal glacier changes data from 1990 to 2020 reveal a consistent decline in both the number and area of glaciers. In 1990, there were 1,996 glaciers covering an area of 2,053.65 km². By 2020, the number of glaciers had decreased to 1,697, and the total glacier area had reduced to 1,702.9 km². This represents a nearly 15% reduction in glacier numbers and over 17% reduction in glacier area (Figure 4.62). The rate of glacier loss has accelerated over the decades, rising from nearly 3% in number and over 5% in area during the 1990 to 2000 period to 5.6% in number and 6.4% in area between 2010 and 2020. This trend indicates a growing rate of glacier loss over time.

The glaciers distribution across different size classes reveals a consistent and significant pattern of glacier loss, with variation in the extent and rate of change over the past three decades. The number of glaciers has decreased substantially across all the size classes in all decades. The smallest glaciers of Class 1 have seen the most significant reduction, with a total loss of 141 glaciers over three decades. The percentage decrease is also notable, with a total reduction of 10.5%, reflecting a severe contraction over the decades. Similarly, glaciers in Class 2 (0.51 – 1.00 km²) have decreased by 84 glaciers, amounting to a 29.5% reduction. Class 3 glaciers (1.01 – 5.00 km²) have also diminished, with a total loss of 69 glaciers and a 23.4% reduction. In contrast, Class 4 (5.01 – 10.00 km²) has shown stability in the number of glaciers, with no net change over the entire period. Class 5 glaciers (≥10.00 km²) have decreased by 5 glaciers, reflecting a 12.8% reduction (Figure 4.63).

Similarly, glacier areas have also seen substantial reductions across most size classes over the decades. Glaciers in Class 1 and Class 2 experienced total area losses of approximately 18% and 28.6%, respectively. The most pronounced decrease was observed in Class 3 glaciers, which lost a total of 131.15 km², reflecting a nearly 23% reduction over the three decades. The second-largest reduction was in Class 5 glaciers, which lost 118.3 km², corresponding to more than a 15% decrease from 1990 to 2020. In contrast, Class 4 glaciers saw a marginal increase, with a 0.7% rise in the glacier area over the same period.

However, these trends varied across each decade and among different size classes. The overall reduction in glacier number and area indicates that smaller glaciers, particularly those in Class 1 and Class 2, have been more affected by climate and environmental changes compared to larger glaciers.

FIGURE 4.62 **GLACIER NUMBER AND AREA PERCENTAGE CHANGES IN EACH DECADE FROM 1990 TO 2020 IN THE TANGGULA SHAN.**

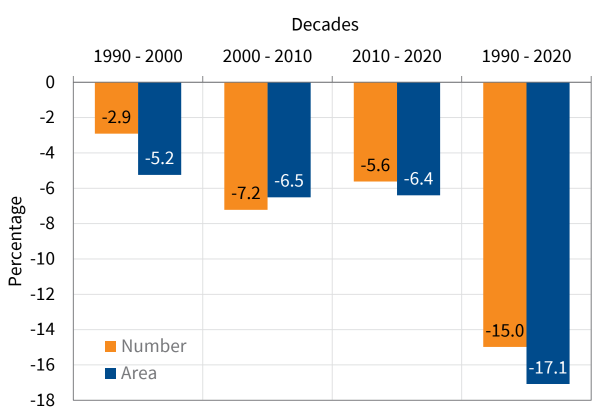
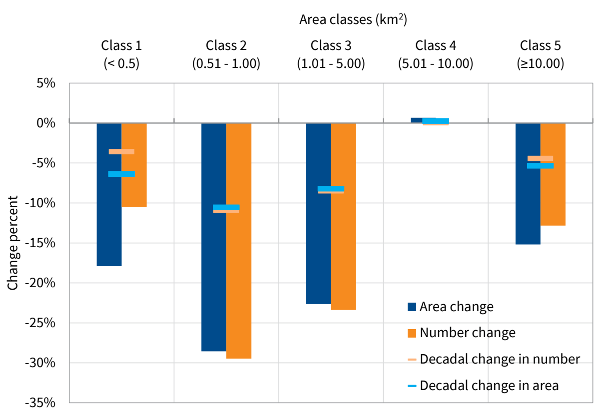


FIGURE 4.63 **GLACIER NUMBER AND AREA CHANGES ACROSS SIZE CLASSES OVER THREE DECADES INCLUDING MEAN DECADAL CHANGE RATE IN THE TANGGULA SHAN.**



Class 4 glaciers have remained relatively stable in number, with only minor changes in area, while Class 5 glaciers have shown a significant decrease in area with only a slight reduction in number. This decline in Class 5 glaciers may be attributed to the shrinkage and fragmentation of these larger glaciers, leading to changes in their size classification.

The glaciers in this mountain range have exhibited significant changes in area across various elevations over the past three decades. Glaciers in this mountain range were mapped from 4,100 masl, where the lowest glacier snout was located at 4,190 masl, to 6,600 masl, with the highest glacier crown at 6,573 masl. Notably, the lowest glacier elevation of 4,190 masl in 1990 has shifted upward to 4,270 masl by 2020, reflecting a sharp retreat of 80 metres at this lowest elevation.

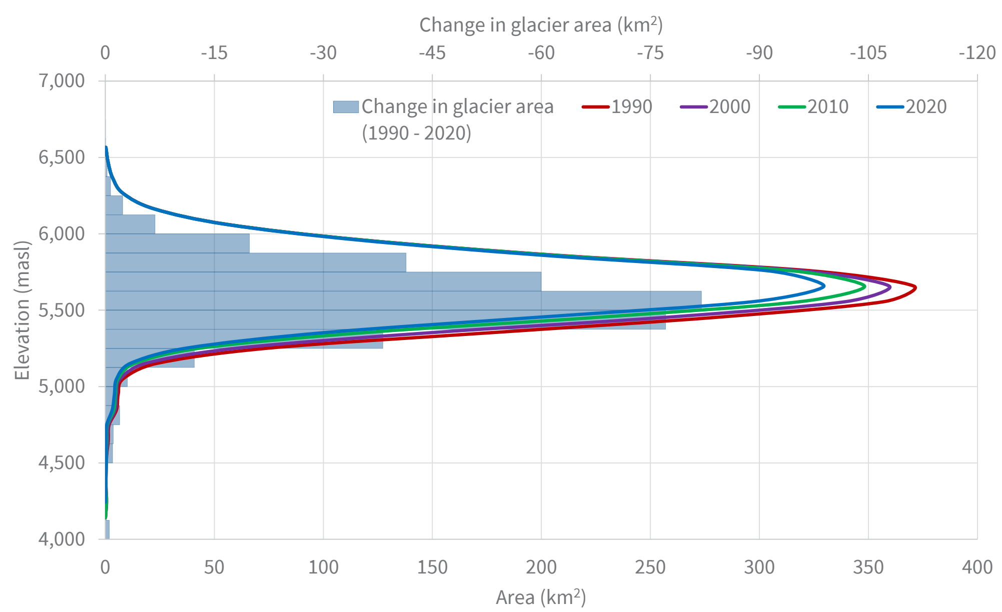
Glaciers at elevations below 4,500 masl have experienced the dramatic reductions of area by 0.82 km², reflecting a total decrease of 59.3% over the three decades. This range saw a notable loss in the most recent decade (2010 – 2020), with a reduction of 0.6 km² (51.6%), highlighting the severe impact of recent climatic changes on glaciers at this elevation.

The amount of glacier area loss increases with elevation up to 5,000 – 5,500 masl, where the most significant reduction occurred, totaling 37.4% over the three decades (Figure 4.64). This elevation range experienced consistent reductions each decade, with the most substantial loss of 17.3% occurring between 2000 and 2010. In contrast, the elevation ranges from 4,500 to 5,000 masl showed a smaller net area loss of about 6 km² over the same period, although percentage losses were still notable in these lower elevations. Overall, while the absolute area loss is more significant at elevation range from 5,000 to 5,500 masl, the percentage losses are more pronounced at elevations below 5,000 masl. Significant area loss was also observed from 5,500 masl to 6,000 masl, with a total reduction of over 130 km² reflecting almost 10% area loss from 1990 to 2020. Although, the rate of loss in this range was relatively slow, with reductions of 2.5%, 2.9%, and 4.4% over the decades, it indicates better preservation compared to lower elevation ranges.

Above 6,000 masl, area loss diminishes, with glaciers showing greater stability above 6,500 masl. The slower rate of area loss at higher elevations suggests greater resilience to recent climate changes, likely due to the cooler temperatures prevalent at these altitudes. Table 4.11 provides the detailed distribution of glacier areas in each time period across 500 metres elevation ranges including area change percentage.

The analysis of glacier changes across different mean slope classes in Tanggula Shan over the past three decades highlights distinct patterns of reduction in both glacier numbers and area, except for a slight increase in glaciers on slopes

FIGURE 4.64 **CHANGE IN GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE TANGGULA SHAN.**



less than 10°. In this <10° slope class, the glacier number initially declined from 1990 to 2000 but then increased in subsequent decades, resulting in a net addition of 6 glaciers from 1990 to 2020. Despite these fluctuations in glacier numbers, the area experienced a modest overall decline of 2%.

The most pronounced changes occurred in the 20° to 30° slope class, which had a net loss of 253 glaciers and a total area reduction of over 90 km^2, reflecting to a 27% decrease (Figure 4.65). The period between 2000 and 2010 was particularly severe, with an 11% reduction in glacier area. In the 10° to 20° slope class, there was a net decrease of 5 glaciers and a significant area loss of 128.53 km^2, equating to a 9% reduction overall. This class also experienced a substantial 8% decrease in the glacier area between 2000 and 2010. Both these slope classes experienced consistent negative trends in both the glacier number and their area, highlighting a significant impact from climate changes.

The 30° to 40° slope class showed a notable loss of 48 glaciers and a 30% reduction in glacier area over three decades. The rate of loss was particularly high between 2000 and 2010, with a 19% decrease in the area. Beyond this range, the changes in glacier numbers and area were minimal, with no glaciers identified on slopes steeper than 50° throughout all decades.

The glacier changes across various aspects in the Tanggula Shan over the past three decades (1990 – 2020) shows notable spatial variations. The northern, northeastern, and northwestern aspects (N, NE, NW) experienced the most substantial glacier retreat in both number and area (Figure 4.66). Collectively, these aspects reported for a significant portion of the total glacier loss, with glacier numbers declining by 81 in the northern aspect, 82 in the northeastern, and 55 in the northwestern. This equates to percentage losses of 13%, 20%, and 16% respectively. In terms of glacier area, the northern aspect experienced the highest reduction at 95.03 km^2 (19%), followed by the northeastern at 75.28 km^2 (20%), and the northwestern at 55.25 km^2 (17%). These steep declines suggest that glaciers in these aspects, while numerous and sizeable, are also more vulnerable.

In contrast, the southern, southeastern, and southwestern aspects (S, SE, SW) exhibited relatively less dramatic changes. Glacier numbers in these aspects declined much less, only 2 glaciers lost in the southern, 29 in the southeastern, and 6 in the southwestern, representing percentage losses of 2%, 23%, and 7% respectively. The area changes followed a similar trend, with southeastern glaciers losing 30.39 km^2 (17%), southern losing 11.63 km^2 (7%), and southwestern 8.97 km^2 (15%). In this group, particularly the southeastern aspect experienced more significant shrinkage, especially in area, the overall changes in this group were less severe than in the northern group.

The eastern and western aspects (E and W) displayed differing patterns. The eastern aspect, while seeing only a moderate decline in glacier numbers (30 glaciers or 16%), showed the highest area loss percentage than other all aspect – 28%. This indicates that glaciers here may be fewer but larger and are retreating significantly in size. The western aspect exhibited the least change overall, with a modest glacier number decline of 14 (9%) and an area loss of 18.54 km^2 (8%). These trends suggest that glaciers on the western aspect are simply smaller and less numerous.

TABLE 4.11 GLACIER AREA DISTRIBUTION AND PERCENTAGE CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN TANGGULA SHAN.

Elevation ranges (masl)	Area (km^2)				Area change (%)			
	1990	2000	2010	2020	1990 - 2000	2000 - 2010	2010 - 2020	1990 - 2020
4,000 – 4,500	1.38	1.22	1.16	0.56	-11.1	-5.4	-51.6	-59.3
4,500 – 5,000	14.76	12.76	10.67	8.83	-13.5	-16.3	-17.2	-40.1
5,000 – 5,500	567.71	496.17	410.46	355.13	-12.6	-17.3	-13.5	-37.4
5,500 – 6,000	1,377.24	1,343.38	1,304.86	1,246.86	-2.5	-2.9	-4.4	-9.5
6,000 – 6,500	92.31	92.18	91.91	91.28	-0.1	-0.3	-0.7	-1.1
6,500 – 7,000	0.25	0.25	0.25	0.25	0	0	0	0
Total	**2,053.65**	**1,945.97**	**1,819.32**	**1,702.91**	**-5.2**	**-6.5**	**-6.4**	**-17.1**

FIGURE 4.65 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES IN THE TANGGULA SHAN.

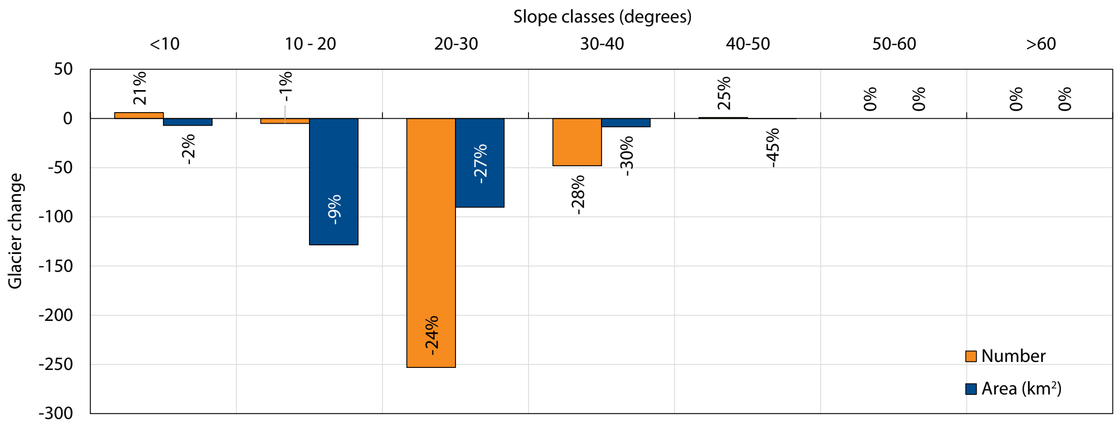
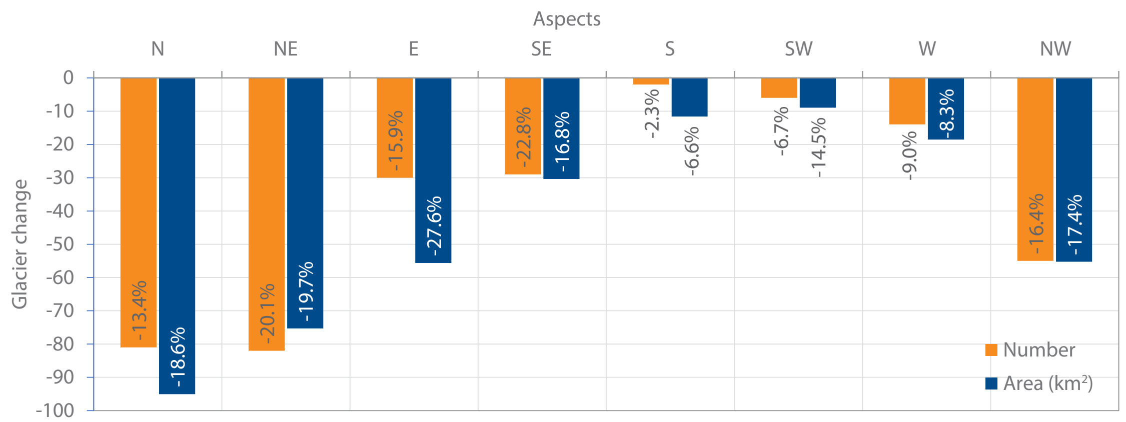


FIGURE 4.66 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES IN THE TANGGULA SHAN.



FIELDWORK PREPARATION IN LANGTANG VILLAGE, NEPAL

4.8 Tibetan Interior Mountain

This mountain range mostly covers the Tibetan Plateau, which is also known as Qinghai-Tibetan plateau. The mountain range is a vast elevated plateau surrounded by massive mountain ranges in the high mountains of Asia, located at the centre of the HKH region. It is bounded by Karakokam and western Kunlun Shan Mountain range in the west, Gangdise and the Himalaya in the south, Tunggula Shan, Nyainqentanglha and Hengduan Shan in the east and Kunlun Shan in the North. The elevation of this mountain ranges from 3,500 masl to 6,800 masl with an average elevation of 5,000 masl. It is extended from 78.102°E to 92.127°E longititude and 29.940°N to 36.033°N latitude covering an area of almost 516,815 km^2 which is almost 12.5% of the total area of the HKH region. Figure 4.67 shows the extent of this mountain range including the glacier distribution.

Glacier distribution in 2020

Altogether, 3,413 glaciers covering 3,702.5 km^2 were identified in this mountain range based on the Landsat images of 2020, which is almost 5.3% of the total glaciers covering almost 7% of the total area coverages within the HKH region (Table 4.1). The glacier in this mountain range only covers 0.7% of the total land area.

The largest glacier mapped in the mountain range is 50.84 km^2, while the average glacier size is about 1.1 km^2. The distribution of glaciers across various size classes reveals a significant number of smaller glaciers, with over 66% of the total glaciers falling into the smallest size Class 1 (<0.5 km^2). However, these small glaciers only account for 10% of the total glacier-covered area and hold less than 3% of the estimated ice reserves.

In contrast, glaciers in the largest size Class 5 (≥10 km^2) make up just 2% of the total number of glaciers but contribute over 31% of the total glacier area and more than 48% of the estimated ice reserves. Mid-

FIGURE 4.67 MAP SHOWING THE GLACIER DISTRIBUTION AND EXTENT OF THE TIBETAN INTERIOR MOUNTAIN RANGE IN THE HKH.

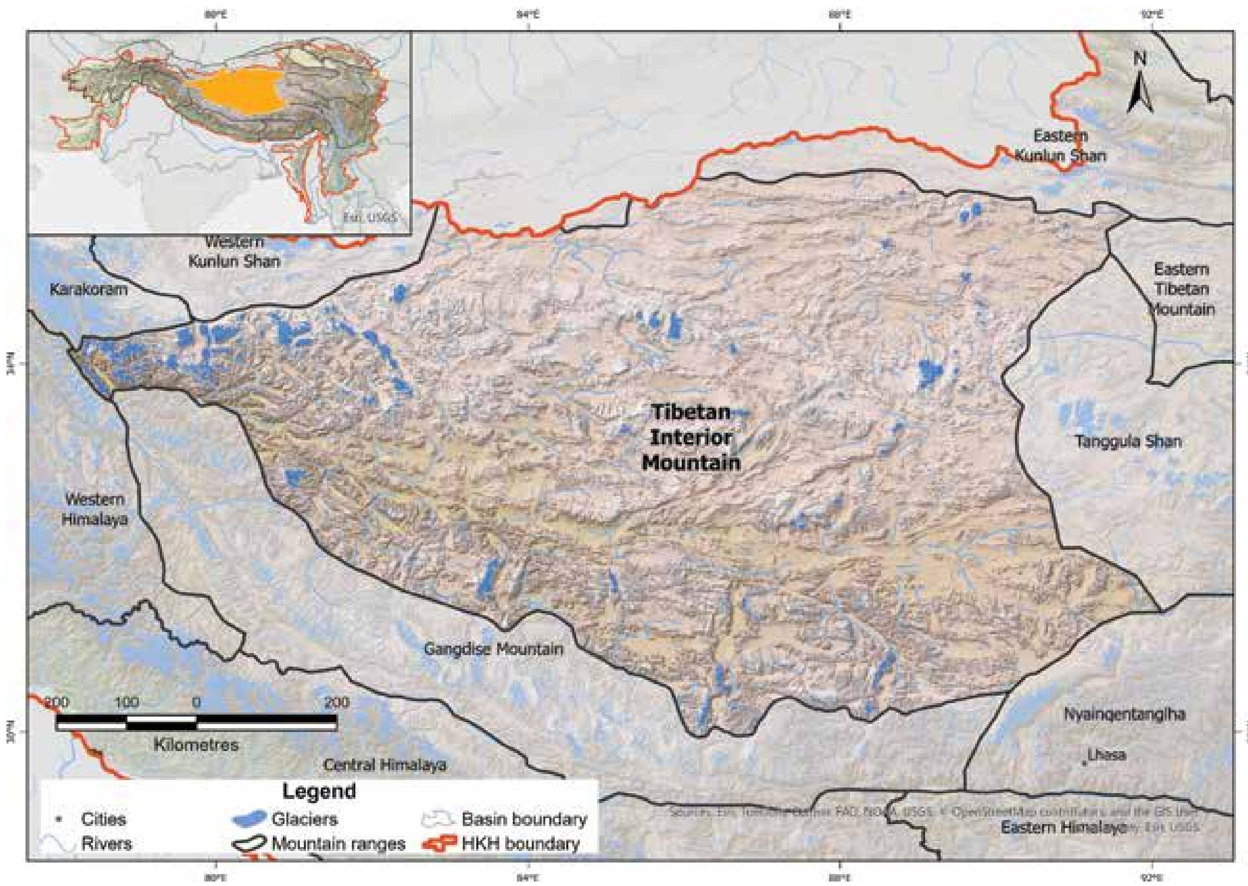
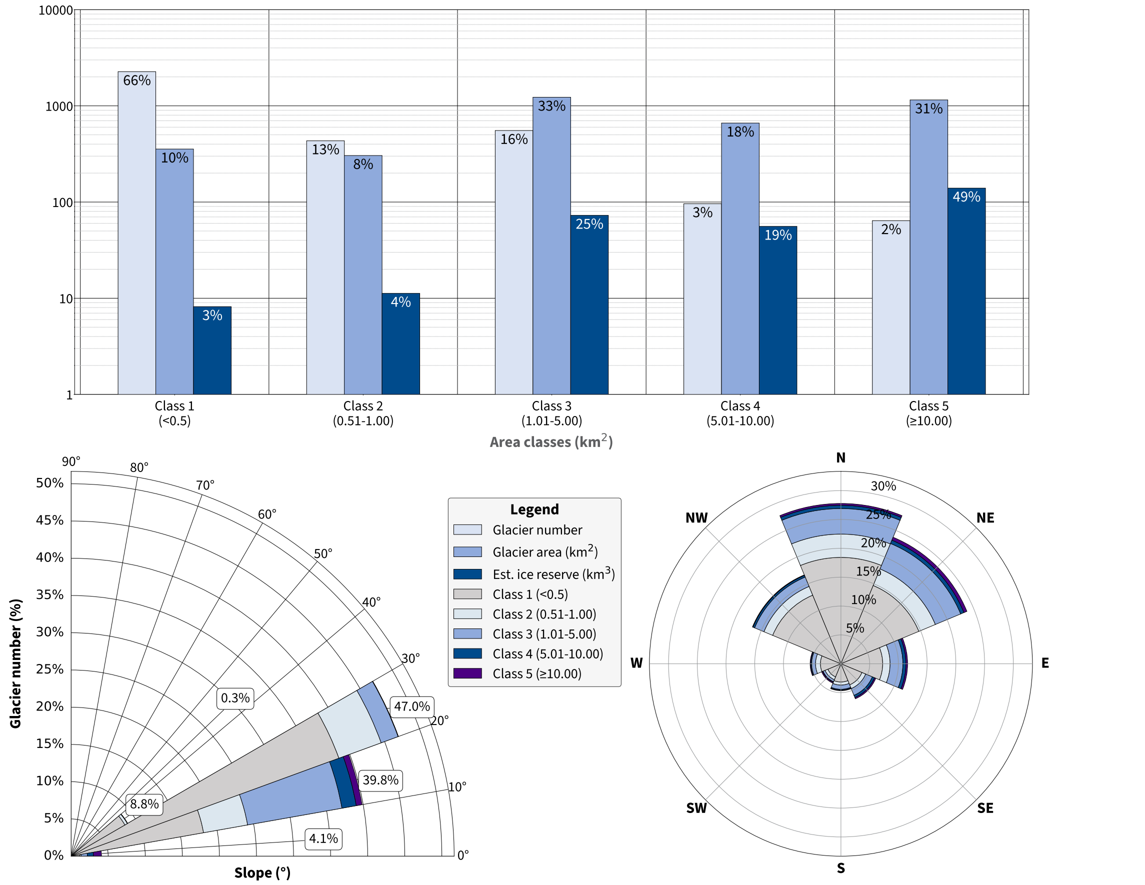


FIGURE 4.68 **GLACIER NUMBER, AREA AND ESTIMATED ICE RESERVES BY AREA SIZE CLASSES** (TOP) **AND ITS DISTRIBUTION ACROSS MEAN SLOPES** (BOTTOM LEFT) **AND ASPECTS** (BOTTOM RIGHT) **IN THE TIBETAN INTERIOR MOUNTAIN RANGE.**



sized glaciers of Class 3 (1 – 5 km²) represents 16% of the total glaciers covering 33% of the total glacier area and hold 25% of the estimated ice reserves, nearly half of what is held by the largest glaciers. Larger glaciers of Class 4 (5 – 10 km²) account for 3% of the total number but cover more than 18% of the glacier area and contain 20% of the total estimated ice reserves (Figure 4.68).

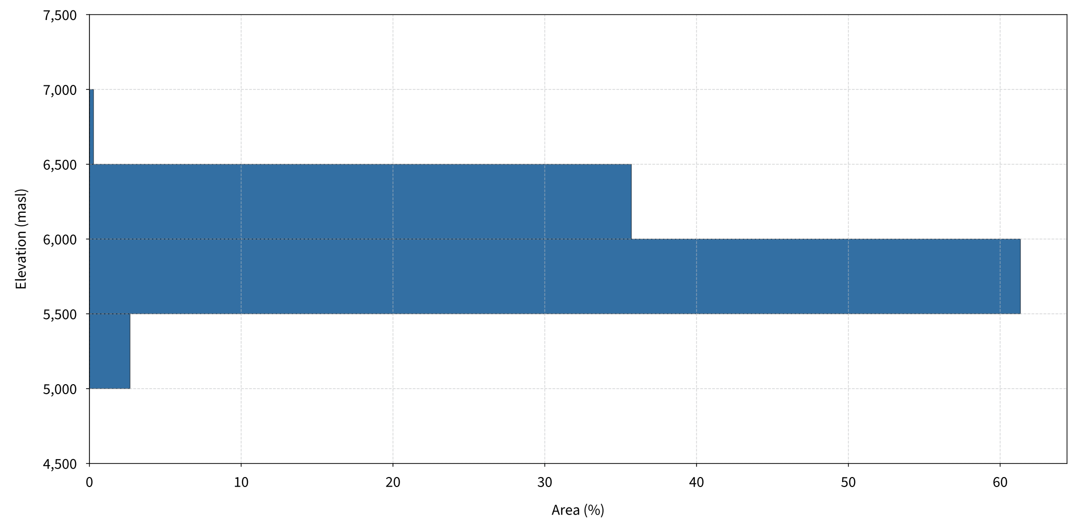
Overall, while smaller glaciers are more numerous, the larger glaciers are crucial for their substantial contributions to the total glacier area and estimated ice reserves, significantly influencing the hydrology of the region.

The glaciers in this mountain range are distributed within a narrow elevation zone from 5,000 masl to 6,700 masl. The highest concentration of glacier area is found between 5,500 masl and 6,000 masl, which accounts for more than 61% of the total glacier area (Figure 4.69). A detailed distribution of glacier area in 100 metre elevation zones shows a progressive increase in glacier area starting from 5,700 masl, peaking in the elevation range of 5,900 – 6,000 masl, which alone accounts for more than 19% of the total glacier area. Beyond 6,000 masl, the glacier area coverage gradually decreases, with 16% at 6,000 – 6,100 masl and 11% at 6,100 – 6,200 masl. After 6,200 masl, there is a noticeable decrease, with glacier area coverage more than halving in each subsequent 100 metre elevation zone. This decline continues in the higher elevation zones above 6,400 masl, collectively contributing less than 1% to the total glacier area.

A similar pattern is observed at lower elevations below 5,700 masl, where glacier area decreases from almost 8% in the 5,600 – 5,700 masl range to about 4% in the 5,500 – 5,600 masl elevation range. Below 5,500 masl, the glacier area decreases considerably, collectively covering less than 1% of the total glacier area below 5,400 masl.

The glaciers distribution across various mean slope classes reveals significant concentration within the slopes 10° – 20° and 20° – 30° (Figure 4.68). Specifically, 49% of the glaciers are within the slope

FIGURE 4.69 **GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN THE TIBETAN INTERIOR MOUNTAIN RANGE.**



classes of 20° – 30° slopes, while 10° – 20° slope class consists of 36% of the total glaciers. Despite the highest number of glaciers in slope class of 20° – 30°, the total glacier area and estimated ice reserves are predominantly contributed by the 10° – 20° slope class, accounting for 60% of the total glacier area and 58% of the total estimated ice reserves. This indicates that glaciers in the 10° – 20° slope range tend to be larger and hold more ice compared to those in higher slopes.

In contrast, the slope class <10° contains only 3% of the glaciers but constitutes a substantial 23% of the total glacier area and 34% of the total ice reserves. This class also has the highest mean area per glacier at 8.51 km², suggesting that the few glaciers present in this category are significantly larger. As the slope steepens beyond 30°, the number of glaciers and their corresponding area and ice reserves decrease sharply. For instance, glaciers in the 30° – 40° slope class account for only 12% of the total number, 2% of the area, and 1% of the ice reserves. This trend continues with even steeper slopes, with negligible glacier presence in the 40° – 50° class and none above 50° slope.

The relationship between size classes and mean slope classes reveals a distinct pattern where larger glaciers tend to occupy lower slope classes. A smaller sized glaciers of Class 1 (< 0.5 km²) are distributed across the slope range from 0° to 50°, with a notable concentration in the slope range of 10° – 30° both in terms of number and area coverage. As glacier size increases, the distribution shifts, with fewer glaciers found in steeper slope range. In case of largest glaciers Class 5 (≥ 10.00 km²), they are almost evenly distributed between slope ranges of <10° and 10° – 20°, with slightly higher number in 10° – 20° slope. However, these glaciers contribute to greater area coverage in the slope range of <10°. Similarly in larger size glaciers of Class 4 (5 – 10 km²), the number and area concentration are higher at slope ranges of 10° – 20° than in slope less than 10° and only one glacier is distributed in slope range of 20° – 30°. This distribution pattern underscores how glacier size interacts with slope angle, influencing their spatial distribution and potential environmental impact in the Tibetan Interior Mountains.

In terms of mean aspects, the northern, northeastern and northwestern aspects dominate the glacier distribution in this mountain range (Figure 4.68). The northern aspect (N) hosts the largest number of glaciers, with 28% of the total glacier in the mountain range, although these glaciers are relatively small and estimated ice reserves, contributing only 22% of the area and 18% of the ice reserves, with a mean glacier area of 0.85 km². The northeastern aspect (NE) is especially significant, holding 24% of the glaciers, but contributing the highest glacier area coverage by 28% of the total and largest estimated ice reserves (30%), suggesting both large and numerous glaciers, with a mean size of 1.30 km². The northwestern aspect (NW), while accounting for 17% of the glacier number, contributes less in terms of area (10%) and estimated ice reserves (9%), and features smaller glaciers with a mean size of 0.67 km². Collectively, these aspects highlight a strong glacial presence in the northern quadrant of the basin, particularly due to the dominance of northeastern aspect glaciers in size and estimated ice reserves.

In contrast, the southern-facing aspects (southern, southeastern and southwestern aspects) are less glaciated in terms of number but present relatively high values in glacier area and estimate ice reserves per glacier. Together they represent just 15% of the total glacier number, with the southern at 5%, the southeastern at 7%, and the southwestern at 4%. Despite these lower glacier numbers, they cover a considerable amount of total glacier area (21%) and estimated ice reserves (25%). The southeastern and southwestern aspects particularly stand out, with the highest mean glacier sizes of 1.63 km^2 and 1.83 km^2, respectively, underscoring the largest glaciers distribution across all aspects.

The eastern and western aspects collectively show a balanced presence. The eastern aspect hosts 12% of the glaciers, contributing 14% each to glacier area and estimated, with a high mean size of 1.29 km^2, indicating fewer but larger glaciers. The western aspect, by contrast, includes only 5% of glaciers, glacier area, and estimated ice reserves, and has a lower mean glacier size of 1.03 km^2. While the aspect glaciers are relatively more substantial, the western aspect ones appear less prominent across all parameters.

Decadal glacier changes from 1990 to 2020

This mountain range has exhibited fluctuating glacier numbers over the decades. From 1990 to 2000, there was a slight decrease of 17 glaciers. This was followed by an increase of 22 glaciers between 2000 and 2010, and a subsequent decline of 5 glaciers in the most recent decade from 2010 to 2020. Overall, these variations have balanced out, resulting in no net change in the total number of glaciers over the three decades.

Conversely, the glacier area has consistently decreased each decade, with the rate of reduction steadily increasing. Initially, the area decreased by approximately 1.2% from 1990 to 2000. This rate grew to more than 1.7% from 2000 to 2010 and further increased to almost 1.5% in the most recent decade from 2010 to 2020. Overall, the glacier area has declined by 4.4% over the three decades (Figure 4.70).

The analysis of glacier changes across various size classes over the past three decades indicates a consistent decline in both the number and area of glaciers (Figure 4.71), except for Class 1 (<0.5 km^2), which showed an increasing trend in numbers. Initially, Class 1 glaciers decreased by 8 from 1990 to 2000. However, from 2000 to 2010, their number increased by 44, and from 2010 to 2020, it rose by an additional 9 glaciers, resulting in a net increase of 2% over the three decades. Despite these fluctuations in number, the glacier area consistently decreased throughout all decades, with a total loss of 4.1% over three decades. The rate of area loss has shown an increasing trend in recent decades.

In contrast, mid-sized and larger glacier classes consistently showed reductions in both number and area. Class 3 glaciers (1.01 to 5.00 km^2) experienced a total decrease of 5% in number and 4.4% in area over the three decades. The percentage loss in the

FIGURE 4.70 DECADAL CHANGES OF GLACIER NUMBER AND AREA IN THE TIBETAN INTERIOR MOUNTAIN RANGE.

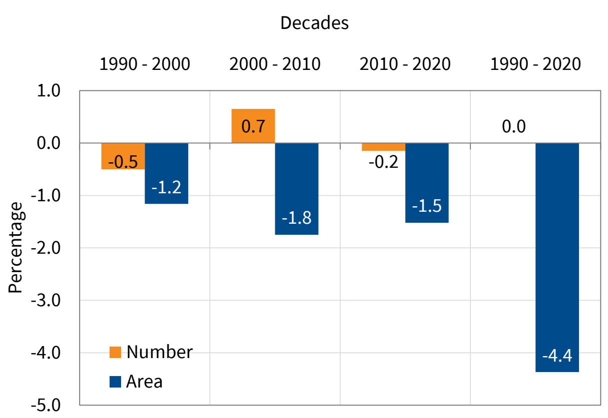
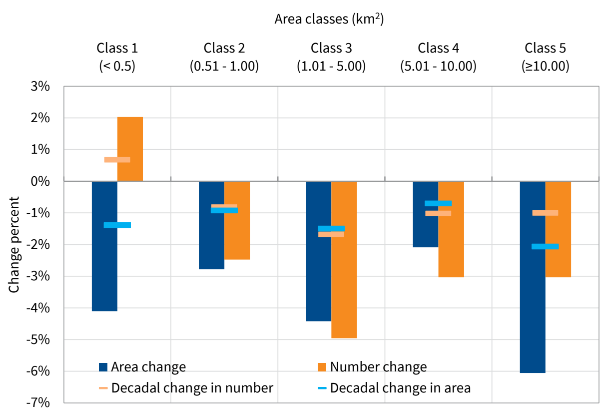


FIGURE 4.71 GLACIER NUMBER AND AREA CHANGES ACROSS SIZE CLASSES OVER THREE DECADES INCLUDING MEAN DECADAL CHANGE RATE IN THE TIBETAN INTERIOR MOUNTAIN RANGE.



Class 3 glaciers increased progressively, from -1.4% in 1990 – 2000 to – 2.1% in 2000 – 2010, and -1.0% in 2010 – 2020. Similarly, Class 5 glaciers (≥10.00 km^2) experienced the most significant area loss, totaling 6.1% over three decades, although the number of glaciers decreased by only 2 during the same period. The percentage loss in area for Class 5 glaciers increased from 1.6% in 1990 – 2000 to 2.4% in 2000 – 2010, and further to 2.2% in 2010 – 2020.

Classes 2 (0.51 – 1.00 km^2) and 4 (5.01 – 10.00 km^2) exhibited similar trends in glacier number and area loss, though on a smaller scale. Class 2 glaciers showed a minimal decrease of 2.5% in number and a 2.8% decrease in area from 1990 to 2020. Class 4 glaciers experienced a 3% loss in number and a 2.1% decrease in area over the same period. Overall, while the smallest glaciers showed a net increase in number, mid-sized and larger glaciers consistently faced reductions in both number and area, with particularly notable losses in the largest size classes.

The glacier area distribution across various elevation ranges over the decades highlights significant differences in the rate and extent of glacier retreat (Table 4.12). Glaciers in this mountain range are confined to a narrow elevation range from 5,000 to 6,800 masl. The most pronounced retreat occurred between 5,500 and 6,000 masl, where glaciers experienced a net loss of nearly 131 km^2, relating to a 5.5% reduction from 1990 to 2020 (Figure 4.72). The rate of loss escalated over time, with a 1.3% decrease from 1990 to 2000, increasing to 2.2% from 2000 to 2010, and maintaining a 2.1% loss in the most recent decade. This pattern indicates a growing retreat rate in recent years.

FIGURE 4.72 CHANGE IN GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE TIBETAN INTERIOR MOUNTAIN RANGE.

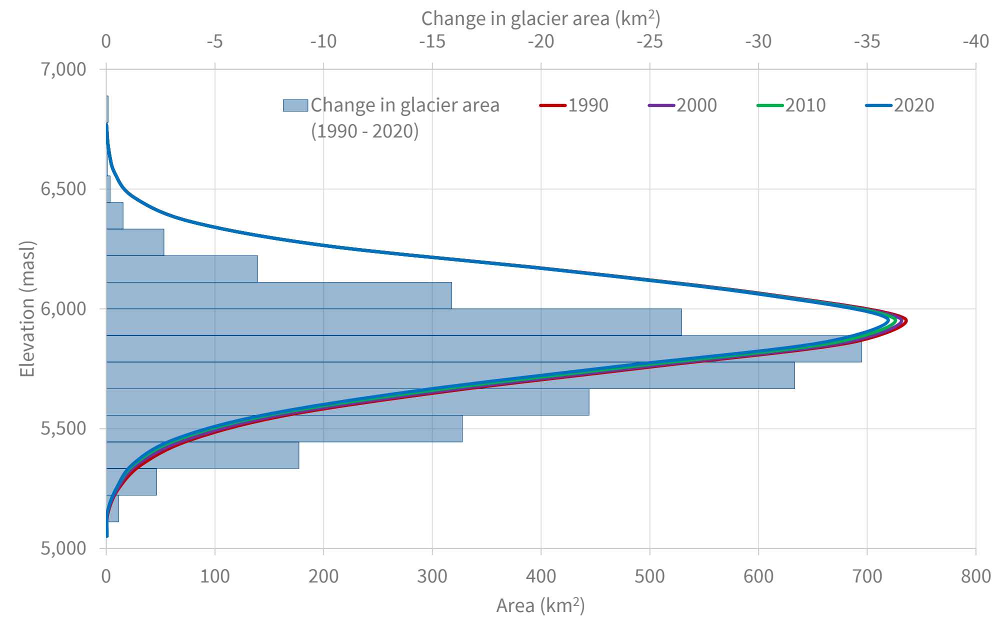


TABLE 4.12 GLACIER AREA DISTRIBUTION AND PERCENTAGE CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE TIBETAN INTERIOR MOUNTAIN RANGE.

Elevation ranges (masl)	Area (km²)				Area change - km² (change percent)			
	1990	2000	2010	2020	1990 - 2000	2000 - 2010	2010 - 2020	1990 - 2020
5,000 – 5,500	126.66	116.15	103.81	99.23	-8.3	-10.6	-4.4	-21.7
5,500 – 6,000	2,402.04	2,370.78	2,319.64	2,271.06	-1.3	-2.2	-2.1	-5.5
6,000 – 6,500	1,332.64	1,329.60	1,326.01	1,322.02	-0.2	-0.3	-0.3	-0.8
6,500 – 7,000	10.34	10.34	10.34	10.21	0	0	-1.3	-1.3
Total	3,871.68	3,826.87	3,759.80	3,702.51	-1.2	-1.8	-1.5	-4.4

In comparison, glaciers at elevations below 5,500 masl experienced a higher percentage of area loss, but the total area lost was significantly smaller, about one-fifth of the total loss in the 5,500 to 6,000 masl. Despite the lower total loss, the loss rate in elevation range below 5,000 masl remained consistent over all decades and accelerated over the decades.

Above 6,000 masl, glacier area reductions have been relatively moderate to minimal. Between 6,000 masl and 6,500 masl, there was a moderate reduction of 10.62 km^2 from 1990 to 2020, reflecting a steady but less severe retreat compared to lower elevations. In the highest elevation range, from 6,500 masl to 7,000 masl, the reduction was minimal, with only a slight decrease of 0.14 km^2 between 2010 and 2020, and stability in the earlier decades from 1990 to 2010. Overall, while glaciers below 5,500 masl have experienced significant reductions, those above this elevation have seen relatively stable conditions, although some degree of retreat is still evident.

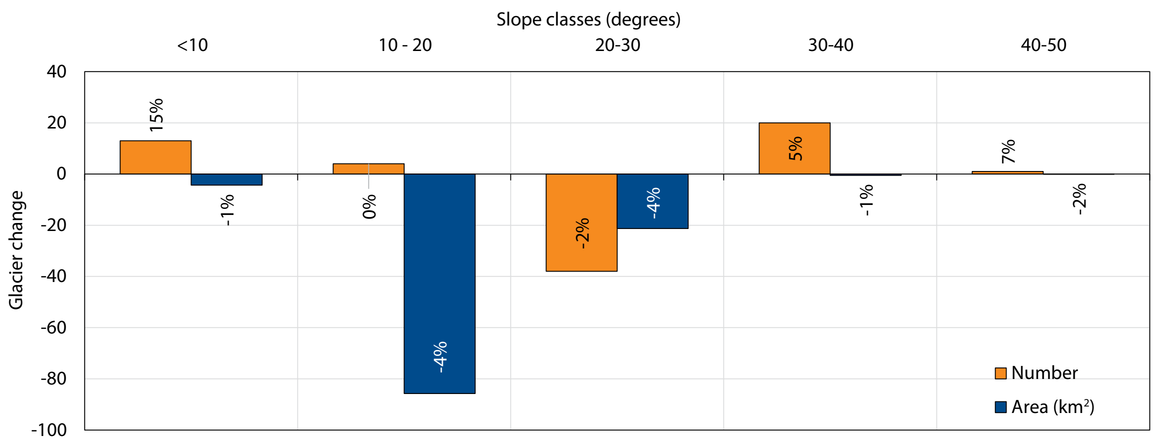
Overall analysis of glaciers in various mean slope classes reveal a most notable reduction in glacier number and areas primarily in the slope range of 20° – 30° (Figure 4.73). This slope ranges lost 38 glaciers and 4% of area loss within three decades. While most of the slope classes over all decades showed an increase in glacier number and decrease in glacier area, the slope class of 20° – 30° showed reduction in both number and area of the glaciers. The lost rate in this class was more significant in all decades with the loss rate in increasing trend in recent decades.

Similarly, the 10°– 20° slope class experienced a notable reduction in glacier area of 4% over three decades, along with the addition of a few glaciers during the same period. The change pattern in number varies from reduction of 7 glaciers in early decade from 1990 to 2000 but addition of 10 and one glaciers respectively in following decades from 2000 to 2020. However, the glacier area was decreasing consistently throughout all decades from 1% in early decades to 2% in recent decades.

Other slope classes had minimal increase in number and reduction in glacier area. Slope class <10° experienced the addition of 13 glaciers from 1990 to 2020 with minor reduction of glacier area by 1%. Similarly, the 30° – 40° and 40° – 50° slope classes showed relatively stable and minor increases in glacier numbers, with minor reduction in glacier area by 1% to 2%. No glaciers were identified above 50° slope class over all decades.

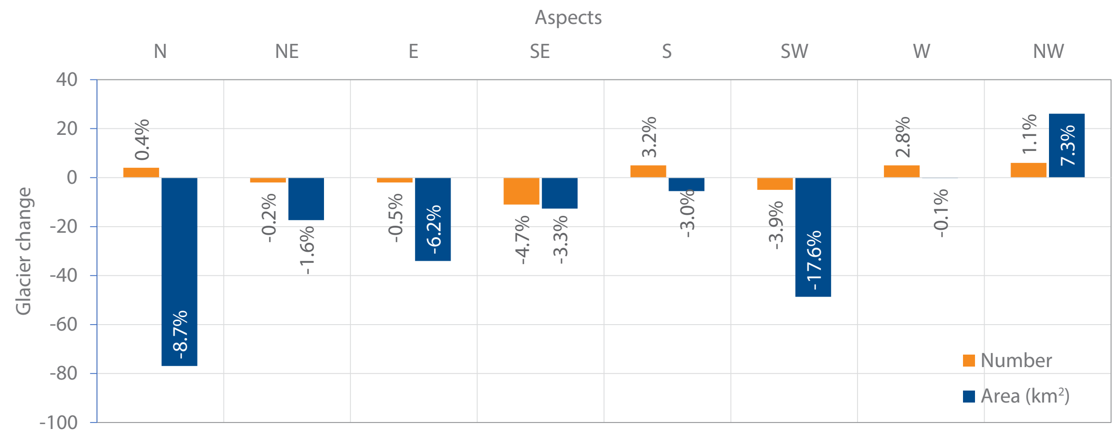
In terms of glacier changes across the various mean aspects, The Tibetan Interior Mountains reveal a pattern of relatively stable glacier numbers but a significant reduction in glacier area across all aspects. The northern (N), northeastern (NE), and northwestern (NW) aspects showed minimal fluctuations in glacier number over the past three decades (Figure 4.74). Specifically, the northern aspect recorded a slight gain of 4 glaciers, the northeastern showed a minor decrease of 2, and the northwestern experienced an increase of 6 glaciers. Despite this numerical stability, all three aspects faced notable glacier area loss. The northern and

FIGURE 4.73 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES IN THE TIBETAN INTERIOR MOUNTAIN RANGE.



YALA GLACIER AND GLACIAL LAKE, LANGTANG VALLEY, NEPAL

FIGURE 4.74 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES IN TIBETAN INTERIOR MOUNTAIN RANGE.



northeastern aspects lost approximately 9% and 2% of their glacier area, respectively. Interestingly, the northwestern aspect diverged from this trend, showing a 7% gain in the glacier area. This could be due to changes in mean aspects of the glaciers with shrinkage and fragmentation of glaciers.

In contrast, the southern (S), southeastern (SE), and southwestern (SW) displayed more pronounced glacier retreat, especially in terms of area. The southeastern and southwestern aspects showed glacier number reductions of 5% and 4%, respectively. The southwestern aspect was particularly impacted, with the highest glacier area loss of 18%, while the southeastern aspect lost 3%.

The southern aspect was somewhat anomalous, with a net gain of 5 glaciers; however, this occurred alongside a 3% area loss, indicating glacier fragmentation or shrinkage.

The eastern (E) and western (W) aspects presented mixed trends. The eastern aspect experienced a minor 1% decline in glacier number but a more significant 6% loss in area, suggesting steady retreat over time. Conversely, the western aspect showed a net gain of 5 glaciers and an almost negligible overall area loss of less than 0.1% over the entire period. However, it did experience a more noticeable 5% area reduction in the last decade, highlighting a potential recent acceleration in glacier retreat.

AUTOMATIC WEATHER STATION AT YALA GLACIER BASE CAMP

4.9 Eastern Tibetan Mountain

This mountain range is a part of the Tibetan Plateau situated in the eastern region, extending across the upper reaches of the Yangtze and Yellow River basins. Bounded by the eastern Kunlun Shan and Qilian Shan to the north and northeast, and by the Hengduan Shan and Tanggula Shan to the south and southwest, it spans from approximately 91.412°E to 102.613°E longitude and 30.953°N to 37.430°N latitude. Encompassing an area of nearly 333,123 km^2, which constitutes approximately 8% of the total area of the HKH region, this mountain range varies in elevation from 2,296 masl to 6,300 masl. Figure 4.75 shows the extent of this mountain range including the glacier distribution.

Glacier distribution in 2020

Glaciers in this mountain range are widely scattered, with relatively fewer in number and smaller total area coverage. Based on Landsat images from 2020, a total of 580 glaciers were identified, covering less than 300 km^2 in area and estimated to hold approximately 17 km^3 of estimated ice reserves (Table 4.1). These figures represent just 0.9% of the total number of glaciers and 0.5% of the total glacier area within the HKH region.

This mountain range exhibit a predominance of smaller glaciers of Class 1 (<0.5 km^2), comprising 80% of the total number of glaciers (Figure 4.76). Despite their abundance, these smaller glaciers collectively cover only 23% of the total glacier area and hold an estimated ice reserve of just 1.6 km^3. This distribution underscores the diversity in glacier sizes within the region, emphasising the significant role of larger glaciers in contributing to the overall estimated ice reserves despite their lower numerical representation. Understanding these size class distributions is essential for assessing the resilience and response of glaciers in the Eastern Tibetan Mountain to climate change and environmental variability.

Mid-sized glaciers of Class 3 (1 – 5 km^2) constitute 10% of the total glacier in the mountain range. These glaciers cover a more substantial area and larger estimated ice reserves compared to all other classes, collectively accounting for 38% of the total glacier area and estimated ice reserves.

FIGURE 4.75 MAP SHOWING THE GLACIER DISTRIBUTION AND EXTENT OF THE EASTERN TIBETAN MOUNTAIN RANGE IN THE HKH.

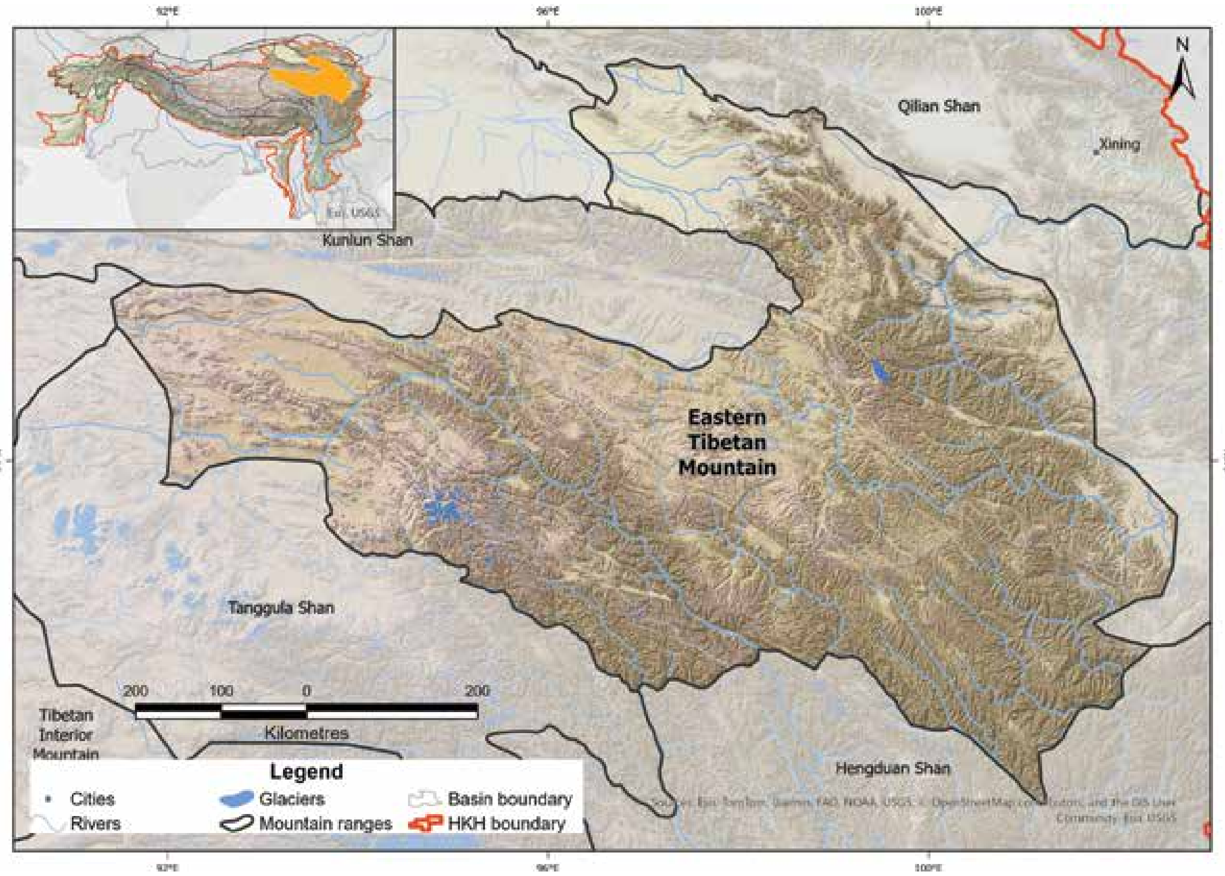
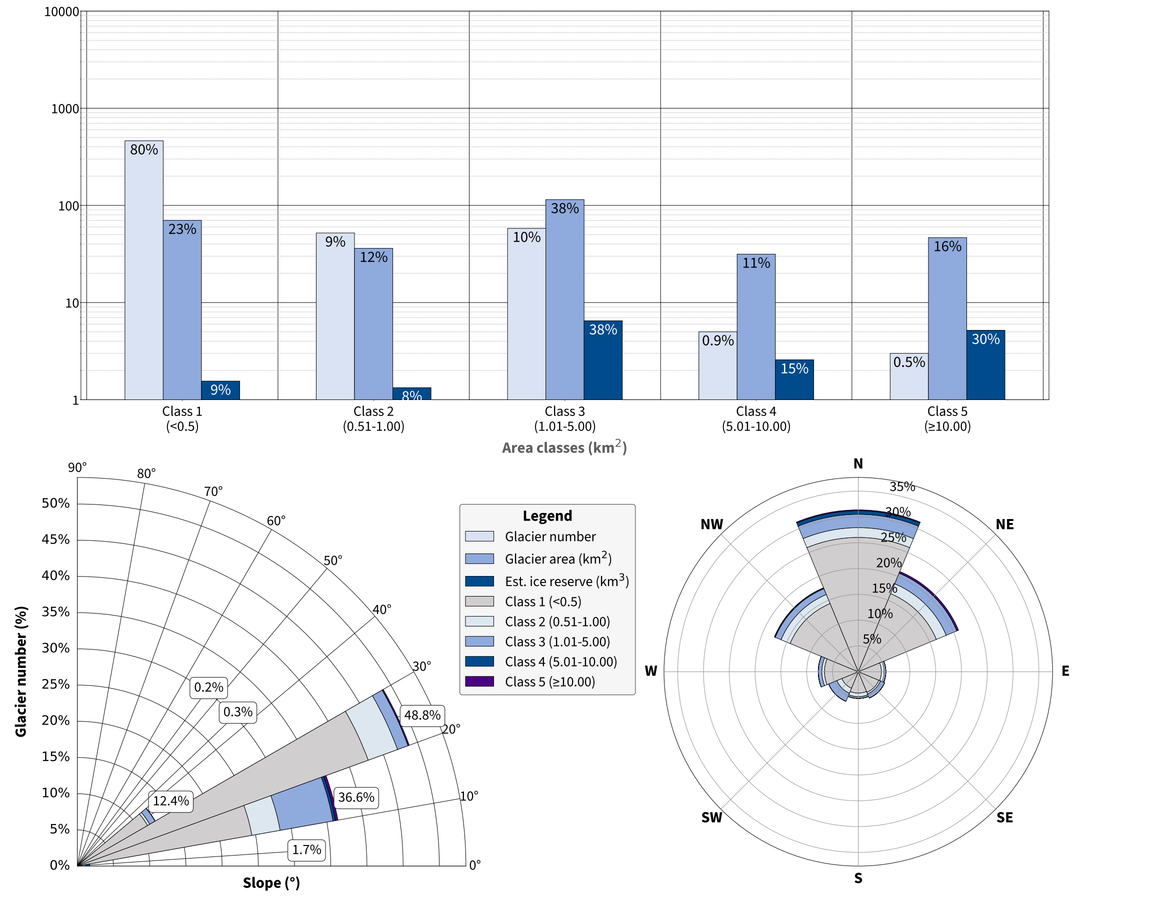


FIGURE 4.76 **GLACIER NUMBER, AREA AND ESTIMATED ICE RESERVES BY AREA SIZE CLASSES** (TOP) **AND ITS DISTRIBUTION ACROSS MEAN SLOPES** (BOTTOM LEFT) **AND ASPECTS** (BOTTOM RIGHT) **IN THE EASTERN TIBETAN MOUNTAIN RANGE.**



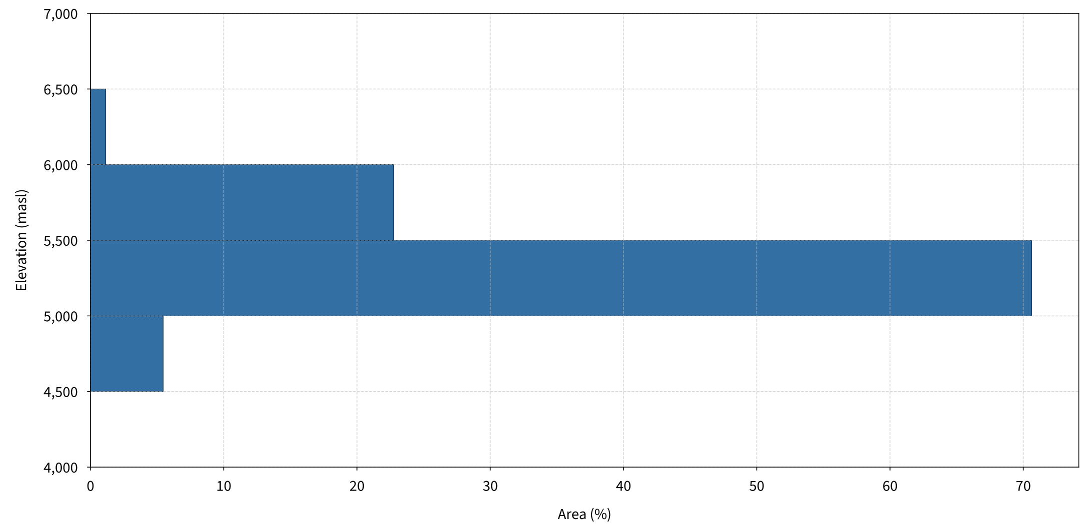
In contrast, the larger glaciers of Class 4 and 5, totaling 8 glaciers including the largest glaciers area of 20 km², significantly contribute to the total glacier area and estimated ice reserves. Class 4 glaciers cover 11% of the total glacier area and hold 15% of the total estimated ice reserves, while Class 5 glaciers cover 16% of the total glacier area and hold 30% of the total estimated ice reserves. Despite their small number, these larger glaciers play a critical role in maintaining substantial ice reserves of this mountain range.

Glaciers in this mountain range are distributed within a narrow elevation range, spanning from 4,500 masl at the lowest snout of the glacier to 6,254 masl at the highest crown part. Majorly, the glacier area covering almost 71% of the total glaciers area are within the elevation zone of 5,000 – 5,500 masl (Figure 4.77). Below 5,000 masl, it just covers 5.5 percent of the total glacier area. Area coverage in each 100 m elevation zone increases gradually from the lower elevation and peaks notably between 5,200 masl and 5,400 masl with highest amount of almost one-fourth (24%) of the total glacier area coverage in 5,300 – 5,400 masl.

However, as elevation exceeds 5,400 masl, there is noticeable decline in glacier area coverage. The area between 5,500 – 5,600 masl decline almost half of the area than in 5,400 – 5,500 masl and this trend increases as elevation increases further. In total, the area covers from 5,500 – 6,000 masl is around 23% of the total glaciers, with an exponentially declining trend within each 100 m elevation zone. Further, at highest elevation from 6,200 to 6,300 masl, glacier area reaches its lowest point covering just 0.1% of the total glacier area, indicating minimal coverage at these extreme heights.

The distribution of glaciers across various mean slope classes reveals a notable concentration in the moderate slope terrain, particularly between 10° to 30° slope, which comprise nearly 84% of the total glaciers in the mountain ranges (Figure 4.76). This range also encompasses approximately 91% of the total glacier area and holds 92% of the total estimated ice reserves in the mountain range. The prevalence of glaciers in these moderate slopes underscores the influence of terrain inclination on glacier formation and sustainability in the area.

FIGURE 4.77 **GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN THE EASTERN TIBETAN MOUNTAIN RANGE.**



Conversely, steeper slopes exceeding 30° accommodate fewer glaciers with smaller area coverages and reduced estimated ice reserves. As slope increases, the number of glaciers and their associated area and estimated ice reserves diminish. For instance, only three glaciers occur within the 40°– 50° slope range, covering minimal areas. Additionally, there is just one glacier located above 50° slope, indicating extremely limited glacier presence in these steep terrains.

In contrast, the slope with less than 10° accommodates 4 glaciers, covering a substantial area coverage of 6.2 km². This overall distribution underscores the prevalence of larger glaciers in gentle slope.

The glacier distribution across various mean aspects in the Eastern Tibetan Mountain reveals notable patterns in size and ice reserves. The northern aspect is particularly prominent, hosting over 31% of the total glaciers and covering approximately 32% of the glacier area in the region (Figure 4.76). This aspect not only accommodates a large number of glaciers but also features a significant portion of the total glacier area.

Following the northern aspect, the northeastern aspect also contains a substantial number of glaciers, accounting for 21% of the total and covering more than 30% of the glacier area. In contrast, the northwestern aspect holds 18% of the glaciers but covers only 13% of the total area, with a mean glacier size of 0.37 km² – suggesting a smaller glacier size distribution than those in the northern and northeastern aspects.

In the southern quadrant, including both eastern and western aspects, the number of glaciers is relatively uniform, ranging from 5% to 8% of the total. These aspects cover a smaller proportion of the glacier area, from about 3% to 10%, with the southwestern aspect showing the highest percentage. Notably, the southeastern aspect stands out with the largest mean glacier size of 0.79 km², indicating a distribution of larger glaciers compared to other aspects.

Decadal glacier changes from 1990 to 2020

The decadal data on glacier changes of this mountain range show a consistent decline in both the number and area of glaciers in each decade (Figure 4.78). On average, the number of glaciers decreased by approximately 5% to 7% per decade,

FIGURE 4.78 **DECADAL CHANGES OF GLACIER NUMBERS AND AREAS IN THE EASTERN TIBETAN MOUNTAIN RANGE.**

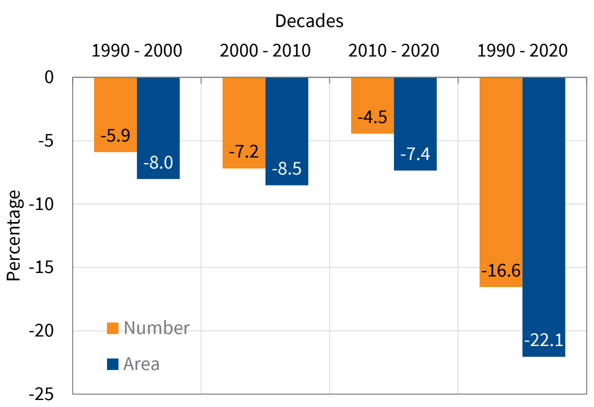
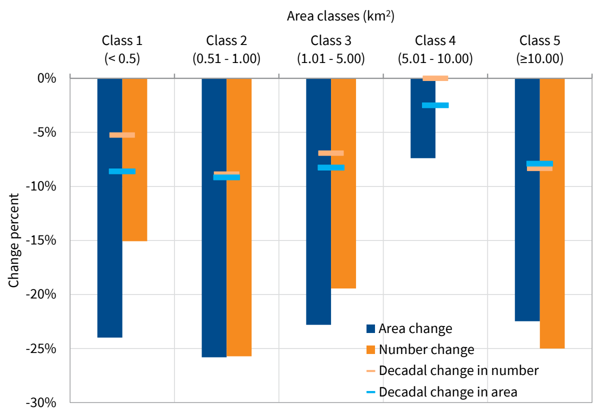


FIGURE 4.79 GLACIER NUMBER AND AREA CHANGES ACROSS VARIOUS SIZE CLASSES OVER THREE DECADES INCLUDING MEAN DECADAL CHANGE RATE IN THE EASTERN TIBETAN MOUNTAIN RANGE.



while the glacier area reduced by about 8% per decade. Over the entire period, the total number of glaciers dropped by more than 16.5%, and the glacier area diminished by 22%.

The distribution of glaciers across different size classes reveals significant and accelerating losses, with both the number and area of glaciers decreasing consistently over the decades (Figure 4.79). The smallest glaciers, Class 1 (<0.5 km²), have seen the most pronounced reductions, with a loss of 82 glaciers and a 24% decrease in glacier area over 30 years. This substantial decline may be due to the retreat of these smaller glaciers to sizes below the threshold considered in this research, and some have likely disappeared entirely.

In contrast, the reduction in the number of larger glaciers is less severe, with a decrease of 18 glaciers in Class 2, just one in Class 5, and no changes in Class 4 over the same period. However, glacier area loss has been observed across all size classes. The most significant area loss occurred in the mid-sized class 3 (1.01 - 5.00 km²), which lost nearly 23% of its area over three decades. Class 2 glaciers experienced a higher percentage of area loss at approximately 26%, but the absolute area lost was one-third of that in Class 3. Despite no change in the number of glaciers in Class 4, there was a modest area reduction of 7.4% over the 30 years. Class 5 glaciers also saw notable area loss, although the absolute reduction was less than half of that observed in Class 3.

In the Eastern Tibetan Mountain, changes in glacier area have varied significantly across different elevation ranges over the past three decades (Table 4.13). In 1990, glaciers were mapped at elevations above 4,468 masl. By 2020, this lowest elevation had shifted upward to 4,510 masl, indicating that glaciers below 4,510 masl had entirely vanished within this period. Initially, from 1990 to 2000, there was a slight increase in glacier area at elevations below 4,500 masl. However, this trend reversed in subsequent decades, leading to a complete disappearance of glaciers in this lower elevation range by 2010 – 2020.

FIGURE 4.80 CHANGE IN GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE EASTERN TIBETAN MOUNTAIN RANGE.

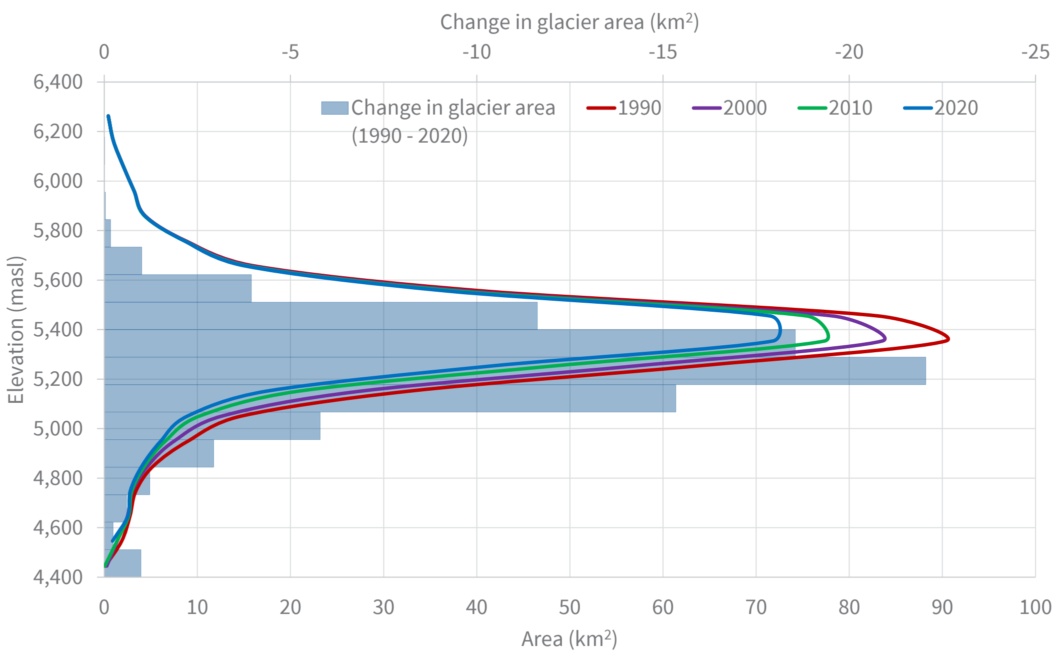


TABLE 4.13 GLACIER AREA DISTRIBUTION AND PERCENTAGE CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE EASTERN TIBETAN MOUNTAIN RANGE.

Elevation ranges (masl)	Area (km²)				Area change (%)			
	1990	2000	2010	2020	1990 - 2000	2000 - 2010	2010 - 2020	1990 - 2020
4,000 – 4,500	0.11	0.27	0.05		137.2	-81.7		
4,500 – 5,000	22.30	19.08	17.82	16.31	-14.4	-6.6	-8.5	-26.8
5,000 – 5,500	284.70	259.03	232.20	211.32	-9.0	-10.4	-9.0	-25.8
5,500 – 6,000	73.25	71.17	69.41	68.10	-2.8	-2.5	-1.9	-7.0
6,000 – 6,500	3.45	3.44	3.44	3.44	-0.2	0.0	-0.1	-0.3
Total	383.81	353.00	322.93	299.17	-8.0	-8.5	-7.4	-22.1

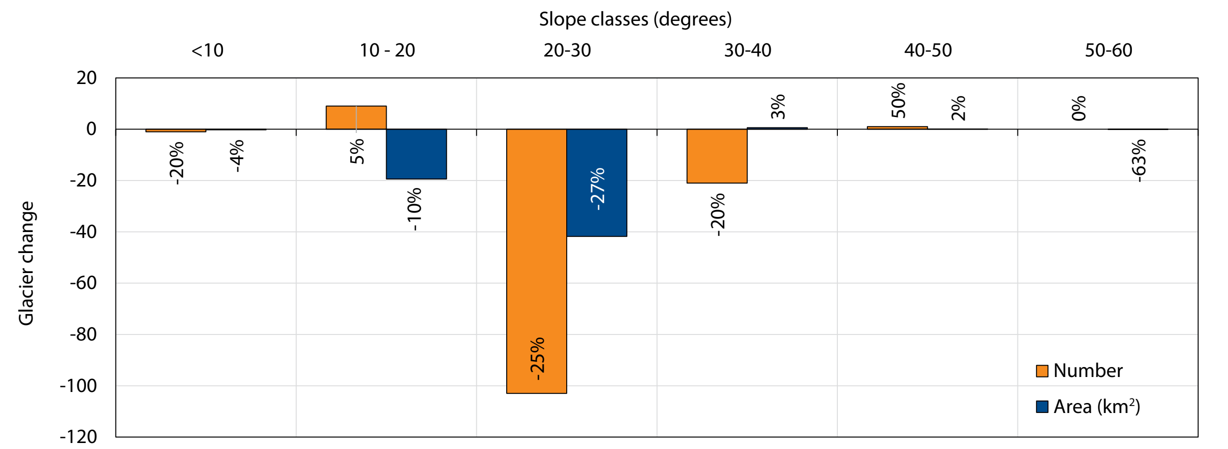
The most significant glacier area loss occurred in the 5,000 to 5,500 masl range, where glaciers have steadily declined over all three decades, resulting in a net loss of nearly 26% over 30 years (Figure 4.80). A similar trend was observed in the 4,500 to 5,000 masl range, with a uniform decrease in glacier area across the decades, culminating in a total reduction of almost 27%. However, the absolute area loss in this range was notably less than that in the 5,000 to 5,500 masl range.

In contrast, glaciers at elevations between 5,500 and 6,000 masl experienced a slower rate of decline, with a gradual reduction of 7% over the past 30 years. The highest elevation range, above 6,000 masl, showed negligible area loss, indicating that glaciers at these altitudes remain relatively stable and less affected by the trends observed at lower elevations.

Glacier distribution across various mean slope classes in this mountain range reveals that the majority of glaciers are found between slopes of 10° and 40° across all decades (Figure 4.81). Very few glaciers are located on slopes below 10° or above 40°, with no glaciers present on slopes exceeding 60°. Over the past three decades, glacier changes have shown diverse patterns, with the most notable changes occurring in the 20° – 30° slope range. This range showed a dramatic decline of 103 glaciers from 1990 to 2020 and experienced the largest area reduction of 41.8 km², reflecting a 27% decrease in glacier area.

In contrast, the 10° – 20° slope class showed relative stability or a slight increase in glacier numbers, although it also experienced a significant area loss of 10% over the same period. Other slope classes, such as <10°, 30° – 40°, and 40° – 50°, displayed fluctuating trends in glacier numbers and area changes in each decade, with minimal overall changes. Consequently, glacier distribution in this mountain range is predominantly concentrated in the moderate slope classes 10° to 40°, while glaciers on gentler slopes below 10° remain relatively stable.

FIGURE 4.81 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES IN THE EASTERN TIBETAN MOUNTAIN RANGE.



THORTHORMI GLACIER AND GLACIAL LAKE IN BHUTAN

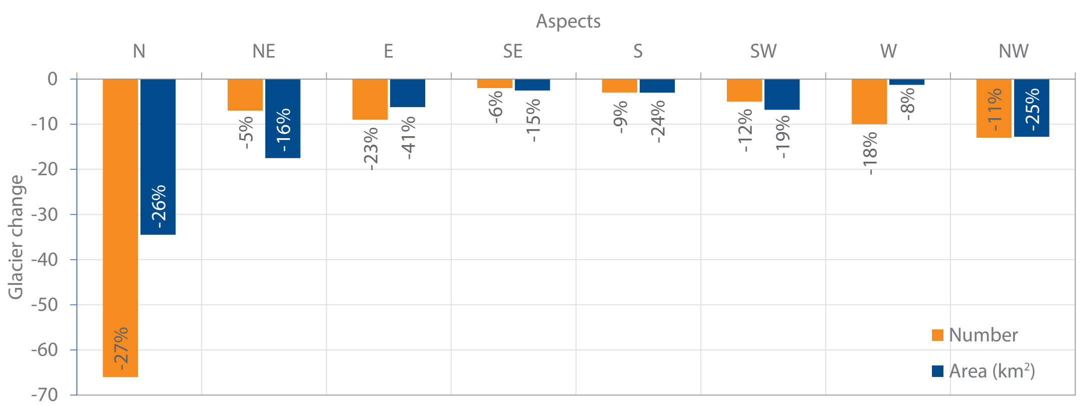
The glacier changes across various mean aspects over the past three decades reveals a consistent trend of glacier retreat, with varying degrees of changes over various aspects. The northern aspect was the most affected, with collectively losing glacier number by 27% and about 26% of the glacier area loss over three decades (Figure 4.82). This indicates not only a shrinkage of glaciers but also disappearance or shrinkage of glaciers below threshold of some smaller glaciers. The northeastern and northwestern aspects also showed substantial glacier area losses of 16% and 25%, respectively, though the change in number was less severe, especially in the northeastern aspect.

Comparatively, southern and southeastern aspects showed minimal changes in both number and area.

The southern aspect showed a minor decrease in glacier number and area loss by 15%. Over the past three decades, this aspect experienced a temporary gain in number during 2000s but ultimately loss of 3 glaciers in 2010s, suggesting any new formations were likely due to the fragmentation of larger glaciers into smaller ones. The southwestern aspect exhibited the most severe loss of area among these groups at 19%, despite only 5 glaciers decrease, again pointing to glacier shrinkage rather than disappearance.

Similarly, the eastern aspect had a notable amount of glacier area reduction by 6.2 km², despite a relatively modest decline of 9 glaciers over three decades. The western aspect showed a moderate loss of 10 glaciers, but the glacier area remained nearly stable over the entire period, with a negligible 1.3 km² loss.

FIGURE 4.82 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES IN THE EASTERN TIBETAN MOUNTAIN RANGE.



4.10 Qilian Shan

This mountain range lies in the northeastern part of the HKH region. It stretches 850 km from northwest to southeast bordering to Qinghai and Gansu provinces of west-central China. This mountain ranges from 93.709°E to 102.902°E longitude and 35.839°N to 35.839°N latitude, covering almost 3.2% of the total area of the HKH region. This mountain range varies in elevation from 1,725 masl to the highest peak of around 5,800 masl. Figure 4.83 showing the extent of the Qilian Shan within HKH including the glaciers distribution.

Glacier distribution in 2020

In 2020, this mountain range consists of 1,488 glaciers covering an area of about 1,017 km² and estimated ice reserves of about 61 km³ (Table 4.1). These figures represent just 2.3% of the total glaciers and 1.8% of the total glacier area in the mountain ranges. In terms of area coverage within mountain range, the glaciers cover just 0.5% of the total land area of the mountain range with an average size of the glacier is about 0.7 km².

The size of the glacier ranges from 0.02 km² to 19.5 km². Smaller-sized glaciers of Class 1 (<0.5 km²) constitute the majority, comprising nearly 72% of the total number of glaciers (Figure 4.84). Despite their abundance, these smaller glaciers only cover 17% of the total glacier area and hold 7% of the total estimated ice reserves in the mountain range.

In terms of area coverage, mid-sized glaciers of Class 3 play a significant role, covering approximately 40% of the total glacier area while accounting for 13% of the total glaciers in the mountain range. Larger-sized glaciers are comparatively fewer in number; Class 4 and Class 5 glaciers represent just 2% and 1% of the total, respectively. However, these larger classes contribute substantially to the total glacier area, accounting for 17% and 14%, respectively, highlighting their importance despite their smaller number.

FIGURE 4.83 MAP SHOWING THE GLACIER DISTRIBUTION AND EXTENT OF THE QILIAN SHAN IN THE HKH.

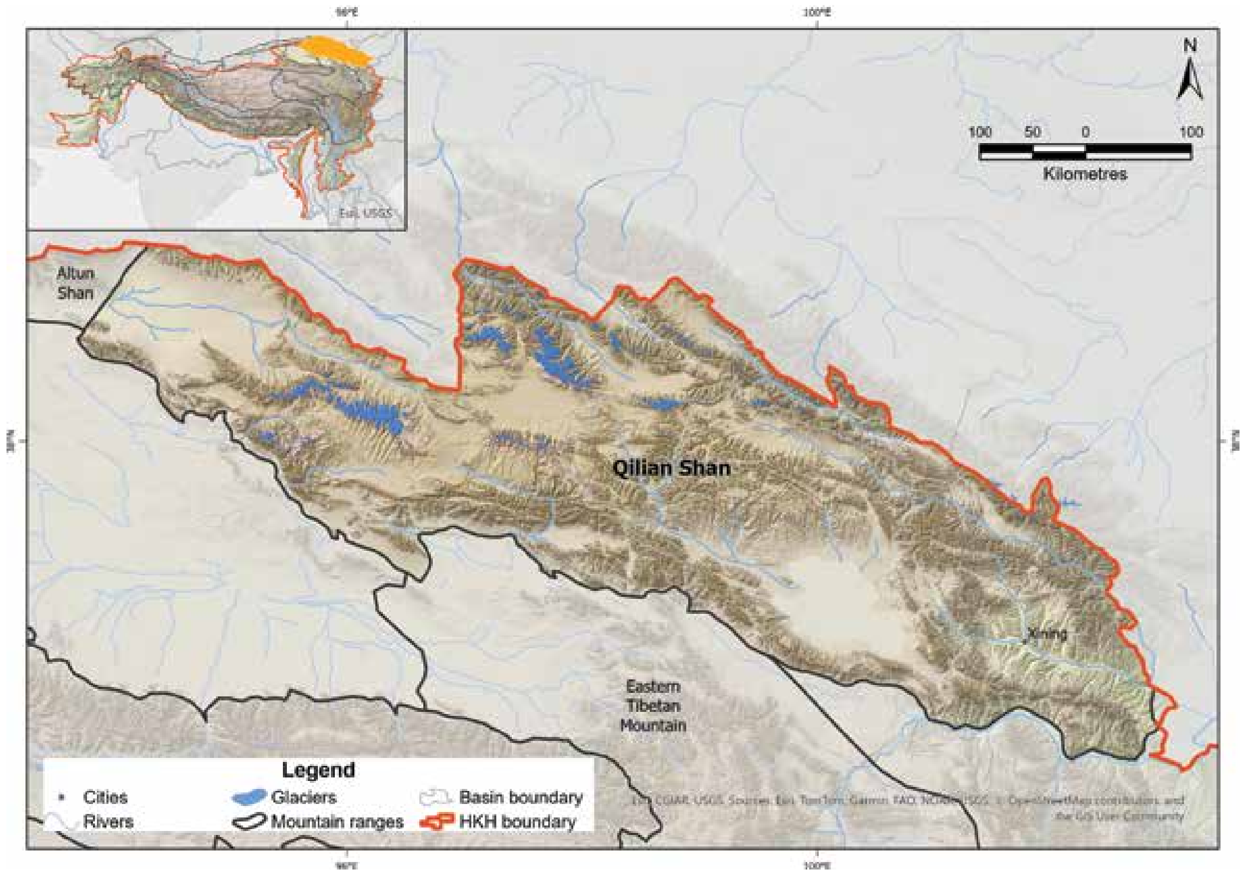
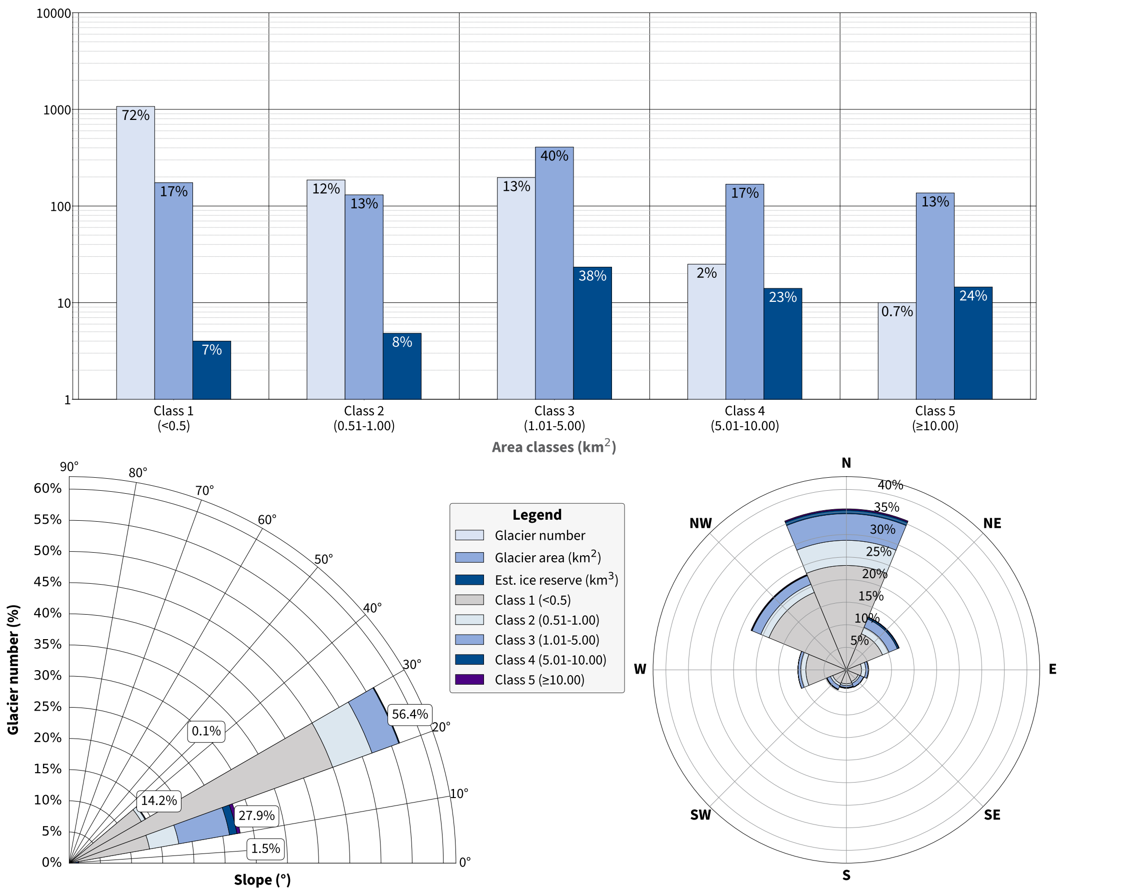


FIGURE 4.84 **GLACIER NUMBER, AREA AND ESTIMATED ICE RESERVES BY AREA SIZE CLASSES** (TOP) **AND ITS DISTRIBUTION ACROSS MEAN SLOPES** (BOTTOM LEFT) **AND ASPECTS** (BOTTOM RIGHT) **IN THE QILIAN SHAN.**



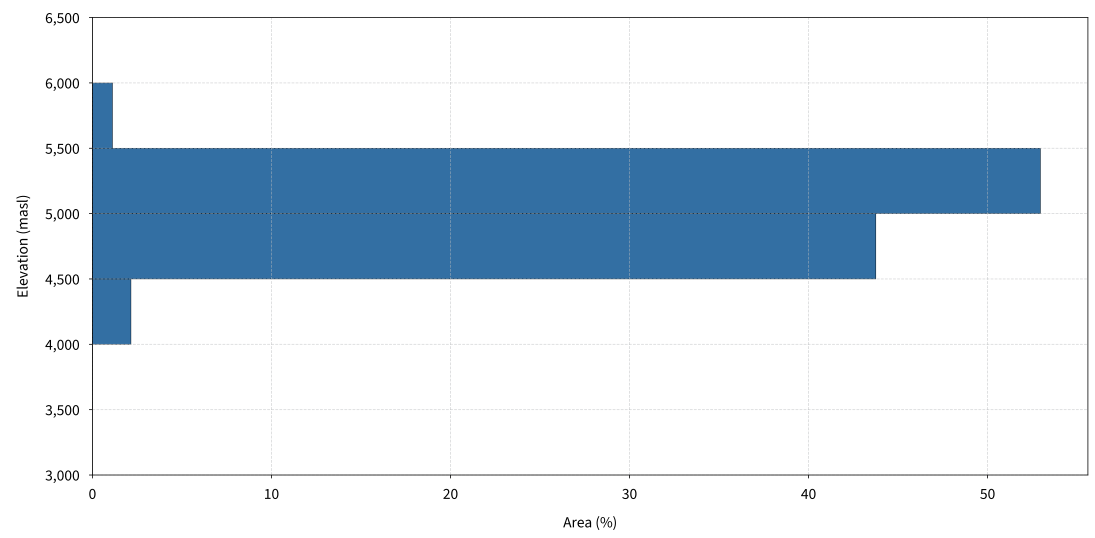
Glaciers in this mountain range span from 3,900 masl to 5,765 masl in elevation. The distribution of glacier areas across 500 m elevation zone shows that nearly 97% of the total glacier areas are concentrated between 4,500 masl to 5,500 masl elevation (Figure 4.85). Above and below this elevation range, the glacier area coverage diminishes significantly, each contributing less than 2% of total glacier area in the mountain range. Below 4,000 masl, the percentage of glacier area is negligible.

A more detailed breakdown of glacier area across 100 m elevation zone illustrates the substantial increase in glacier area as elevation rises. Notably, glacier areas begin to increase significantly from 4,400 masl, representing 1.4% of the total area at elevation between 4,400 masl to 4,500 masl and peaks between 5,000 masl and 5,100 masl, covering more than 18% of the total glacier area. Above 5,100 masl, the glacier area gradually declines, indicating reduced glacier presence at higher elevations. For instance, at 5,100 – 5,200 masl, the area coverage is over 16% of the total glacier area, decreasing to approximately 11% at 5,200 – 5,300 masl. Further the area coverage diminishes considerably beyond 5,300 masl, reaching minimal coverage at 5,700 – 5,800 masl.

In terms of various mean slope class of the glacier, the majority of glaciers are concentrated in moderate slope ranges of 10° to 30°, collectively comprising 80% of the total glaciers in the mountain range (Figure 4.84). These glaciers cover a substantial area of approximately 89% of the total glacier area in the region.

Conversely, glaciers in steeper slope classes above 30° are much fewer in number and cover a significantly smaller area. Slopes between 30° to 40° consist of 18% of the total glacier number but only covering 5% of the total glacier area. Similarly, glaciers in the <10° and 40° – 50° slope classes are sparse, with minimal area coverage and negligible estimated ice reserves.

FIGURE 4.85 **GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN THE QILIAN SHAN.**



Like in other mountain ranges, the larger glaciers are dominantly distributed in the gentle slope class of 10° – 20° and less than 10° slopes with higher percentage of number and area in 10° – 20°. As the size decreases to smaller one, it is distributed widely across various slope classes up to 50°. The highest concentration is in slope range from 10° – 40° for smaller size Class 1(<0.5km²). The mid-sized glaciers of Class 3 are also distributed within the slope ranges of 10°– 30°.

In terms of mean glacier aspects, the distribution of glaciers varies significantly across different aspects. The northern aspect found the most prominent consisting of more than 35% of the total glaciers covering an area over 42% (Figure 4.84). These aspects also host more than 43% of the total estimated ice reserves in the mountain range. The second and third prominent aspects hosting 22% and 14% of total glacier number and 15% to 17% of the total area coverage in the mountain range are the northwestern and northeastern aspects respectively. Comparatively, the northeastern aspect host larger sized glacier than in the northwestern aspect, which is reflected by the larger mean area per glacier of 0.88 km² in northeastern aspect.

The western aspect also has considerable number of glaciers, containing 11% of the total glacier in the mountain range, but its area coverage is comparatively less compared to the north quadrant aspects, which is just 6% of the total glacier area in the mountain range.

In contrast, all other aspects, such as southern, southeastern, southwestern and eastern aspects, have comparatively fewer glaciers and cover a smaller amount of glacier area. Each consists of around 4% to 5% of the total glacier numbers and 4% to 6% of the total glacier area coverages. However, the less numerous and less area coverages in southern aspect, these aspects had higher mean area per glacier like in northern and northeastern aspects, indicating the larger glacier distribution. Overall, the distribution reveals that northern quadrant aspects host the most extensive and voluminous glaciers, while other aspects in southern quadrant including eastern and western aspects show comparatively fewer glaciers and less area coverages.

Decadal glacier changes from 1990 to 2020

In this mountain range, 1,551 glaciers covering an area of 1,171.76 km² were mapped in 1990. By 2020, the number of glaciers had decreased to 1,490, and their total area had reduced to 1,016.87 km². This decline has been gradual yet consistent throughout the decades. From 1990 to 2000, the number of glaciers decreased by 0.64%, followed by a 1.5% reduction from 2000 to 2010, and a more pronounced drop of over 1.8% in the most recent decade, 2010 to 2020. Overall, there was nearly a 4% reduction in the number of glaciers over the past three decades.

Similarly, the glacier area has also declined steadily. From 1990 to 2000, the area decreased by 4.6%, followed by a slight reduction of 4.2% from 2000 to 2010. The most recent decade, 2010 to 2020, saw a more significant reduction of 5.1%, leading to a total decrease of 13.2% in glacier area over the thirty-year period (Figure 4.86).

The classification of glaciers by size reveals a consistent decline in both glacier numbers and area across all categories, with the most pronounced losses occurring in the mid-sized Class 3 (1.01 to 5.00 km²). This class saw a reduction of 40 glaciers from 1990 to 2020, along with a significant area decrease of nearly 16% over the three decades (Figure 4.87).

In contrast, the smallest Class 1 (<0.5 km²) glaciers experienced the second largest area reduction, totaling 10% over the same period. Despite this, the number of glaciers in this class increased slightly by 0.8% over the three decades. This increase in glacier number is attributed to the addition of 21 glaciers

FIGURE 4.86 DECADAL CHANGES OF GLACIER NUMBER AND AREA IN THE QILIAN SHAN.

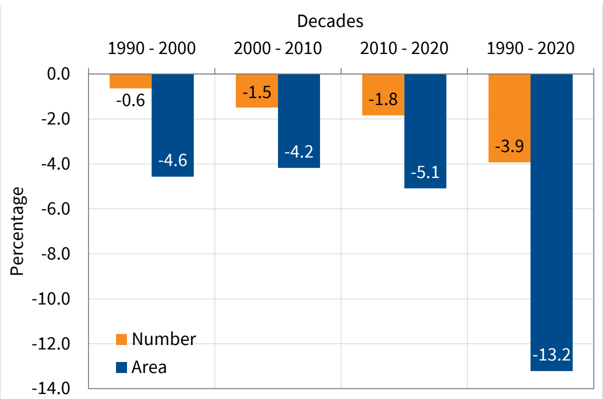
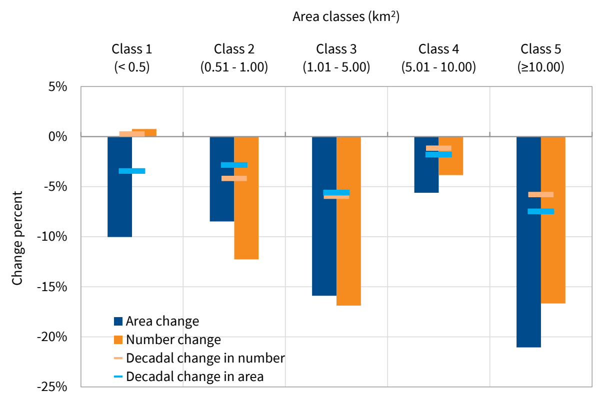


FIGURE 4.87 GLACIER NUMBER AND AREA CHANGES ACROSS SIZE CLASSES OVER THREE DECADES INCLUDING MEAN DECADAL CHANGE RATE IN THE QILIAN SHAN.



in earlier years, although the number subsequently declined in later decades. Throughout, the area of glaciers in this size class has shown a steady decrease.

Class 2 (0.51 to 1.00 km²) displayed a mixed trend in glacier numbers, with fluctuations in different decades but an overall reduction of 26 glaciers from 1990 to 2020. This class also saw a net decrease in the glacier area of 8.5% over the same period. The fluctuations in glacier numbers, coupled with a consistent loss of glacier area, reflect the ongoing shrinkage and fragmentation of larger glaciers into smaller sizes. This trend has led to the reduction of some glaciers below the size threshold for their class, and in some cases, the complete disappearance of smaller glaciers.

Larger glacier size classes, specifically Class 4 (5.01 to 10.00 km²) and Class 5 (≥10.00 km²), exhibited relatively stable numbers with only minor fluctuations. Class 4 saw a net reduction of 1 glacier and experienced a more modest area loss of 5.6% from 1990 to 2020. This underscores a consistent, though less dramatic, area loss, highlighting ongoing glacier shrinkage. Class 5, the largest glacier class, experienced a significant area reduction of over 21% over the same period, indicating considerable shrinkage among the largest glaciers.

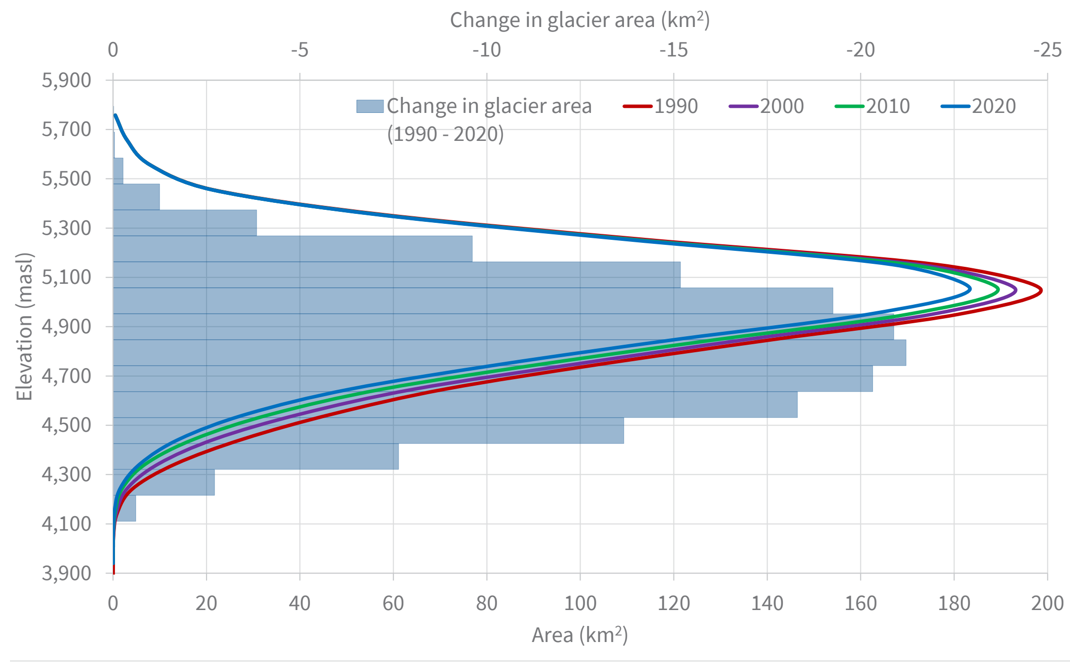
Over the past three decades, glaciers in the Qilian Shan have only been found at elevations above 3,800 masl. The lowest glacier snout has shifted upward from 3,863 masl in 1990 to 3,929 masl in 2020. This shift is evidenced by a reduction of glacier area below 4,000 masl by 0.03 km², reflecting a loss of over 67% in the early decades from 1990 to 2000. No additional changes in glacier area were recorded in the subsequent decades.

The most significant reductions in glacier area occurred between 4,500 masl and 5,000 masl, where nearly 100 km² of glacier area was lost, reflecting an 18.3% reduction over three decades (Figure 4.88 and Table 4.14). The area lost in each decade in this elevation range was notably larger and showed an increasing trend compared to other elevation zones. In contrast, the area loss below 4,500 masl was comparatively smaller, amounting to about one-third of the loss observed between 4,500 masl and 5,000 masl, with a reduction rate of nearly 25% over the same period.

TABLE 4.14 GLACIER AREA DISTRIBUTION AND PERCENTAGE CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE QILIAN SHAN.

Elevation ranges (masl)	Area (km²)				Area change (%)			
	1990	2000	2010	2020	1990 - 2000	2000 - 2010	2010 - 2020	1990 - 2020
3,500 – 4,000	0.05	0.02	0.02	0.02	-67.3	0	0	-67.3
4,000 – 4,500	46.58	35.39	26.96	21.91	-24	-23.8	-18.7	-53
4,500 – 5,000	544.97	514.63	483.08	444.98	-5.6	-6.1	-7.9	-18.3
5,000 – 5,500	568.67	556.66	549.91	538.52	-2.1	-1.2	-2.1	-5.3
5,500 – 6,000	11.50	11.46	11.45	11.44	-0.3	-0.1	-0.1	-0.5
Total	**1,171.76**	**1,118.16**	**1,071.40**	**1,016.87**	**-4.6**	**-4.2**	**-5.1**	**-13.2**

FIGURE 4.88 CHANGE IN GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES FROM FROM 1990 TO 2020 IN THE QILIAN SHAN.



Significant area reductions were also observed between 5,000 masl and 5,500 masl, with a net loss of 5.3% from 1990 to 2020. The decadal changes in this range showed a gradual decline: 2.1% from 1990 to 2000, 1.2% from 2000 to 2010, and 2.1% from 2010 to 2020. Above 5,500 masl, however, minimal reduction in glacier area was observed, indicating a relatively stable condition in the higher elevation range.

The glaciers across different slopes exhibited distinct patterns of change in both number and area. The most significant reductions were observed in the 20° to 30° slope class, which experienced a 6% decrease in the number of glaciers and a 14% reduction in glacier area over the past three decades (Figure 4.89). The 30° to 40° slope class also showed reductions, with an 8% decline in the number of glaciers and a 7% decrease in area from 1990 to 2020, although there was a slight increase in the number of glaciers between 2000 and 2010.

In contrast, the slope classes of 10° to 20° and less than 10° showed increases in glacier numbers throughout all decades. However, the glacier area in the 10° to 20° slope class decreased over each decade, resulting in an overall reduction of 6% in glacier area over thirty years. Conversely, glaciers in less than 10° slope class experienced an overall increase in area by 6% over the same period, although there was a decline in the 2000 to 2010 decade.

For higher slopes of 40° to 50°, there was a slight overall increase in both glacier number and area throughout the decades. No glaciers were found above the mean slopes greater than 50°.

DOWNHILL VIEW TO LANGTANG VALLEY FROM YALA GLACIER DURING GLACIER MASS BALANCE MONITORING EXPEDITION, 2025

FIGURE 4.89 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES IN THE QILIAN SHAN.

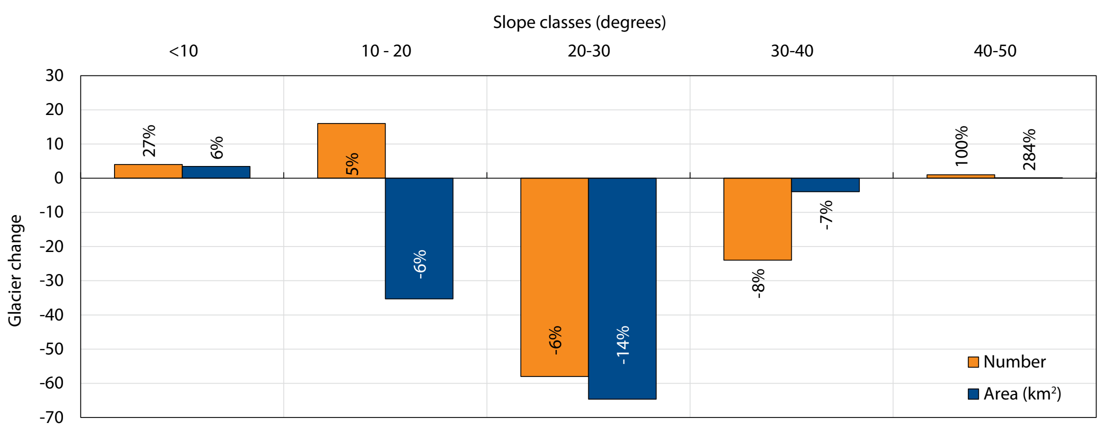
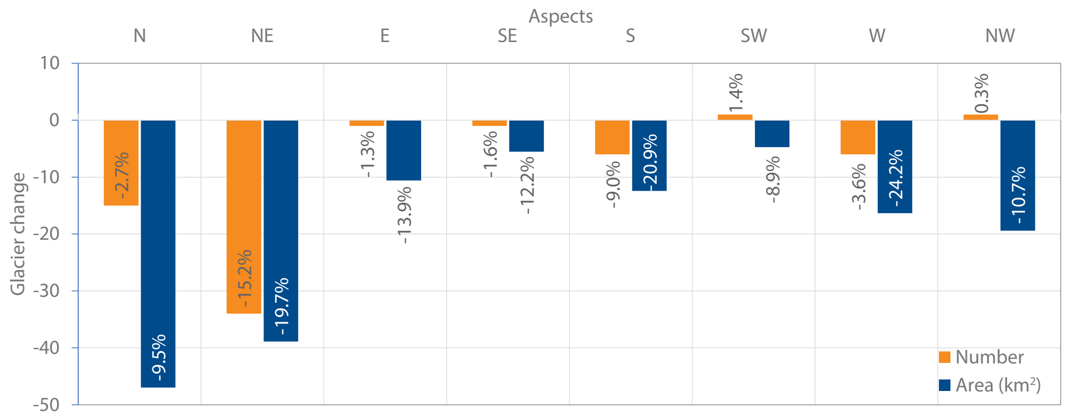


FIGURE 4.90 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES IN THE QILIAN SHAN.



The analysis of glacier changes across various aspect classes in the Qilian Shan reveals pronounced degradation, especially on the northern, northeastern, and northwestern aspects. The northeastern aspect experienced the most significant reduction in glacier number, losing 34 glaciers equivalent to a 15% decrease alongside the second highest area loss of approximately 39 km², representing a 20% decline over the past three decades (Figure 4.90). The northern aspect faced the greatest area loss, shedding nearly 47 km² and 15 glaciers during the same period. Although the northwestern aspect showed no net change in glacier number, it still suffered a notable area loss of 19.40 km² (−11%), underscoring that glacier thinning and shrinkage can occur even without a drop in glacier number.

In contrast, the southern, southeastern, and southwestern aspects exhibited relatively lower, though steady, glacier retreat throughout the three decades. Of these, the southern aspect was the most impacted, losing 6 glaciers (−9%) and undergoing a significant area reduction of 12.43 km² (−21%).

The southeastern aspect showed stability in glacier number, with a loss of just 1 glacier (−2%), but still experienced consistent area loss by 5.52 km² (−12%), indicating progressive degradation. Interestingly, the southwestern aspect recorded a slight gain of 1 glacier (+1%) yet still showed a 4.74 km² (−9%) decrease in area. These findings highlight that apparent numerical stability or minor gains in glacier number can mask the underlying decline in glacier area, reflecting ongoing thinning and fragmentation.

Similarly, the eastern aspect exhibited minimal change in glacier number, losing only 1 glacier (−1%), but still experienced a substantial area loss of 10.60 km² (−14%), indicating that glaciers are shrinking rather than disappearing. The western aspect, on the other hand, underwent the most severe area loss proportionally – losing 16.35 km², which accounts for a 24.21% reduction – despite a relatively modest glacier number decline of 6 glaciers (−4%). These observations suggest that glacier health in these areas is more impacted by area loss than by glacier disappearance, pointing toward intensified melting and climate-driven stressors.

4.11 Kunlun Shan

This mountain range covers northern section of the HKH region, extending over 2,000 km² from the Pamirs in Tajikistan in the west to the Kunlun pass and the adjacent ranges of Qinghai province in China in the east. The mountain range is quite narrow in the west and comparatively much wider in the east. It is characterised by formidable width with not exceeding 200 kms. Inside the HKH region, its width ranges from 80 to 100 kms mostly covering the southern portion of the mountain range. The range includes prominent peaks such as Burhan Budai, Bayan Har and A'nyêmaqên (Amne Machin). Geographically, in the western edges it acts as a significant barrier between the high Tibetan plateau to the south and the Tarim basin to the north in western China.

This natural division plays a crucial role in shaping regional climate patterns and water distribution, influencing both local ecosystems and human settlements. To the north in eastern edges, a branch of the Altun Mountains continues this geographical alignment. It features diverse landscapes ranging from rugged peaks to broad valleys, with elevations varying considerably across its span. The elevation varies from 2,657 masl to 7,131 masl.

The mountain range is divided into two sections: western and eastern Kunlun Shan. The western Kunlun Shan stretches from Pamir in Tajikistan to Heishi Bei Lake within HKH region. Figure 4.91 showing the extent of both the sub mountain ranges and the glacier distribution over the Kunlun Shan.

Glacier distribution in 2020

The glaciers in the Kunlun Shan are categorised into two main sections: western and eastern Kunlun and Shan. Based on the Landsat images of 2020, a total of 2,300 glaciers were identified in these mountain ranges where western and eastern sections cover 44 and 56% of the total glaciers in the mountain range. These glaciers collectively cover an area exceeding 3,295 km² and contain a total estimated ice reserve of 380 km³ (Table 4.1). Overall, the Kunlun Shan account for approximately 3.6% of the total number of glaciers and nearly 6% of the total glacier area

FIGURE 4.91 MAP SHOWING THE GLACIER DISTRIBUTION AND EXTENT OF THE KUNLUN SHAN IN THE HKH.

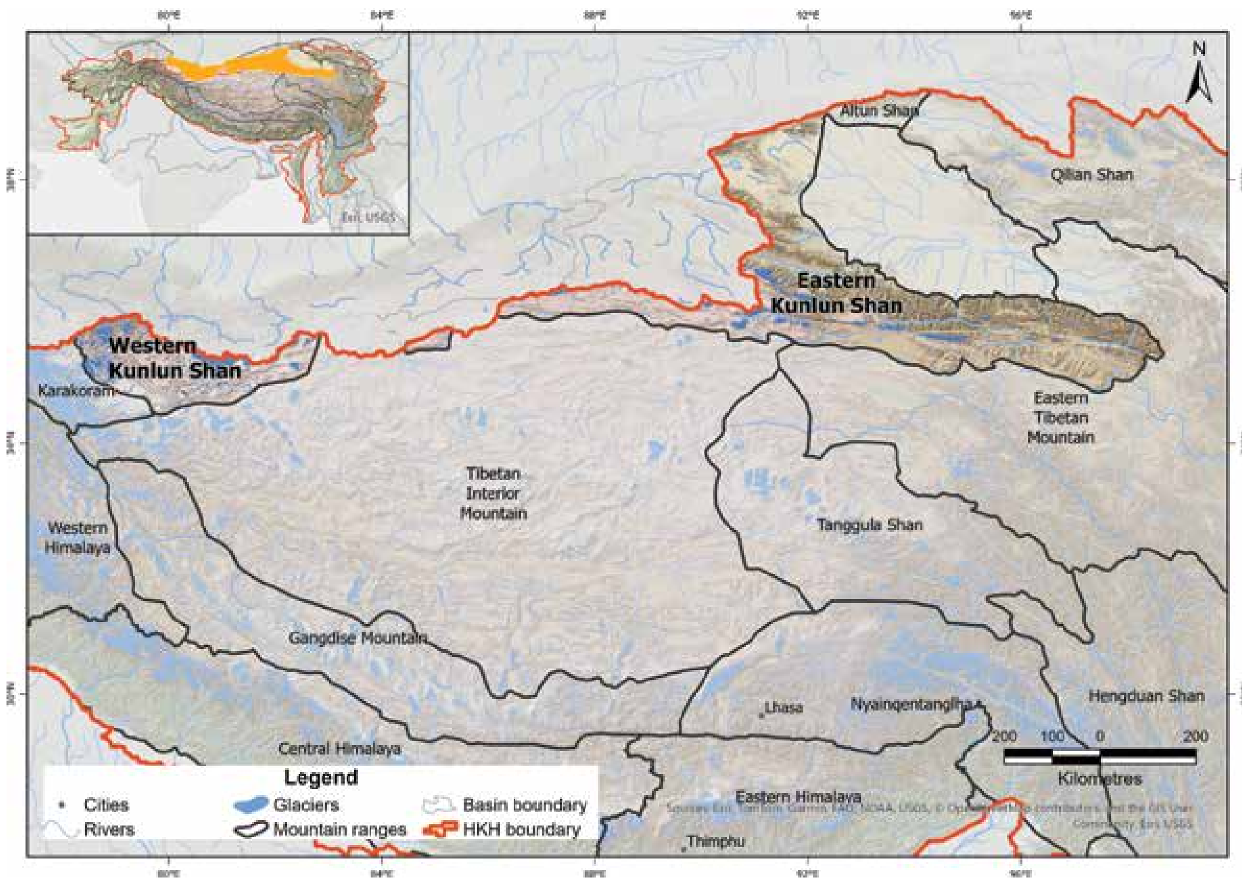
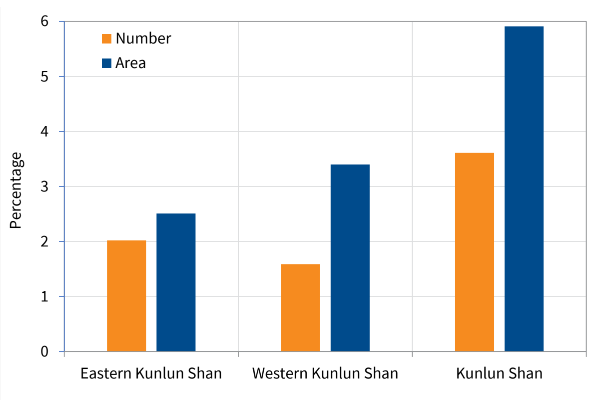


FIGURE 4.92 **GLACIER NUMBER AND AREA PERCENTAGE DISTRIBUTION IN THE SUB-MOUNTAIN RANGES OF THE KUNLUN SHAN.**



within the HKH region. The percentage distribution of glacier number and area in each section of the mountain range in terms of total glaciers in the HKH region is given in Figure 4.92.

The largest glacier in the Kunlun Shan region spans 234.5 km^2 and is located in the western Kunlun Shan, while the largest glacier in the eastern Kunlun Shan covers 95 km^2. There are four glaciers larger than 100 km^2, all situated in the western Kunlun Shan. The glacier size distribution reveals a predominance of small glaciers: those in Class 1 (<0.5 km^2) make up over 64% of the total number of glaciers in this mountain range. This distribution pattern is similar in both western and eastern sections, where these small glaciers represent 66% and 63% of the total number, respectively. Despite their high numbers, glaciers in this smallest size Class 1 cover only about 9% of the total glacier area and account for just 1.6% of the estimated ice reserves in the mountain ranges. Each section reflects this pattern, covering approximately 6% and 10% of the glacier area and holding 1% to 3% of the estimated ice reserves in the western and eastern sections, respectively.

The distribution of glacier numbers consistently decreases as the glacier size increases, while the glacier area coverage correspondingly increases. Mid-sized glaciers, specifically those in Class 2 and Class 3, account for about 15% of the total glacier numbers in Class 2 and nearly 17% in Class 3. However, in the larger glacier classes (4 and 5), the number decreases from 2.4% in Class 4 to 2% in Class 5. Conversely, the area and estimated ice reserves show a substantial increase with larger glacier sizes. The area coverage rises from 7.3% and 23.7% of the total glacier area in mid-sized glaciers of Class 2 and 3, and to 11.5% and nearly 50% in larger glaciers of Class 4 and 5, respectively. Similarly, estimated ice reserves jump from 0.7% to 2% in mid-sized glaciers, reaching 7% and 35.6% in larger glaciers. This pattern of fewer glaciers in larger size classes, coupled with their greater area and estimated ice reserves compared to mid-sized and smaller sized glaciers, is consistent across both sections of the Kunlun Shan range, as illustrated in the Figure 4.93 and Figure 4.94.

The glaciers in Kunlun Shan spans from the lowest elevation of glacier snout of 4,600 masl in eastern Kunlun Shan up to the highest elevation of 7,150 masl in western Kunlun Shan. The distribution of glacier areas over various elevation ranges reveals that the glaciers at the lower elevation below 5,000 masl are mostly present in the eastern Kunlun Shan covering a small fraction of just 0.35% of the total glacier area in the mountain range (Table 4.15). The area distribution increases significantly above 5,000 masl showing the stark contrast between eastern and western Kunlun Shan. The highest percentage of area distributed in eastern Kunlun is at elevation range of 5,000 to 5,500 masl with containing 23.8% of the total. Whereas in western Kunlun Shan, the elevation ranges of 6,000 to 6,500 masl cover the highest area coverage of almost 29.6% of the total. Overall, the highest area coverage is at elevation ranges of 5,500 – 6,000 masl covering altogether 42.7% of the total glacier area in this mountain range (Figure 4.95). The glacier area above 6,500 masl is minimal and extremely sparse, consisting of less than 1% of the total glacier area.

Therefore, the glacier distribution in the Kunlun Shan shows that the eastern Kunlun Shan is more prominent in lower elevations at 5,000 – 5,500 masl compared to the western Kunlun Shan dominating at elevations ranges from 5,500 masl to 6,500 masl. The distribution highlights the eastern Kunlun Shan's significant glacier presence in the lower elevations than the western Kunlun Shan's extensive glacier coverage at higher elevations, illustrating the contrasting roles of each section across the mountain range.

The mean slope distribution of glaciers reveals additional insights into the differences between the western and eastern Kunlun Shan (Figure 4.96). In the eastern Kunlun Shan, the majority of glaciers are situated on slopes between 10° – 30°, comprising

FIGURE 4.93 **DISTRIBUTION OF GLACIER NUMBER IN EACH AREA SIZE CLASSES OF SUB-MOUNTAIN RANGES IN THE KUNLUN SHAN.**

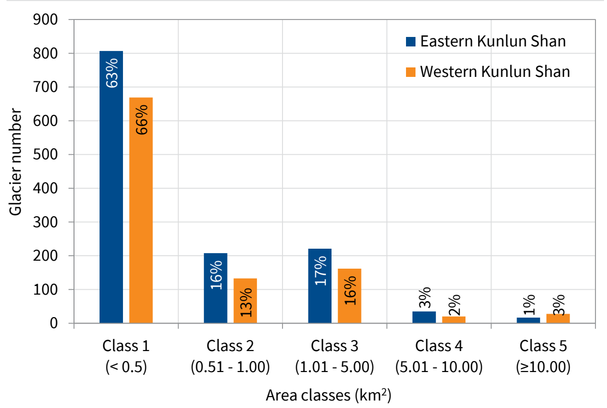


FIGURE 4.94 **DISTRIBUTION OF GLACIER AREA IN EACH AREA SIZE CLASSES OF SUB-MOUNTAIN RANGES OF THE KUNLUN SHAN.**

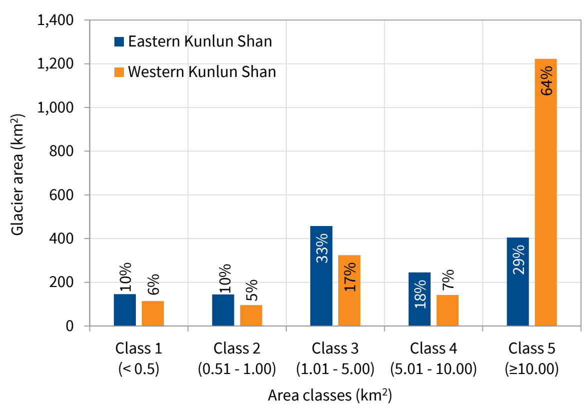


FIGURE 4.95 **GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN THE KUNLUN SHAN.**

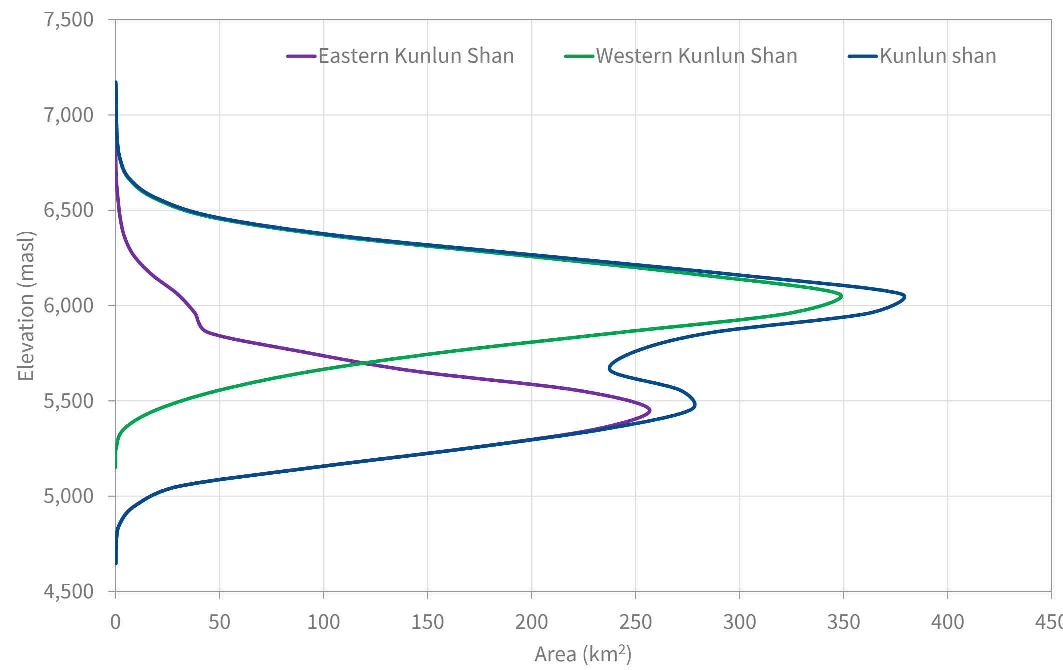


TABLE: 4.15 **GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN THE KUNLUN SHAN.**

Elevation range (masl)	Area (km²)			Area percentage		
	Eastern Kunlun Shan	Western Kunlun Shan	Kunlun Shan	Eastern Kunlun Shan	Western Kunlun Shan	Kunlun Shan
4,500 – 5,000	11.57		11.57	0.83		0.35
5,000 – 5,500	784.60	24.50	809.12	56.15	1.29	24.55
5,500 – 6,000	537.29	870.51	1,407.79	38.45	45.86	42.72
6,000 – 6,500	62.41	974.64	1,037.05	4.47	51.35	31.47
6,500 – 7,000	1.54	27.90	29.44	0.11	1.47	0.89
7,000 – 7,500		0.39	0.389		0.02	0.01
Total	1,397.40	1,897.94	3,295.36	100.00	100.0	100.0

88% of the total number and 73% of the glacier area. Glaciers on steeper slopes of 30° – 40° are sparse, covering just 2% of the area and holding only 1% of the ice reserves. Conversely, in the western Kunlun Shan, a significant proportion of the glacier area and ice reserves are found on flatter slopes of less than 10°, which account for 53% of the total area and 77% of the estimated ice reserves. The glaciers on these flatter slopes are larger and more voluminous compared to those on steeper inclines, which contribute minimally to both glacier area and ice reserves.

The disparity in glacier characteristics between the two ranges is particularly evident in the mean area per glacier across different slope classes. In the eastern Kunlun Shan, glaciers on less than 10° slopes, although few in number, are substantially larger, with a mean area of 11.05 km^2. In the western Kunlun Shan, glaciers in the same slope class are even larger, averaging 44.13 km^2 per glacier. This trend highlights the pronounced size differences in glaciers found on flatter terrain between the two ranges. In both ranges, glaciers on slopes of 20° – 30° dominate numerically, but the western Kunlun Shan has a more pronounced presence of large glaciers on flatter slopes, reflecting a different glaciological regime.

Overall, the comparative analysis underscores that the western Kunlun Shan, with its larger and more voluminous glaciers, contrasts sharply with the eastern Kunlun Shan, where glaciers are generally smaller and more numerous but cover a lesser total area and hold less ice. These differences in glacier distribution and characteristics are crucial for understanding the hydrological and climatic implications for each region.

The distribution of glaciers across different aspects in the eastern and western Kunlun Shan reveals contrasting patterns. In both subranges, the northern, northeastern, and northwestern aspects dominate in terms of glacier numbers (Figure 4.97). However, the southern and southeastern hold the majority of glacier areas and estimated ice reserves, especially in western Kunlun Shan. Additionally, glaciers on eastern and western aspects exhibit significant variation in area and estimated ice reserves between the two ranges, underscoring the influence of regional topographic and climatic conditions on glacier development and distribution.

In the eastern Kunlun Shan, the northern, northeastern, and northwestern aspects are the most populated with collectively consisting of about 63% of the total glacier number. Yet, they cover roughly 48% of the total area and contain approximately 35% of the total estimated ice reserves in this mountain range. Despite their numerical dominance, these glaciers are relatively smaller than southern, southeastern and eastern aspects, with lower mean area values, especially on the northeastern of 0.73 km^2 and northwestern aspect of 0.57 km^2. This suggests a relatively high concentration of smaller glaciers are distributed in these aspects.

FIGURE 4.96 GLACIER NUMBER DISTRIBUTION ACROSS MEAN SLOPE CLASSES IN THE SUB-MOUNTAIN RANGES OF THE KUNLUN SHAN.

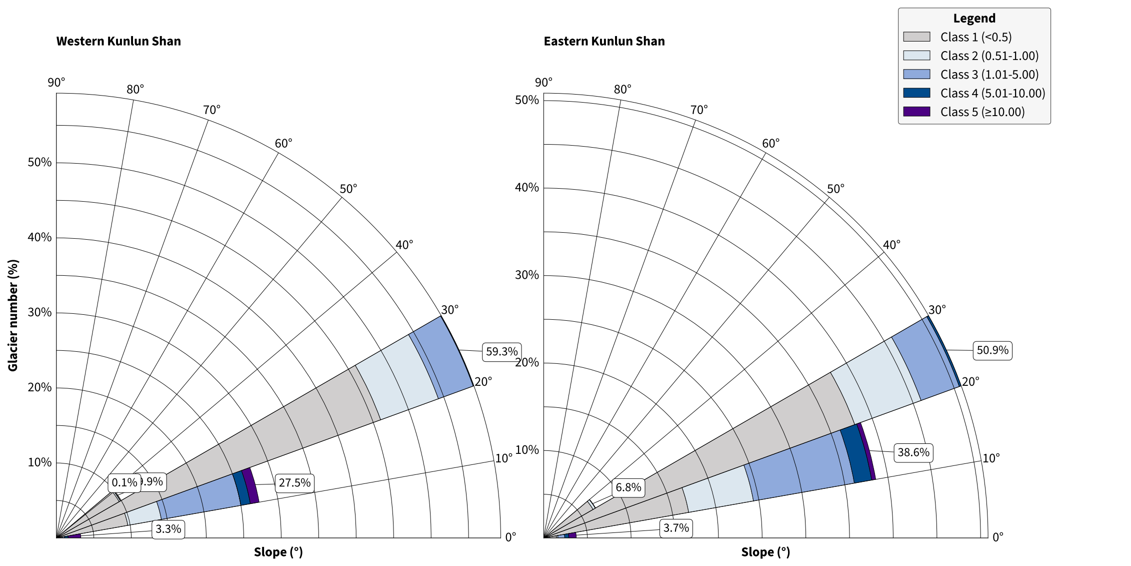
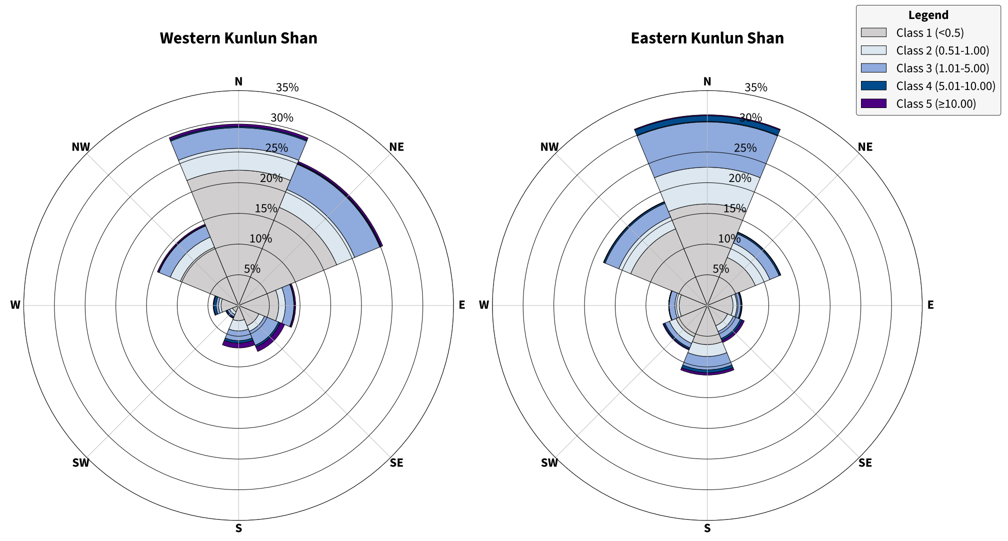


FIGURE 4.97 GLACIER NUMBER DISTRIBUTION ACROSS MEAN ASPECTS IN THE SUB-MOUNTAIN RANGES OF THE KUNLUN SHAN.



Conversely, the southern, southeastern, and southwestern aspects in the eastern Kunlun Shan consists of about 26% of total glaciers in this range, but they contribute significantly to a larger glacier area and estimated ice reserves – about 38% of total area and 43% of total estimated ice reserves in this mountain range. These glaciers are generally larger in size, particularly on the southeastern aspect, where the average glacier area exceeds 2.3 km^2. Among these aspects, the southern aspect, although more glacier-rich than the other two aspects, also exhibits substantial estimated ice reserves, emphasising the importance of south-facing slopes in ice storage despite their lesser extent in glacier number than in northern aspect.

In the western Kunlun Shan, the disparity between glacier number and area and estimated ice reserves is even more pronounced. The northern, northeastern and northwestern aspects account collectively a striking 70% of the total glacier number yet cover only 28% of the glacier area and contain just 13% of the estimated ice reserves. Comparatively, these glaciers are consistently smaller even than north-facing aspects in eastern Kunlun Shan, with average areas under 0.8 km^2, highlighting a concentration of smaller ice bodies with relatively low contributions to total ice reserves.

In contrast, south-facing glaciers in the western Kunlun Shan, though comprising only 17% of the total glaciers, are disproportionately large and voluminous. They occupy about 60% of the total glacier area and store 76% of total estimated ice reserves in this mountain range. The southern aspect alone holds the largest share of both area and estimated ice reserves of 32% and 43%, respectively, with an average glacier size exceeding 8.5 km^2. These findings reflect the dominance of massive glaciers in southern aspect of the western Kunlun Shan, likely influenced by specific topographic and climatic factors.

Regarding the eastern and western aspects, both eastern and western Kunlun Shan exhibit distinct patterns. In the eastern Kunlun Shan, eastern glaciers are slightly larger and more voluminous than their western aspect, with 6% of total glaciers covering 10% of total glacier area and holding 19% of total estimated ice reserves compared to slightly higher number glaciers (6%) but covering only 4% of the total glacier area and holding only 3% of the total estimated ice reserves in the western aspect. However, in western Kunlun Shan, the trend is reversed. The western glaciers, though fewer in number consisting only 4% of the total, are significantly larger in average area of 3.1 km^2 with covering 7% of the total glacier area and contain more estimated ice reserves than in the eastern aspect glaciers with containing 9% of total glacier and 5% of the total area. This emphasises that the western aspect have fewer glaciers but are dominated by larger glaciers in the western Kunlun Shan.

Decadal glacier changes from 1990 to 2020

The decadal changes of glaciers within this mountain range have been relatively modest compared to other mountain ranges in the HKH region. In 1990, there were 2,323 glaciers covering an area of 3,384.2 km^2. By 2020, the number of glaciers had slightly decreased to 2,300 and the total glacier area had reduced to 3,295.4 km^2. This data reveals a minor overall reduction in both glacier numbers and area.

Figure 4.98 illustrates the percentage changes in glacier number and area over each decade from 1990 to 2020 across two sub-mountain ranges. It shows that the eastern Kunlun Shan experienced higher percentages of change compared to the western Kunlun Shan. Specifically, the western Kunlun Shan demonstrated a consistent decline in both the number and area of glaciers throughout the decades, with an overall loss of approximately 2% in glacier number and 6% in glacier area over three decades.

In contrast, the eastern Kunlun Shan showed some fluctuations in glacier numbers and area. Early decades saw slight increases of 0.3% in glacier number and 0.14% in glacier area. However, in the later decades, both the number and area of glaciers began to decrease. Over the three decades, there was no significant change in glacier numbers, while the reduction in glacier area was minimal.

Across various glacier sizes in this mountain range, there has been a consistent decline in both the number and area of glaciers over the decades. However, the smallest glaciers of Class 1 (<0.5 km^2) exhibited a modest increase in numbers throughout all decades, with an overall rise of 1.2% in glacier number over three decades (Figure 4.99). Despite this, these glaciers experienced a notable decrease in area, with reductions of 1.8% from 1990 to 2000 to about 2% from 2010 to 2020, resulting in a total area reduction of 3.1% over thirty years. Conversely, medium and larger glaciers have shown decreases in both number and area. The most significant declines were observed in mid-sized glaciers of Class 3 (1.01 – 5.00 km^2), with a substantial 6.4% drop in number and a significant 5.6% reduction in area over three decades. Similarly, larger glaciers of Class 4 (5.01 – 10.00 km^2) also experienced reductions in both number and area, with a total area decrease of 1.6%. The largest glaciers, Class 5 (≥10.00 km^2), saw a reduction of two glaciers with a decrease of glacier area by 1.25% over three decades.

This trend varies between the eastern and western Kunlun Shan. The most pronounced reductions in both glacier number and area were observed in the Eastern Kunlun range compared to the Western Kunlun Shan. In Eastern Kunlun, the number of glaciers decreased by 2 to 26 across different size classes, with the highest loss in Class 3. The glacier area in this region also saw a reduction of 2.4% in Class 4 and 9% in class 3 over three decades.

In contrast, western Kunlun Shan experienced a reduction of four glaciers in Class 2 over three decades. This decrease was compensated by an increase in the number of glaciers in Class 1 (the smallest size category), suggesting that larger glaciers are shrinking into smaller ones. Glacier area in the western Kunlun Shan showed slight reductions, ranging from 0.1% in Class 4 to about 3% in Class 2, while Class 1 glaciers experienced a minor increase of 0.3% in area, attributed to the shrinkage of adjacent larger glaciers and addition to smaller glaciers size class.

FIGURE 4.98 DECADAL CHANGES OF GLACIER NUMBER (LEFT) AND AREA (RIGHT) IN THE SUB-MOUNTAIN RANGES OF THE KUNLUN SHAN.

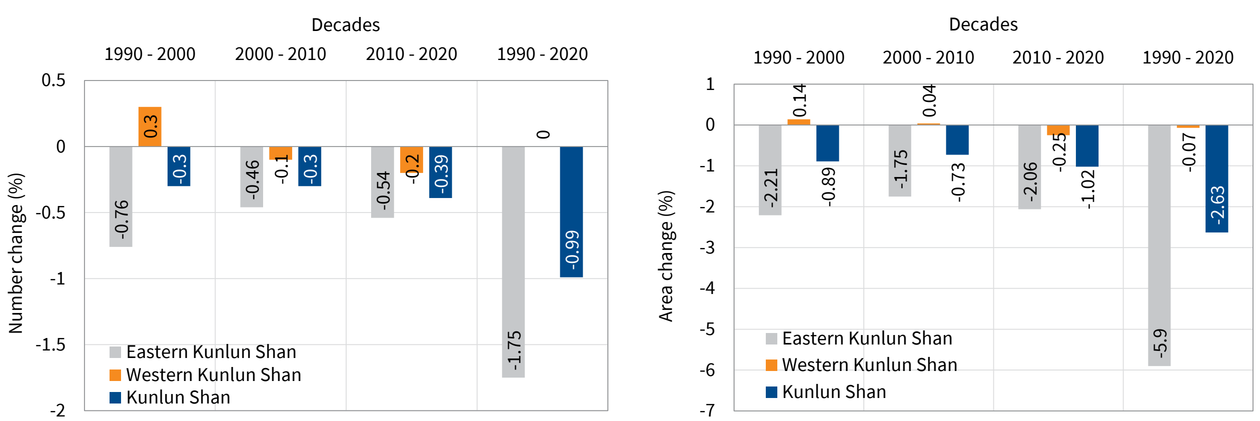
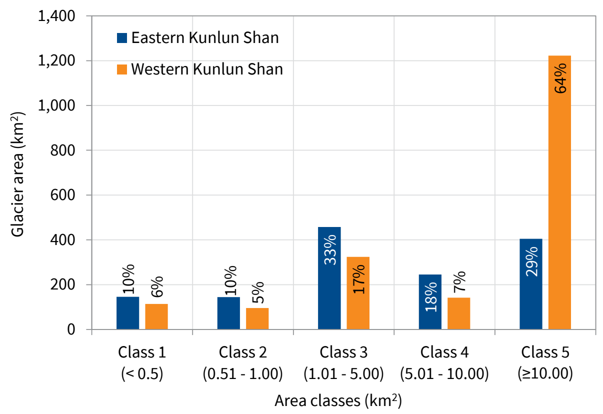


FIGURE 4.99 PERCENTAGE CHANGES OF GLACIER NUMBER AND AREA WITH RESPECT TO GLACIER SIZE CLASSES IN THE KUNLUN SHAN FROM 1990 – 2020.



The glacier changes across various elevation ranges indicate that the majority of glacier area reductions occurred in lower-elevation zones below 5,500 masl. Across the entire Kunlun Shan, the most significant area reduction in all decades is observed at elevation range from 5,000 masl to 5,500 masl with an overall reduction of 77.9 km^2 equivalent to about 9% over three decades (Table 4.16). The lower elevation below 5,000 masl also showed substantial decreases though there was a slight increase in glacier area in the most recent decade from 2010 to 2020 due to surging of one glacier in western Kunlun Shan. Higher elevation zones above 6,000 masl exhibited minor changes.

Comparatively eastern Kunlun Shan has experienced the larger glacier area reduction than in western Kunlun Shan. In eastern Kunlun Shan, the highest portion of area had reduced at elevation ranges of 5,000 to 5,500 masl in all three decades. At 4,500 – 5,000 masl range, it initially loss by 2 to 3 km^2 in each decade but showed notable increase by 2.2 km^2 in most recent decade from 2010 to 2020, resulting overall reduction by 15% of the glacier area in three decades. The increase in area in recent decades is due to the surging of a glacier in the region. The 5,000 – 5,500 masl zone consistently showed declines throughout the three decades. In the 5,500 – 6,000 masl range, changes were minimal. Higher elevation zones, such as 6,000 – 6,500 masl and 6,500 – 7,000 masl, exhibited negligible changes. Overall, the eastern Kunlun Shan saw a significant reduction of 5.9% in glacier areas from 1990 to 2020.

The western Kunlun Shan showed a contrasting trend, particularly in the 5,000 – 5,500 masl, where glacier area increased notably over three decades, despite a decline in the most recent decade. Other elevation ranges, including the 5,500 – 6,000 masl, experienced minimal reductions. The western Kunlun Shan overall showed a slight decrease of 0.1% in glacier area from 1990 to 2020, reflecting a balance between increases in lower elevations and minor reductions elsewhere.

Over the past three decades, glacier changes across different mean slope classes in the Kunlun Shan have revealed distinct spatial patterns between the eastern and western subregions, as well as across the entire range. In the eastern Kunlun Shan, there has been a marked decrease in both glacier number and area, most notably within the 20 – 30° slope class. This class experienced a loss of 25 glaciers, alongside a 7% reduction in glacier area, highlighting its vulnerability. Interestingly, while glaciers on steeper slopes have predominantly

TABLE 4.16 GLACIER AREA DISTRIBUTION AND PERCENTAGE CHANGES ACROSS ELEVATION RANGES IN THE KUNLUN SHAN FROM 1990 TO 2020.

Elevation ranges (masl)	Area (km²)				Area change (%)			
	1990	2000	2010	2020	1990 - 2000	2000 - 2010	2010 - 2020	1990 - 2020
4,500 – 5,000	13.64	10.95	9.36	11.57	-19.7	-14.5	23.6	-15.2
5,000 – 5,500	887.03	863.57	841.99	809.12	-2.6	-2.5	-3.9	-8.8
5,500 – 6,000	1,416.99	1,413.19	1,411.56	1,407.79	-0.3	-0.1	-0.3	-0.7
6,000 – 6,500	1,036.71	1,036.42	1,036.70	1,037.05	0.0	0.0	0.0	0.0
6,500 – 7,000	29.43	29.45	29.45	29.44	0.1	0.0	0.0	0.0
7,000 – 7,500	0.39	0.39	0.39	0.39	0.0	0.0	0.0	0.0
Total	**3,384.19**	**3,353.97**	**3,329.45**	**3,295.36**	**-0.9**	**-0.7**	**-1.0**	**-2.6**

retreated, the flatter slope class (<10°) recorded an increase of eight glaciers. This pattern suggests that glacier shrinkage and fragmentation alter the average slope characteristics of glaciers.

In contrast, the western Kunlun Shan exhibited comparatively stable glacier conditions during the same period. The only notable change was a small loss in the 30° – 40° slope class, with a reduction of four glaciers. However, the total number of glaciers remained unchanged overall. Importantly, this region recorded a modest increase in glacier area – particularly in the <10° slope class, which expanded by 6.57 km². This localised gain is attributed to glacier surging, a phenomenon where glacier movement accelerates, causing ice to flow and expand over downstream.

When considering the entire Kunlun Shan, the most significant glacier number losses occurred in the steeper slope classes (20°– 40°), with the greatest decline seen in the 20°– 30° category (Figure 4.100). Meanwhile, the most substantial area loss was observed in the 10°– 20° slope class, which lost over 32 km² area. Additional area reductions were also evident in the 20° – 30° and 30° – 40° classes, with consistent decline across all three decades. Though minor area gains occurred in the 10°– 20° slope class, these were primarily linked to glacier surging events as well as fragmentation and shrinkages larger glaciers alters the mean slope class rather than new glacier formation.

Overall, the data indicates a clear trend of glacier retreat and fragmentation across the Kunlun Shan, predominantly in steeper slope classes. These patterns are likely driven by ongoing climate change and associated environmental factors, with some localised variations due to dynamic glacial behaviours such as surging.

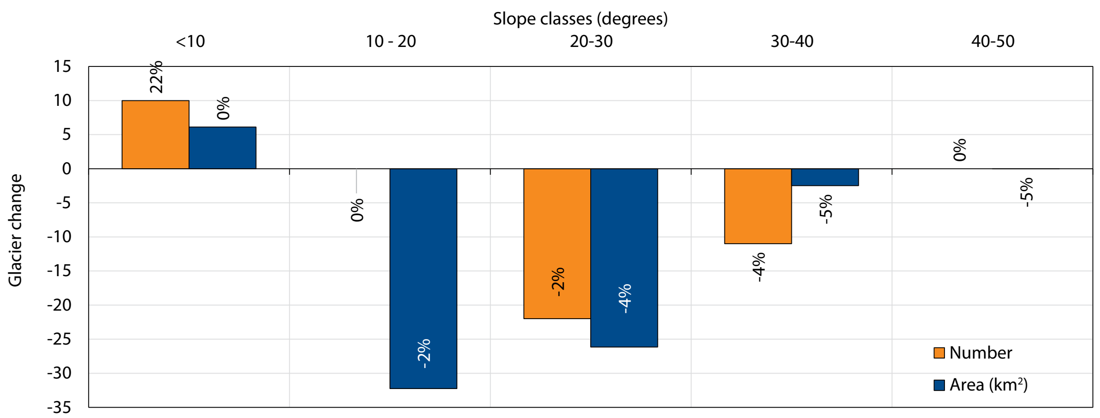
The comparative analysis of glacier changes across different mean aspect classes over the past three decades reveals distinct trends between the eastern and western Kunlun Shan. In the eastern Kunlun Shan, glacier retreat is most pronounced on the northern, northeastern, and northwestern aspects, which together lost approximately 51 km², accounting for about 27.5% of the total glacier area in these aspects. Glacier numbers showed variability, with a slight gain of one glacier in the northern aspect, but a decline of two and five glaciers in the northeastern and northwestern aspects, respectively. The southern, southeastern, and southwestern aspects also experienced retreat, with a collective area loss of around 16.2%, accompanied by consistent decreases in glacier number, particularly during the early decade from 1990 to 2000. The eastern and western aspects showed contrasting behaviours, with the eastern aspect undergoing more substantial losses in both glacier area and number compared to the relatively stable western aspect.

In contrast, the western Kunlun Shan demonstrated significantly more stable glacier conditions. The northern, northeastern, and northwestern aspects lost a modest 6 km², amounting to just 2.3% of the area lost, with only minor fluctuations in glacier number. The southern aspect showed a small loss of about 2.27 km² (−0.4%), with minimal change in glacier numbers. Interestingly, the southeastern and southwestern aspects exhibited slight gains in glacier area by 1.5% and 0.2% respectively, alongside the addition of one glacier each. These modest gains may be attributed to the alteration of mean aspects due to fragmentation and shrinkage. Similar minimal changes were observed in eastern and western aspects, reflecting a general stability in glacier extent across these aspects in the western Kunlun Shan.

When considering the entire Kunlun Shan, the northern, northeastern, and northwestern aspects experienced the most significant glacier loss, with an overall 15.5% reduction in area (Figure 4.101).

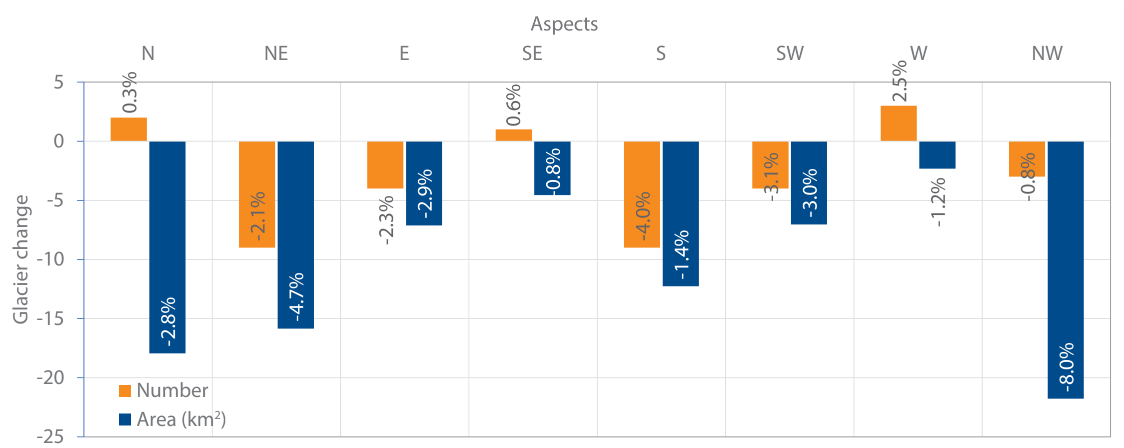
Although the northern aspect showed a slight increase in glacier number, it was not enough to offset the broader trend of retreat. Similarly, the southern, southeastern, and southwestern aspects lost approximately 5.1% of glacier area collectively over the same period, despite a minor gain in glacier number in the southeastern aspect. These findings emphasise a widespread but regionally variable retreat of glaciers, influenced by aspects of the glaciers, climatic conditions, and topographic characteristics across the Kunlun Shan.

FIGURE 4.100 CHANGES IN GLACIER NUMBER AND AREA ACROSS MEAN SLOPE CLASSES IN THE KUNLUN SHAN FROM 1990-2020.



THANA GLACIER, A SOUTHEAST-FACING BENCHMARK GLACIER IN BHUTAN'S CHAMKHAR VALLEY

FIGURE 4.101 CHANGES IN GLACIER NUMBER AND AREA ACROSS MEAN ASPECTS IN THE KUNLUN SHAN FROM 1990-2020.



TSHO ROLPA GLACIAL LAKE, ONE OF THE POTENTIALLY DANGEROUS GLACIAL LAKES IN ROLWALING VALLEY, NEPAL.

4.12 Pamir Mountain

The Pamir Mountain Range is a vast and rugged highland region situated in Central and South Asia. It lies at the convergence of several major mountain ranges, including the Tian Shan, Karakoram, Kunlun Shan, and Hindu Kush, forming a dramatic and interconnected network of peaks and valleys. The Pamirs span across parts of Tajikistan, Kyrgyzstan, Afghanistan, and China, with most of its area located within Tajikistan's Gorno-Badakhshan Autonomous Region. This region is part of the broader Pamir-Alay Mountain system, which links the Tian Shan, Karakoram, Kunlun, and Hindu Kush ranges.

The Pamirs border with the Hindu Kush mountains in the south, extending along Afghanistan's Wakhan Corridor in Badakhshan Province and touching the Chitral and Gilgit-Baltistan regions of Pakistan. It merges with the Tian Shan Mountains through Kyrgyzstan's Alay Valley in the north. The east part ranges toward China's Kongur Tagh, separated from the Kunlun Mountains by the Yarkand Valley. Within the Hindu Kush Himalaya (HKH) boundary, the Pamirs encompass the upper northern regions and the Wakhan Valley in northeastern Afghanistan.

This strategic location has made the Pamirs a historic crossroads for trade, culture, and migration, particularly along the ancient Silk Road. The region's towering peaks, deep valleys, and high-altitude plateaus create a unique and awe-inspiring landscape, while its isolation has preserved a rich cultural heritage and diverse ecosystems. Figure 4.102 shows the glacier distribution and spatial extent of the Pamir region within the HKH.

Glacier distribution in 2020

A total of 1,710 glaciers were mapped, covering an area of 952.65 km^2 and holding an estimated ice reserve of 50 km^3, based on 2020 Landsat imagery (Table 4.1). The glaciers in this mountain range account for 2.7% of the total number of glaciers and 1.7% of the total glacier area in the HKH region. Additionally, these glaciers cover approximately 2.4% of the total land area of the mountain range within the HKH.

FIGURE 4.102 MAP SHOWING THE GLACIER DISTRIBUTION AND EXTENT OF THE PAMIR MOUNTAIN RANGE IN THE HKH.

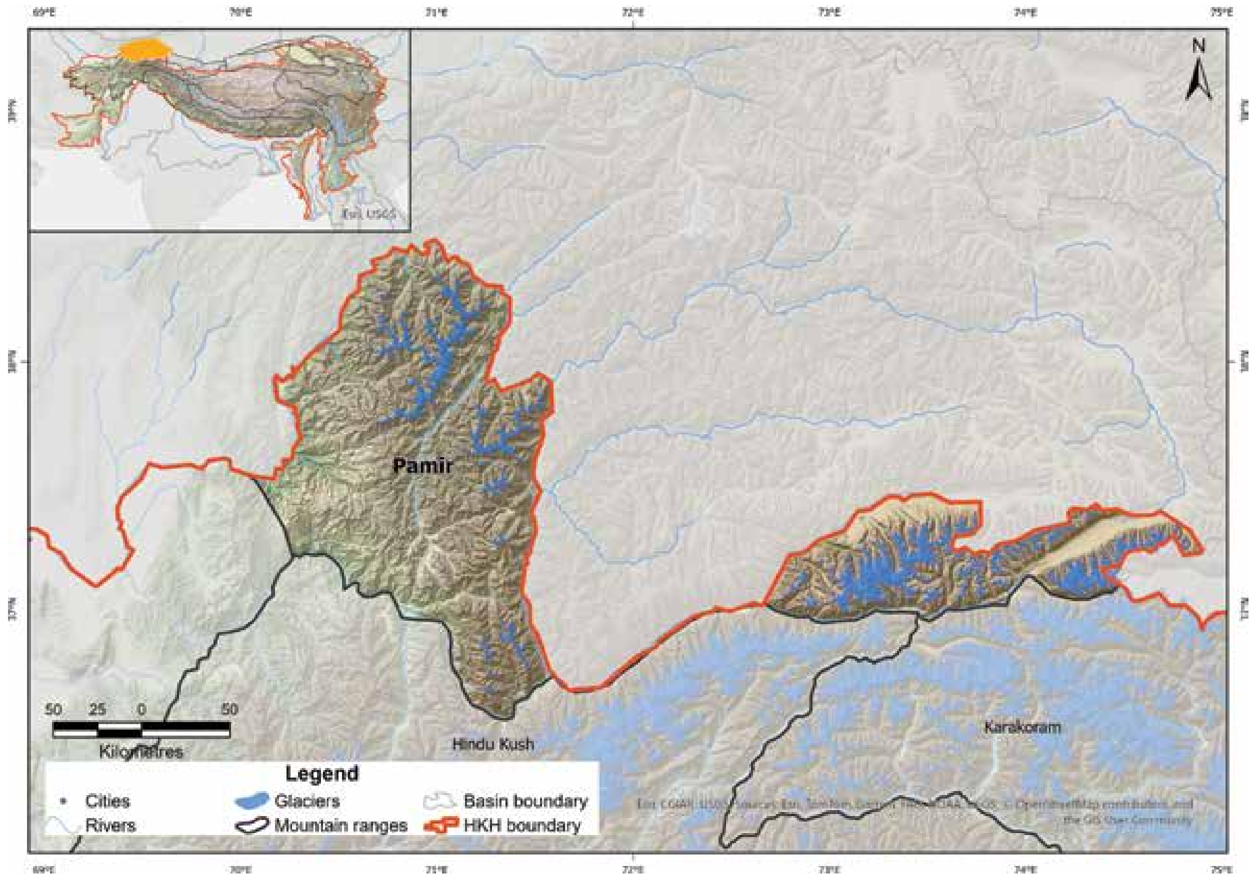
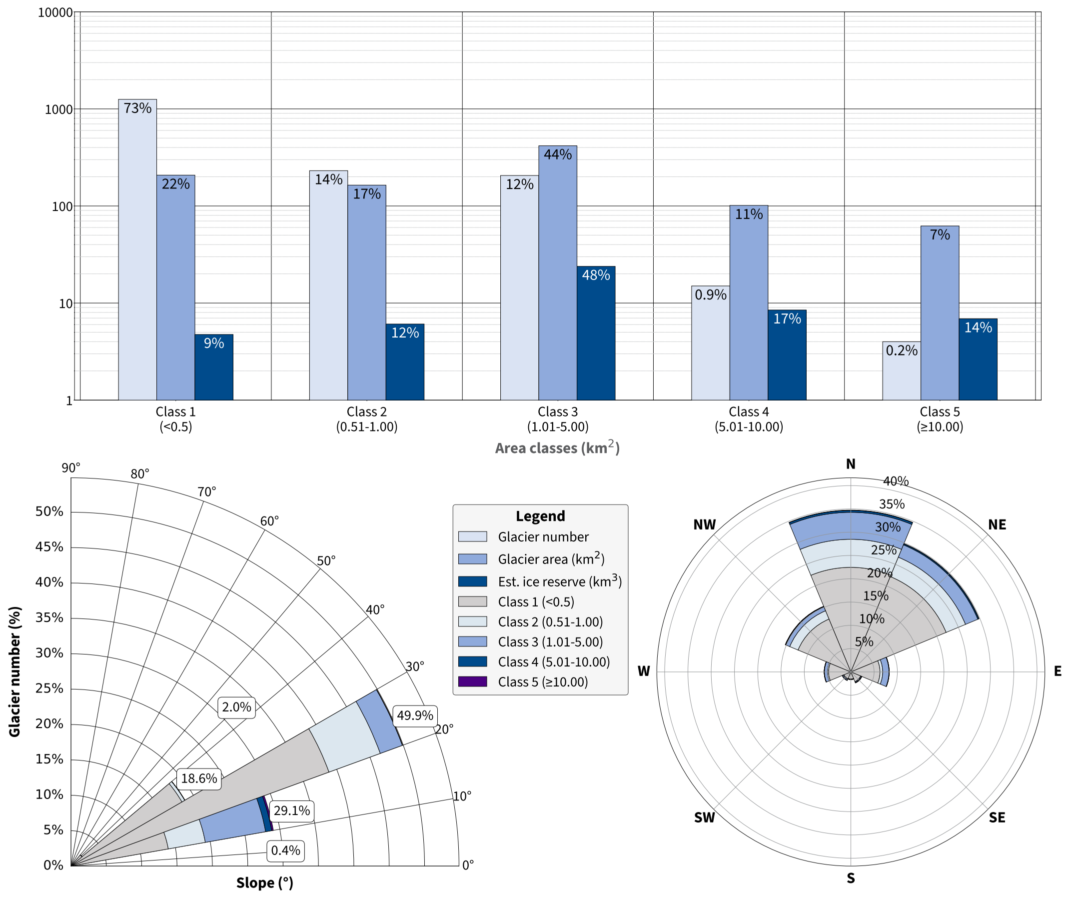


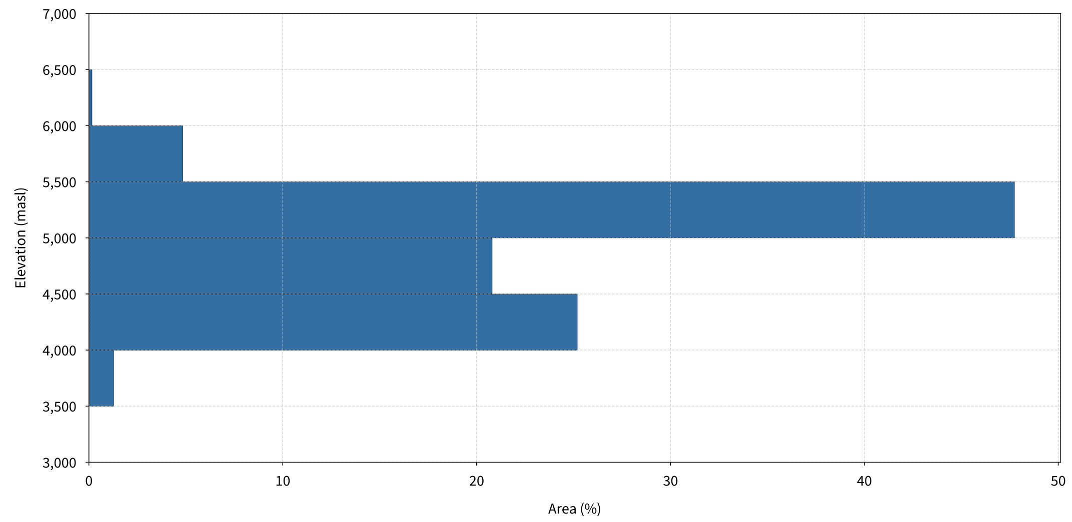
FIGURE 4.103 **GLACIER NUMBER, AREA AND ESTIMATED ICE RESERVES BY GLACIER AREA SIZE CLASSES** (TOP) **AND DISTRIBUTION OF GLACIER NUMBER (IN %) ACROSS MEAN SLOPES** (BOTTOM LEFT) **AND ASPECTS** (BOTTOM RIGHT) **IN THE PAMIR MOUNTAIN RANGE.**



The largest glacier of this mountain ranges is 17.8 km² located in the Wakhan valley of the northeastern part of Afghanistan. The glacier size distribution in the Pamir Mountain Range is characterised by a dominance of small glaciers (< 0.5 km²), which make up 73% of the total glacier number but cover only 22% of the glacierised area and hold 9% of the estimated ice reserves (Figure 4.103). Medium-sized glaciers (1.01 – 5.00 km²), though fewer in number (12% of the total), cover 44% of the area and contribute nearly half (48%) of the ice reserves, making them the most significant for regional water storage. Large (5.01 - 10.00 km²) and very large glaciers (≥10.00 km²) are rare, consisting only 14 and 4 glaciers, respectively, but they combine cover 18% of the area and hold 31% of the ice reserves. This right-skewed distribution highlights the critical role of medium and large glaciers in sustaining water resources, while small glaciers, despite their high numbers, are more vulnerable to climate change.

The glaciers in this mountain range span elevations from 3,550 masl to 6,300 masl, with the highest concentration found between 5,000 and 5,500 masl (Figure 4.104). Below 4,000 masl, only a small fraction of the glacier area is distributed. The majority of the glacier area lies above 4,000 masl, with each 500 m elevation band covering more than 20% of the total glacier area. The most glacierised zone is the 5,000 to 5,500 masl, accounting for approximately 48% of the total glacier area. These elevation ranges benefit from colder temperatures and significant snow accumulation, supporting large and stable glaciers, making it a critical contributor to the region's ice reserves and water resources. Above 5,000 masl, glacier area coverage decreases significantly due to steep terrain and limited snow accumulation area, which hinder glacier growth. Overall, the distribution highlights the importance of mid-elevation ranges (4,000 to 5,500 masl) for maintaining glacier health and sustaining water resources in the mountain range.

FIGURE 4.104 **GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN THE PAMIR MOUNTAIN RANGE.**



The mean slope classes of individual glaciers range up to 50°, clearly indicating that glaciers cannot sustain significant ice mass on steeper slopes. The majority of glaciers are found on moderate slopes, and as the slope increases, there is a marked decrease in the number, area, and estimated ice reserves of the glaciers (Figure 4.103).

Most notably, the mean slope class of 10° – 20° holds the largest share of glaciers (almost 24% of the total glaciers), contributing the most to both the glacier area covering 56% of the total and 69% of the total estimated ice reserves in the mountain range. The glaciers in this class are relatively large, with an average size of 1.3 km², making them the most important class in terms of area coverage and estimated ice reserves. The 20° – 30° slope class contains the highest number of glaciers, consisting of more than 52% of the total glaciers in the mountain ranges. This class covers about 37% of the glacier area coverages and a smaller portion (28%) of the total estimated ice reserves, indicating the smaller glacier size having 0.4 km² average glacier size. This suggests that their overall contribution to the estimated ice reserves is less than that of the glaciers with gentler mean slopes. The number, area and estimated ice reserves of the glaciers have significantly decreased in higher mean slopes. The 30° – 40° slope class represents a smaller number of glaciers (21.2%), but these glaciers are significantly smaller, with an average size of just 0.16 km². This class contributes very little to the overall glacier area (6%) and ice reserves (3%), highlighting that glaciers on steeper slopes are generally smaller and less significant in terms of total ice volume. Beyond 40°, in the 40°– 50° and higher slope classes, the number of glaciers is very low or nonexistent. The 40° – 50° class holds only 2.5% of the glaciers, and these glaciers are extremely small, contributing negligibly to both the glacier area and estimated ice reserves. Similarly, there are no glaciers in the 50° – 60° and >60° slope classes, emphasising that steeper slopes are unfavourable for sustaining glacier ice and snow accumulation.

The distribution of glaciers across mean slope classes verses area size classes reveals that smaller glaciers are more abundant and predominantly concentrated in moderate slope ranges of 10° – 30° (Figure 4.103). As glacier size increases, their numbers decline significantly, with only 4 glaciers in the ≥10.00 km² class, all located in the 10° – 20° slope class. In terms of area, the 10° – 20° and 20° – 30° slope classes dominate, contributing over 56% and 37% of the total glacier area in the mountain range, respectively. Moderate-sized glaciers (1 – 5 km²) cover more than 30% of the total glacier area, primarily in the 10° – 20° slope range, with an additional 13.3% in the 20° – 30° range. In contrast, smaller glaciers (<0.5 km²) account for 12.4% of the total area in the 20° – 30° slope class and about 4% in the 10° – 20° slope, indicating that smaller glaciers tend to have steeper mean slopes compared to larger glaciers. This pattern suggests a relationship between glacier size and slope, with smaller glaciers favouring steeper terrain and larger glaciers being more common in gentler slopes.

The distribution of glaciers across different aspect classes reveals a clear pattern, with the northern and northeastern aspects hosting the largest number of glaciers and covering the most significant areas (Figure 4.103). Together, the northern and northeastern aspects account for nearly 65% of the total glaciers, covering more than 69% of the total glacier area and approximately 67% of the total estimated ice reserves in the mountain ranges, with the northern aspect holding the largest share. Although glaciers on these slopes are relatively smaller in mean area than in southeastern, they represent a substantial portion of both the total glacier area and the estimated ice reserves in the region.

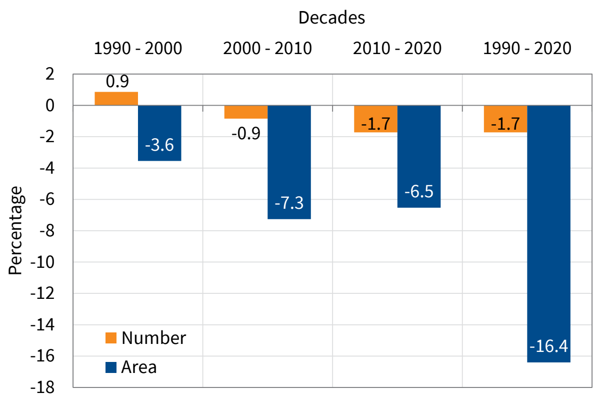
In contrast, the southeastern aspect has a much smaller number of glaciers, making up only 3% of the total. These glaciers are larger, with a higher mean area per glacier of 0.75 km^2, but they cover a minimal proportion of the total area and estimated ice reserves, contributing just 3% of the total glacier area and 6% of the total estimated ice reserves. Similarly, the southern aspect has the fewest glaciers, representing less than 2% of the total, and covering less than 1% of the total glacier area. This suggests that glaciers are rare and generally smaller on south-facing slopes.

Other aspects, including eastern, western, and northwestern, show a more moderate glacier presence. The eastern aspect comprises 8% of the total glacier number and 9% of the total area, while the western and northwestern aspects contribute 6% and 15% of the total number of glaciers, and 4% and 12% of the total glacier area, respectively. Glaciers on the western and northwestern aspects have a smaller mean area per glacier (0.43 km^2) compared to those on the northern and eastern aspects, indicating a distribution of smaller glaciers on these western and northwestern aspects.

Decadal glacier changes from 1990 to 2020

Over the past three decades, the glaciers in the Pamir Mountain Range within HKH boundary have shown a consistent pattern of decline in both number and area. Between 1990 and 2000, there was a slight increase in the number of glaciers by 0.86%, but this was followed by a small decrease of 0.85 % from 2000 to 2010. The most significant decline in glacier numbers occurred between 2010 and 2020, with a loss of 1.7%. Over the

FIGURE 4.105 **DECADAL CHANGES OF GLACIER NUMBER AND AREA IN THE PAMIR MOUNTAIN RANGE.**



entire 1990 to 2020 period, this mountain range lost 1.7%, indicating a steady reduction in the number of glaciers over time (Figure 4.105).

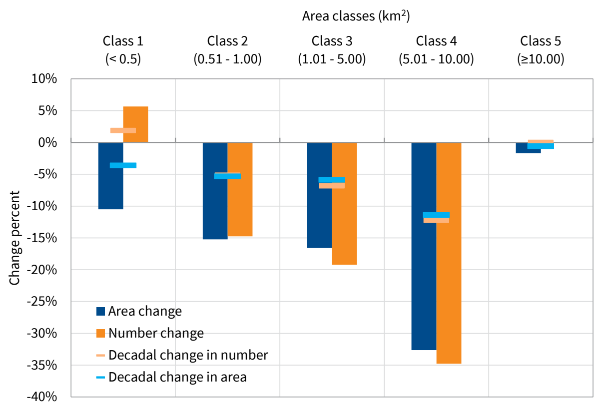
In terms of glacier area, the region experienced a modest decrease of -3.5 % between 1990 and 2000, which was followed by a more significant decline of -7.3 % from 2000 to 2010. The reduction continued between 2010 and 2020, albeit at a slightly slower pace, with -6.5% of glacier area lost. Overall, the 1990 to 2020 period saw a total loss of -16.4% of glacier area, marking a clear trend of shrinking glaciers in the region.

These decadal changes reflect a gradual and ongoing retreat of glaciers in the Pamir Mountain Range, with the most notable changes occurring in the most recent decade. The data highlights the broader impact of climate change on the glaciers of this region, which are continuing to shrink and contribute to broader environmental shifts.

The analysis of changes across different size classes reveals those mid-sized glaciers in Class 3 (1 – 5 km^2) experienced the most significant reductions, both in number and area. Over three decades, this class lost 49 glaciers and nearly 17% of its area. The rate of loss has consistently accelerated, with the highest percentage of reductions occurring in the most recent decade, from 2010 to 2020.

The second largest area loss was observed in Class 4 glaciers (5 – 10 km^2), which lost nearly one-third of their total area between 1990 and 2020, alongside the disappearance of 8 glaciers. However, this class shows the highest percentage loss in both number and area (Figure 4.106). This substantial area loss is partly due to the reduction in glacier numbers, as shrinking glaciers are reclassified into smaller size class.

FIGURE 4.106 **CHANGE IN GLACIER NUMBER AND AREA ACROSS GLACIER SIZE CLASSES (INCLUDING MEAN DECADAL CHANGE RATE) IN THE PAMIR MOUNTAIN RANGE FROM 1990-2020.**



Smaller glaciers in Class 1 (< 0.5 km^2) and Class 2 (0.51 – 1.00 km^2) also showed significant area losses, with reductions of approximately 11% and 15%, respectively, over the three decades. However, the number of glaciers in Class 1 increased by about 6% over the three decades. This indicates that the fragmentation and shrinkage of larger glaciers have led to their reclassification into smaller size class, while some smaller glaciers have either disappeared or shrunk below the threshold of 0.02 km^2. Across all size categories, the largest losses occurred in the most recent decade, from 2010 to 2020, compared to previous decades. Over the past three decades, glaciers in this mountain range have been mapped at elevations ranging from 3,430 masl to 6,230 masl. During this period, the lowest elevation of the glacier has shifted upward by 116 metres, rising from 3,438 masl in 1990 to 3,554 masl in 2020. The rate of this upward shift has ranged between 30 and 40 metres per decade, with a notably higher rate observed in the most recent decades. This upward shift was also evidenced by the complete area loss by 2010 below 3,500 masl.

The glacier area distribution across different elevation ranges in the mountain ranges reveals that the most significant reductions in glacier area occurred at the 4,000 to 4,500 masl range, where glaciers shrank by more than 23% over three decades (Figure 4.107 and Table 4.17). This zone experienced a steady rate of retreat, with a relatively uniform loss of around 24 km^2 per decade. The 3,500 to 4,000 masl range also showed a notable decline, with a total reduction of 16.3 km^2, representing over 57% of the total glacier area in this range over the same period.

In the 4,500 to 5,000 masl range, the retreat pattern fluctuated, with the most substantial loss occurring between 2000 and 2010, when approximately 11.7% of the glacier area was lost. The retreat slowed in the 2010 to 2020 period, but the total reduction over the three decades still amounted to around 23%, similar to the 4,000 – 4,500 masl range.

At higher elevations, particularly above 5,000 masl, the changes in glacier area were more modest. The 5,500 – 6,000 masl range experienced a slight increase in glacier area during the 1990s, followed by a small but consistent retreat in subsequent decades, resulting in a total loss of about 5% by 2020. The 6,000 – 6,500 masl range showed the least change, with nearly no retreat and a total loss of only 2.7%, suggesting that glaciers at these higher altitudes have remained relatively stable.

Overall, glaciers in the range have retreated significantly, particularly below 5,000 masl, where rising temperatures and other environmental factors seem to have a more pronounced impact. In contrast, higher elevation appears more resilient, showing only minimal retreat or no significant changes at all.

In terms of mean slope classes, the most dramatic declines in both glacier number and area occurred in the 20° – 30° slope class, which had a drastic reduction of 8% in glacier number and 17% in glacier area over the three decades (Figure 4.108). The second most significant changes were observed in the 10° – 20° slope class. Despite considerable reductions in glacier area, this class experienced a steady increase in the number of glaciers each decade, with a 2% to 4% increase per decade, although the 2000 – 2010 period showed a slower growth rate. The glacier area reduction remained relatively consistent at around 3% per decade, leading to a total decrease of 5% from 1990 to 2020.

In contrast, the 30° – 40° slope class exhibited more fluctuation in glacier numbers. Initially, there was a small gain of 6 glaciers between 1990 and 2000, followed by a loss of 12 glaciers from 2000 to 2010, and then gain of 1 glacier from 2010 to 2020, resulting in an overall loss of 5 glaciers over the three decades. In terms of area, this class consistently retreated throughout each decade, with a total area reduction of 13% over the 30-year period. However, the retreat rate in this class was smaller compared to the 20° – 30° slope class.

FIGURE 4.107 DISTRIBUTION AND CHANGES IN GLACIER AREA ACROSS ELEVATION RANGES IN THE PAMIR MOUNTAIN RANGE FROM 1990 TO 2020.

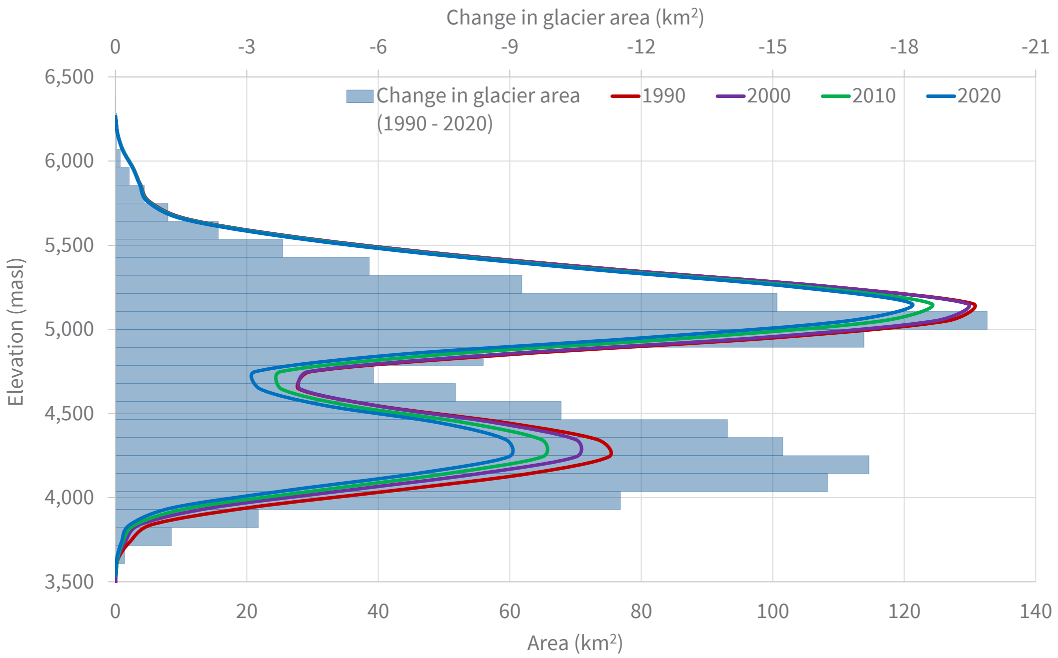


TABLE : 4.17 GLACIER AREA DISTRIBUTION AND PERCENTAGE CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE PAMIR MOUNTAIN RANGE.

Elevation Range (masl)	Area (km²)				Decadal change in area (%)				
	1990	2000	2010	2020	1990-2000	2000-2010	2010-2020	1990-2020	Mean decadal change
3,000 – 3,500	0.02	0.01			-66.7				-66.7
3,500 – 4,000	28.43	20.36	16.12	12.11	-28.4	-20.8	-24.8	-57.4	-24.7
4,000 – 4,500	312.77	287.94	263.94	239.95	-7.9	-8.3	-9.1	-23.3	-8.4
4,500 – 5,000	257.17	252.25	222.82	198.15	-1.9	-11.7	-11.1	-23	-8.2
5,000 – 5,500	491.12	488.27	467.40	454.78	-0.6	-4.3	-2.7	-7.4	-2.5
5,500 – 6,000	48.47	48.67	47.40	46.16	0.4	-2.6	-2.6	-4.8	-1.6
6,000 – 6,500	1.55	1.59	1.59	1.51	2.7	-0.1	-5.1	-2.7	-0.8
Total	**1,139.54**	**1,099.08**	**1,019.26**	**952.65**	**-3.6**	**-7.3**	**-6.5**	**-16.4**	**-5.8**

FIGURE 4.108 CHANGES IN GLACIER NUMBER AND AREA ACROSS MEAN SLOPE CLASSES IN THE PAMIR MOUNTAIN RANGE FROM 1990 -2020.

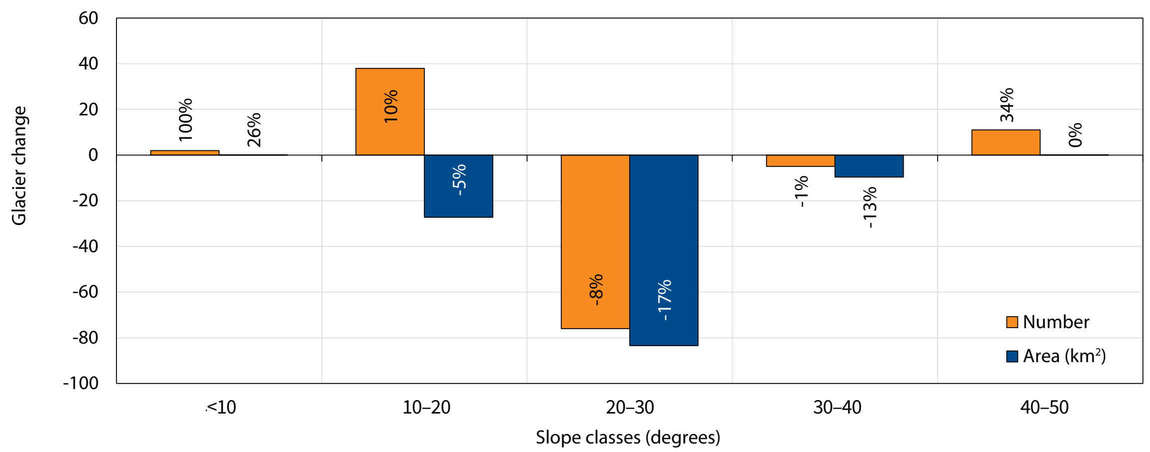
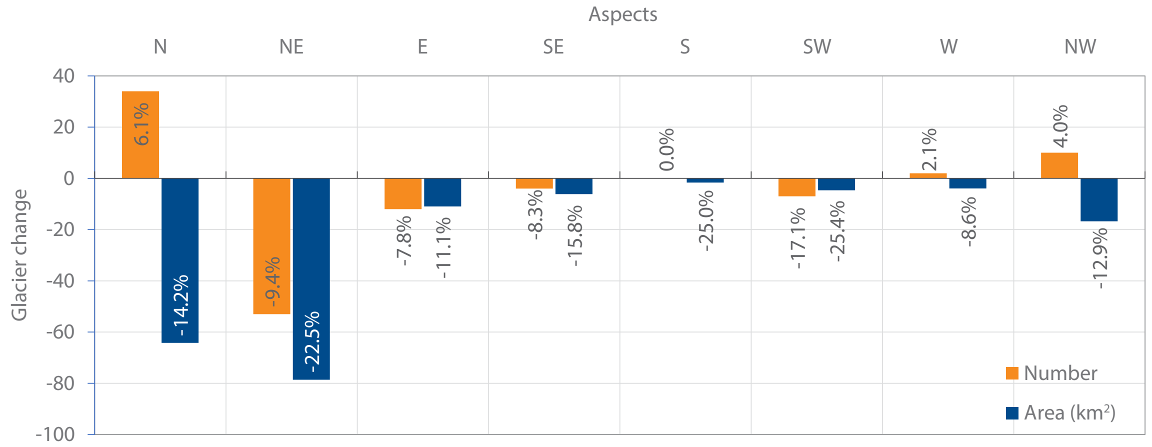


FIGURE 4.109 CHANGE IN GLACIER NUMBER AND AREA ACROSS MEAN ASPECTS THE PAMIR MOUNTAIN RANGE FROM 1990 TO 2020.



In addition, the gentle slope class of <10° showed a slight increase in both glacier numbers and area, particularly in the most recent decade. These changes suggest that the loss of glacier ice has mainly occurred in the steeper portions of glaciers, which has led to shifts in the mean slope. As a result, some glaciers have moved into new slope class, contributing to an increase in the number of glaciers in certain classes. At the same time, losses in the glacier area have been observed across all slope classes.

Glaciers on the northern, northeastern, and northwestern aspects in this mountain range displayed mixed but notable trends over the past three decades. The northeastern aspect experienced the most significant retreat, with a glacier area loss of approximately 78.6 km² (–22.5%) and a net loss of 53 glaciers, indicating extensive retreat and shrinkage (Figure 4.109). The northern aspect also showed a substantial area loss of 14.2%, yet it paradoxically saw a net increase of 34 glaciers, suggesting fragmentation of larger glaciers into smaller ones. A similar pattern emerged in the northwestern aspect, which lost nearly 13% of its area, while gaining 10 glaciers overall. Notably, the northwestern showed growth in both glacier number and area during the 1990 – 2000 period, but experienced consistent declines in subsequent decades. In contrast, the northern aspect exhibited a steady increase in glacier numbers across all decades, accompanied by a consistent decrease in area, reinforcing the idea of ongoing fragmentation. These trends collectively suggest that continued glacier shrinkage leads to the fragmentation of larger glaciers and potential shifts in their mean aspects due to changes in size and shape.

In contrast, the southern, southeastern, and southwestern aspects demonstrated relatively stable conditions over the past three decades, with only minor changes in both glacier number and area. Among these, the southern aspect experienced the least glacier area loss, amounting to just 1.6 km², and no change in glacier numbers, indicating remarkable stability. In contrast, the southeastern and southwestern aspects recorded slight decreases in glacier numbers, losing 4 and 7 glaciers, respectively, over the same period. In terms of area, the southeastern aspect lost 6.2 km², while the southwestern showed a slightly smaller reduction of 4.7 km². Interestingly, despite the relatively low absolute area loss, all three aspects recorded higher percentage losses than all north facing aspects, suggesting that even small absolute losses are significant relative to their total glacierised area.

The eastern and western aspects exhibited relatively more moderate changes compared to the north and south facing aspects. The eastern aspect experienced a total glacier area loss of 11.0 km², corresponding to an 11.1% reduction, along with a decline of 12 glaciers. The most substantial area retreat on this aspect occurred during the 2000 – 2010 decade. In contrast, the western aspect showed a smaller area reduction of 8.6% over the three decades and even recorded an increase of 2 glaciers.

DURING THE FIELD EXPEDITION IN RIKHA SAMBA GLACIER, MUSTANG, NEPAL.

SECTION V

Status and decadal changes of glacier in the major river basins of the HKH Region

Glaciers in the HKH region contribute to 10 major river basins and two interior basins in the Tibetan Plateau, which collectively supports lives and livelihood of millions of people living in these river basins. For a comprehensive understanding of glacier distribution and changes over the HKH region, it has been analysed based on these 10 major river basins and two interior basins in Tibetan plateau.

The Figure 5.1 and Table 5.1 provides a comprehensive overview of the river basins within the HKH region, highlighting their geographic extent, elevation ranges and area coverages including the statistics of glaciers mapped from 2020 Landsat imagery. Each river basin displays distinct geographical features and varying elevation profiles, reflecting diverse geography and cryospheric dynamics across the HKH region. The Qinghai-Tibetan and Yangtze River basins are the largest, covering over 15% and 13% of the total HKH area, respectively. In comparison, the Indus, Ganges, and Brahmaputra River basins are known for their wide elevation ranges, stretching from below 100 masl to over 8,000 masl, and accounting for more than 13%, 6%, and 10% of the HKH area. The Tarim basin, despite covering less than 1% of the region, has one of the highest elevation ranges, extending from 3,200 masl to 7,952 masl. Smaller river basins such as the Amu Darya, Irrawaddy, and Mekong cover less than 5% of the region but still contain substantial glaciers and snow cover, playing a vital role in regional hydrology. The diversity in size and elevation across these basins highlights the complex and varied landscape of the HKH region.

The glacier distribution across the basins in the HKH region reveals a marked variability in terms of concentration and coverage (Figure 5.2). In the southern and western parts, basins like the Indus, Ganges, and Brahmaputra River basins host dense clusters of glaciers due to favourable geographic and climatic conditions, such as high altitudes, expansive mountainous terrain, and strong monsoon and winter effects. The Indus River basin stands out with the highest concentration, holding 41% of the total glaciers and covering 44% of the glacier area in the HKH region. Its glaciers range from 2,329 to 8,570 masl elevation, indicating the lowest elevation extent of the glaciers in the region. It also hosts the largest glacier in the region, covering 1,007.86 km². Similarly, the Brahmaputra and Ganges basins also contribute significantly, with glaciers comprising 20% and 13% of the region's total glaciers, and covering 17% and 13% of the glacier area, respectively.

In contrast, basins in the eastern and northern parts of the region, such as the Irrawaddy, Salween, Mekong, Yangtze, and Yellow River basins have minimal glacier coverage and contribute less to the total glacier area. Among these, the Salween and Yangtze River basins hold over 3% of the region's glaciers and cover 2% and 3% of the glacier area, respectively. Other basins, including Mekong and Yellow, contain less than 1% of the glaciers and

FIGURE 5.1 MAP SHOWING GLACIER DISTRIBUTION ACROSS 10 MAJOR RIVER BASINS AND TWO INTERIOR BASINS IN THE HKH REGION.

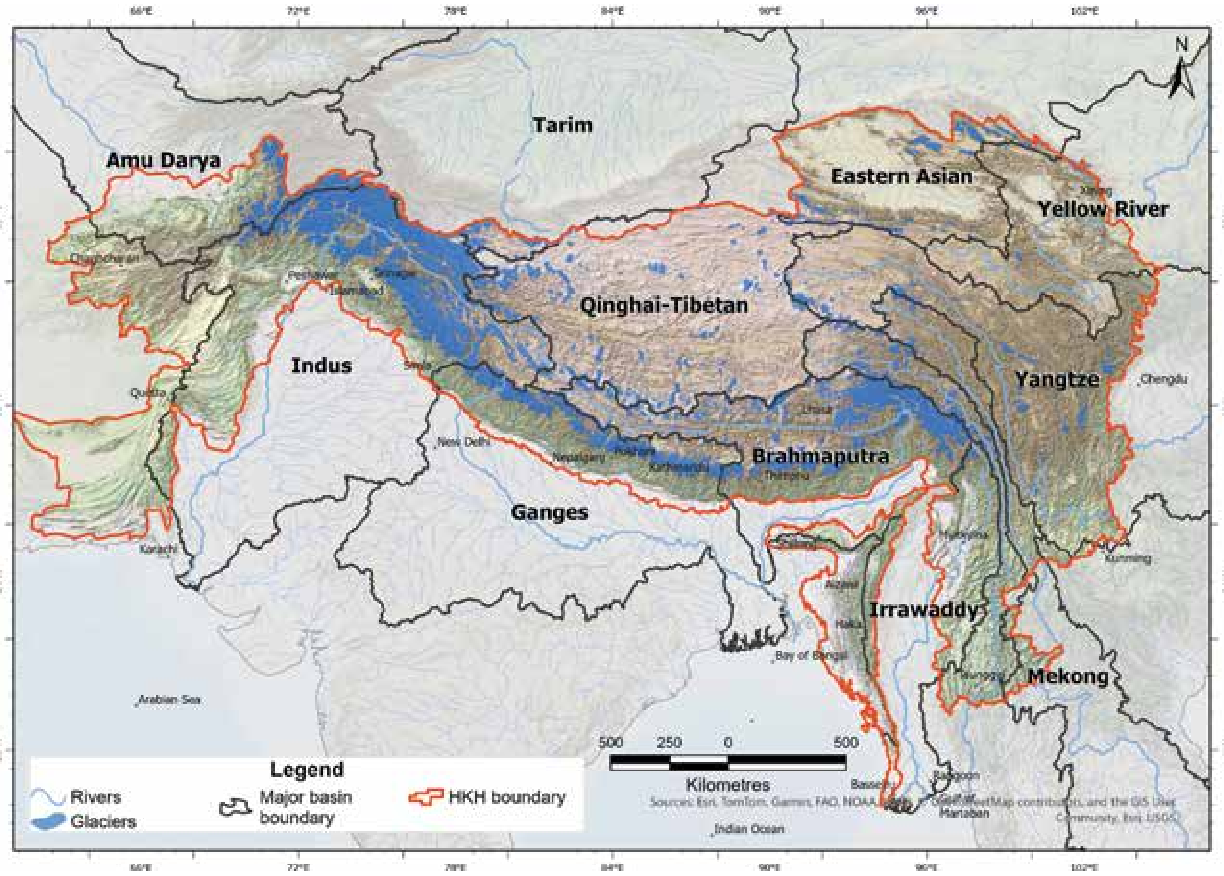
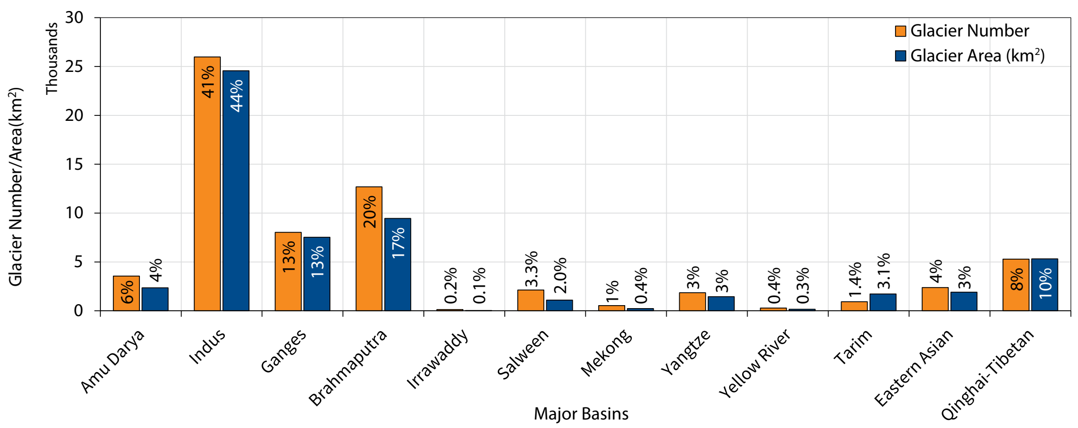


FIGURE 5.2 GLACIER NUMBER AND AREA DISTRIBUTION ACROSS 10 MAJOR RIVER BASINS AND TWO INTERIOR BASINS IN THE HKH REGION.



contribute a very small proportion of the glacier area, ranging from 0.1% to 0.4%. The two interior River basins – Eastern Asian and Qinghai-Tibetan, cover significant portions of glacier area and contain a substantial number of glaciers, further contributing to the diversity of glacier distribution across the HKH region.

The decadal glacier changes between 1990 and 2020, as shown in the Table 5.2 and Figure 5.3, reveal significant regional variations in glacier area loss and retreat across different river basins. Most basins experienced a steady decline, although some basins showed more dramatic reductions, particularly in recent decades.

TABLE 5.1 GLACIER DISTRIBUTION AND TOPOGRAPHIC CHARACTERISTICS OF THE MAJOR RIVER BASINS IN THE HINDU KUSH HIMALAYA (HKH).

River basins	Total area (km²) with in HKH	Spatial extent within HKH (Longitude/ Latitude)- (degrees)	Elevation ranges (masl)	Glacier (2020)						
				Number		Area		Elevation Range (masl)	Largest glacier (km²)	Average size (km²)
				count	percent	km²	percent			
Amu Darya	166,686	64.0297E - 74.901 E 34.483N - 38.488N	250 – 7,160	3,551	5.6	2,348.34	4.2	3,224 – 7,191	39.12	0.66
Indus	555,450	66.160E - 81.824E 26.710N - 37.066N	62 – 8,054	25,986	40.8	24,571.19	44.0	2,329 – 8,570	1,007.86	0.95
Ganges	244,806	77.054E - 88.948E 26.357N - 31.457N	60 – 8,848	8,029	12.6	7,518.52	13.5	3,436 – 8,811	125.8	0.94
Brahmaputra	432,480	82.016E - 97.775E 25.102N - 31.279N	0 – 8,440	12,687	19.9	9,450.32	16.9	2,607 – 8,091	166.74	0.74
Irrawaddy	202,745	93.474E - 98.876E 15.958E - 28.772E	0 – 5,709	127	0.2	32.91	0.1	3,990 – 5,691	2.73	0.26
Salween	211,122	91.276E - 100.043E 19.290N - 32.767N	120 – 6,930	2,122	3.3	1,091.25	2.0	3,519 – 6,859	38.28	0.51
Mekong	138,876	93.859E - 101.171E 19.815N - 33.826N	350 – 6,145	540	0.8	233.40	0.4	2,979 – 6,121	13.10	0.43
Yangtze	565,102	90.544E - 105.045E 24.831N - 35.805N	330 – 7,145	1,854	2.9	1,437.50	2.6	3,414 – 7,145	50.63	0.78
Yellow River	250,540	95.890E - 105.043E 32.159N - 38.330N	1,638 – 6,254	283	0.	156.26	0.3	4,097 – 6,254	20.02	0.55
Tarim	26,729	74.468E - 87.346E 34.633N - 37.284N	3,240 – 7,952	920	1.4	1,726.40	3.1	5,195 – 7,126	234.51	1.88
Eastern Asian	280,527	82.331E - 101.156E 34.686N - 39.319N	2,400 – 6,722	2,377	3.7	1,906.34	3.4	3,929 – 6,804	95.04	0.80
Qinghai-Tibetan	629,463	78.298E - 93.158E 29.662N - 36.470N	4,150 – 6,951	5,285	8.3	5,309.59	9.5	4,964 – 6,924	50.84	1.00
HKH	4,192,446	60.853E - 105.045E 15.957N - 39.319N	0 – 8,848	63,761	100	55,782.04	100	2,329 – 8,811	1,007.86	0.87

HOPER GLACIER IN THE NAGAR VALLEY OF GILGIT-BALTISTAN, PAKISTAN, NESTLED WITHIN THE KARAKORAM RANGE.

The Salween, Yangtze, and Yellow River basins were the most affected, with glacier area losses exceeding 22%. The Salween Basin experienced the highest retreat, with nearly 33% of its glacier area lost over the past three decades. These basins underwent rapid glacier loss, especially between 2000 and 2010, driven by climate change and rising temperatures. In contrast, the Tarim River basin displayed more variability, with slight increase in glacier area (0.1% per decade) during the 1990 – 2000 and 2000 – 2010 periods. However, overall, it experienced a small decrease of 0.1%, with a noticeable reduction of 0.22% between 2010 and 2020, indicating regional fluctuations in glacier behaviour.

Other basins, such as the Amu Darya, Ganges, Brahmaputra, and Irrawaddy River basins, also showed substantial reductions in glacier area, with losses of 15.2%, 20.9%, 15.9%, and 19.2%, respectively. The most substantial declines occurred between 2010 and 2020, highlighting a period of accelerated glacier retreat. The Indus River basin exhibited more stable trends, with about 6% of glacier area lost over three decades. The decrease of glacier area in this basin was relatively consistent, with around 2% lost per decade and slightly higher loss of 2.4% in recent decades of 2010 – 2020.

The two interior basins – Qinghai-Tibetan and Eastern Asian, as well as Mekong River basins displayed the relatively moderate glacier retreat, with loss of 6.3%, 9% and 11% over three decades. This indicates a relatively slower retreat rate in these basins.

Overall, glacier retreat is a widespread phenomenon across all river basins, with an 11.6% loss in the entire HKH region over three decades. This trend has accelerated, particularly in recent years. Loss percentages are more significant in the eastern part of the region, while the southern basins, especially the Indus, Ganges, and Brahmaputra River basins, have experienced the highest volumetric and absolute area loss. Detailed changes in each basin and its sub-basins are illustrated in the following sections. These findings highlight the urgent need for targeted climate adaptation and risk mitigation strategies, especially in high-mountain regions that rely on glacier meltwater for water supply and agriculture.

FIGURE 5.3 **GLACIER NUMBER AND AREA CHANGE PERCENTAGE IN THE 10 MAJOR RIVER BASINS AND TWO INTERIOR BASINS OVER THREE DECADES IN THE HKH REGION.**

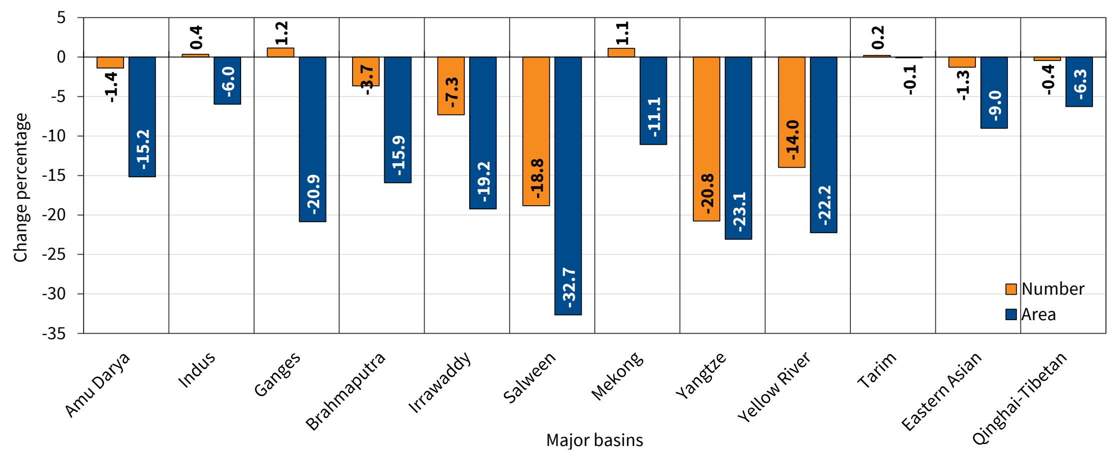


TABLE 5.2 **DECADAL CHANGES IN GLACIER NUMBER AND AREA ACROSS MAJOR RIVER BASINS IN THE HINDU KUSH HIMALAYA (1990–2020).**

SN	River basins	Glacier number				Glacier area (km^2)				Percentage change in number(area)			
		1990	2000	2010	2020	1990	2000	2010	2020	1990 – 2000	2000 – 2010	2010 – 2020	1990 – 2020
1.	Amu Darya	3,601	3,603	3,578	3,551	2,767.99	2,709.88	2,578.18	2,348.34	0.06 (-2.1)	-0.7 (-4.9)	-0.8 (-8.9)	-1.39 (-15.2)
2.	Indus	25,893	25,905	26,079	25,986	26,130.26	25,713.63	25,166.12	24,571.19	0.05 (-1.6)	0.7 (-2.1)	-0.4 (-2.4)	0.4 (-6.0)
3.	Ganges	7,938	8,149	8,053	8,029	9,500.52	8,873.24	8,230.50	7,518.52	2.7 (-6.6)	-1.2 (-7.2)	-0.3 (-8.7)	1.1 (-20.9)
4.	Brahmaputra	13,168	13,317	13,197	12,687	11,241.63	10,803.51	10,266.13	9,450.32	1.1 (-3.9)	-0.9 (-5.0)	-3.9 (-7.9)	-3.7 (-15.9)
5.	Irrawaddy	137	137	128	127	40.76	40.33	36.73	32.91	0.0 (-1.05)	-6.6 (-8.9)	-0.8 (-10.4)	-7.3 (-19.2)
6.	Salween	2,614	2,586	2,330	2,122	1,620.61	1,436.09	1,237.88	1,091.25	-1.1 (-11.4)	-9.9 (-13.8)	-8.9 (-11.8)	-18.8 (-32.7)
7.	Mekong	534	538	541	540	262.46	254.60	244.97	233.40	0.7 (-3.0)	0.6 (-3.8)	-0.2 (-4.7)	1.1 (-11.1)
8.	Yangtze	2,340	2,213	2,061	1,854	1,868.71	1,749.81	1,601.52	1,437.50	-5.4 (-6.4)	-6.9 (-8.5)	-10.0 (-10.2)	-20.8 (-23.1)
9.	Yellow River	329	322	293	283	200.96	179.23	162.85	156.26	-2.1 (-10.8)	-9.0 (-9.1)	-3.4 (-4.0)	-14.0 (-22.2)
10.	Tarim	918	919	921	920	1,727.85	1,730.06	1,731.42	1,726.42	0.1 (0.1)	0.2 (0.1)	-0.1 (-0.3)	0.2 (-0.1)
11.	Eastern Asian	2,408	2,409	2,402	2,377	2,095.20	2,032.86	1,976.25	1,906.34	0.04 (-3.0)	-0.3 (-2.8)	-1.0 (-3.5)	-1.3 (-9.0)
12.	Qinghai-Tibetan	5,308	5,294	5,301	5,285	5,664.59	5,574.23	5,442.10	5,309.59	-0.3 (-1.6)	0.1 (-2.4)	-0.3 (-2.4)	-0.4 (-6.3)
13.	HKH	65,188	65,393	64,884	63,761	63,121.52	61,097.47	58,674.63	55,782.02	0.3 (-3.2)	-0.8 (-4.0)	-1.7 (-4.9)	-2.2 (-11.6)

YALA BASE CAMP, LANGTANG VALLEY, NEPAL

KYANJIN GOMPA AND LIRUNG GLACIER IN LANGTANG VALLEY, NEPAL

5.1 Amu Darya River Basin

The Amu Darya River, one of the longest and significant rivers in Central Asia, originates from two major headstreams: the Panj River in Tajikistan and the Bakhsh River in Kyrgyzstan (Novikov et al., 2009; Babow et al., 2012). Flowing west-northwest, it traverses diverse landscapes before eventually emptying into the Aral Sea. Along its course, the Amu Darya delineates portions of the borders between Afghanistan, Tajikistan, Uzbekistan, and Turkmenistan, as well as the border between Uzbekistan and Turkmenistan (Lioubimtseva et al., 2014; Glantz et al., 2005). Within the Hindu Kush Himalayas (HKH) region, the Amu Darya River basin is situated entirely within Afghanistan, encompassing approximately a quarter of the total basin area. This region is characterised by its rugged terrain and significant glacial influence, which plays a crucial role in the hydrology and ecology of the basin.

The glaciers of Amu Darya River basin are distributed within three basins i.e. Surkhab, Kokcha and Wakhan. Among these three basins, the Wakhan basin encompasses more than half (59 %) of the total basin area. However, only 29% of the basin falls within the HKH region. Therefore, the total area coverage within the HKH boundary is dominated by the Surkhab basin, which encompasses around 45% of the total area. Kokcha and Wakhan basins cover around 30% and 25 % of total area coverage of the basin within the HKH. The glaciers within these three basins extend from 38°20’44” N to 34°34’28” N latitude and 74°53’04”E to 67°37’52”E longitude. The spatial distribution of glaciers in each basin and extent of the Amu Darya River basin within the HKH region is shown in Figure 5.4.

Glacier distribution in 2020

There are 3,551 glaciers in the Amu Darya River basin, encompassing a total area of 2,348.34 km^2 with ice reserves amounting to 158.89 km^3. The Wakhan basin hosts the majority of these glaciers, with 64% (2,286 glaciers), followed by the Kokcha basin consisting of 27% (960) of the total glaciers and Surkhab basin accounting 9% (305) of the total glaciers

FIGURE 5.4 MAP SHOWING GLACIER DISTRIBUTION AND EXTENT OF THE AMU DARYA RIVER BASIN WITHIN HKH REGION.

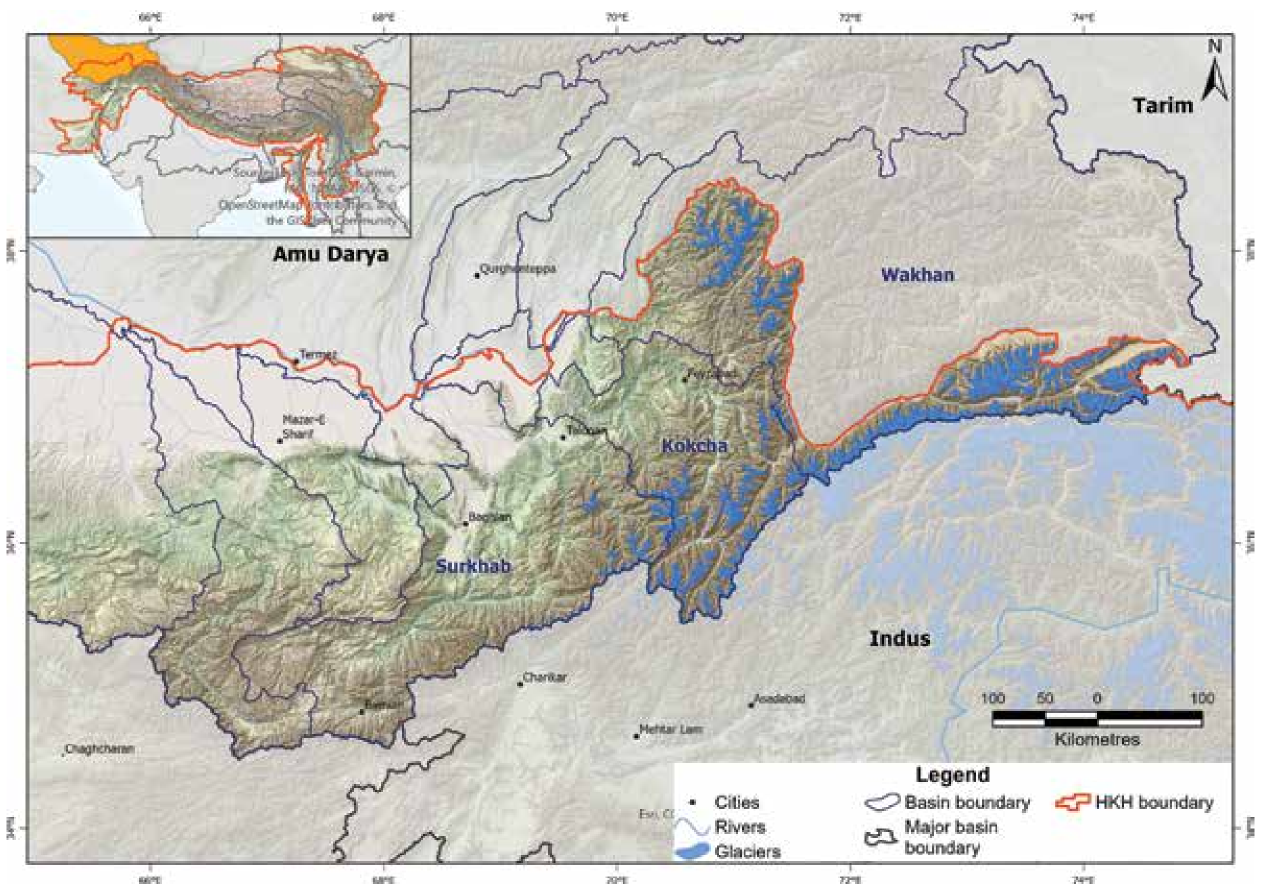


FIGURE 5.5 **GLACIERS DISTRIBUTION ACROSS BASINS** (TOP LEFT), **AREA CLASSES** (TOP RIGHT), **MEAN SLOPES** (BOTTOM LEFT) **AND ASPECTS** (BOTTOM RIGHT) **IN THE AMU DARYA RIVER BASIN.**

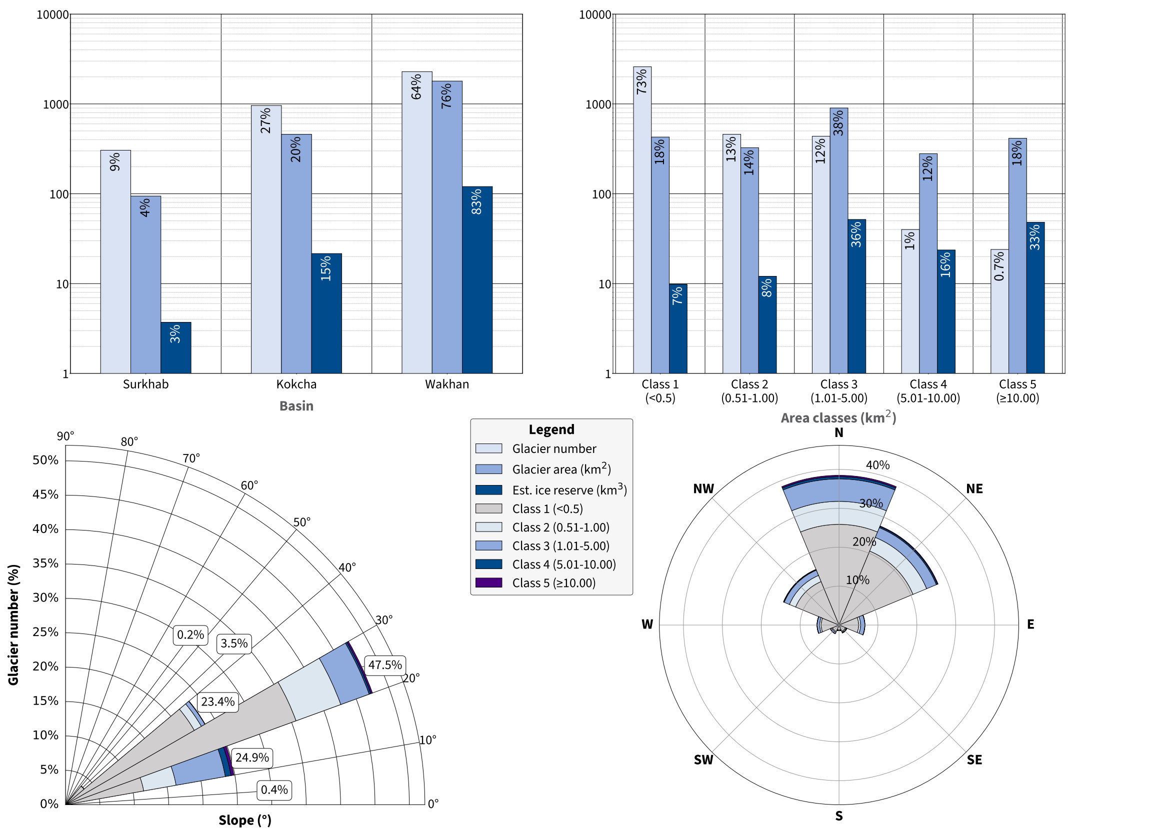


TABLE 5.3 **GLACIER DISTRIBUTION IN THE AMU DARYA RIVER BASIN.**

Basin		Number	Area (km²)	Largest area (km²)	Estimated ice reserve (km³)	Elevation (masl)		Mean slope (deg)
						Min	Max	
Amu Darya	Surkhab	305	94.21	5.24	3.71	3706	5783	27
	Kokcha	960	458.48	10.50	21.60	3631	6788	27
	Wakhan	2286	1795.65	39.12	120.25	3224	7191	26
	Total	**3551**	**2348.34**	**39.12**	**145.55**	**3224**	**7191**	**26**

in the basin. The area distribution reflects a similar pattern, with Wakhan comprising 76% of the glacier area, Kokcha 20%, and Surkhab 4%. A summary of this distribution of glaciers is shown in Table 5.3 and an illustration of it is shown in Figure 5.5.

The size of the glaciers in the basin ranges from 0.02 to 39.12 km², with both the smallest and largest glaciers situated in the Wakhan basin. To understand the glacier size distribution, glaciers were divided into five size classes (Figure 5.5 and Table 5.4) showing an inverse distribution in number and area coverages of the glaciers. The smallest glaciers of Class 1 (<0.5 km²), while numerous (comprising 73% of the total glacier number), occupy only 18% of the total area and hold about 7% of the estimated ice reserves. Conversely, mid-sized glaciers of Class 3 (1 – 5 km²), though representing just 12% of the glacier number, cover 38% of the total glacier area, highlighting their significant contribution to the basin's ice mass. The largest glaciers of Classes 4 and 5, despite comprising only 1% of the total glacier number, account for 30% of the glacier area and hold nearly half (49%) of the basin's estimated ice reserves, underscoring their importance to the region's mass balance and vulnerability to climate change.

In terms of elevation range, glaciers within the Amu Darya River basin are distributed across a broad

TABLE 5.4 **GLACIER NUMBER, AREA AND ESTIMATED ICE RESERVES ACROSS SIZE CLASSES IN THE AMU DARYA RIVER BASIN WITHIN THE HKH.**

Area classes	Glacier number		Area		Estimated ice reserves		Mean area per glacier (km²)
	count	%	km²	%	km³	%	
Class 1 (< 0.5)	2,590	72.9%	427.36	18.2%	9.77	6.7%	0.2
Class 2 (0.51 - 1.00)	460	13.0%	326.03	13.9%	12.08	8.3%	0.7
Class 3(1.01 - 5.00)	437	12.3%	900.81	38.4%	51.78	35.6%	2.1
Class 4 (5.01 - 10.00)	40	1.1%	279.52	11.9%	23.68	16.3%	7.0
Class 5 (≥10.00)	24	0.7%	414.63	17.7%	48.23	33.1%	17.3
Total	**3,551**	**100%**	**2,348.34**	**100%**	**145.55**	**100%**	**0.7**

elevation range, spanning from approximately 3,200 masl to 7,200 masl. The hypsometric distribution of the glacier area indicates that over 96% of the total glacierised area is concentrated within the 4,000 – 6,000 masl elevation range, with a pronounced concentration i.e. over 75% are situated between 4,500 masl and 5,500 masl. Within this range, the Wakhan basin holds a dominant position, accounting for 65% of the glacier area. In fact, across all elevation ranges, Wakhan consistently holds more glacier area than the combined total of both the Kokcha and Surkhab basins.

Wakhan's dominance in glacier coverage, particularly at the lower elevations, can be attributed to its extensive, low-lying debris-covered glaciers. These large glaciers are not only found at relatively low elevations but also contribute significantly to the overall glacier area. Likewise, the lowest elevation at which glaciers are present across the whole Amu Darya basin is also present in this sub basin, which corresponds to the terminus of its largest glacier. The highest point of glaciation in the basin reaches up to the upper reaches of Noshaq Peak, the tallest mountain in Afghanistan, standing at 7,492 masl. Furthermore, in the key elevation range of 4,500 to 5,500 masl, the Wakhan basin alone contributes 19.7% of the total glacier area of the Amu Darya River basin. Within the 5,000 to 5,500 masl range, this contribution increases to 36.3%. This significantly overshadows the recorded areas in Kokcha and Surkhab. In Kokcha basin, the highest glacier area was noted at 9% of the total glacier area in the Amu Darya River basin at the 4,500 – 5,000 masl elevation, while Surkhab contributed only 2.4% in the same range. Further details about the area-elevation distribution of the glaciers is given in Table 5.5, and a broader overview is provided graphically in Figure 5.6.

Moving upwards to higher elevations above 5,500 masl, the glacier area diminished sharply across all three basins. Surkhab basin exhibited a particularly low glacier presence, with no glaciers recorded beyond 6,000 masl. The decline continued at higher elevation above 6,000 masl and beyond 6,500 masl, where glacier areas became negligible or non-existent. Overall, these patterns illustrate the strong influence of elevation on glacier distribution and coverage, with marked variations among the sub-basins, particularly within the 4,500 to 5,500 masl range, where glacier extent is most pronounced.

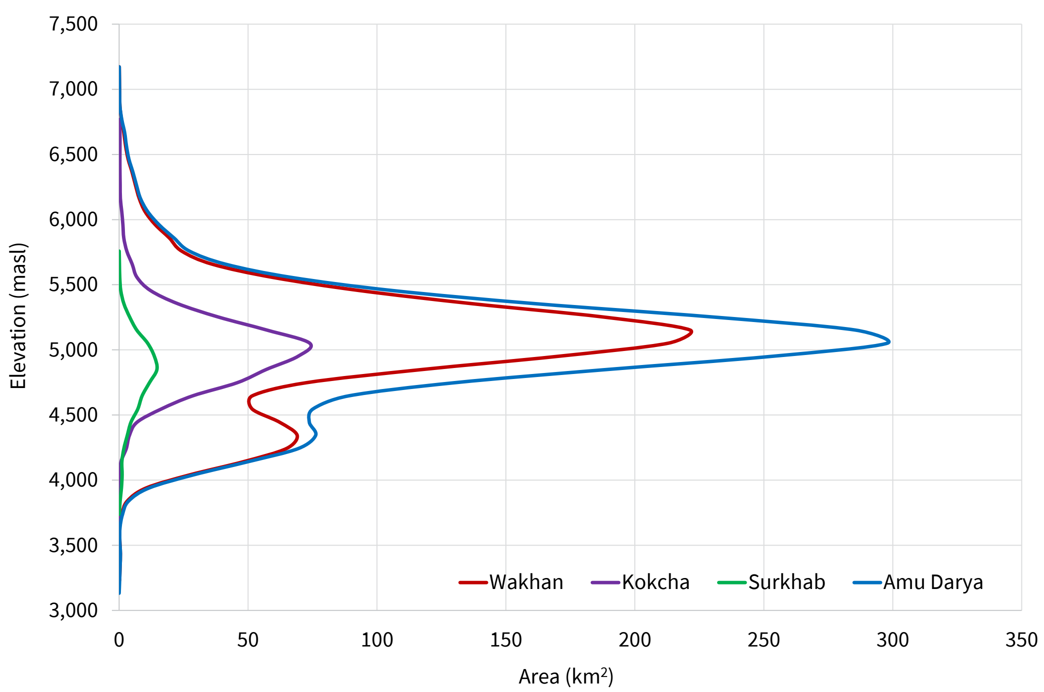
Additionally, to understand the further topographic characteristics of the glaciers in the basin, it has been categorised into six different mean slope classes and eight aspect classes considering the average values of each individual glacier's slope and aspect. The majority (49%) of glaciers fall within the slope class of 20º – 30º. Despite the majority in number, this slope class only contributes 42% of glacier area and 38% of total estimated ice reserves. The most substantial glacier area (48%) and estimated ice reserves (56%) are found in the slope class ranging from 10º – 20º, even though this class constitutes only 20% of the total glacier number. This is primarily due to the prevalence of large debris-covered valley glaciers in this category. A graphical representation of the glaciers within different aspects and slope can be seen in Figure 5.5.

In terms of aspects, the majority of glaciers exhibit a mean northern orientation, comprising more than one-third (nearly 39%) of the glaciers (Figure 5.5). These glaciers account for approximately 46% of the total glacier area and hold almost 48% of the total estimated ice reserves in the basin. Notably, glaciers with a northern aspect also have the largest average size, 0.79 km², highlighting a tendency for

TABLE 5.5 GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN EACH BASIN OF THE AMU DARYA RIVER BASIN.

Elevation Range (masl)	Wakhan		Kokcha		Surkhab		Amu Darya	
	km²	%	km²	%	km²	%	km²	%
3,000 – 3,500	1.05	0.1					1.05	0.0
3,500 – 4,000	15.15	0.8	0.70	0.2	1.34	1.4	17.20	0.7
4,000 – 4,500	271.90	15.1	14.79	3.2	11.83	12.6	298.53	12.7
4,500 – 5,000	463.17	25.8	216.94	47.3	56.23	59.7	736.35	31.4
5,000 – 5,500	852.16	47.5	204.48	44.6	24.42	25.9	1,081.07	46.0
5,500 – 6,000	153.61	8.6	18.27	4.0	0.39	0.4	172.27	7.3
6,000 – 6,500	32.70	1.8	2.52	0.5			35.22	1.5
6,500 – 7,000	5.73	0.3	0.76	0.2			6.49	0.3
7,000 – 7,500	0.18	0.0					0.18	0.0
Total	1,795.65	100.0	458.48	100.0	94.21	100.0	2,348.34	100

FIGURE 5.6 GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN THE AMU DARYA RIVER BASIN.



larger glaciers to develop on north-facing slopes, likely due to reduced solar radiation. Likewise, glaciers with northeastern and northwestern aspects make up 28% and 15% of the total glacier number respectively. These glaciers cover around 26% and 13% of the total glacier area and contribute similarly to the total estimated ice reserves in the basin.

In contrast, southern, southeastern and southwestern aspects encompass the least percentage of glaciers, each containing 1 to 2% of the total glaciers in the basin. They also represent the lowest proportions of glacier area and estimated ice reserves, with just 1 – 2% each of the total. However, despite their limited number and area coverage, the glaciers of southeastern aspects have a relatively high mean size of 0.67 km², the second largest among all aspects, suggesting the presence of fewer but larger glaciers in this aspect.

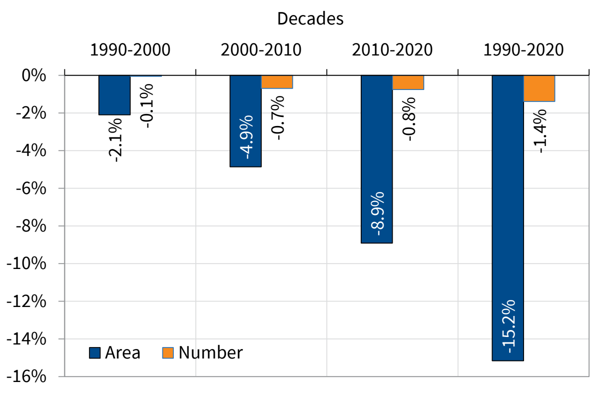
Glaciers with eastern and western aspects also consist of significant proportions of glaciers in the basins. Each comprising about 6 – 7% of the total glacier covering about 4 to 6% of the total glacier area and holding 3 to 5% of the total estimated ice reserves in the basin.

Decadal glacier changes from 1990s to 2020

Over the past three decades, glaciers in the Amu Darya River basin underwent a collective reduction in both their area coverage and number, with a decrease of 15% in glacier area and 1.4% in glacier number (depicted in Figure 5.7). The interdecadal changes shows the accelerating trend of glacier loss in both number and area with higher percentage loss in recent decade (2010 – 2020). However, these overall figures conceal considerable variation across different sub-basins, basins, area classes, and slope categories.

Among the three basins, the Wakhan basin exhibited a more prominent loss in the glacier area of 14% (Figure 5.9). Meanwhile, the Surkhab basin witnessed a larger decline in glacier numbers with a 5% reduction (Figure 5.8). When comparing the changes in glacier area and number across the three decades, the decade from 2010 to 2020 was particularly marked by accelerated change, especially in the Surkhab basin, which lost 23% of its glacier area (28.5 km²) and in terms of the magnitude, the Wakhan basin experienced the largest reduction in area, losing approximately 113.2 km² (6%) during this period.

FIGURE 5.7 INTERDECADAL GLACIER NUMBER AND AREA CHANGES IN THE AMU DARYA RIVER BASIN.



When considering area classes, the basin experienced a decline in both glacier numbers and areas across most categories, with the exception of the smallest glaciers Class 1 (<0.5 km²), which showed a 6.6% increase in number over 30 years. Glaciers in Class 2 (0.51 – 1.00 km²) and Class 3 (1.01 – 5.00 km²) showed substantial declines in number, with reductions of 17.6% and 18.2%, respectively (Figure 5.10). However, the largest loss in area and number was seen in the larger glacier Class 4 (5.01 – 10.00 km²), with a 24.5% reduction in glacier number and a 22% decrease in area. The increase in the smallest glacier class and substantial decreases in larger glacier class is largely due to the fragmentation and shrinkage of larger glaciers rather than an actual gain in glacial mass. Regarding changes over the decades, the latter period from 2010 to 2020 displayed a comparatively more substantial transformation in both glacier area and number. The most noteworthy distinction is evident in the reduction of glacier area in Class 5, wherein the area reduction is nearly tripled during the latter decade.

The glacier area has experienced significant changes across various elevation ranges. In 1990, the lowest snout of the glacier in the Wakhan basin was mapped at 3,116 masl, but it has since shifted upward to 3,224 masl, indicating a retreat of over 108 metres in just three decades. Additionally, glaciers below 3,224 masl have completely disappeared

FIGURE 5.8 DECADAL GLACIER NUMBER CHANGES IN THREE BASINS OF THE AMU DARYA RIVER BASIN.

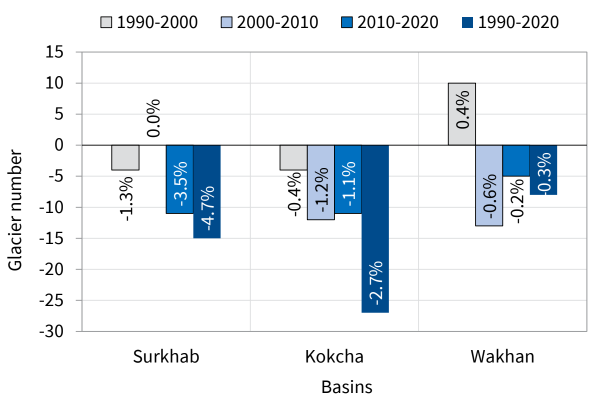


FIGURE 5.9 DECADAL GLACIER AREA CHANGES IN THREE BASINS OF THE AMU DARYA RIVER BASIN.

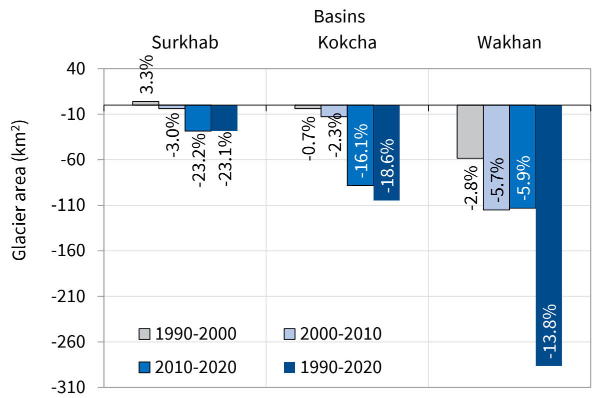
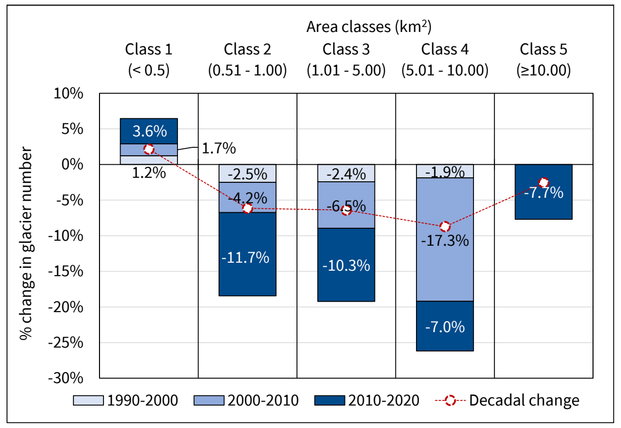
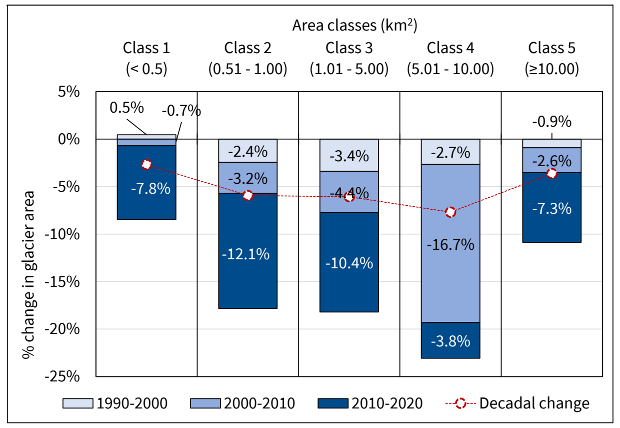


FIGURE 5.10 INTERDECADAL GLACIER AREA AND NUMBER CHANGES ACROSS SIZE CLASSES IN THE AMU DARYA RIVER BASIN.





during this time. Similarly, in the Surkhab and Kockha basins, the lowest elevations of glaciers have shifted between 30 and 80 metres upward over the same period.

The glacier area-elevation distribution from 1990 to 2020 reveals a decline in glacier area across most elevation zones, with the most significant loss occurring between 4,500 and 5,500 masl (Figure 5.11 and Table 5.6). During this period, nearly 295 km² (approximately 30%) of glacier area was lost, with the most pronounced decline of 179 km² (over 19%) occurring between 2010 and 2020. This highlights a rapid acceleration in melting during the last decade. Within this elevation range, the 4,500 – 5,000 masl range experienced a remarkable reduction of 188.8 km² (20.4%), while the 5,000 – 5,500 masl range also showed considerable losses of about 106 km² (9%), including a notable decline of 65 km² (6%) from 2010 to 2020.

In contrast, the area loss below 4,500 masl was less extensive in terms of absolute area, but it represented a higher percentage reduction. For instance, in the 3,000 – 3,500 masl range, the glacier area decreased by only 0.45 km² (more than 30%) over the entire 30 years, with a consistent decline of –0.15 km² per decade, indicating a more gradual melting process compared to higher elevations. More substantial declines were observed in the 3,500 – 4,000 masl and 4,000 – 4,500 masl ranges, which experienced total reductions of 17.5 km² (50%) and 93.3 km² (24%), respectively, with losses accelerating in each subsequent decade.

FIGURE 5.11 GLACIER AREA DISTRIBUTION AND CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE AMU DARYA RIVER BASIN.

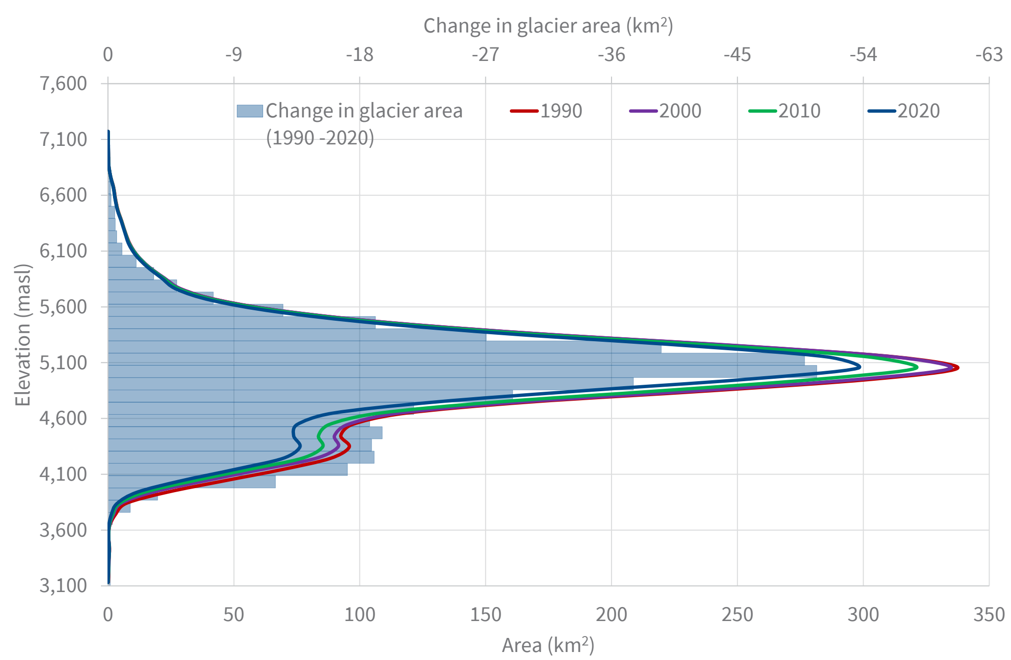


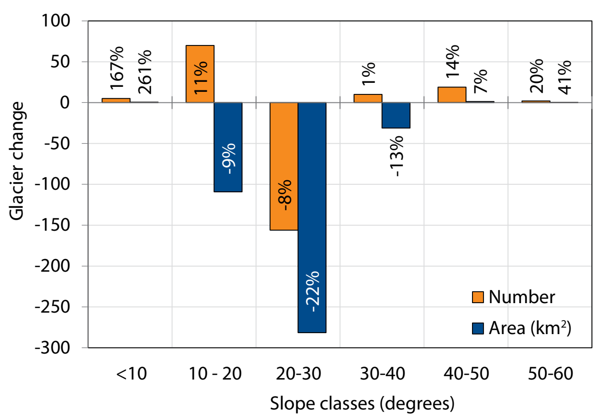
TABLE: 5.6 GLACIER AREA DISTRIBUTION AND PERCENTAGE CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE AMU DARYA RIVER BASIN WITHIN THE HKH.

Elevation range (masl)	Area (km²)				Area change (%)				
	1990	2000	2010	2020	1990-2000	2000-2010	2010-2020	1990-2020	Per decade
3,000 – 3,500	1.51	1.35	1.21	1.05	-10.2	-10.9	-12.7	-30.1	-11.3
3,500 – 4,000	34.68	26.14	21.78	17.20	-24.6	-16.7	-21.02	-50.4	-20.8
4,000 – 4,500	391.83	362.85	335.20	298.53	-7.4	-7.6	-10.9	-23.8	-8.6
4,500 – 5,000	925.16	906.70	850.65	736.35	-2.0	-6.2	-13.4	-20.4	-7.2
5,000 – 5,500	1,186.84	1,185.01	1,146.11	1,081.07	-0.2	-3.3	-5.7	-8.9	-3.04
5,500 – 6,000	184.12	184.27	180.25	172.27	0.08	-2.2	-4.4	-6.4	-2.2
6,000 – 6,500	36.84	36.62	36.21	35.22	-0.6	-1.1	-2.7	-4.4	-1.5
6,500 – 7,000	6.83	6.75	6.60	6.49	-1.2	-2.2	-1.7	-5.0	-1.7
7,000 – 7,500	0.18	0.18	0.18	0.18	0.0	-0.6	0.6	0.0	0.0
Total	2,767.99	2,709.88	2,578.18	2,348.34	-2.10	-4.9	-8.9	-15.2	-5.3

Above 5,500 masl, glacier areas exhibited varying levels of stability. The 5,500 – 6,000 masl range showed an 11.85 km² (6.5%) area lost over three decades, while the 6,000 – 6,500 masl and 6,500 north-western section 7,000 masl ranges showed minimal changes. The 7,000 – 7,500 masl range remained unchanged, suggesting relative stability at these elevations, potentially due to reduced exposure to warming influences.

Overall, glacier areas have dramatically decreased across different elevation ranges over the past three decades, with the most significant losses occurring between 4,500 and 5,500 masl, particularly in the last decade.

FIGURE 5.12 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES IN THE AMU DARYA RIVER BASIN.



In terms of slope classes, glaciers of mean slopes 20° – 30° range experienced the largest total losses in both area and number, particularly during the last decade (2010–2020). Glaciers in slope classes below 10° showed an increase in number, especially from 2010 to 2020, though this was accompanied by a reduction in area, highlighting the complex dynamics of glacier shrinkage and fragmentation. Conversely, glaciers in the 10° – 20° and 20° – 30° slope classes suffered significant declines, with the 20° – 30° class losing 156 glaciers and 281.6 km² of glacier area (Figure 5.12). Slope classes above 30° exhibited mixed trends, with some showing slight increases in glacier numbers and area, particularly in the 30° – 40° and 40° – 50° slope class. However, these gains were relatively modest and did not offset the broader pattern of glacier retreat.

Overall, the data underscores a consistent pattern of glacier retreat in the Amu Darya River basin, particularly in lower slope classes, which aligns with the broader impacts of climate change observed across the region. The fragmentation of larger glaciers into smaller ones, coupled with an overall decline in glacial area, indicates ongoing and potentially accelerating glacial retreat within the basin.

Over the past three decades from the 1990s to 2020, the Amu Darya River basin experienced a significant decline in both the number and area of glaciers across nearly all aspect classes. However, a few aspects showed slight increases in glacier numbers. Notably, the northern and northwestern aspects recorded modest increases in glacier number, with

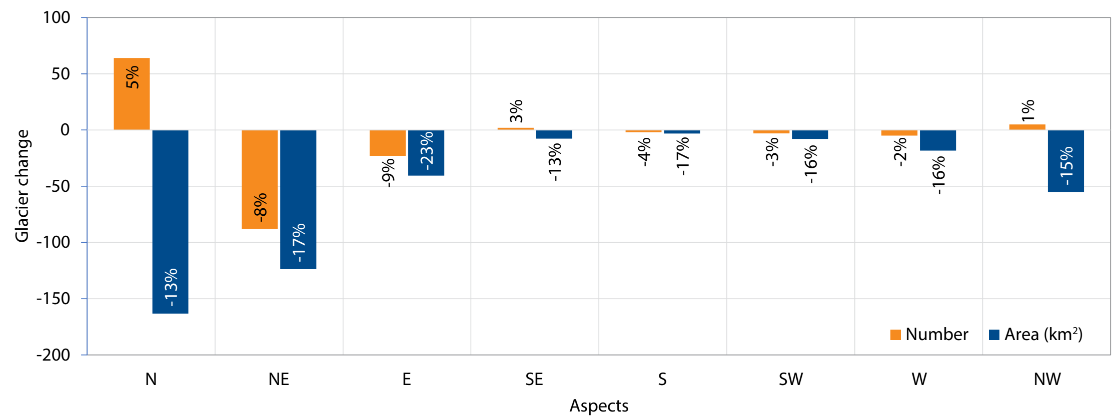
RETRIEVING DATA FROM THE AUTOMATIC WEATHER STATION IN THE DEBRIS COVERED PART (ABLATION ZONE) OF THE PONKAR GLACIER, MANANG DISTRICT, NEPAL.

increases of approximately 5% and 1%, respectively. Despite these numerical gains, both aspects experienced consistent and substantial reductions in the glacier area. The northern aspect showed the highest absolute area loss, exceeding 13%, making it the most affected in terms of glacier area loss (Figure 5.13). The northwestern aspect followed closely, with a glacier area loss of over 15% between 1990 and 2020. Similarly, the northeastern aspect experienced the second highest area loss, amounting to roughly 17%, and recorded the greatest decline in glacier number, losing approximately 8.3% over the three decades. These trends highlight a broader pattern of glacier retreat, where minor increases in glacier number are due to fragmentation of glaciers and alteration of glacier's mean aspect with shrinkage and retreat in glacier extent.

In contrast, the southern, southeastern and southwestern aspects displayed relatively smaller numbers and area losses, although losses accelerated in the most recent decade of 2010 to 2020. The southeastern and southern aspects showed minimal overall glacier number change, with southeastern gaining just 2 glaciers and southern aspects losing 2 glaciers, while southwestern aspect experienced a small loss of 3 glaciers. Despite this apparent stability in glacier numbers, all these three aspects lost between 3 to 8 km² in glacier area over three decades, with notable acceleration in recent decade particularly in southern aspect, which lost almost 17% of its area in the last decade alone.

Similarly, the eastern and western aspects lost considerable amount of loss in glacier number and area shrinkages. Comparatively the eastern aspect lost higher number and area shrinkages than in the western aspect.

FIGURE 5.13 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES IN THE AMU DARYA RIVER BASIN.



5.2 Indus River Basin

The Indus River is a transboundary river that stretches from the high peaks of the Hindu Kush Karakoram-Himalaya range in the north to the arid alluvial plains of Pakistan in the south. It originates at Lake Ngangla Rinco in the northwest of Mount Kailash in western Tibet and flows northwest through Jammu and Kashmir (Rajbhandari et al., 2014). After passing through the Nanga Parbat massif, the river takes a sharp bend towards the left and continues south-southwest through Pakistan, ultimately emptying into the Arabian Sea near Karachi (Khan and Adams, 2019). The basin covers a total area of 1,116,086 km², of which 555,450 km² lies within the HKH region. The Indus basin spans four countries, with the largest portion in Pakistan, followed by substantial portions in India, China and Afghanistan (Laghari et al., 2012). For this assessment, the upper reaches of the Indus River basin have been divided into three basins: Kabul, Panjnad, and Upper Indus, which have been further subdivided into 17 sub-basins. The Kabul basin, originating in Afghanistan and flowing into Pakistan, includes the Panjsher-Ghorband, Alingar-Alishing-Nuristan, Kunar, and Swat sub-basins. The Upper Indus basin, flowing through China and Pakistan, comprises the Gilgit, Hunza, Shigar, Shyok, Zanskar, Shingo, Astor, and Upper Indus sub-basins. The remaining sub-basins, including Jhelum, Chenab, Ravi, Beas, and Sutlej, fall under the Panjnad basin.

Glacier distribution in 2020

Based on the Landsat images of 2020, a total of 25,986 glaciers encompassing an area of 24,571.19 km² and estimated ice reserves of 3,235 km³ have been mapped in the Indus River basin (Table 5.7). Figure 5.14 shows the spatial distribution of these glaciers extending between latitude 30.45°N to 37.08° N and longitude 69.36°E to 81.65° E, spanning an elevation from 2,329 masl to 8,570 masl. This basin contains the highest concentration of glaciers in the HKH region, comprising nearly 41% of total glacier number and over 44% of total glacier area in the region.

FIGURE 5.14 MAP SHOWING GLACIER DISTRIBUTION AND EXTENT OF THE INDUS RIVER BASIN WITHIN THE HKH REGION.

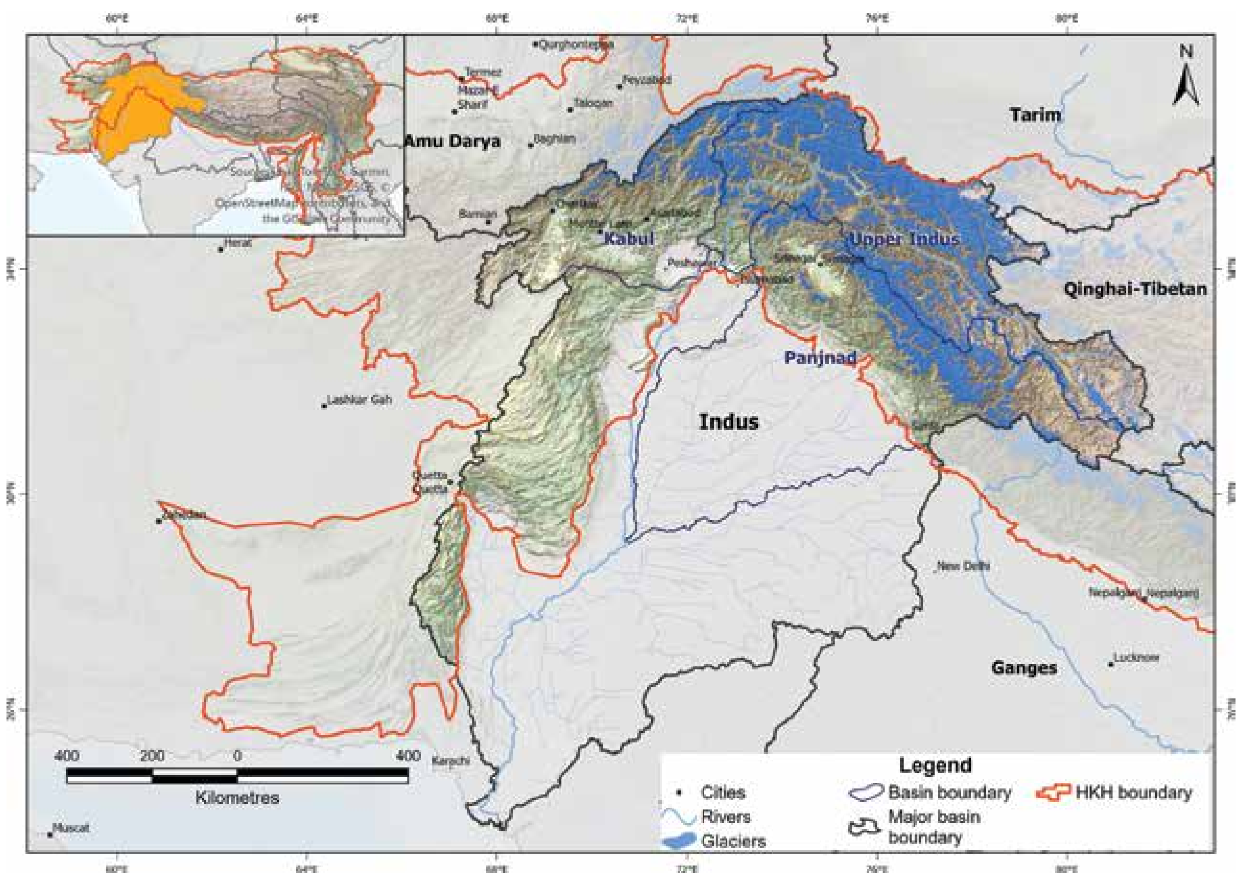
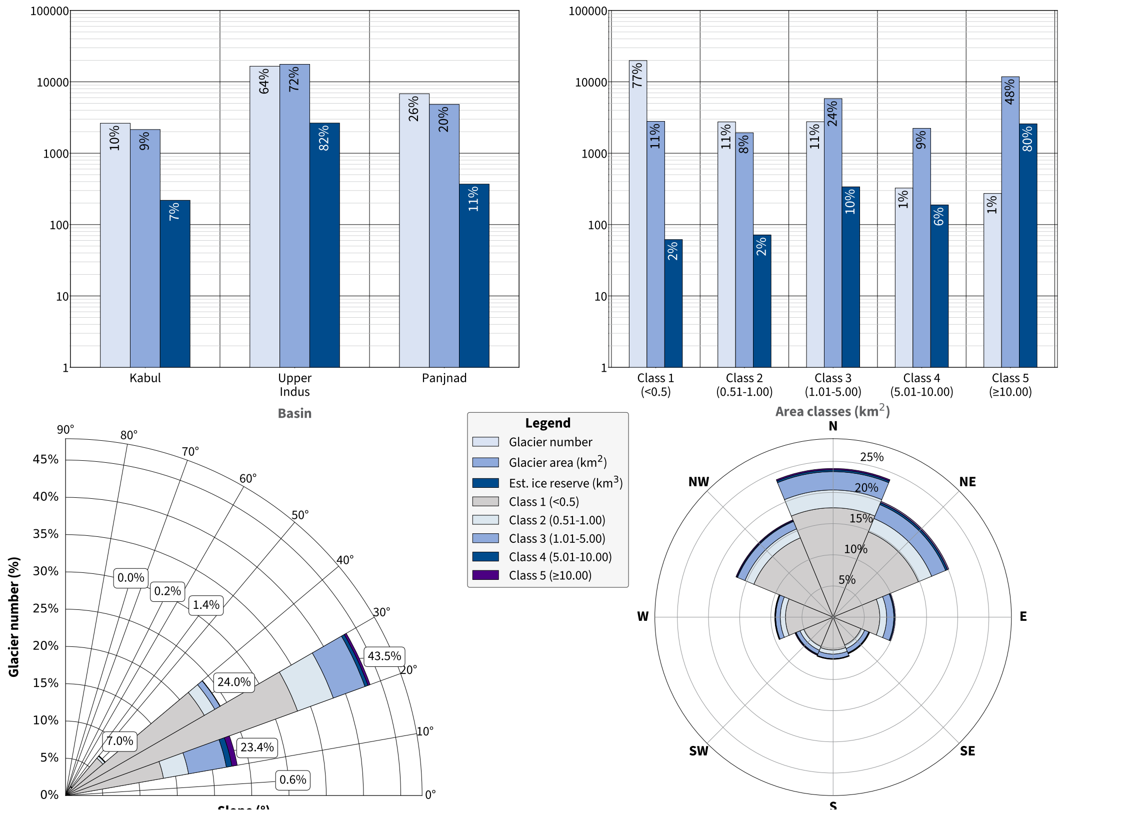


FIGURE 5.15 **GLACIERS DISTRIBUTION ACROSS THE SUB-BASINS** (TOP LEFT), **AREA CLASSES** (TOP RIGHT), **MEAN SLOPE** (BOTTOM LEFT) **AND ASPECTS** (BOTTOM RIGHT) **IN THE INDUS RIVER BASIN.**



The glacier distribution across the basin is markedly heterogeneous. The Upper Indus basin is the predominant glaciated zone, containing 72% of the total glacierised area and 64% of the glacier number in the Indus River basin, corresponding to 17,592 individual glaciers. In contrast, the Kabul Basin is the least glaciated, containing only 2,622 glaciers, equating to 10% of the total glacier number and 9% of the glacierised area in the Indus River basin (Figure 5.15).

The Siachen Glacier, located in the Shyok sub-basin of the Upper Indus basin, is identified as the largest glacier in the entire basin and in the HKH region, covering a surface area of 1,007.86 km². Furthermore, the Shyok sub-basin contributes 27.3% of the total glacierised area and 20% of the glacier number within the Indus River basin, highlighting its critical importance to the region's cryosphere. This spatial dominance emphasises the Shyok sub-basin's significant role in hydrological processes and glacier dynamics in the region. The Figure 5.16 and Table 5.7 shows the detailed distribution of glacier number and area in each sub-basin of the Indus River basin.

Remarkably, 18 of the 25 glaciers larger than 100 km² in the entire Hindu Kush Himalaya region lies within the Indus River basin, with almost all concentrated in the Upper Indus, and just one each in the Kabul and Panjnad basins. This includes most of the region's largest glaciers, such as the Siachen glacier, which is the largest in the HKH region, as well as 8 other glaciers that exceed 200 km² in size. Moreover, It also hosts all of the HKH region's ten longest glaciers. Among them, the longest is the Siachen Glacier, measuring 85.9 km, followed by some notable ones like Biafo Glacier at 72.9 km, Baltoro Glacier at 65.4 km, Batura Glacier at 59.2 km and Hispar Glacier at 57.2 km.

While examining glacier size distribution, the majority of the glaciers fall under the smaller sized classes. Specifically, 76% of glaciers, amounting to 19,871 individual glaciers fall into the smallest area Class 1 (<0.5 km²). Despite their numerical dominance, these smaller glaciers cover only 11% of the total glacier area. In contrast, the largest glaciers of Class 5 (≥10.00 km²), though they make up just 1% of the total number, account for more than 48% of the total glacier area. They also dominate the total

FIGURE 5.16 **GLACIER NUMBER AND AREA DISTRIBUTION WITHIN EACH SUB-BASIN OF THE INDUS RIVER BASIN.**

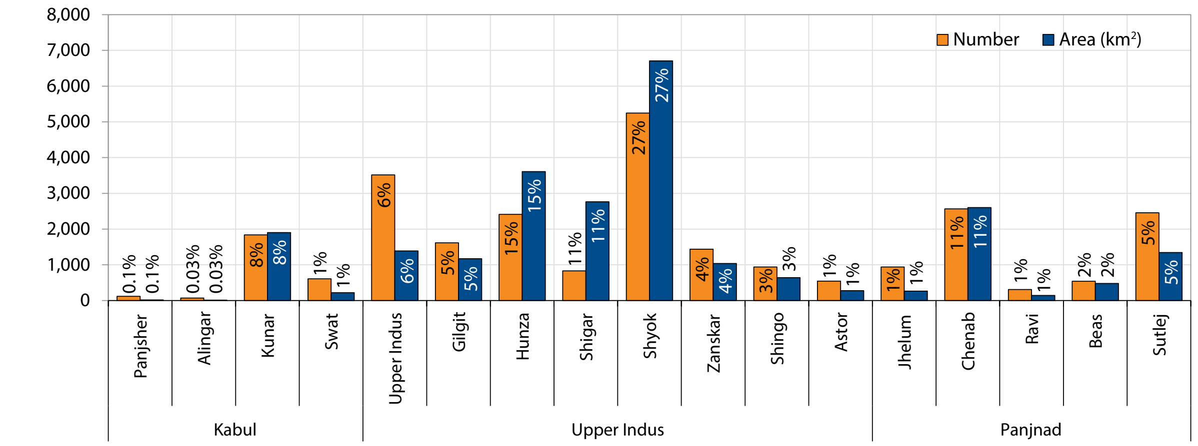


TABLE 5.7 **GLACIER DISTRIBUTION ACROSS THE SUB-BASINS AND BASINS OF THE INDUS RIVER BASIN.**

Basin	Sub-basin	Number	Area (km²)	Largest area (Km²)	Estimated ice reserve (km³)	Elevation (masl)		Mean slope (Deg)
						Min	Max	
Kabul	Alingar-Alishing-Nuristan	69	8.47	1.24	0.201	4,002	5,545	33
	Kunar	1,837	1,903.19	195.91	208.643	3,132	7,553	28
	Panjsher-Ghorband	117	17.18	2.20	0.479	3,922	5,327	30
	Swat	607	218.33	7.67	9.652	3,279	5,808	26
	Sub-total	2,630	2,147.17	195.91	218.975	3,138	7,553	28
Upper Indus	Astor	545	276.86	45.49	21.045	2,929	8,039	25
	Gilgit	1,616	1,171.06	77.96	90.748	2,568	7,723	28
	Hunza	2,412	3,607.32	412.98	551.458	2,329	7,747	32
	Shigar	830	2,764.72	690.95	669.488	2,774	8,570	32
	Shingo	940	639.04	43.88	44.494	3,625	7,067	25
	Shyok	5,247	6,708.43	1,007.86	1,097.676	3,245	7,664	28
	Upper Indus	3,515	1,389.91	57.49	81.864	2,733	7,810	25
	Zanskar	1,439	1,037.49	69.79	89.519	3,930	6,469	25
	Sub-Total	16,544	17,594.81	1,007.86	2,646.292	2,329	8,570	27
Panjnad	Beas	538	477.19	33.21	35.551	3,070	6,211	29
	Chenab	2,567	2,601.13	113.17	233.099	2,413	7,101	29
	Jhelum	941	264.09	7.54	10.659	3,362	6,172	25
	Ravi	308	143.02	10.02	7.021	3,097	5,890	29
	Sutlej	2,458	1,343.78	45.33	82.895	3,873	6,990	25
	Sub-total	6,812	4,829.21	113.17	369.225	2,413	7,101	27
Total		**25,986**	**24,571.19**	**1,007.86**	**3,234.491**	**2,329**	**8,570**	**27**

estimated ice reserves in the basin, encompassing about 80% of the total estimated ice reserves. The mid-sized glaciers in Class 3 (1.01 – 5.00 km²) showed the second highest amount of glacier area contribution by nearly 24% of the total glacier area in the river basin, yet they only contain about 11% of the total glacier number (Figure 5.15). Overall, this distribution illustrates an inverse relationship: while there are many small glaciers, larger glaciers dominated in the total glacier area coverage. This trend is also reflected in the average size of these glaciers, with the mean area per glacier across the river basin calculated at 0.94 km².

This basin is also notable for containing glaciers at both the lowest and second highest elevations in the HKH region, ranging from 2,350 masl to 8,500 masl. The elevational distribution of glaciers positions the Upper Indus basin as the primary glaciation zone, showcasing both the lowest and highest glacierised elevations, highlighting the complex topography and climatic variability of the basin (Figure 5.17). In contrast, the Kabul basin features relatively narrower elevational distribution of glaciers, corresponding with its lower glacier abundance (Table 5.8).

Within the Indus River basin, approximately 78% of the glacierised area is concentrated between 4,500 and 6,000 masl, with the highest concentration of 32% occurring between 5,000 and 5,500 masl. In the lower elevation ranges (<2,500 masl and 2,500 – 3,000 masl), glacier coverage is minimal across all basins, with no glaciers present in the Kabul basin below 3,000 masl. As elevation increases from 3,000 to 4,000 masl, glacier distribution becomes more pronounced. The Upper Indus basin shows a notable increase in glacier area, rising from 1.1% at 3,000 – 3,500 masl to 3.3% at 3,500 – 4,000 masl. Similarly, the other two basins had substantial increase in glacier area coverage, from 0.2% at 3,000 – 3,500 masl to about 3% at 3,500 – 4,000 masl.

FIGURE 5.17 **GLACIER AREA VERSES ELEVATION DISTRIBUTION IN THE INDUS RIVER BASIN.**

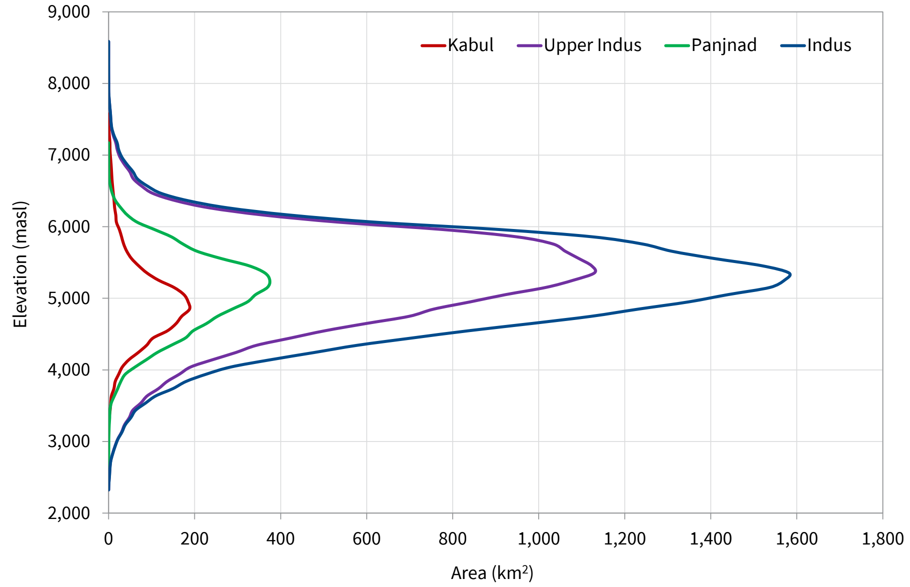


TABLE 5.8 **GLACIER AREA DISTRIBUTION ACROSS ELEVATION IN THE BASINS OF THE INDUS RIVER BASIN.**

Elevation Range (masl)	Kabul		Upper Indus		Panjnad		Indus	
	Area (km²)	Area percent	Area (km²)	Area percent	Area (km²)	Area percent	Area (km²)	Area percent
<2,500			0.81	0.005	0.06	0.001	0.88	0.004
2,500 – 3,000			33.63	0.2	1.26	0.03	34.89	0.1
3,000 – 3,500	5.03	0.2	192.66	1.1	8.23	0.2	205.92	0.8
3,500 – 4,000	62.97	2.9	581.30	3.3	108.02	2.2	752.29	3.1
4,000 – 4,500	340.00	15.8	1496.18	8.5	586.90	12.2	2,423.07	9.9
4,500 – 5,000	836.84	39.0	3395.90	19.3	1,287.63	26.7	5,520.38	22.5
5,000 – 5,500	601.49	28.0	5,272.79	30.0	1,774.95	36.8	7,649.23	31.1
5,500 – 6,000	185.53	8.6	4,913.01	28.0	891.77	18.5	5,990.30	24.4
6,000 – 6,500	72.56	3.4	1391.69	7.9	163.52	3.4	1627.77	6.6
6,500 – 7,000	33.98	1.6	247.29	1.4	6.83	0.1	288.10	1.2
7,000 – 7,500	8.73	0.4	60.14	0.3	0.04	0.001	68.91	0.3
7,500 – 8,000	0.04	0.002	9.00	0.05			9.04	0.04
8,000 – 8,500			0.34	0.002			0.34	0.001
>8,500			0.06	0			0.07	0
Total	2,147.17	100	17,594.81	100	4,829.21	100	24,571.19	100

Glacier area coverage continues to grow significantly, reaching 8.5% to about 16% at 4,000 – 4,500 masl, with further higher concentrations occurring at 5,000 – 5,500 masl across all three basins. Beyond 6,000 masl, glacier area coverage drops sharply in all basins, with minimal glacier presence above 7,000 masl. Overall, distribution reveals a complex relationship with elevation. Understanding these distribution patterns is also crucial for predicting the impacts of climate change on regional water resources and ecosystems.

For the slope analysis, glaciers are categorised into six distinct classes on their mean slope. Approximately 45% of these glaciers have mean slopes ranging from 20° to 30° (Figure 5.15). In contrast, the majority of the glacier area (54%) is associated with glaciers that have slopes of 10° to 20°, even though these glaciers represent only 19% of the total number. Notably, the Siachen Glacier, including other larger glaciers with an area greater than 100 km², which falls into this slope category, is a debris-covered glacier, highlighting the role of low-slope debris-covered glaciers in contributing significantly to the glacierised area within the basin. The steepest slope category (50° to 60°) is underrepresented, with only 12 glaciers contributing a minimal 0.04% to the total glacierised area. This reflects the typical presence of small, apron/hanging type glaciers on these steeper slopes, which have a limited impact on the overall glacial landscape.

Aspect classification, which categorises glaciers according to the orientation of their slopes, reveals the dominance of the northern, northeastern and northwestern aspects in the Indus River basin (Figure 5.15). Collectively, these aspects account for over 60% of the total glaciers' number, span more than half of the total glacier area, and hold approximately 42% of the total estimated ice reserves. Among these aspects, northern aspect alone hosts 24% of the glaciers, over 21% of the total glacier area and nearly 15% of the total estimated ice reserves, indicating the highest glacier concentration in the basin. The northeastern and northwestern aspects follow closely, with 20% and 17% of glaciers, covering 19% and 13% of the total glacier area respectively.

In contrast, the southern, southeastern, and southwestern aspects show a different pattern. They host a smaller portion of glacier number, collectively nearly 20% of the total glacier in the basin, yet their glaciers are slightly larger on average, with mean areas ranging from 1.0 to 1.1 km². Despite the lower glacier numbers, these aspects together contribute approximately 22% of the total glacier area and a similar portion of the estimated ice reserves. This distribution pattern highlights their substantial role in the basin's glaciology, even with fewer glaciers.

The eastern and western aspects present the most distinctive distributions. The eastern aspect stands out with just 10% of the glaciers, contributes a notable 18% of glacier area and holds the largest portion of estimated ice reserves at 29%. With the highest mean glacier size at 1.66 km², this aspect contains the largest glacier masses in the basin. Conversely, the western aspect is more balanced, accounting for 9% of glaciers, 8% of glacier area, and 8% of estimated ice reserves, but with a relatively smaller mean area of 0.77 km², placing it on the lower end in terms of glacier size and reserves.

Decadal glacier changes from 1990s to 2020

Over the past thirty years, the Indus River basin has witnessed a significant reduction in its glacier area, decreasing by approximately 6.7% from 26,331.1 km² in 1990 to 24,570.1 km² in 2020. This reduction in glacier area has been accompanied by a modest increase in glacier numbers, which have grown by 0.4% from 25,859 glaciers in 1990 to 25,950 in 2020. This trend indicates that while the glaciers are shrinking in size, they are also fragmenting into smaller, more numerous units.

The decadal analysis from 1990 to 2020 indicates an accelerating retreat of glaciers, particularly evident in the last two decades. The rate of glacier area loss intensified, increasing from –1.6% between 1990 and 2000 to –3.1% between 2010 and 2020, underscoring the escalating impacts of climate change on these glacial systems. This pattern of accelerated retreat is consistently observed across most basins and sub-basins (Figure 5.18, Figure 5.19 and Table 5.9). For instance, the Sutlej sub-basin experienced a significant area reduction of 15% over the three decades, equating to nearly 240 km² of lost glacier area. In terms of absolute area loss, the Chenab sub-basin was most affected, with a total reduction exceeding 285 km², which represents approximately 9.9% of its glacier area as of 1990. The Chenab sub-basin also exhibited the most substantial increase in glacier numbers, with over 30 additional glaciers recorded, reflecting a 1.4% increase. A similar trend of glacier number increment was observed in the Shingo sub-basin. On a broader basin-wide scale, the Upper Indus basin saw the greatest overall loss in glacier area, with a reduction of approximately 900 km², amounting to about 5.2% of its original glacier area in 1990. The recent decade (2010 – 2020) marked a distinct increase in glacier area loss, with the Upper Indus basin losing nearly double the area compared to the previous decade (2000 – 2010). While the number of glaciers increased in the first two decades, there was a notable decline in glacier numbers during the last decade (2010 – 2020). This suggests that the glaciers, having fragmented due to mass loss and retreat, eventually lost significant mass and disappeared. The fragmentation of glaciers is particularly noticeable in the Shyok and Gilgit sub-basins, where smaller glaciers proliferated despite an overall area loss, indicating the breakup of larger glaciers.

Overall, the glacier number has seen an increase, with the Upper Indus basin adding more than 80 glaciers in just one decade (2000 – 2010). The Panjnad basin recorded the greatest percentage increase in glacier numbers at around 2% (Figure 5.18). This increase in glacier numbers is primarily due to the fragmentation of larger glaciers as they continued to lose area over the years. Additionally, the presence of surging glaciers in the basin, especially in the Upper Indus sub-basin, has led to the merging of some glaciers, increasing their area but reducing their overall number.

Over the three decades, glaciers across all size classes experienced reductions in both area and number, except for the smallest size Class 1 (<0.5 km²), which showed an impressive increase of glacier number by 4.6%. This class consistently increased, especially between 2000 and 2010, with a 2.3% increase, indicating strong increases in smaller glaciers. However, despite these increases in number, the glacier area in this class experienced a significant decline, with a total area reduction of 5.4% from 1990 to 2020 (Figure 5.20).

In contrast, larger glacier classes showed significant declines. Class 2 (0.51 – 1.00 km²) lost both glacier number and area with a total decrease of lost 12.5% over the three decades. The largest glacier area loss was observed in mid-sized glacier Class 3 (1.01 – 5.00 km²), which lost nearly 590.4 km² (in percent 9.2% loss) of glacier area over three decades along with the reduction of glacier number by 10.6%. In the largest size Class 5 (≥10 km²), there was a steep

FIGURE 5.18 DECADAL CHANGES IN GLACIER NUMBER OF THE BASINS IN THE INDUS RIVER BASIN.

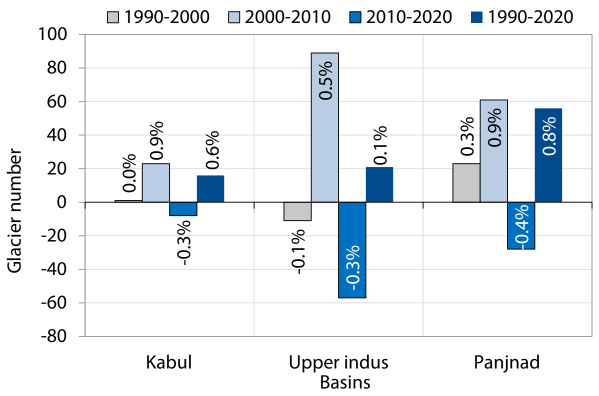


FIGURE 5.19 DECADAL CHANGES IN GLACIER AREA OF THE BASINS IN THE INDUS RIVER BASIN.

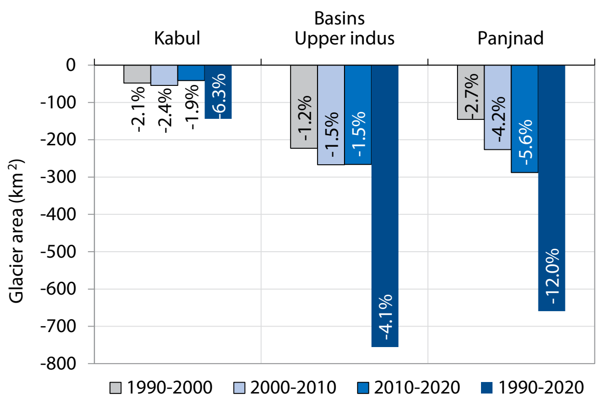


TABLE 5.9 DECADAL CHANGES IN GLACIER NUMBER AND AREA IN THE INDUS RIVER BASIN AND ITS SUB-BASINS AND BASINS FROM 1990 TO 2020.

Basin	Sub-basin	Number				Area (km²)				Decadal change percent (number / area)				Change percent per decade
		1990	2000	2010	2020	1990	2000	2010	2020	1990 – 2000	2000 – 2010	2010 – 2020	1990 – 2020	
Kabul	Panjsher	120	116	117	117	20.84	18.21	17.87	17.18	3.3 / -12.6	0.9 / -1.8	0 / -3.8	-2.5 / -17.5	1.4 / -6.1
	Alingar	73	72	72	69	9.48	9.16	9.04	8.47	1.4 / -3.3	0 / -1.4	-4.2 / -6.3	-5.5 / -10.6	-0.9 / -3.7
	Kunar	1,820	1,827	1,842	1,837	2,007.77	1,975.79	1,937.33	1,903.19	-0.4 / -1.6	0.8 / -1.9	-0.3 / -1.8	0.9 / -5.2	0.1 / -1.8
	Swat	601	600	607	607	252.96	239.70	224.25	218.33	0.2 / -5.2	1.2 / -6.4	0 / -2.6	1 / -13.7	0.4 / -4.8
	Total	**2,614**	**2,615**	**2,638**	**2,630**	**2,291.04**	**2,242.86**	**2,188.48**	**2,147.17**	**0 / -2.1**	**0.9 / -2.4**	**-0.3 / -1.9**	**0.6 / -6.3**	**0.2 / -2.1**
Upper Indus	Upper Indus	3,528	3,524	3,536	3,515	1,592.20	1,530.78	1,448.56	1,389.91	0.1 / -3.9	0.3 / -5.4	-0.6 / -4	-0.4 / -12.7	0 / -4.4
	Gilgit	1,604	1,603	1,616	1,616	1,248.80	1,230.78	1,189.87	1,171.06	0.1 / -1.4	0.8 / -3.3	0 / -1.6	0.7 / -6.2	0.3 / -2.1
	Hunza	2,416	2,411	2,418	2,412	3,652.03	3,648.51	3,639.62	3,607.32	0.2 / -0.1	0.3 / -0.2	-0.2 / -0.9	-0.2 / -1.2	0.1 / -0.4
	Shigar	823	817	828	830	2,788.28	2,786.15	2,778.85	2,764.72	0.7 / -0.1	1.3 / -0.3	0.2 / -0.5	0.9 / -0.8	0.8 / -0.3
	Shyok	5,254	5,240	5,266	5,247	6,816.65	6,789.87	6,750.51	6,708.43	0.3 / -0.4	0.5 / -0.6	-0.4 / -0.6	-0.1 / -1.6	0.1 / -0.5
	Zanskar	1,458	1,456	1,455	1,439	1,187.91	1,126.33	1,092.16	1,037.49	0.1 / -5.2	-0.1 / -3	-1.1 / -5	-1.3 / -12.7	-0.3 / -4.4
	Shingo	905	924	938	940	746.16	710.21	671.93	639.04	-2.1 / -4.8	1.5 / -5.4	0.2 / -4.9	3.9 / -14.4	-0.1 / -5
	Astor	535	536	544	545	318.55	305.07	289.28	276.86	-0.2 / -4.2	1.5 / -5.2	0.2 / -4.3	1.9 / -13.1	0.5 / -4.6
	Total	**16,523**	**16,511**	**16,601**	**16,544**	**18,350.59**	**18,127.71**	**17,860.78**	**17,594.81**	**0.1 / -1.2**	**0.5 / -1.5**	**-0.3 / -1.5**	**0.1 / -4.1**	**0.1 / -1.4**
Panjnad	Jhelum	948	946	943	941	297.93	286.01	277.58	264.09	0.2 / -4	-0.3 / -2.9	-0.2 / -4.9	-0.7 / -11.4	-0.1 / -3.9
	Chenab	2,532	2,537	2,560	2,567	2,887.73	2,849.05	2,759.82	2,601.13	-0.2 / -1.3	0.9 / -3.1	0.3 / -5.8	1.4 / -9.9	0.3 / -3.4
	Ravi	303	304	308	308	170.71	163.65	153.30	143.02	-0.3 / -4.1	1.3 / -6.3	0 / -6.7	1.7 / -16.2	0.3 / -5.7
	Beas	526	526	535	538	548.91	531.12	505.62	477.19	0 / -3.2	1.7 / -4.8	0.6 / -5.6	2.3 / -13.1	0.8 / -4.6
	Sutlej	2,447	2,466	2,494	2,458	1,583.35	1,513.23	1,420.54	1,343.78	-0.8 / -4.4	1.1 / -6.1	-1.4 / -5.4	0.4 / -15.1	-0.4 / -5.3
	Total	**6,756**	**6,779**	**6,840**	**6,812**	**5,488.63**	**5,343.06**	**5,116.86**	**4,829.21**	**-0.3 / -2.7**	**0.9 / -4.2**	**-0.4 / -5.6**	**0.8 / -12**	**0.1 / -4.2**
Grand Total		**25,893**	**25,905**	**26,079**	**25,986**	**26,130.26**	**25,713.63**	**25,166.12**	**24,571.19**	**0 / -1.6**	**0.7 / -2.1**	**-0.4 / -2.4**	**0.4 / -6**	**0.1 / -2**

increase in glacier area loss in the last decade (2010 – 2020), nearly doubling that of the previous decade (2000–2010). This indicates that even larger glaciers are experiencing accelerated loss due to climate change in recent decades.

Overall, the glacier area across all the classes has decreased significantly, with the only increase in numbers occurring in smallest glaciers of Class 1 (<0.5 km^2) (Figure 5.20). This trend reflects the shrinkage and fragmentation of larger glaciers that change into smaller sizes, while even the smaller glaciers are also diminishing in the area. This highlights the significant impact of climate change on glacial systems, suggesting that while larger glaciers are suffering severe losses, smaller glaciers are proliferating yet simultaneously experiencing area reductions.

The glaciers in the Indus River basin have undergone significant changes across different elevation ranges. In 1990, the lowest snout of a glacier in the Upper Indus basin was at 2,305 masl, but it has since shifted upward to 2,329 masl, indicating a retreat of about 20 metres over a thirty-year period. This retreat varies among different basins, sub-basins, and individual glaciers. Some glaciers in the Upper Indus basin are advancing or surging downward but have not reached elevations below this lowest point.

The glacier area-elevation distribution from 1990 to 2020 shows that the greatest area loss occurring between 4,500 and 6,000 masl, where over 1,246 km^2 (~ 6.1 %) of glacier area was lost from 1990 to 2020 (Figure 5.21 and Table 5.10). This elevation range contains the majority of the glacier area and has experienced a notable reduction in glacier extent across all decades, with the highest levels of loss observed in recent decades within each basin and sub-basin. Within these ranges, the most significant area loss occurred at 4,500 – 5,500 masl, emphasising the need for continued monitoring and adaptive strategies in response to climate impacts.

At the lower elevations, particularly below 3,000 masl, experienced minimal changes, indicating that the primary focus of glacier retreat was concentrated in the higher elevations. However, in terms of percentage loss, it experienced the highest relative area reduction, with losing 17 % and 11% of the glacier area in below 2,500 masl and 2,500 – 3,000 masl range respectively. The data also shows a more significant area loss between 2000 and 2010 compared to previous decades.

The higher elevation ranges above 6,500 masl maintained more stable conditions. Overall, the data highlights a clear need for urgent attention to the implications of glacier retreat on regional water resources and ecosystems.

A similar trend is evident in the slope classes, where glaciers on slopes of 20° – 30° have experienced the largest area loss, totaling nearly 572 km^2, or about 6% of the total glacier area in this class (Figure 5.22). Across all slope classes, there has been a notable increase in glacier area loss in recent decades compared to earlier periods. However, regarding glacier numbers, only the 20° – 30° slope class has seen a decline, while most other classes recorded a modest increase. Notably, the 10° – 20° slope class gained over 400 glaciers over three decades, representing a 9% rise from its original count

TABLE 5.20 INTERDECADAL GLACIER NUMBER AND AREA CHANGES ACROSS SIZE CLASSES IN THE INDUS RIVER BASIN.

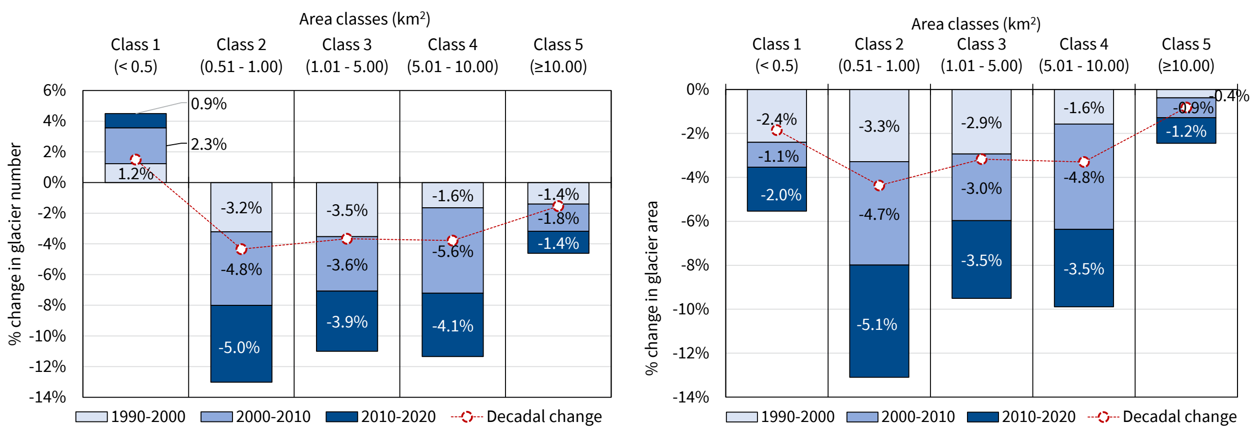
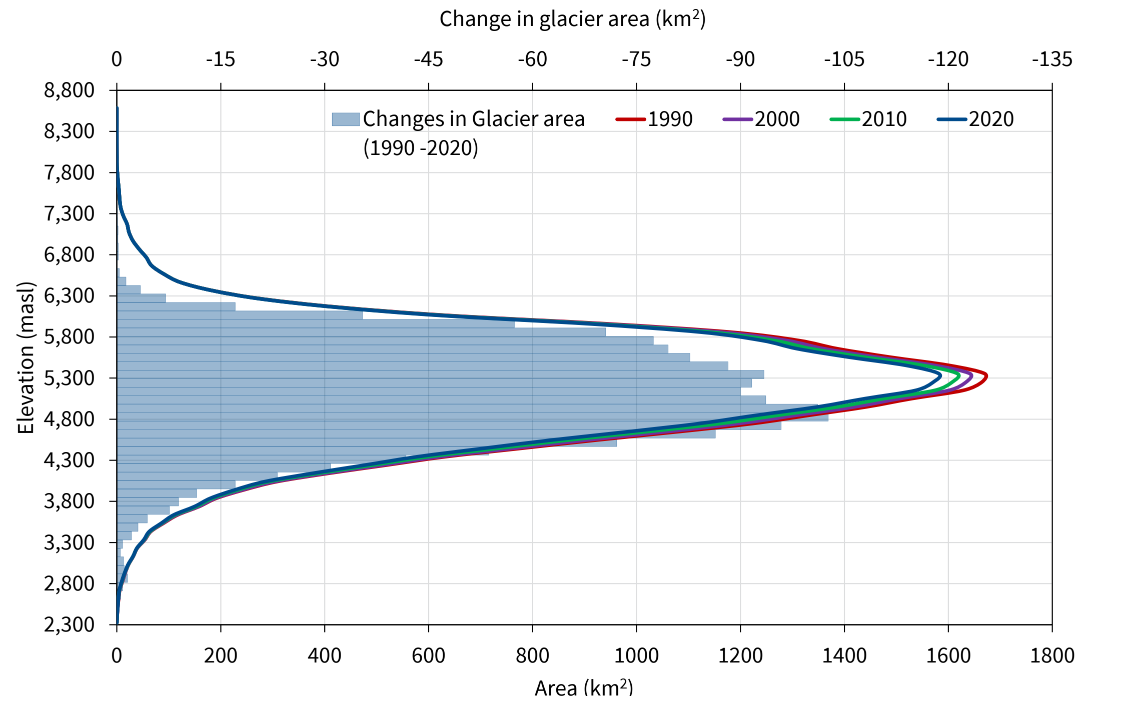


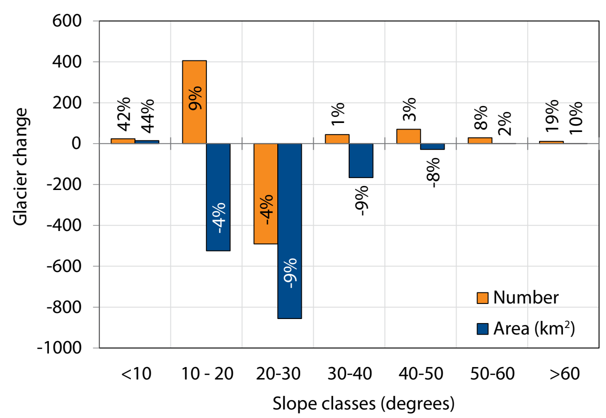
FIGURE 5.21 GLACIER AREA DISTRIBUTION AND CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE INDUS RIVER BASIN.



in 1990. This increase may be attributed to the shrinking of glaciers in steeper areas, as the average slope of individual glaciers is calculated based on the slope pixels bound by the glacier boundary.

Glacier changes across various mean aspects in the Indus basin between 1990 and 2020 indicate a distinct and consistent trend of overall glacial retreat, particularly evident in terms of area, even though glacier numbers occasionally increased (Figure 5.23). This pattern suggests a trend of glacier fragmentation or thinning, where larger glaciers shrink or break into smaller ones. Among

FIGURE 5.22 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES IN THE INDUS RIVER BASIN.



the different aspects, the northern, northeastern, and northwestern, home to the majority of glaciers in the basin, experienced the most pronounced changes, reflecting both severity and variability in glacial behaviour.

The northern aspect exhibited a steady rise in glacier numbers, increasing by nearly 3% over the three decades. However, this was accompanied by a significant area loss, amounting to approximately 7%, marking it as the second-highest area reduction among all aspects. The northwestern aspect followed a similar trend, with a 2% gain in glacier number but a 4% loss in glacier area, suggesting ongoing glacier shrinkage despite the slight increase in glacier number. In contrast, the northeastern aspect experienced the most severe changes, with a 2% reduction in glacier number and a substantial 10% loss in glacier area, highlighting its heightened vulnerability to climatic conditions.

In contrast, the southern, southeastern, and southwestern aspects, which are generally more exposed to solar radiation, showed smaller glacier numbers but still experienced significant area losses. The southern aspect lost 1% of its glaciers

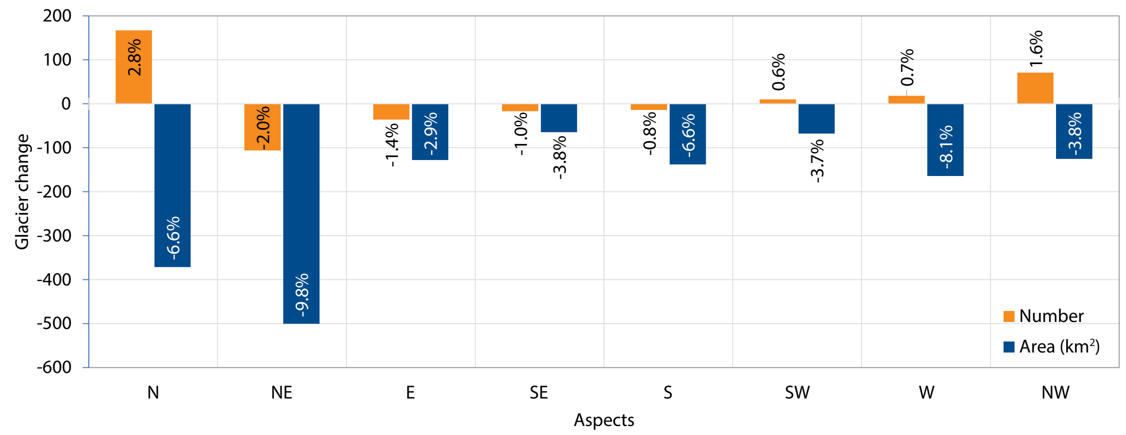
TABLE 5.10 GLACIER AREA DISTRIBUTION AND PERCENTAGE CHANGES ACROSS VARIOUS ELEVATION RANGES FROM 1990 TO 2020 IN THE INDUS RIVER BASIN.

Elevation range (masl)	Area (km²)				Area change (%)				
	1990	2000	2010	2020	1990 – 2000	2000 – 2010	2010 – 2020	1990 – 2020	Per decade
<2,500	1.05	1.05	0.89	0.88	0.0	-15.4	-1.8	-16.9	-5.7
2,500 – 3,000	38.94	38.03	35.52	34.89	-2.3	-6.6	-1.8	-10.4	-3.6
3,000 – 3,500	213.42	212.36	209.07	205.92	-0.5	-1.5	-1.5	-3.5	-1.2
3,500 – 4,000	801.83	793.88	770.81	752.29	-1.0	-2.9	-2.4	-6.2	-2.1
4,000 – 4,500	2,644.68	2,602.64	2,506.20	2,423.07	-1.6	-3.7	-3.3	-8.4	-2.9
4,500 – 5,000	6,000.07	5,883.35	5,709.63	5,520.38	-1.9	-3.0	-3.3	-8.0	-2.7
5,000 – 5,500	8,095.17	7,957.36	7,828.05	7,649.23	-1.7	-1.6	-2.3	-5.5	-1.9
5,500 – 6,000	6,310.70	6,209.53	6,100.56	5,990.30	-1.6	-1.8	-1.8	-5.1	-1.7
6,000 – 6,500	1,657.00	1,648.55	1,638.49	1,627.77	-0.5	-0.6	-0.6	-1.8	-0.6
6,500 – 7,000	288.84	288.35	288.51	288.10	-0.2	0.1	-0.1	-0.3	-0.1
7,000 – 7,500	69.11	69.08	68.94	68.91	-0.1	-0.2	-0.04	-0.3	-0.1
7,500 – 8,000	9.04	9.04	9.04	9.04	0.0	0.0	0.0	0.0	0.0
8,000 – 8,500	0.34	0.34	0.34	0.34	0.0	0.0	0.0	0.0	0.0
≥8,500	0.07	0.07	0.07	0.07	0.0	0.0	0.0	0.0	0.0
Total	26,130.26	25,713.62	25,166.13	24,571.19	-1.6	-2.1	-2.4	-6.0	-2.0

and 7% of its area, while the southeastern and southwestern aspects lost 4% each in area, despite minor fluctuations in glacier number. These patterns underscore the heightened sensitivity of southern-facing glaciers to warming temperatures.

The eastern and western aspects demonstrated the most contrasting behaviours. The eastern aspect, despite a 1% loss in glacier number, showed a moderate 3% reduction in area. Meanwhile, the western aspect gained a small number of glaciers (less than 1%) but lost a substantial 8% of its glacier area, suggesting extensive thinning or fragmentation of larger glaciers.

TABLE 5.23 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES IN THE INDUS RIVER BASIN.



LOWER NGOLE GLACIAL LAKE AFTER 2024 GLOF IN THE THAME VALLEY, EVEREST REGION, NEPAL.

STAKE PREPARATION FOR GLACIER MASS BALANCE MONITORING IN YALA GLACIER, LANGTANG VALLEY, NEPAL

5.3 Ganges River Basin

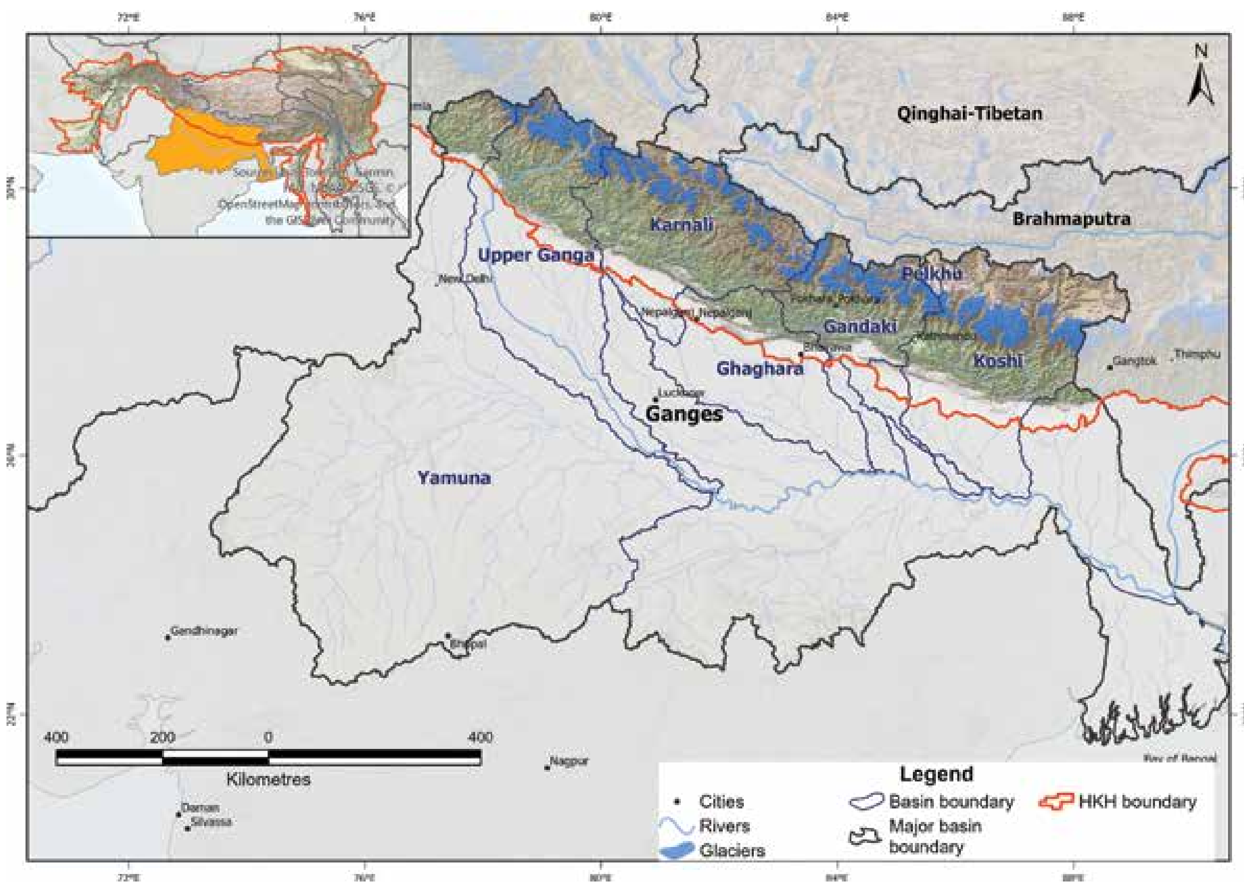
The Ganges River basin is a transboundary river system that spans four countries: Bangladesh, China, India and Nepal. The Ganges River originates from the confluence of the Bhagirathi and Alaknanda rivers at Devaprayag in Uttarakhand, India, and flows for approximately 2,500 km before reaching the Bay of Bengal (Bhadwal et al., 2017). The basin covers an area of about 1 million km², of which 244,806 km² lies within the HKH region. Its elevation ranges from sea level to 8,850 masl at the summit of Mount Everest (Bajracharya and Shrestha, 2011).

The glacierised regions of the Ganges River basin are divided into five basins and 26 sub-basins. The largest tributaries include the Yamuna, Upper Ganga, Ghagara (Kali and Karnali in western Nepal), Gandaki (or Narayani in central Nepal), and Koshi in eastern Nepal. In addition to that, the area of the Ganges River basin within the HKH region is 244,697 km², distributed between 27.53° – 31.42° N latitude and 77.98° – 88.70° E longitude. The five glacierised basins of the Ganges River basin are Koshi, Gandaki, Karnali, Upper Ganga, and Yamuna and one inland basin named Pelkhu. Figure 5.24 shows the glacier distribution across various basins and sub-basins within the Ganges River basin.

Glacier distribution in 2020

In 2020, 8,029 glaciers were mapped in the Ganges River basin, covering a total area of 7,518.52 km². These glaciers are distributed between 80° and 88.7° E longitude and 27.5° and 30.6° N latitude, with elevations ranging from 3,436 masl to 8,811 masl. Among these glaciers, 31% of the glacier area falls within the Koshi basin, followed by 25% in the Gandaki basin and 22% in the Upper Ganga basin (Figure 5.25 and Table 5.11). In terms of glacier numbers, the Karnali basin contains the highest number, with 2,461 glaciers (representing 31%), followed by the Koshi basin with 2,129 glaciers (27%). Despite being a smaller glacier area, the Karnali basin has the highest number of glaciers, largely due to the presence of many small glaciers.

FIGURE 5.24 MAP SHOWING GLACIER DISTRIBUTION AND EXTENT OF THE GANGES RIVER BASIN WITHIN THE HKH REGION.



Within the sub-basins, the Arun sub-basin stands out as it contains the largest number and area of glaciers, with 963 glaciers (about 12% of the total), covering 15% of the total glacier area in the Ganges River basin. However, the Yamuna basin is an exception, accounting for only 2% of both the glacier number and area. This indicates a somewhat uneven distribution of glaciers across the basins.

The size of the glaciers varies significantly, ranging from the smallest at 0.02 km² to the largest, the Gangotri glacier, which measures 125.8 km² and is in the Bhagirathi sub-basin at Uttarakhand, India. This is the only glacier in the river basin that exceeds 100 km² in size. Additionally, there are five other glaciers larger than 50 km², with four of these found in the Koshi basin and one in the Upper Ganga basin.

The distribution of glaciers in various area size classes shows the glaciers in this River basin are predominantly smaller in size, with a remarkable over 71% of the glaciers are in size Class 1, measuring less than 0.5 km². However, this class contributes only 12.5% of the total glacier area and holds only 4% of the total estimated ice reserves in the River basin (Figure 5.25).

Moving to larger size classes, Class 2 glaciers (0.51 – 1.00 km²) make up 12% of the total number, covering 9% of the total glacier area and containing 4% of the ice reserves. Class 3 glaciers (1.01 – 5.00 km²) represent 13% of the total number but account for a more significant 30% of the total area and 21% of the ice estimated reserves, with a mean area of 2.1 km².

In contrast, largest sized glaciers Class 4 (5.01 – 10.00 km²) and Class 5 (≥ 10.00 km²) consists of fewer number but considerably more impactful. Class 4 consists of only 2% of the total glaciers, contributing 13% to the total area and 14% to the total estimated ice reserves. Class 5, though the smallest group with just 1% of the total number, covers 36% of the glacier area and contains 58% of the estimated ice reserves, demonstrating their crucial role in the basin's glacial dynamics.

The elevation of glaciers in the Ganges River basin varies from 3,436 masl to 8,811 masl. The lowest glacier is found in the Gandaki basin, while the highest is in the Koshi basin, which also features the most extensive range of glacier elevations, spanning from 3,768 masl to 8,811 masl. In contrast, the Yamuna basin has a narrower range, with elevations between 3,970 masl and 6,295 masl. The Gandaki basin has elevations ranging from 3,436 masl to 8,105 masl, and the Karnali basin ranges from 3,571 masl to 7,622 masl.

The distribution of glacier areas across different elevation ranges in the Ganges River basin reveals that over 81% of the glacier area is concentrated between 5,000 and 6,500 masl, with the majority (more than 64%) located within the 5,000 – 6,000 masl range. This distribution varies among the five basins: Yamuna, Upper Ganga, Karnali, Gandaki, and Koshi (Figure 5.26 and Table 5.12).

At elevations of 3,000 to 3,500 masl, glacier presence is minimal, with only the Karnali and Gandaki basins showing slight coverage. In the 3,500 to 4,000 masl range, glacier prominence increases, particularly in the Karnali and Gandaki basins, which cover 0.64% and 0.7% of the glacier area within their respective basins.

FIGURE 5.25 **GLACIERS DISTRIBUTIONS ACROSS VARIOUS BASINS** (TOP LEFT)**, AREA CLASSES** (TOP RIGHT)**, MEAN SLOPES** (BOTTOM LEFT) **AND ASPECTS** (BOTTOM RIGHT) **IN THE GANGES RIVER BASIN.**

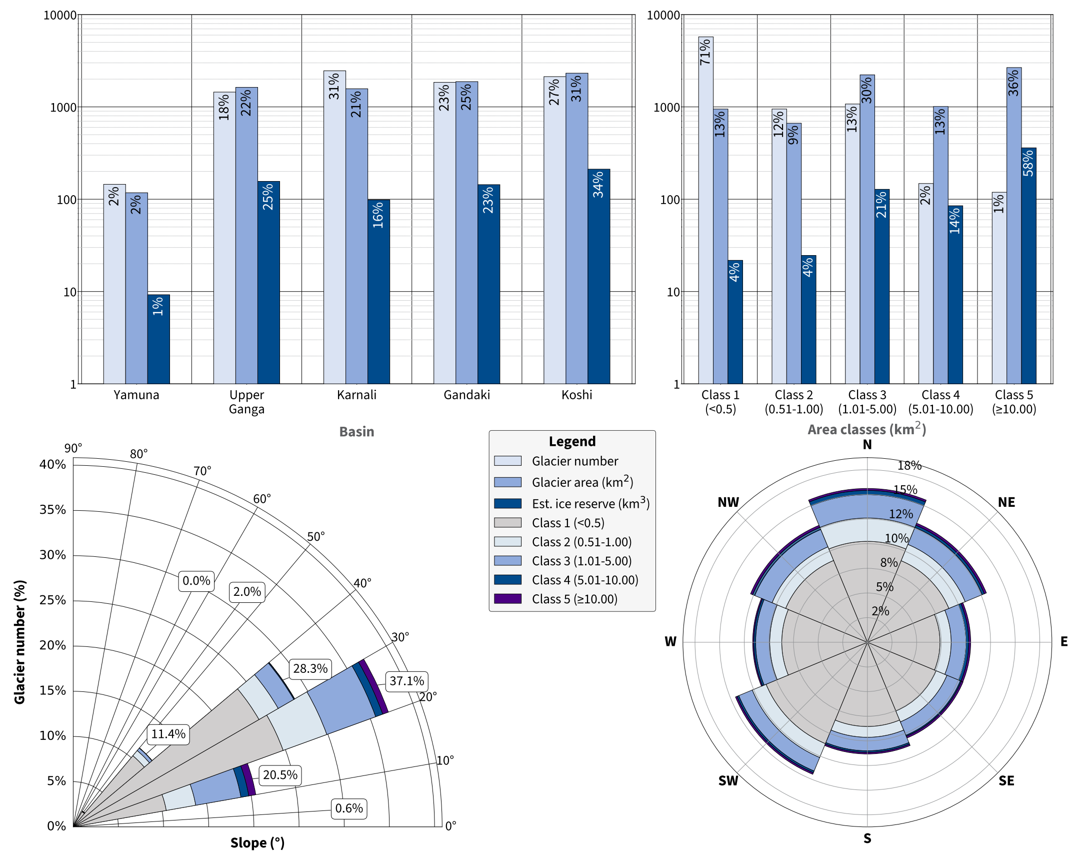


TABLE 5.11 **DISTRIBUTION OF GLACIERS IN SUB-BASINS AND BASINS OF THE GANGES RIVER BASIN.**

Basin	Sub-basins	Number	Area (km²)	Largest area (km²)	Estimated ice reserve (km³)	Elevation (masl)		Mean slope (deg)
						Min	Max	
Yamuna	Tons	128	111.92	22.80	9.04	3,970	6,295	28
	Yamuna	17	5.54	1.30	0.19	4,462	5,481	24
	Total	**145**	**117.46**	**22.80**	**9.23**	**3,970**	**6,295**	**28**
Upper Ganga	Bhagirathi	505	606.74	125.80	67.64	4,083	6,936	28
	Bhilanga	54	80.20	30.14	7.42	4,150	6,570	27
	Mandakini	69	39.82	5.83	2.03	3,927	6,676	30
	Alaknanda	716	829.57	48.24	74.67	3,816	7,454	29
	Pindar	104	71.88	10.24	4.42	3,944	6,733	33
	Total	**1,448**	**1,628.20**	**125.80**	**156.19**	**3,816**	**7,454**	**29**
Karnali	Kali	746	521.87	48.95	38.38	3,571	7,050	30
	West Seti	284	125.98	12.34	6.00	4,124	6,981	31
	Kawari	37	24.60	6.40	1.26	3,652	6,856	24
	Humla	740	448.55	12.57	25.12	4,361	7,622	27
	Mugu	204	104.22	7.43	4.95	4,531	6,815	28
	Tila	56	22.50	6.00	1.06	4,273	6,297	34
	Bheri	394	324.49	23.95	21.56	4,168	7,549	31
	Total	**2,461**	**1,572.21**	**48.95**	**98.33**	**3,571**	**7,622**	**29**
Gandaki	Kali Gandaki	508	504.19	27.43	36.97	4,009	8,105	29
	Seti	40	69.60	44.13	8.05	3,960	7,629	38
	Marshyangdi	407	464.49	28.25	36.47	3,656	7,713	31
	Budi Gandaki	382	393.58	29.85	29.04	3,436	7,995	32
	Trishuli	509	448.05	45.52	33.37	3,716	7,366	31
	Total	**1,846**	**1,879.92**	**45.52**	**143.91**	**3,436**	**8,105**	**31**
Koshi	Indrawati	34	13.20	4.09	0.58	4,863	5,869	23
	Sunkoshi	211	187.54	22.82	14.02	4,075	7,972	29
	Tamakoshi	336	248.02	30.07	19.81	4,451	7,324	28
	Likhu	29	18.73	7.73	1.11	4,479	6,694	24
	Dudh Koshi	295	350.18	75.75	34.94	4,416	8,320	30
	Arun	963	1,140.81	64.21	102.00	3,768	8,811	26
	Tamor	261	362.25	71.98	39.30	4,231	8,465	27
	Total	**2,129**	**2,320.73**	**75.75**	**211.75**	**3,768**	**8,811**	**27**
Grand Total		**8,029**	**7,518.52**	**125.80**	**619.41**	**3,436**	**8,811**	**29**

FIGURE 5.26 GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN THE GANGES RIVER BASIN.

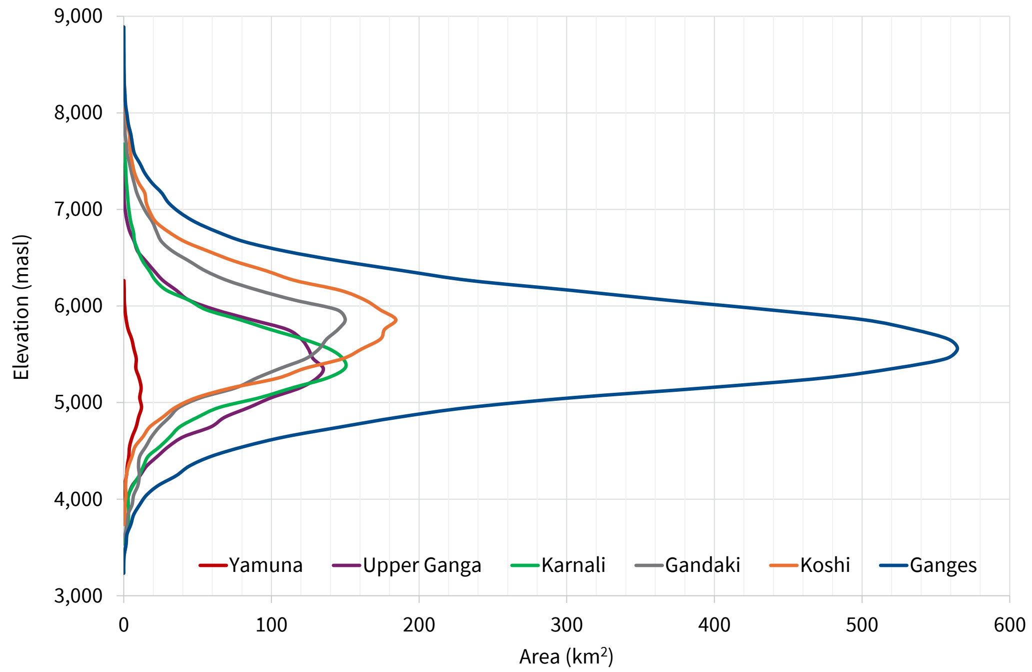


TABLE 5.12 ELEVATION-WISE GLACIER AREA AND PERCENTAGE DISTRIBUTION IN THE GANGES RIVER BASIN.

Elevation range (masl)	Yamuna		Upper Ganga		Karnali		Gandaki		Koshi		Ganges	
	km²	%	km²	%	km²	%	km²	%	km²	%	km²	%
3,000 - 3,500							0.45	0.02			0.45	0.01
3,500 - 4,000	0.07	0.06	1.23	0.08	10.11	0.6	13.04	0.69	1.59	0.07	26.04	0.3
4,000 - 4,500	8.88	7.6	58.49	3.6	49.95	3.2	47.71	2.5	13.36	0.6	178.39	2.4
4,500 - 5,000	40.20	34.2	283.30	17.4	208.79	13.3	126.46	6.7	99.89	4.3	758.64	10.1
5,000 - 5,500	49.72	42.3	613.58	37.7	641.92	40.8	447.06	23.8	497.42	21.4	2,249.71	29.9
5,500 - 6,000	17.71	15.1	504.36	31.0	494.03	31.4	709.46	37.7	869.78	37.5	2,595.35	34.5
6,000 - 6,500	0.88	0.7	142.02	8.7	124.95	7.9	376.82	20.0	597.47	25.7	1,242.13	16.5
6,500 - 7,000			24.27	1.5	32.29	2.1	115.66	6.2	168.63	7.3	340.85	4.5
7,000 - 7,500			0.95	0.1	9.84	0.6	36.82	2.0	52.75	2.3	100.37	1.3
7,500 - 8,000					0.33	0.02	6.20	0.3	16.83	0.7	23.36	0.3
8,000 - 8,500							0.24	0.01	2.70	0.1	2.95	0.04
>8500									0.30	0.01	0.30	0.00
Total	117.46	100.0	1628.20	100.0	1,572.21	100.0	1,879.92	100.0	2,320.73	100.0	7,518.52	100.0

As elevation rises to 4,000 to 5,000 masl, glacier distribution becomes more significant, especially in the Upper Ganga, Karnali, and Gandaki basins, which account for 21%, 16.5%, and 9.5% of the total glacier area in these basins, respectively. In the subsequent elevation range of 5,000 to 5,500 masl, the Upper Ganga and Karnali basins dominate, covering 37.7% and 40.8% of the glacier area within those basins. Meanwhile, the Koshi and Gandaki basins maintain substantial coverage at 5,500 to 6,000 masl elevation range, with 37.5% and 37.7% of the total glacier area within those basins respectively. This indicates that the 5,000 to 6,000 masl range is critical for glacier mass across the Ganges River basin.

In the higher elevations of 6,000 to 6,500 masl, the Gandaki and Koshi basins remain significant contributors, with glacier coverage of 20% and 25.7%, respectively. This distribution suggests that glaciers are evenly spread among the basins between 5,000 and 6,500 masl, except in the Yamuna basin, which consistently shows lower glacier coverage compared to the other four basins. However, at elevations above 7,000 masl, glacier coverage declines sharply, reflecting the steep topography and harsh environmental conditions that limit glacier sustainability.

The analysis of glacier distribution across various mean slope classes reveals important insights into how slope gradients influence glacier characteristics. In this river basin, the 10° – 20° and 20° – 30° slope classes dominate, collectively accounting for 54.5% of the total number of glaciers, covering over 83% of the glacierised area and holding 91% of the estimated ice reserves.

While the 30° – 40° slope class contains approximately 30% of the total number of glaciers, its contribution to glacier area and estimated ice reserves is significantly lower, at 12.8% and 7%, respectively, compared to the 10° – 20° and 20° – 30° classes (Figure 5.25). In higher slope classes, there is a marked decline in the number, area, and estimated ice reserves of glaciers, indicating unfavourable conditions for glacier formation and sustainability.

As slope steepness increases, both the number and size of glaciers decrease. This trend is reflected in the mean glacier area for each slope class, which ranges from 0.1 to 0.4 km² in slopes greater than 30°. In contrast, the mean area of glaciers in slope classes below 30° ranges from 1 to 2 km², with the highest mean area observed in the 10° – 20° class. Overall, this distribution trend highlights the significant impact of slope characteristics on glacier dynamics and the potential consequences of climate change for glacier health in the region.

The distribution of glaciers across various aspects in the Ganges River basin is relatively balanced, with a noticeable concentration in the northern and northeastern directions. The northern (N), northeastern (NE), and northwestern (NW) aspects collectively account for approximately 41% of the total glacier number (Figure 5.25), while contributing about 46% of the total glacier area and 47% of the estimated ice reserves. Among these, the northern aspect stands out as the most dominant, hosting 16% of glaciers, 18% of the glacier area, and 19% of the total estimated ice reserves. Notably, all three aspects exhibit mean glacier sizes of 1 km² or more, indicating not just a higher number of glaciers, but also substantial glacier area and reserves.

In comparison, the southern (S), southeastern (SE), and southwestern (SW) aspects each contain a similar number of glaciers, with the southwestern aspect slightly ahead, comprising 14% of the total glacier number. However, these three aspects each contribute only about 10 – 11% of the glacier area and between 10 – 13% of the estimated ice reserves, with the southern aspect showing a slightly higher proportion in both. This suggests a fairly even glacier presence in these aspects, with moderately sized glaciers contributing meaningfully to the basin's estimated ice reserves.

The eastern (E) aspect, despite hosting only 10% of the glaciers, contributes a relatively higher 12% of the glacier area and 13% of the estimated ice reserves, and features the largest mean glacier size at 1.11 km². This implies that glaciers in the eastern aspect are fewer but comparatively larger in size, playing a significant role in the basin's glacial landscape.

The western aspect stands out as the least glacier distribution among all, with only 12% of the glacier number, 9% of the glacier area, and 8% of the total estimated ice reserves. The glaciers in this aspect are also among the smallest, with a mean size of 0.74 km², highlighting a relatively minimal glacial distribution in this aspect of the basin.

Decadal glacier changes from 1990s to 2020

The changes in glaciers within the Ganges River basin from 1990 to 2020 reveal alarming trends of retreat, with significant variations in loss across different basins. The Koshi and Karnali basins experienced the most substantial reductions, with total glacier area declines of 21.4% and 25.4%, averaging 7.7% and 9.3% per decade, respectively (Figure 5.27 and Figure 5.28). In contrast, the Upper Ganga basin showed a notable 6.7% increase in the number of glaciers, although it faced a significant area loss of 18.6%, averaging 6.6% per decade. The Gandaki basin also recorded an overall decline of 18.5% of glacier area over three decades, maintaining a similar average decadal change of 6.6%. While its retreat rates are slightly lower than

FIGURE 5.27 DECADAL CHANGE IN GLACIER NUMBER WITHIN EACH BASIN OF THE GANGES RIVER BASIN.

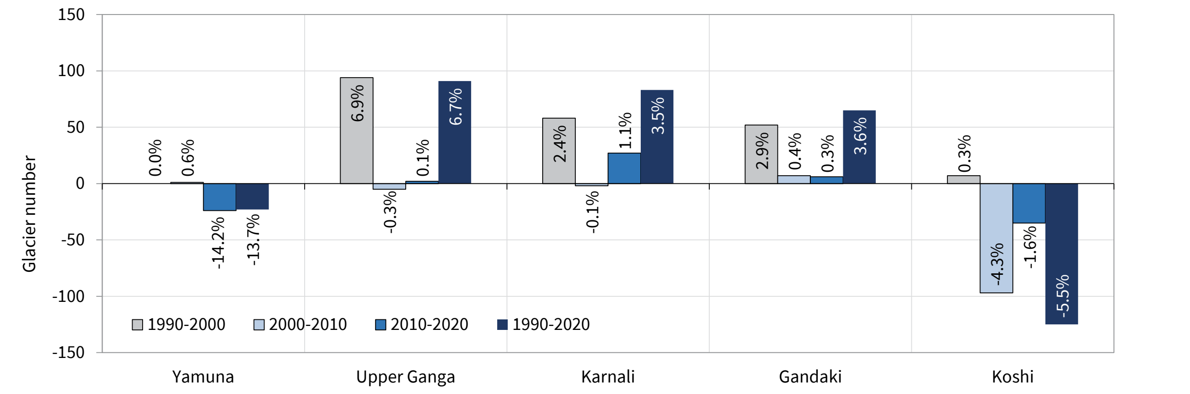
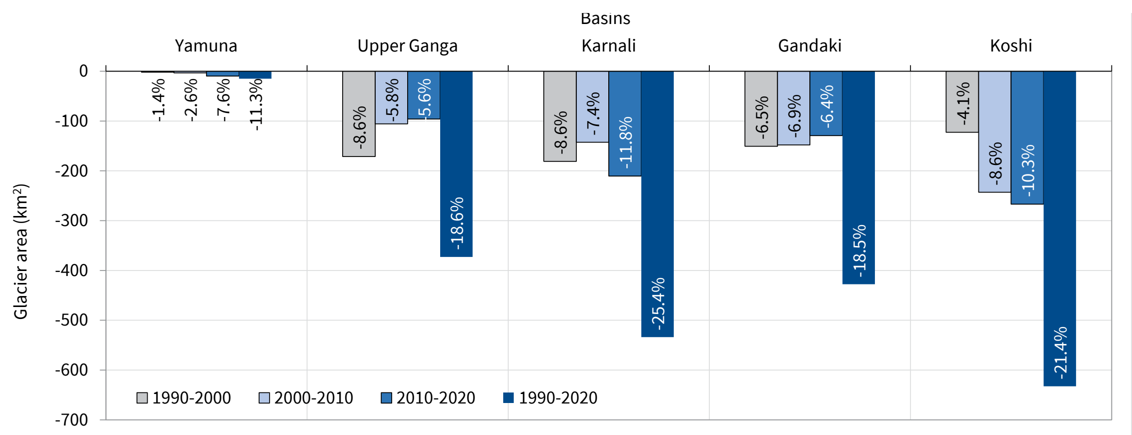


FIGURE 5.28 DECADAL CHANGE IN GLACIER AREA WITHIN EACH BASIN OF THE GANGES RIVER BASIN.



those of the Upper Ganga, the persistent decline raises concerns about future water resources. Lastly, the Yamuna basin experienced a total decrease of 11.3%, with an average loss of 3.9% per decade. This rapid retreat has serious implications for local hydrology and the ecosystems dependent on these glaciers.

Interdecadal analysis reveals contrasting patterns in changes to glacier area and number (Figure 5.27, Figure 5.28 and Table 5.13). For instance, the Upper Ganga basin showed greater area loss in the first decade (1990 – 2000) compared to subsequent decades. Conversely, the Koshi basin experienced more than double the area loss in the last two decades compared to the first. Similar fluctuating patterns of interdecadal changes are observed across the other basins, with varying losses in different decades. Notably, the number of glaciers increased in nearly all basins during each decade, except for the Yamuna and Koshi basins. The Koshi basin showed a slight increase in glacier numbers during the first decade (1990 – 2000), but these numbers significantly declined in the following decades. Similarly, the Yamuna basin showed no change in glacier numbers from 1990 to 2010, but it experienced losses in the recent decade (2010 – 2020). This trend signifies not only the shrinkage and fragmentation of glaciers but also an increasing number of glaciers disappearing or shrinking below the threshold size in recent decades.

Overall, glaciers in the Ganges River basin have shrunk approximately by 21% over three decades, with an average decadal loss of 7.5%, while the number of glaciers increased by 1.1%. However, the interdecadal trend indicates a rising pattern of glacier area loss, particularly pronounced in the recent decade from 2010 to 2020.

TABLE 5.13 DECADAL CHANGE IN GLACIER NUMBER AND AREA IN THE GANGES RIVER BASIN AND ITS SUB-BASINS AND BASINS FROM 1990 – 2020.

Basin	Sub-basins	Number				Area (km²)				Decadal change in number / area (%)				Change per decade – number/ area (%)
		1990	2000	2010	2020	1990	2000	2010	2020	1990 – 2000	2000 – 2010	2010 – 2020	1990 – 2020	
Yamuna	Tons	151	151	152	128	125.74	124.12	121.01	111.92	0 / -1.3	0.7 / -2.5	-15.8 / -7.5	-15.2 / -11	-5 / -3.8
	Yamuna	17	17	17	17	6.68	6.39	6.08	5.54	0 / -4.3	0 / -4.8	0 / -8.8	0 / -17	0 / -6
	Total	168	168	169	145	132.41	130.51	127.09	117.46	0 / -1.4	0.6 / -2.6	-14.2 / -7.6	-13.7 / -11.3	-4.5 / -3.9
Upper Ganga	Bhagirathi	480	499	505	505	728.66	667.93	634.93	606.74	4 / -8.3	1.2 / -4.9	0 / -4.4	5.2 / -16.7	1.7 / -5.9
	Bhilanga	49	53	52	54	94.40	87.47	83.97	80.20	8.2 / -7.3	-1.9 / -4	3.8 / -4.5	10.2 / -15	3.4 / -5.3
	Mandakini	59	61	66	69	55.33	46.42	43.00	39.82	3.4 / -16.1	8.2 / -7.4	4.5 / -7.4	16.9 / -28	5.4 / -10.3
	Alaknanda	675	742	723	716	1,024.18	939.97	881.20	829.57	9.9 / -8.2	-2.6 / -6.3	-1 / -5.9	6.1 / -19	2.1 / -6.8
	Pindar	94	96	100	104	98.42	87.86	81.00	71.88	2.1 / -10.7	4.2 / -7.8	4 / -11.3	10.6 / -27	3.4 / -9.9
	Total	**1,357**	**1,451**	**1,446**	**1,448**	**2,000.99**	**1,829.65**	**1,724.09**	**1,628.20**	**6.9 / -8.6**	**-0.3 / -5.8**	**0.1 / -5.6**	**6.7 / -18.6**	**2.2 / -6.6**
Karnali	Kali	719	739	734	746	688.88	632.25	591.73	521.87	2.8 / -8.2	-0.7 / -6.4	1.6 / -11.8	3.8 / -24.2	1.2 / -8.8
	West Seti	250	262	268	284	190.19	162.45	145.94	125.98	4.8 / -14.6	2.3 / -10.2	6 / -13.7	13.6 / -33.8	4.4 / -12.8
	Kawari	48	48	48	37	37.14	33.42	29.13	24.60	0 / -10	0 / -12.8	-22.9 / -15.5	-22.9 / -33.8	-7.6 / -12.8
	Humla	692	706	702	740	596.18	555.41	506.74	448.55	2 / -6.8	-0.6 / -8.8	5.4 / -11.5	6.9 / -24.8	2.3 / -9
	Mugu	208	209	207	204	142.67	130.02	118.77	104.22	0.5 / -8.9	-1 / -8.7	-1.4 / -12.3	-1.9 / -27	-0.6 / -9.9
	Tila	53	56	60	56	33.14	29.29	26.72	22.50	5.7 / -11.6	7.1 / -8.8	-6.7 / -15.8	5.7 / -32.1	2 / -12.1
	Bheri	408	416	415	394	417.97	382.43	363.53	324.49	2 / -8.5	-0.2 / -4.9	-5.1 / -10.7	-3.4 / -22.4	-1.1 / -8.1
	Total	**2,378**	**2,436**	**2,434**	**2,461**	**2,106.17**	**1,925.27**	**1,782.56**	**1,572.21**	**2.4 / -8.6**	**-0.1 / -7.4**	**1.1 / -11.8**	**3.5 / -25.4**	**1.2 / -9.3**
Gandaki	KaliGandaki	497	506	511	508	594.64	564.76	533.66	504.19	1.8 / -5	1 / -5.5	-0.6 / -5.5	2.2 / -15.2	0.7 / -5.4
	Seti	40	44	44	40	79.66	75.45	71.63	69.60	10 / -5.3	0 / -5.1	-9.1 / -2.8	0 / -12.6	0.3 / -4.4
	Marshyangdi	368	386	395	407	535.08	519.31	492.65	464.49	4.9 / -2.9	2.3 / -5.1	3 / -5.7	10.6 / -13.2	3.4 / -4.6
	BudiGandaki	373	376	377	382	488.11	456.92	432.60	393.58	0.8 / -6.4	0.3 / -5.3	1.3 / -9	2.4 / -19.4	0.8 / -6.9
	Trishuli	503	521	513	509	610.21	540.65	478.60	448.05	3.6 / -11.4	-1.5 / -11.5	-0.8 / -6.4	1.2 / -26.6	0.4 / -9.8
	Total	**1,781**	**1,833**	**1,840**	**1,846**	**2,307.69**	**2,157.09**	**2,009.15**	**1,879.92**	**2.9 / -6.5**	**0.4 / -6.9**	**0.3 / -6.4**	**3.6 / -18.5**	**1.2 / -6.6**
Koshi	Indrawati	37	37	37	34	20.14	18.36	16.35	13.20	0 / -8.9	0 / -10.9	-8.1 / -19.3	-8.1 / -34.5	-2.7 / -13
	Sun Koshi	211	211	214	211	255.03	247.66	227.83	187.54	0 / -2.9	1.4 / -8	-1.4 / -17.7	0 / -26.5	0 / -9.5
	Tama Koshi	372	361	346	336	358.23	341.67	297.14	248.02	-3 / -4.6	-4.2 / -13	-2.9 / -16.5	-9.7 / -30.8	-3.3 / -11.4
	Likhu	28	28	28	29	27.32	25.31	23.03	18.73	0 / -7.3	0 / -9	3.6 / -18.7	3.6 / -31.4	1.2 / -11.7
	Dudh Koshi	281	290	297	295	453.56	425.45	390.71	350.18	3.2 / -6.2	2.4 / -8.2	-0.7 / -10.4	5 / -22.8	1.6 / -8.2
	Arun	1,075	1,076	977	963	1390.58	1,350.32	1,246.78	1,140.81	0.2 / -2.8	-9.2 / -7.7	-1.5 / -8.6	-10.4 / -18	-3.5 / -6.4
	Tamor	250	258	265	261	448.40	421.96	385.77	362.25	3.2 / -5.9	2.7 / -8.6	-1.5 / -6.1	4.4 / -19.2	1.5 / -6.9
	Total	**2,254**	**2,261**	**2,164**	**2,129**	**2,953.26**	**2,830.73**	**2,587.60**	**2,320.73**	**0.4 / -4.1**	**-4.3 / -8.6**	**-1.7 / -10.4**	**-5.5 / -21.4**	**-1.9 / -7.7**
Grand Total		**7,938**	**8,149**	**8,053**	**8,029**	**9,500.52**	**8,873.24**	**8,230.50**	**7,518.52**	**2.7 / -6.6**	**-1.2 / -7.2**	**-0.3 / -8.7**	**1.1 / -20.9**	**0.4 / -7.5**

In terms of area class, all glacier size categories in the Ganges River basin exhibited a negative trend, consistently losing area across the decades (Figure 5.29). Among them, the mid-sized glaciers in Class 3 (1.01 – 5.00 km²) and the largest glaciers in Class 5 (≥ 10.00 km²) experienced the most significant reductions in area, each losing over 600 km². Specifically, the largest glaciers in Class 5 (≥10 km²) lost an astounding 704.75 km² over three decades. In percentage terms, Class 4 (5.01 – 10.00 km²) and Class 2 (0.51 – 1.00 km²) showed the highest area losses, with declines of 28.0% and approximately 26.6%, respectively, amounting to area losses of 393.30 km² and 241.67 km² over the same period. Interestingly, mid-sized glaciers in Class 3 experienced a slightly higher percentage loss of 21.3% compared to the 20.9% loss seen in the largest size class.

In contrast, the number of glaciers generally followed a negative trend across most size classes, except for the smallest size class (< 0.5 km²), which showed an increase in numbers during all decades. This rise can be attributed to the fragmentation of larger glaciers as they retreat and lose mass and the area loss in all the size classes indicates the shrinkage of glaciers in all classes. The number of glaciers in the larger classes (Classes 2 to 5) showed notable reductions, with more significant losses observed in Class 2.

Regarding interdecadal changes, a similar pattern is observed across the decades (Figure 5.29). The smallest size class is the only one that showed a slight area increase during the 1990 – 2000 decade, while other classes experienced continued loss.

The glaciers in the Ganges River basin have undergone significant changes across various elevation ranges. Notably, the lowest glacier snout has shifted upward by 162 metres, moving from 3,274 masl in 1990 to 3,436 masl in 2020. This shift indicates a complete loss of glacier area below 3,400 masl over the past three decades. The upward movement of the lowest elevation varies from basin to basin, and this trend is observed consistently across different basins and sub-basins within the region.

The glacier area distribution in various elevation ranges from 1990 to 2020 highlights significant area losses in most elevation ranges. The greatest loss occurred between 5,000 masl and 5,500 masl range, where there was a 26% reduction in area over three decades (Figure 5.30 and Table 5.14). This elevation range also contains the majority of the glacierised area, making this decline particularly concerning. Notably, the lowest elevation range below 3,400 masl experienced a complete loss of its glacial area over the three decades.

Above 3,500 masl, glacier area distribution became more pronounced, with increasing amounts of area loss observed, particularly up to the 5,500 masl range. In terms of percentage, the area losses ranged from 35.3% in the 3,500 – 4,000 masl range to 26% in the 5,000 – 5,500 masl range. While the percentage losses are significant at lower elevations, the absolute area loss was highest in the 5,000 – 5,500 masl range, reflecting both its size and the impact of climate change.

For elevations above 5,500 masl, the absolute area / percentage loss gradually decreased up to 6,500 masl, with minimal loss observed beyond this elevation.

FIGURE 5.29 **INTERDECADAL GLACIER NUMBER AND AREA CHANGES ACROSS SIZE CLASSES OVER THREE DECADES IN THE GANGES RIVER BASIN.**

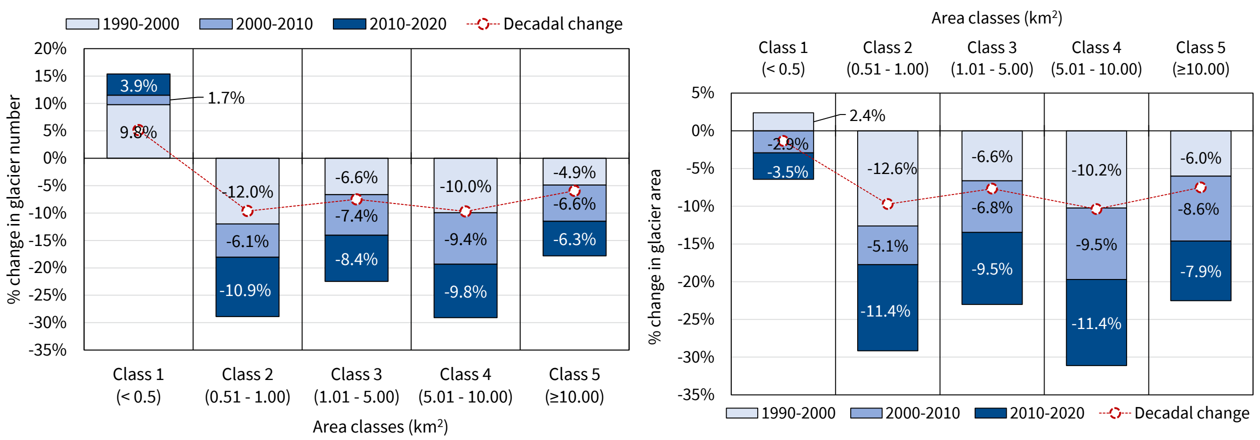


FIGURE 5.30 GLACIER AREA DISTRIBUTION AND CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE GANGES RIVER BASIN.

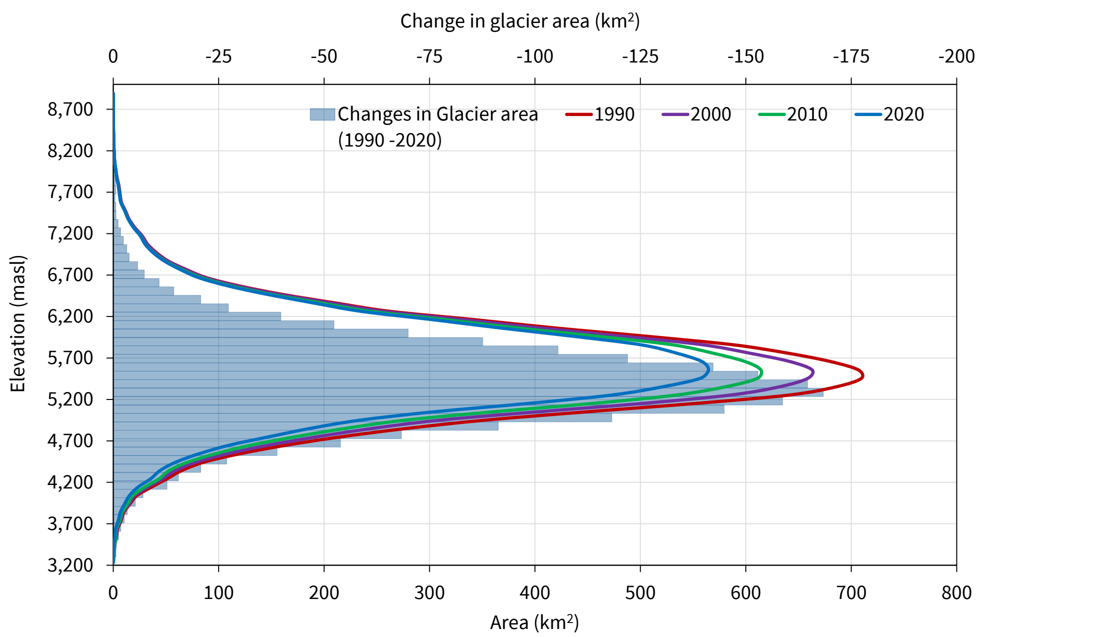


TABLE 5.14 GLACIER AREA DISTRIBUTION AND PERCENTAGE CHANGES ACROSS VARIOUS ELEVATION RANGES FROM 1990 TO 2020 IN THE GANGES RIVER BASIN.

Elevation range (masl)	Area (km²)				Area change (%)				
	1990	2000	2010	2020	1990 - 2000	2000 - 2010	2010 - 2020	1990 - 2020	Per decade
3,000 – 3,500	1.94	1.90	1.81	0.45	-1.8	-5.1	-75.3	-77.0	-27.4
3,500 – 4,000	40.27	37.17	33.42	26.04	-7.7	-10.1	-22.1	-35.3	-13.3
4,000 – 4,500	261.3.0	237.76	216.03	178.39	-9.0	-9.1	-17.4	-31.7	-11.9
4,500 – 5,000	1,129.26	1,002.01	895.30	758.64	-11.3	-10.6	-15.3	-32.8	-12.4
5,000 – 5,500	3,039.10	2,781.53	2,542.01	2,249.71	-8.5	-8.6	-11.5	-26.0	-9.5
5,500 – 6,000	3,122.50	2,953.15	2,773.75	2,595.35	-5.4	-6.1	-6.4	-16.9	-6.0
6,000 – 6,500	1,396.57	1,358.00	1,291.78	1,242.13	-2.8	-4.9	-4.0	-11.2	-3.9
6,500 – 7,000	371.80	366.65	349.59	340.85	-1.4	-4.7	-2.5	-8.3	-2.8
7,000 – 7,500	106.96	106.36	100.69	100.37	-0.6	-5.3	-0.3	-6.2	-2.1
7,500 – 8,000	25.29	25.06	23.01	23.36	-0.9	-8.2	1.5	-7.6	-2.5
8,000 – 8,500	3.04	3.10	2.80	2.95	1.8	-9.5	5.2	-3.0	-0.8
>8,500	0.30	0.30	0.30	0.30	0.0	0.0	0.0	0.0	0.0
Total	9,498.33	8,872.98	8,230.50	7,518.52	-6.6	-7.2	-8.7	-20.9	-7.5

This trend indicates that while the lower and mid-elevation ranges are experiencing severe declines, the higher elevations are somewhat more stable, although still affected by broader climatic changes. Overall, these patterns underscore the alarming trends of glacier retreat across the Ganges River basin, particularly in critical lower elevation areas.

Additionally, the same trend of glacier area loss was evident across all basins and sub-basins. The inter-decadal changes reveal that from 2010 to 2020, there was a notable decline in glacier areas, underscoring the accelerated effects of climate change in the recent decade.

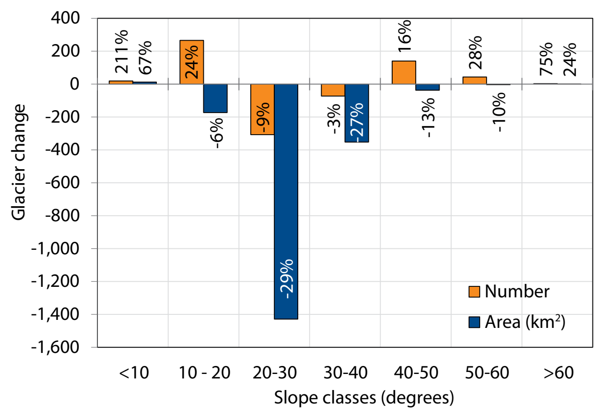
The decadal analysis of glacier changes over the past three decades highlights a clear relationship between glacier dynamics and mean slope classes, with both glacier number and area showing distinct trends across slope classes. Slopes in the 10° – 20° range experienced the largest increase in glacier number, gaining 266 glaciers, yet paradoxically also recorded a significant area loss of around 173 km², indicating widespread glacier fragmentation rather than growth. In comparison, gentler slopes (<10°) showed a modest increase of 19 glaciers and a relatively small increases in area about 12 km².

Mid-slope ranges, particularly 20° – 30° and 30° – 40°, showed the most dramatic area losses, with glacier shrinkage reaching 29% and 27% respectively (Figure 5.31). These classes also recorded significant declines in glacier numbers, underscoring their vulnerability to climate-driven retreat. Conversely, glaciers on steeper slopes (40° – 50° and 50° – 60°) experienced moderate increases in glacier numbers by 140 and 43 glaciers, respectively, though they too lost substantial glacier area, over 13% and 10%, respectively, highlighting continued glacial mass loss despite numerical gains. The steepest slopes (>60°) showed the least change, with slight increases in both glacier number and area.

Overall, these trends suggest that glacier fragmentation, rather than net formation, is a dominant process driving the observed increase in glacier numbers in certain slope classes. The consistent area loss across nearly all slope ranges and decades further supports the notion that shrinking and fragmenting glaciers alter their mean slope characteristics, thereby contributing to the varied increases and losses in glacier numbers observed across the basin.

Over the past three decades, glacier changes across various mean aspects have consistently shown a significant reduction in glacier area, regardless

FIGURE 5.31 GLACIER NUMBER AND AREA CHANGES ACROSS VARIOUS MEAN SLOPE CLASSES OVER THREE DECADES IN THE GANGES RIVER BASIN.



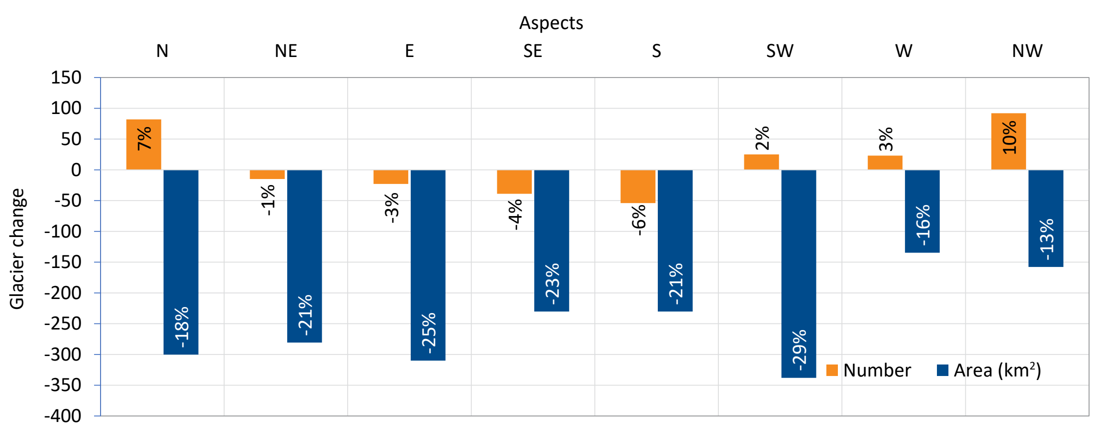
of fluctuations in glacier numbers. Notably, the northern and northwestern aspects exhibited a marked increase in glacier numbers throughout all decades – northern glaciers increased by 7%, and northwestern glaciers grew by nearly 10%. However, this growth in number was accompanied by substantial area losses: around 18.5% in the northern aspect and 13% in the northwestern aspect In contrast, the northeastern aspect displayed a distinctly different trend, marked by a simultaneous decrease in both glacier numbers and area. Over three decades, it experienced a net loss of 15 glaciers and more than 21% of its glacier area. This underscores a pattern of persistent and severe glacier shrinkage across all time periods.

Glaciers located in the eastern, southeastern, and southern aspects also underwent consistent declines in both number and area, with only slight gains during the early 1990s in the eastern and southern aspects. Among these, the eastern aspect recorded the second-highest area loss of 25%, while the southern and southeastern aspects experienced similarly high losses of over 21% and 23%, respectively.

The southwestern aspect showed the most extreme area loss, with nearly 28.6% of its glacier area vanishing over three decades. This occurred despite a net increase of 25 glaciers, further emphasising the different trend between glacier number and area. Similarly, the western aspect also showed this divergence, while there were initial gains in glacier numbers in the 1990s, a steady decline followed in subsequent decades. Over time, this aspect experienced a moderate but notable area loss of more than 16%.

Altogether, the increasing number of glaciers coupled with substantial area losses points to a broader phenomenon of glacier fragmentation and rapid retreat. As larger glaciers shrink and break into smaller ones, their mean aspect orientations are often altered, leading to observed shifts in glacier distribution across different aspects and decades. These changes in glacier mean aspects and number reflect the dynamic response of glaciers to ongoing retreat. However, the persistent and substantial area loss across all aspects and throughout each decade highlights the severe and widespread impacts of regional climate change, driving this sustained glacier decline (Figure 5.32).

FIGURE 5.32 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES IN THE GANGES RIVER BASIN.



LUGGE TSHO, A POTENTIALLY DANGEROUS GLACIAL LAKE IN BHUTAN.

5.4 Brahmaputra River Basin

The Brahmaputra River is one of the major transboundary rivers of South Asia, traversing through four countries: China (Tibet Autonomous Region), India, Bhutan and Bangladesh. It originates from the Chemayungdung Glacier in the Kailash Range, near Lake Manasarovar in southwestern Tibet, at an elevation of approximately 5,300 masl (Palash et al., 2023; Sarma et al., 2004). From the headwaters, it flows eastwards along the Tibet Autonomous Region of China, then bends south towards the Indian states of Arunachal Pradesh and Assam, and into Bangladesh. Flowing eastward for about 1,100 kilometres, the river courses between the main Himalayan range to the south and the Kailash Range to the north. Upon reaching the Namcha Barwa massif, it takes a sharp southward turn, carving through the Himalayas via the Yarlung Tsangpo Grand Canyon, considered one of the world's deepest gorges.

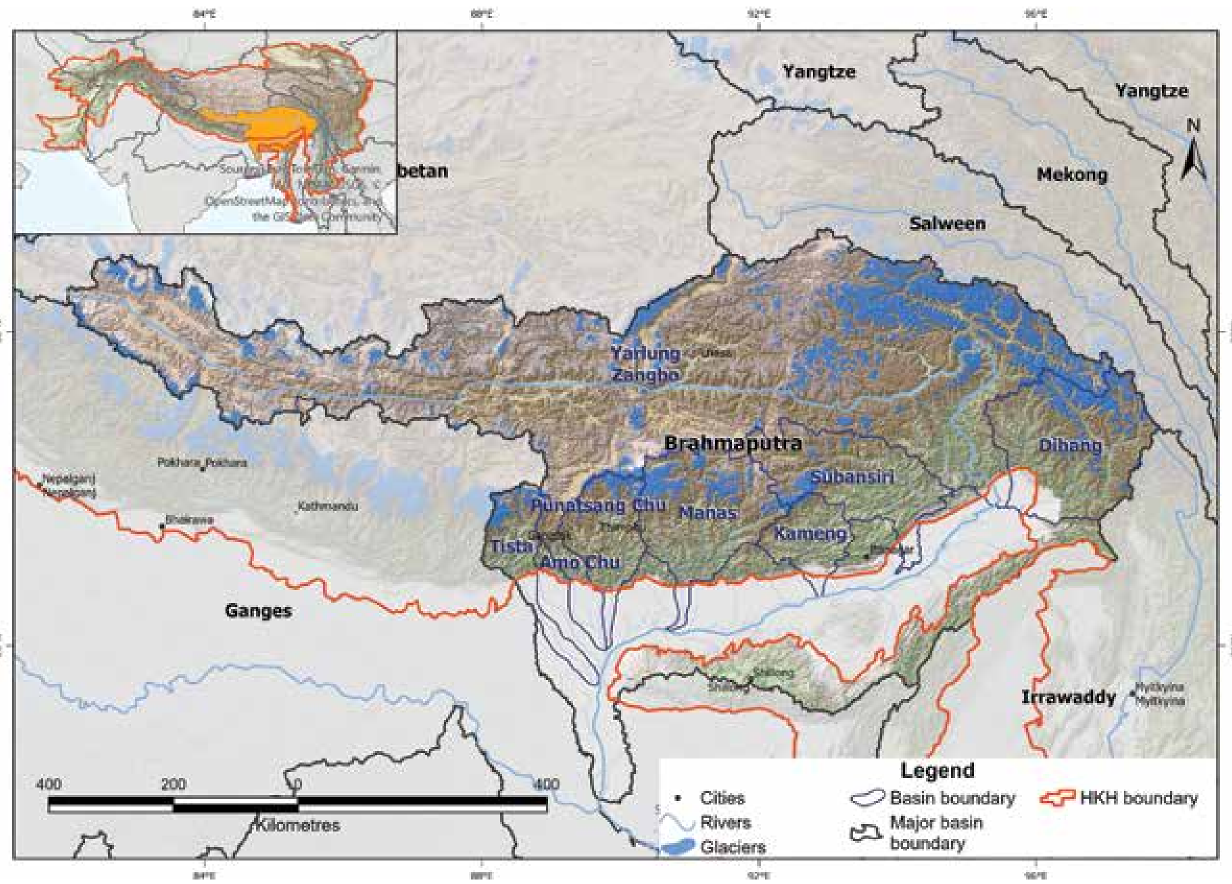
The Brahmaputra River basin covers approximately 580,000 km², with a rich and diverse landscape that supports millions of people through agriculture, transportation, and ecosystems. However, frequent and devastating floods pose significant challenges to the region's development and sustainability. The basin's fertile plains and vast biodiversity further underscore its critical environmental and socioeconomic importance.

Within the HKH, the basin encompasses more than 71% of the total area, majorly covering all the hills and mountain areas in the northern and northeastern parts. The basin has been divided into 8 main basins which are further sub divided into 25 sub-basins. Much of the basin area is dominated by the Yarlung Zango basin, which covers 68 % of the total area of the whole basin. Even with all the other basins combined, this basin still has larger area coverage. Figure 5.33 shows the glacier distribution across each basin in the Brahmaputra River basin.

Glacier distribution in 2020

In 2020, a total of 12,687 glaciers were identified within the basin, covering a total area of 9,450.32 km² and holding an estimated ice reserve of 746.92

FIGURE 5.33 MAP SHOWING GLACIER DISTRIBUTION AND EXTENT OF THE BRAHMAPUTRA RIVER BASIN WITHIN THE HKH REGION.



km³. These glaciers extend between 27.49°N and 31.03°N latitude and 82.03°E to 97.76°E longitude. Remarkably, 68.8% of the glaciers by number and 66% of the glacier area are situated in the Yarlung Zangbo basin, making it the primary glaciated region in the river basin (Figure 5.34). In contrast, the other seven basins account for only 31% of the glacier number and 33.7% of the glacier area. The Amo Chu basin has the fewest glacier number, with just 32 glaciers (0.25% of the total), while the Kameng basin has the smallest glacier area at 22.17 km² (0.2% of the total glacier area).

Among the sub-basins, the Yigong Zangbo sub-basin, located at the northeastern part of the basin, contains the highest number of glaciers (3,527 glaciers, or 27.8%), with a total area of 3,358 km², representing 36% of the total glacier area. Table 5.15 provides details on the distribution of glaciers in each sub-basin of the Brahmaputra River basin.

The largest glacier in the Brahmaputra River basin covers an area of 166.74 km² area and is situated in the Yigong Zangbo sub-basin of the Yarlung Zangbo Basin in Tibet, Autonomous Region of China. In addition, there is another glacier in the same sub-basin that exceeds 100 km². The river basin also contains seven other glaciers that surpass 50 km². These includes one glacier in the Lohit sub-basin of the Dihang basin; three in the Yigong Zangbo and one in the Langkamu sub-basins of the Yarlung Zangbo basin; one in the Zemu sub-basin of the Tista basin in India; and one in the Kurichu sub-basin of the Manas Chu basin in Bhutan.

The glacier distribution across various area size classes in the Brahmaputra River basin showcases a complex interplay between the number of glaciers and their contributions to area and ice reserves. A significant majority of the glaciers fall into the smallest size Class 1 (less than 0.5 km²), with 75% of the total glacier. Although they are numerous, these smallest glacier class contribute only 15% to the total glacier area and just 4% to the estimated ice reserves, indicating that while they are abundant, their impact on the basin's overall glacial landscape is limited. The mid-sized glaciers of Class 2 (0.51 and 1.00 km²) and Class 3 (1.01 and 5.00 km²) both representing 11% of the total glacier number.

FIGURE 5.34 **GLACIER DISTRIBUTION ACROSS BASINS** (TOP LEFT), **AREA CLASSES** (TOP RIGHT), **MEAN SLOPE** (BOTTOM LEFT) **AND ASPECT** (BOTTOM RIGHT) **IN THE BRAHMAPUTRA RIVER BASIN.**

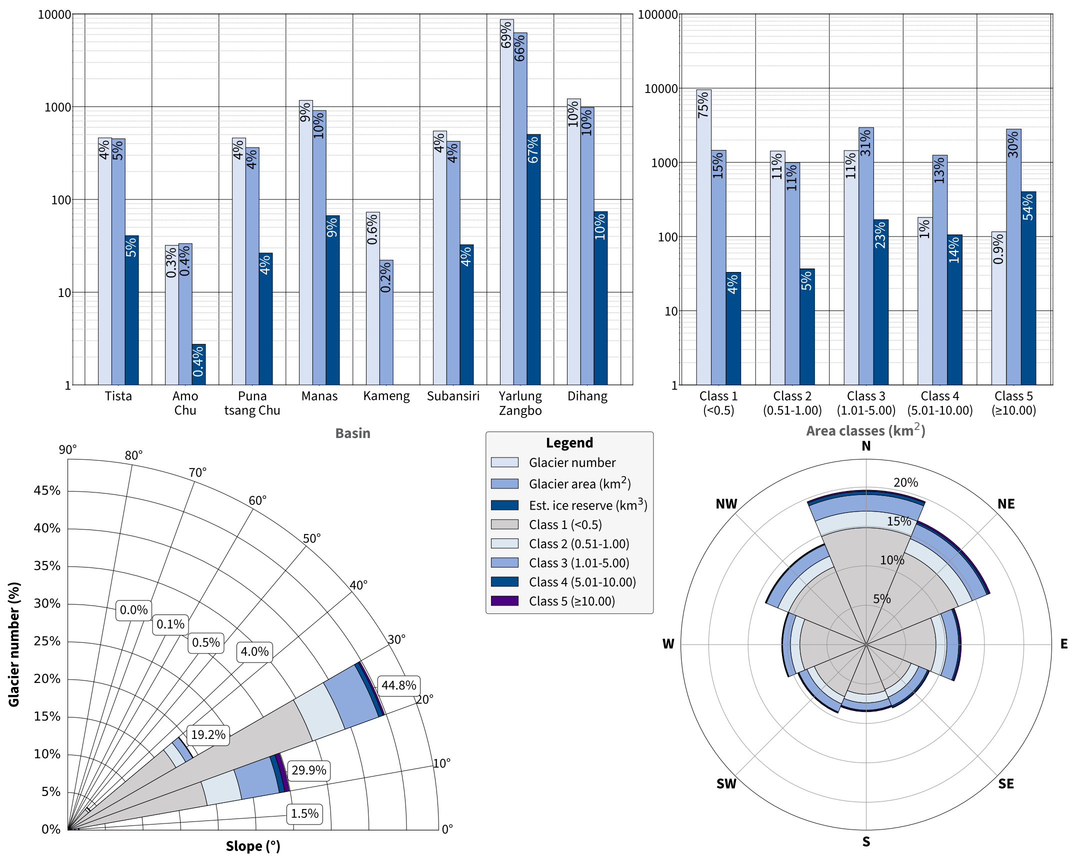


TABLE: 5.15 **DISTRIBUTION OF GLACIER IN THE SUB-BASINS AND BASINS OF THE BRAHMAPUTRA RIVER BASIN.**

Basin	Sub-basins	Number	Area (km²)	Largest area (Km²)	Estimated ice reserve (km³)	Elevation (masl) Min	Elevation (masl) Max	Mean slope (Deg)
Yarlung Zangbo	Maquan	1,068	717.81	26.18	50.35	4,914	6,991	23
	Yarlung Zangbo	1,146	610.35	32.33	37.47	3,032	7,260	25
	Dogxung Zangbo	323	59.04	2.38	1.82	5,526	6,388	23
	Xiangqu	132	32.83	3.75	1.23	5,413	6,655	24
	Nianchu	143	232.48	28.57	18.72	4,944	7,167	23
	Langkamu	151	196.92	81.55	22.38	5,143	7,147	24
	Lhasa	835	436.33	22.76	23.94	5,009	7,094	22
	Nyang	1400	622.78	23.47	37.96	3,886	6,817	28
	Yigong Zangbo	3,531	3,357.91	166.74	308.79	2,756	6,903	26
	Total	**8,729**	**6,266.45**	**166.74**	**502.66**	**2,756**	**7,260**	**25**
Tista	East Rathong	46	30.69	7.04	1.79	4,333	7,269	30
	Talung	76	92.90	27.30	8.23	3,894	8,029	33
	Zemu	224	246.57	78.93	25.57	4,221	8,091	28
	Changme	115	80.91	15.76	5.12	4,475	6,990	24
	Total	**461**	**451.06**	**78.93**	**40.72**	**3,894**	**8,091**	**28**
Amo Chu	Amo Chu	32	33.43	15.52	2.75	4,805	6,959	26
Punatsang Chu	Wang Chu	55	29.55	6.63	1.66	4,373	7,074	28
	Mo Chu	158	105.28	10.42	6.14	4,069	6,719	27
	Pho Chu	247	227.86	36.12	18.64	4,083	7,097	24
	Total	**460**	**362.70**	**36.12**	**26.45**	**4,069**	**7,097**	**26**
Manas	Mangde Chu	143	97.55	20.00	6.81	4,681	7,244	19
	Chamkhar Chu	112	64.07	15.16	4.43	4,699	6,634	20
	Kuri Chu	545	546.67	56.81	44.54	4,508	7,350	26
	Dangme Chu	370	201.65	12.69	11.18	4,480	6,475	25
	Total	**1,170**	**909.94**	**56.81**	**66.96**	**4,480**	**7,350**	**24**
Kameng	Kameng	73	22.17	3.38	0.84	4,351	6,618	30
Subansiri	Subansiri	547	424.09	49.22	32.51	4,107	7,004	27
Dihang	Lohit	1062	899.40	92.79	70.35	2,607	6,547	23
	Dibhang	153	81.08	4.79	3.69	3,773	5,269	22
	Total	**1,215**	**980.48**	**92.79**	**74.04**	**2,607**	**6,547**	**23**
Grand total		**12,687**	**9,450.32**	**166.74**	**746.92**	**2,607**	**8,091**	**25**

However, the mid-sized glaciers of Class 3 play a more significant role, accounting for 31% of the total glacier area and holding 23% of total estimated ice reserves in the river basin (Figure 5.34).

The larger glaciers of Class 4 (5.01 – 10.00 km²) and Class 5 (≥ 10.00 km²) comprise only 1% each of the total number but significantly impact the overall area and estimated ice reserves. The Class 4 contribute 13% of the area and 14% of the reserves, while the largest glaciers class hold an impressive 30% of the total area and 54% of the estimated ice reserves. This reflects a substantial contribution to the basin's overall glacial cover and emphasises the critical role played by these larger glaciers in the basin's hydrology and climate regulation, despite their lower numbers.

The elevation of glaciers in the Brahmaputra River basin ranges from 2,607 masl to 8,091 masl. The glacier with lowest elevation is located in the Lohit sub-basin of the Dihang basin, while the highest elevation glacier can be found in the Zemu sub-basin of the Tista basin. The Tista basin showcases the widest range of glacier elevations, extending from 3,800 masl to 8,100 masl. In contrast, the Amo Chu basin, which has the smallest glacier area, features a narrower elevation range of 4,800 masl to 7,000 masl. Additionally, the Yarlung Zangbo basin, known for its high glacier concentration, exhibits the most extensive elevation range from 2,700 masl to 7,300 masl.

The distribution of glacier area across various elevation ranges reveals that approximately 92% of glacier coverage is concentrated between 4,500 and 6,500 masl, with the majority (65%) found in the 5,000 masl to 6,000 masl elevation range (Figure 5.35). In lower elevations below 3,500 masl, glacier presence is minimal, particularly in the Dihang and Yarlung Zangbo basins, which together account for less than 1% of the total glacier area. Glaciers in other basins are predominantly found above 3,800 to 4,000 masl.

As elevation increases from 3,500 to 4,500 masl, there is a notable increase in glacier area, especially in the Yarlung Zangbo, Dihang, and Punatsangchu basins, where glaciers cover between 7% and 12% of the total area within these basins. Other basins show minimal glacier coverage, generally below 1% to 2%. Above 4,500 masl, glacier area increases significantly across all basins, peaking between 5,000 and 6,000 masl. The Manas, Subansiri, and Tista basins show the highest coverage at 5,500 to 6,000 masl, while Yarlung Zangbo, Punatsang chu, Kameng, and Amo chu basins exhibit their peak coverage between 5,000 and 5,500 masl, comprising nearly 35% to 52% of their total glacier area. In the Dihang basin, the maximum glacier coverage is found at 4,500 to 5,000 masl, accounting for 43.5% of the glaciers in that basin. The detail distribution of glacier area across various elevation ranges in each main basin and the Brahmaputra River basin is given in Table 5.16 and illustrated in Figure 5.35.

These elevation ranges are critical for glacial masses, which plays a vital role in contributing to river flow. The elevation ranges from 5,000 masl to 5,500 masl alone contains a substantial portion of the glaciers, representing about 35% of the total glacier area within the Brahmaputra River basin. Conversely, glacier coverage declines sharply at elevations above 6,000 masl.

The distribution of glaciers across different mean slope classes in the Brahmaputra River basin reveals important patterns regarding glacier area, total estimated ice reserves, and slope gradients. Approximately 46% of the glaciers exhibit mean slopes between 20° and 30°, which contribute 40% of the total glacier area and hold 32% of the estimated ice reserves (Figure 5.34). This indicates that glaciers in this slope range are prevalent but tend to be smaller in size.

In contrast, glaciers with mean slopes between 10° and 20° comprise 26% of the total glacier number while encompassing the largest glacier area,

FIGURE 5.35 GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN EACH BASIN OF THE BRAHMAPUTRA RIVER BASIN.

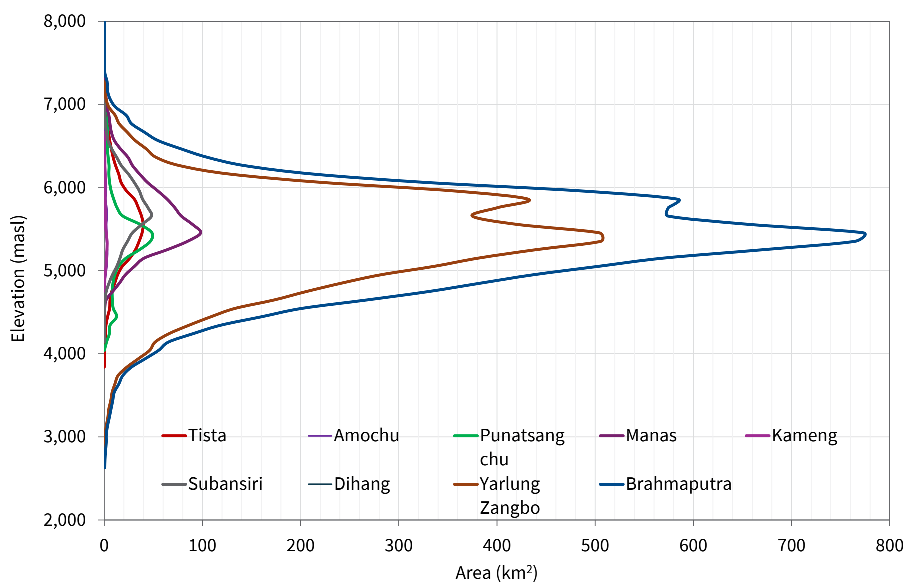


TABLE: 5.16 ELEVATION – WISE GLACIER AREA DISTRIBUTION ACROSS THE MAIN BASINS IN THE BRAHMAPUTRA RIVER BASIN.

Elevation Range (masl)	Tista		Amochu		Punatsang chu		Manas		Kameng		Subansiri		Dihang		Yarlung Zangbo		Brahmaputra	
	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
2,500 – 3,000													3.54	0.36	1.10	0.02	4.64	0.05
3,000 – 3,500													8.22	0.84	17.89	0.3	26.11	0.3
3,500 – 4,000	0.17	0.0											22.43	2.3	90.74	1.4	113.34	1.2
4,000 – 4,500	7.72	1.7			26.24	7.2	0.02	0.0	0.10	0.4	0.38	0.1	96.75	9.9	359.49	5.7	490.70	5.2
4,500 – 5,000	43.24	9.6	2.21	6.6	45.10	12.4	47.83	5.3	1.78	8.0	16.45	3.9	426.79	43.5	1,034.80	16.5	1,618.21	17.1
5,000 – 5,500	150.42	33.3	14.07	42.1	168.46	46.4	319.16	35.1	11.48	51.8	100.22	23.6	351.89	35.9	2,167.63	34.6	3,283.32	34.7
5,500 – 6,000	165.70	36.7	11.38	34.1	85.35	23.5	358.84	39.4	4.98	22.5	205.74	48.5	59.63	6.1	1,983.51	31.7	2,875.13	30.4
6,000 – 6,500	59.88	13.3	5.02	15.0	22.26	6.1	149.71	16.5	3.57	16.1	92.95	21.9	11.22	1.1	522.91	8.3	867.52	9.2
6,500 – 7,000	16.51	3.7	0.75	2.2	14.88	4.1	30.43	3.3	0.27	1.2	8.34	2.0	0.02	0.0	85.70	1.4	156.90	1.7
7,000 – 7,500	5.88	1.3			0.41	0.11	3.95	0.43			0.01	0.00			2.65	0.04	12.90	0.1
7,500 – 8,000	1.49	0.33															1.49	0.02
8,000 – 8,500	0.04	0.01															0.04	0.00
Total	451.06	100.0	33.43	100.0	362.69	100.0	909.94	100.0	22.17	100.0	424.09	100.0	980.48	100.0	6,266.43	100.0	9,450.29	100.0

contributing 48% of the total glacier coverage and 61% of the estimated ice reserves. This suggests that larger glaciers, including debris-covered, are concentrated within this slope range, providing significant contributions to regional hydrology.

The analysis shows a marked decline in both the number and area of glaciers above a mean slope of 40°, indicating that these steeper slopes are unfavourable for glacier formation and sustainability. Overall, the data emphasise that moderate slopes from 10° to 30° are essential for the majority of glaciers in the Brahmaputra River basin, serving as key zones for significant glacier presence and ice reserves. In contrast, steeper slopes limit glacier formation and sustainability, underscoring the critical relationship between slope gradients and glacial dynamics in this region.

The glacier distribution across various aspects in the Brahmaputra River basin reveals the northern (N), northeastern (NE), and northwestern (NW) aspects collectively emerge as the most significant in terms of glacier presence and resource content (Figure 5.34). Together, they account for nearly 51% of the total glacier number, covering about 49% of the total glacier area, and storing approximately 45% of the total estimated ice reserves. Among these, the northern and northeastern aspects each contribute 19% of the total glacier area, with the northeastern aspect holding the highest ice reserves (19%) among this group and second highest overall aspects. Although the northwestern aspect hosts a substantial 14% of the glaciers, it contributes less in terms of area and estimated ice reserves, likely due to smaller glacier sizes with mean area of 0.56 km^2, compared to the relatively moderate sizes in the northern (0.73 km^2) and northeastern with mean area of 0.73 km^2 and 0.83 km^2 respectively. Hence, these north facing glaciers reflect a robust glaciated region with both quantity and significant ice reserves.

In contrast, the southern (S), southeastern (SE), and southwestern (SW) aspects show a more modest glacial distribution. Collectively, these aspects hold around 27% of the glacier number with an even distribution, contributing 27% of the glacier area and 26% of the ice reserves. Among them, the southeastern aspect is the most prominent, with 11% of the glacier area and 12% of the total estimated ice reserves, along with a relatively higher mean glacier size of 0.94 km^2 suggesting the larger glaciers distribution. The southern and southwestern aspects, though similar in glacier number, lag in area coverage by about 8% each and estimated ice reserves by about 7% each, with mean glacier sizes of 0.71 km^2 and 0.63 km^2 respectively. This south-facing glaciers reflects a significant, though not dominant, part of the basin's glacier cover is important in spatial extent, but with generally smaller and less voluminous glaciers compared to north-facing glaciers.

The eastern (E) and western (W) aspects show contrasting patterns. The eastern aspect, although hosting only 12% of the glaciers, contributes a notable 17% of the glacier area and a leading 24% of the total estimated ice reserves, making it the most voluminous ice coverage aspect of the basin. Its glaciers are also the largest in size, with a mean area of 1.06 km^2, suggesting fewer but substantial glaciers. Conversely, the western aspect is the least significant, with just 11% of the glacier number covering 7% of the total glacier area, and only 5% of the total estimated ice reserves, and the smallest mean glacier size (0.50 km^2). This east-west contrast highlights how glacier size and ice reserves vary significantly depending on orientation, likely driven by differences in topographic shading, precipitation patterns, and solar exposure.

Decadal glacier changes from 1990s to 2020

Over the past three decades from 1990 and 2020, glaciers in the Brahmaputra River basin experienced a significant reduction in both areas and numbers, with glacier area declining by 16% and glacier number decreasing by 3.6%. The largest relative reduction in the glacier area occurred in the Kameng, Punatsang Chu and Manas basins, which lost 20% to 22.3% of its glacier area. However, the Yarlung Zangbo basin experienced the most substantial absolute area loss, with over 1,156 km^2 of glacier area lost, representing a 15.6% reduction in its glacier area over three decades. The Tista basin showed a decline of 13.7% of glacier area, maintaining a steady but concerning loss rate of around 4.8% throughout all decades. In contrast, the Amochu basin showed a more moderate reduction of 8.1% of the total area in the basin over three decades, indicating a gradual decline. Other basins – Subansiri, Dihang faced 12.5% and 14.9% of the total glacier area loss over three decades respectively.

The changes in glacier numbers varied across different basins and sub-basins. The Yarlung Zangbo, Manas, and Subansiri basins experienced the most significant declines, losing approximately 4%, 8%, and 7% of their total glacier numbers over three decades, respectively. While these basins initially saw a slight increase in glacier numbers in the first decade, they later experienced substantial losses. In contrast, the Dihang, Punatsang Chu,

FIGURE 5.36 **INTERDECADAL CHANGES IN GLACIER NUMBER** (BOTTOM) **AND AREA** (TOP) **WITHIN EACH BASIN OF THE BRAHMAPUTRA RIVER BASIN.**

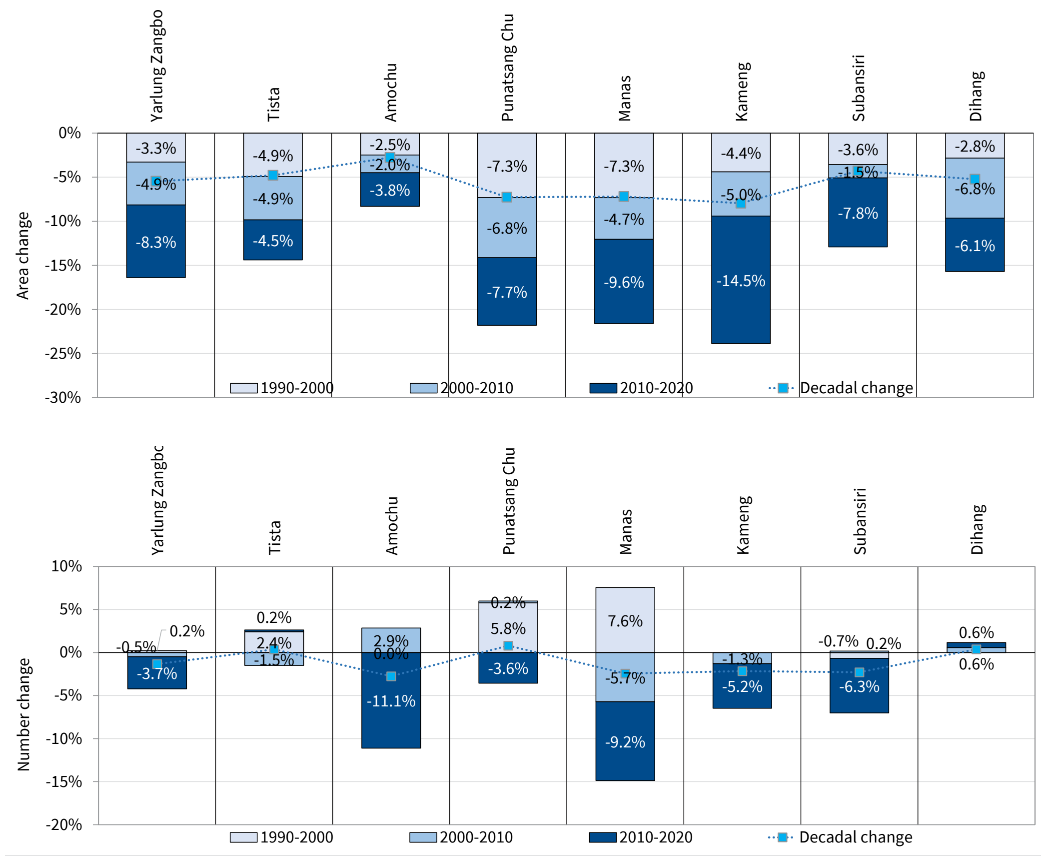


TABLE 5.17 **GLACIER AREA DISTRIBUTION AND PERCENTAGE CHANGES ACROSS VARIOUS ELEVATION RANGES FROM 1990 TO 2020 IN THE BRAHMAPUTRA RIVER BASIN.**

Basin	Sub-basins	Number				Area (km²)				Decadal change in Number / Area (%)				
		1990	2000	2010	2020	1990	2000	2010	2020	1990-2000	2000-2010	2010-2020	1990-2020	Change per decade
Yarlung Zangbo	Maquan	1,088	1,106	1,106	1,068	923.39	856.42	792.01	717.81	1.7 / -7.3	0 / -7.5	-3.4 / -9.4	-1.8 / -22.3	-0.6 / -8
	Yarlung Zangbo	1,274	1,281	1,257	1,146	797.57	767.18	710.52	610.35	0.5 / -3.8	-1.9 / -7.4	-8.8 / -14.1	-10 / -23.5	-3.4 / -8.4
	Dogxung Zangbo	361	360	363	323	91.82	82.59	76.39	59.04	-0.3 / -10.1	0.8 / -7.5	-11 / -22.7	-10.5 / -35.7	-3.5 / -13.4
	Xiangqu	134	134	136	132	51.26	47.30	39.40	32.83	0 / -7.7	1.5 / -16.7	-2.9 / -16.7	-1.5 / -35.9	-0.5 / -13.7
	Nianchu	145	145	146	143	264.10	257.21	245.84	232.48	0 / -2.6	0.7 / -4.4	-2.1 / -5.4	-1.4 / -12	-0.5 / -4.2
	Langkamu	150	151	153	151	223.69	217.92	210.85	196.92	0.7 / -2.6	1.3 / -3.2	-1.3 / -6.6	0.7 / -12	0.2 / -4.1
	Lhasa	857	865	863	835	565.04	542.02	499.81	436.33	0.9 / -4.1	-0.2 / -7.8	-3.2 / -12.7	-2.6 / -22.8	-0.8 / -8.2
	Nyang	1581	1569	1532	1400	785.06	758.36	703.29	622.78	-0.8 / -3.4	-2.4 / -7.3	-8.6 / -11.4	-11.4 / -20.7	-3.9 / -7.4
	Yigong Zangbo	3,501	3,500	3,511	3,531	3,720.77	3,650.15	3,552.08	3,357.91	0 / -1.9	0.3 / -2.7	0.6 / -5.5	0.9 / -9.8	0.3 / -3.4
	Total	**9,091**	**9,111**	**9,067**	**8,729**	**7,422.70**	**7,179.16**	**6,830.19**	**6,266.45**	**0.2 / -3.3**	**-0.5 / -4.9**	**-3.7 / -8.3**	**-4 / -15.6**	**-1.3 / -5.5**
Tista	East Rathong	49	49	45	46	37.96	36.12	33.53	30.69	0 / -4.8	-8.2 / -7.2	2.2 / -8.5	-6.1 / -19.1	-2 / -6.8
	Talung	72	72	71	76	97.58	95.43	94.84	92.90	0 / -2.2	-1.4 / -0.6	7 / -2	5.6 / -4.8	1.9 / -1.6
	Zemu	223	231	228	224	285.70	272.96	260.19	246.57	3.6 / -4.5	-1.3 / -4.7	-1.8 / -5.2	0.4 / -13.7	0.2 / -4.8
	Changme	112	115	116	115	101.44	92.44	83.97	80.91	2.7 / -8.9	0.9 / -9.2	-0.9 / -3.6	2.7 / -20.2	0.9 / -7.2
	Total	**456**	**467**	**460**	**461**	**522.68**	**496.96**	**472.53**	**451.06**	**2.4 / -4.9**	**-1.5 / -4.9**	**0.2 / -4.5**	**1.1 / -13.7**	**0.4 / -4.8**
Amo Chu		35	35	36	32	36.37	35.47	34.75	33.43	0 / -2.5	2.9 / -2	-11.1 / -3.8	-8.6 / -8.1	-2.8 / -2.8
Punatsang Chu	Wang Chu	56	56	55	55	37.67	34.65	32.51	29.55	0 / -8	-1.8 / -6.2	0 / -9.1	-1.8 / -21.6	-0.6 / -7.8
	Mo Chu	154	164	168	158	132.79	121.73	110.99	105.28	6.5 / -8.3	2.4 / -8.8	-6 / -5.1	2.6 / -20.7	1 / -7.4
	Pho Chu	240	256	254	247	284.38	265.16	249.30	227.86	6.7 / -6.8	-0.8 / -6	-2.8 / -8.6	2.9 / -19.9	1 / -7.1
	Total	**450**	**476**	**477**	**460**	**454.83**	**421.54**	**392.80**	**362.70**	**5.8 / -7.3**	**0.2 / -6.8**	**-3.6 / -7.7**	**2.2 / -20.3**	**0.8 / -7.3**
Manas	Mangde Chu	138	145	145	143	119.76	114.61	108.39	97.55	5.1 / -4.3	0 / -5.4	-1.4 / -10	3.6 / -18.5	1.2 / -6.6
	Chamkhar Chu	125	123	121	112	84.65	78.18	74.50	64.07	-1.6 / -7.6	-1.6 / -4.7	-7.4 / -14	-10.4 / -24.3	-3.6 / -8.8
	Kuri Chu	597	643	603	545	641.18	612.95	590.63	546.67	7.7 / -4.4	-6.2 / -3.6	-9.6 / -7.4	-8.7 / -14.7	-2.7 / -5.2
	Dangme Chu	410	455	419	370	293.94	250.33	232.62	201.65	11 / -14.8	-7.9 / -7.1	-11.7 / -13.3	-9.8 / -31.4	-2.9 / -11.7
	Total	**1,270**	**1,366**	**1,288**	**1,170**	**1,139.53**	**1,056.06**	**1,006.14**	**909.94**	**7.6 / -7.3**	**-5.7 / -4.7**	**-9.2 / -9.6**	**-7.9 / -20.1**	**-2.4 / -7.2**
Kameng		78	78	77	73	28.55	27.29	25.92	22.17	0 / -4.4	-1.3 / -5	-5.2 / -14.5	-6.4 / -22.3	-2.2 / -8
Subansiri		587	583	584	547	484.44	467.09	460.08	424.09	-0.7 / -3.6	0.2 / -1.5	-6.3 / -7.8	-6.8 / -12.5	-2.3 / -4.3
Dihang	Lohit	1,050	1,049	1,055	1,062	1,059.84	1,028.55	957.62	899.40	-0.1 / -3	0.6 / -6.9	0.7 / -6.1	1.1 / -15.1	0.4 / -5.3
	Dibhang	151	152	153	153	92.70	91.40	86.08	81.08	0.7 / -1.4	0.7 / -5.8	0 / -5.8	1.3 / -12.5	0.4 / -4.3
	Total	1,201	1,201	1,208	1,215	1,152.54	1,119.94	1,043.71	980.48	0 / -2.8	0.6 / -6.8	0.6 / -6.1	1.2 / -14.9	0.4 / -5.2
Grand Total		**13,168**	**13,317**	**13,197**	**12,687**	**11,241.63**	**10,803.51**	**10,266.13**	**9,450.32**	**1.1 / -3.9**	**-0.9 / -5**	**-3.9 / -7.9**	**-3.7 / -15.9**	**-1.2 / -5.6**

CREVASSE ON THE YALA GLACIER

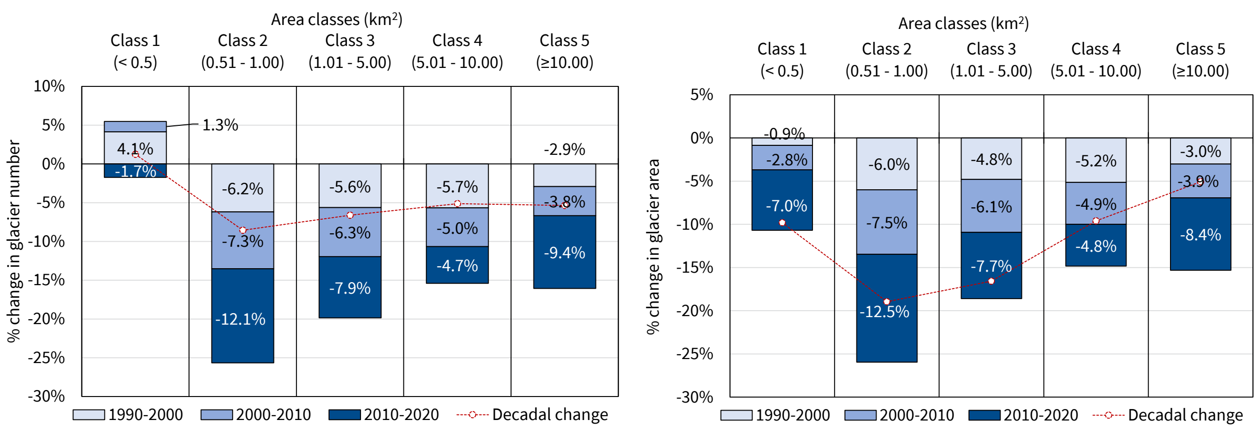
and Tista basins recorded slight increases in glacier numbers over the same period. Overall, the Brahmaputra River basin faced a 3.7% decline in glacier numbers, highlighting vulnerability across various basins and sub-basins. The detail changes in glacier number and area within the basins, sub-basins of the Brahmaputra River basin is given in Table 5.17 and interdecadal losses are illustrated in Figure 5.36.

Interdecadal analysis reveals that glacier fragmentation intensified during the earlier decade (1990 – 2000), leading to an increase in the number of smaller glaciers. This was followed by a marked decline in glacier numbers during the subsequent decades, which suggests an acceleration in glacier retreat processes. This pattern of fragmentation, coupled with the progressive retreat, indicates the gradual disappearance of these smaller, fragmented glaciers over time. Moreover, the rate of glacier area loss increased markedly during the most recent decade (2010 – 2020).

The analysis of glacier number and area changes across various size classes from 1990 to 2020 demonstrates a consistent and alarming decline across all size classes, with notable differences in the rates of loss. The Class 1 (<0.5 km^2) glacier lost 10.4% of glacier area over three decades, with a sharp increase in percentage decline from 0.9% in the 1990 – 2000 period to 7% in 2010 – 2020. Class 2 (0.51 – 1.00 km^2) glacier exhibited a highest percentage glacier area reduction by almost 24% over three decades. However, the mid-sized Class 3 (1.01 – 5.00 km^2) and largest sized Class 5 (≥10.00 km^2) faced the most significant total area loss of 625.7 km^2 and 480.7 km^2 over three decades. Notably, these classes had a relatively lower percentage loss of 17.5% and 14.6% over three decades respectively compared to Class 2 (0.51 – 1.00 km^2). Similarly larger glacier sized Class 4 (5.01 – 10.00 km^2) had a total area reduction of 2005.3 km^2, with loss percentages of more than 14% over three decades. The interdecadal comparative analysis underscores an increasing trend of glacier retreat across all classes, with higher percentage loss in recent decades from 2010 to 2020, highlighting the urgent need for monitoring and research to address the environmental implications in the region (Figure 5.37).

The trend in glacier number reflects a similar pattern of decline. Initially, Class 1 (<0.5 km^2) experienced a 4.1% increase in glacier numbers but later faced a decline of nearly 2% from 2010 to 2020. Overall, this class showed an increase of almost 4% over three decades. In contrast, all other classes consistently experienced reductions in glacier numbers throughout the period. Class 2 (0.51 – 1.00 km^2) and Class 3 (1.01 – 5.00 km^2) showed the highest percentage losses, with declines of 23.6% and 19%, respectively, from 1990 to 2020. Meanwhile, larger glaciers in Class 4 (5.01 – 10.00 km^2) and Class 5 (≥10.00 km^2) faced smaller declines, losing 31 and 21 glaciers, with percentage changes of –14.6% and –15.3%. This change in glacier numbers signifies that the retreat of glaciers leads to fragmentation, resulting in the conversion of larger glaciers into smaller sizes, which increases the number of smaller glaciers. And the consistent reduction in glacier area across all classes indicates the shrinkage of smaller glaciers as well, with some decreasing below the area threshold of 0.02 km^2 or disappearing.

FIGURE 5.37 INTERDECADAL GLACIER NUMBER AND AREA CHANGES ACROSS SIZE CLASSES OVER THREE DECADES IN THE BRAHMAPUTRA RIVER BASIN.



Significant glacier retreat has been observed across various elevation ranges, with a notable upward shift of the lowest elevation of the glacier snout from 2,469 masl in 1990 to 2,607 masl in 2020. This indicates the retreat of glaciers by 138 metres over three decades, leading to the complete loss of glaciers below 2,600 masl in 2020. This upward shift of the lowest elevation of the glacier snout of the basin is particularly evident in the Lohit sub-basin of the Dihang basin, located in the northeastern part of the Brahmaputra River basin. In contrast, other sub-basins exhibited varying shifts in elevation of glacier snouts, ranging from 2 to 229 metres over the same period. Most of these basins maintained glacier elevations above 3,000 masl, except for the Dihang and Yarlung Zangbo basins, where glacier snouts dropped to as low as 2,600 masl over all time periods. The highest retreat of the lower glacier snout occurred in the Dibhang sub-basin of the Dihang basin, where the glacier snout rose by 229 metres, from 3,544 masl in 1990 to 3,773 masl in 2020.

The analysis of glacier area changes across various elevation ranges reveals that the most significant losses occurred between 5,000 masl and 5,500 masl, with a total area reduction exceeding 17.5% over three decades (Figure 5.38 and Table 5.18). This elevation range coincides with a higher concentration of glaciers within the basin. Substantial losses were also observed in the ranges of 4,500 – 5,000 masl and 5,500 – 6,000 masl, each experiencing declines of more than 16% during the same period. Conversely, lower elevation ranges below 4,000 masl exhibited minimal glacier concentration and area loss; however, they demonstrated the highest percentage losses, including the complete disappearance of glaciers below 2,600 masl starting in 2010. Above 4,000 masl, the loss of glacier area increases significantly up to 6,000 masl, but the concentration and percentage loss begin to decline at elevations above 6,000 masl, where losses are minimal and glaciers appear more stable, particularly above 7,000 masl. Interdecadal comparisons reveal an increasing trend in the rate of glacier area loss over all elevation ranges, particularly pronounced in the recent decade from 2010 to 2020. Similar patterns of area loss are also observed in all the basins and sub-basins.

The analysis of glacier changes across various mean slope classes reveals distinct trends in both the number and area of glaciers over three decades. The most significant reductions were noted in the 20° to 30° slope class, where the glacier area decreased by 24% and the number of glaciers dropped by 12% (Figure 5.39). The 30° to 40° slope class also experienced declines, with a total loss of 2% in glacier numbers and 17% in area, underscoring the critical retreat of glaciers in these ranges.

FIGURE 5.38 GLACIER AREA DISTRIBUTION AND CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE BRAHMAPUTRA RIVER BASIN.

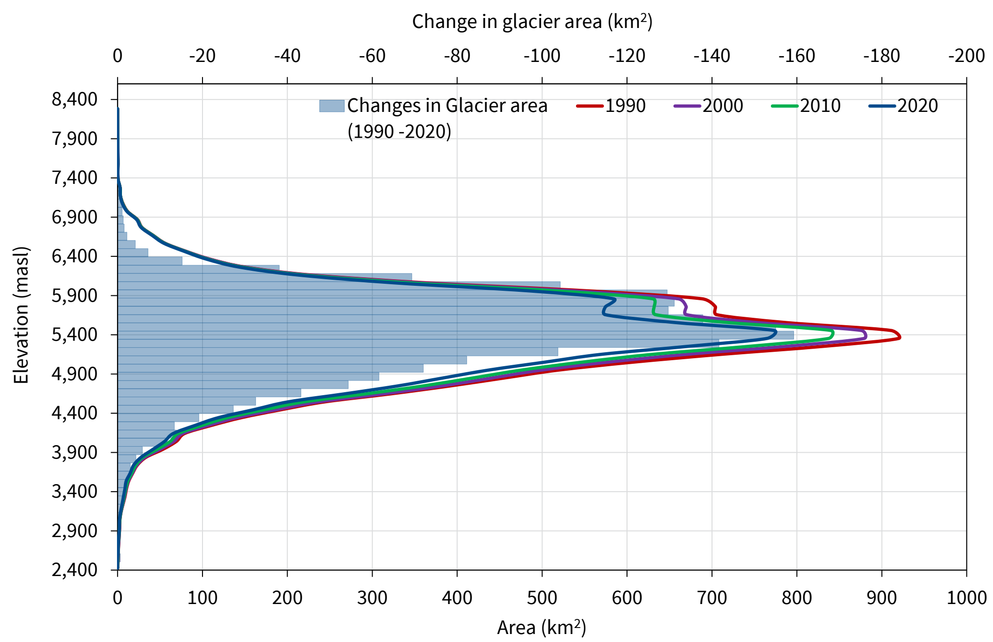
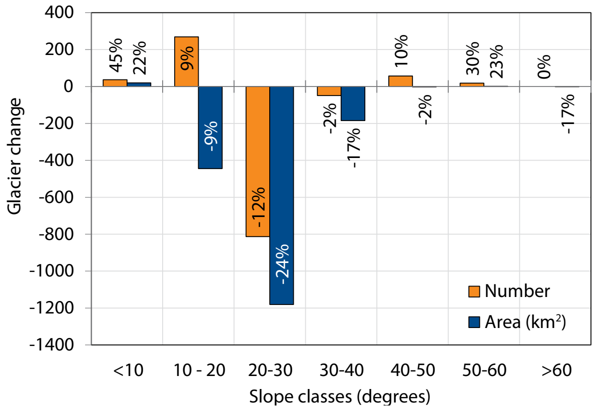


TABLE 5.18 GLACIER AREA DISTRIBUTION AND PERCENTAGE CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE BRAHMAPUTRA RIVER BASIN.

Elevation range (masl)	Area (km²)				Area change (%)				
	1990	2000	2010	2020	1990 - 2000	2000 – 2010	2010 – 2020	1990 – 2020	Per decade
<2,500	0.17								
2,500 – 3,000	7.00	6.64	5.57	4.64	-5.2	-16.1	-16.7	-33.7	-12.7
3,000 – 3,500	31.96	30.85	29.20	26.11	-3.5	-5.4	-10.6	-18.3	-6.5
3,500 – 4,000	141.20	135.32	126.05	113.34	-4.2	-6.9	-10.1	-19.7	-7.0
4,000 – 4,500	596.92	576.96	535.86	490.70	-3.3	-7.1	-8.4	-17.8	-6.3
4,500 – 5,000	1,931.61	1,872.11	1,766.21	1,618.21	-3.1	-5.7	-8.4	-16.2	-5.7
5,000 – 5,500	3,980.84	3,792.23	3,599.16	3,283.32	-4.7	-5.1	-8.8	-17.5	-6.2
5,500 – 6,000	3,439.04	3,290.51	3,131.57	2,875.13	-4.3	-4.8	-8.2	-16.4	-5.8
6,000 – 6,500	934.38	922.11	896.94	867.52	-1.3	-2.7	-3.3	-7.2	-2.4
6,500 – 7,000	162.67	161.46	160.36	156.90	-0.7	-0.7	-2.2	-3.5	-1.2
7,000 – 7,500	14.00	13.62	13.56	12.90	-2.8	-0.4	-4.8	-7.9	-2.7
7,500 – 8,000	1.73	1.59	1.55	1.49	-8.1	-2.5	-3.6	-13.7	-4.7
8,000 – 8,500	0.10	0.10	0.10	0.04	0.0	0.0	-58.8	-58.8	-19.6
Total	11,241.62	10,803.48	10,266.10	9,450.29	-3.9	-5.0	-7.9	-15.9	-5.6

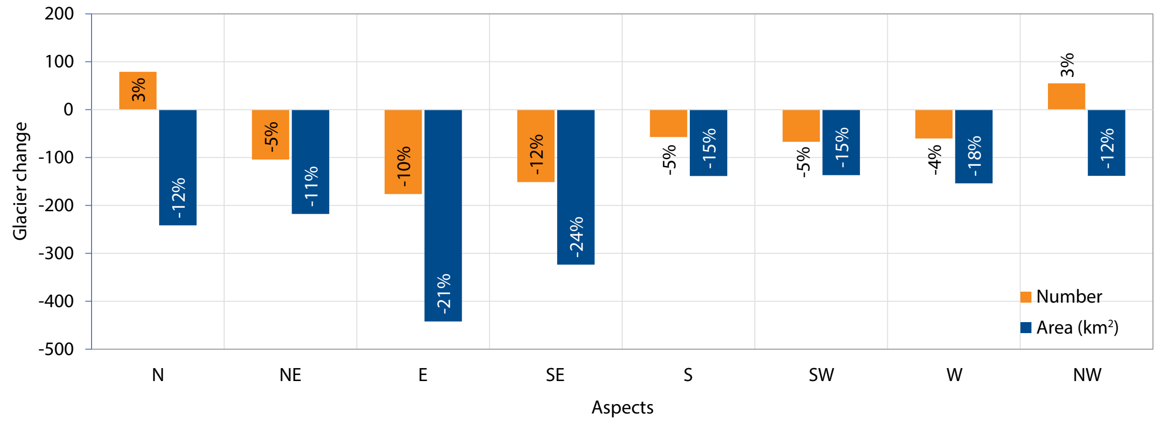
FIGURE 5.39 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES IN THE BRAHMAPUTRA RIVER BASIN.



In contrast, glaciers in the 10° to 20° slope class showed an increase in numbers by 9%, despite an area loss of 9% during the same period. This suggests that the retreat of glaciers at higher slopes may be contributing to a shift in mean slope, leading to an increase in the number of glaciers in the lower slope classes. This trend is further supported by the growth observed in the gentler slope class (below 10°), where both the number and area of glaciers increased. The observed increase in both the number and area of glaciers in gentler slope classes may be attributed to the retreat of glaciers at higher slope angles or the fragmentation of larger glaciers into smaller ones, which alters the mean slope of the glacier. The steeper slope class higher than 40° consists of minimal number and area coverage. However, there were slight increases in number, but it also shows minimal area loss. This information highlights the complex relationship between slope steepness and glacier stability, with gentler slopes exhibiting more resilience against the ongoing impacts of climate change.

The analysis of glacier changes across various mean aspects over the past three decades reveals distinct patterns of retreat, fragmentation, and directional variability in glacier behaviour. The northern, northeastern, and northwestern aspects collectively exhibited a mixed trend in glacier numbers but a consistent decline in glacier area. Both the northern and northwestern aspects showed increases in glacier numbers during the first two decades, followed by a decline in the most recent decade (2010 – 2020). Despite this fluctuation, they recorded an overall increase in glacier numbers of 3.3% and 3.2%, respectively. However, this was accompanied by a continuous reduction in glacier area, with total losses of approximately 12% in the northern and 12.3% in the northwestern aspects over the three decades.

FIGURE 5.40 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES IN THE BRAHMAPUTRA RIVER BASIN.



In contrast, the northeastern aspect experienced a significant decline in both metrics. Glacier numbers dropped sharply by 4.6%, and glacier area decreased by nearly 11% over the same period. Notably, the most severe decline in glacier numbers occurred during the last decade (2010 –2020), while earlier decades showed only minimal gains or stability. This suggests that rapid glacier shrinkage and fragmentation in this aspect has led to a shift in their mean aspect, effectively reclassifying many glaciers into adjacent aspects. These changes in mean aspects of the glaciers justify the observed loss in the northeastern aspect and the corresponding gains in others, further highlighting the dynamic and sensitive nature of glacier responses to climate and topographic influences.

Comparatively, the southeastern, southern, and southwestern aspects experienced a more consistent decline in both glacier number and area, although there were minor increases in glacier number during the 1990 – 2000 period, particularly in the southern and southwestern aspects (Figure 5.40). Among them, the southeastern aspect was the most affected, experiencing a 12% loss in glacier number and nearly 24% glacier area loss over three decades. The southern and southwestern aspects experienced relatively lower but still substantial losses, each with about 2% decrease in glacier number and over 15% glacier area loss. These changes also reflect the fragmentation and shrinkage-driven reclassification of glaciers into adjacent aspects, as their shapes and orientations evolved due to continued area loss.

Similarly, the eastern and western aspects followed the overall pattern of retreat and fragmentation. The eastern aspect faced the sharpest reduction in both glacier number and area among all aspects, with a 10% loss in glacier number and 21% area loss over the past three decades. The western aspect also exhibited significant changes, with a glacier number decline of over 4% and an area loss of 18.5%.

LIRUNG PEAK IN LANGTANG VALLEY, NEPAL

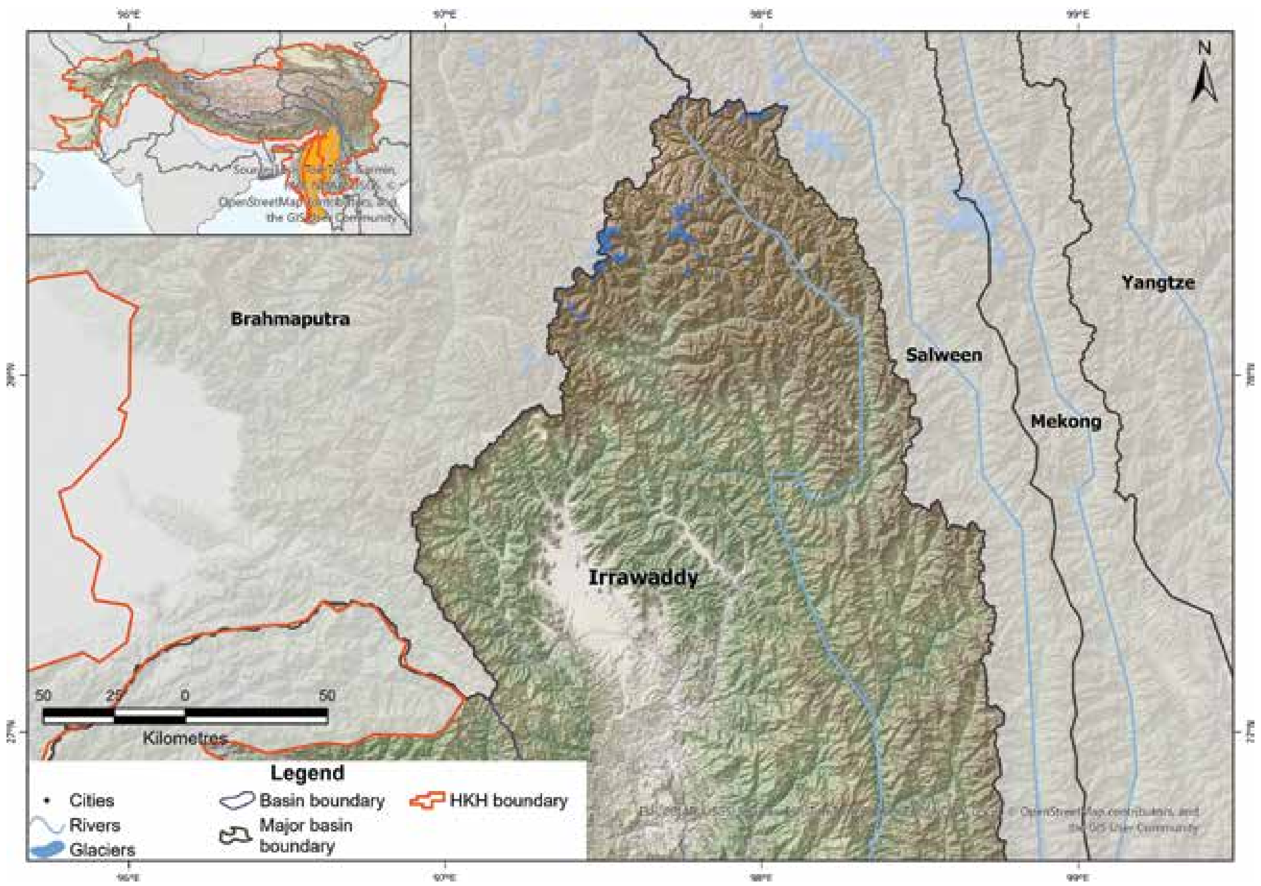
5.5 Irrawaddy River Basin

The Irrawaddy (Irawadi) or Ayeyarwady River basin mostly falls within Myanmar, but small sections of the basin are in China and India (Zhao et al., 2023). The Irrawaddy River which is around 2,100 km long, flows from north to south through Myanmar and supports the livelihoods of millions of people within the country (Sirisena et al., 2021). It originates from the confluence of the N'mai and Mali Rivers and is augmented by the Chindwin at Pakokku. The N'mai rises in the eastern glaciers of the Tibet Autonomous Region of China, while the Mali rises in Kachin's northern mountains. These rivers flow relatively straight north to south before emptying through the Irrawaddy Delta into the Andaman Sea, forming one of the two largest delta systems in Southeast Asia (Furuichi et al., 2009; Sirisena et al., 2021). The basin features a varied topography, with rugged mountains in the north, broad plateaus and floodplains around 500 masl in the central region, and flat, low-lying deltaic areas in the south. The western branch of the Mali River originates from the end of the southern Himalayas, north of Putao, and is called Nam Kiu locally. The easternmost branch of N'mai River is the largest stream among the two that originates in the Languela Glacier north of Putao. It flows through the country from north to south dissecting the centre and empties through a nine-armed delta into the Indian Ocean. From Myitkyina, the river is about 2,050 km long and the drainage basin encompasses about 426,501 km^2 of which 202,745 km^2 falls within the territory of HKH region.

Glacier distribution in 2020

In the Irrawaddy River basin, 127 glaciers have been identified, spanning a total area of 32.91 km^2 and estimated to hold ice reserves of approximately 1.2 km^3 (Table 5.1). All glaciers in this basin are clean-ice types. It has the lowest number and area of glaciers in the HKH region, representing just 0.2% and 0.06% of the total number and area, with all glaciers concentrated in a single sub-basin in the northern part. The distribution of glaciers in this basin is shown in the Figure 5.41.

FIGURE 5.41 MAP SHOWING GLACIER DISTRIBUTION AND EXTENT OF THE IRRAWADDY RIVER BASIN WITHIN THE HKH REGION.



The glaciers in the basin range in size from 0.02 km² to 2.7 km². The glacier size distribution is predominantly characterised by a high number of small glaciers (Figure 5.42). Out of a total of 127 glaciers, 87% fall into the smallest size Class 1 (<0.5km²), contributing 43% of the total glacier area and 25% of the estimated ice reserves. This indicates that, although the smaller glaciers are numerous, their individual impact on the glacier landscape is relatively limited. While size Class 2 (0.51 to 1.00 km²) contains only 9 glaciers and mid-sized Class 3 (1.01 to 5.00 km²) consists only 7 glaciers, they play a more substantial role in overall area and estimated ice reserves distribution, collectively contributing 47% and 75% of the total area and estimated ice reserves in the basin.

The glaciers in the Irrawaddy River basin range in elevation from 3,990 to 5,691 masl. An analysis of glacier area distribution reveals that over 93% of the glacier area is concentrated between 4,500 and 5,500 masl (Figure 5.43), with 67% located specifically between 4,800 and 5,200 masl. Coverage is minimal at lower elevations; for instance, the 3,900 to 4,000 masl range contributes only 0.02%, and the 4,000 to 4,100 masl range covers 0.66%. As elevation increases, area coverage gradually rises, peaking at 4,700 to 4,800 masl, which accounts for 7.43% of the total area.

The most substantial concentration of glacier areas occurs between 4,900 and 5,100 masl, where the area coverage reaches 17% at 4,900 to 5,000 masl and nearly 21% at 5,000 to 5,100 masl. Together, these two ranges represent a significant 37% of the total glacier area, highlighting their importance for glacier formation in the basin.

Above 5,100 masl, glacier area begins to decline. The range from 5,100 to 5,200 masl still contributes nearly 16.7% of the total area, but coverage drops sharply in the subsequent ranges, falling to around 8% at 5,200 to 5,300 masl and further to 3.3% at 5,300 to 5,400 masl.

The distribution of these glaciers varies significantly across different slope classes, highlighting the relationship between glacier size and slope. The majority of glaciers (48%) fall within the 20 º – 30º slope range (Figure 5.42), which accounts for the largest portion of glacier area (63%) and the highest estimated ice reserves (69%). This indicates that glaciers in this slope class are both more numerous and larger compared to those in other classes. In addition, glaciers with slopes between 10º and 20º represent 33% of the total number, contributing 31% of the area and 28% of the estimated ice reserves. This emphasises the importance of moderate slopes in supporting glacier formation and size within the basin.

FIGURE 5.42 **GLACIER DISTRIBUTION ACROSS AREA CLASSES** (TOP), **MEAN SLOPE** (BOTTOM LEFT) **AND ASPECT** (BOTTOM RIGHT) **IN THE IRRAWADDY RIVER BASIN.**

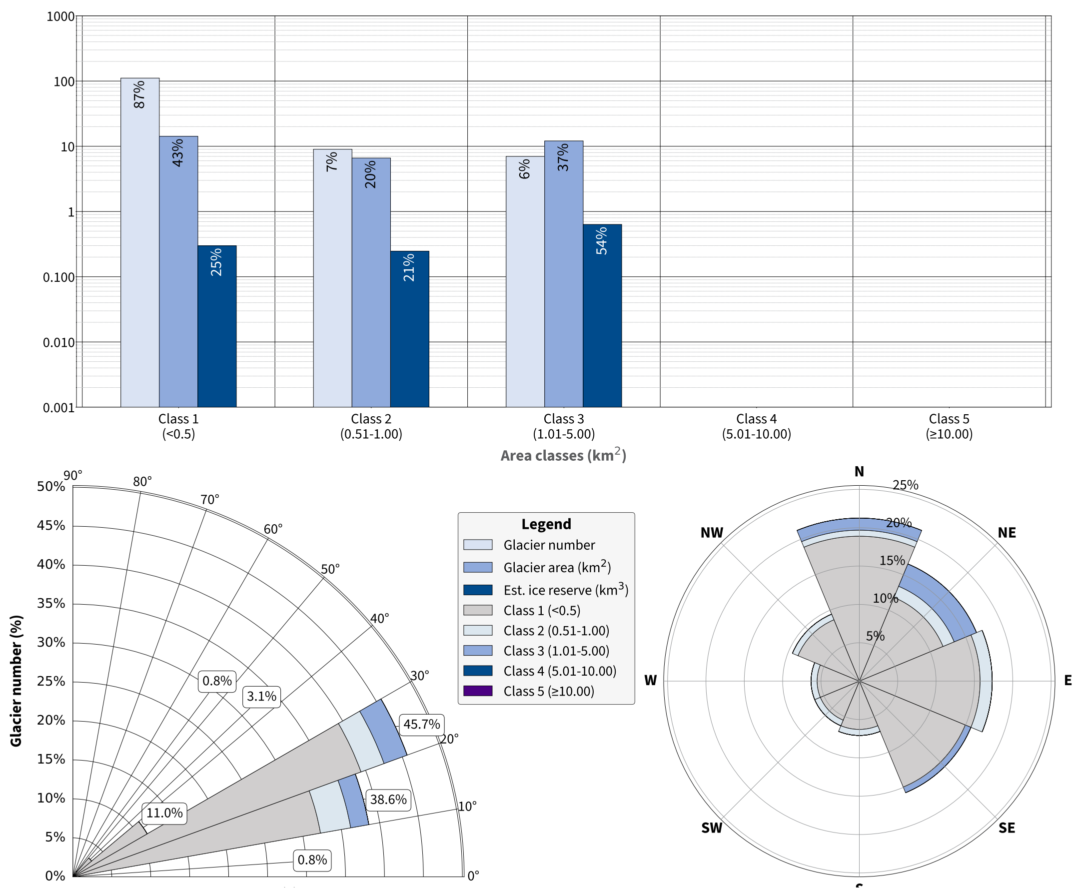
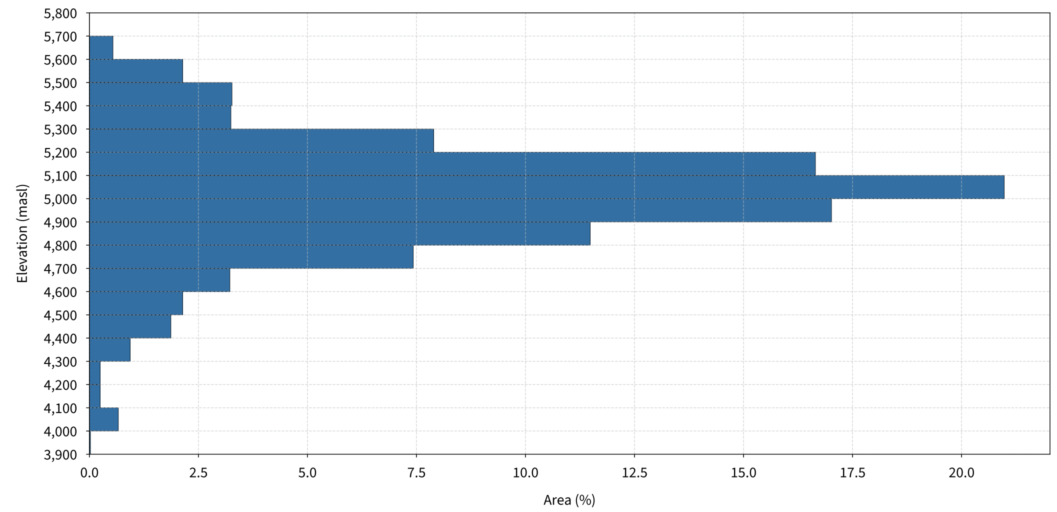


FIGURE 5.43 **GLACIER DISTRIBUTION ACROSS 500 m ELEVATION RANGES IN THE IRRAWADDY RIVER BASIN.**



Conversely, glaciers on gentler slopes (less than 10º) are scarce, with only one glacier contributing negligible area and reserves. On the other end of the spectrum, glaciers with slopes greater than 30º are fewer and cover significantly less area, suggesting that larger glaciers tend to be found in the moderate slope categories. Interestingly, the mean area per glacier increases with slope, peaking in the 20º – 30º range at 0.34 km², before declining in steeper classes. This trend underscores that while smaller glaciers dominate in number, the larger glaciers primarily occupy moderate slopes.

The glacier distribution across different mean aspects in the Irrawaddy River basin reveals a clear dominance of the northern, northeastern, eastern, and southeastern aspects in all entities (Figure 5.42) – number, area and estimated ice reserves. Each of these aspects hosts more than 16% of the basin's total glaciers, with the northern aspect alone accounting for the highest number of 21%. However, the northeastern aspect stands out most prominently in terms of area coverage and ice storage. This aspect holds 35% of the total glacier area and a striking 45% of the basin's estimated ice reserves, underscoring its critical role in basin's water resources. Moreover, glaciers on the northeastern aspect are relatively larger, as indicated by the highest mean glacier size in the basin (0.54 km²).

In contrast, the southern, southwestern, western, and northwestern aspects contain fewer and generally smaller glaciers, contributing minimally to the basin's total glacier area and estimated ice reserves. Each of these aspects comprises less than 10% of the total glacier number, with the southwestern and western aspects recording the lowest presence at only 6% each. Correspondingly, their contributions to glacier area and estimated ice reserves are modest, ranging between 3–5% for area and 2–4% for estimated ice reserves.

Decadal glacier changes from 1990s to 2020

Between 1990 and 2020, the number of glaciers increased by 7%, while their total area decreased by 19%. Interdecadal changes show consistent decrease in both glacier numbers and areas, with the largest reductions occurring in the recent decades between 2010 and 2020 (Figure 5.44), underscoring the increasing trend of glacier retreat due to changes in climate.

FIGURE 5.44 DECADAL GLACIER NUMBER AND AREA CHANGES IN THE IRRAWADDY RIVER BASIN.

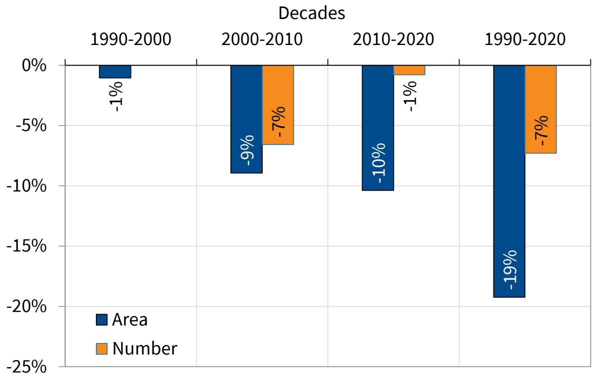
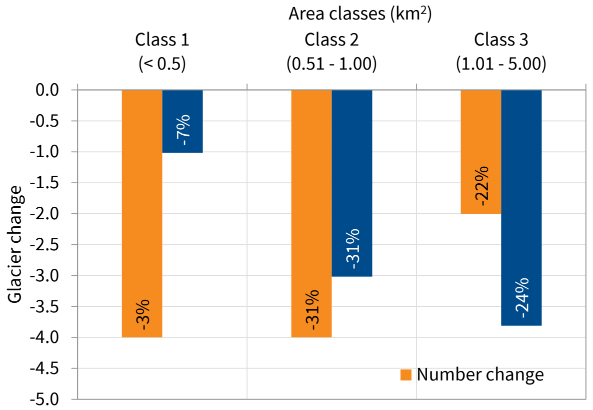


FIGURE 5.45 GLACIER NUMBER AND AREA CHANGES ACROSS SIZE CLASSES OVER THREE DECADES IN THE IRRAWADDY RIVER BASIN.



The glacier changes in the Irrawaddy River basin from 1990 to 2020 show a clear trend of decline, particularly among small- to mid-sized glaciers. The smallest glaciers of Class 1 (less than 0.5 km^2), experienced fluctuations in number, with a net decrease of 4 glaciers over three decades. This size class showed the sharpest decline between 2000 and 2010, though there was a slight recovery afterward. Overall, their number decreased by 3%, and their area shrank by 1.02 km^2, representing a 7% loss.

Class 2 (0.51 and 1.00 km^2) sized glaciers also declined notably, with a total loss of 4 glaciers and a sharp over 31% reduction in area over three decades (Figure 5.45). This class exhibited some temporary growth in number and area from 2000 to 2010, but it was followed by a substantial loss in the recent decade, indicating increasing instability or sensitivity to climatic factors.

For the Class 3 (1.01 – 5.00 km^2) glaciers, the number dropped by two over the three decades, with a 22% decrease. The area loss was the highest in this group, totaling 3.81 km^2 or 24% of its area in 1990. Most of this loss occurred between 2000 and 2010, reinforcing the observation that this decade had the most significant glacier retreat.

Glacier area changes across different elevation ranges in the Irrawaddy River basin from 1990 to 2020 reveal a distinct pattern of retreat that is most pronounced between 4,500 and 5,500 masl (Figure 5.46 and Table 5.19). While higher elevations above 5,500 masl have remained relatively stable, areas below this threshold have experienced the greatest losses, both in absolute terms and percentage decline.

The most dramatic retreat occurred between 4,500 and 5,000 masl, where glacier area decreased by 4.5 km^2, marking a significant 25% reduction. This elevation range exhibited consistent losses across all decades, with the most severe decline –2.6 km^2 – occurring between 2000 and 2010. This suggests that glaciers in this range are particularly vulnerable to climate variability and rising temperatures.

In the 5,000 – 5,500 masl range, glaciers shrank by 3.01 km^2, a 15% reduction over three decades. Although the rate of decline here was more gradual, the steady downward trend across all decade's points to ongoing, temperature-driven melting, even at relatively higher altitudes.

Below 4,500 masl, glacier retreat was also evident. Glaciers between 4,000 and 4,500 masl lost nearly 18.5% of their area, with some variability in the rate of change across different decades. Despite this fluctuation, the overall trajectory remained negative.

Over 5,500 masl, glaciers showed minimal change, with only a 1% net loss in area over the three decades. This indicates relative stability at these higher elevations.

Glacier changes across different slope classes in the Irrawaddy Basin from 1990 to 2020 show the most pronounced losses occurring in moderate slope ranges, particularly between 20° and 30° (Figure 5.47). This slope class experienced the greatest reductions in both glacier number and area, with a loss of 13 glaciers, equating to a 17.6% decline, and a reduction in glacier area by 5.07 km^2, or 19.5%. In contrast, glaciers on gentler slopes (10° – 20°) showed an increase in number by

FIGURE 5.46 GLACIER AREA DISTRIBUTION AND CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE IRRAWADDY RIVER BASIN.

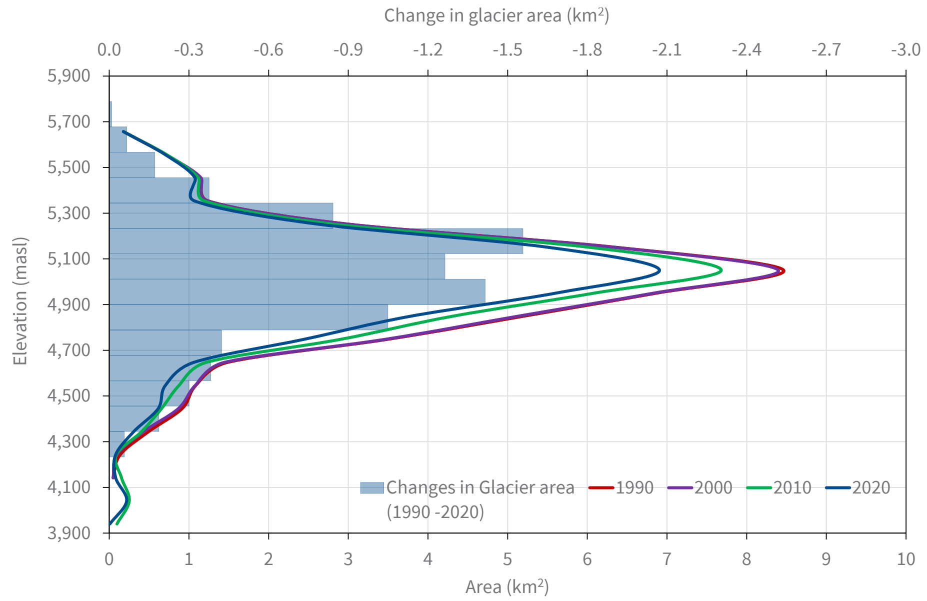


TABLE 5.19 GLACIER AREA DISTRIBUTION AND PERCENTAGE CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE IRRAWADDY RIVER BASIN.

Elevation Range (masl)	Area (km²)				Area change (%)				
	1990	2000	2010	2020	1990 - 2000	2000 - 2010	2010 - 2020	1990 - 2020	Per decade
3,500 – 4,000			0.10	0.01			-91.7		-91.7
4,000 – 4,500	1.60	1.44	1.56	1.30	-9.6	7.9	-16.3	-18.4	-6.0
4,500 – 5,000	18.13	17.94	15.39	13.59	-1.0	-14.2	-11.7	-25.0	-9.0
5,000 – 5,500	20.14	20.05	18.78	17.13	-0.5	-6.3	-8.8	-15.0	-5.2
5,500 – 6,000	0.89	0.89	0.90	0.88	0.1	0.9	-2.0	-1.0	-0.3
Total	40.76	40.33	36.73	32.91	-1.0	-8.9	-10.4	-19.2	

9 glaciers, representing a 27.3% rise over the same period. Despite this numerical increase in the 10° – 20° slope class, the total glacier area within this class declined by 2.04 km^2 (16.7%), indicating widespread shrinkage among individual glaciers. This apparent contradiction on increase in glacier number with losses in glacier area clearly indicates the shrinkage and fragmentation of larger glaciers into smaller and disconnected ones. As glaciers retreat and break apart, their mean slope values changed and reclassified into different slope class, contributing to an increase in number but a decrease in overall glacier area.

Flatter slopes (<10°) and steeper slopes ranging from 40° to 50° experienced relatively minimal losses in both glacier number and area over three decades. The <10° slope class lost just 1 glacier, with

FIGURE 5.47 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES IN THE IRRAWADDY RIVER BASIN.

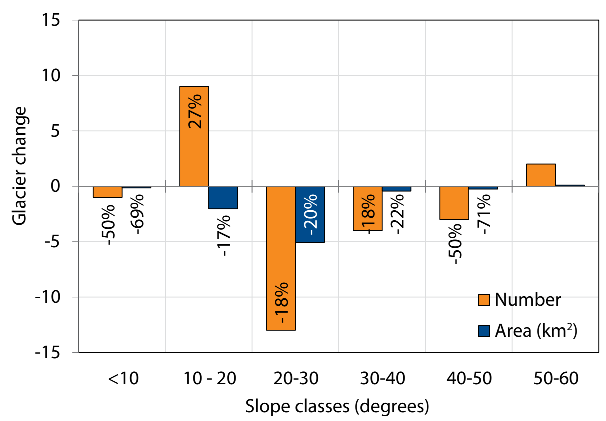
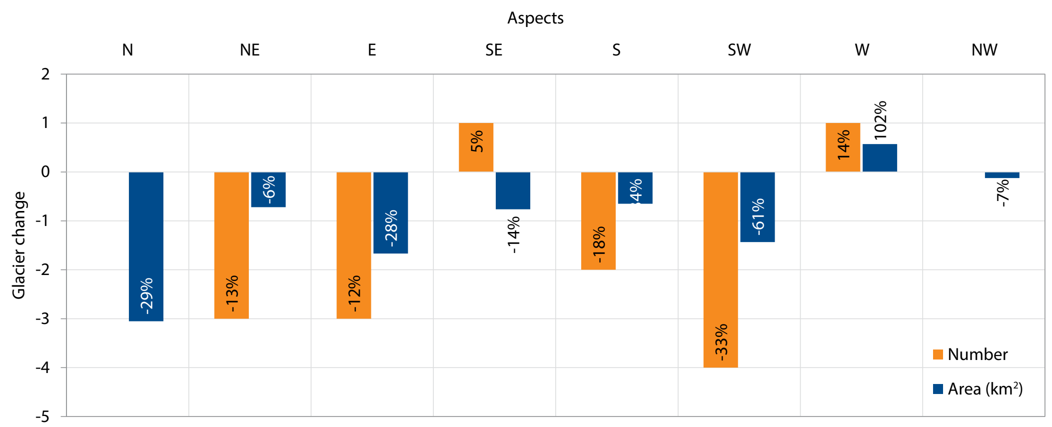


FIGURE 5.48 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES IN THE IRRAWADDY RIVER BASIN.



a corresponding area reduction of 0.15 km², while the 40° – 50° slope class loss of 3 glaciers and an area decrease of 0.25 km².

Glacier changes across different aspects reveal relatively minimal variation in both glacier number and area compared to other basins in the region (Figure 5.48). The northern and northwestern aspects remained largely stable in terms of glacier number over the three decades, although there were minor fluctuations of one or two glaciers in each decade. Despite this numerical stability, glacier area in these aspects consistently declined, with the northern slopes losing approximately 3.05 km² and the northwestern slopes losing 0.12 km², indicating steady glacier retreat.

The southwestern aspect experienced the most significant reduction in glacier number, losing a total of four glaciers over three decades. This decline occurred evenly across the two decades between 2000 – 2010 and 2010 – 2020. Additionally, the southwestern aspect recorded the third highest glacier area loss, with a total reduction of 1.43 km². The loss was steady throughout all decades, highlighting a consistent trend of glacier retreat.

Southern aspects also showed notable glacier losses, with a reduction of two glaciers and a total area loss of 0.65 km² over the three decades. Meanwhile, eastern aspects experienced the second highest glacier area loss, shrinking by 1.67 km², alongside a loss of three glaciers, reflecting substantial retreat in both glacier number and area.

In contrast, southeastern and western aspects displayed a slight increase in glacier number, each gaining one glacier over the study period. However, this increase in number was accompanied by consistent area losses, 0.76 km² for the southeast and 0.57 km² for the west, suggesting that glacier fragmentation or reclassification may be contributing to the rise in number, even as the overall glacier area continues to diminish.

5.6 Salween River Basin

The Salween River basin is a key hydrological region in Southeast Asia, spanning across three countries: China, Myanmar, and Thailand. Originating from the Tibetan Plateau, the Salween River flows southward through deep mountain canyons in Yunnan, China, before entering Myanmar and forming part of Thailand's western border (Lamb et al., 2019). The basin sustains over 10 million people (Johnston et al. 2017; Lamb et al., 2019), providing essential resources for fisheries, agriculture, and livelihoods. It is divided into four basins: Naqu River, Yuqu Jiang River, Middle-Reaches, and the Middle and Lower Reaches. Figure 5.49 shows the distribution of glaciers in each basin in the upper section of the Salween River basin.

Glacier distribution in 2020

As of 2020, the Salween River basin contains 2,122 glaciers, covering a total area of 1,091.25 km² and holding total estimated ice reserves of 75.5 km³. In comparison to the other basins, this basin represents only 2% of the total glacier area and 3.3% of the total number of glaciers of the HKH region. The glaciers are situated between latitudes 30.45°N and 37.08°N, and longitudes 69.36°E and 81.65°E, with an elevation range from 3,519 masl to 6,859 masl. Glacier distribution is highly uneven across the basin. The Middle and Lower Reaches contain the highest concentration, representing nearly 52% of the total glacierised area and 44% of the glaciers in the Salween River basin. This is followed by the Naqu River basin, which holds 32% of the total glacier area and 38% of the glaciers, while the Yuqu Jiang basin has the fewest glaciers and smallest area. The details of the glacier distribution in each basin are shown in Figure 5.51 and Table 5.20.

The glaciers in the basin range in size from 0.02 km² to the largest glacier, which measures 38.3 km² and is located in the Middle and Lower Reaches. The distribution of glaciers by size class reveals that the smallest class of glaciers, those smaller than 0.5 km², dominates in number, accounting for 81% of the total (Figure 5.51). However, this class represents only 24% of the total glacier area and contributed 8% of the total estimated ice reserves. In contrast, the largest class (≥10 km²) contains just 12 glaciers,

FIGURE 5.49 MAP SHOWING GLACIER DISTRIBUTION AND EXTENT OF THE SALWEEN RIVER BASIN WITHIN THE HKH REGION.

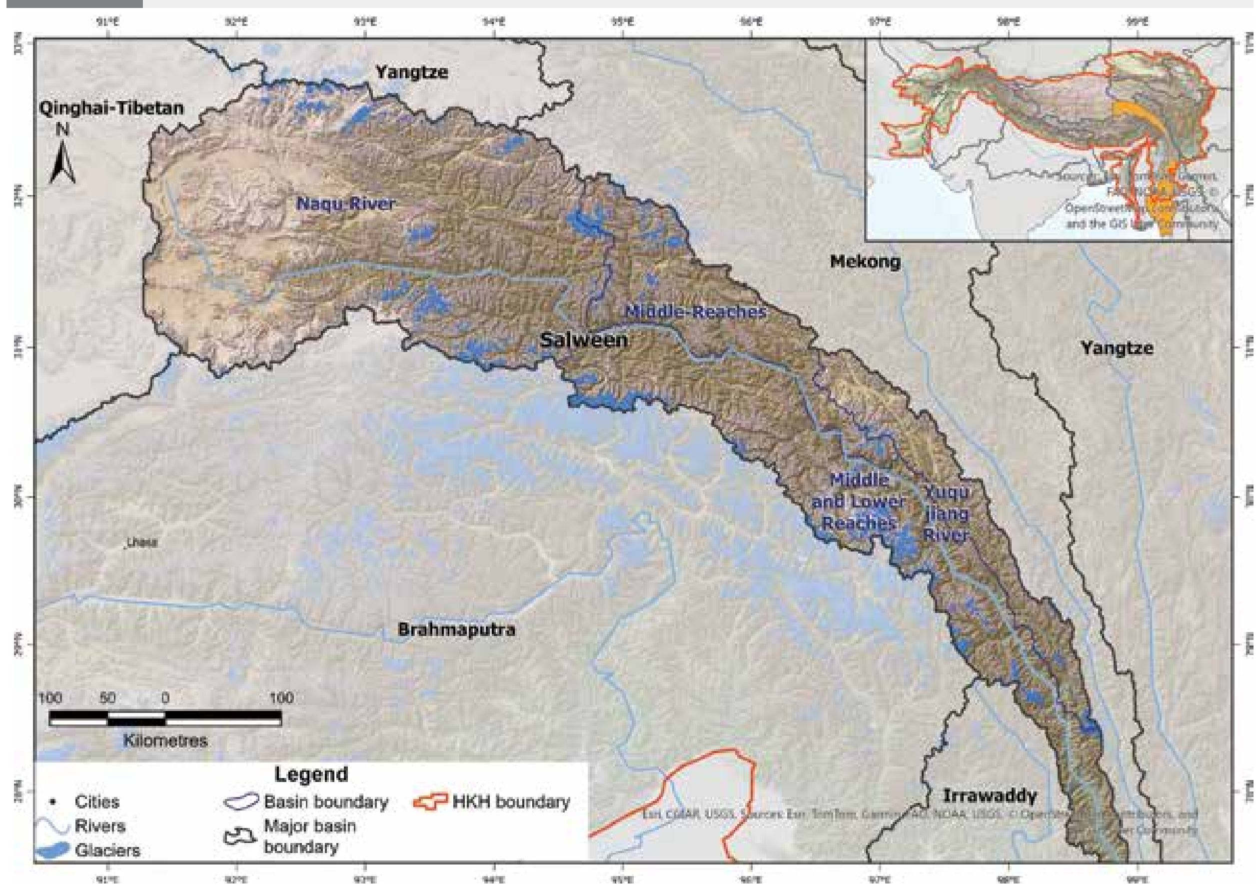


TABLE 5.20 DISTRIBUTION OF GLACIER IN THE BASINS OF THE SALWEEN RIVER BASIN.

Basin	Number	Area (km²)	Largest area (km²)	Estimated ice reserve (km³)	Elevation (masl)		Mean slope (deg)
					Min	Max	
Middle and Lower Reaches	939	566.34	38.28	40.19	3,519	6,480	22
Middle Reaches	285	132.61	14.76	12.37	2,979	6,251	23
Naqu River	807	344.42	33.26	20.05	4,270	6,859	22
Yuqu jiang River	91	47.88	12.61	2.92	3,820	6,453	26
Total	**2,122**	**1,091.25**	**38.28**	**75.53**	**3,519**	**6,859**	**22**

yet these cover 25% of the glacier area and hold 48% of the total estimated ice reserves in the basin. Mid-sized glaciers in Class 3 (1 – 5 km^2) provide the highest area coverage, accounting for nearly 28% of the glacier area despite making up only 8% of the total number of glaciers in the basin. This distribution illustrates that while smaller glaciers are more numerous, larger glaciers are crucial for the basin's overall estimated ice reserves.

Glaciers in the Salween River basin range from 3,519 masl to 6,859 masl, with the lowest glacier located in the Middle and Lower Reaches, and the highest in the Naqu River basin. The distribution glacier area across various elevation ranges showed that more than 89% of the glacier area is concentrated between 5,000 masl and 6,000 masl, with the majority (55%) between 5,000 masl and 5,500 masl (Figure 5.51).

Among its basins – the Middle and Lower Reaches, Naqu River, Middle Reaches, and Yuqu Jiang River, it shows distinct patterns. In the lower elevation ranges of 3,000 to 4,000 masl, glacier presence is minimal, with only a small area observed in the Middle and Lower Reaches and Naqu River. As elevation increases, particularly in the 4,000 to 4,500 masl range, glaciers become more prevalent, with the Middle and Lower Reaches leading in area coverage.

FIGURE 5.50 **GLACIERS DISTRIBUTION ACROSS BASINS** (TOP LEFT), **AREA CLASSES** (TOP RIGHT), **MEAN SLOPE** (BOTTOM LEFT) **AND ASPECTS** (BOTTOM RIGHT) **IN THE SALWEEN RIVER BASIN.**

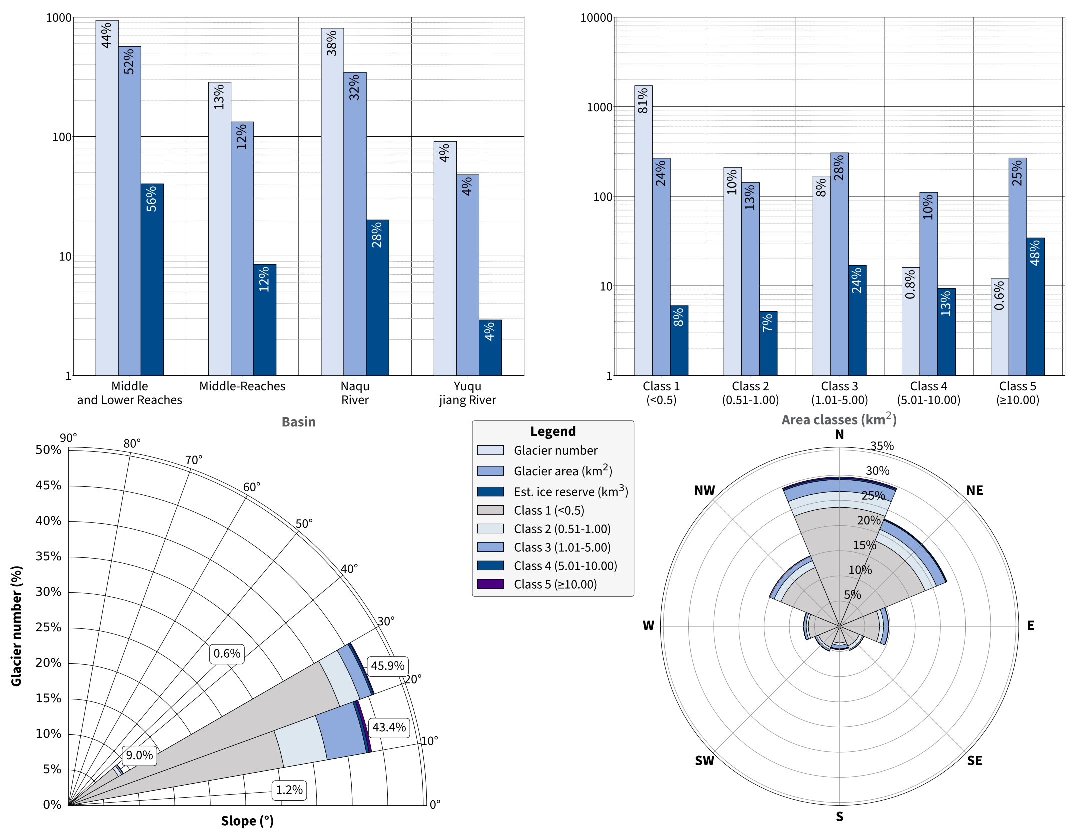
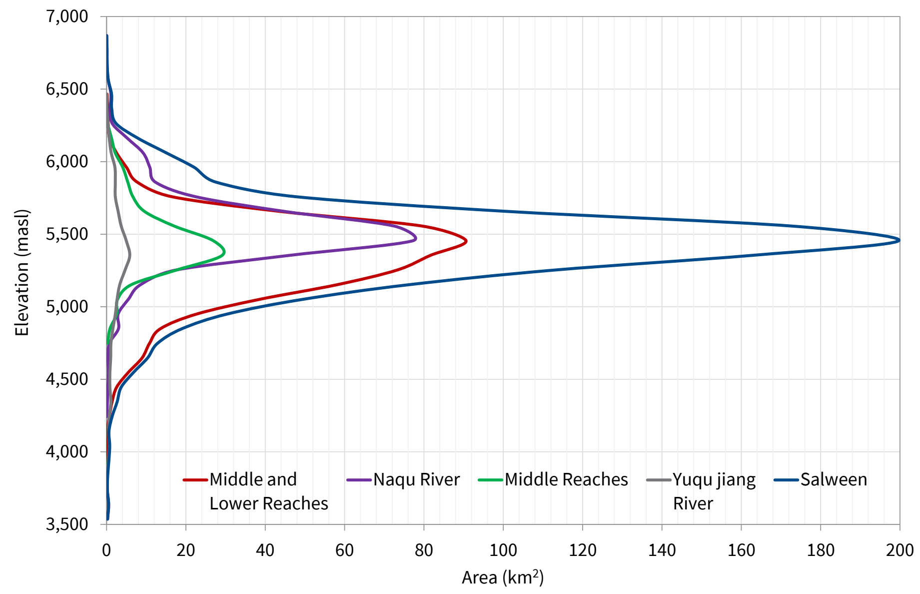


FIGURE 5.51 GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN EACH BASIN OF THE SALWEEN RIVER BASIN.



At elevations between 4,500 and 5,000 masl, the Middle and Lower Reaches exhibit a significant concentration of glaciers, covering approx. 11% of total glacier area in the basin. This trend continues in the 5,000 to 5,500 masl range, where they dominate 60.4% of glacier area in the basin. In comparison, the Naqu River also shows considerable glacier coverage in these ranges, particularly with 45% at 5,000 to 5,500 masl, though it does not reach the levels seen in the Middle and Lower Reaches.

However, the glacial area begins to decline at higher elevations. Between 5,500 and 6,000 masl, the Middle and Lower Reaches still maintain a strong presence with approx 27% of glacier area in the basin, while the Naqu River slightly outpaces it with 47.4% within the basin. This indicates that the Naqu River may have favourable conditions for glacier retention at higher altitudes. Beyond 6,000 masl, both basins see a sharp decrease in glacier area, with only a few kilometres reported, particularly in the Naqu River and Yuqu Jiang River.

Overall, the comparative analysis highlights that the Middle and Lower Reaches are the most significant contributors to glacier area in the Salween River basin, particularly in the optimal elevation range of 5,000 to 6,000 masl. The Naqu River follows with substantial glacier coverage, especially at higher elevations than in other basins. In contrast, the Middle Reaches and Yuqu Jiang River show less glacier area overall, indicating that elevation and geographic conditions heavily influence glacier distribution across these basins.

The distribution of glaciers across various mean slope classes highlights important trends in glacier presence, area, and estimated ice reserves. In the flatter slope class of less than 10°, there are fewer glaciers, accounting for only 1% of the total, but these glaciers are relatively large, with a mean area of 1.91 km^2. The slope class of 20° to 30°, however, contains over 50% of the total glacier number, covering 36% of the total glacier area and holding 29% of the estimated ice reserves (Figure 5.50). In contrast, the 10° to 20° slope class hosts 38% of the total glaciers and encompasses the largest area, accounting for over 56% of the total glacier area and 59% of the estimated ice reserves. With a mean area of 0.76 km^2, the glaciers in this class are smaller on average compared to those in the flatter slopes.

As slope steepness increases beyond 30°, both the number and area of glaciers decrease significantly, with no glaciers mapped above a mean slope of 50°, indicating that such steep slopes are less conducive to glacier formation and retention. In the 30° to 40° and 40° to 50° classes, the mean area per glacier drops further to 0.2 km^2 and 0.09 km^2, respectively, emphasising that fewer glaciers exist in these steeper slopes, and those that are quite small.

The glacier distribution across various mean aspect classes in the Salween River basin reveals a strong preference for northern, northeastern and northwestern aspects, in all entities – glacier number, area and estimated ice reserves (Figure 5.50). Northern aspects are the most dominant, hosting 30% of the total glaciers, which account for 34% of the basin's total glacier area and 38% of the estimated ice reserves. The northeastern and northwestern aspects follow as the second and third most glacier-rich aspects. The northeastern consists of 23% of the glaciers, covering 22% of the area and holding 19% of the total estimated ice reserves in the basin. The northwestern, with 15% of the glacier number, accounting 15% of the glacier area and 17% of the estimated ice reserves. These three northern-facing classes collectively represent the majority of glacier presence in the basin.

In addition to their dominance in number area and estimated ice reserves, these aspects are also home to relatively larger glaciers, as indicated by their higher mean glacier sizes, ranging from 0.5 km² to 0.6 km², with the largest average size found in the northern aspect. This further signifies the major role in freshwater resources contributor of the basins.

In contrast, southern, southeastern and southwestern aspects support significantly fewer and smaller glaciers. Each of these aspects holds only 5% of the total glacier number. The southeastern and southwestern aspects each contribute just 3% of the total glacier area. However, the southern aspect stands out by contributing a comparatively large share of glacier area, 10% of the total, despite having a low glacier number. This results in the highest mean glacier size in the basin, exceeding 1 km², suggesting the presence of a few, but very large, glaciers in this aspect.

Eastern and western aspects also exhibit limited glacier presence. The eastern aspect, while accounting for 10% of the glaciers, contributes only 9% of the total glacier area and just 6% of the estimated ice reserves. Its average glacier size is moderate, at 0.45 km². The western aspect consists only 7% of the glacier number, with the lowest percentage of area and estimated ice reserves and the smallest mean glacier size at just 0.30 km². These findings further highlight the reduced glacier formation and preservation in the western aspect.

Decadal glacier changes from 1990s to 2020

From 1990 to 2020, the Salween River basin experienced significant glacier retreat. Overall, the total glacier area diminished from 1,620.61 km² in 1990 to 1,091.25 km² in 2020, marking a substantial reduction of approximately 33%. The rate of decline accelerated particularly in the recent decade, with a pronounced decrease of 11.4% from 1990 to 2000, followed by a slightly less loss of 9.5% from 2000 to 2010, and a continued more pronounced decline of 16% from 2010 to 2020 (Figure 5.52 and Table 5.21).

In terms of glacier number, it declined by 18.8%, from 2,614 glaciers in 1990 to 2,122 glaciers in 2020. This reduction reflects not only a shrinkage in glacier size but also the gradual transformation of glaciers into perennial snow/ice patches. The rate of glacier loss accelerated from 2000 to 2010. The glacier number decreased by over 1% between 1990 and 2000, but this rate increased to approx. 10% between 2000 and 2010, underscoring the intensifying impact of climate change (Figure 5.52).

In comparing the basins, the Middle and Lower Reaches exhibit a significant total reduction of 31.3%, with the most notable loss occurring between 2000 and 2010. Similarly, the Middle Reaches experienced a total decline of 32.6%, initially showing slight loss by 12% between 1990 to 2000 then slight growth between 2000 to 2010 before facing sharp losses in recent decade of 2010 to 2020. The Naqu River basin showed the most substantial total area decreased by 35.1%, reflecting a consistent pattern of loss. In contrast, the Yuqu Jiang River basin, with a total reduction of 30.5%, also demonstrated consistent declines over all decades (Table 5.21).

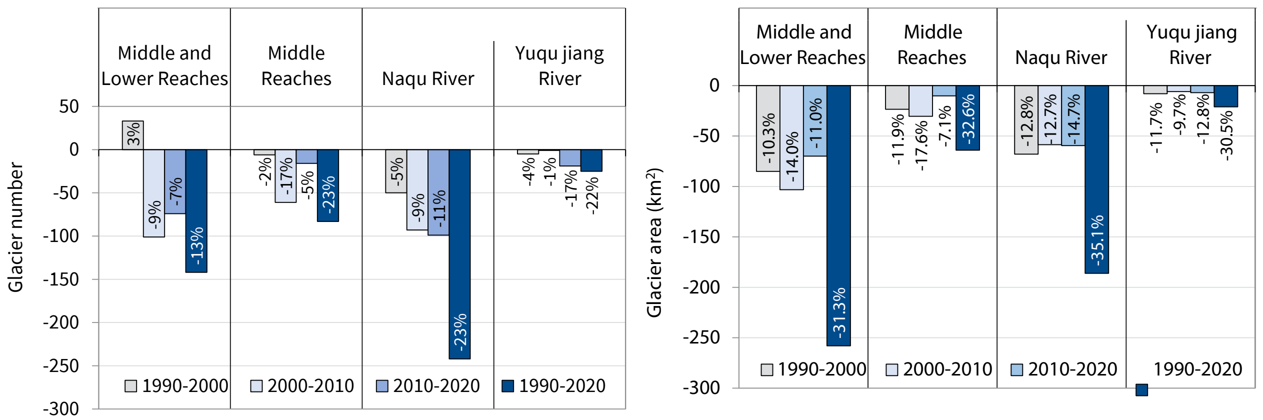
Overall, the trends indicate an accelerating rate of glacier retreat, particularly evident in the last decade. While the total reductions are comparable within all the basins, the specific rates of loss vary, with the Middle and Lower Reaches and Naqu River showing the most pronounced declines. This underscores the impact of climate change on glacial dynamics throughout the basin, highlighting the urgent need for continued monitoring and research to address the implications of these changes for water resources and ecosystems.

Glaciers of all size classes experienced reductions in both area and number, with the exception of the smallest class (under 0.5 km²), which showed a 4% increase from 1990 to 2000 before declining. Despite this initial growth, the total glacier area in this class has steadily decreased, resulting in an overall loss of about 26.7% over the past three decades (Figure 5.53). This indicates that the smaller glaciers often consist

TABLE 5.21 DECADAL CHANGES IN GLACIER NUMBER AND AREA IN THE SALWEEN RIVER BASIN AND ITS MAIN BASINS FROM 1990 TO 2020.

Basin	Number				Area (km²)				Decadal change - Number / Area (%)				
	1990	2000	2010	2020	1990	2000	2010	2020	1990-2000	2000-2010	2010-2020	1990-2020	per decade
Middle and Lower Reaches	1,081	1,114	1,013	939	824.41	739.40	636.20	566.34	3.1 / -10.3	-9.1 / -14	-7.3 / -11	-13.1 / -31.3	-4.4 / -11.8
Middle-Reaches	368	362	301	285	196.68	173.25	142.80	132.61	-1.6 / -11.9	-16.9 / 17.6	-5.3 / -7.1	-22.6 / -32.6	-7.9 / -12.2
Naqu River	1,049	999	906	807	530.62	462.62	403.97	344.42	-4.8 / -12.8	-9.3 / -12.7	-10.9 / -14.7	-23.1 / -35.1	-8.3 / -13.4
Yuqu jiang River	116	111	110	91	68.91	60.83	54.91	47.88	-4.3 / -11.7	-0.9 / -9.7	-17.3 / -12.8	-21.6 / -30.5	-7.5 / -11.4
Total	**2,614**	**2,586**	**2,330**	**2,122**	**1620.61**	**1436.09**	**1,237.88**	**1,091.25**	**-1.1 / -11.4**	**-9.9 / -13.8**	**-8.9 / -11.8**	**-18.8 / -32.7**	**-6.6 / -12.3**

FIGURE 5.52 INTERDECADAL GLACIER NUMBER (LEFT) **AND AREA** (RIGHT) **CHANGES IN EACH BASIN OF THE SALWEEN RIVER BASIN.**



of limited mass, less thermal inertia and/or less insulated by surrounding topography, making them more exposed and susceptible to climate changes.

Significant reductions were also noted in size Class 2 (0.51 – 1.00 km²) and Class 3 (1.01 – 5.00 km²), with both categories showing steady decreases in number and area each decade. Over three decades, the number of glaciers in these classes has declined by more than 40%, with Class 2 experiencing a more pronounced loss of 45%. In terms of area, Class 2 and Class 3 glaciers decreased by 47% and 42%, respectively. Notably, Class 3 experienced the most significant absolute area loss, totaling nearly 222 km².

In contrast, larger glaciers have shown moderate changes, with only five glaciers lost in Class 4 (5.01 – 10.00 km²) and two in Class 5 (≥ 10.00 km²). Nonetheless, their areas have still decreased by over 26% (39.6 km²) in Class 4 and 15% (46 km²) in Class 5, over the same period, indicating that even larger glaciers are not immune to the impacts of climate change, despite their relatively stable numbers.

Changes in glacier areas have also been noted across different elevation ranges. In 1990, the lowest elevation of the glacier snout was at 3,346 masl, which retreated to 3,519 masl by 2020, indicating an upward shift of 173 metres over three decades. This retreat and upward movement of the glacier snout varied across different basins, ranging from 26 metres to 173 metres. The greatest shift was observed in the Middle and Lower Reaches basin, while the smallest shift occurred in the Yuqu basin.

Over the past three decades, from 1990 to 2020, glacier areas have undergone significant changes across various elevation ranges, with distinct trends observed in each decade (Table 5.22). The most pronounced area loss occurred between 5,000 and 5,500 masl, which experienced a total decline of 38.4% over this period (Figure 5.54). In comparison, elevations below 5,000 masl showed minimal overall loss; however, the percentage losses were notable, with reductions of 13% in the 3,500 to 4,000 masl range and 38.3% in the 4,500 to 5,000 masl range over three decades. The interdecadal losses followed a similar pattern, ranging from 13% to 17% in each decade. At the lowest elevations, below 3,500 masl, glacier area loss was around 14% in the first decade (1990 to 2000), but by 2000, no glaciers were mapped at this elevation, indicating their complete disappearance.

In contrast, glacier distribution and losses above 5,500 masl showed relatively stable conditions. The elevation range of 5,500 to 6,000 masl experienced consistent area reductions of approximately 7.1% to 7.8% in each decade, totalling a 20.6% loss over three decades. However, at elevations above 6,000 masl, both absolute area and percentage losses were minimal, with little to no change observed.

Similar loss patterns were observed across all four basins of the Salween with the most significant distribution and loss occurring in the Middle and Lower Reaches basin at elevations between 5,000 and 5,500 masl, where a reduction of approximately 34% was noted over three decades. The Naqu basin followed closely, experiencing a loss of about 46.3%, while the Yuqu basin showed a reduction of around 41.4% in the same elevation range. Although the percentage loss in each basin and in each decade was higher below 5,000 masl, the absolute area losses were still less than those observed at the 5,000 to 5,500 masl elevation range across all basins and decades.

FIGURE 5.53 INTERDECADAL GLACIER CHANGES ACROSS SIZE CLASSES OVER THREE DECADES IN THE SALWEEN RIVER BASIN.

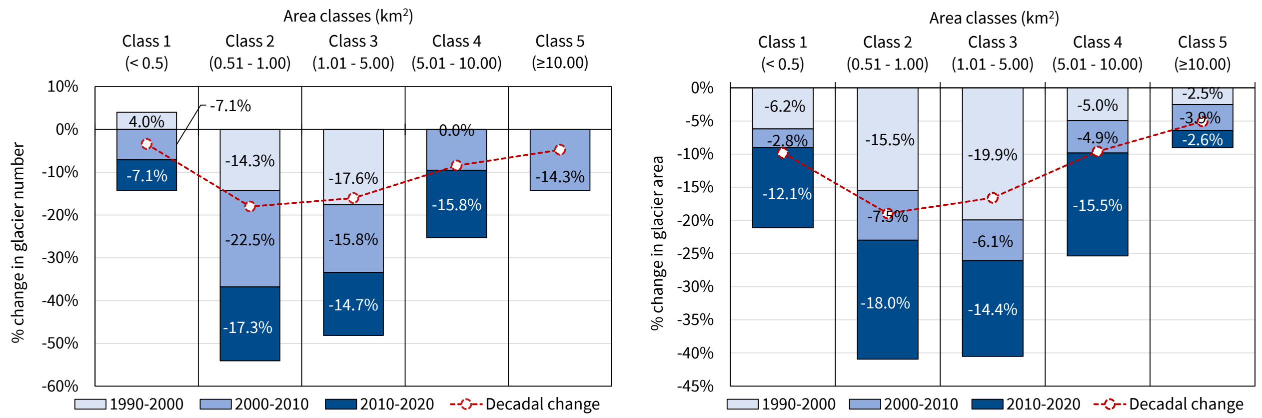


FIGURE 5.54 GLACIER AREA DISTRIBUTION AND CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE SALWEEN RIVER BASIN.

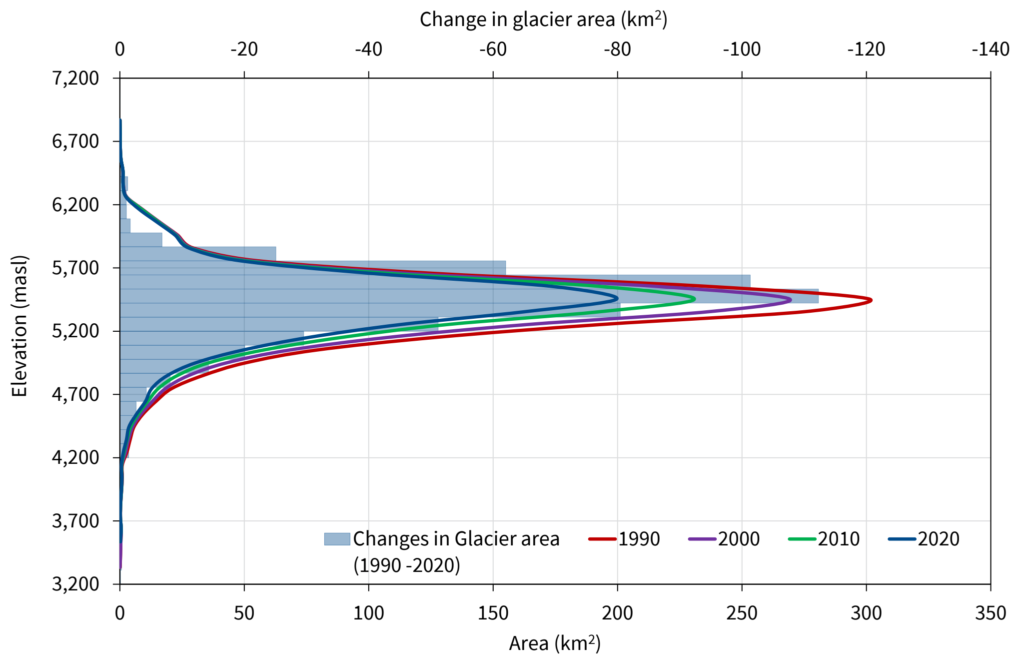


TABLE 5.22 GLACIER AREA DISTRIBUTION AND PERCENTAGE CHANGES ACROSS VARIOUS ELEVATION RANGES FROM 1990 TO 2020 IN THE SALWEEN RIVER BASIN.

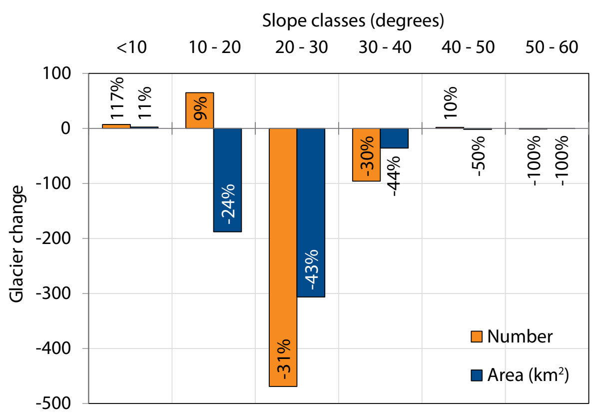
Elevation range (masl)	Area (km²)				Area change (%)				
	1990	2000	2010	2020	1990 - 2000	2000 - 2010	2010 - 2020	1990 - 2020	Per decade
3,000 – 3,500	0.348	0.300			-13.8				-13.8
3,500 – 4,000	2.080	2.053	1.778	1.803	-1.3	-13.4	1.4	-13.3	-4.4
4,000 – 4,500	14.571	12.662	10.507	9.093	-13.1	-17.0	-13.5	-37.6	-14.5
4,500 – 5,000	128.663	110.511	92.919	79.392	-14.1	-15.9	-14.6	-38.3	-14.9
5,000 – 5,500	975.868	846.003	702.579	601.029	-13.3	-17.0	-14.5	-38.4	-14.9
5,500 – 6,000	468.030	433.543	399.880	371.405	-7.4	-7.8	-7.1	-20.6	-7.4
6,000 – 6,500	30.357	30.327	29.524	27.839	-0.1	-2.6	-5.7	-8.3	-2.8
6,500 – 7,000	0.697	0.688	0.688	0.687	-1.3	0.0	-0.1	-1.4	-0.5
Total	1,620.61	1,436.09	1,237.88	1,091.25	-11.4	-13.8	-11.8	-32.7	-12.3

The analysis of glacier changes across various mean slope classes from 1990 to 2020 reveals significant trends in both the number and area of glaciers. Glaciers in the <10° slope class showed notable resilience, experiencing initial declines of one glacier but recovering with substantial growth in subsequent decades by increasing in 5 and 3 numbers of glaciers in the subsequent decades, resulting in an overall increase in number by 7 and area by 11% (2.45 km²). In contrast, the 10° – 20° slope class showed an increase in number in the first two decades (1990 – 2000 and 2000 – 2010) and ultimately no changes in last decade from 2010 to 2020, leading the total gain in number by 9% over three decades. However, the area suffered severe losses of 24% in three decades, with drastic reduction in each decade by around 63 km² per decade. This contrasts with the slope ranges of 20° – 30° exhibiting the most substantial loss in both numbers and area, with total loss of number by 31% losing almost 43% of the total glacier area over three decades indicating the extreme vulnerability of glacier with this mean slope ranges (Figure 5.55).

Similarly, 30° – 40° classes exhibited concerning declines in both numbers by 30% and area 44%, but its absolute values are considerably less compared to the slope range of 20° – 30°. Meanwhile, glaciers in the 40°– 50° class initially gained numbers but faced a slight decline, thereafter, resulting in a net increase in number by just 2 glaciers, while the area experiences consistent decreases with a total loss of 1.9 km² (50%). The 50° – 60° class suffered a complete loss in the last decade, indicating critical vulnerability.

Overall, this analysis highlights the decline of glaciers in moderate to steep slopes. The loss of glaciers on steeper slopes has altered the mean slopes of individual glaciers, resulting in an increase in the number of glaciers at gentler to moderate slopes. However, the area across all slope classes has steadily decreased in each decade, with the exception of a slight increase in area within the gentler slope class. This increases due to the addition of glaciers in the gentler slope class because of the changes in mean slope for those individual glaciers with loss portion of glacier on the steeper slope.

FIGURE 5.55 GLACIER NUMBER AND AREA CHANGES ACROSS VARIOUS MEAN SLOPE CLASSES OVER THREE DECADES IN THE SALWEEN RIVER BASIN.



In terms of mean aspects of the glaciers, its changes reflect widespread retreat, with considerable variability in glacier number and area loss across different aspects. The northern, northeastern, and northwestern aspects showed the most significant and consistent declines in both glacier number and area. The northern aspect experienced the largest loss, with 90 glaciers disappearing and an area loss of 162 km^2, representing a more than 30% decline over three decades. The northeastern aspect showed the steepest drop in glacier numbers, losing 22% of its glaciers, and suffered a significant area loss of over 36% (Figure 5.56). Similarly, the northwestern aspect experienced a 21.7% reduction in glacier number and a 30.2% decrease in glacier area, indicating consistent but slightly slower retreat compared to the northern and northeastern aspects.

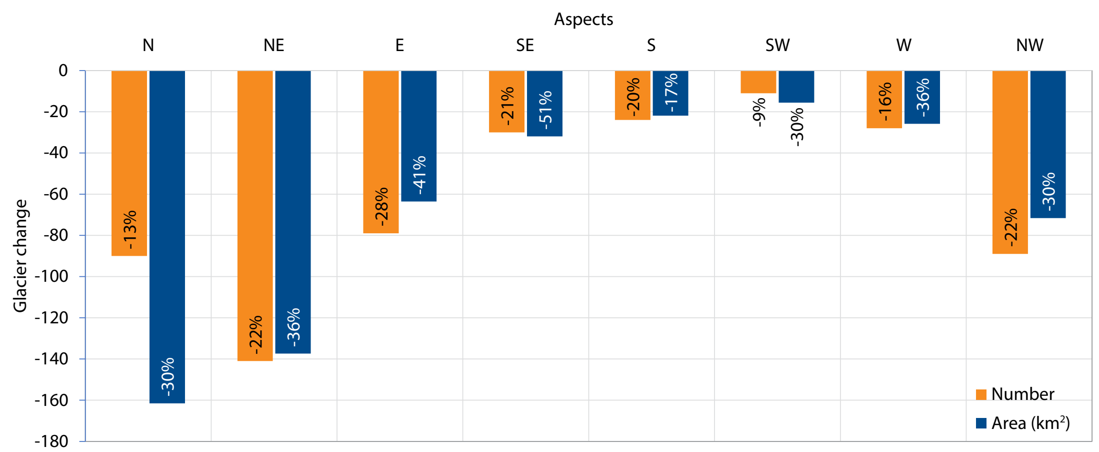
In contrast, the southeastern, southern, and southwestern aspects also experienced notable glacier losses, but these were less pronounced in both glacier numbers and area. The southeastern aspect lost 30 glaciers, with a drastic reduction in glacier area of more than 50%, while the southern aspect showed a loss of 24 glaciers and a 17% decline in glacier area over the three decades. The southwestern aspect experienced about a 9% decline in glacier numbers and nearly 30% in the area. These aspects, more directly exposed to the sun, are particularly susceptible to melting, making them some of the fastest retreating in the basin.

The eastern and western aspects experienced moderate losses in both glacier numbers and areas. The eastern aspect lost nearly 41% of its glacier area and 79 glaciers over the three decades. However, the absolute area loss here was considerably less than in the northern-facing aspects. Similarly, the western aspect saw a relatively smaller absolute loss compared to the northern aspects, but its percentage losses were significant, with over 36% area loss and about 16% decline in glacier number.

Overall, the results highlight that glacier retreat is occurring across all aspects of the Salween River basin, with eastern, southeastern, and northeastern aspects being particularly vulnerable. These areas not only experienced steep losses in the glacier area but also significant reductions in glacier numbers. However, the absolute area losses were considerably higher in the northern, northeastern, and northwestern aspects, where glacier distribution is also much more significant. In comparison, while the other aspects showed smaller absolute losses, the percentage of loss was notably higher, emphasising their increased vulnerability.

The consistent reduction in glacier area, alongside the larger number of glaciers lost, suggests the disappearance of smaller glaciers, some of which have retreated beyond the area threshold considered in this study. Additionally, the variability in glacier number loss across different aspects can also be attributed to the shrinkage and fragmentation of larger glaciers into smaller ones, which alters their mean aspect and leads to their reclassification into different aspect categories. This fragmentation process further complicates the assessment of glacier retreat in various aspects and reflects the widespread and ongoing changes in the basin.

FIGURE 5.56 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES IN THE SALWEEN RIVER BASIN.



5.7 Mekong River Basin

The Mekong River basin is a vital ecological and cultural region in Southeast Asia, encompassing a diverse landscape that stretches approximately 4,900 kilometres from its source in the Tibetan Plateau to its delta in Vietnam, where it meets the South China Sea. This basin covers around 822,821.66 km^2, traversing six countries: China, Myanmar, Laos, Thailand, Cambodia, and Vietnam (Zhang et al., 2020; Chen et al., 2024). The basin plays a crucial role in the livelihoods of approximately 60–65 million people, who rely on its waters for agriculture, fishing, and transportation, making it a cornerstone of the region's economy and cultural identity. The River basin is divided into four main basins: Angqu, Ziqu, Middle Reaches, and Mekong Main Trunk. 91% of the basin is encompassed by the Middle Reaches, although only 7% of the Middle Reaches fall within the HKH region. Despite this, it remains the largest basin, contributing 43% of the total area within the Mekong basin. Figure 5.57 below shows the extent of each basin boundary in the upper section of the Mekong River basin including glacier distributions.

Glacier distribution in 2020

Based on Landsat images from 2020, 540 glaciers were mapped within the basin, covering a total area of 233.4 km^2. Overall, in the HKH region, this river basin consists of only about 1% of glacier number covering 0.4% of the total glacier area coverage. These glaciers are located between 80° to 88.7° E longitude and 27.5° to 30.6° N latitude, with elevations ranging from 2,979 to 6,121 masl. The glaciers in the Mekong River basin were distributed in the three main basins including one glacier in the main trunk basin. Among these glaciated basins, The Ziqu basin holds the highest number and area

FIGURE 5.57 MAP SHOWING GLACIER DISTRIBUTIONS AND EXTENT OF THE MEKONG RIVER BASIN WITHIN THE HKH REGION.

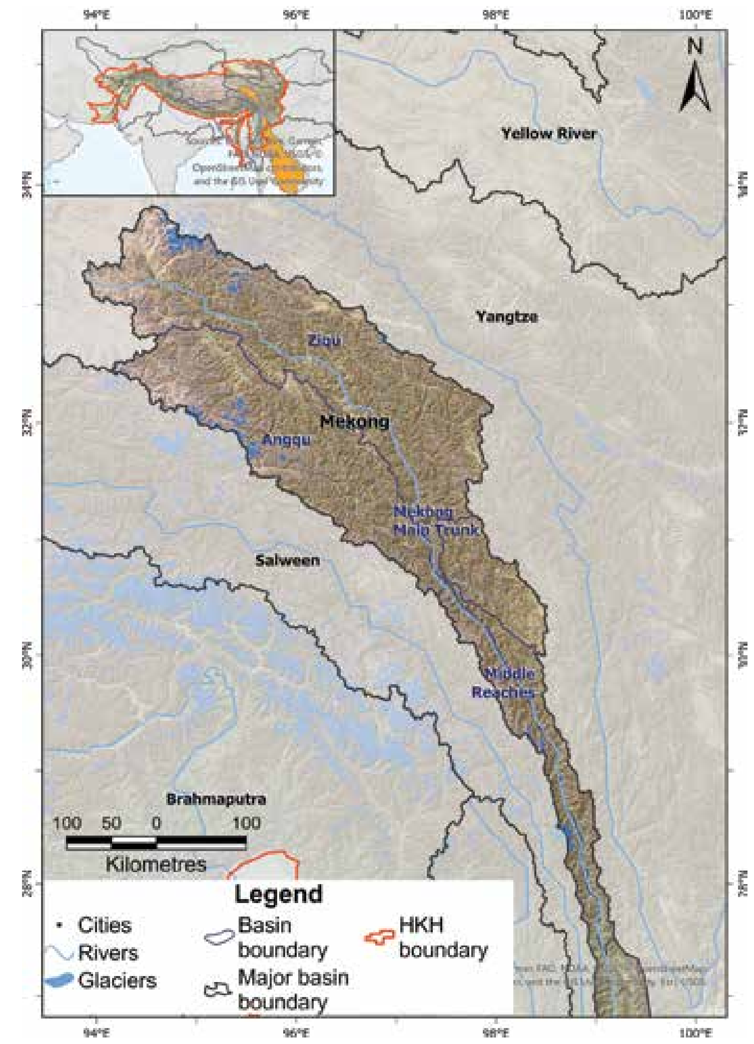


FIGURE 5.58 **GLACIER DISTRIBUTION ACROSS BASINS** (TOP LEFT), **AREA CLASSES** (TOP RIGHT), **MEAN SLOPES** (BOTTOM LEFT) **AND ASPECTS** (BOTTOM RIGHT) **IN THE MEKONG RIVER BASIN.**

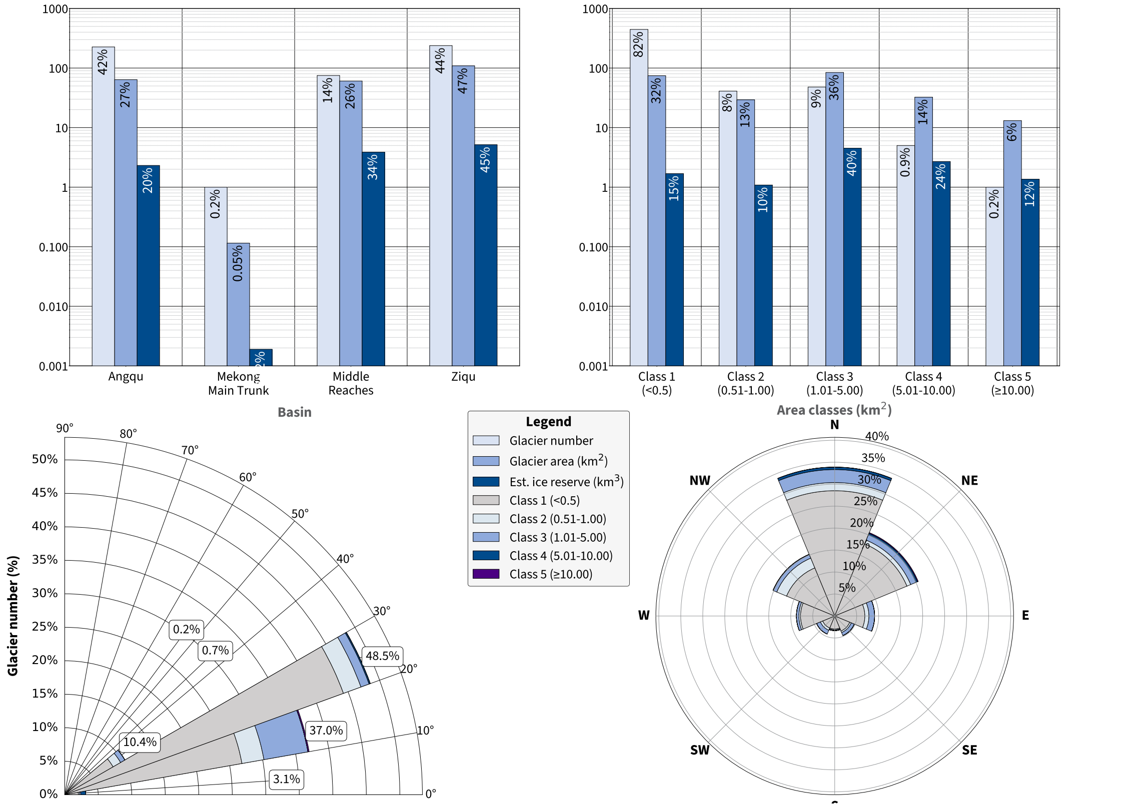


TABLE 5.23 **DISTRIBUTION OF GLACIER IN THE BASINS OF THE MEKONG RIVER BASIN.**

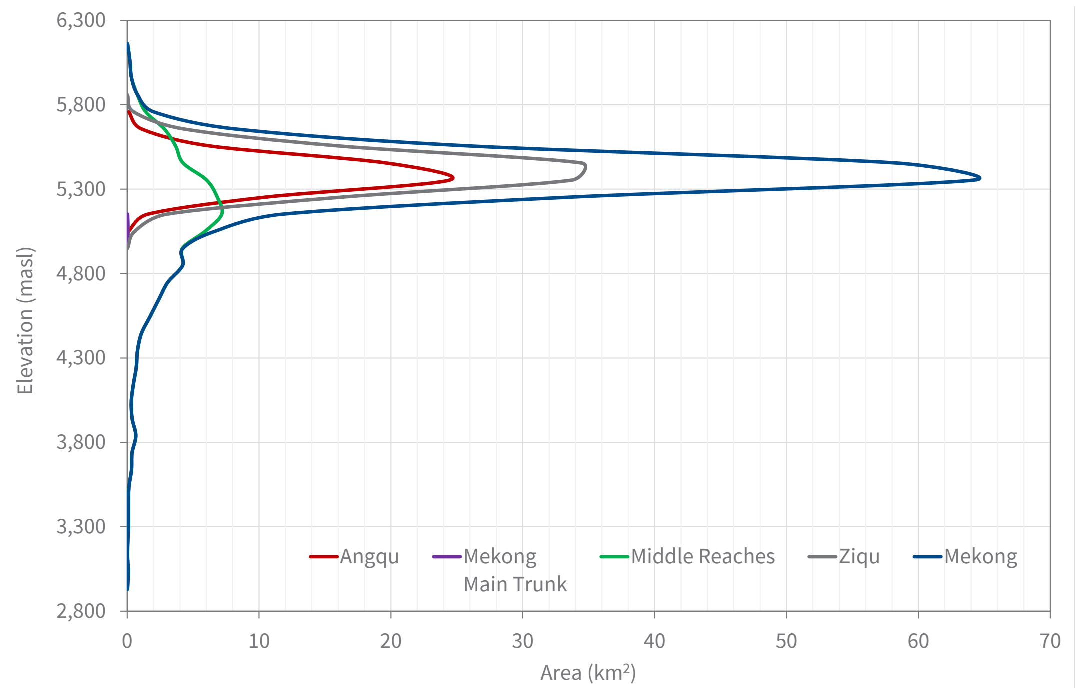
Basin	Number	Area (km²)	Largest Area (Km²)	Estimated Ice Reserve (km³)	Elevation (masl)		Mean Slope (Deg)
					Min	Max	
Angqu	226	63.79	5.41	2.315	5,040	5,787	22
Mekong Main Trunk	1	0.12	0.12	0.002	4,965	5,165	21
Middle Reaches	75	60.54	14.76	12.373	2,979	6,251	23
Ziqu	238	108.96	6.59	5.157	4,989	5,811	22
Total	**540**	**233.40**	**14.76**	**19.847**	**2,979**	**6,121**	**22**

coverage of glaciers, with 238 glaciers (44%) and 47% of the total glacier area in the Mekong River basin, followed by the Angqu basin with 226 glaciers (42%) and 42% of the total glacier area. Despite its size, the Middle Reaches has the fewest glaciers (75 glaciers) with the least area coverage (26% of total glacier area) (Figure 5.58 and Table 5.23).

The largest glacier in the Mekong River basin measures 14.76 km² and is in the Middle Reaches basin (Table 5.23). This basin also has the highest average glacier size at 0.81 km², indicating a greater distribution of larger glaciers compared to other basins. The distribution across various size classes reveals that the majority of glaciers fall within the smallest size class (less than 0.5 km²), which accounts for nearly 81% of all glaciers in the Mekong River basin, contributing 31.5% of the total glacier area (Figure 5.58).

Mid-sized glaciers in Class 3 (1.01 – 5.00 km²) make the most significant contribution to the total glacier area, representing almost 36% of the total area despite comprising only 48 glaciers. In contrast, Class 2 (0.51 – 1.00 km²) and 4 (5.01 – 10.00 km²) contribute only 13% and 14% of the total glacier area, respectively, with 41 and 5 glaciers each. Notably, the largest size class (≥10.00 km²) contains just one glacier but contributes approximately 6% of the total glacier area in the basin.

FIGURE 5.59 **GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN EACH BASIN OF THE MEKONG RIVER BASIN.**



This distribution illustrates that while smaller glaciers (less than 0.5 km²) dominate in number, it is the mid-sized and larger glaciers that significantly contribute to the overall glacier area. In terms of estimated ice reserves, the most substantial contributions also come from the mid to larger-sized glacier classes (3, 4, and 5), underscoring their importance in the basin's glacier dynamics.

The glaciers in the Mekong River basin are situated at elevations ranging from 2,979 masl to 6,121 masl, with both the highest and lowest glaciers found in the Middle Reaches basin. In contrast, other basins within the Mekong River system have glaciers concentrated in a narrower elevation range of 4,980 masl to 5,811 masl. Notably, nearly 75% of the total glacier area in the Mekong River basin is found between 5,000 masl and 5,500 masl (Figure 5.59). In contrast, glacier distribution significantly decreases both below 5,000 masl and above 5,500 masl. Specifically, the elevation range of 4,500 to 5,000 masl includes only 15.65 km², accounting for just 6.7% of the total glacier area. In comparison, the range from 5,500 to 6,000 masl contains a slightly larger area of 37.33 km², contributing about 16% of the total glacier area in the basin. Above 6,000 masl, glaciers comprise a mere 0.1% of the total area, highlighting the concentration of glacier coverage in the mid-elevation ranges.

The distribution of glacier areas across each basin at various elevation ranges reveals that the Ziqu basin has the largest glacier area, covering 88.07 km², followed by the Angqu basin at 55.3 km² and the Middle Reaches basin at 30.2 km² within the 5,000 to 5,500 masl range. This elevation range represents the most extensive glacier coverage across all basins in the Mekong River basin. While the Middle Reaches basin exhibits a broader elevation range for glacier area distribution, the Ziqu and Angqu basins have a higher concentration of glacier area within a narrower elevation range.

Glaciers have been categorised into six slope classes and eight aspect classes. Slope classes between 10° – 20° and 20° – 30° dominate (Figure 5.60), covering approximately 80% of the glacier area and 85% of the glacier count. In terms of aspects, the northern and northwestern aspect dominates, each representing almost 34% and 21% of the total glacier number and contributing significantly to glacier area of 32.5% and 28% and estimated ice reserves of about 31% and 36%, respectively (Figure 5.59). Interestingly, southern aspects had the least glaciers containing just 18 glaciers with covering just about 2% of the total glacier area. And the adjacent southeastern and southwestern aspects account for 5% and 4% of glacier numbers covering 6% and 7% of the total glacier area in the basin, respectively.

The glacier distribution in the Mekong basin varies significantly across mean slope classes, impacting glacier size, area, and estimated ice reserves. The mean slope classes of glaciers of 10° – 20° and 20° – 30° dominated in number, area and estimated ice reserves, with the highest number distribution of 52.4% in 20° – 30° and the highest glacier area coverage and estimated ice reserves of 51.3% and 52.7% respectively in 10° – 20°.

The <10° slope class contains 6 glaciers, accounting for 1.1% of the total number and covering 6.746 sq. km (2.9% of the total area), with a mean area of 1.12 km². In contrast, the 10° – 20° slope class features the largest number of glaciers (177), representing 32.8% of the total and covering 119.784 km² (51.3% of the total area) while holding 52.7% of the ice reserves. The 20° – 30° class sees a peak in glacier numbers at 283, but the mean area per glacier decreases to 0.29 km², indicating smaller sizes. As slope steepness increases, particularly in the 30° – 40° (68 glaciers), 40° – 50° (5 glaciers), and 50° – 60° (1 glacier) classes, both the number and size of glaciers decline, with minimal reserves. Notably, there are no glaciers on slopes greater than 60°, underscoring the unsuitability of such steep terrain for glacier formation. Overall, most glaciers are found in the gentler slope classes, where they contribute significantly to total area and estimated ice reserves, while steeper slopes are characterised by fewer and smaller glaciers.

Decadal glacier changes from 1990s to 2020

Over the past three decades (1990 – 2020), glaciers in the Mekong River basin have undergone significant changes, with notable variations among the basins. Overall, the Mekong River basin experienced an 11% reduction in glacier area, while the number of glaciers increased slightly by 1%, primarily due to glacier fragmentation (Table 5.2 and 5.24). Among the basins, Ziqu experienced the most severe glacier area loss of 14%, despite a 1% increase in glacier number (equivalent to 3 additional glaciers), indicating both shrinkage and fragmentation. Similarly, the Angqu basin saw an 11% reduction in glacier area, accompanied by a gain of 3 glaciers, suggesting a similar trend of fragmentation (Figure 5.60 and Table 5.24).

Both the Ziqu and Angqu basins showed an accelerating trend of glacier loss, with the highest percentage decline occurring in the most recent decade (2010 – 2020). The Middle Reaches basin experienced a comparatively smaller glacier area loss of 6% over three decades, maintaining a steady decline of 2% per decade. Among all basins, Ziqu basin exhibited the steepest decadal glacier loss of 6% between 2010 and 2020, making it the most affected in terms of absolute glacier shrinkage.

Meanwhile, the Mekong Main Trunk, which contains only one glacier, experienced the most drastic proportional loss, with nearly 46% of its glacier area disappearing. This underscores the vulnerability of small glaciers, which are more susceptible to rapid decline. Overall, the analysis highlighted a widespread glacier retreat across the Mekong basin, with fragmentation playing a key role in the slight increase in glacier numbers despite significant area losses.

FIGURE 5.60 **INTERDECADAL GLACIER NUMBER** (LEFT) **AND AREA** (RIGHT) **CHANGES IN EACH BASIN OF THE MEKONG RIVER BASIN.**

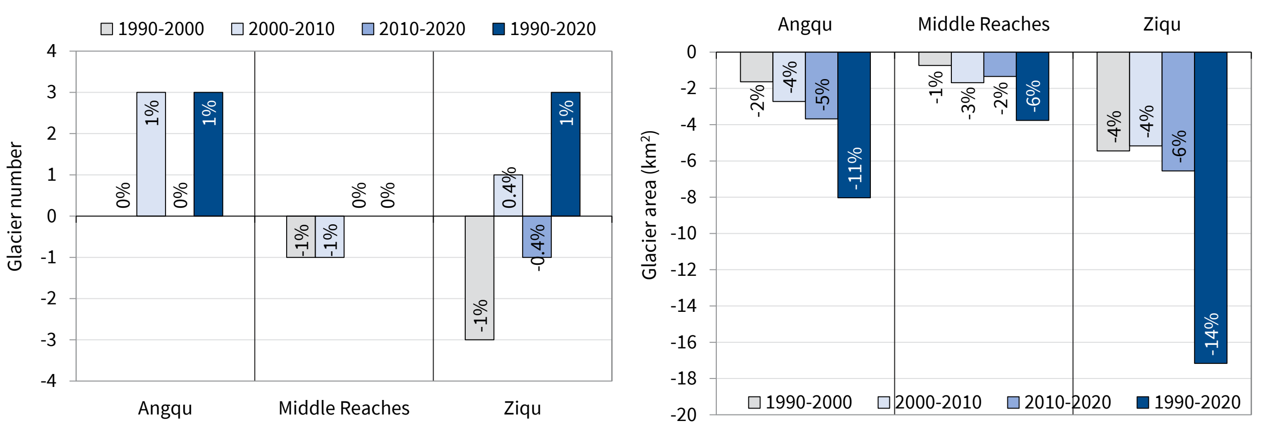


FIGURE 5.61 **INTERDECADAL GLACIER NUMBER** (LEFT) **AND AREA** (RIGHT) **CHANGES ACROSS SIZE CLASSES OVER THREE DECADES IN THE MEKONG RIVER BASIN.**

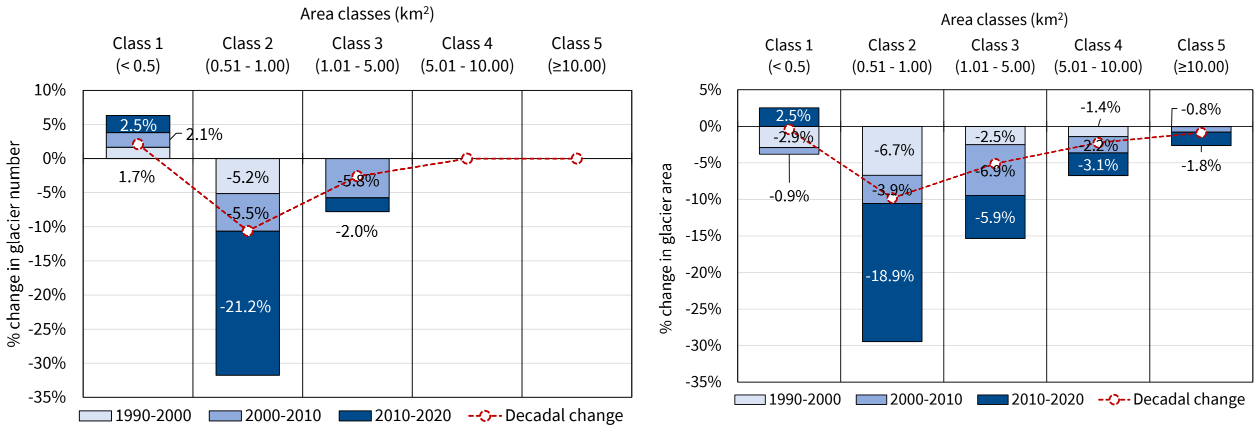


TABLE 5.24 **DECADAL CHANGES IN GLACIER NUMBER AND AREA IN THE MEKONG RIVER BASIN AND ITS BASINS FROM 1990 TO 2020.**

Basin	Number				Area (km²)				Decadal change - Number / Area (%)				
	1990	2000	2010	2020	1990	2000	2010	2020	1990-2000	2000-2010	2010-2020	1990-2020	per decade
Angqu	223	223	226	226	71.82	70.19	67.47	63.79	0 / -2.3	1.3 / -3.9	0 / -5.5	1.3 / -11.2	0.4 / -3.9
Middle Reaches	75	76	75	75	64.31	63.57	61.89	60.54	-1.3 / -1.1	-1.3 / -2.7	0 / -2.2	0 / -5.9	-0.9 / -2
Ziqu	235	238	239	238	126.12	120.67	115.50	108.96	-1.3 / -4.3	0.4 / -4.3	-0.4 / -5.7	1.3 / -13.6	-0.4 / -4.8
Mekong Main Trunk	1	1	1	1	0.21	0.17	0.12	0.12	0 / -19.6	0 / -33.1	0 / 0	0 / -46.3	0 / -17.6
Total	534	538	541	540	262.46	254.60	244.97	233.40	-0.7 / -3	0.6 / -3.8	-0.2 / -4.7	1.1 / -11.1	-0.1 / -3.8

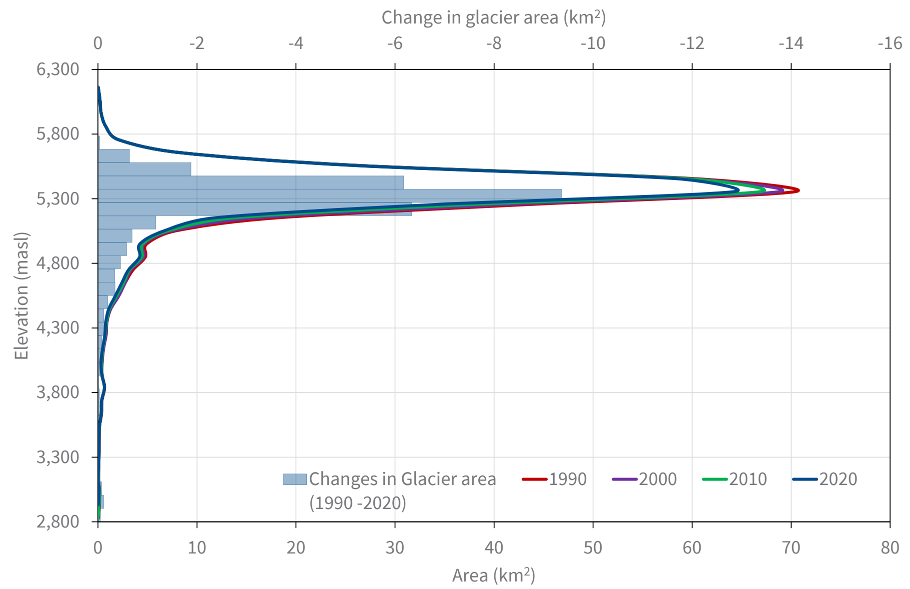
The analysis of glacier changes across different size classes reveals that mid-sized glaciers Class 2 (0.51 – 1.00 km²) and 3 (1.01 – 5.00 km²) have experienced the most severe losses in both number and area (Figure 5.61). The Class 2 (0.51 – 1.00 km²) glaciers showed the greatest decline, losing 17 glaciers and shrinking by over 27% in area over the past three decades. This trend was particularly pronounced in the last decade (2010 – 2020), which accounted for the highest reduction of 11 glaciers and nearly 19% of glacier area loss (Figure 5.62). Similarly, glaciers in the Class 3 (1.01 – 5.00 km²) declined by four in number and lost almost 15% of their total glacier area, indicating a steady but significant retreat.

In contrast, the smallest sized glaciers of Class 1 (<0.5 km²) increased in glacier number 27 over time, showing consistent growth across all decades. However, this increase is largely due to the fragmentation and shrinkage of larger glaciers, as evidenced by their overall area loss of 1.4% despite a small gain in the last decade by 2.5% of glacier area.

Larger glaciers of Class 4 (5.01 – 10.00 km²) and Class 5 (≥10.00 km²) remained stable in number but continued to lose area, highlighting a gradual yet persistent decline. The Class 4 (5.01 – 10.00 km²) glaciers shrank by 6.6% over three decades, while the largest glaciers Class 5 (≥10.00 km²) lost 2.6% of their area. Although these larger glaciers demonstrate greater resilience compared to smaller ones, they remain vulnerable to long-term climate impacts.

Overall, the trends across glacier size classes indicate that the increase in the number of smaller glaciers is a direct result of fragmentation and shrinkage of larger glaciers. While larger glaciers have maintained their number, they are steadily losing area, reinforcing the ongoing effects of glacial retreat in the region.

FIGURE 5.62 GLACIER AREA DISTRIBUTION AND CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE MEKONG RIVER BASIN.



Glaciers across various elevation ranges reveal a clear upward shift of the lowest elevation of the glacier snout over the past three decades, while the maximum elevation remains stable in all the basins. Overall, the lowest elevation of the glacier snout was shifted upwards from 2,870 masl in 1990 to 2,979 masl in 2020, indicating a 109 metre shifting of lowest elevation of glaciers upward in the Mekong River basin. Among the basins, the Middle Reaches experienced the most significant shift upward of lowest elevation of the glaciers indicating the vertical glacier retreat by 109 metres, followed by the Ziqu (41 meters) and Mekong Main Trunk (45 metres) basins. The Angqu basin also showed an upward shift of 63 metres by 2010, which remained unchanged through 2020. These changes highlight a consistent pattern of glacier retreat at lower elevations, leading to the disappearance of glaciers at lower altitudes, while those at higher elevations remain relatively stable.

The analysis of glacier area changes across different elevation ranges over the past three decades reveals a consistent retreat, with the most significant losses occurring between 4,500 – 5,500 masl. The 5,000 – 5,500 masl elevation range experienced the highest magnitude of glacier loss within the river basin, with a total loss of 24.9 km² (12.5%) over 30 years (Figure 5.62 and Table 5.25). This range recorded the highest absolute glacier loss, with a steady decline of approximately 3.5% to 5.3% per decade. The Ziqu basin showed nearly 16% glacier area loss, while the Angqu basin recorded an even higher loss of 17%, making this range particularly vulnerable to climate change. The accelerating retreat rate underscores the need for critical long-term monitoring. Similarly, glaciers at 4,500 – 5,000 masl lost 2.41 km² (13.3%), with the steepest reduction occurring between 2010 – 2020 (-5.8%), indicating a worsening trend.

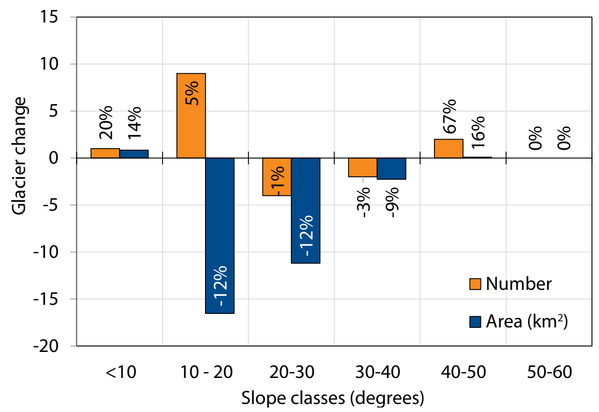
At lower elevations (below 4,500 masl), glacier losses were relatively smaller in absolute terms but significantly higher in percentage decline. The 2,500 – 3,000 masl range showed a total reduction of 0.16 km², with a dramatic 80% loss occurring in 2010 – 2020, suggesting that glaciers at these low elevations are on the verge of disappearing. Similarly, glaciers in the 3,000 – 3,500 masl range lost 0.17 km² (32%) over three decades, while those in the 3,500 – 4,000 masl range retreated by 0.13 km² (7%), indicating a slower but steady decline. A more noticeable shrinkage was observed at 4,000 – 4,500 masl, with a total loss of 0.63 km² (~16%), and the highest retreat rate occurring between 2000 – 2010 (-9%). These trends highlight that while lower-elevation glaciers are disappearing faster in percentage terms, mid-elevation glaciers are suffering the most in total loss.

In contrast, higher elevations (above 5,500 masl) showed glacier area losses were moderate but showed signs of increasing in recent decades, suggesting that warming trends are beginning to affect even high-altitude glaciers. The 5,500 – 6,000 masl range experienced a total retreat of 0.65 km² (1.7%), with the highest decline occurring in 2010 – 2020 (-0.78%). Notably, the retreat rate was highest in the Angqu basin (4%), compared to just 0.3% in the Middle Reaches and 2% in the Ziqu basin, indicating that some basins are more vulnerable than others at this altitude.

TABLE 5.25 GLACIER AREA DISTRIBUTION AND PERCENTAGE CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE MEKONG RIVER BASIN.

Elevation Range (masl)	Area (km²)				Area change (%)				
	1990	2000	2010	2020	1990 – 2000	2000 – 2010	2010 – 2020	1990 – 2020	Per decade
2,500 – 3,000	0.19	0.19	0.12	0.02	0.0	-35.3	-80.2	-87.2	-38.5
3,000 – 3,500	0.53	0.52	0.47	0.36	-1.5	-9.7	-23.3	-31.7	-11.5
3,500 – 4,000	1.98	1.97	1.89	1.85	-0.8	-3.9	-2.2	-6.8	-2.3
4,000 – 4,500	3.95	3.97	3.61	3.32	0.4	-8.9	-8.2	-16.0	-5.5
4,500 – 5,000	18.05	17.40	16.61	15.65	-3.6	-4.5	-5.8	-13.3	-4.7
5,000 – 5,500	199.56	192.55	184.42	174.64	-3.5	-4.2	-5.3	-12.5	-4.3
5,500 – 6,000	37.98	37.79	37.62	37.33	-0.5	-0.4	-0.8	-1.7	-0.6
6,000 – 6,500	0.23	0.23	0.23	0.23	0.0	0.0	0.9	0.9	0.3
Total	262.46	254.60	244.97	233.40	-3.0	-3.8	-4.7	-11.1	-3.8

FIGURE 5.63 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES IN THE MEKONG RIVER BASIN.



Above 6,000 masl, glacier retreat was negligible, and some areas even showed slight growth. A minor 0.89% increase in glacier area was observed in 2010 – 2020, possibly due to local snowfall variations. This suggests that glaciers at these highest elevations remain the most stable and are currently less affected by climate change. However, continuing monitoring is essential to assess potential future impacts.

Glacier changes across different mean slope classes indicate a consistent trend of retreat, with variations depending on slope steepness. The most significant changes in both glacier number and area occurred in slopes below 30°, where glacier retreat was most pronounced (Figure 5.63). Glaciers with a mean slope of less than 10° initially increased by two from 1990 to 2000 but lost one in the following decade, leading to a fluctuating but overall increase in glacier area. Similarly, glaciers in the 10° – 20° slope class exhibited the highest net increase in number, adding nine glaciers over three decades, although with periodic fluctuations. In contrast, glaciers in the 20° – 30° slope class experienced a net loss of four glaciers, indicating higher vulnerability to climate-driven changes. Despite these numerical variations, both the 10° – 20° and 20° – 30° slope categories suffered the greatest glacier area loss, with reductions of 12% and 9% of total glacier area, respectively, over three decades. Notably, the most substantial area loss occurred between 2010 and 2020, reflecting an accelerating trend of glacier retreat.

In comparison, steeper slopes (≥30°) displayed greater stability in glacier numbers but still showed noticeable area shrinkage. The 30° – 40° slope range exhibited unstable trends, with a net decline of two glaciers, while glaciers on steeper slopes (40° – 50°) remained relatively stable, gaining two glaciers in the last decade. These changes are likely due to glacier fragmentation and shrinkages, which alters the overall distribution of glacier mean slopes. In terms of area loss, glaciers of 30° – 40° slope class experienced moderate shrinkage, losing about 9% of their total area, whereas glaciers in the 40° – 50° range showed minimal changes, with some localised gains.

Analysis of glacier changes across different aspect classes reveals a consistent trend of retreat, with notable variations in both glacier area and number depending on aspect orientation. The most significant changes occurred in northwestern aspect glaciers, where the total glacier area decreased by approximately 7.27 km² 10.6%, while the number of glaciers increased only by 7 glaciers 5.6% over the four decades (1990 – 2020) (Figure 5.64). This increase in glacier count, despite an overall reduction in area, indicates fragmentation, where larger glaciers are breaking into smaller units due to retreat and thinning.

In contrast, northern, northeastern, and eastern-facing glaciers experienced a reduction in both glacier count and area, suggesting a relatively uniform pattern of shrinkage. The eastern facing glaciers, in particular, recorded the most severe area loss in relative terms (-14.74%), highlighting their vulnerability to climatic changes. Meanwhile, southwestern, western, and northwestern aspects saw an increase in glacier count, suggesting that as glaciers retreat, their average distribution also shifts, potentially influencing their response to local topographic and microclimatic conditions.

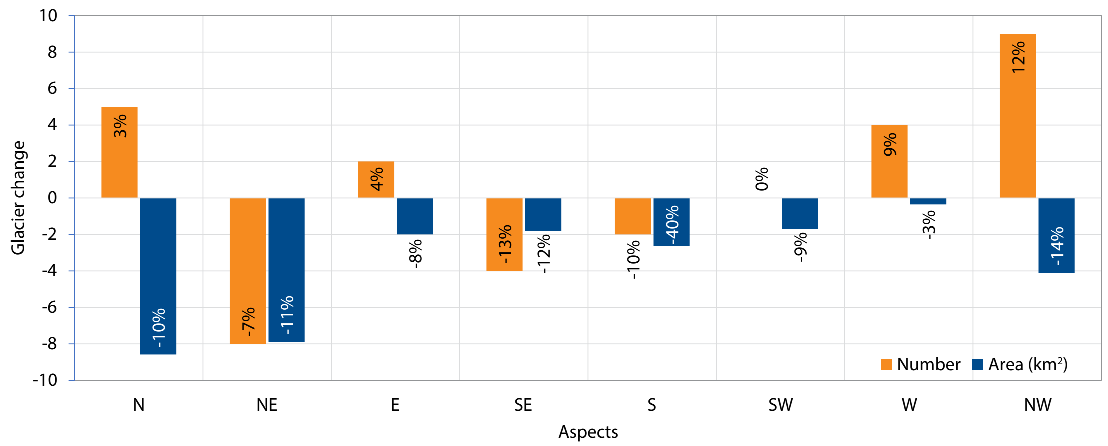
Interestingly, southeastern-facing glaciers are the only aspect class that showed a net increase in area (+0.98 km² viz. 9%). When examining interdecadal trends, distinct fluctuations emerge. From 1990 to 2000, most aspect classes experienced a reduction in glacier number, particularly in the eastern (-4 glaciers) and southwestern (-2 glaciers) aspects. This suggests that in the initial decade, glacier shrinkage was the dominant process. However, between 2000 and 2010, several aspect classes, including western (+3), southwestern (+4), and northwestern (+7) glaciers, exhibited an increase in count, pointing towards accelerated fragmentation during this period. This decade also saw continued area loss across almost all the aspects, with the most pronounced reductions in northeast (-4.12%) and western (-8.31%) aspects.

Between 2010 and 2020, fragmentation trends became more complex. The northwestern aspect, which had previously seen an increase in glacier count, experienced a slight decline (-2 glaciers), while western glaciers increased by four, reinforcing the notion that fragmentation and retreat occur non-linearly. Notably, the northern aspect displayed an increase in both glacier count (+3) and area (+0.34 km²), an anomaly that could be attributed to the fact that as glaciers retreat, their remaining sections may predominantly reside in shaded, high-altitude northern slopes, effectively shifting the average aspect of the overall glacier.

Despite variations in interdecadal trends, the overarching pattern across all aspect classes confirms a general retreat of glaciers. The relative differences in glacier area loss suggest that aspect plays a crucial role in modulating glacier dynamics. Northern and northeastern aspect glaciers, typically receiving less direct solar radiation, might have initially been more resilient but are now experiencing accelerated retreat. Conversely, southern and southwestern glaciers, historically more exposed to solar radiation, have likely undergone prolonged retreat, leading to more pronounced fragmentation over the decades.

This aspect-controlled retreat pattern aligns with broader glaciological principles, where direct solar radiation, wind exposure, and local microclimate influence differential melting rates. While all aspects have experienced net area loss, the variability in glacier number trends underscores the complexity of glacier response mechanisms, influenced by both climatic and topographic factors.

FIGURE 5.64 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES IN THE MEKONG RIVER BASIN.



5.8 Yangtze River Basin

The Yangtze River basin is a vast and diverse region that covers nearly one-fifth of China's total land area. It is home to the longest river in China and the third longest in the world – the Yangtze River, which originates in the Tibetan Plateau and flows empties into the East China Sea near Shanghai (Li and Zhang 2022). The basin is divided into three main sections based on elevation and landscape: the upper course with deep valleys and mountains, the middle course characterised by valleys, gorges, and the famous Three Gorges, and the lower course with a gradual downward slope, calmer waters, and more suitable conditions for fishing and farming. Across the basin, average annual rainfall ranges from about 300 mm in the west to 2,400 mm in the east, while mean yearly temperatures vary between roughly 9 °C and 18 °C. (Yao et al., 2017). The Basin is a vital region for China, serving as the country's principal waterway, while also being home to nearly one-third of the Chinese population and contributing to one fourth of the GDP (Li and Zhang, 2022; Zhang et al., 2023).

For this assessment, we have divided the basin into 4 basins: Jialing, Jinsha, Minjiang and Yalong. The Yangtze basin covers an area of 712,243.25 km², of which 73% (520187.3 km²) lies within the HKH region. Among the basins that lie within the HKH region, the Jinsha basin covers 50.5 % of the area and the rest is distributed among the three basins, with the Jialing basin encompassing only 4 % of the total basin area. The extent of these basins and glacier distribution across these basins is shown in Figure 5.65.

Glacier distribution in 2020

As of 2020, the Yangtze River basin contained 1,857 glaciers with a total area of 1,437.54 km². The glaciers are distributed between 30.45°N and 37.08° N latitude and 69.36°E and 81.65° E longitude, across an elevation range from 2,390 masl to 8,563 masl. Glacier distribution is heavily skewed towards the Jinsha basin, which consists of 79% of the glacier area and 69% of the glacier number. The Jialing basin has the least number of glaciers, with only 6 glaciers encompassing just 0.02% of the glacier area (Figure 5.66 and Table 5.26).

FIGURE 5.65 MAP SHOWING GLACIER DISTRIBUTION AND EXTENT OF THE YANGTZE RIVER BASIN WITHIN THE HKH REGION.

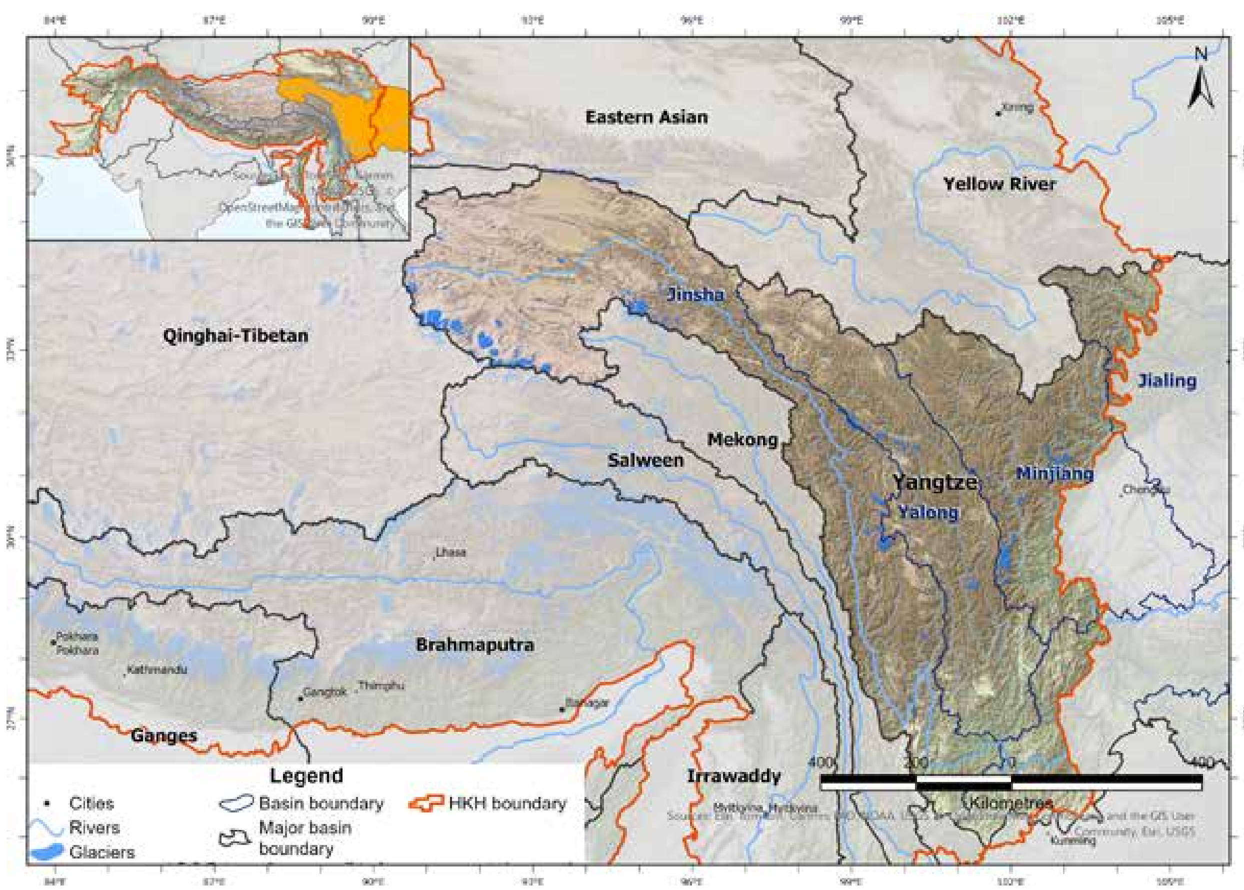


FIGURE 5.66 **GLACIER DISTRIBUTION ACROSS BASINS** (TOP LEFT)**, AREA CLASSES** (TOP RIGHT)**, MEAN SLOPE** (BOTTOM LEFT) **AND ASPECTS** (BOTTOM RIGHT) **IN THE YANGTZE RIVER BASIN.**

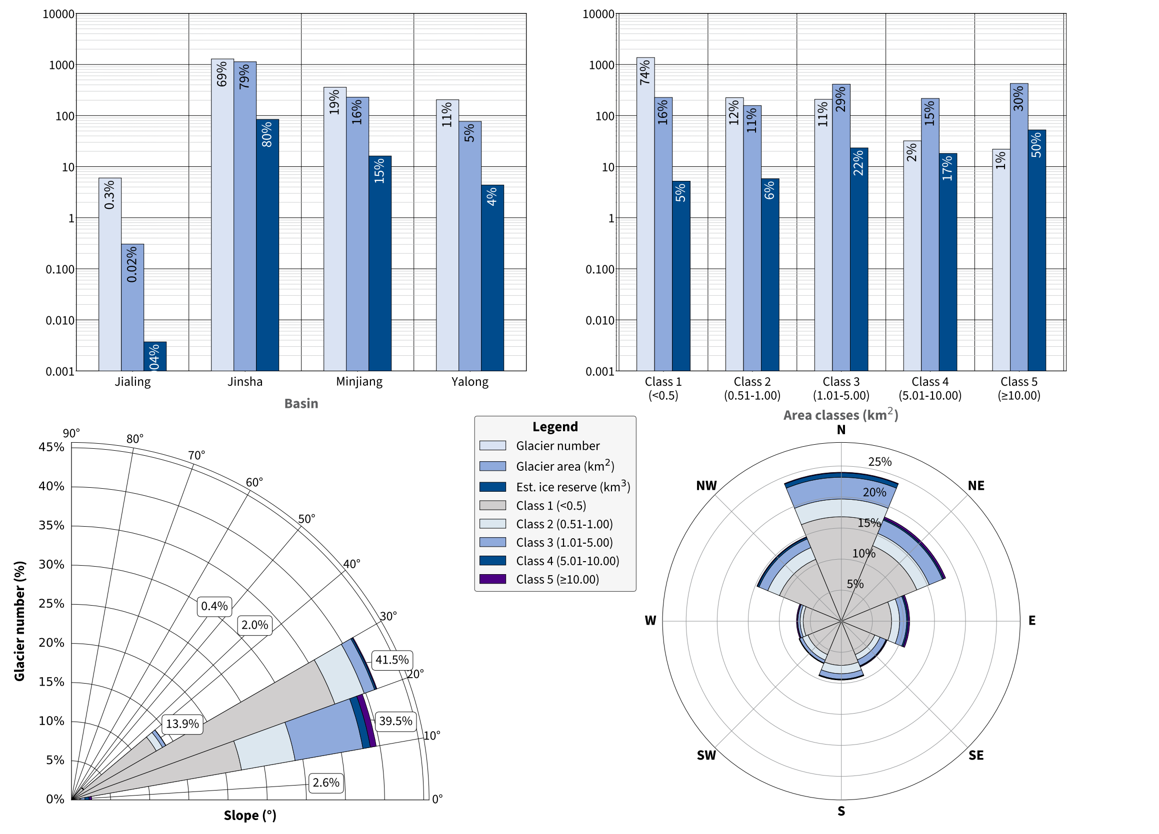


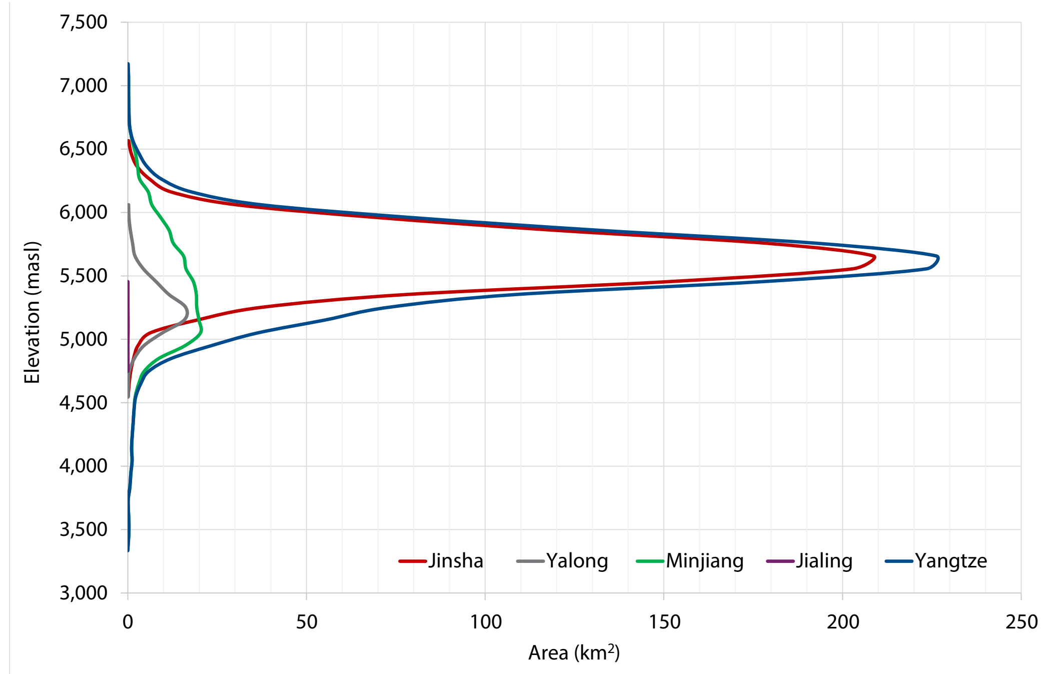
TABLE: 5.26 **DISTRIBUTION OF GLACIER IN THE BASINS OF THE YANGTZE RIVER BASIN.**

Basin	Number	Area (km²)	Largest area (km²)	Estimated ice reserve (km³)	Elevation (masl)		Mean slope (deg)
					Min	Max	
Jinsha	1285	1130.94	50.63	84.283	4500	6573	21
Minjiang	359	229.31	23.76	16.173	3414	7145	28
Jialing	6	0.31	0.12	0.004	4709	5456	36
Yalong	204	76.94	15.20	4.369	4522	6084	23
Total	**1854**	**1437.50**	**50.63**	**104.829**	**3414**	**7145**	**23**

The glacier area size distribution in the basin reveals an inverse relationship between glacier number, area, and estimated ice reserves. Smaller glaciers are far more numerous but cover less area and hold smaller amounts of estimated ice reserves, while larger glaciers are fewer but occupy significantly larger areas and contain a much higher proportion of the basin's estimated ice reserves (Figure 5.66). The majority of glaciers in the basin belong to the smallest size class, Class 1 (<0.5 km²), which comprises 73% of the glaciers (1,371 glaciers). However, these small glaciers contribute only 15.7% of the total glacierised area and hold only 5% of the total estimated ice reserves.

In contrast, the largest glaciers Class 5 (≥10.00 km²), though making up only 1.2% of the total number, accounts for nearly 30% of the total glacier area and nearly 50% of the basin's estimated ice reserves. Similarly, mid-sized glaciers in Class 2 (0.5 – 1 km²) and Class 3 (1 – 5 km²) make up a more substantial proportion of the total number of glaciers, with 12% and 11% of the total respectively. The area and estimated ice reserves contributions of these classes differ significantly. Class 3 glaciers cover the second-largest share of glacier area, approximately 29% of the total, and hold about 22% of the total estimated ice reserves. Meanwhile, Class 2 glaciers, while more numerous, occupy only 11% of the total

FIGURE 5.67 **GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN EACH BASIN OF THE YANGTZE RIVER BASIN.**



area, which is less than half of that covered by the Class 3 glaciers, and contribute just 6% of the total estimated ice reserves, only a fraction of what the Class 3 glaciers hold.

Finally, Class 4 glaciers, the larger in size (5 – 10 km²), account for only 2% of the total number of glaciers but cover 15% of the total glacier area and contain 17% of the basin's estimated ice reserves. This illustrates the disproportionate influence of large glaciers on the basin's total estimated ice reserves, despite their small numbers.

The elevation range of glaciers in the Yangtze River basin spans from 3,414 masl to 7,145 masl. Both the lowest and highest glaciers are in Minjiang basin. The glacier area distribution across various elevation ranges in the basin demonstrates a highly skewed pattern, with the vast majority of glacier area concentrated in the elevation range between 5,000 – 6,000 masl. The largest proportion of glacier area is found between 5,500 and 6,000 masl, which alone accounts for 59.4% of the total glacier area (Figure 5.67). This is followed by the 5,000 – 5,500 masl elevation range, contributing 31.4% of the glacier coverage. Together, these two elevation ranges contain over 90% of the total glacier area in the basin, highlighting their critical importance in glacier storage.

In contrast, lower elevation range hold only a small fraction of the glacier area. For instance, areas between 4,500 and 5,000 masl account for just 3.3%, and anything below 4,500 masl holds less than 1% of the glacier area combined. Specifically, elevations between 3,000 – 4,000 masl contribute a negligible 0.16%, reflecting the highly limited glacier extent at these altitudes due to warmer temperatures and higher melting rates.

At the uppermost elevations, glaciers are also minimal. The 6,000 – 6,500 masl range contains only 5.1% of the total glacier area, while elevations above 6,500 masl contribute less than 0.2% combined. This suggests that while glaciers exist at extreme altitudes, their spatial extent is small, likely due to the steep topography and limited accumulation zones.

The distribution across its main basins reveals Jinsha basin dominated with containing the largest glacier covered area where it holds nearly 70% of its glacier area in the 5,000 – 6,000 masl range and another 26% in 5,000 – 5,500 masl range (Table 5.27). This basin alone contributes a significant portion of the total glacier area in the Yangtze River basin. In contrast, the Yalong basin has the highest concentration of its glaciers (79.3%) between 5,000 and 5,500 masl, with minimal presence in higher elevation zones.

TABLE: 5.27 GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN EACH BASIN OF THE YANGTZE RIVER BASIN.

	Jinsha		Yalong		Minjiang		Jialing		Yangtze	
Elevation	Area (km²)	Area (%)	Area (km²)	Area (%)	Area (km²)	Area (%)	Area (km²)	Area (%)	Area (km²)	Area (%)
3,000 – 3,500					0.23	0.1			0.23	0.02
3,500 – 4,000					2.05	0.9			2.05	0.14
4,000 – 4,500					6.74	2.9			6.74	0.47
4,500 – 5,000	5.74	0.5	6.99	9.1	34.36	15.0	0.068	22.3	47.15	3.28
5,000 – 5,500	293.13	25.9	61.01	79.3	97.05	42.3	0.24	77.9	451.42	31.40
5,500 – 6,000	779.81	69.0	8.73	11.3	65.38	28.5			853.92	59.40
6,000 – 6,500	52.05	4.6	0.22	0.3	20.65	9.0			72.92	5.07
6,500 – 7,000	0.21	0.0			2.57	1.1			2.79	0.19
7,000 – 7,500					0.28	0.1			0.28	0.02
Total	1,130.94	100.0	76.943	100.0	229.31	100.0	0.304	100.0	1,437.49	100

The Minjiang basin, while smaller in glacier area than Jinsha basin has a wider elevation distribution from 3,400 masl to almost 7,150 masl. It holds a notable portion of its glacier area both in the 5,000 – 5,500 masl (42.3%) and 5,500 – 6,000 masl (28.5%) ranges, reflecting moderately high mountain terrain. Interestingly, the Minjiang basin also contributes the most to glacier area below 5,000 masl among all sub-basins, especially in the 4,500 – 5,000 masl range where it holds 15% of its glacier area, far more than the others. The Jialing basin has a negligible glacier presence overall, with most of its limited area (77.9%) in the 5,000 – 5,500 masl range.

In terms of slope, glaciers are categorised into six classes. The majority of glaciers are found within moderate slope classes, particularly between 10° and 30°. The 10° – 20° slope class dominates, hosting 35% of the total glaciers, but accounting for a disproportionately high 67% of total glacier area and 74% of the total estimated ice reserves (Figure 5.66). This class also has the high mean glacier size at 1.5 km², indicating the presence of large, expansive glaciers on gentler terrain. Similarly, the 20° – 30° slope class contains the highest number of glaciers (45%), but these are much smaller in size, contributing only 20% of the total glacier area and 13% of the estimated ice reserves. The lower mean area per glacier (0.34 km²) suggests a prevalence of smaller, possibly fragmented glaciers in this slope class.

In contrast, steeper slope classes such as 30° – 40°, 40° – 50° and above show a sharp decline in both glacier numbers and contribution to area and estimated ice reserves. The 30° – 40° class contains 15% of glaciers, contributing only 5% of glacier area and 3% of the estimated ice reserves, with a small mean size of 0.25 km². The trend continues to diminish in the 40° – 50° and 50° – 60° classes, which together hold less than 3% of the total glaciers and account for a negligible share of glacier area and reserves.

Interestingly, the flatter slope class of <10°, while containing only 1% of glaciers, holds a notable 8% of glacier area and 10% of the ice reserves, with an exceptionally high average glacier size of 4.5 km². This suggests that very large glaciers tend to occupy flatter terrain, possibly at valley bottoms or accumulation zones.

The glacier distribution across various mean aspect classes in the Yangtze River basin demonstrates a relatively balanced spread across all directions, with a clear dominance in the northern, northeastern, and northwestern aspects (Figure 5.66). The northern aspect alone contains 24% of the total glaciers and contributes significantly to both glacier area (26%) and estimated ice reserves (26%). Northeastern and northwestern aspects further enhance this trend, comprising 18% and 15% of the glacier number respectively, while accounting for 20% and 12% of the glacier area, and 20% and 10% of the estimated ice reserves. Glaciers in these three aspects also tend to be larger in size, with average glacier areas ranging from 0.65 km² to 0.86 km².

Eastern-facing glaciers stand out due to their substantial contribution despite a smaller glacier number. Although they represent only 11% of the total glaciers, it contributes 15% of the total area and 17% of the estimated ice reserves, featured it with the largest average glacier size in the basin at 1.04 km². This indicates the presence of fewer but significantly larger and more ice reserves in the eastern aspect.

In contrast, the southern, southeastern, and southwestern aspects host a smaller share of the glaciers, ranging from 7% to 9% in number. These aspects contribute relatively less to the overall glacier area (4% – 8%) and estimated ice reserves (3% – 7%). Among them, the southeastern aspect is slightly more prominent across all metrics, while the southwestern aspect consistently ranks lowest, suggesting smaller and less numerous glaciers.

The western aspect presents a unique case. Despite having only 7% of the glaciers, comparable to the southwestern aspect, it contributes a much larger share of glacier area (8%) and estimated ice reserves (12%). This reflects the presence of relatively large glaciers in this aspect, as supported by the second-highest mean glacier size in the basin at 0.90 km².

Decadal glaciers change from 1990s to 2020

Between 1990 and 2020, the Yangtze River basin experienced a significant decline in glacier coverage. The glacier area decreased by approximately 23%, from 1,868 km² in 1990 to 1,437 km² in 2020. Similarly, glacier numbers declined by 20.6%, from 2,340 glaciers in 1990 to 1857 in 2020, indicating not only a reduction in glacier size but also their gradual disappearance into perennial snow/ice patches.

The rate of glacier area and number loss accelerated over the past three decades, with the maximum rate of decline in the last decade i.e. 2010 to 2020. Glacier number loss increased from -5.4% between 1990 and 2000 to -10% between 2010 and 2010, which is nearly double the rate, highlighting the heightened impact of climate change. In the case of area loss trends there was around 2% difference between each decadal change percentages (Table 5.28).

Sub-basin analyses show that the Yalong basin experienced the largest relative area reduction of 43% from its area in 1990, equating to a loss of 58 km². However, in the total magnitude of area loss, the Jinsha basin suffered the greatest loss, with a reduction exceeding 286 km², representing 20% of its 1990 glacier area. All the basins saw a decrement in their glacier area and number across the decades. It is also Jinsha basin, which has the largest magnitude of glacier number loss of 259 glaciers, however, that is only 16% change from its 1990 glacier number and if you look at the percentage wise change in their area, Yalong basin lost 32% of its glaciers, however, that number is only 96 glaciers (Figure 5.68).

Over the past three decades, glacier changes across different area size classes in the Yangtze River basin exhibit a clear size-dependent retreat pattern. The most pronounced losses occurred among smaller and mid-sized glaciers, those under 5 km² in area. The smallest glaciers of Class 1 (<0.5 km²), experienced the most dramatic decline, losing a total of 298 glaciers over the three decades. This sharp reduction highlights not only the disappearance of many small glaciers but also the retreat of others below the area threshold used in the study. Glacier loss in this class accelerated over time, with a total

FIGURE 5.68 INTERDECADAL GLACIER NUMBER (LEFT) AND AREA (RIGHT) CHANGES IN EACH BASIN OF THE YANGTZE RIVER BASIN.

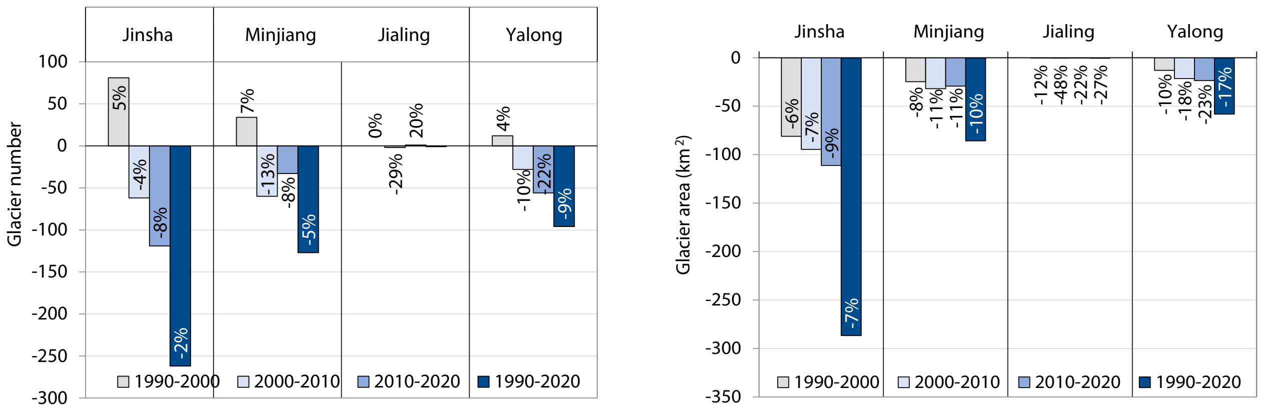
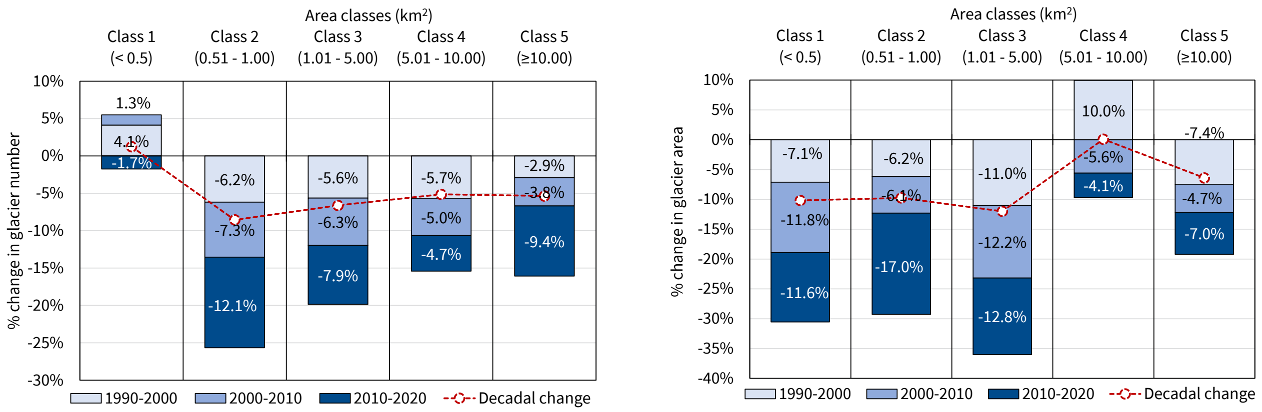


TABLE: 5.28 DECADAL CHANGES OF GLACIER NUMBER AND AREA IN THE YANGTZE RIVER BASIN AND ITS BASINS FROM 1990 TO 2020.

Basin	Number				Area (km2)				Decadal change - Number / Area (%)				
	1990	2000	2010	2020	1990	2000	2010	2020	1990–2000	2000–2010	2010–2020	1990–2020	per decade
Jinsha	1,547	1,466	1,404	1,285	1,417.67	1,336.64	1,242.09	1,130.94	5.2 / -5.7	-4.2 / -7.1	-8.5 / -8.9	-16.9 / -20.2	-2.5 / -7.2
Minjiang	486	452	392	359	315.10	290.38	258.50	229.31	7 / -7.8	-13.3 / -11	-8.4 / -11.3	-26.1 / -27.2	-4.9 / -10
Jialing	7	7	5	6	0.85	0.75	0.39	0.31	0 / -11.8	-28.6 / -47.5	20 / -22	-14.3 / -63.9	-2.9 / -27.1
Yalong	300	288	260	204	135.10	122.05	100.54	76.94	4 / -9.7	-9.7 / -17.6	-21.5 / -23.5	-32 / -43	-9.1 / -16.9

FIGURE 5.69 INTERDECADAL GLACIER NUMBER (LEFT) AND AREA (RIGHT) CHANGES ACROSS SIZE CLASSES OVER THREE DECADES IN THE YANGTZE RIVER BASIN.



area reduction of 28%, underscoring the high vulnerability of small glaciers to climate warming (Figure 5.69).

Glaciers in Class 2 (0.51 – 1.00 km²), though slightly more resilient than those in Class 1, still exhibited steady and significant declines, with a 27% reduction in both glacier number and area. Class 3 glaciers (1.01 – 5.00 km²), while larger, experienced the greatest absolute area loss, shrinking by over 192 km² throughout the study period. This class also accounted for the second highest loss in glacier number and nearly one-third (32%) of total glacier area reduction, reflecting not only glacier shrinkage but also fragmentation into smaller units. This fragmentation process leads to an increase in the number of smaller glaciers within the lower size classes, while simultaneously causing the disappearance or retreat of some glaciers below the minimum area threshold, resulting in a decline in the overall number within the smallest size class.

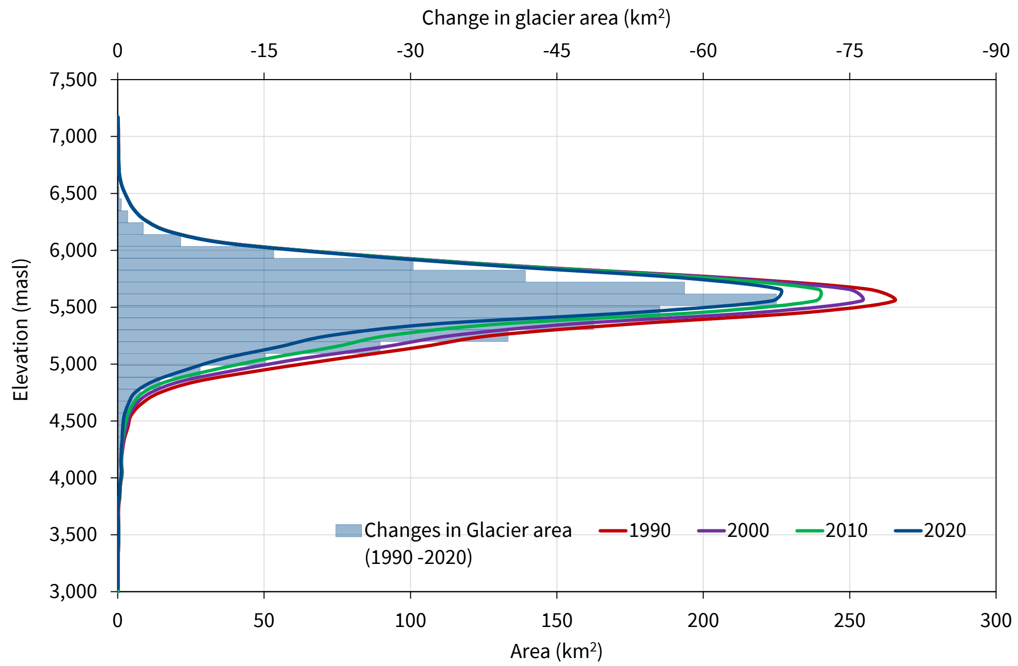
Larger glaciers in Class 4 (5.01 – 10.00 km²) remained relatively stable in number, with a slight net gain. However, their area changed more dynamically experiencing a gain during the 1990s followed by consistent losses in the subsequent decades, ultimately resulting in a near-zero net change over three decades. This suggests a transition phase for many glaciers in this category.

The largest glaciers (≥10.00 km²), despite being few in numbers, also experienced significant decline, losing 4 glaciers and 18% of their area. This indicates that even the most massive glaciers are not immune to the effects of climate change. The data also suggest that some larger glaciers are shrinking and fragmenting into smaller ones, contributing to slight gains in glacier numbers within Class 4 and balancing the area loss to some extent.

Overall, the retreat trends highlight that while smaller glaciers are disappearing rapidly, larger glaciers are also undergoing shrinkages and fragmentation, revealing a complex and ongoing reclassification of glacier size in the Yangtze River basin due to climate change.

Glacier retreat is also clearly reflected in the upward shift of glacier snouts over time. Between 1990 and

FIGURE 5.70 GLACIER AREA DISTRIBUTION AND CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE YANGTZE RIVER BASIN.



2020, the minimum elevation of glacier termini rose by approximately 465 metres, shifting from 2,949 masl in 1990 to 3,414 masl by 2020. This significant elevation change indicates that glaciers in the basin have completely vanished below 3,400 metres after 2010, highlighting the severity of glacier loss at lower elevations.

Over the past three decades, elevation dependent glacier area changes in the Yangtze River basin exhibit a clear and accelerating retreat pattern, with the most significant losses occurring in elevation ranges between 4,500 masl and 6,000 masl, where glacier coverage is most concentrated (Figure 5.70 and Table 5.29). The most significant glacier area reductions were observed in elevation range of 5,000 to 5,500 masl, which lost almost 270 km², accounting for over 37% of the glacier area in this range. This was followed by the 4,500 – 5,000 masl range, which lost 57.15 km², or 54.8% of its glacier area, and the 5,500 – 6,000 masl range, which lost 97.17 km², or 10.2%. These elevation ranges, being the core area of glacier area concentration in the basin, represent the largest contributions to the overall area loss due to their extensive glacier coverage.

Despite having smaller glaciers' area coverage to start with, lower elevation ranges also experienced dramatic loss. For instance, the 3,000 – 3,500 masl range lost a 78.6% of glacier area, losing 0.87 km² area, indicating that glaciers at these lower elevations are highly vulnerable and many have already disappeared. Similarly, the 3,500 – 4,000 masl range experienced a 21.7% reduction in glacier area over the three decades, showing the vulnerability of glaciers.

At higher elevations, glacier loss was less significant in absolute terms, but still notable. The 6,000 – 6,500 masl range exhibited a reduction of 1.67 km² (a 2.2% decline), while the 6,500 – 7,000 masl range lost just 0.26 km², representing an 8.5% decrease. The 7,000 – 7,500 masl range showed minimal changes, with a loss of just 0.04 km².

This pattern of glacier area loss, characterised by accelerating losses over each decade, was consistent across all the basins in the Yangtze River basin. The 5,000 – 5,500 masl range consistently accounted for the largest losses, with the Jinsha basin contributing the most to this decline, followed by the Yalong and Minjiang basins. The 4,500 – 5,000 masl range also experienced significant reductions in both Jinsha and Minjiang basin, while the Jialing basin, which started with the least glacier area, experienced the highest percentage losses, over 79% in the 4,500 – 5,000 masl range and 54% in the 5,000 – 5,500 masl range over the past three decades.

Overall, these patterns underscore a substantial and accelerating glacier retreat across all elevation ranges and basins, with especially rapid changes

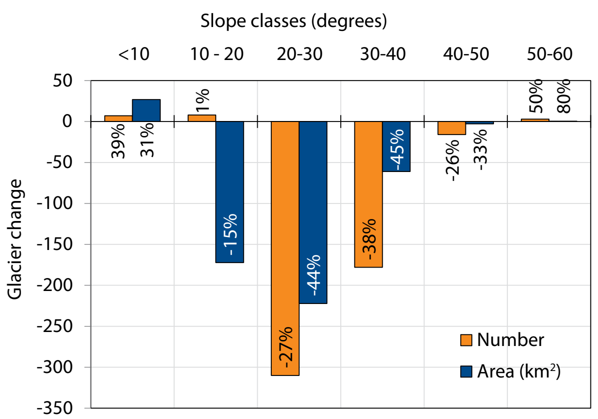
TABLE: 5.29	GLACIER AREA DISTRIBUTION AND PERCENTAGE CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE YANGTZE RIVER BASIN.

Elevation range (masl)	Area (km²)				Area change (%)				
	1990	2000	2010	2020	1990 – 2000	2000 – 2010	2010 – 2020	1990 – 2020	Per decade
2,500 – 3,000	0.07	0.08			24.6				24.6
3,000 – 3,500	1.10	1.10	0.28	0.24	0.0	-74.3	-17.0	-78.6	-30.4
3,500 – 4,000	2.62	2.24	2.20	2.05	-14.2	-2.1	-6.7	-21.7	-7.7
4,000 – 4,500	10.23	9.25	8.01	6.74	-9.6	-13.4	-15.9	-34.1	-12.9
4,500 – 5,000	104.30	84.31	66.97	47.15	-19.2	-20.6	-29.6	-54.8	-23.1
5,000 – 5,500	721.36	644.88	550.10	451.42	-10.6	-14.7	-17.9	-37.4	-14.4
5,500 – 6,000	951.08	930.13	896.80	853.92	-2.2	-3.6	-4.8	-10.2	-3.5
6,000 – 6,500	74.60	74.57	73.92	72.92	0.0	-0.9	-1.3	-2.2	-0.8
6,500 – 7,000	3.04	2.97	2.97	2.79	-2.4	0.0	-6.3	-8.5	-2.9
7,000 – 7,500	0.32	0.28	0.28	0.28	-13.0	0.0	0.0	-13.0	-4.3
Total	1,868.71	1,749.81	1,601.52	1,437.49	-6.4	-8.5	-10.2	-23.1	-8.4

at mid-to-lower elevations below 5,500 masl. The continuing upward shift of glacier presence highlights the pressing impacts of climate warming on the glaciers in the Yangtze River basin.

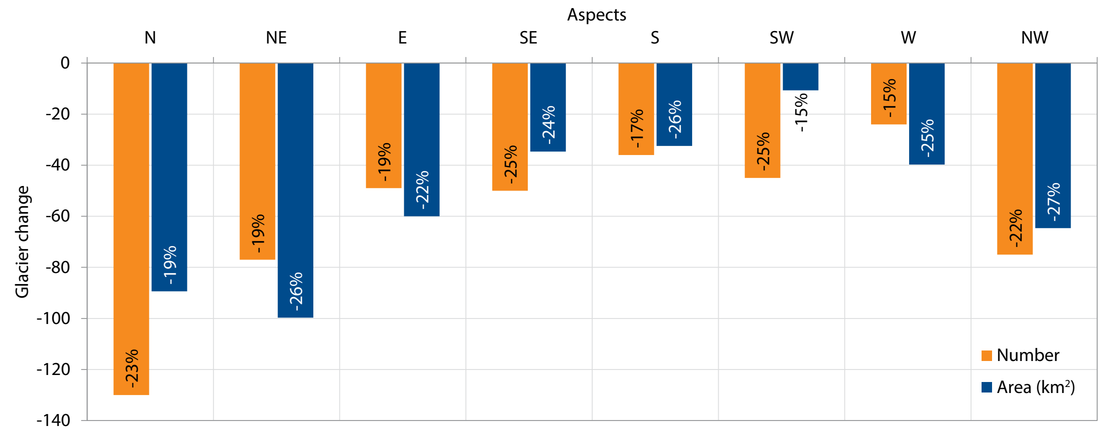
Glacier changes across different mean slope classes reveal that the most substantial losses occurred in the mid-slope ranges between 20° and 40° (Figure 5.71). The 20° – 30° class experienced the most significant reductions, with glacier numbers declining by 27% (310 glaciers) and glacier area shrinking by 44% (222.3 km²) over the past three decades. Similarly, the 30° – 40° slope class experienced a 38% decline in glacier numbers (178 glaciers) and over 45% reduction in area (approximately 61 km²), with the steepest losses occurring between 2000 and 2010. In contrast, the gentler slope classes <10° and 10° – 20° – showed a more mixed pattern. While both classes saw slight increases in glacier numbers (7 and 8 glaciers respectively), their area trends differed: the <10° class gained around 27 km², whereas the 10° – 20° class lost a significant 172 km², or 15% of its total glacier area. This contrasting trend likely reflects the presence of larger glaciers on gentler slopes, which have since fragmented and altered in form as they retreated. Meanwhile, steeper slope classes, particularly 40° – 50°, 50° – 60°, and >60°, exhibited minimal changes across all decades, with the >50° classes remaining almost unchanged, highlighting their limited glacier coverage.

FIGURE 5.71 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES IN THE YANGTZE RIVER BASIN.

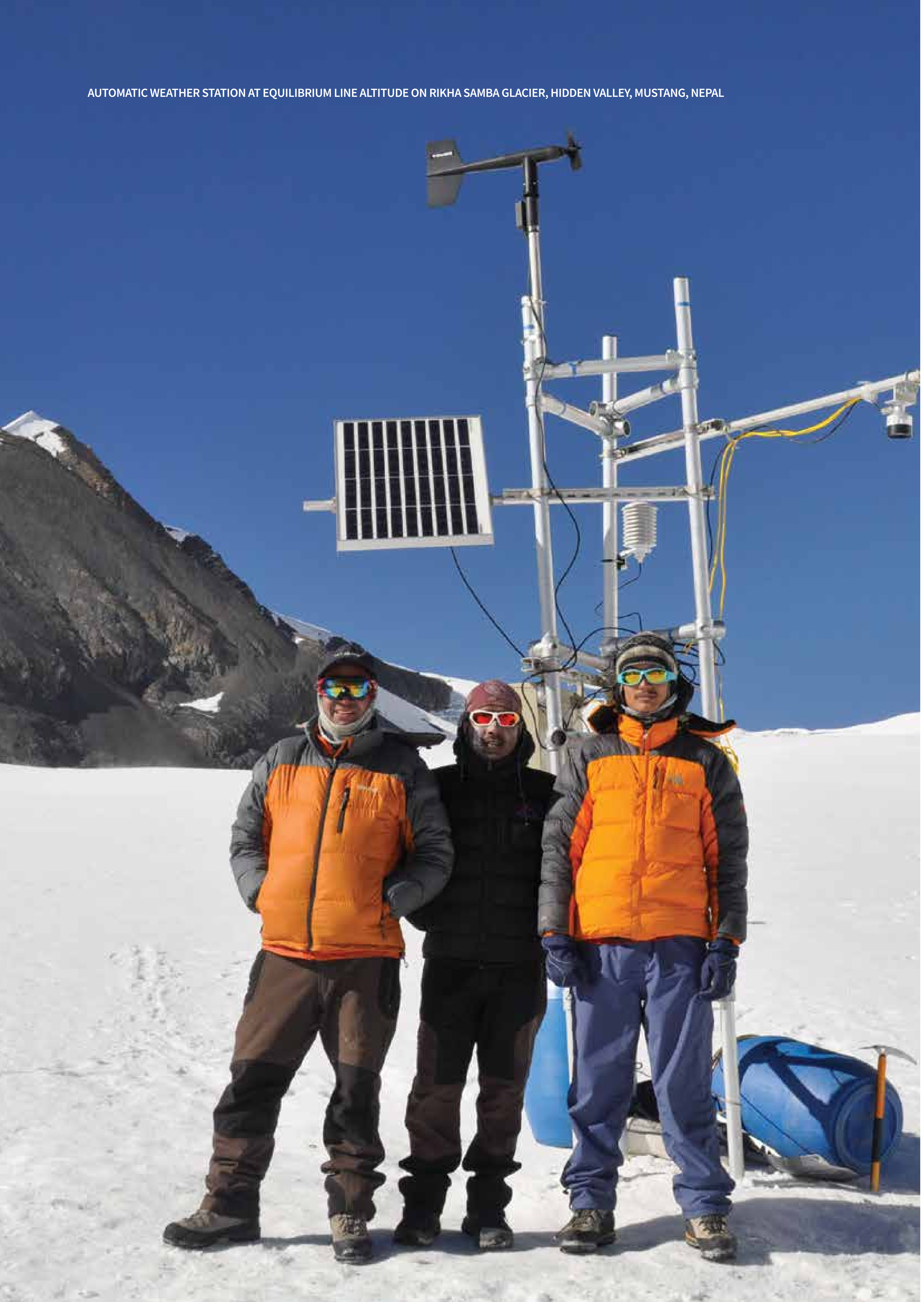


Glacier changes across different mean aspect classes in the Yangtze River basin over the past three decades show a consistent and widespread decline in both glacier number and area across nearly all orientations, though the magnitude varies by aspect. The northern aspect, which generally harbour larger and more persistent glaciers, experienced significant losses with a 22.6% reduction in glacier number (130 glaciers) and a 19% decrease in area (89.39 km²) (Figure 5.72). The northeastern and eastern aspects also showed substantial area losses of 26% and 22% respectively, reflecting their high sensitivity to warming. Interestingly, southeastern and southern aspects, typically more exposed to solar radiation, experienced even steeper relative declines, particularly in glacier number 25.3% for southeastern and 17% for southern aspects. The southwestern and western aspects displayed a mixed pattern, with slight temporary area gains in 2000 – 2010, but long-term declines overall. The northwestern aspect had one of the largest area losses at 26.7%, despite a slightly slower rate of glacier number reduction. Overall, while all aspects experienced glacier retreat, the results highlight a strong dependence of their orientation and their response to climate change, with southern and eastern slopes showing higher vulnerability due to greater solar exposure, and northern aspects seeing significant absolute losses due to their higher initial glacier coverage. Importantly, the losses in glacier numbers and area across all aspect classes are not only due to retreat but also reflect the shrinkage and fragmentation of glaciers, which often leads to changes in their mean aspect as their geometry reorients over time. This process complicates aspect-based classification and highlights the dynamic response of glaciers to ongoing climate change.

FIGURE 5.72 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES IN THE YANGTZE RIVER BASIN.



SNOW DENSITY MEASUREMENT DURING FIELD EXPEDITION



5.9 Yellow River Basin

The Yellow River basin, known as Huang He in Chinese, is a crucial region in northern China, encompassing an area of approximately 795,000 square kilometres. It is home to the Yellow River, which is the second longest river in China, stretching about 5,464 kilometres (3,395 miles) from its source in the Bayan Har Mountains of Qinghai province to its mouth at the Bohai Sea in Shandong province (Jiang et al., 2015, 2021). The basin traverses seven provinces and two autonomous regions, including Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong. Historically regarded as the cradle of Chinese civilisation, the Yellow River has played a vital role in agriculture, culture, and economy. The basin falls in arid, semi-arid, and semi-humid areas in China and has a diversified climate, severely fluctuating topography, various types of landforms, and rich vegetation types (Liu et al., 2011; Sun et al., 2004)

For this assessment, we have divided the basin into 2 basins: Datong and Upper Reaches. The basin covers an area of 345,805.13 km^2, of which 66% (227,238.07 km^2) lie within the HKH region. Among the basins that lie within the HKH region, the Upper Reaches basin covers 74% of the area and then the Datong basin with 26% (Figure 5.73).

Glacier distribution in 2020

As of 2020, the Yellow River basin contained 283 glaciers, covering a total area of 156.26 km^2 and holding an estimated ice reserve of 9.8 km^3 (Table 5.30). Within the broader HKH region, this basin accounts for approximately 0.3% of the total glacier area and 0.4% of the total glaciers in the region, with an average glacier size of 0.55 km^2. These glaciers are distributed between 30.45°N and 37.08° N latitude and 69.36°E and 81.65° E longitude, spanning an elevation range from 4,097 masl to 8,300 masl.

Glaciers in this River basin is distributed in two basins – Upper Reaches and Datong basins. The distribution is highly concentrated in the Upper Reaches which contains 72% of the total glacier area and 61% of the total glacier number (Figure 5.74 and Table 5.30). In contrast, the Datong basin accounts for 28% of the total glacier area but holds a higher

FIGURE 5.73 MAP SHOWING GLACIER DISTRIBUTION AND EXTENT OF THE YELLOW RIVER BASIN WITHIN THE HKH REGION.

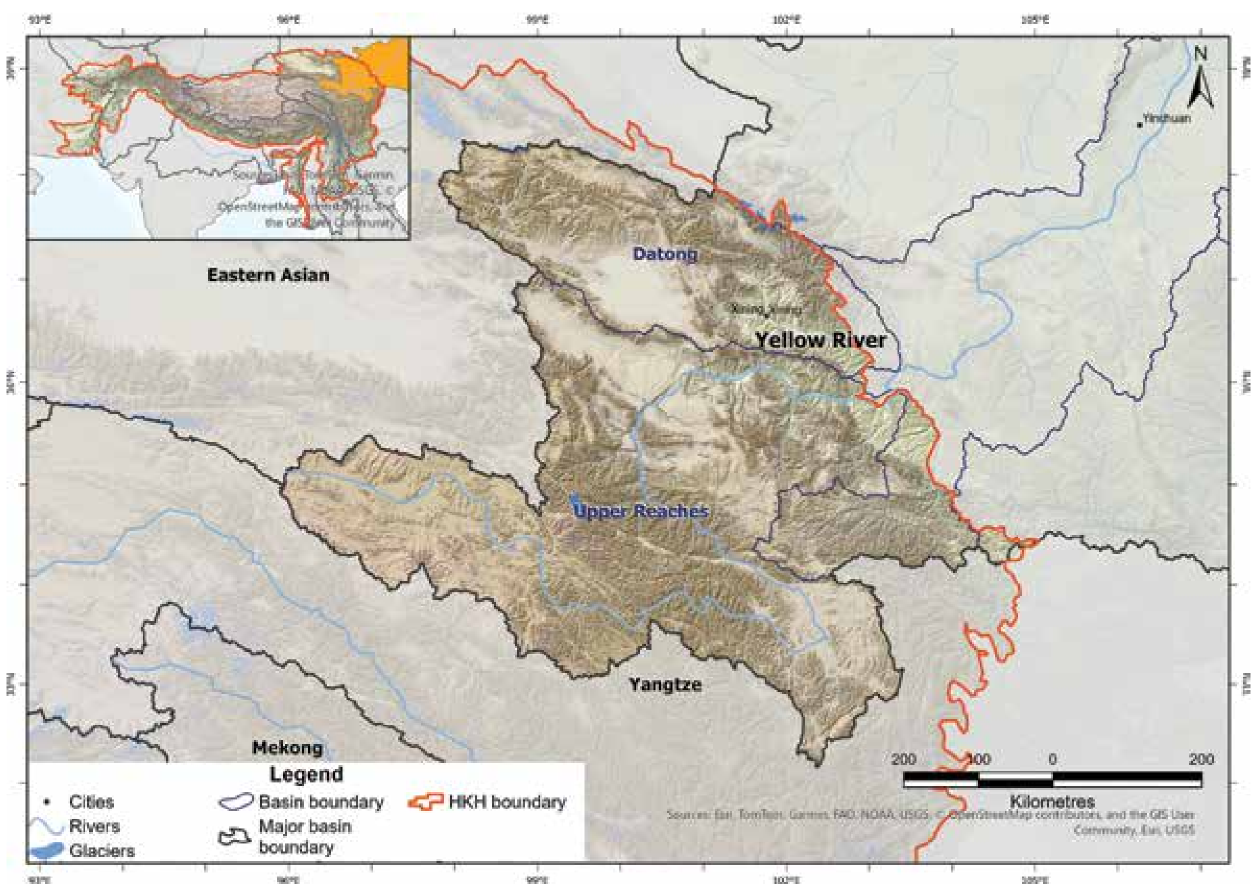
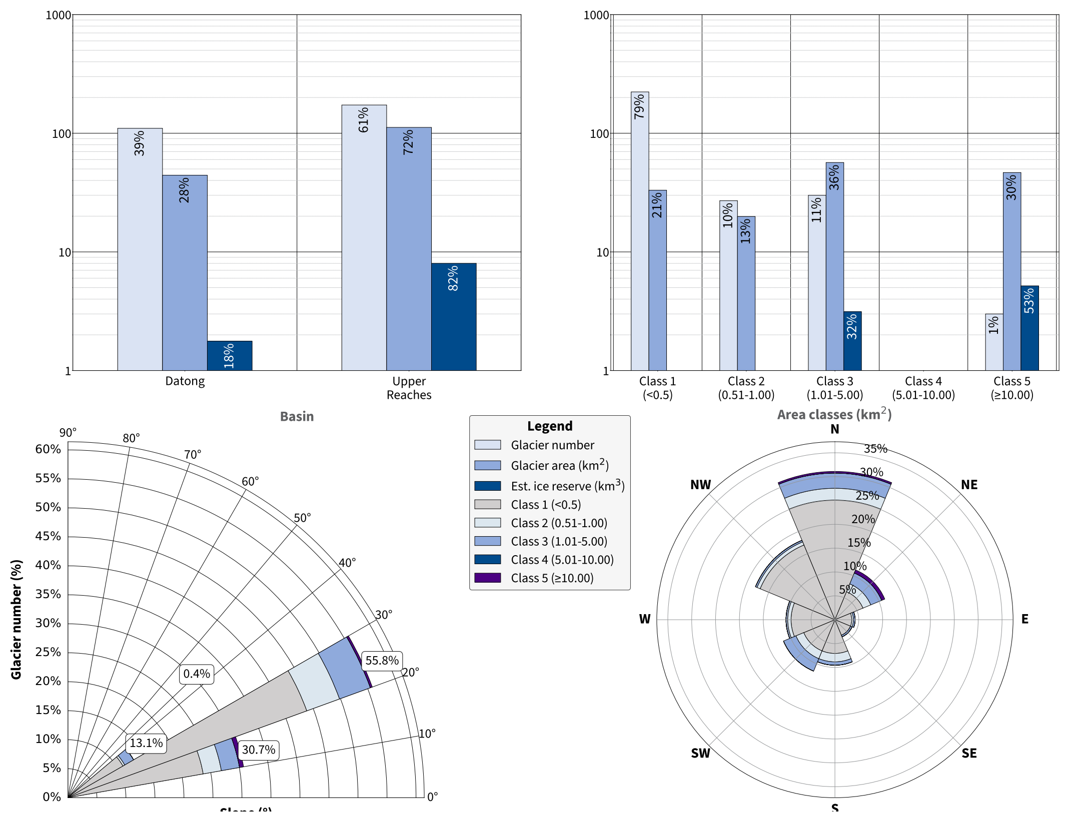


TABLE 5.30 **DISTRIBUTION OF GLACIER IN THE BASINS OF THE YELLOW RIVER BASIN.**

Basin	Number	Area (km²)	Largest area (km²)	Estimated ice reserve (km³)	Elevation (masl)		Mean slope (Deg)
					Min	Max	
Datong	110	44.26	2.39	1.768	4,097	5,268	21
Upper Reaches	173	112.01	20.2	8.012	4,198	6,254	25
Total	**283**	**156.26**	**20.2**	**9.780**	**4,097**	**6,254**	**24**

FIGURE 5.74 **GLACIER DISTRIBUTION ACROSS BASINS** (TOP LEFT), **AREA CLASSES** (TOP RIGHT), **MEAN SLOPE** (BOTTOM LEFT) **AND ASPECTS** (BOTTOM RIGHT) **IN THE YELLOW RIVER BASIN.**



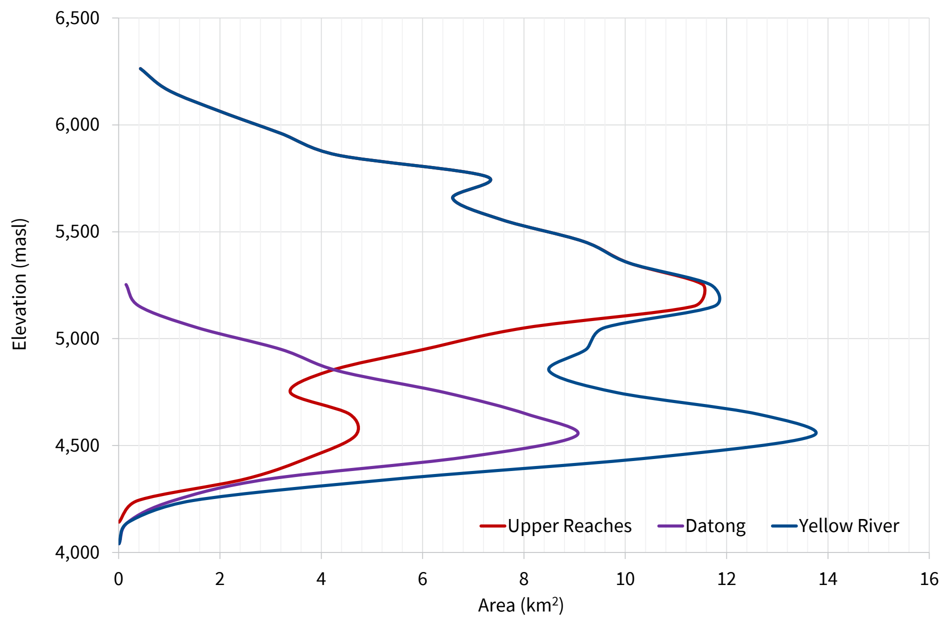
proportion of glaciers (39%) indicating that glaciers in this basin are generally smaller. Comparatively, glaciers in the Upper Reaches basin are larger, with an average size of 0.65 km², whereas in Datong basin, the average glacier size is 0.4 km².

The largest glacier in this river basin spans 20.2 km² and located in the Upper Reaches basin, while the Datong basin hosts its largest glacier of 2.39 km² (Table 5.30). A classification of glaciers based on area size reveals that vast majority are smaller in size, with 78.8% of the glaciers (223 glaciers) falling into smallest size Class 1 (< 0.5 km²). However, despite their dominance in number, these glaciers represent only 21% of the total glacierised area and 7% of the total estimated ice reserves in the basin (Figure 5.74), emphasising their limited contribution to long-term water resources. Their small mean size (0.1 km²) also makes them highly vulnerable to climate change and rapid retreat.

In contrast, the largest glaciers of Class 5 (≥10 km²), though few in number (only 3 glaciers or only 1 % of the total), dominate in terms of area coverage by 30% of the total and hold a massive 53% of the total estimated ice reserves in the river basin. With an average glacier size of 15.5 km², these glaciers serve as the primary long-term water resources in the basin, sustaining river flow and water resources during drier periods.

However, the mid-sized glaciers of Class 2 (0.51 – 5.00 km²) and Class 3 (1.01 – 5.00 km²) accounted equivalent number of glaciers, 10% and 11% of total glaciers in the river basin respectively. Among them, Class 3 glaciers contributed significantly by covering

FIGURE 5.75 **GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN EACH BASIN OF THE YELLOW RIVER BASIN.**



36% of the total glacier area and storing 32% total estimated ice reserves, highlighting their important role in maintaining water availability in the basin.

Overall, the glacier size distribution is heavily skewed towards smaller glaciers, which are most vulnerable to climate change. While the largest glaciers store the majority of the estimated ice reserves, the potential loss of small and mid-sized glaciers could have a substantial impact on local water availability in the coming decades.

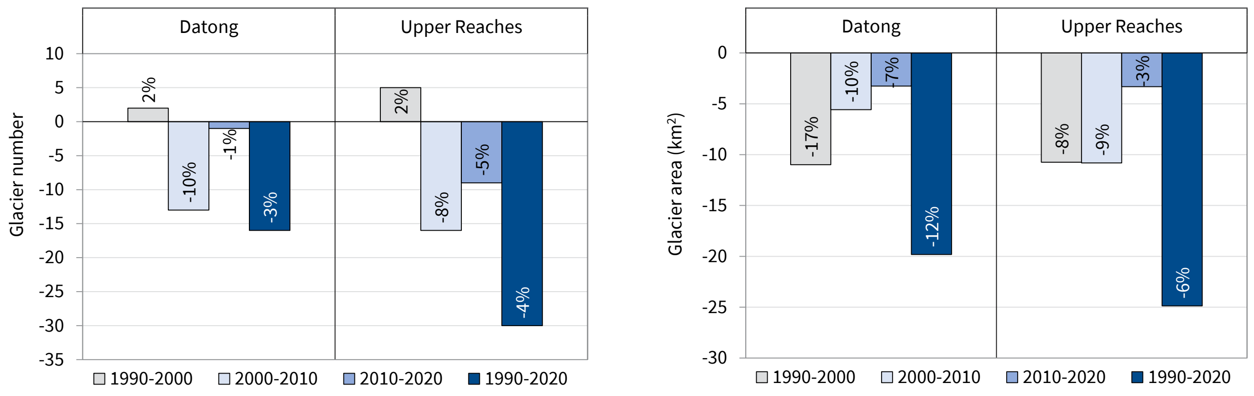
The elevation range of glaciers in the Yellow River basin spans from 4,097 masl to 6,254 masl. The elevation-based glacier area distribution in the Yellow River basin highlights the distinct characteristics in the Upper Reaches and Datong basins. The Upper Reaches basin predominantly features glaciers at higher elevations, with the largest concentration between 5,000 – 5,500 masl, whereas the Datong basin has most of its glacierised area below 5,500 masl, with a significant concentration in the 4,500 – 5,000 masl range. Considering the entire Yellow River basin, glaciers are most abundant in the 4,500 – 5,000 masl range, comprising 34.48% of the total glacier area. The 5,000 – 5,500 masl range follows closely with 33.45%, while the 5,500 – 6,000 masl range accounts for 18.52%. Lower elevations (4,000 – 4,500 masl) contain 11.36%, and the highest elevation zone (6,000 – 6,500 masl) holds only 2.20% of the total glaciers (Figure 5.75).

The Datong basin has most of its glacier area at lower elevations below 5,500 masl. The 4,500 – 5,000 masl range dominates, covering 31.07 km², which is nearly 70% of the total glacier area in Datong basin. The 4,000 – 4,500 masl range contains 11.08 km², further emphasising the presence of low-altitude glaciers. The 5,000 – 5,500 masl range has a minimal glacier area of just 2.11 km², and there are no recorded glacier areas above 5,500 masl in Datong basin.

In contrast, the Upper Reaches basin has a wider glacier distribution spanning from 4,000 masl to 6,500 masl, with significantly larger glacier areas compared to Datong basin (Figure 5.75). The 5,000 – 5,500 masl range contains the highest glacier coverage (50.16 km²), making it the most dominant elevation range in Yellow River basin. The 5,500 – 6,000 masl range follows, with 28.94 km², reinforcing the prevalence of high elevation glaciers. The 4,500 – 5,000 masl range holds 22.80 km², while the lower elevations (4,000 – 4,500 masl) contribute much less, with only 6.67 km², which is almost half of the glaciers area in Datong basin. At the highest elevation range (6,000 – 6,500 masl), glacier coverage is minimal, with just 3.44 km².

Glaciers in the Yellow River basin are categorised into six classes based on their mean slope, revealing a distinct pattern in their distribution. The majority of glaciers are concentrated in the 20° – 30° slope class, which accounts for 58% of the total glaciers, covering 57% of the total glacierised area and

FIGURE 5.76 INTERDECADAL GLACIER NUMBER (LEFT) AND AREA (RIGHT) CHANGES IN EACH BASIN OF THE YELLOW RIVER BASIN.



holding 55% of the estimated ice reserves (Figure 5.74). The 10° – 20° slope class ranks second, containing 25% of the total glaciers, covering 32% of the total glaciersed area, and storing 37% of the total estimated ice reserves in the river basin.

As the slope increases, the number and area of glaciers decline sharply. The 30° – 40° slope class contains only 45 glaciers, covering 11% of the total glacier area, with a significantly lower 0.5% share of estimated ice reserves. Glaciers in the 40° – 50° slope class are nearly absent, with just one recorded glacier, and no glaciers exist above 50° slope classes, indicating that steeper slopes do not favour glacier survival.

The mean glacier size follows a clear trend, where glaciers on gentler slopes are generally larger, while those on steeper slopes are progressively smaller and more fragmented. The mean glacier area in the 10° – 20° slope class is 0.7 km², which decreases to 0.54 km² in the 20° – 30° class and drops further to just 0.09 km² in the 40° – 50° class. This pattern suggests that steeper slopes lead to higher ice instability, reducing glacier size and promoting fragmentation.

The aspect analysis reveals a relatively balanced glacier distribution across various cardinal directions, with a notable concentration in northern and northeastern-aspects. The northern aspect hosts the highest number of glaciers (31.1%), covering 26.8% of the total glacier area and storing 23.7% of the total estimated ice reserves (Figure 5.74). This suggests that north-facing slopes provide favourable conditions for glacier retention due to reduced solar radiation exposure.

The northeastern aspect leads in glacier area and estimated ice reserves, covering 37% of the total glacier area and holding 53% of the total estimated ice reserves. It also exhibits the largest mean glacier area (1.79 km²), significantly surpassing other aspects. This indicates that northeastern slopes are particularly conducive to sustaining larger glaciers, likely due to favourable climatic conditions and shading effects.

In contrast, while the northwestern aspect contains more glaciers than the northeastern aspect (18% vs. 11%), its glacier area is significantly smaller, covering only 7% of the total glacier area. This suggests that northwestern glaciers tend to be smaller in size, which is also reflected in the smallest mean glacier size of just 0.23 km² in the basin.

The eastern and southeastern aspects support the least glacier development, collectively accounting for only 4% of the total glacier area and 2% of the total estimated ice reserves. The mean glacier sizes in these aspects are relatively small, averaging around 0.3 km² per glacier.

The southern, southwestern, and western aspects contain a comparable number of glaciers, each accounting for about 10 – 12% of the total glaciers in the basin. However, the southwestern aspect stands out, covering 12% of the total glacierised area and holding 9% of the total estimated ice reserves – almost double that of the southern and western aspects, which contribute only 6 – 7% of the total glacierised area and 4% of total ice reserves. This suggests that the southwestern aspect is relatively more favourable for glacier preservation compared to the southern and western slopes.

Decadal glacier changes from 1990s to 2020

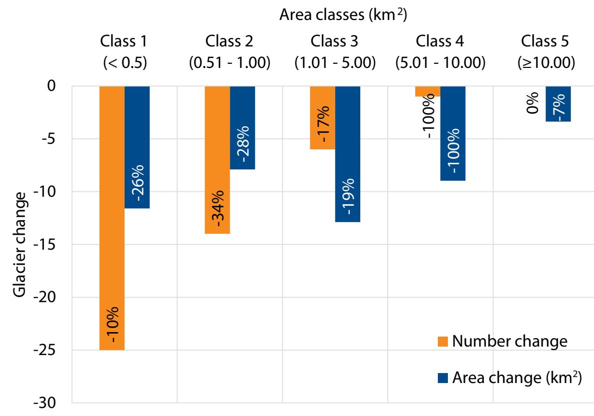
Between 1990 and 2020, the Yellow River basin experienced a significant decline in glacier coverage. The glacier area decreased by approximately 22%, from 200.96 km² in 1990 to 156.26 km² in 2020 (Table 5.31). Similarly, glacier numbers increased by 14%, from 329 glaciers in 1990 to 283 in 2020, indicating not only a fragmentation of larger glaciers into smaller glaciers as the glaciers recede and shrink.

Glacier retreat in the Yellow River basin intensified over the past three decades, with glacier numbers and area decreasing by 14% and 22%, respectively, between 1990 and 2020. Glacier numbers declined by 2% during 1990 – 2000, followed by sharper decreases of 9% in 2000 – 2010 and 3% in 2010 – 2020. Similarly, glacier area decreased by 11% between 1990 and 2000, 9% during 2000 – 2010, and 4% during 2010 – 2020, culminating in a total area reduction of 22% over the study period.

Both the basins within the Yellow River basin experienced glacier numbers and area loss across all decades. The Datong basin lost about 30% (19 km²) of its glacier area, whereas the Upper reaches basin lost a much larger area i.e. 25 km², which is around 18% of its original area in 1990 (Figure 5.76).

Over the three decades, glaciers across all size classes saw reductions in both areas and numbers. The largest decrease in glacier number was from the smallest size Class 1 (<0.5 km²), which lost 25 glaciers (11%) and almost 26% of the area lost over three decades. Similarly, glaciers of Class 2 (0.51 –

FIGURE 5.77 GLACIER NUMBER AND AREA CHANGES ACROSS VARIOUS MEAN ASPECTS OVER THREE DECADES IN THE YELLOW RIVER BASIN.



1.00 km²) declined by 34.1% in number and 28.4% in area, showing that smaller glaciers are particularly vulnerable to climate-induced melting (Figure 5.77).

The mid-sized glacier of Class 3 (1.01 – 5.00 km²) experienced the largest area loss, with nearly 13 km² equivalent to 18.5% of their area over the three decades. The decline accelerated after 2010, suggesting increasing climate pressure. A striking observation is the complete disappearance of glaciers in Class 4 (5.01 – 10.00 km²), which vanished entirely after 1990 meaning they have shrunk down to smaller size classes.

In contrast, the largest glacier Class 5 (≥10.00 km²) remained stable in number, but their area reduced slightly by 6.7%, indicating that larger glaciers are more resilient due to their thicker ice reserves. However, even these glaciers are not immune to long-term melting trends.

TABLE 5.31 DECADAL CHANGES OF GLACIER NUMBER AND AREA IN THE YELLOW RIVER BASIN AND ITS BASINS FROM 1990 TO 2020.

	Year	Datong		Upper Reaches		Yellow River	
		Number	Area (km²)	Number	Area (km²)	Number	Area (km²)
Status	1990	126	64.08	203	136.88	329	200.96
	2000	124	53.09	198	126.14	322	179.23
	2010	111	47.52	182	115.32	293	162.85
	2020	110	44.26	173	112.01	283	156.26
Change percent	1990 – 2000	2%	-17%	2%	-8%	2%	-11%
	2000 – 2010	-10%	-10%	-8%	-9%	-9%	-9%
	2010 – 2020	-1%	-7%	-5%	-3%	-3%	-4%
	1990 – 2020	-13%	-31%	-15%	-18%	-14%	-22%
	per decade	-3%	-12%	-4%	-6%	-3%	-8%

Similar to other river basins, this basin has also experienced glacier retreat, leading to a shift in the lowest glacier snout elevation from 4,085 masl to 4,097 masl. However, the extent of this elevation shift varies among individual glaciers. In the Upper Reaches basin, the glacier snout has retreated more significantly, rising from 4,155 masl to 4,198 masl, indicating a greater rate of retreat compared to the Datong basin, where the shift is relatively smaller, from 4,085 masl to 4,097 masl. This suggests that glaciers in the Upper Reaches are experiencing more pronounced melting and retreat.

The area-elevation distribution from 1990 to 2020 reveals significant glacier area loss across most elevation ranges. The most substantial decline occurred between 4,000 and 4,500 masl, where nearly 49% of the glacier area (16.93 km²) was lost over three decades (Figure 5.78 and Table 5.32). The highest rate of retreat was observed during the 1990 – 2000 and 2000 – 2010 periods. Similarly, glaciers in the 4,500 – 5,000 masl range also experienced significant shrinkage, losing approximately 24% of their area. However, the rate of retreat noticeably slowed after 2000.

Glacier loss decreases at higher elevations, indicating that lower-altitude glaciers are more vulnerable to melting. The 5,000 – 5,500 masl range showed a reduction of over 17%, with the most significant decline occurring between 2000 and 2010. In contrast, glaciers above 5,500 masl exhibited minimal changes, and those located above 6,000 masl remained largely unaffected throughout the study period. These findings suggest that glacier retreat is severe at lower elevations, likely due to rising temperatures and increased melting rates.

FIGURE 5.78 GLACIER AREA DISTRIBUTION AND CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE YELLOW RIVER BASIN.

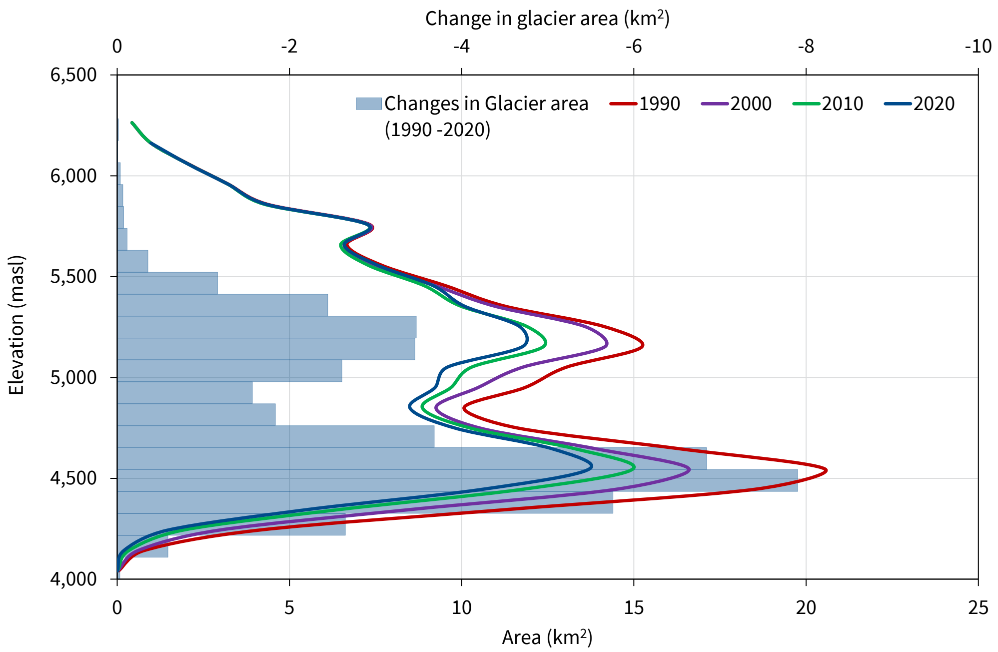
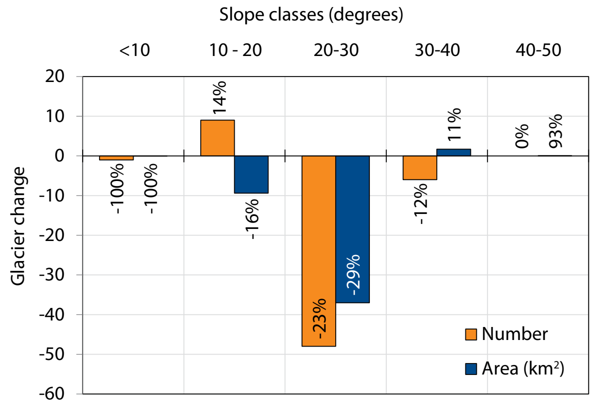


TABLE 5.32 GLACIER AREA DISTRIBUTION AND CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE YELLOW RIVER BASIN.

Elevation Range (masl)	Area (km²)				Area change (%)				
	1990	2000	2010	2020	1990 - 2000	2000 - 2010	2010 - 2020	1990 - 2020	Per decade
4,000 – 4,500	34.67	26.50	20.41	17.74	-23.6	-23.0	-13.0	-48.8	-19.9
4,500 – 5,000	70.42	60.76	57.07	53.88	-13.7	-6.1	-5.6	-23.5	-8.5
5,000 – 5,500	63.17	59.69	53.42	52.27	-5.5	-10.5	-2.2	-17.3	-6.1
5,500 – 6,000	29.24	28.84	28.51	28.94	-1.4	-1.2	1.5	-1.0	-0.3
6,000 – 6,500	3.45	3.44	3.44	3.44	-0.5	0.1	0.0	-0.4	-0.1
Total	200.95	179.23	162.85	156.26	-10.8	-9.1	-4.0	-22.2	-8.0

FIGURE 5.79 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES IN THE YELLOW RIVER BASIN.



A comparison between the two basins reveals that the Datong basin experienced greater glacier loss at lower elevations than the Upper Reaches basin, indicating a faster retreat rate in Datong basin. Over three decades, nearly 11 km² of glacier area was lost in Datong basin at elevations between 4,000 and 4,500 masl, whereas the Upper Reaches lost only 6.3 km². However, in terms of percentage change, both basins showed nearly identical glacier loss, with 48.7% in the Upper Reaches basin and 48.9% in Datong basin. This pattern persisted across each decade and was also observed in the 4,500 – 5,000 masl range.

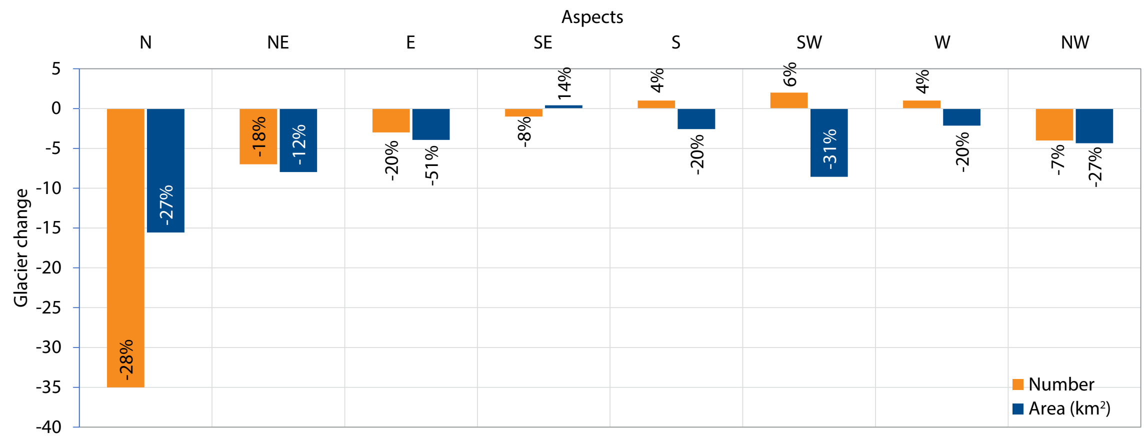
In contrast, glacier loss in the 5,000 – 5,500 masl range differed significantly between the two basins. The Upper Reaches basin experienced a much sharper decline, losing 17.76% of its glacier area, whereas glaciers in Datong basin were relatively more stable, with only a 3.4% decrease. The rate of glacier loss in the Upper Reaches basin was significantly higher during the earlier decades, particularly between 1990 – 2000 and 2000 – 2010. However, in more recent years, the rate of loss has evened out between the two basins, with a 2.4% decrease in the Upper Reaches basin and a slightly higher 2.8% loss in the Datong basin.

The analysis of glaciers based on mean slope classes highlights the significant influence of slope steepness on glacier stability. Glaciers with mean slopes ranging between 20° and 30° experienced the greatest area loss, shrinking by approximately 37 km² (29%) over three decades (Figure 5.79). This category also recorded the highest number of glacier losses, with 48 glaciers disappearing from the category, averaging a decline of 16 glaciers per decade. However, the rate of loss was particularly pronounced during the earlier periods of 1990 – 2000 and 2000 – 2010, before slowing down in the most recent decade.

In contrast, glaciers in the 10° – 20° slope range exhibited an increase of 9 glaciers over three decades, despite a 16% loss in glacier area. This trend suggests that while glaciers in this class may have experienced shrinkage and fragmentation, the basin reclassification of smaller glaciers has contributed to an overall change in number. These changes indicate that glacier retreat is not uniform, and that shrinkages and fragmentation can alter the distribution of glacier mean slopes.

Meanwhile, glaciers in the 30° – 40° slope class demonstrated mixed patterns, with a decreasing of 6 glaciers but a slight gain in glacier area. This suggests localised variations, where some glaciers have retreated while others have stabilised or even slightly gained in certain areas. These contrasting

FIGURE 5.80 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES IN THE YELLOW RIVER BASIN.



trends highlight the complexity of glacier dynamics and the varying influence of slope steepness on glacier stability across different regions.

In terms of mean aspects, the changes over the past three decades indicate a general pattern of decline. Northern aspect glaciers experienced the largest absolute losses in both number (a decline of 35 glaciers or 28.5%) and area (27.1%, or 15.56 km²) (Figure 5.80). The northeastern and eastern aspects also showed notable area losses of 12.2% and 51.1% respectively, though changes in glacier number were smaller. Interestingly, southeastern and southern aspects glaciers showed some resilience or even minor gains, southeastern aspect increased of one glacier and slightly increased in area by just 0.4 km², while southern aspect had lost 2.6 km² of glacier area which is nearly 20% despite gaining one glacier, indicating shrinkage of existing glaciers. In the southwestern, western, and northwestern aspects, glacier numbers were relatively stable or slightly increased, but area reductions were significant, especially southwestern with a 30.6% area loss. These trends highlight that while some aspects may temporarily gain glacier numbers, likely due to fragmentation, glacier area continues to decline, and losses are also driven by shrinkage and reorientation of glacier masses, which results in mean aspect shifts over time.

STREAM DRILLING ON THE YALA GLACIER FOR STAKE INSTALLATION

5.10 Tarim River Basin

The Tarim River basin is a vast and arid region located in northwestern China, bordered by the Tian Shan mountains to the north and the Kunlun Mountains to the south (Sun et al., 2008). The Taklamakan Desert dominates much of the basin, while the Tarim River flows along its northern edge, originating from the Karakoram Mountains and terminating at the now dry Lop Nur Salt Lake.

As an endorheic basin, the Tarim River basin has no outflows, leading to all water flowing into the basin being lost through evaporation or seepage. It is one of the driest place in China, receiving around 68 mm of precipitation per year (Li et al., 2019). Despite the harsh climate, the basin sustains a unique ecosystem, including a riparian corridor along the Tarim River that supports desert poplar forests. Notably, only 19% of the basin lies within the HKH region, covering an area of 24,582.99 km². Figure 5.81 showing the extent of the basin within HKH region including glacier distribution.

Glacier distribution in 2020

As of 2020, the Tarim River basin contained 920 glaciers with a total area of 1,724.9 km² and holding 251.28 km³ estimated ice reserves. Overall, in the HKH region, this basin encompasses more than 1.4% glacier number and 3.1% of the total glaciers area, with an average size of 1.9 km², indicating the relatively larger number of glacier distribution. These glaciers are distributed between 30.45°N and 37.08° N latitude and 69.36°E and 81.65° E longitude, across an elevation range from 5,195 masl to 7,126 masl.

The size of the glaciers in this basin ranges from 0.02 km² to the largest glaciers of 234.5 km², including four glaciers of size greater than 100 km². The distribution of glaciers across different area size classes in the Tarim River basin reveals a distinct inverse relationship between glacier numbers and their contribution to total glacier area and estimated ice reserves (Figure 5.82). The smallest glaciers (<0.5 km²), though highly abundant, comprising 68% of the total (629 glaciers), contribute only 6% of the overall glacier area and a mere 1% of the

FIGURE 5.81 MAP SHOWING GLACIER DISTRIBUTION AND EXTENT OF THE TARIM RIVER BASIN WITHIN THE HKH REGION.

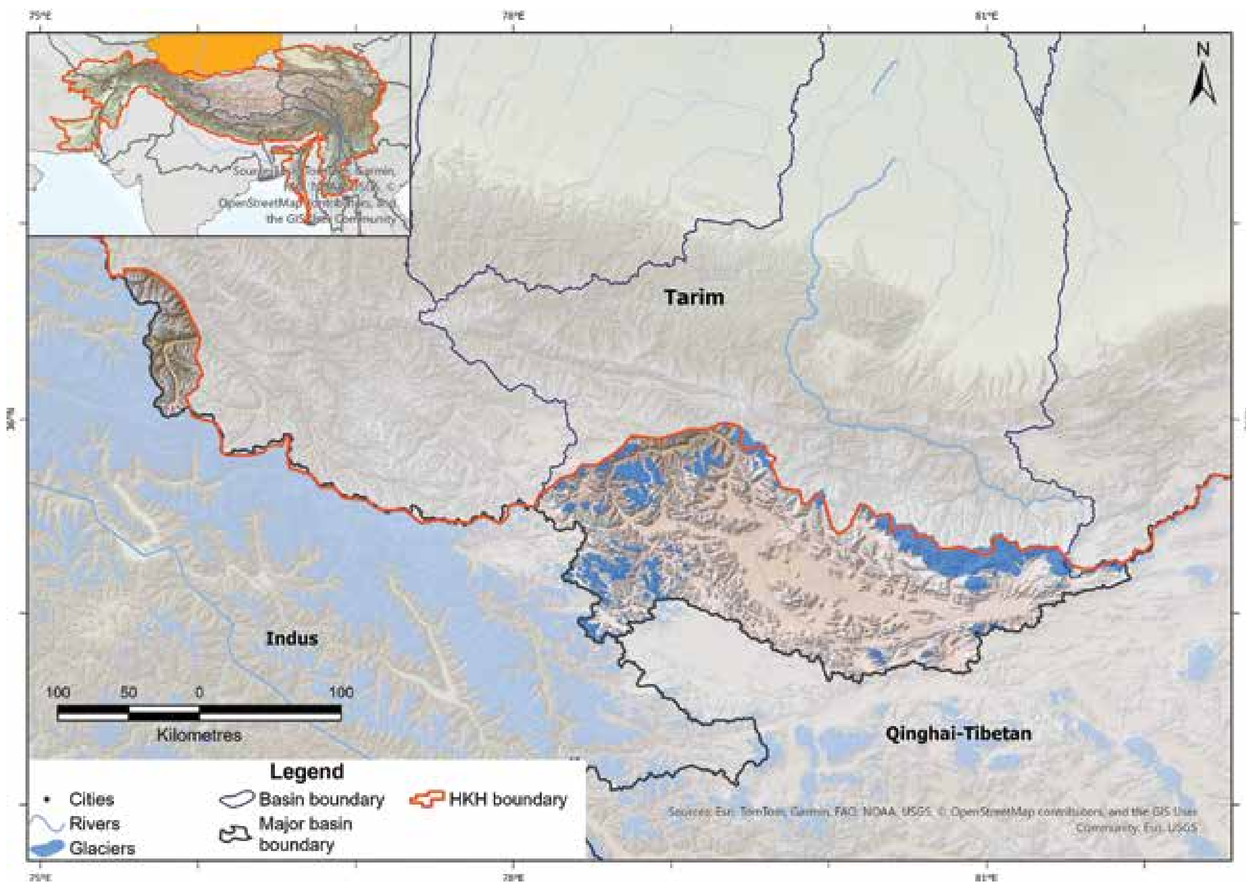
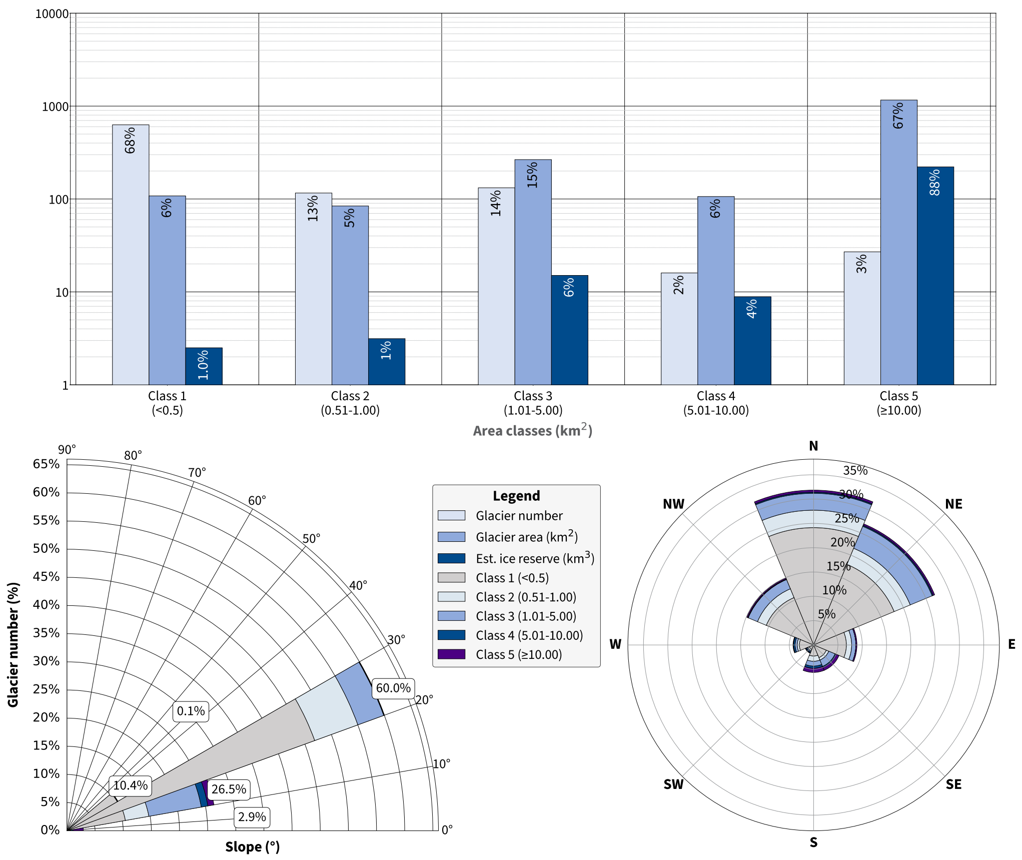


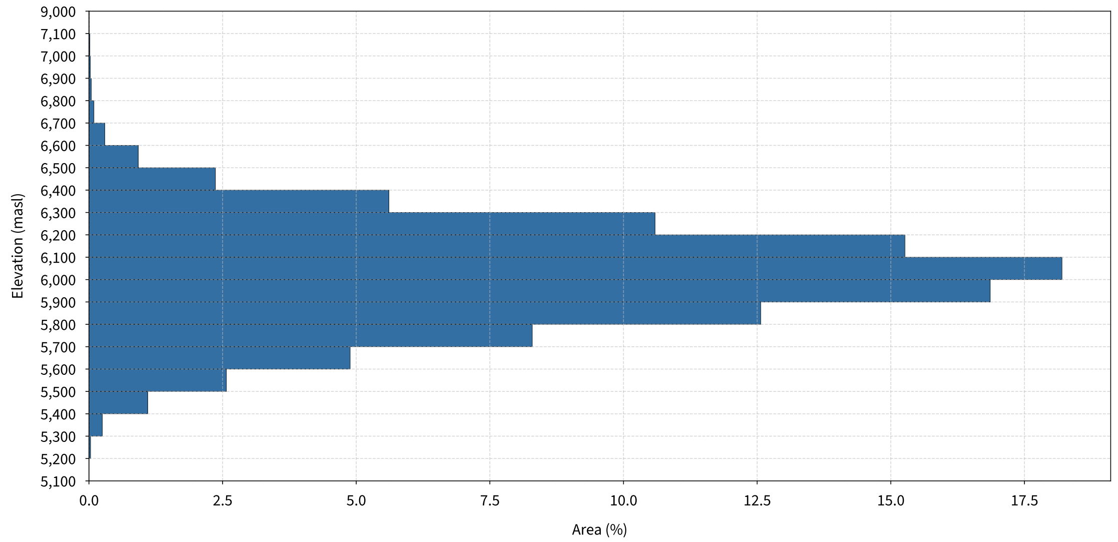
FIGURE 5.82 **GLACIER DISTRIBUTION IN ACROSS AREA CLASSES** (TOP)**, MEAN SLOPES** (BOTTOM LEFT) **AND ASPECTS** (BOTTOM RIGHT) **IN THE TARIM RIVER BASIN.**



total estimated ice reserves, with an average size of just 0.17 km². Similarly, glaciers in the Class 2 (0.51 – 1.00 km²) account for 13% of the glacier number but contribute just 5% of the area and 1% of the estimated ice reserves. In contrast, the largest glaciers of Class 5 (≥10 km²), which represent only 3% of the total glaciers (27 glaciers), overwhelmingly dominate the landscape, covering 67% of the total glacier area and holding 88% of the estimated ice reserves, with an average size of 43.05 km² per glacier. Mid-sized glaciers, Class 3 (1.01 – 5.00 km²) and Class 4 (5.01 – 10.00 km²), while less numerous (14% and 2% respectively), make a more balanced contribution, accounting for 15% and 6% of the area, and 6% and 4% of the estimated ice reserves, respectively. This inverse pattern underscores a critical imbalance: while smaller glaciers are far more prevalent, they play a limited role in the region's ice storage, whereas a handful of large glaciers are critically important for maintaining the basin's hydrological balance, making them central to water resource planning and climate resilience.

Glaciers in this basin within the HKH region are mainly mapped above 5,100 masl with the lowest snout elevation of 5,195 masl and topmost elevation of the crown part is 7,126 masl. The glacier area distribution across various elevation ranges in the Tarim basin shows a highly concentrated pattern, with the vast majority of glacier coverage found between 5,500 and 6,500 masl (Figure 5.83). Specifically, glaciers in the 6,000 – 6,500 masl range account for the largest coverage, comprising over half (52%) of the total glacier area, followed closely by the 5,500 – 6,000 masl range with 45.2%. Together, these two elevation ranges contain over 97% of the total glacier area, indicating that this altitude range represents the core glaciated region of the basin (Figure 5.83). In contrast, glacier areas below 5,500 masl and above 6,500 masl are minimal, each accounting for just around 1.4% of the total, while glaciers above 7,000 masl are almost negligible, contributing less than 0.1%. This distribution reflects the narrow elevation range in which climatic and topographic conditions are optimal for glacier formation and preservation in the Tarim River basin within the HKH region.

FIGURE 5.83 **GLACIER AREA DISTRIBUTION ACROSS 500 m ELEVATION RANGES IN THE TARIM RIVER BASIN.**



The mean slope of the glacier in this basin ranges from 0° to 50°, where the distribution across various classes shows a strikingly inverse pattern between glacier number and their contribution to total glacier area and estimated ice reserves. While the majority of glaciers, almost 60% belong to the 20° – 30° slope class (Figure 5.82), they contribute only 14% of the total area and just 4% of the estimated ice reserves. Similarly, the gentler slope class 10° – 20° consist of less than half of the glaciers in 20° – 30° slope class, just 23% of the total glacier, they contribute more than double the glacier area (29%) and four times higher the estimated ice reserves (16%) than in 20° – 30° slope class. A stark difference is observed in the flatter slope class (<10°), consisting of extremely few glaciers of just 2% (19 glaciers), yet they dominated in both glacier area by covering more than half (56%) of the total glacier area and extremely high volume (79%) of the total estimated ice reserves in the basin. These glaciers have an exceptionally large mean area of 50.86 km², indicating they are significantly larger and thicker than those on steeper slopes. Meanwhile, the glaciers in steeper slopes above 30° are fewer in number, just 14% of glaciers covering significantly less area of 1% and just 0.2% of the estimated ice reserves in 30° – 40° slopes, and negligible beyond 40° slopes, highlighting the limiting effects of steep terrain on glacier stability.

Overall, this distribution underscores the larger valley glaciers which generally occur on flatter mean slopes less than 10° are the main reservoirs of ice, whereas the numerous smaller cirque and niche glaciers above 20° on steeper slopes contribute far less to the overall ice storages and are also highly vulnerable to climate change impacts.

Aspect plays a crucial role in glacier distribution, with distinct variations observed in total glacier number, area and estimated ice reserves. The majority of glaciers are oriented towards northern (32%), northeastern (27%) and northwestern (15%) aspects (Figure 5.82), they collectively comprising only 29% (12%, 11% and 6% respectively) of the total glacier area and even less to the estimated ice reserves by 13% (5%,4% and 3% respectively), with relatively smaller glaciers of size around 0.7 – 0.8 km².

Converse to this, the southern aspect alone covers more one-third (34%) of the total glacier area and nearly half (46%) of the total estimated ice reserves by just 6% of the glaciers in the basin, suggesting the larger glaciers distribution. Similarly, southeastern aspect also consists of the same number of glaciers (6%), but they contribute almost half (18%) of area and less than half (22%) of the estimated ice reserves than in the southern aspect. This aspect also has considerably higher mean size glaciers of 6.1 km², indicating the larger glacier distribution.

Meanwhile, glaciers on other aspects such as the southwestern, western, and eastern have fewer glaciers but still contribute to the intermediate amount of overall glacier area and estimated ice reserves. The glaciers on the southwestern and western aspects have notably larger mean sizes of 7.7 km² and 3.2 km², respectively, suggesting a distribution of relatively larger glaciers in these aspects as well.

Decadal glacier changes from 1990s to 2020

Between 1990 and 2020, the Tarim basin experienced minimal changes in all metrics – glacier number, area and estimated ice reserves. Over these three decades, the total glacier area decreased by just 0.08% (1.43 km^2), while the glacier number showed a slight increase of 2 glaciers (0.2%). The rate of glacier area and number change fluctuated over time. In the first two decades (1990 – 2010), there was a slight increase in glacier area, followed by a general decline in the last decade (2010 – 2020) (Figure 5.84).

Compared to other river basins in the region, this basin showed the minimal changes across various size classes. Smaller glaciers of Class 1 (<0.5 km^2) and Class 2 (0.5 – 1 km^2) experienced a mix of gains and losses in number across decades, resulting in a net increase of 4 and net loss of 1 respectively. However, these changes resulted into negligible area changes, with less than 0.2% to 1.6% variation in each decade and overall loss of 0.3% and 0.7% respectively.

In the mid-size Class 3 (1.01 – 5.00 km^2), glacier numbers declined slightly (by 1), with a corresponding area reduction of approximately 2.35 km^2 or 1%, indicating minor shrinkage. No changes in glacier number were observed in the larger sized Class 4 (5.01 – 10.00 km^2) and Class 5 (≥10 km^2). However, Cass 5 experienced some positive gain in glacier area of about 2 km^2, which is due to surging of one glacier. The Class 4 showed a minor reduction of glacier area over three decades (Figure 5.85).

The glacier area-elevation distribution from 1990 to 2020 reveals distinct elevation dependent loss trends. Although the basin experienced relatively fewer overall losses compared to other river basins, the most significant decline occurred between 5,500 and 6,000 masl, where glaciers lost approximately 1% of their area (Figure 5.86). However, some elevation ranges showed gains, particularly between 5,000 and 5,500 masl, which saw the greatest overall gain in area of 4.52 km^2 (a 23.4% increase), despite the minor loss during last decades (2010 – 2020). The reason for this gain in area is due to the surging of one specific glacier, whose snout extended from 5,453 masl in 1990 to 5,321 masl in 2000 and again minor retreated or shifted upward in 2020 to 5,356 masl. Meanwhile, higher elevation ranges above 6,000 masl showed negligible area changes, suggesting that glaciers on these ranges remained relatively stable over last three decades.

Glacier changes across different slope classes exhibit distinct trends, with most slope ranges showing overall stability and minimal fluctuations in both glacier number and area over the past three decades. Glaciers with mean slopes of less than 10° experienced a slight increase, gaining two glaciers and expanding by 1.9 km^2 in area. This growth is largely attributed to the surging behaviour of large, gently sloped glaciers. In contrast, moderate slopes between 10° – 20° and 20° – 30° displayed a mixed pattern, while glacier numbers increased slightly, both classes experienced reductions in glacier area. The area loss in the 10° – 20° range was relatively minor, whereas the 20° – 30° class saw the largest decrease, losing 2.15 km^2 over three decades despite the gain of one glacier. Steeper slopes between 30°–40° showed notable retreat, with a reduction of three glaciers and a total area loss of approximately 0.98 km^2. Slopes steeper than 40° exhibited no changes in glacier number or area, likely due to the absence or minimal presence of glaciers in such extreme terrain (Figure 5.87).

Glacier retreat patterns also show distinct variations across different mean aspects. Over the past three decades, the changes in both glacier number and area have been relatively modest overall, yet they reveal important spatial trends. Northern and northeastern aspects experienced a net loss in both number and area, which lost two and three glaciers including total area reduction of 3.01 km^2 and 2.6 km^2 over three decades (Figure 5.88).

In contrast, eastern (E) and northwestern (NW) aspects showed gains. Eastern aspect glaciers gained two in number but still recorded a minor area loss of 0.65 km^2 (–0.93%), indicating that while smaller glaciers may be forming or appearing due to fragmentation, the overall mass is reducing. Northwestern aspect gained three glaciers and saw a slight area increase of 0.91 km^2 (+0.83%), pointing toward shrinkages and fragmentation of glaciers alters the mean aspects of the glaciers.

Interestingly, southeastern (SE) aspect, despite no net change in glacier number, recorded a substantial area increase of 5.52 km^2 (+1.78%). This may indicate expansion or surging events in a few large glaciers. Southern (S) aspect remained stable in number but showed a net area loss of 2.35 km^2 (–0.40%), indicating that despite no visible changes in glacier number, retreat is occurring.

Western (W) and southwestern (SW) aspects also showed minor increases. Western aspect gained two glaciers and 0.49 km^2 of area (+0.39%), while southwestern aspect had no change in glacier count but recorded a small area gain of 0.25 km^2 (+0.19%). Overall, these nuanced gains and losses across aspects highlight the complex dynamics of glacier response to climatic and topographic influences.

FIGURE 5.84 INTERDECADAL GLACIER NUMBER AND AREA CHANGES IN THE TARIM RIVER BASIN.

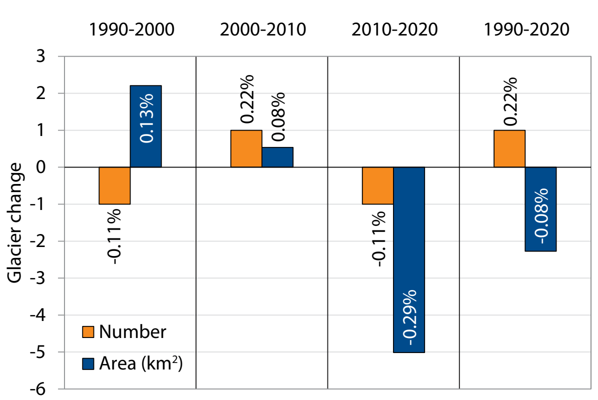


FIGURE 5.85 GLACIER NUMBER AND AREA CHANGES ACROSS SIZE CLASSES OVER THREE DECADES IN THE TARIM RIVER BASIN.

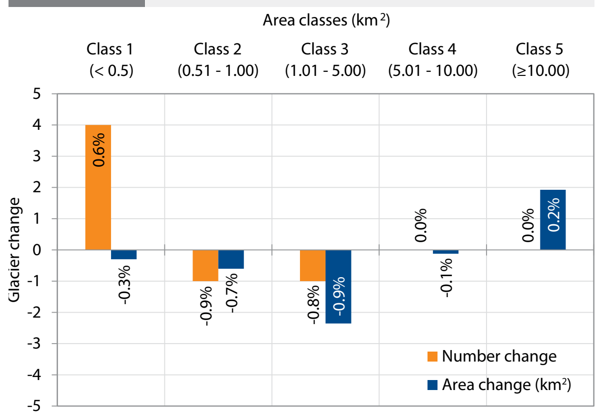


FIGURE 5.86 GLACIER AREA DISTRIBUTION AND CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN THE TARIM RIVER BASIN.

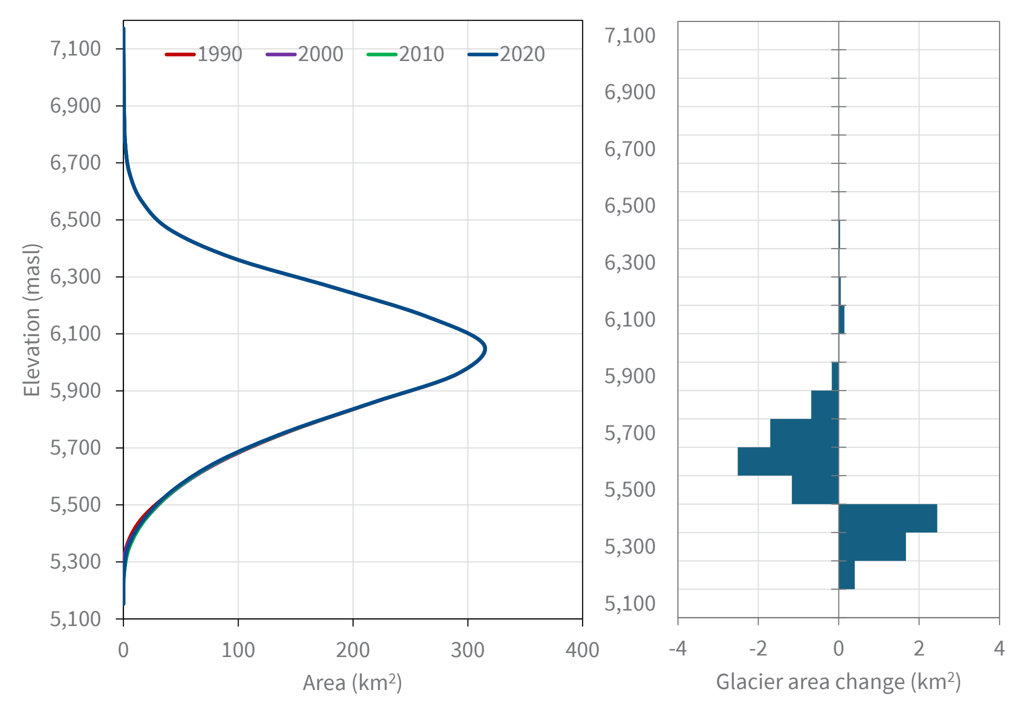


FIGURE 5.87 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES IN THE TARIM RIVER BASIN.

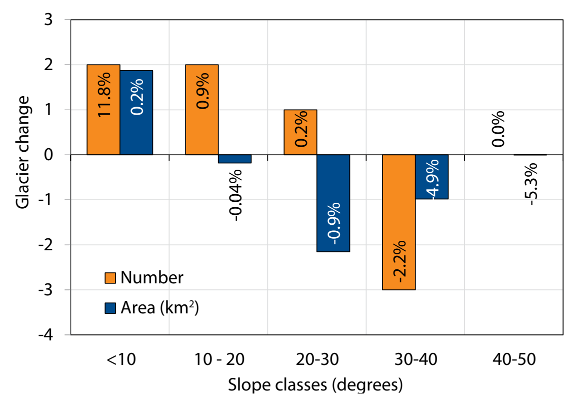
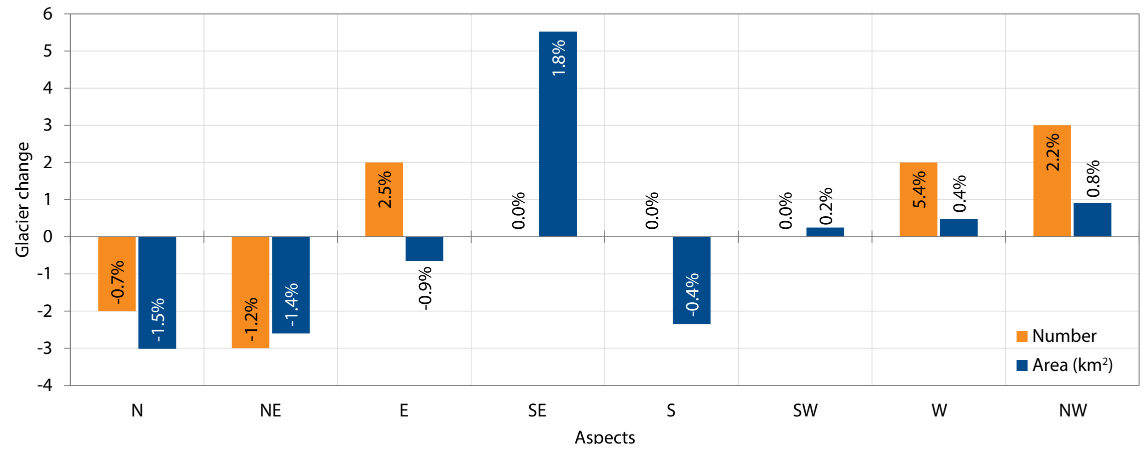


FIGURE 5.88 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES IN THE TARIM RIVER BASIN.



CHUBDA GLACIER AND GLACIAL LAKE IN BHUTAN

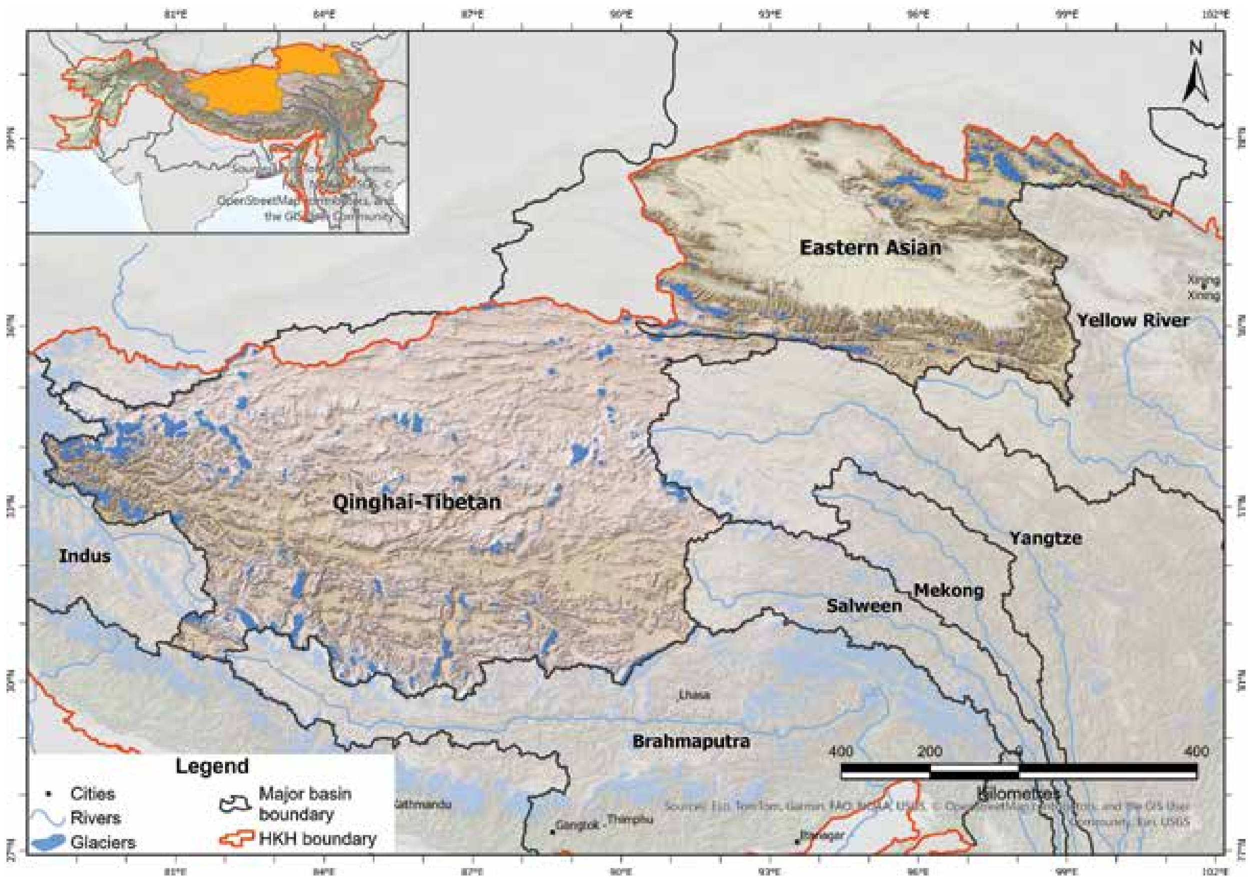
5.11 Interior Basins

Within the HKH region, two major interior drainage systems, the Eastern Asian basin and the Qinghai-Tibetan basin, play a critical role in shaping the region's hydrology, climate, and ecosystems, particularly across the central and eastern parts of the Tibetan Plateau.

The Eastern Asian interior basin spans a substantial geographic area in the northeastern part of the HKH region, particularly across eastern Tibet, parts of China, and adjacent areas. Covering approximately 280,527 km², it accounts for around 6.7% of the total HKH area. Geographically, it lies to the north and northwest of the Yangtze and Yellow River basins and in the northeastern corner of the Qinghai-Tibetan interior basin. This interior basin is characterised by a harsh continental climate, marked by cold and arid conditions, and a diverse landscape of mountains and plateaus. Rich in cultural heritage shaped by millennia of human history, the region holds significant importance in both regional and global contexts.

The Qinghai-Tibetan interior basin, lies in southwestern China, encompassing parts of Qinghai Province and the Tibet Autonomous Region. With elevations averaging over 4,500 masl, this basin forms a core part of the Tibetan Plateau. It is also the largest and one of the highest plateaus on Earth. Spanning approximately 629,500 km², this interior basin accounts for over 15% of the HKH region and is bounded by the Ganges and Brahmaputra River basins to the south, the Salween, Mekong, and Yangtze River basins to the east, the Tarim and Eastern Asian interior basins to the northwest and northeast, and the Indus River basin to the west. The landscape is incredibly diverse, featuring vast alpine grasslands, snow-capped mountains, and numerous lakes, including the iconic Qinghai Lake and the sacred Lake Mansarovar, revered for its cultural and religious significance. The region is home to a variety of ethnic groups, notably Tibetans and Hui communities, and holds deep cultural importance. Ecologically, it supports unique biodiversity and fragile ecosystems that are increasingly vulnerable to climate change and human pressures. The location and extent of these interior basins including the glacier distribution is shown in Figure 5.89.

FIGURE 5.89 MAP SHOWING GLACIER DISTRIBUTIONS AND EXTENT OF THE INTERIOR BASINS WITHIN THE HKH REGION.

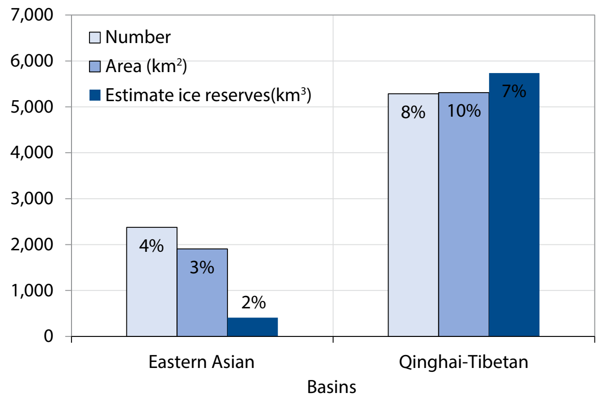


Glacier Distribution in 2020

As of 2020, the Eastern Asian and Qinghai-Tibetan interior basins together account for approximately 12% of the total glaciers in the HKH region, covering around 13% of the total glacier area and containing about 9.5% of the region's estimated ice reserves. Among the two, the Qinghai-Tibetan basin holds the largest share, with 5,285 glaciers covering 5,309.59 km² and storing an estimated ice reserves of 411 km³. This represents about 8% of the total glacier number and 10% of the glacierised area within the entire HKH region. In comparison, the Eastern Asian basin contains 2,375 glaciers, spanning an area of 1,906.34 km², and holds an estimated 128 km³ of estimated ice reserves. This accounts for approximately 3.7% of the region's glaciers and 3.4% of the total glacier area in the HKH (Figure 5.90 and Table 5.33). These glaciers extend between 30.45° N and 37.08° N latitude and 69.36° E to 81.65° E longitude across the Qinghai-Tibetan and Eastern Asian regions.

The largest glaciers in these two basins varies significantly in size. The Eastern Asian basin contains the largest glacier, covering an area of 95.1 km², while the Qinghai-Tibetan basin's largest glacier spans 50.84 km² (Table 5.33). Despite these standout features, glaciers in both basins are predominantly small, with a diverse distribution across glacier classes.

FIGURE 5.90 GLACIER NUMBER, AREA AND ESTIMATED ICE RESERVES IN THE INTERIOR BASINS WITHIN HKH.



Class 1 glaciers (<0.5 km²), the smallest sized glacier, dominate in number – account for more than 67% (1,601 glaciers) of glaciers in eastern Asian and 69% (3644 glaciers) in Qinghai-Tibetan. However, their contribution of total glacier area and estimated ice reserves are minimal – only about 14.3% and 11% of the total glacierised area, and only 5% and 3% of the total estimated ice reserves, respectively, within each Eastern Asian and Qinghai-Tibetan (Figure 5.91 and Figure 5.92).

Moving up in size, their numbers decline significantly, with each subsequent size class containing roughly five-time fewer glaciers than the class below. In the Eastern Asian basin, Class 2 glaciers (0.51 – 1.00 km²) make up 14.5% of the total glacier number (345 glaciers) while contributing almost 13% of the glacier area and 7% of total estimated ice reserves. In Qinghai-Tibetan basin, Class 2 glaciers (0.51–1.00 km²) represent 12% of the total glaciers, covering an area of 8% and just 7% of the total estimated ice reserves in the basin.

Mid-sized glaciers of Class 3 (1.01 – 5.00 km²), are crucial to sustaining the region's ice mass. Although they represent only 15.6% of glaciers in the eastern Asian basin and 15% in the Qinghai-Tibetan basin, they contribute significantly – almost 40.3% and 32% of the total glacier area, and approximately 34% and 25% of the total estimated ice reserves, respectively.

Larger glaciers are far fewer in number but hold a disproportionately larger share of glacier area and estimated ice reserves in both the basins. Glaciers in the Class 4 (5.01 – 10.00 km²) and Class 5 (≥10.00 km²) each contains less than or equal to 2% of the total glaciers in the basin. However, in the Eastern Asian basin, Class 4 glaciers cover 16.8% of the total glacier area and 21% of total estimated ice reserves. In same class, the Qinghai-Tibetan basin had similar portion of area of about 16% and 18% of estimated ice reserves in the basin, but in absolute terms, these values are more than double compared to that in Eastern Asian basin.

TABLE 5.33 GLACIER DISTRIBUTION IN EACH INTERIOR BASIN IN THE HKH REGION.

Interior Basin	Number	Area (km²)	Largest area (km²)	Estimated ice reserve (km³)	Elevation (masl)		Mean slope (Deg)
					Min	Max	
Eastern- Asian	2,377	1,906.34	95.04	128.47	3,929	6,804	23
Qinghai-Tibetan	5,285	5,309.59	50.84	410.83	4,964	6,924	21
Total	7,662	7,215.93	95.04	539.30	3,929	6,924	22

FIGURE 5.91 GLACIER DISTRIBUTION ACROSS AREA SIZE CLASSES IN THE EASTERN ASIAN BASIN.

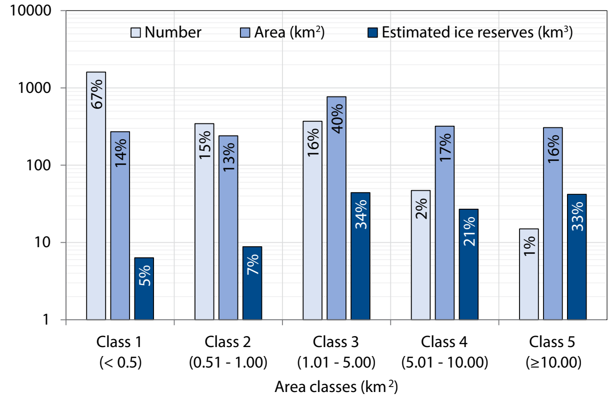
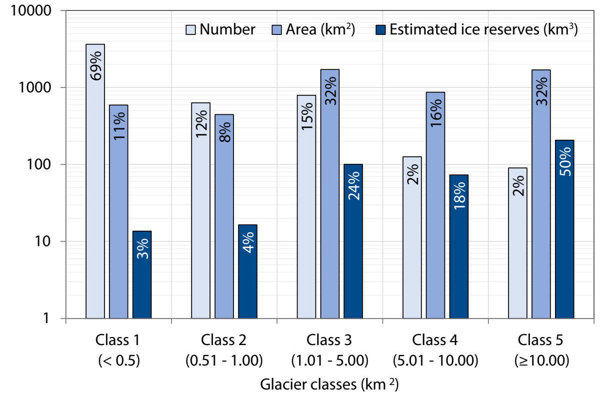


FIGURE 5.92 GLACIER DISTRIBUTION ACROSS AREA SIZE CLASSES IN THE QINGHAI-TIBETAN BASIN.

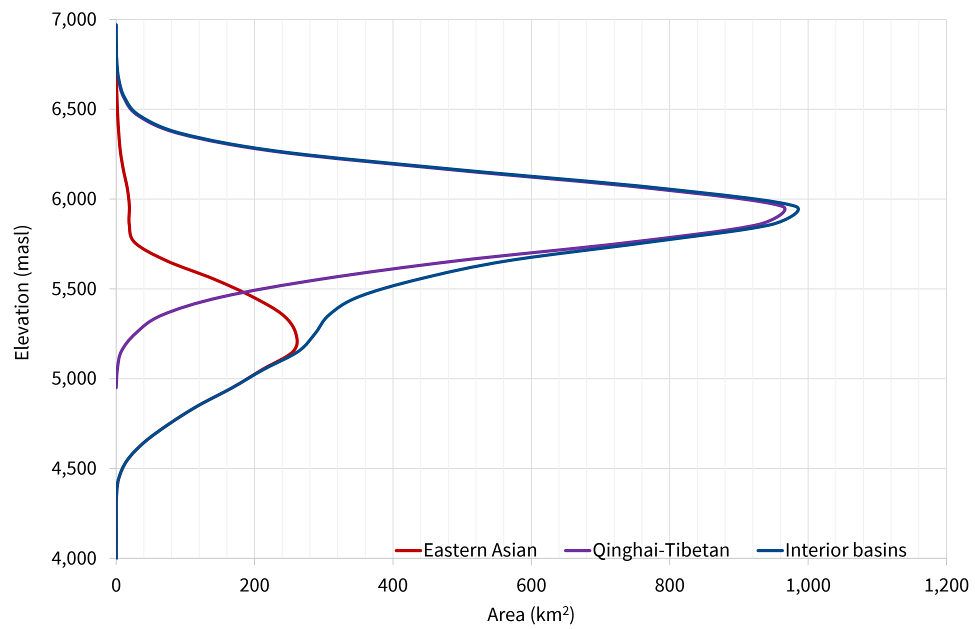


In the largest Class 5 (≥10.00 km²), the Eastern Asian basin contribute around 16% of area and one-third (33%) of total estimated ice reserves but represent an extremely small fraction of the total number, with only 15 glaciers (0.63%). Similarly, in the Qinghai-Tibetan basin, almost 32% of total glacier area and 50% of the total estimated ice reserves are contributed by this largest sized glacier. However, comparatively between these two basins the Qinghai-Tibetan have more than three to four times higher amount of the glaciers in all metrices.

Overall, both the basins demonstrated a clear inverse relationship between glacier numbers and their contribution to area and estimated ice reserves. While small glaciers are numerous, they contribute significantly less to glacier area and estimated ice reserves. In contrast, the fewer larger sized glaciers play an enormous role, holding an extensively higher amount of glacier area and estimated ice reserves and contribute majority of the water resources in the basins.

The elevation of glaciers in these interior basins ranges from approximately 3,900 masl to 7,000 masl. The lowest glacier elevation is found in the Eastern Asian basin at 3,929 masl, while the highest occurs in the Qinghai-Tibetan basin at 6,924 masl. Notably, the minimum elevation of glaciers in the Qinghai-Tibetan basin is about 1,000 metres higher, at 4,964 masl, than that in the Eastern Asian basin. However, the maximum elevation differ by only about 100 metres, with Eastern Asian glaciers reaching up to 6,804 masl compared to 6,924 masl in the Qinghai-Tibetan basin.

FIGURE 5.93 GLACIER AREA DISTRIBUTION ACROSS ELEVATION RANGES IN EACH INTERIOR BASIN OF THE HKH REGION.



The distribution of glacier areas across various elevation ranges reveals distinct differences between the Eastern Asian and Qinghai-Tibetan basins, reflecting their contrasting topographical and climatic settings (Figure 5.93 and Table 5.34). In the Eastern Asian basin, glaciers are primarily concentrated at elevation ranges from 4,500 masl to 5,500 masl, with the major chunk of glacier area over 61% were distributed at elevation range from 5,000 masl to 5,500 masl. Additionally, a substantial portion of almost 22% distributed at elevation range of 4,500 – 5,000 masl, and another 15% are distributed in 5,500 – 6,000 masl elevation range, respectively. Above 6,000 masl, glacier coverage drops sharply, with only about 2% of the total glacier area, indicating limited high-altitude terrain support significant glacier formation and preservations.

Conversely, the Qinghai-Tibetan basin exhibits a very different pattern, with glaciers predominantly concentrated at higher elevations. Nearly 65% of the basins glacier area are distributed between 5,500 – 6,000 masl, and another 30.4% between 6,000 – 6,500 masl. Glacier presence below 5,500 masl is minimal, comprising only around 5% of the total glacier area. However, this still represents a significant portion in absolute terms, and no glaciers exist below 5,000 masl. This reflects the elevated nature of the Tibetan Plateau, where even the base elevation is high, pushing glacier formation into much higher zones possibly due to broad and gentle terrain.

Based on the mean slopes of the glaciers, both interior basins show a strong concentration of glaciers on moderate slopes between 10° and 30°, accounting for approximately 83% to 87% of the total glacier number (Figure 5.94). However, despite this similarity in slope preference, the glacier area, estimated ice reserves, and average glacier size differ significantly between the two basins.

TABLE 5.34 GLACIER AREA DISTRIBUTION ACROSS THE ELEVATION RANGES IN EACH INTERIOR BASIN.

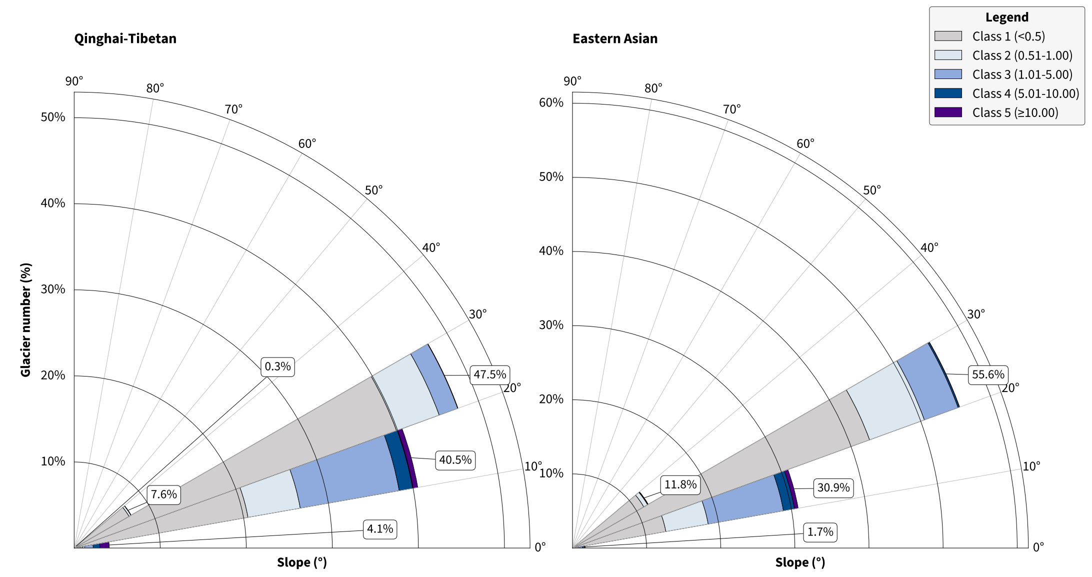
Elevation	Eastern Asian		Qinghai-Tibetan	
	Area (km²)	Area percent	Area (km²)	Area percent
3,500 – 4,000	0.02	0.0		
4,000 – 4,500	4.17	0.2		
4,500 – 5,000	419.02	22.0	0.02	0.0
5,000 – 5,500	1,165.35	61.1	255.63	4.8
5,500 – 6,000	277.74	14.6	3,423.15	64.5
6,000 – 6,500	38.49	2.0	1,615.54	30.4
6,500 – 7,000	1.54	0.1	15.24	0.3
Total	1,906.34	100.0	5,309.59	100.0

In the Eastern Asian basin, the majority of glaciers (57%) occur on slopes between 20° and 30°, although these glaciers are relatively small, covering only 33% of the glacier area and accounting for 22% of the estimated ice reserves. The largest amount of glacier area (55%) and estimated ice reserves (57%) is distributed on slightly gentler slopes (10°–20°), despite consisting of only 26% of the glaciers. This suggests that fewer but larger glaciers dominate in this slope class, with an average glacier size of 1.69 km². Interestingly, although only 1% of glaciers are found on flatter slopes (<10°), they account for 9% of the glacier area and 20% of the estimated ice reserves, with an average size of 5.65 km², indicating the presence of a few large, low-slope glaciers. Steeper slopes above 30° contribute very little to glacier area and estimated ice reserves, highlighting the limited role of high-gradient terrain in sustaining glaciers in this basin.

The Qinghai-Tibetan basin shows a similar trend in slope preference but with even more pronounced concentration on gentle terrain. Over one-third (36%) of glaciers are found on 10° – 20° slopes, contributing to 57% of the glacier area and 53% of the estimated ice reserves, closely mirroring the pattern in Eastern Asian basin. However, glaciers on <10° slopes in the Qinghai-Tibetan basin play a much more dominant role than in Eastern Asian basin, accounting for 26% of the glacier area and a substantial 39% of the estimated ice reserves, despite representing only 3% of glacier number. These glaciers also have the largest average area per glacier (8.98 km²) across both basins. In contrast, steeper slopes above 30° contain very few glaciers and contribute minimally to both area and estimated ice reserves, only around 2% in total, suggesting that, as in the Eastern Asian basin, high slope angles are generally unfavourable for glacier development and preservation.

Comparatively, while both basins have the majority of their glaciers on moderate slopes, the Qinghai-Tibetan basin has a much stronger representation of large, low-slope glaciers, which are major contributors to total estimated ice reserves. This reflects the influence of the broad, high-elevation and relatively gentle terrain of the Tibetan Plateau, compared to the steeper and more dissected landscape of the Eastern Asian basin. Overall, terrain slope plays a critical role in glacier size and ice retention, with gentle slopes supporting fewer but significantly larger and more ice-rich glaciers.

FIGURE 5.94 GLACIER DISTRIBUTION IN VARIOUS MEAN SLOPES OF THE INTERIOR BASINS.

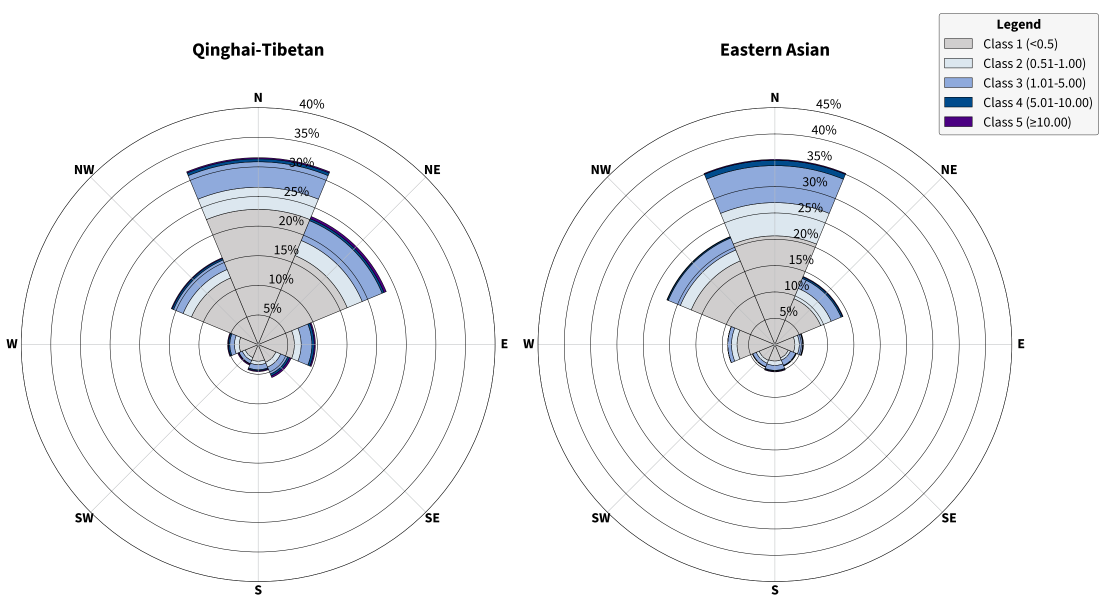


The distribution of glaciers across different aspects classes shows a clear dominance of northern, northeastern, and northwestern aspects (Figure 5.95). However, the degree to which the aspect influences glacier characteristics, such as area, estimated ice reserves, and average size, differs considerably between the two basins.

In the Eastern Asian basin, northern aspect dominates glacier distribution, with 35% of the glaciers located on these slopes, accounting for 41% of the total glacier area and 36% of the estimated ice reserves. Northeastern and northwestern aspects also host a substantial number of glaciers consisting of 14% and 22% of total glaciers in the basin, though these tend to be smaller in both area covering 14% each and holding estimated ice reserves of 13% and 11%, respectively. While the eastern, southeastern and southern aspects contain relatively few and similar number of glaciers around 4 to 5% each. But they had larger mean glacier size greater than 1 km², with relatively larger glacier area distribution of 10%, 6% and 8% and holding 19%, 6% and 9% of the estimated ice reserves, respectively.

Similar pattern of distribution is observed in the Qinghai-Tibetan basin with higher quantity than in Eastern Asian basin. Northern, northeastern and northwestern aspects remain the most numerous collectively consisting of 71% of the total glaciers covering 56% of glacier area and holding 50% of the total estimated ice reserves in the basin. But among them, northern aspect holds the highest in glacier number (32%) and northeastern aspect has the highest share of glacier area (23%) and estimated ice reserves (23%). Notably, southeastern aspect glaciers, which represent only 6% of glacier number, contribute a substantial 12% of glacier area and 14% of estimated ice reserves, with the largest average glacier size of 2.01 km². Southern, southwestern, eastern and western aspects in the Qinghai-Tibetan basin also support relatively larger glaciers with average size greater than 1 km². Whereas all these four aspects consisting of relatively fewer glaciers of about 4 to 5 % and covers 6 to 7% each of glacier area except the eastern aspects which contain considerable number of glaciers with 10% covering 12% of the total glacier area and estimated ice reserves in the basin. Overall, this suggest that the basin covers evenly size glaciers in all the aspects except that the northern and northwestern aspect has slightly smaller sized glaciers.

FIGURE 5.95 GLACIER DISTRIBUTION IN VARIOUS ASPECTS OF THE INTERIOR BASINS.



Decadal glacier changes from 1990s to 2020

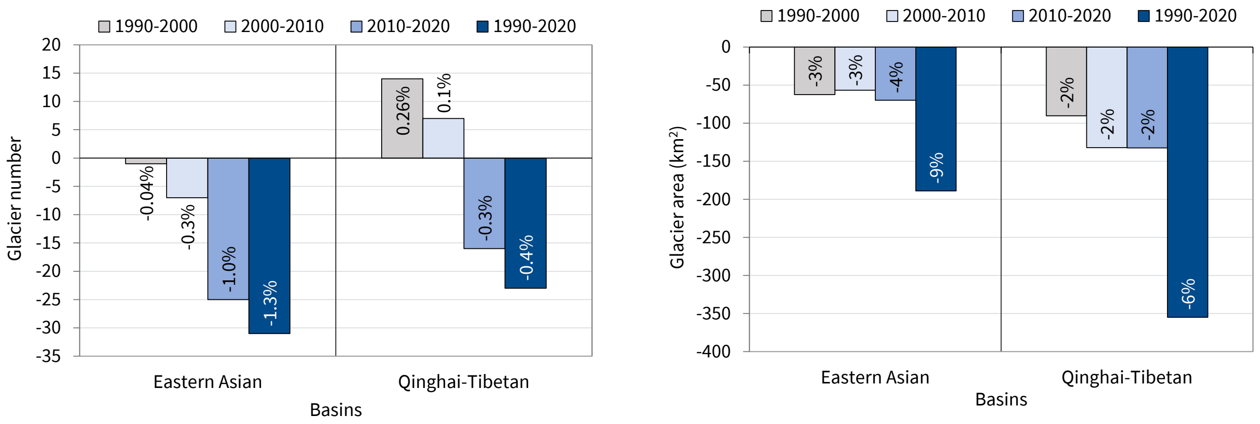
Over the past three decades, both the interior basins showed the consistent loss in both glacier numbers and areas, proportionally higher rate of loss in Eastern Asian basin than in Qinghai-Tibetan basin. But in absolute terms, both the distribution and changes in glacier area was higher in Qinghai-Tibetan basin. The Eastern Asian basin has undergone the total glacier area decline by over 9% and the decline in number by about 1.3% over past three decades. The rate of loss remained fairly consistent across the decades, though the decline slightly accelerated in the most recent period (2010 – 2020) (Figure 5.96).

Similarly, the Qinghai-Tibetan basin experienced a total glacier area loss of approximately 6.3%, while the number of glaciers declined by less than 0.5% over the same period. The absolute glacier area loss per decade remained relatively consistent; however, the overall trend indicates an increase in area loss in recent decades. The most significant losses occurred between 2000 and 2020, with 132.13 km² lost from 2000 to 2010 (a 2.4% decrease) and 132.51 km² lost from 2010 to 2020 (a 2.5% decrease). The number of glaciers showed some fluctuation: a decrease of 14 glaciers (0.26%) from 1990 to 2000, a slight increase of 7 glaciers (0.13%) from 2000 to 2010, and another decline of 16 glaciers (0.30%) from 2010 to 2020.

The impact of glacial retreat has not been uniformed across size classes. In the smallest glacier sized Class 1 (<0.5 km²), both basins showed an increase in glacier numbers, suggesting glacier retreat and fragmentation of larger glaciers to smaller ones. The Qinghai-Tibetan basin experienced a much larger increase (+111 glaciers) compared to Eastern Asian basin (+49), although both showed a modest percentage increase of 3%. However, both basins experienced an overall area loss in this class. The Eastern Asian basin lost 5.4% and over 4% loss in Qinghai-Tibetan basin. This indicates that while the number of small glaciers increased, they were shrinking in size or forming from retreating larger glaciers (Figure 5.97 and Figure 5.98).

The mid-sized classes of Class 2 (0.51 – 1.00 km²) and Class 3 (1.01 – 5.00 km²) experienced most significant reductions in glacier numbers and areas in both the basins. Eastern Asian basin had lost 20 glaciers (–5%) and an around 4% of the glacier area in Class 2, and 54 glaciers (–13%) with almost 11% of glacier area in the size Class 3 over the past three decades. Similarly, the most extensive glacier number and area loss in the Qinghai-Tibetan basin has occurred in the size Class 3 with losing 52 glaciers (–6%) and 103.83 km² (–6%), while the Class 2 lost 69 glaciers (–10%) and 10% of glacier area in same time periods. Overall, the losses were more pronounced in Qinghai-Tibet basin, both in number and area, reflecting more severe shrinkages in these size categories.

FIGURE 5.96 DECADAL GLACIER NUMBER (LEFT) AND AREA (RIGHT) CHANGES IN THE INTERIOR BASINS OF THE HKH REGION.



However, for the larger size classes (Class 4: 5.01 – 10.00 km² and Class 5: ≥10.00 km²), the patterns diverged somewhat. These classes experienced relatively smaller reductions in glacier numbers but experienced more significant losses in glacier area. In Class 4 sized glaciers, the Eastern Asian basin lost moderate area loss by 3% with losing minimal glaciers. Conversely Qinghai-Tibetan basin lost 11 glaciers and about 8% of the glacier area over three decades, indicating a more consistent retreat in this size class. The relatively stable glacier number in Eastern Asian basin might indicate that some glaciers remained intact but thinned, whereas Qinghai-Tibetan basin glaciers in this class experienced both fragmentation and shrinkage.

Similarly, glaciers in the size Class 5, in Qinghai-Tibetan basin, followed the same pattern as those in the size Class 4, experiencing more pronounced abosulte area losses of 104.01 km² (–6%) vis-à-vis the 56.01 km² (-15%) area loss in Eastern Asian basin, alongside the loss of Classes 1 and 2 glaciers, respectively. This suggests that larger glaciers were more likely to fragment, with consistent thinning and retreat occurring across both basins.

Glaciers have undergone significant changes across various elevation ranges between 1990 and 2020, with distinct trends observed between the Eastern Asian and Qinghai-Tibetan basins. In the Eastern Asian basin, the lowest snout elevation of glaciers shifted upward by 66 metres over the three decades, retreating from 3,863 masl in 1990 to 3,929 masl in 2020. This upward shift resulted in a complete loss of glacier area below 3,900 masl, indicating pronounced retreat at lower elevations. In contrast, the Qinghai-Tibetan basin did not exhibit a comparable uniform rise in snout elevation. Instead, glacier retreat in this region varied more significantly between individual glaciers, reflecting a more heterogeneous response to environmental and climatic factors across the interior basins.

FIGURE 5.97 GLACIER NUMBER AND AREA CHANGES ACROSS SIZE CLASSES OVER THREE DECADES IN EASTERN ASIAN INTERIOR BASIN.

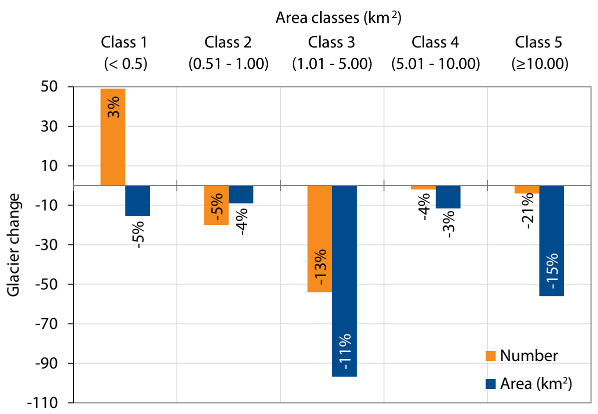
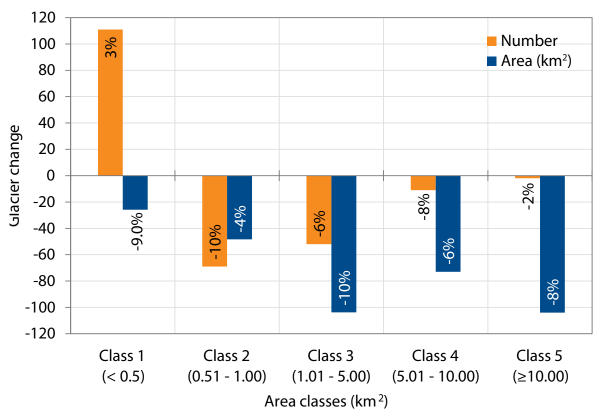


FIGURE 5.98 GLACIER NUMBER AND AREA CHANGES ACROSS SIZE CLASSES OVER THREE DECADES IN QINGHAI-TIBETAN INTERIOR BASIN.



The distribution of glacier areas across different elevation ranges revealed distinct patterns of area loss between the Eastern Asian and Qinghai-Tibetan basins (Figure 5.99 and Table 5.35). At lower elevation range from 3,500 – 4,500 masl, glaciers were present only in the Eastern Asian basin, which experienced substantial relative losses, approximately 67% of glacier area disappeared at 3,500 – 4,000 masl and over 65% at 4,000 – 4,500 masl. Despite these high percentage losses, the absolute area lost in these lower elevation range was relatively small compared to higher elevation.

The most significant glacier area losses occurred at 4,500 and 5,500 masl in the Eastern Asian basin. In this basin, glaciers retreated drastically, with area losses of nearly 90 km^2 across the 4,500 – 5,000 masl and 5,000 – 5,500 masl elevation range, accounting for about 18% and 7.2% of the total area in these elevation ranges, respectively, over the 30 year period.

Similarly, in the Qinghai-Tibetan basin, the most substantial glacier retreat was observed between 5,000 – 6,000 masl. About 63.2 km^2 of glacier area was lost at 5,000 – 5,500 masl, representing approximately 20% of the glacier area lost over three decades. Even more pronounced area loss was observed at 5,500 – 6,000 masl elevation range, where glaciers shrank by 265.5 km^2, accounting for about 7.2% of the glacier area in that range over same period. These findings highlight that while both basins experienced severe glacier retreat, the elevation ranges most affected varied slightly, with Eastern Asian showing peak losses just below 5,500 masl and Qinghai-Tibet exhibiting its greatest losses between 5,000 and 6,000 masl.

At the highest elevations above 6,000 masl, glacier area changes were less dramatic in both the basins. Both basins showed minimal changes in the 6,000 – 6,500 masl range, with only slight fluctuations in glacier area, and no significant change at 6,500 – 7,000 masl in Eastern Asian basin, reflecting a more stable situation at these extreme elevations. Qinghai-Tibetan basin, showed a slight reduction at this elevation, with a 0.8% loss.

The rate of glacier loss also varies by terrain steepness. In the Eastern Asian basin, glaciers on gentler slopes (<10°) increased in number by 8 glaciers over three decades, alongside a modest area gain of about 6%. Conversely, glaciers on moderate slopes (10° – 30°) saw the most substantial

FIGURE 5.99 GLACIER AREA DISTRIBUTION AND CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN EASTERN ASIAN (LEFT) AND QINGHAI-TIBETAN (RIGHT) INTERIOR BASINS.

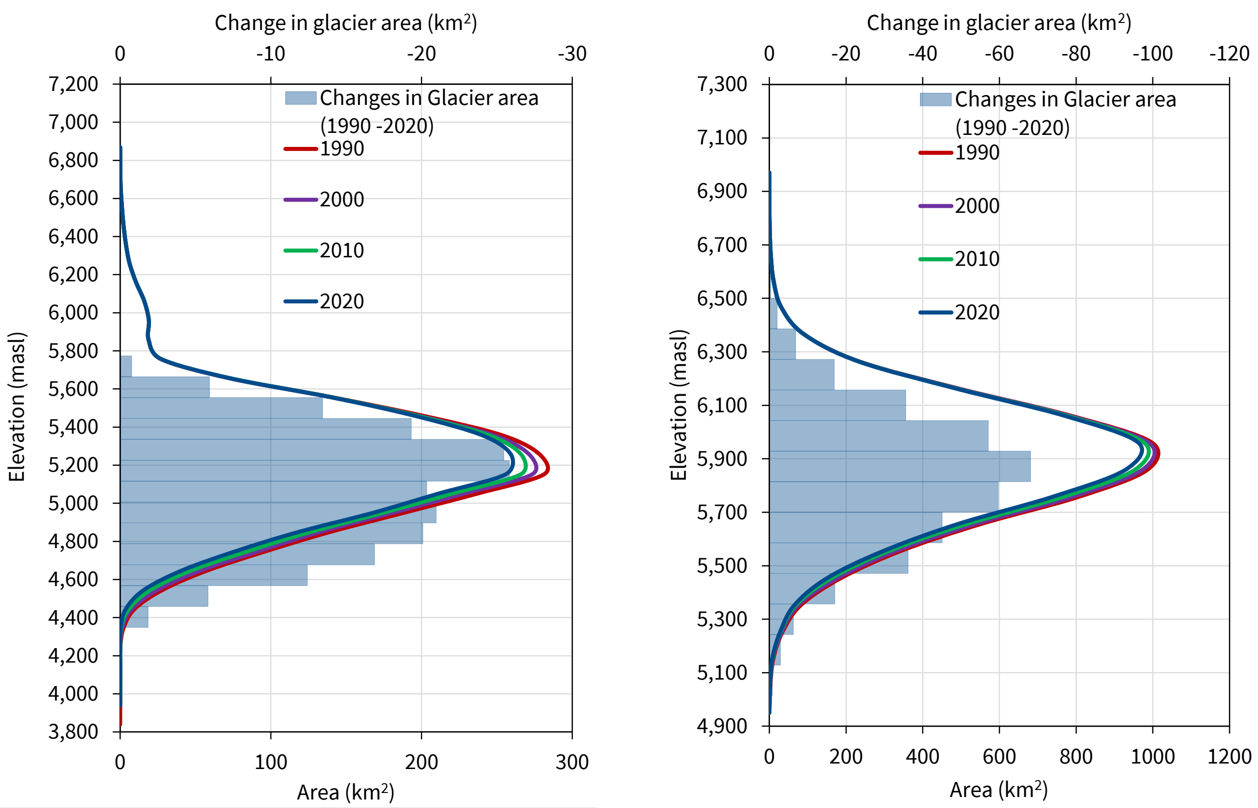


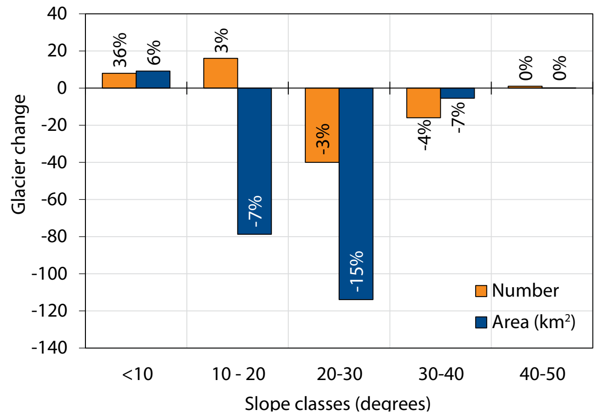
TABLE 5.35 DECADAL GLACIER AREA DISTRIBUTION AND CHANGES ACROSS ELEVATION RANGES FROM 1990 TO 2020 IN EACH INTERIOR BASIN.

Elevation	Area (km²)				Area change percentage				
	1990	2000	2010	2010	1990 – 2000	2000 – 2010	2010 – 2020	1990 – 2020	Per decade
Eastern Asian									
3500 - 4000	0.049	0.016	0.016	0.016	-66.7	0.0	0.0	-66.7	-22.2
4000 - 4500	11.939	9.166	6.582	4.167	-23.2	-28.2	-36.7	-65.1	-29.4
4500 - 5000	509.733	483.503	453.069	419.023	-5.1	-6.3	-7.5	-17.8	-6.3
5000 - 5500	1,255.330	1,223.106	1,198.008	1,165.350	-2.6	-2.1	-2.7	-7.2	-2.4
5500 - 6000	278.117	277.048	278.545	277.743	-0.4	0.5	-0.3	-0.1	-0.04
6000 - 6500	38.485	38.477	38.486	38.494	-0.02	0.02	0.02	0.02	0.01
6500 - 7000	1.540	1.540	1.540	1.540	-0.02	0.02	0.02	0.02	0.01
Total	**2,095.194**	**2,032.857**	**1,976.246**	**1,906.334**	**-3.0**	**-2.8**	**-3.5**	**-9.0**	**-3.1**
Qinghai Tibetan									
4500 - 5000	0.12	0.04	0.02	0.02	-66.7	-39.9	0.0	-80.0	-35.5
5000 - 5500	318.82	299.14	273.19	255.63	-6.2	-8.7	-6.4	-19.8	-7.1
5500 - 6000	3,688.61	3,624.64	3,528.26	3,423.15	-1.7	-2.7	-3.0	-7.2	-2.5
6000 - 6500	1,641.67	1,635.04	1,625.25	1,615.54	-0.40	-0.60	-0.60	-1.59	-0.5
6500 - 7000	15.35	15.36	15.38	15.24	0.03	0.11	-0.90	-0.77	-0.3
Total	**5,664.59**	**5,574.23**	**5,442.09**	**5,309.59**	**-1.6**	**-2.4**	**-2.4**	**-6.3**	**-2.1**

area losses, particularly in the 20° – 30° slope class, which lost more than 15%. This class also saw a net decrease of 40 glaciers, suggesting widespread retreat and fragmentation on moderately inclined terrain. Glaciers on steeper slopes (30° – 50°) also experienced losses, but to a lesser extent, and showed some variability in glacier number. Steepest slopes (>50°) showed no glacier presence or changes, indicating limited glacier development in those areas due to gravitational instability or lack of accumulation zones (Figure 5.100).

In the Qinghai-Tibetan basin, the trends were somewhat similar but showed more pronounced area losses overall. The greatest area loss occurred in the 10 – 20° slope class, where glaciers retreated by a staggering 263.13 km^2, accounting for an 8.1% reduction over the period. Interestingly, while glacier number increased by 5 in this class, the area loss suggests fragmentation or down wasting of large glaciers into smaller remnants. The 20° – 30° slope class also experienced substantial area loss of 96.27 km^2 (10.2%) and a reduction of 78 glaciers, pointing to significant glacial retreat on mid-slopes. On flatter slopes (<10°), Qinghai-Tibetan basin gained 23 glaciers, and despite minor fluctuations in area, they recorded a net area gain by 0.7%, indicating better

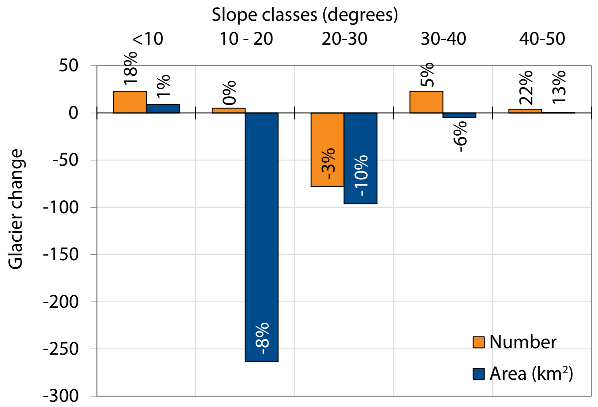
FIGURE 5.100 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES IN THE EASTERN ASIAN BASIN.



glacier stability in low-slopes. Higher slope classes (30° – 50°) showed minor area changes and small fluctuations in glacier number, while slopes steeper than 50° again remained glacier-free (Figure 5.101).

Overall, both basins experienced the most significant glacier losses on moderate slopes (10° – 30°), which appear to be particularly sensitive to climatic changes. Eastern Asia basin exhibited a greater percentage loss, especially in the 20° – 30° slope class, whereas the Qinghai-Tibetan basin

FIGURE 5.101 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN SLOPE CLASSES OVER THREE DECADES IN THE QINGHAI TIBETAN BASIN.



showed a more substantial absolute area loss, most notably in the 10° – 20° slope class. In contrast, glaciers with gentler slopes (<10°) in both basins demonstrated greater resilience, with even showing area gain. This may be attributed to the pronounced retreat of glacier portions on steeper terrain, which often results in fragmentation and reduction into smaller remnants. As these remnants persist, the overall mean slope of the affected glaciers can shift toward gentler gradients, potentially enhancing their stability and influencing future patterns of retreat. This pattern underscores the important influence of slope on glacier response to climate variability.

The mean aspects of glaciers also play a critical role in their retreat patterns. In the Eastern Asian basin, glaciers with northeastern aspect experienced the highest number and percentage losses, with 30 glaciers disappearing, about 8.3% reduction, alongside the largest area loss of nearly 49 km² (around 15.8%). Glaciers facing southern, southeastern and eastern also showed a significant reduction with losing around 2 to 7 glaciers and of around 11 to 13 km² area over three decades (Figure 5.102). Interestingly, northern glaciers in this basin showed a net gain of 10 glaciers (about 1.2%) over three decades but still lost 47.6 km² in area (5.8%), suggesting retreat through thinning or fragmentation. The northwestern aspect experienced minimal changes in glacier number but lost around 37 km² (12%) of glacier area, reflecting a slower but steady decline. In contrast, glaciers with southwestern (SW) aspect displayed few gains in glacier numbers during early decades from 1990 to 2010 but ultimately lost about 4.1 km² (5.5%) in area.

FIGURE 5.102 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES IN THE EASTERN ASIAN BASIN.

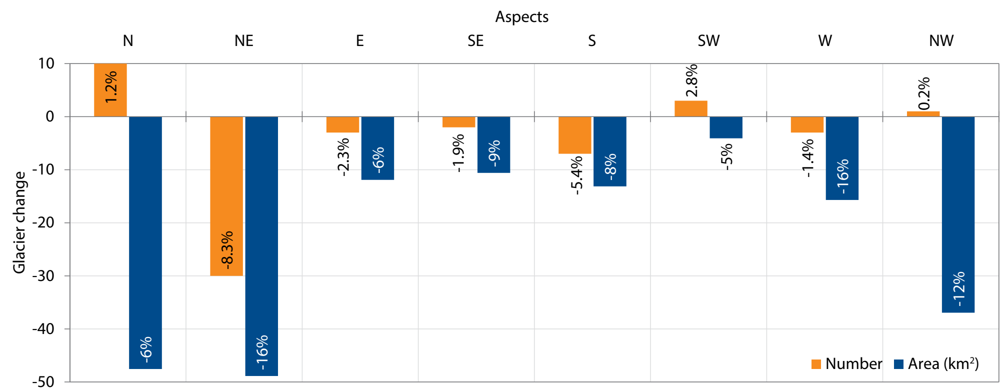
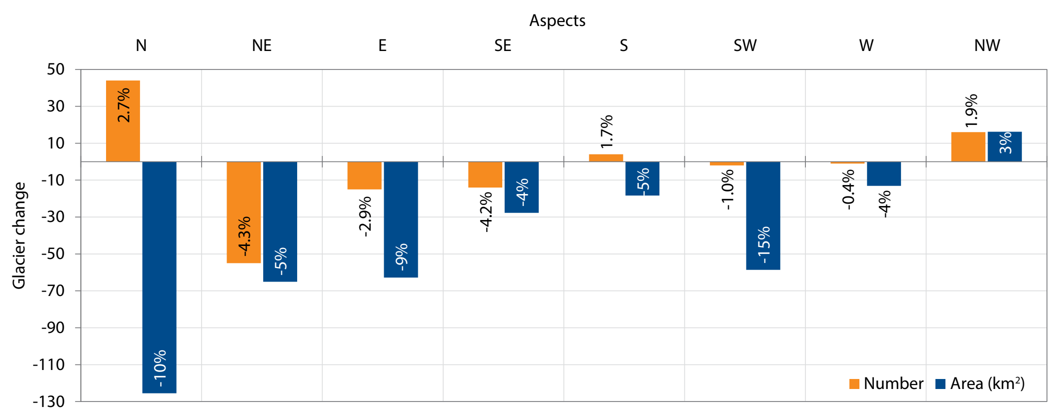
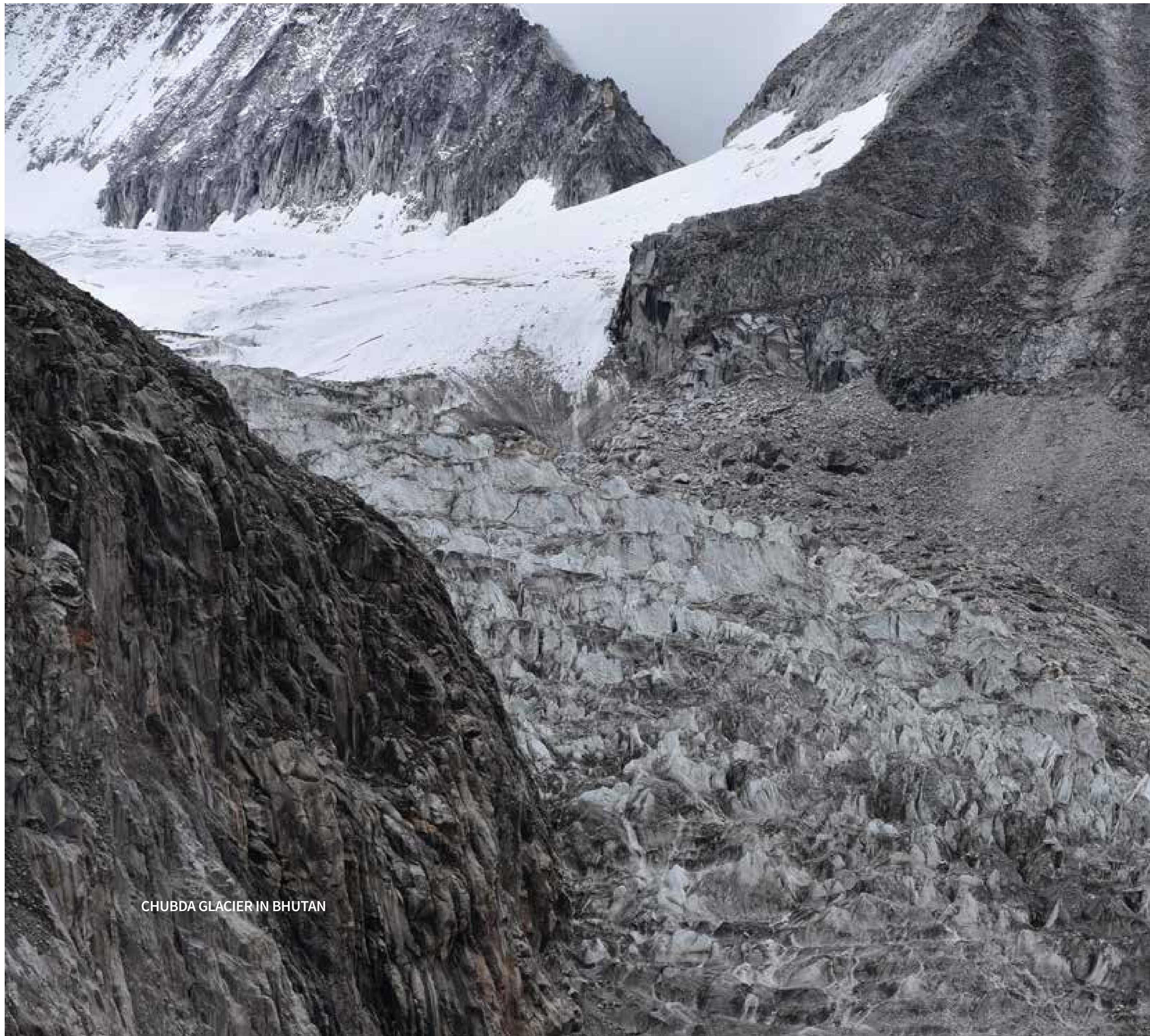


FIGURE 5.103 GLACIER NUMBER AND AREA CHANGES ACROSS MEAN ASPECTS OVER THREE DECADES IN THE QINGHAI TIBETAN BASIN.

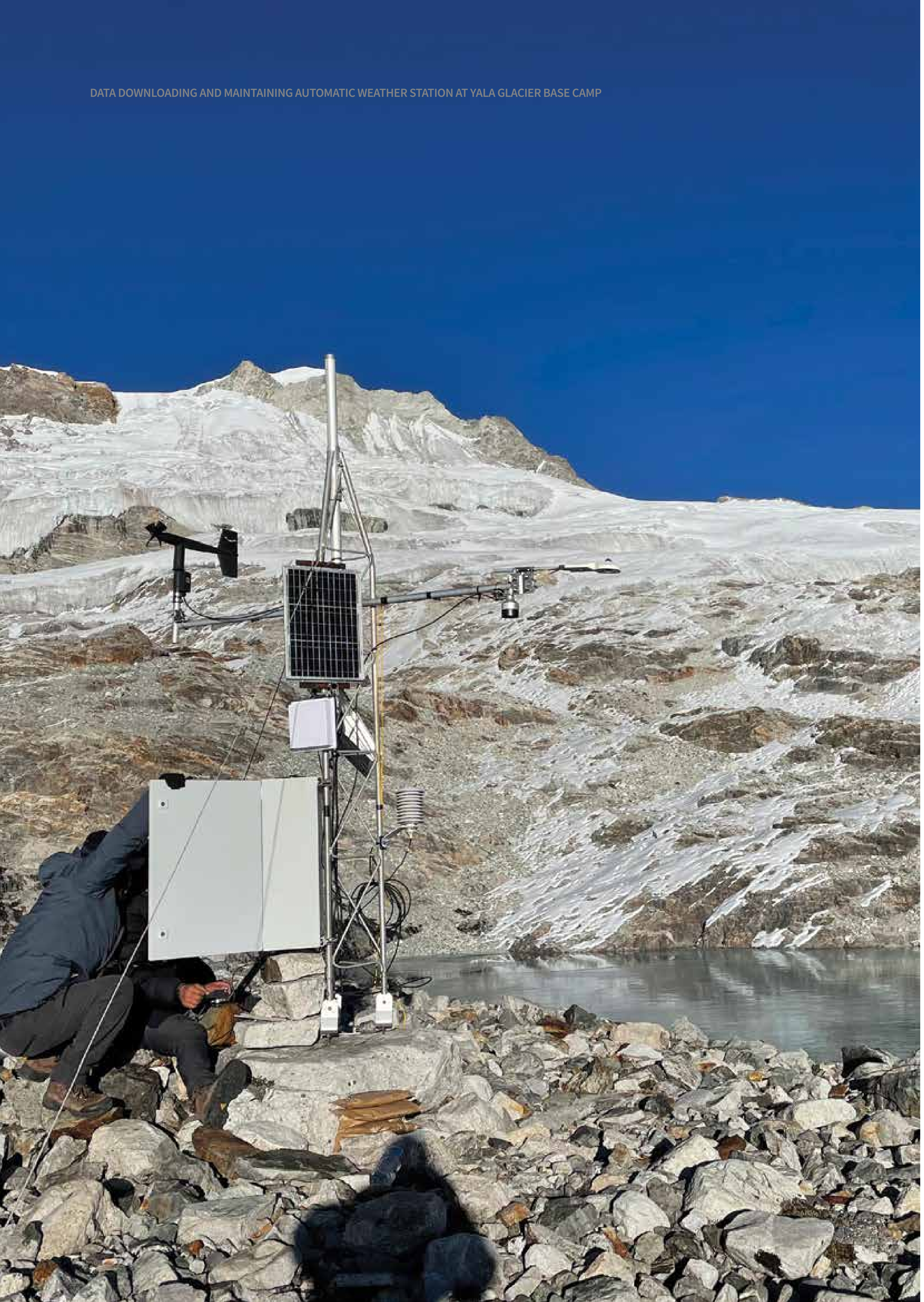


In the Qinghai-Tibetan basin, glacier area losses were more widespread across all aspects, with especially severe declines in eastern and northeastern aspects, losing 62.8 km² (9.2%) and 65.1 km² (5.1%) respectively (Figure 5.103). The southwestern aspect also showed a dramatic reduction of glacier area by about 15% despite relatively stable glacier numbers, reflecting intense melting without losing glaciers. Interestingly, northern aspect glaciers in this basin gained 44 glaciers over the period (2.7%) but lost over 125 km² of area (9.9%), indicating significant thinning. This apparent increases in number are likely due to the glacier retreat and fragmentation of larger glaciers to smaller one, which caused shifts in their geometrics and reclassification into the northern aspect. Northwestern aspect is the only category to show net area gain (+16.2 km², or 2.8%) along with a modest increase in glacier numbers. This, too, can be attributed to the fragmentation and shrinkages of larger glaciers, whose reduced fragments shifted into the northwestern aspect, thereby altering their mean aspect classification.



CHUBDA GLACIER IN BHUTAN

FIELD MONITORING AND CAPACITY BUILDING TRAINING IN PASSU GLACIER, PAKISTAN


DATA DOWNLOADING AND MAINTAINING AUTOMATIC WEATHER STATION AT YALA GLACIER BASE CAMP

SECTION VI

Conclusions

This research report provides a comprehensive database and detailed analysis of the status and shrinkage of glaciers in the HKH region from 1990 to 2020. This is a first-of -its- kind database prepared based on a systematic semi-automatic object based image classification method. It was generated using consistent data source with narrow temporal images (±1 year from the base year), uniform spatial resolution and, ensuring high accuracy and allowing for reliable comparisons of decadal trends across individual glaciers. Additionally, the data was meticulously cross-checked through manual intervention, particularly to address issues such as shadowing and low contrast between glacier boundaries and adjacent terrain, especially along the lateral and distal part of the glacier. This was undertaken by overlaying the respective satellite imagery and verifying it against high-resolution satellite images from Google Earth, as well as by comparing it with various global and regional glacier inventories, including RGI, GAMDAM, and the Chinese Second-Generation Glacier Inventories. These extensive verification processes have significantly enhanced the credibility of the current database. As a result, the database serves as a robust and reliable source of evidence for monitoring and understanding the decadal changes in glaciers across the HKH region. This research makes a valuable contribution to significantly expanding knowledge on cryosphere changes in this critical region, supporting future research and climate-related policy decisions.

The study presents an extensive mapping of 63,746 glaciers across the HKH region, covering an area of 55,774.48 km^2 and estimated ice reserves of 5,737 km^3, based on 2020 Landsat images. It provides detailed analysis of the spatial patterns of glacier characteristics, including area, size, types, and topographic variations, while tracking changes in these features over time. This analysis highlights the dynamic processes shaping glaciers and offering insights into broader cryospheric changes within the region. Most glaciers are smaller in size (≤0.5 km^2), but larger glaciers (≥10 km^2) cover a significant portion of the region's glacier area and hold the majority of ice reserves, underlining the importance of larger glaciers in regional cryospheric water resources. Glacier distribution is strongly influenced by elevation, with the highest concentrations found between 4,000 – 6,000 masl. Glaciers at lower elevations are scarce, and those above 7,000 masl are minimal, reflecting the sensitivity of glaciers to elevation, terrain morphology and regional climatic conditions. Glaciers predominantly occur on slopes less than 30°, which aid in snow accumulation and glacier preservation. Additionally, majority of the glaciers face northern and northeastern aspects, highlighting the role of terrain orientation in glacier dynamics. The study underscores the complex interplay of geographical, topographical, and climatic factors in shaping glacier distribution and their changes over time, offering essential insights for climate adaptation and water resource management in the region.

The decadal datasets show a consistent retreat of glaciers over the past three decades, from 1990 to 2020, with notable acceleration in the recent decade. Over the three decades, the total glacier area in the region has shrunk by approximately 12%, while estimated ice reserves has declined by nearly 9%. The most recent decade (2010 – 2020) witnessed the highest rate of reduction, with a 5% loss in glacier area compared to the previous decades. This trend is especially pronounced in the eastern part of the region, where smaller glaciers dominate, making them more vulnerable to climate change.

Smaller glaciers, particularly those under 0.5 km², have increased in number due to glacial fragmentation, but continue to experience significant area loss and at an accelerating pace. While larger glaciers remain relatively more stable, they are also shrinking at a slower rate. The highest rates of glacier retreat have been observed in the elevation range of 4,000 – 5,500 masl, where glacier area has declined by up to 14.5% over the study period. Additionally, lower elevation zones (below 3,500 masl) show evidence of glacier retreat and an upward shift in glacier terminus varying not only for individual glaciers, but also by regions, basins and sub-basins, over the past three decades.

Geographically, glacier loss varies across different latitudinal and longitudinal bands. The highest percentage losses in glacier area have occurred in southern latitudes (27°N – 30°N) and eastern longitudes (100°E – 104°E), where glacier distributions are smaller. Similarly, glaciers on moderate slopes (20°– 30°) show the highest retreat, with around a 12% reduction in area, emphasising their susceptibility to climate change. Meanwhile, aspect-related trends indicate that glaciers with northeastern (NE), eastern (E), and southeastern (SE) have experienced the greatest shrinkage due to increased solar radiation exposure, whereas glaciers on the northwestern (NW) aspect have remained relatively more stable.

The distribution and rate of losses glacier area varies across each individual glaciers, sub-basins, basins, and mountain ranges. The distribution and changes across the various mountain ranges demonstrated that the highest distribution and retreat both have happened in the Himalayan range, with both absolute and relative losses being significantly higher in the eastern sub-mountain ranges particularly in Hengduan Shan (about 33%), followed by Gangdise (about 24%) and Eastern Tibetan mountain (at 22%) over the last three decades. The mountain ranges in the northern and western parts of the HKH region, particularly Karakoram, Pamir and Kunlun Shan have had minimal losses over the thirty-year- period, although the rate of loss has been on the rise in the recent decades. In contrast, the Karakoram Mountain range showed the highest stability, with only a 1.7% decrease in the glacier area. Glacier numbers declined notably in ranges like Hengduan Shan (15%) and Eastern Tibetan (16.5%), while smaller glaciers increased in number in several regions due to the fragmentation and shrinkage of larger ice masses. The most substantial glacier area losses occurred predominantly between the elevation of 5,000 and 5,500 masl, with reductions reaching as high as 37.4% in Tanggula Shan and 34.2% in Hengduan Shan within this elevation range. The Himalayan range also showed significant area loss at this elevation range, with highest amount of loss occurring in the central Himalaya.

Across the major river basins of the HKH region, a similar pattern of glacier distribution and change was observed. The highest concentration of glaciers was found in the Indus, Brahmaputra, and the Ganges River Basins, consisting of approximately 44%, 17%, and 13% of the total glacier area of the region, respectively. These basins also experienced the most significant absolute glacier area losses. However, when considering the rate of glacier loss, basins in the eastern part of the HKH exhibited the most dramatic changes, the Salween Basin lost 33% of its glacier area over three decades, followed by the Yangtze and Yellow River basins with losses of 23% and 22%, respectively. In contrast, the Tarim Basin showed remarkable stability, with a minimal 0.1% decrease in glacier area during the same period.

The distribution and change patterns further vary across different glacier size classes and terrain characteristics. All the basins are dominated by smaller glaciers under 0.05 km², which account for over 67% of the total glacier number in each basin. However, glaciers larger than 1 km² contribute disproportionately to the overall glacier area and estimated ice reserves, accounting for more than 65% of the total glacier area and over 80% of the estimated ice reserves in each basin, except in basins with relatively few glaciers, such as the Irrawaddy. Notably, the Indus, Ganges, and Brahmaputra River basins contain most of the largest glaciers, with 21 out of the 25 glaciers exceeding 100 km², of which 18 are in the Indus basin.

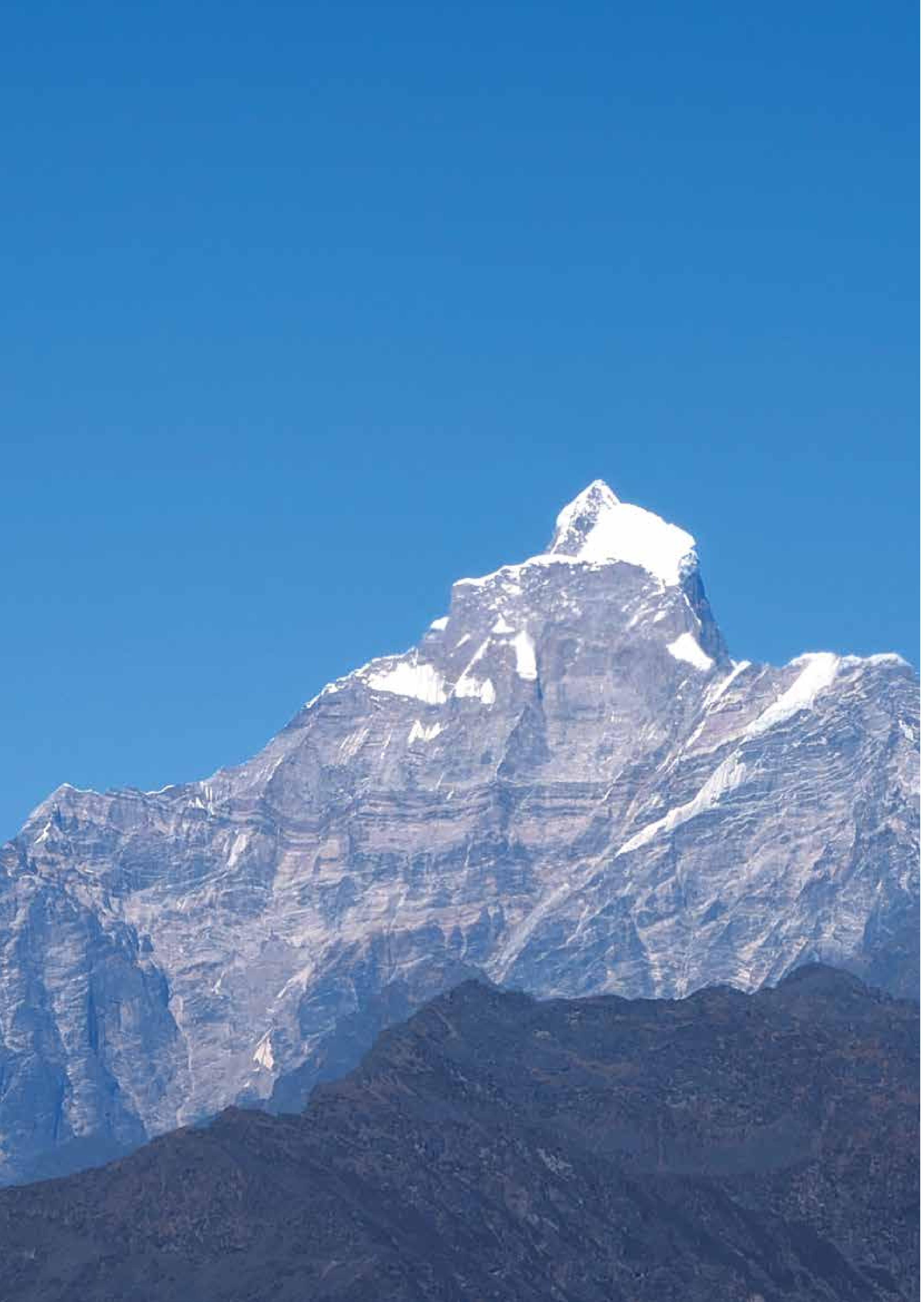
Furthermore, glaciers in these three basins span across the widest elevation ranges, from the lowest snout elevation of around 2,400 masl in the Indus River basin to the highest glacier summit elevation reaching 8,811 masl in the Ganges River basin. Notably, these three basins are the only ones containing glaciers that extend above 8,000 masl. However, the concentration and loss of glacier areas across various elevation ranges reveal that the highest losses generally occur between 4,500 and 5,500 masl in most of the river basins. Exceptions include the Ganges and Brahmaputra River basins, as well as the Qinghai-Tibetan interior basin, where the highest absolute glacier area loss is observed between 5,000 and 6,000 masl.

Glaciers are predominantly located on moderate slopes ranging from 10° to 30°, while steeper slopes greater than 30° generally host fewer and smaller glaciers, in nearly all the river basins. Although the number of glaciers fluctuates across slope classes, the glacier area consistently shows a declining trend in all slope class, with an accelerating rate of loss across all basins. Regarding the mean aspects, glaciers tend to be more concentrated on northern, northeastern, and northwestern aspects in most basins, with a few exceptions. In contrast, southern aspect typically contain fewer glaciers, but these are often larger in size, indicating greater exposure and vulnerability to melting. Changes in both glacier number and area vary across different slope and aspect classes, a pattern also reflected in shifts in the mean slope and aspect of individual glaciers over time. These shifts are largely driven by glacier shrinkage and the fragmentation of larger glaciers into smaller ones.

These findings highlight the escalating pace of glacier retreat in the HKH region and its potential implications for water resources, ecosystems, and the livelihoods of the downstream communities relying largely on glacier-fed rivers for freshwater supply, particularly during the dry seasons. Given the observed trends, there is an urgent need for coordinated climate action to reduce future impacts, including development of sustainable water management strategies and the continued monitoring of glacier changes to inform timely adaptation responses.

Importantly, this dataset also offers a valuable resource for advancing technological solutions. It can serve as a training base for the development of automated monitoring tools using satellite imagery, including deep learning and artificial intelligence (AI) models, to detect and analyse continuous changes in glacier extent and dynamics with greater speed and accuracy.

Beyond documenting retreat trends, this dataset holds substantial value for a wide range of applications. It provides a scientifically robust foundation for modelling glacio-hydrology to assess current and future water availability under various climate scenarios. It also facilitates the development of basin-specific climate adaptation strategies and disaster risk reduction measures, particularly in areas where glacier meltwater is critical to water supply and where the rapid formation and expansion of glacial lakes, driven by rapid glacier melts, increases the risk of glacial lake outburst floods (GLOFs). Furthermore, the standardised and comparable nature of the dataset across basins and national boundaries enhances its utility for fostering transboundary water cooperation. By quantifying accurate estimates of current glacier water storage and projections of its future changes, the dataset plays a crucial role in guiding long-term regional water security planning, infrastructure development, and climate-resilient policy development.



SECTION VII

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