A preliminary inventory of supraglacial lakes of Pakistan

EvK2CNR

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Contents

Credits

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The dataset is available freely accessible from https://geoportal.mountaingenius.org/portal/

Summary

The United Nations Development Programme (UNDP) and EvK2CNR launched the "Glaciers and Students" project, funded by the Italian Agency of Development Cooperation, with the aim of mapping all the glaciers of Pakistan. 13,032 glaciers, covering an estimated 13,547 km2 have been mapped in this huge repository.

This Preliminary inventory of glacial lakes of the Pakistan aims to map the supraglacial lakes located on the glacier surfaces mapped previously within the Glaciers and Students project. In order to guarantee homogeneity with the Glacier Inventory, the supraglacial lake mapping will consider the same resolution (ESA Sentinel 2 images) and the same year (2022) used for glaciers. This homogeny ensures the rigorous scientific approach required to create here a knowledgebase to evaluate in the next future which morphometric factors control the development of glacial lakes.

This Preliminary Inventory has mainly a methodological aim. During this project a method will be set up for 1) analyzing the inter and intra-annual variability in the lake development; 2) detecting and mapping (semi-automatically) the supraglacial lakes; 3) managing and reducing the uncertainty related to the mapping. Furthermore, this inventory is considered preliminary because it does not include the proglacial lakes.

In this study, we analysed the inter- and intra-annual variability of supraglacial lakes in the region between 2020 and 2022. We found significant variability in the number of lakes, not only from one year to the next, but also from one month to the next. This is due to changing glacier surface conditions throughout the year. The number and extent of the lakes are comparable from one year to another only when analysing satellite images acquired in September (September is the last month of the summer precipitation before their freezing in October). This underlines that this period is the best for studying supraglacial lakes via remote sensing. For this reason, this preliminary inventory used satellite images acquired in September 2022, and we strongly recommend using this period of the year for future studies of supraglacial lakes.

This study allowed to map supraglacial lakes located on **142** glaciers of Pakistan. **Almost all the glacial lakes are in the basins located more in the north.** 99% of the glacial lakes are in 7 basins:

Hunza (37%), Shigar (32%), Shyok (9%), Chitral (13%), Gilgit (5%), Shaksgam (2%), and Indus (1%). The main morphological features of these glacial lakes are a mean glacier slope of 21°, that could be considered gentle. The glacial lakes lie at a mean altitude of around 3961 (from 3700 to 4200) m a.s.l, on glaciers presenting a minimum elevation of 3320 m a.s.l.. The median size of lakes is 1895 m2.

We performed an analysis of our results to evaluate the errors and uncertainties affecting our measurements. According to this analysis, the methodology we developed enables us to map lakes with an areal uncertainty of approximately ±2%.

the total surface area of supraglacial lakes results equal to 5.16 km^2 corresponding to 2722 lakes.

Background

Why do we need to study glacial lakes?

The Karakorum is a mountain range situated in the northen region of Pakistan and is one of the most interesting places in the world to observe the glacial dynamics taking place in this period of climate change.

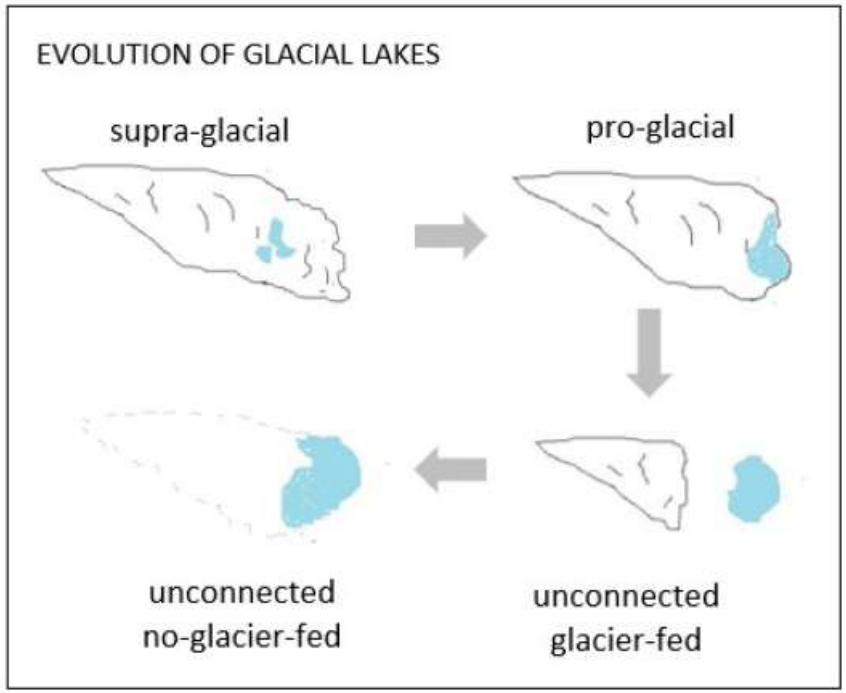
The Karakorum differentiates itself from the vast majority of mountain areas, including the bordering ones, for the stable trend of its glacier mass and for the presence of glacier surges. The first phenomenon is known as the **"Karakorum anomaly"** and is a unicum: instead of receding due to global warming, the glaciers there seem to be stable and even slightly growing (Bocchiola and Diolaiuti; 2013; Minora et al; 2016; Farinotti et al., 2021). The second singularity is **Surging**, which consists in phases of accelerated glacier flow interspersed with phases of normal flow (Diolaiuti et al; 2003; Belo' et al; 2008). A third event that makes this area really stimulating for research is the recurrence of **GLOFs**, which are destructive hazards that originate from the sudden release of a considerable amount of water and debris after the collapse of a glacial lake (Bazai 2021). GLOFs are a serious threat to Pakistan, which is among the countries most affected by climate change, with extraordinarily high numbers of people exposed to floods.

In Karakorum the most frequent trigger of GLOFs is the blockage of a river due to glacier advance, but other causes include ice avalanches and rock landslides falling into the lake, calving glaciers, excessive water input from precipitation or ice melting. The three variables mentioned in the previous paragraph are evident: all the responsible glaciers had extraordinary elevation ranges and were surging or affected by surging tributaries, and most of them had steep icefall segments in the upper parts; around 90% of the GLOFs originated from five ice dammed lakes that had resealed (Karambar-Ishkoman, Shimshal, Kumdan-Shyok, Hunza Central, Shaksgam); steep slopes followed by a gradual recessional limb, narrow valleys, high reliefs and rivers with a particular drainage called "Trellised" were the most affected; in many cases the events were preceded by unusually warm days and the most vulnerable seasons were late

spring and summer, because of the higher temperatures which influence glacier ablation, timing and amount of lake filling, and because of the monsoon (Hewitt et al. 2013; Bazai 2024).

Typologies of glacial lakes

Four types of high-elevated lakes can be distinguished according to Ageta et al., 2000 and Salerno et al., 2012: (i) SUPRA-GLACIAL lakes, which develop on the surface of a downstream portion of a glacier. (ii) PRO-GLACIAL lakes, which are in contact with the glacier fronts. Some of these lakes store large quantities of water and are susceptible to GLOFs (glacial lake outburst floods). In contrast, lakes that are not directly connected with glacier ice but that may have a glacier located in their hydrological basin are termed UNCONNECTED glacial lakes. This last category of lakes could be (iii) GLACIER-FED or (iv) NON-GLACIER-FED, according to the possible presence of a glacier in the basin.



As mentioned in many parts of this report, this preliminary inventory does not include the pro-glacial lakes, i.e., all lakes which are located frontally or laterally with respect to the glaciers (outside the boundaries of the glacier inventory). The main reason is because in the next future climatic and morphological factors controlling the development of supraglacial lakes will be analyzed. As reported in the figure, supraglacial lakes represent the first stage of the lake development. These kinds of lakes need to be studied independently from the proglacial lakes, which represent an evolution of supraglacial lakes, but other causes contribute to this kind of process: mainly the characteristics of the frontal dam.

Supraglacial Lakes and factors controlling their development

The distribution of supraglacial lakes on the glacier tongue is influenced by the surface gradient. Based on the research carried out on several Bhutanese glaciers, Reynolds (2000) presents a simple relationship. A steeper gradient generally means a higher flow velocity, which then raises the probability of the opening of surface crevasses, and meltwater is more likely diverted off the glacier surface. Only a small number of supraglacial lakes form under such circumstances. When the values of the surface gradient exceed a particular limit, no supraglacial lakes emerge since all of the meltwater is effectively drained downglacier. Reynolds (2000) also quantifies this relationship. Other papers, however, question these intervals, especially the limit for the formation of supraglacial lakes. Salerno et al. (2012) applied the techniques of remote sensing to compile the database of all the glacial lakes in the Sagarmatha National Park. An analysis of the obtained data suggests that supraglacial lakes may emerge on reaches sloping more than 10° but are usually short-lived. On the other hand, Salerno et al. (2012) confirmed the value of 2° of the surface gradients as the upper threshold for the development of large supraglacial lakes.

As regards climate conditions, the relationships with formation of supraglacial lakes are not completely understood. Generally, warmer air temperatures increase surface melting, leading to the formation of supraglacial lakes. Further, higher precipitation rates, especially in the form of rain, can increase the water volume, promoting lake enlargement (Wendleder at al., 2021).

State of GLOF research in the region

In the following we report a short review of the GLOFs in Karakorum (alphabetical order):

- Bazai et al. 2024 –GLOF and surge date and lake volume measurement since 1970 obtained using remote sensing techniques. The average surge velocity and volume related to each of the 23 GLOFs from eight surge cycles are reported and analysed by these authors. The list of the events is reported, only the date of the GLOFs is reported, no other details are accessible.Bazai et al. 2021 – Identification of 179 outbursts occurred in the Karakorum between 1533 and 2020, through in situ analyses, scientific literature, unpublished reports, testimonies, cross-correlation techniques and remote sensing. The list of events is not included, and the information can be deducted from a table on glaciers' characteristics and from two featured maps; there are no indications of date and damage.
- Bhambri et al. 2019 – Identification of 146 events in the Karakorum, all originated from ice dammed lakes, reporting only the names of the responsible glaciers without further data or maps. The main sources were Hewitt 1982, Hewitt and Liu 2010, Emmer 2018, Iturrizaga 2005 and Zhang 1992, implemented with remote sensing evidence for the most recent GLOFs.
- EM-DAT – The International Disaster Database collects data on natural hazards occurring worldwide; it was used to discover the number of casualties of the events, but no correspondence was found, probably also due to the lack of precise information on date and location of many of the events reported.
- Hewitt et al. 2013 – Reconstruction of historical records of GLOFs in the Upper Yarkand Basin and Upper Indus Basin because of glaciers blocking rivers. The article reports 24 and 71 events in the two basins, the oldest was in 1533 and the latest 2009. It presents date, glacier, river dammed, optional comments and sources, which are Hewitt 1982, Kreutzmann 1994 and 2009, Hewitt and Liu 2009.
- ICIMOD 2022 Database of High Mountain Asia - It reports 146 events occurred in Pakistan from 1661 to 2021, with the coordinates of the lakes and other 55 attributes.
- International Programme on Landslides Project no. 179 "Database of glacial lake outburst floods (GLOFs)" – Online database, created in the context of the International Consortium on Landslides (ICL) at the Board of Representatives in Paris 2012 and in

collaboration with international and national actors such as ICIMOD, of GLOFs occurred worldwide from the Little Ice Age onwards, drawing from scientific literature, existing databases and unpublished reports.

- Veh et al. 2022 Database – Global database that reports 159 GLOFs (included those without any information on location, that have not been included in the final list) occurred in Pakistan from 1661 to 2021. It examined 769 sources and conducted remote sensing analyses to verify the events after the 1980s. The database includes 57 attributes, such as location, date, characteristics of the lake, cause and impacts, and reports the geographic coordinates of the lake. Only GLOFs with a precise or at least plausible date and with at least a reference are included.

Existing Inventories of glacial lakes in the region

To understand the status of research on glacial lakes in Karakorum, this section investigates the quantity and quality of inventories redacted on them in the area. From oldest to most recent, the following list reports the main works which tried to map the supraglacial lakes in the region. A direct comparison with this preliminary inventory is not possible for many reasons. First, the many inventories do not cover the entire area. Secondly, they use a coarse resolution (mainly Landsat sensors), and finally none of them focused their attention on just supraglacial lakes (whereas this preliminary inventory does not consider the PROglacial lakes).

- Zhang et al. 2015 - Inventory of glacial lakes in Pamir, Hindu Kush, Karakorum, Himalayas and Tibetan Plateau, created with ArcGIS by a single operator through manual digitisation on 1990, 2000, and 2010 **Landsat** TM/ETM+ data. It is available on the Third Pole Environment Database at http://en.tpedatabase.cn/;
- ICIMOD 2018 - ICIMOD has curated a few databases of glacial lakes in HMA, but only the "Indu Kush Himalaya Database" covers Karakorum. It was created on around 200 **Landsat** 5 TM and Landsat 7 ETM+ images of 2005 ± 2 years with little to no cloud and snow coverage. The glacial lakes were digitalized semi-automatically with the band ratio threshold condition method and manual checking. The attribute data comes from a 90 m resolution SRTM DEM. It is available at: http://rds.icimod.org/Home/DataDetail?metadataId=35856&searchlist=True;

- Senese et al. 2018 – Inventory of CKNP glacial lakes, realised through PARC (Pakistan Agricultural Research Council) and PMD (Pakistan Meteorological Department) 2015 datasets and 11 2013 Eleven **Landsat**-8 images. The database is open access, available online at: users.unimi.it/glacial;
- Kumar et al. 2020 – Inventory of glacial lakes in Nubra and Shyok basins, Karakorum Range, realised through a combination of automatic and manual methods using 2002, 2013, and 2017 **Landsat** and Sentinel images. No information on the availability of shapefiles is provided;
- Li et al. 2020 - Inventory of glacial lakes in the China–Pakistan Economic Corridor between 2016 and 2018, realised with semi-automatic instruments using **Landsat** 8 OLI images. Further data are available in attachment to the article, but no shapefiles are provided;
- Qayyum et al. 2020 – Inventory of glacial lakes in the HKKH region obtained through manual digitalisation on **Planet** Scope imagery. No information on the availability of shapefiles is provided;
- Ashraf et al. 2021 - Lake inventory created to assess the risk of outbursts in the HKH region of Pakistan. It was created through 2013 **LANDSAT**-8 OLI
- Muneeb et al. 2021 - Inventory of glacial lakes in the **Hunza** River Basin (Western Karakorum) developed on **Sentinel** 2B satellite images with semi-automated processing techniques, visual analysis, comparison with ICIMOD inventory and verification through Google Earth. No information on the availability of shapefiles is provided;
- Zheng et al. 2021 - Inventories of glacial lakes of the Third Pole for the years 1990, 2015 and 2050-2100 (projected) realised on 403 **Landsat** 4–5 Tematic Mapper scenes for 1990 and 294 Landsat 8 Operational Land Imager (OLI) scenes for 2015, with an automated water body classification algorithm. Ulterior data are available at https://doi.org/10.5281/zenodo.4477947, but no shapefiles are provided;
- Gupta et al. 2022 - Inventory of the Indus River basin glacial lakes, realised manually using 157 high-resolution **Landsat** and Indian Remote Sensing satellite images. No information on the availability of shapefiles is provided;
- Lesi et al. 2022 - Inventory on the evolution of glacial lakes of the China-Pakistan Economic Corridor from 1990 to 2020, realised through a combination of semi-automatic and manual methods using 71 **Landsat** Thematic Mapper (TM), Thematic Mapper Plus (ETM+) and Landsat 8 Operational Land Imager (OLI) images. No information on the availability of shapefiles is provided;

- Li et al. 2022 - Inventory on the evolution of Himalayan, Karakorum and Hindu Kush glacial lakes from 1990 to 2020, realised through a combination of automatic and manual methods using 651 **Landsat** images between 1990 and 2020. It is downloadable in shapefile format after request.

The Aims of this Preliminary supraglacial lake Inventory

This research activity builds upon the existing Project "*Glaciers and Students,* which developed the inventory of Pakistan glaciers using ESA Sentinel 2 satellite data. This project generated a new inventory of glaciers based on satellite data with 10 meters of resolution. Here we developed a specific methodology for creating the *Preliminary Supraglacial Lake inventory*. This inventory aims to map the supraglacial lakes of Pakistan Karakorum located on the glacier surfaces mapped previously within the *Glaciers and Students* project. In order to guarantee homogeneity with the Glacier Inventory the supraglacial lake mapping will consider the same resolution (the ESA Sentinel 2) and the same year (2022) used for glaciers. This homogeny ensures the rigorous scientific approach required to create here a knowledgebase to evaluate in the next future which morphometric factors control the development of glacial lakes.

WP1 METHODOLOGY

This Preliminary Inventory has mainly a methodological aim. During this project a method will be set up for 1) analyzing the inter and intra-annual variability in the lake development; 2) detecting and mapping (semi-automatically) the supraglacial lakes; 3) managing and reducing the uncertainty related to the mapping.

WP2 INVENTORY

A preliminary inventory of the entire mountain range will be created once the methodology is set up. This inventory is considered preliminary because it does not include the pro-glacial lakes, i.e., all lakes which are located frontally or laterally to the glaciers (outside the boundaries of the glacier inventory).

Methodology

Data

With the aim of mapping and characterizing the supraglacial lakes located over the Pakistani Karakoram, different satellite imagery and products were utilized. This section divides the so used data into three main sub-sections, one for each type, i.e., The new inventory of 13,032 glaciers in Pakistan: the "Glaciers & Students" Project (Diolaiuti et al., 2024) and the Sentinel-2 and PlanetScope satellite data retrieved for lake mapping.

The recent glacier Inventory for Pakistan: the "Glaciers & Students" Project

The new inventory of 13,032 glaciers in Pakistan: the "Glaciers & Students" Project is the new Pakistan inventory for glacier outlines. This inventory provided a snapshot of world glaciers in a specific date, from 2022, based on Sentinel-2 optical satellite. In this research, all the available glaciers were analysed, i.e., 13,032 glaciers covering a total area of 13,547 km^2.

Satellite data

In order to automatically map the supraglacial lakes over the Pakistani Karakoram, two optical satellite sources were implemented, Sentinel-2 and PlanetScope from the European Space Agency (ESA). Sentinel-2 imagery was accessed through Google Earth Engine (GEE) platform, while PlanetScope dataset was downloaded from Planet Explorer (https://www.planet.com/explorer/). In detail, Harmonized Sentinel-2 MSI Level-1C product was used, which is already corrected by the radiometric offset useful for the Processing Baseline 04.00 (https:// sentiwiki.copernicus.eu/web/s2-processing; (Traversa and Di Mauro, 2024). This dataset presents solar

exoatmospheric irradiance in the VIS-SWIR wavelengths, thanks to 13 bands spanning from 423 nm to 2370 nm at 10-20-60 m spatial resolution. PlanetScope satellite constellation instead presents a very high spatial resolution of 3 m in the VIS-NIR wavelengths, providing eight bands from 431 nm to 885 nm. In this study, SuperDove, one of the PlanetScope groups of individual cubesats, was employed, using the Level 3B reflectance product, where radiometric and sensor corrections are applied to the data and the images are orthorectified, projected (UTM projection) and harmonized with respect to Sentinel-2 imagery. Sentinel-2 imagery was used in the wide-scale analyses for the entirety of available glaciers. On the other hand, PlanetScope images were applied in the analyses of only three glaciers, representative of three Mountain Regions in High Mountain Asia, i.e., Baltoro Glacier in Karakoram, Khumbu Glacier in Eastern Himalaya and Atrak Glacier in Hindu-Kush (the method was tested in different parts of High Mountain Asia to increase the accuracy). The choice of focusing on three glaciers lead back to the high resolution of PlanetScope images and their low swath width (32.5 x 19.6 km for SuperDove), as well as the impossibility to easily access the dataset given its cost (PlanetScope images are not free access). Nevertheless, the implementation of PlanetScope imagery allowed us to evaluate the effect of pixel resolution on the capacity of detecting supraglacial lakes by means of satellite remote sensing, thanks to the comparison of same glacier lakes extracted via Sentinel-2 images.

One of the two Sentinel 2 satellites (https://www.satimagingcorp.com)

The Planetscope SuperDove satellite (https://www.planet.com)

Geographic and climatic features

The Karakorum Range is home to around 30,540 glaciers, each covering at least 0.01 km², and these glaciers together occupy roughly 40,124 km² (RGI Consortium, 2017). This makes it the third largest glacial region in the world, trailing only behind the polar regions. The area is marked by high-altitude terrain, featuring peaks that soar over 8,000 meters, including the world's second-highest mountain.

The glaciers in the Karakorum are shaped by both monsoonal and westerly weather patterns, which create a complex system of precipitation throughout the region. The two main atmospheric systems influencing precipitation are the Indian summer monsoon (ISM), which is strongest during the summer months from June to September, and Western disturbances, which occur in winter from January to April (Bookhagen & Burbank, 2010). Interestingly, the Karakorum receives minimal influence from the ISM, with most of its precipitation resulting from Western disturbances (Bookhagen & Burbank, 2010).

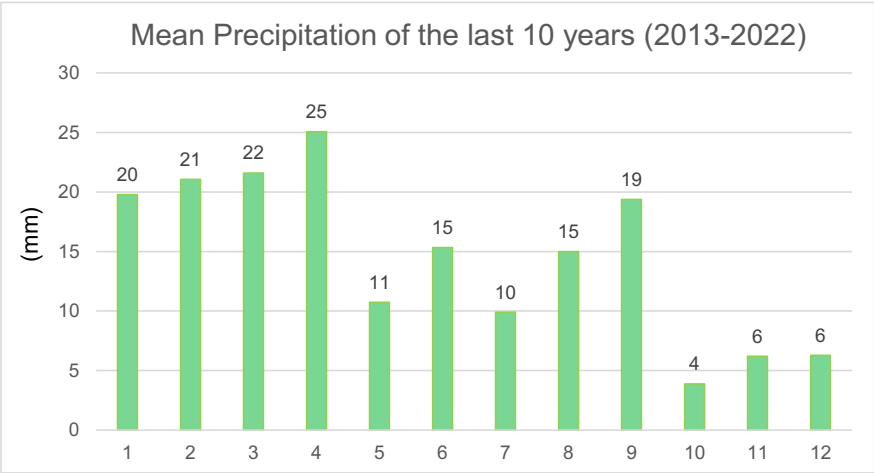
A key feature of the Karakorum is the presence of extensive supraglacial lakes that form during the melt season when meltwater collects on the glacier surfaces. Studies show that these lakes are crucial for enhancing ice melting, as they absorb solar radiation and help with internal drainage. The existence of these lakes can significantly affect glacier dynamics, leading to increased melt rates and potential instability. Recent research has documented changes in the size and distribution of these supraglacial lakes, underscoring the importance of creating high-resolution inventories to better understand how they evolve in response to climate conditions.

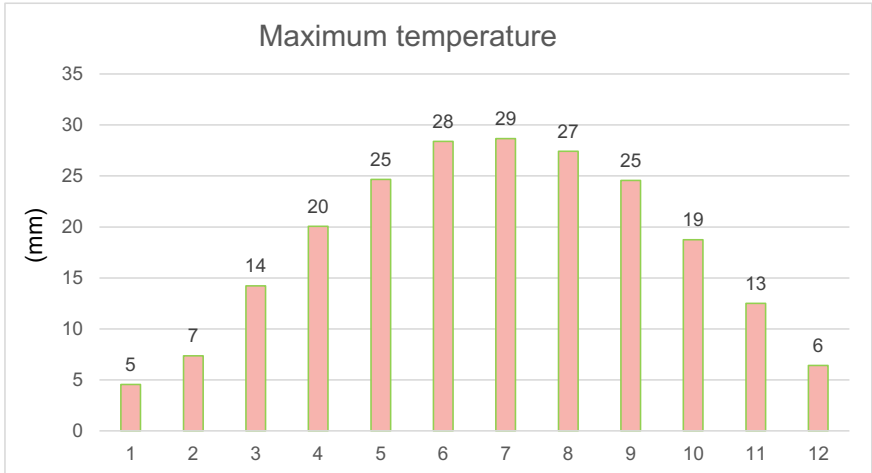
Bocchiola and Diolaiuti (2013) analyzed seasonal climate trends from 17 weather stations across the upper Karakoram, grouped into three regions. Total precipitation shows limited change overall, with some increases in Chitral-Hindu Kush and Gilgit, and decreases in the Kotli area. Maximum precipitation remains mostly stable. Wet days are rising in Gilgit and decreasing in Chitral. Minimum temperatures show a general increase, except in summer, when decreases occur especially in Chitral and Gilgit. Maximum temperatures are rising consistently across all regions. Cloud cover is increasing in Gilgit but declining elsewhere. These trends suggest a warming signal—especially for max temperatures—that is partly linked to global temperature anomalies. Altitude-dependent variability highlights the need for high-altitude observations when assessing climate impacts in this region.

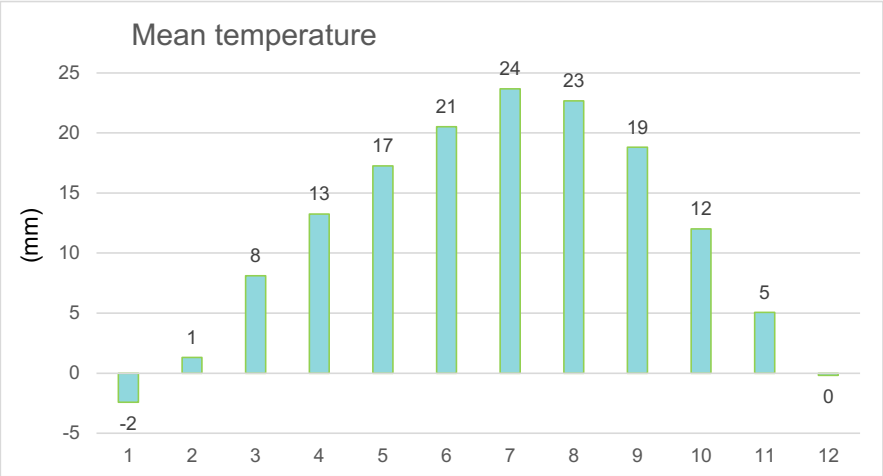
While the previous analysis outlines regional-scale climate trends across the upper Karakoram, recent observations from the Skardu meteorological station offer a valuable localized perspective. Skardu, located in the Indus Valley near key glacier systems, provides consistent and continuous data for the last decade (2013–2022), making it a useful reference for assessing present-day climatic conditions affecting supraglacial lake evolution.

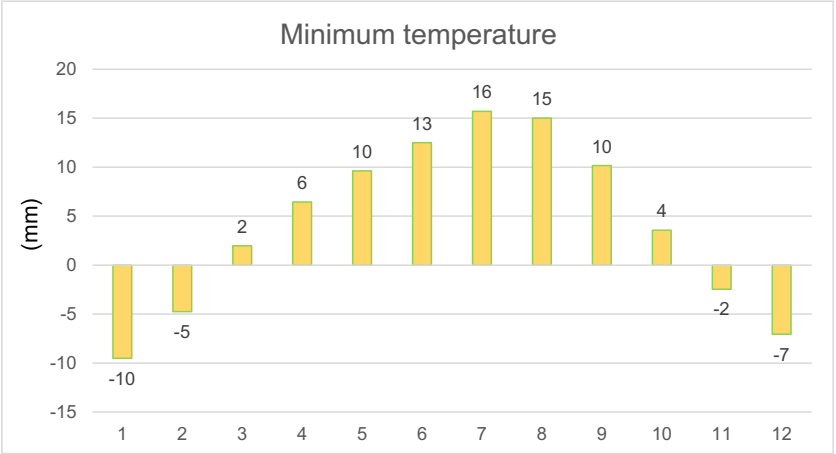
Average monthly temperatures over this period range from a minimum of –2 °C in January to a maximum of 24 °C in July. Maximum temperatures vary between 5 °C (January) and 29 °C (July), while minimum temperatures fluctuate between –10 °C (January) and 16 °C (July).

Precipitation data (expressed as monthly means in mm) indicate higher values during the winter and spring months, with a peak of 25 mm in April. The driest period occurs in late summer and autumn, reaching a minimum of 4 mm in October.









These recent observations at Skardu help contextualize current glacial and hydrological processes and provide an important benchmark for monitoring climate-sensitive phenomena in the central Karakoram.

Inter-seasonal analysis

Considering the frequency analysis of precipitation shown in the previous paragraph, the best month of mapping the supraglacial lakes in this region should be the month of October considering that during this month we have the lowest mean precipitation. The same month has been selected in other regions of the High Mountain Asia as reported by Salerno et al., 2012 and Salerno et al., 2018. However, during this month there is a high probability that lakes freeze. For this reason, this inventory was created analyzing satellite imagines of September.

Particularly, we decided for this inventory the following criteria: 1) 2022 was chosen as a reference year for homogeneity with the Glacier Inventory; 2) we selected images with cloud cover < 10%; 3) we consider as priority September, which is characterized by the end of summer precipitation. Images were visually selected to avoid both cloud presence and widespread snow cover.

Consequently, 73 Sentinel-2 images were used in GEE to cover the study area between 2022/Sep/02 and 2022/Sept/29.

In both datasets, summer season 2022 was considered to produce a snapshot of supraglacial lakes present in Pakistan. Detailly, PlanetScope images date to 2022/Aug/19, 2022/Aug/31 and 2022/Oct/24 respectively for Baltoro (five images), Atrak (one image) and Khumbu (one image) Glaciers.

NDWI thresholds: calibration and validation

In this section, methodology related to the automatic mapping of supraglacial lakes and the dataset construction is provided. In detail, the first section focuses on the NDWI threshold calculation, the second section shows the meteorological analyses useful to identify the best timeframe to detect the lakes and the third section explains the dataset building by means of GEE through a cleaning process fundamental to exclude possible artifacts.

With the aim of detecting supraglacial lakes over the HMA, the Normalized Difference Water Index (NDWI) was applied to the radiance and reflectance measurements acquired respectively by Sentinel-2 and PlanetScope satellites (Gao, 1996; McFeeters, 1996). Hereafter, the NDWI was calculated with the following formula (Gao, 1996):

$$NDWI = \frac{B_{green} - B_{NIR}}{B_{gree} + B_{NIR}} \quad (1)$$

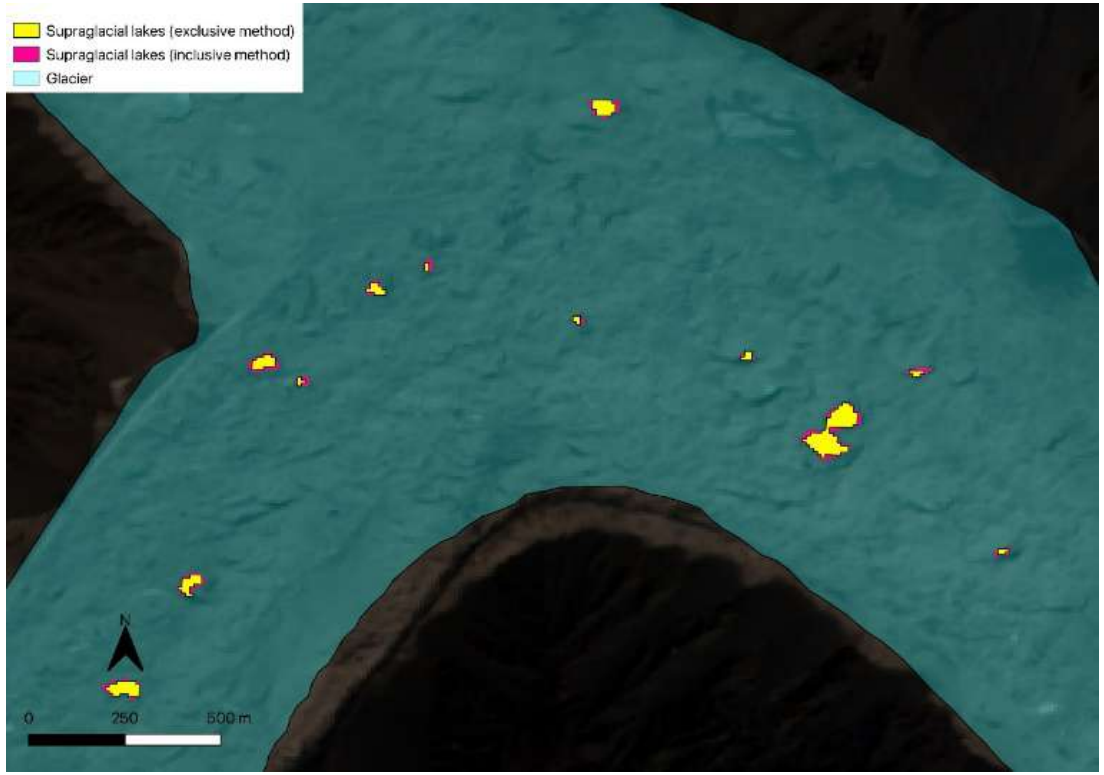
where B stands for Sentinel-2 and PlanetScope bands, specifically the Green and NIR bands, which are respectively Bands 3 and 8 (wavelengths 525-595 nm and 727-957 nm at 10 m spatial resolution) and Bands 4 and 8 (wavelengths 547-583 nm and 845-885 nm) respectively for the two satellites.

This index can enhance water-feature presence, minimising the presence of soil and vegetation (McFeeters, 2013, 1996). The choice to apply the NDWI to Sentinel-2 L1C radiance instead of L2A reflectance over the entire HMA, considers the topographic effect impacting the L2A products and derived indices, which reduces the reliability of this product over areas with complex topography (Ma et al., 2024), such as over glaciers in HMA. In fact, in areas exhibiting large variations of terrain slopes, topographic correction leads to overcorrected reflectance in weakly illuminated areas, since strong bidirectional brightness variations cannot be excluded with the Lambertian assumption (https://step.esa.int/thirdparties/sen2cor/2.10.0/docs/S2-PDGS-MPC-L2A-ATBD-V2.10.0.pdf). In particular, this effect can wrongly lead to water detection over shadowed glacier ice and snow patches, which are relatively common over HMA glaciers.

Although various thresholds were already applied to NDWI for extracting water bodies, from -0.10 to 0.30 (McFeeters, 2013; Wang et al., 2020), in this study new thresholds were calculated to be applied to the specific case of HMA using Sentinel-2 radiance and PlanetScope reflectance. In order to do so, 90 lakes were manually mapped on the Sentinel-2 and PlanetScope imagery, equally subdivided over the three common glaciers of the two datasets, i.e, Baltoro Glacier in Karakoram, Khumbu Glacier in Eastern Himalaya and Atrak Glacier in Hindu-Kush. In the case of Sentinel-2, the process was carried out twice, using as calibration lakes, features which include only certain water pixels ("exclusive" method) and features which considered also uncertain pixels at the edges of the detected lakes ("inclusive" method). This double-method approach allowed us to estimate the best possible threshold, in consideration of the limitations due to spatial resolution of the satellite leading to mixed pixels at the edges of lake features. A pixel weighted mean was then calculated over the 90 lakes present on the three glaciers.

The obtained NDWI thresholds were 0.28±0.05 and 0.25±0.05 for the exclusive and inclusive methods respectively. Through another manually digitized lake dataset of 300 supraglacial lakes and equally distributed in Hindu-Kush, Karakoram and Himalaya Regions (30 total glaciers), these thresholds were validated. In order to consider a wider range of possibilities, also other thresholds were considered in the validation process, i.e., means subtracted with one, two and three times the standard deviation (StD; empirical rule). In both exclusive and inclusive cases, the statistics (percent error, calculated by subtracting validation dataset area with the corresponding lake area from the NDWI-based dataset) were found to be improved in the case of the mean subtracted with three times the StD (0.05 x 3). As for the exclusive method, with a NDWI threshold >0.13 (0.28 - 0.15), we found an underestimation of -18±22% on average. As for the inclusive method (thresholds >0.10, calculated from 0.25-0.15 NDWI), we obtained a mean overestimation of +6±19%. At this stage,

aiming at obtaining the best possible percent error with NDWI thresholds (with hundredth precision), also the NDWI thresholds values in between the two identified thresholds (0.13 and 0.10) were tested, i.e., >0.12 and >0.11. This last step of NDWI threshold validation led to underestimations of -10±21% and -2±20% respectively for 0.12 and 0.11 NDWI values. Therefore, the NDWI threshold providing the best statistics resulted in pixels showing values >0.11 and this threshold was then applied to Sentinel-2 imagery in the present research. With a similar approach, another threshold of NDWI applicable to PlanetScope reflectance images was calibrated and validated, leading to the best statistics at NDWI threshold >0.05, which showed a percent error of -1±10%. The obtained dataset from PlanetScope was then used to calculate the difference in mapping supraglacial lakes over these three glaciers with Sentinel-2 dataset, in order to quantify the pixel-size (9 m^2 vs 100 m^2) effect over mapping capacity.



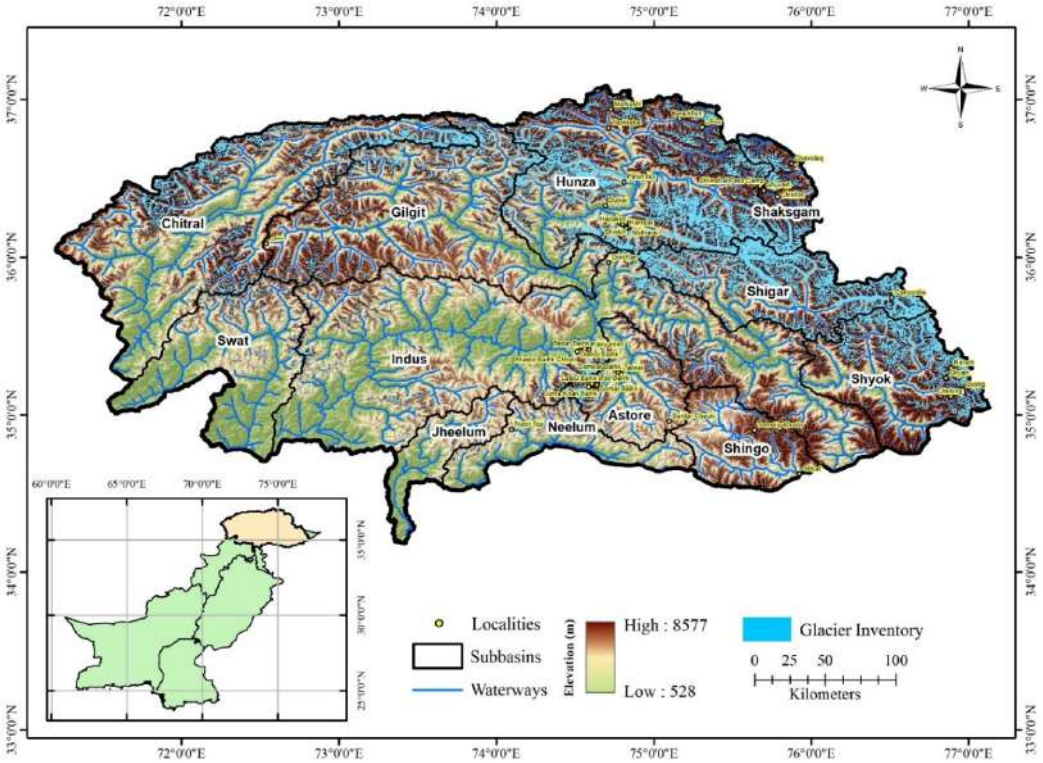
In conclusion, the development of the methodology has been concluded reporting an uncertainty of 2%. This means that for each glacier, the total surface of glacial lakes has been estimated with a very low error (within 2%).

Supraglacial lake extraction through Sentinel-2 NDWI by means of Google Earth Engine and cleaning of the dataset

Thanks to the implementation of the GEE platform, we were able to handle the high quantity of necessary images useful to cover the entire extent of the glaciers of Pakistan in 2022. NDWI (eq. 1) was applied to Sentinel-2 images covering the glaciers and the maps were then binary classified based on the NDWI threshold previously defined (NDWI > 0.11). The new classified map was then masked using the glacier inventory to exclude all other water bodies except for supraglacial features. Finally, the masked raster was polygonised and only the features having NDWI higher than 0.11 were maintained. A size (area) threshold was also applied, deleting all those features made up of less than five pixels (< 500 m^2) (Lesi et al., 2022). However, this dataset needed a visual check and cleaning process from artifact presence. In fact, several pixels were wrongly classified as water bodies, e.g., snow patches in shadows, crevasses and debris-free glacier ice in certain light conditions (poorly illuminated). In fact, at the expense of the 0.11 threshold, which is relatively low if compared to other previous researchers (McFeeters, 2013), the process allowed the inclusion of as many lakes as possible, in consideration of the unprecedented vastness of the analysed area and its intrinsic environmental heterogeneity. The data cleaning was carried out in GEE, thanks to the use of RGB and NDWI maps based on Sentinel-2 imagery contemporary to lake inventory period, as well as the use of Google Maps at a very high spatial resolution (paying attention to the discrepancy in image timing).

The preliminary inventory of supraglacial lakes

According to new glacier inventory, in order to provide an overview of the glaciers of Pakistan, we divided its northern territory, with the regions of Gilgit-Baltistan, Khyber Pakhtunkhwa and Azad Jammu and Kashmir, into its main basins. Two basins' divisions were adopted. In the high order subdivision, we identified 5 major basins, i.e. the Gilgit, Indus, Jhelum, Kabul and Tarim basins. In the second subdivision, we split these five basins into lower order basins, leading to a total of 12 basins, i.e.: Astore, Chitral, Gilgit, Hunza, Indus, Jhelum, Neelum, Shaksgam, Shigar, Shingo, Shyok, Swat. This last subdivision can be useful for an assessment of the country's water resources and was adopted to describe the lakes distribution in Pakistan.

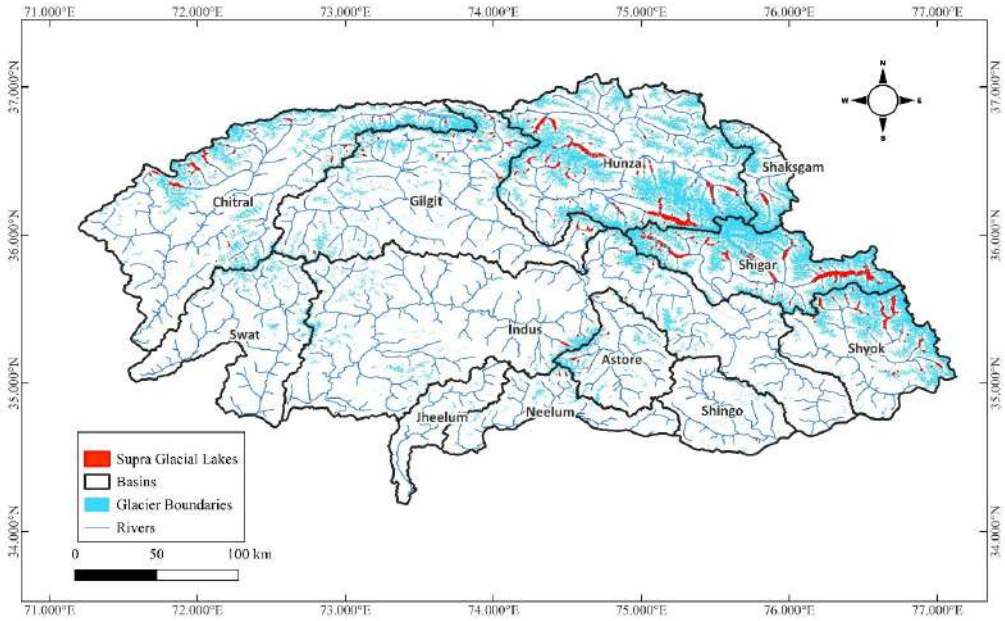


Considering the frequency analysis of precipitation shown in the "Methodology Section", the best month for mapping the supraglacial lakes in this region should be the month of October considering that during this month we usually have the lowest mean precipitation. However, this choice could also consider the month of September since that during this month the temperature is higher than October. Consequently, as a compromise, for this preliminary inventory, 73 Sentinel-2 images were used in GEE to cover between 2022/Sep/02 and 2022/Sept/29.

This study allowed to map 2722 new glacial lakes located on 142 glaciers of Pakistan. These glaciers have a median size of 30 km². The smaller glacier is 3 km² and the maximum is the Baltoro Glacier (756 km²). This result will allow us to address the new research effort that will be focused only on glaciers larger than 3 km². Recently, in the new Glacier Inventory of Pakistan, 13,032 glaciers have been mapped. Only 20% of these glaciers are larger than 3 km². Therefore, it is evident that the preliminary lakes inventory allowed to reduce the future research efforts.

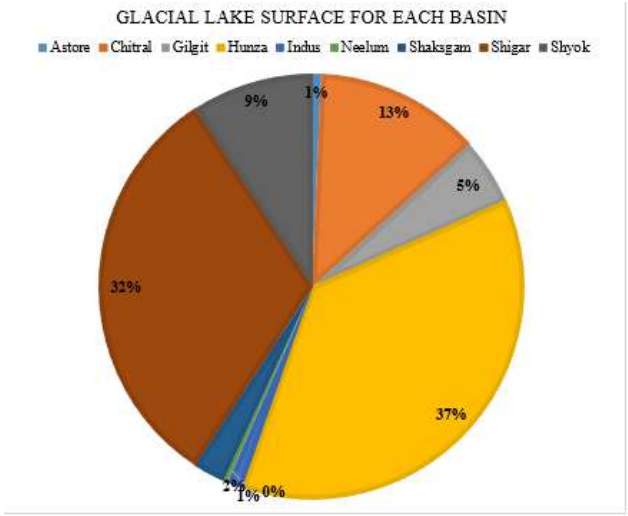
Another important result is that **all the glacial lakes are in the basins located more in the north**: Hunza (37%), Shigar (32%), Shyok (9%), Chitral (13%), Gilgit (5%), Shaksgam (2%), and Indus (1%). 99% of the glacial lakes are in 7 basins, and Chitral basin alone includes almost half of glacial lakes of the overall region. In this basin, the glacier that was able to develop more supraglacial lakes was the **Baltoro** Glacier. This glacier developed 519 small glacial lakes for a total surface area of 1.1 km². The second glacier with widespread glacial lakes if the **Hispar Glacier** with 354 small glacial lakes for a total surface area of 0.62 km².

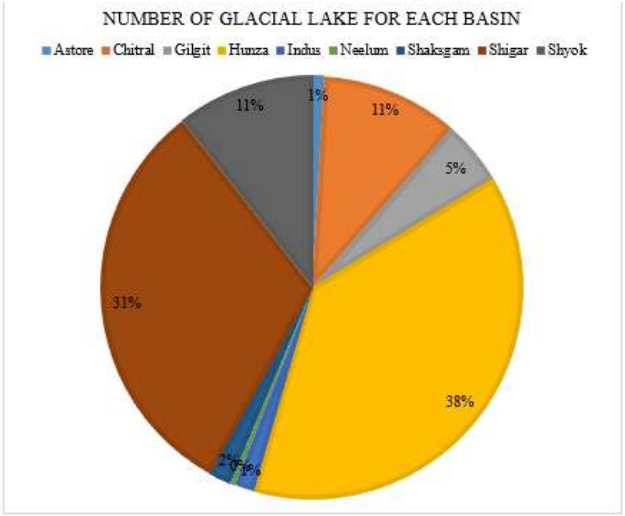
The main morphological features of these glacial lakes are a **mean glacier slope of 21°**, that could be considered gentle, although this data refers to the overall glacier: accumulation and ablation basin. In this study it was not possible to distinguish between the two kinds of glacier basins. Therefore, this slope is overestimated, and future research efforts will allow to obtain a more accurate threshold of this parameter that is fundamental for building predictive models for the future development of the glacier.

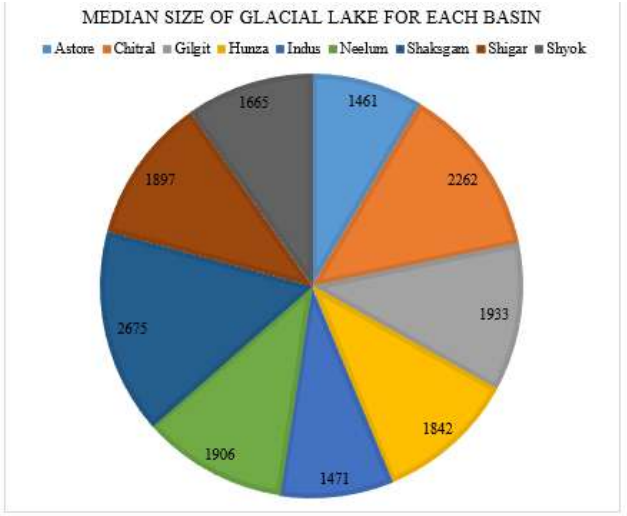


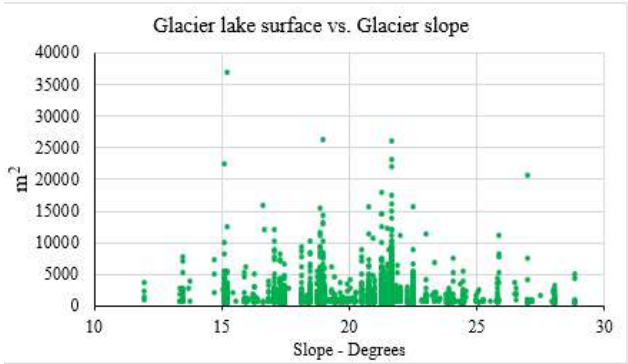
The glacial lakes lie at a mean altitude of around 3961 (from 3700 to 4200) m a.s.l, on glaciers presenting a minimum elevation of 3320 m a.s.l.. The median size of lakes is 1895 m².

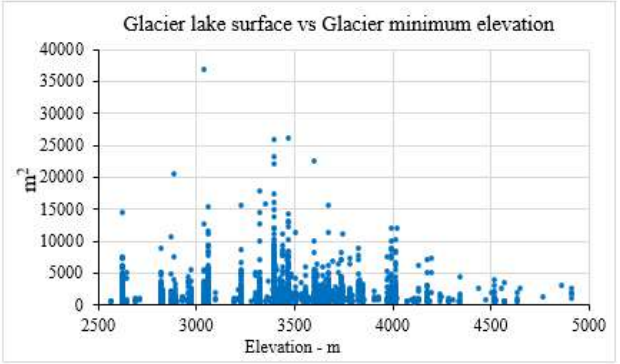
Basin	Total lake area (m2)	Number of lakes	Mean elevation of lakes (m a.s.l.)	Minimum glacier elevation (m a.s.l.)	Glacier slope (°)	Mean lake area
Astore	36523	25	3856	3532	21	1461
Chitral	646986	286	4184	3738	19	2262
Gilgit	261020	135	3676	3339	21	1933
Hunza	1907858	1036	3814	3106	20	1842
Indus	60299	41	3787	3438	28	1471
Neelum	17150	9	3857	3588	19	1906
Shaksgam	125712	47	4171	3991	17	2675
Shigar	1623778	856	4017	3301	21	1897
Shyok	477859	287	4244	3568	22	1665
Totale complessivo	**5157186**	**2722**	**3961**	**3320**	**21**	**1895**

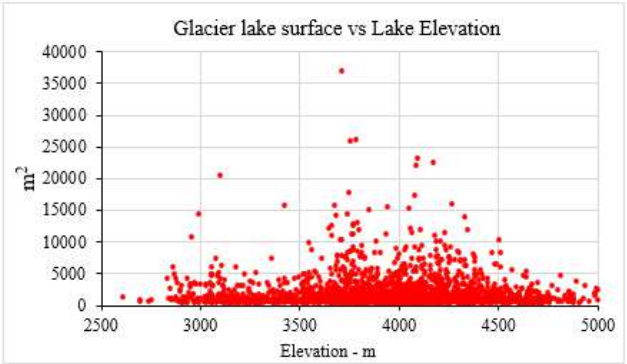

GLACIAL LAKE SURFACE FOR EACH BASIN
Astore Chitral Gilgit Hunza Indus Neelum Shaksgam Shigar Shyok
1%
13%
5%
37%
0%
1%
2%
32%
9%

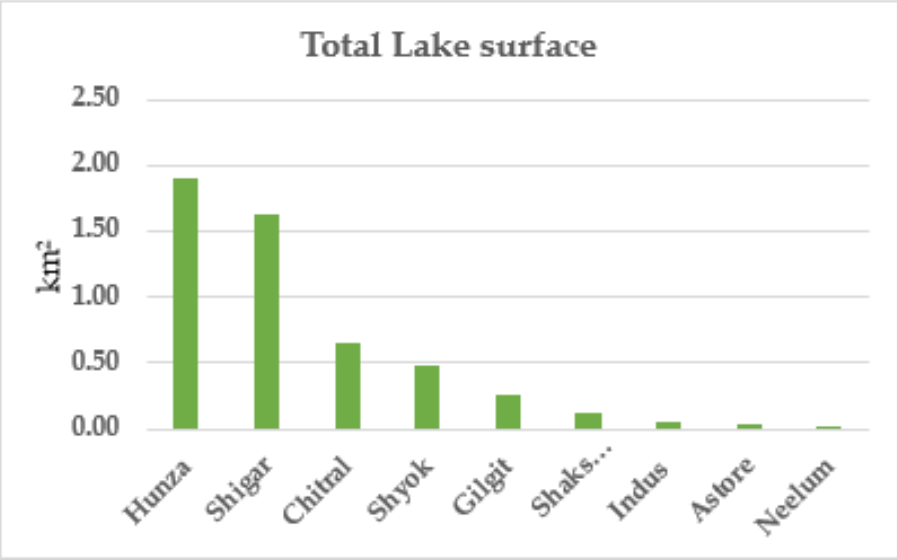

NUMBER OF GLACIAL LAKE FOR EACH BASIN
Astore Chitral Gilgit Hunza Indus Neelum Shaksgam Shigar Shyok
1%
11%
5%
38%
1%
2%
31%
11%

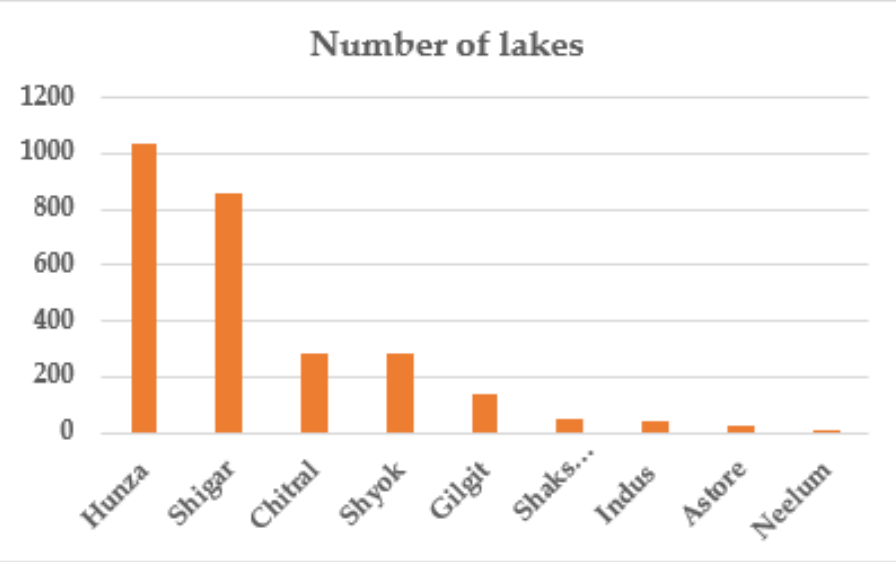

MEDIAN SIZE OF GLACIAL LAKE FOR EACH BASIN
Astore Chitral Gilgit Hunza Indus Neelum Shaksgam Shigar Shyok
1461
2262
1933
1842
1471
1906
2675
1897
1665


Glacier lake surface vs. Glacier slope
m2
40000
35000
30000
25000
20000
15000
10000
5000
0
10
15
20
25
30
Slope - Degrees


Glacier lake surface vs Glacier minimum elevation
m2
40000
35000
30000
25000
20000
15000
10000
5000
0
2500
3000
3500
4000
4500
5000
Elevation - m


Glacier lake surface vs Lake Elevation
m2
40000
35000
30000
25000
20000
15000
10000
5000
0
2500
3000
3500
4000
4500
5000
Elevation - m





Basins	Total Lake Area km2	Number of Lakes
Hunza	1.91	**1036**
Shigar	1.62	**856**
Chitral	0.65	**286**
Shyok	0.48	**287**
Gilgit	0.26	**135**
Shaksgam	0.13	**47**
Indus	0.06	**41**
Astore	0.04	**25**
Neelum	0.02	**9**
TOTAL	**5.16**	**2722**

Analysis on inter- and intra-annual variability in the distribution of supraglacial lakes

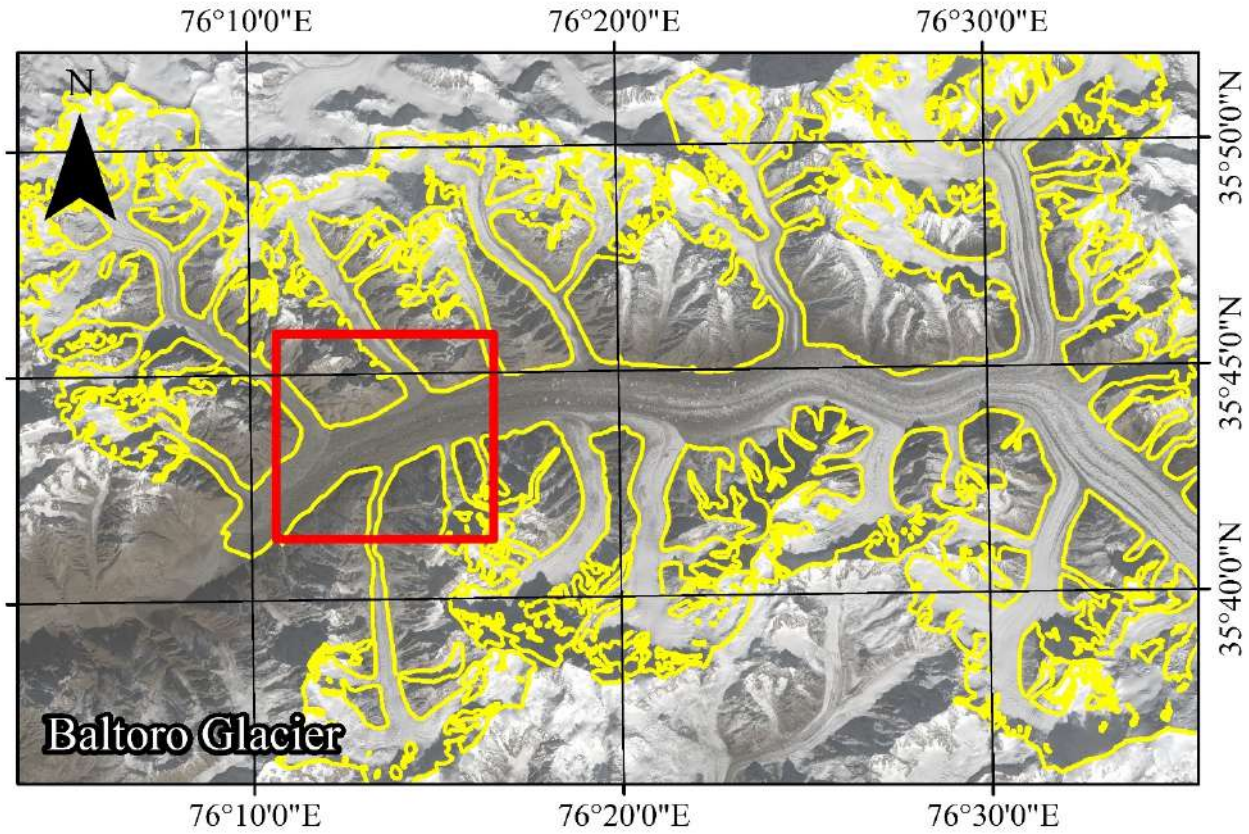
This inventory is considered preliminary because, according to its aims, these analyses were carried out to develop a methodological framework in order to map correctly the supraglacial lakes in the entire regions. In fact, the inventory has been realized using a single Sentinel image related to a single date, so it is strongly dependent on the climate (temperature and precipitation) of the year and on the season related to the selected image. Therefore, the methodology approach adopted here considered even a deep evaluation of the inter- and infra-annual variability of the supraglacial lake development.

We selected the Baltoro glacier as a case study to evaluate the inter- and intra-annual variability of supraglacial lakes of the region. This glacier was selected because it is the largest glacier in the region with **519 supraglacial lakes mapped in this preliminary inventory, i.e., 21% of supraglacial lakes of the entire region**.

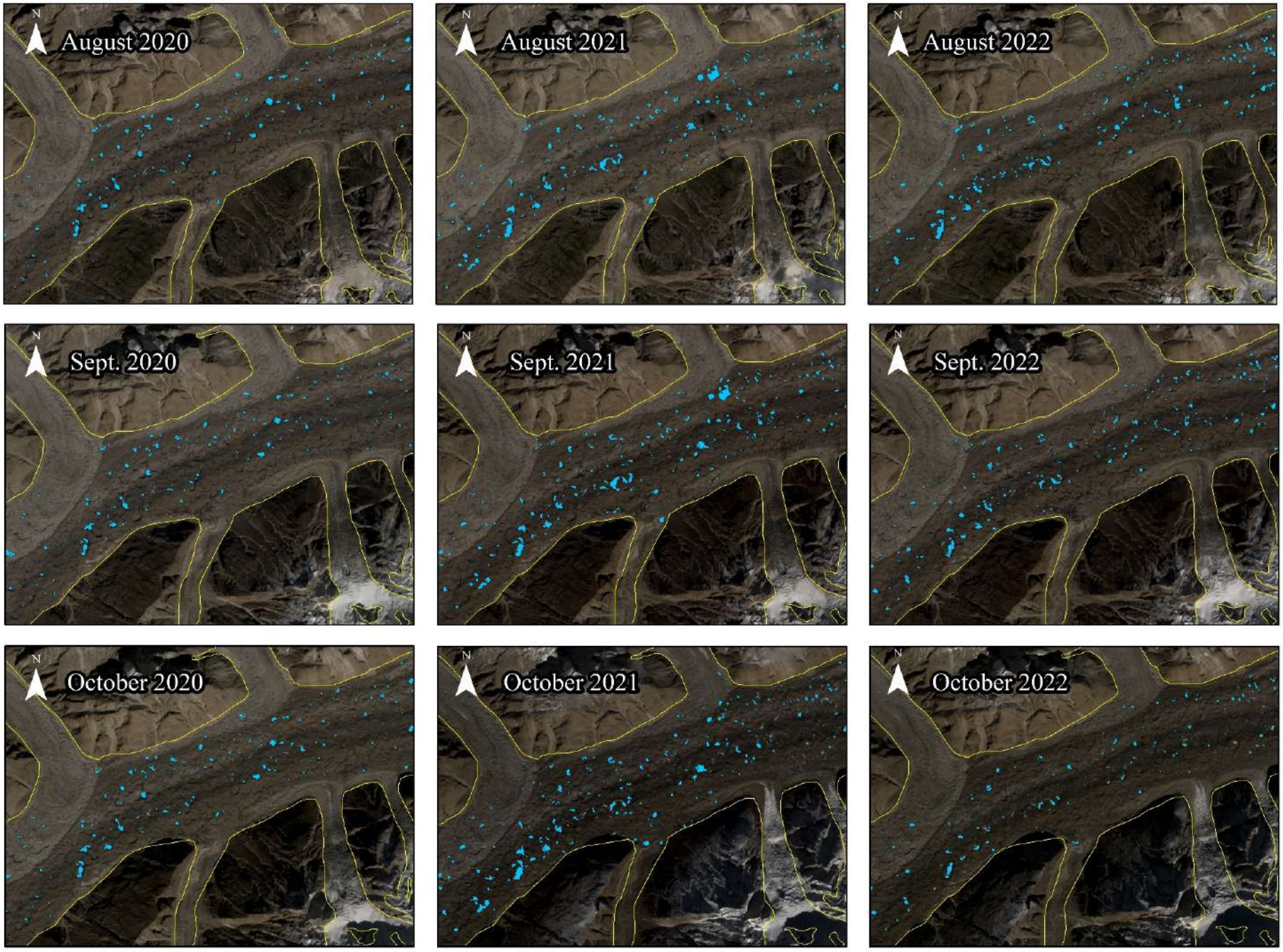
A big effort has been made to map the supraglacial lakes of Baltoro Glacier in three years (2020, 2021, and 2022) and for three months: August, September, and October. All these images have been processed according to the same methodology and procedures described in this report. Therefore, each of the 9 maps of supraglacial lakes of the Baltoro Glacier is associated with an uncertainty of 2%. We carried out the mapping of the entire glacier, but here we propose the focused map only of the lower part of the glacier where development of glacial lakes and possible proglacial lakes is more likely (Salerno et al., 2012, Salerno et al., 2017).

We can see the digitalized supraglacial lakes in 9 images that differ among them for the year and for the month of mapping. Easily we can appreciate that the variance in lake distribution, both in terms of number of lakes and size, is incredibly high. Many lakes appear and disappear between two months and between two years.

This first consideration clarifies that speaking about Number of Lakes and Lakes Size is strictly related to the images used to map the lakes, i.e., the date of the satellite acquisition.



* RBG True Color Composite Sentinel 2-L1C Images of corresponding months have been used for the background reference.


August 2020
August 2021
August 2022
Sept. 2020
Sept. 2021
Sept. 2022
October 2020
October 2021
October 2022

In the Table reported below, we provide a statistical analysis of lakes mapped on Baltoro Glacier in the three years (2020, 2021, and 2022) and for the three months (August, September, and October); statistics are referred for homogeneity to the glacier area below 4100 m a.s.l..

Firstly, we can observe that the number of lakes varies from 121 to 228, i.e. around 62%, while the total area varies by 0.43 km^2, from 0.24 km^2 to 0.67 km^2, i.e., 95%. We can simplify saying that the date of the mapping can double the number of supraglacial lakes or halve them compared to the previous or the following year, both in terms of area and number of lakes. Therefore, reporting the number of supraglacial lakes of Pakistan does not make sense because its number is strictly related to the climatic condition of the date of data acquisition.

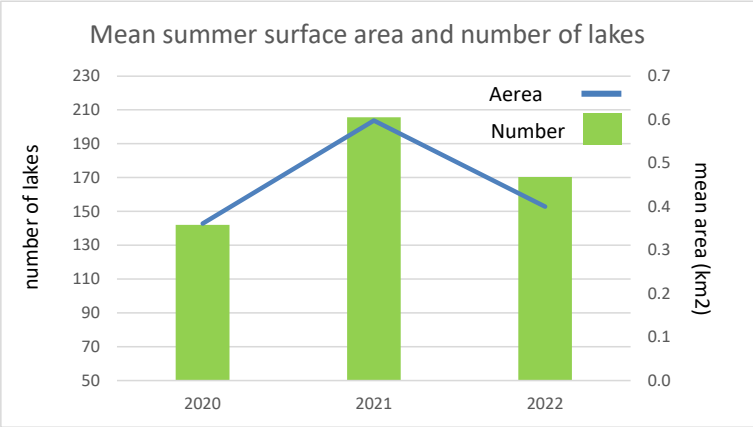
Date	Month/Year	Total Area (km2)	mean	Number of lakes	mean	Differences in Area (%)	Differences in number of lakes (%)	Standard Deviation in Lake Areas	Standard Deviation in number of lakes
	August 2020	0.36		140		-21%	-19%		
	August 2021	0.56		185		24%	7%	**10%**	**17%**
	August 2022	0.51		194		13%	12%		
			0.48		**173**				
	September 2020	0.36		139		-21%	-19%		
	September 2021	0.67		228		48%	32%	**16%**	**26%**
	September 2022	0.45		196		-1%	14%		
			0.49		**212**				
	October 2020	0.37		147		-19%	-15%		
	October 2021	0.56		204		24%	18%	**16%**	**26%**
	October 2022	0.24		121		**-47%**	-30%		
			0.39		**163**				
	Mean	**0.45**		**173**				**13%**	**23%**
	Maximum	**0.67**		**228**		**48%**	**32%**		
	Minimum	**0.24**		**121**		**-47%**	**-30%**		
	RANGE (max-min)	**0.43**		**107**		**95%**	**62%**		

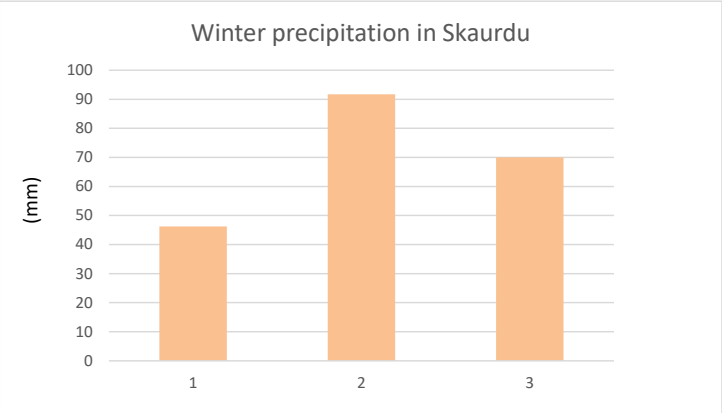
If we refer to a mean condition for Baltoro Glacier (below 4100 m a.s.l.) the total area of supraglacial lakes is 0.45 ±16% km² (mean range 0.38-0.52) and the number of lakes should be 163±23% (mean range 126-200).

In the graphs reported below this variability has been aggregated at annual scale, so we can observe that 2021 has a quantity of lakes, both in terms of area and number, around double than the previous year (2020), while 2022 is in the middle of the two years.

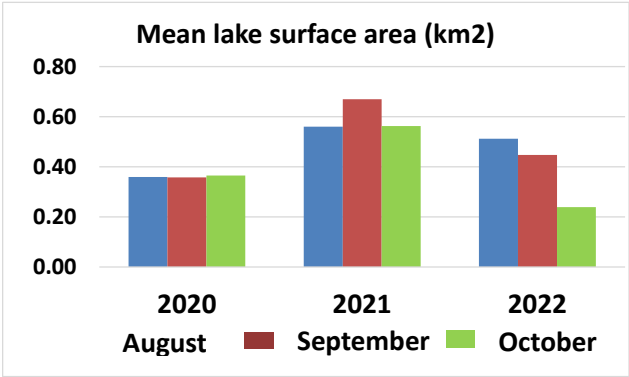
We investigated the reason for these differences using temperature data coming from the Skardu station and from the MODIS Sensor, while we used just the precipitation data from the Skardu station. Generally, in this region data are decidedly scares/absent, and the station of Skardu is far from the glacier by 55 km². Other information does not exist to interpret our lake behavior, so we use the temperature data of the glacier surface derived from the MODIS sensor for the 7 days before the data of the satellite image used for mapping the lakes on Baltoro.

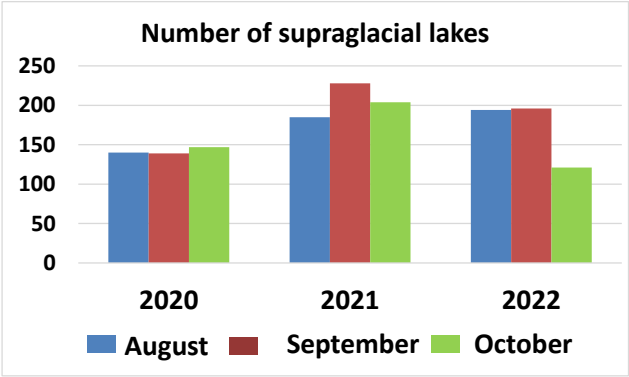
We tested many combinations of temperature aggregations (30 days, 15 days, 7 days, same day) for reproducing the differences in the abundance of lakes among the three years without results. The difference in the amount of precipitation of the previous 4 months seems able to reproduce the INTER-annual differences among lakes. This could mean that when the warm season starts (generally in June) and the lake starts melting, their number and size could be related to the winter precipitation, or probably to the precipitation falling during the winter and that remains on the glacier until lakes start melting (effective winter precipitation).



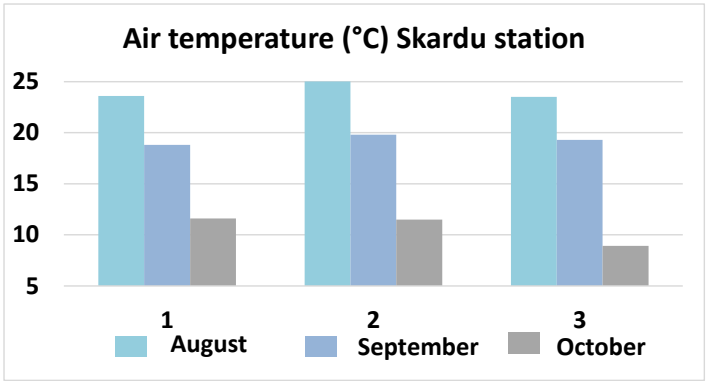


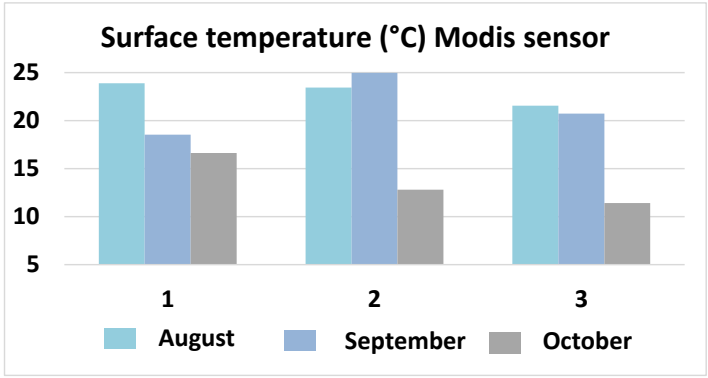
Further, we analyzed the INTRA-annual variability of lakes analyzing the graphs reported below, on the left in terms of size and on the right in terms of number of lakes. We can see that in 2020 and 2022 the lakes are almost constant in the three months. We only observe an increase during September 2021, and this could be due to higher temperature observed during this month with the MODIS sensor. This is common even in 2022, but the months of October present fewer lakes both in terms of size and on the right in terms of number of lakes (see the table above for statistics).





We investigated the reasons for these differences using temperature data coming from the Skardu station and from the MODIS Sensor, as described above. We found that, using both sources, the month of October 2022 is colder than the previous months of October in 2020, and 2021. We estimate a difference of -2 °C and these climatic factors, over 3500 m a.s.l. could be responsible for an early freezing of lakes. In conclusion the intra-annual variability in this region seems more related to the temperature than the precipitation.





Final remarks:

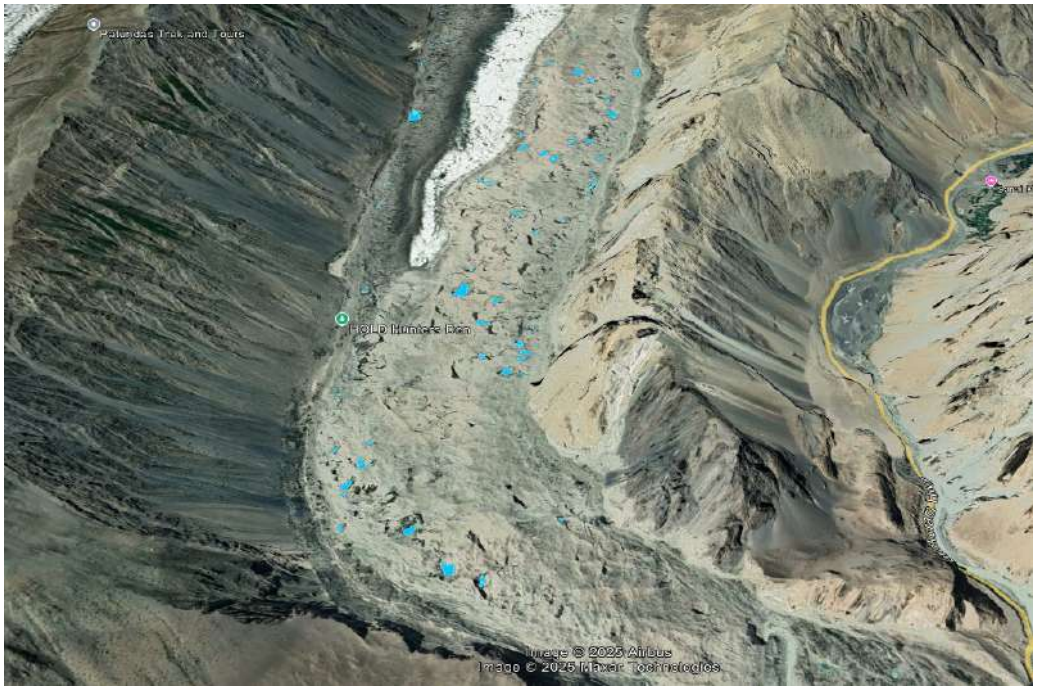
This analysis pointed out that in this region the Number of Lakes and Lakes' Size are strictly related to the images used to map the lakes, i.e., the date of the acquisition. We can simplify saying that this date can double or halve the number of supraglacial lakes compared to the previous or the following year, both in terms of area and number of lakes. We observed that 2021 has a quantity of lakes, both in terms of area and number, around double than the previous year (2020), while 2022 is in the middle of the two years.

Unexpectedly, we found that the reason for these inter-annual differences is probably due to the difference in the amount of winter precipitation. This could mean that when the warm season starts (generally in June) and the lakes start melting, their number and size could be directly related to the winter precipitation, or if we want to be more precise, probably to the precipitation falling during the winter and that remains on the glacier until the lakes start melting (effective winter precipitation considering the wind transport). Afterwards, during the warm season the lakes seem to remain stable. So, the main factor driving the lake distribution seems to occur during the winter. This hypothesis has many repercussions: first, following the trend of supraglacial lakes could provide more insights in precipitation than temperature trends.

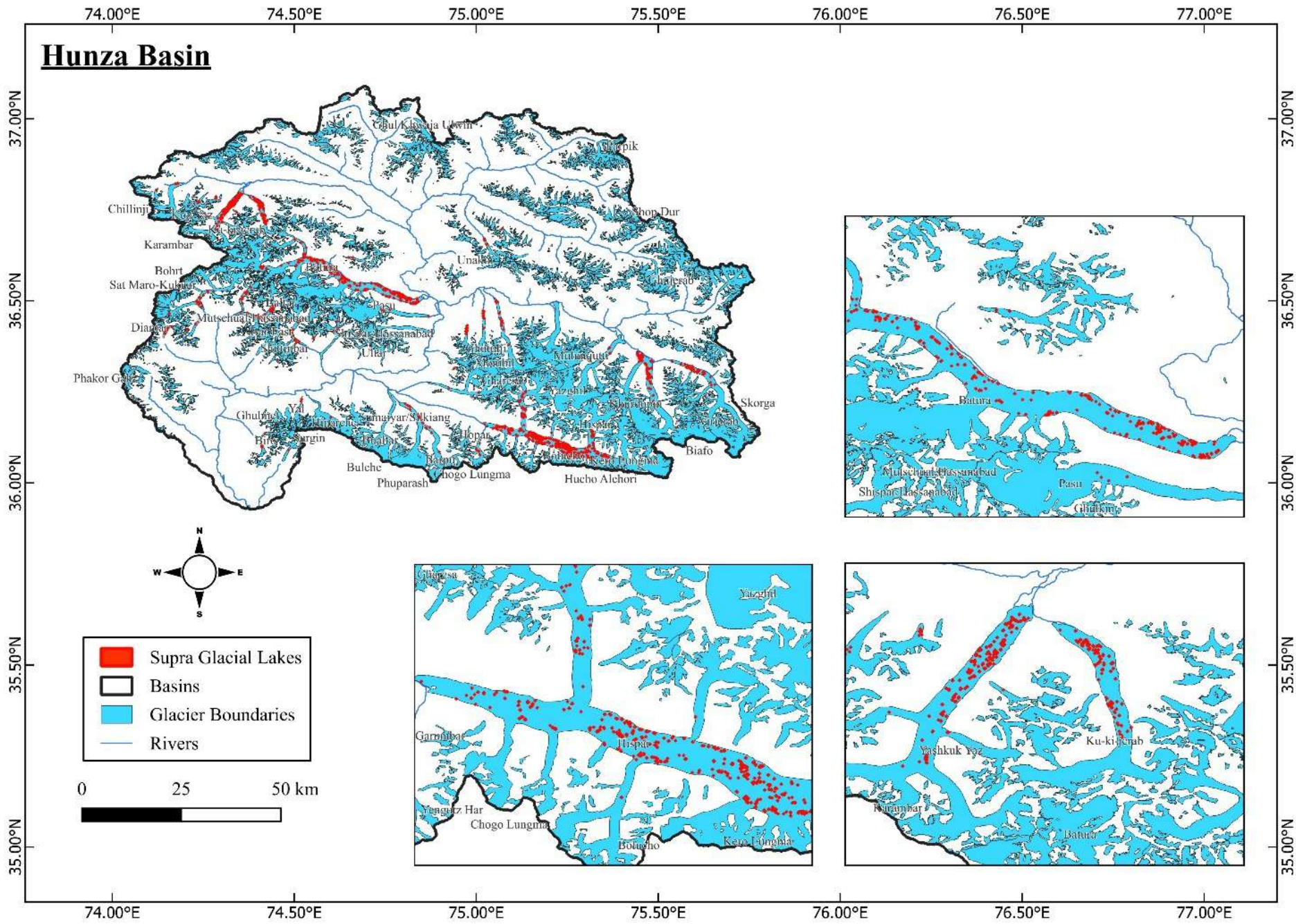
As regards the intra-annual variability of lakes, we observed that in 2020 and 2022 the lakes are almost constant in the three months. Therefore, the intra-annual variability seems less important than the inter-annual one. Late September and the beginning of October remain the best periods for mapping the lake in the area. For these reasons, this inventory considered **September 2022 as a reference period for mapping supraglacial lakes because the difference in area among the analyzed scene is almost zero (-1%); this means that this month represents a climatic mean condition of the last three years.**

Hunza Basin

The Hunza Basin (1,863 km²) spans the Hunza River between the Nagar and Bola Das confluences, featuring major glaciers like Kukuar (103.80 km²) and Baltar (68.87 km²) in its northern reaches. Towering peaks such as Batura Sar (7,795 m a.s.l.) and Rakaposhi (7,788 m a.s.l.) demarcate its borders. The basin's meltwater sustains irrigation systems but it is prone to landslides due to sediment-rich terrain. Hunza is the basin characterized by the highest presence of glacial lakes in the region. A total of 1036 glacial lakes were identified in the Hunza Basin on 27 glaciers. In terms of lake surface this basin represents 37% of the whole region (1.91 km2), while in terms of number of lakes this basin represents 38% of the whole region (1036/2722).The glacier with the highest number of lakes is Batura Glacier (224 lakes) followed by the Hispar Glacier (354 lakes) and Yashkuk Yaz (106). Furthermore, we observe that in this basin the lakes are mainly located on glaciers with gentle slopes (<23°) and that the mean elevation where lakes tend to develop is at around 3850 m a.s.l.. The density of the lakes (lake area/glacier area) is an important parameter to study the factor controlling the lake development (Salerno et al., 2017) and for this reason this inventory will report this parameter for each glacier. The Batura Glacier shows the highest lake density; therefore its morphological factors need to be studied in detail in the next future in order to develop predictive models of the of the glacial melting.

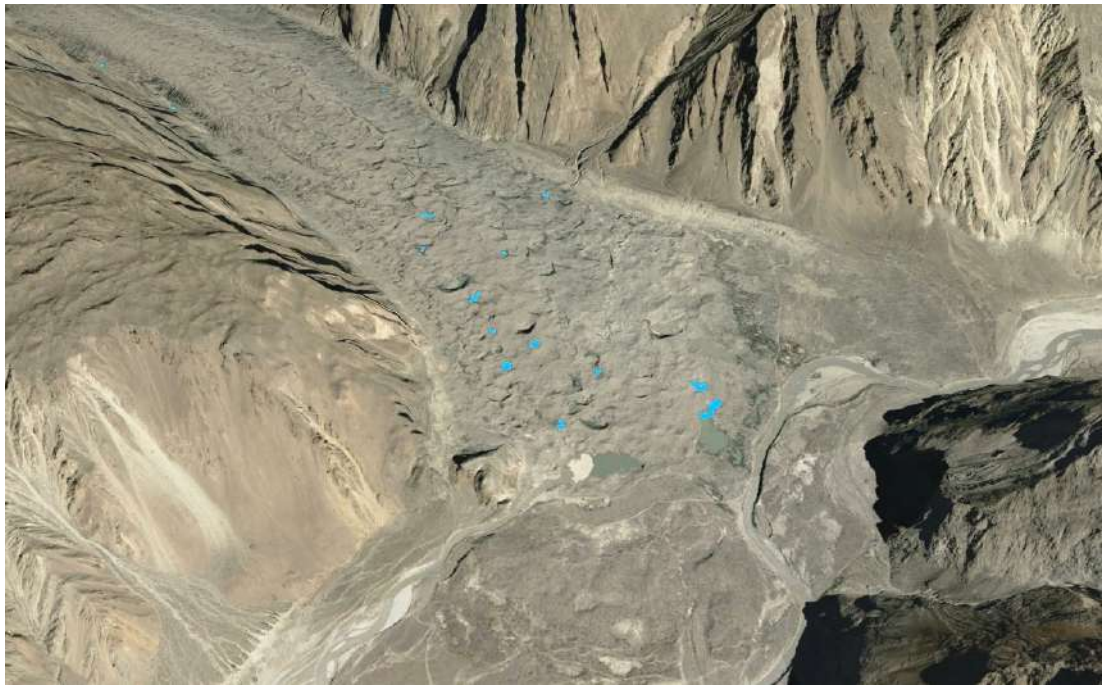


Glacial lakes in the Hunza Basin. Google Earth, Accessed March 2025.


Hunza Basin
74.00°E
74.50°E
75.00°E
75.50°E
76.00°E
76.50°E
77.00°E
37.00°N
36.50°N
36.00°N
35.50°N
35.00°N
Chillinji
Karambar
Bohrt
Sat Maro-Kuh
Diamir
Phakor Go
Ghulkin
Bulche
Phuparash
Chogo Lungma
Hucho Alchori
Biafo
Skorga
Batura
Pasu
Yazghil
Hispar
Garumbar
Yengutz Har
Botucho
Yashkuk Yaz
Ku-ki-Kanjab
N
S
W
E
Supra Glacial Lakes
Basins
Glacier Boundaries
Rivers
0
25
50 km

Shigar Basin

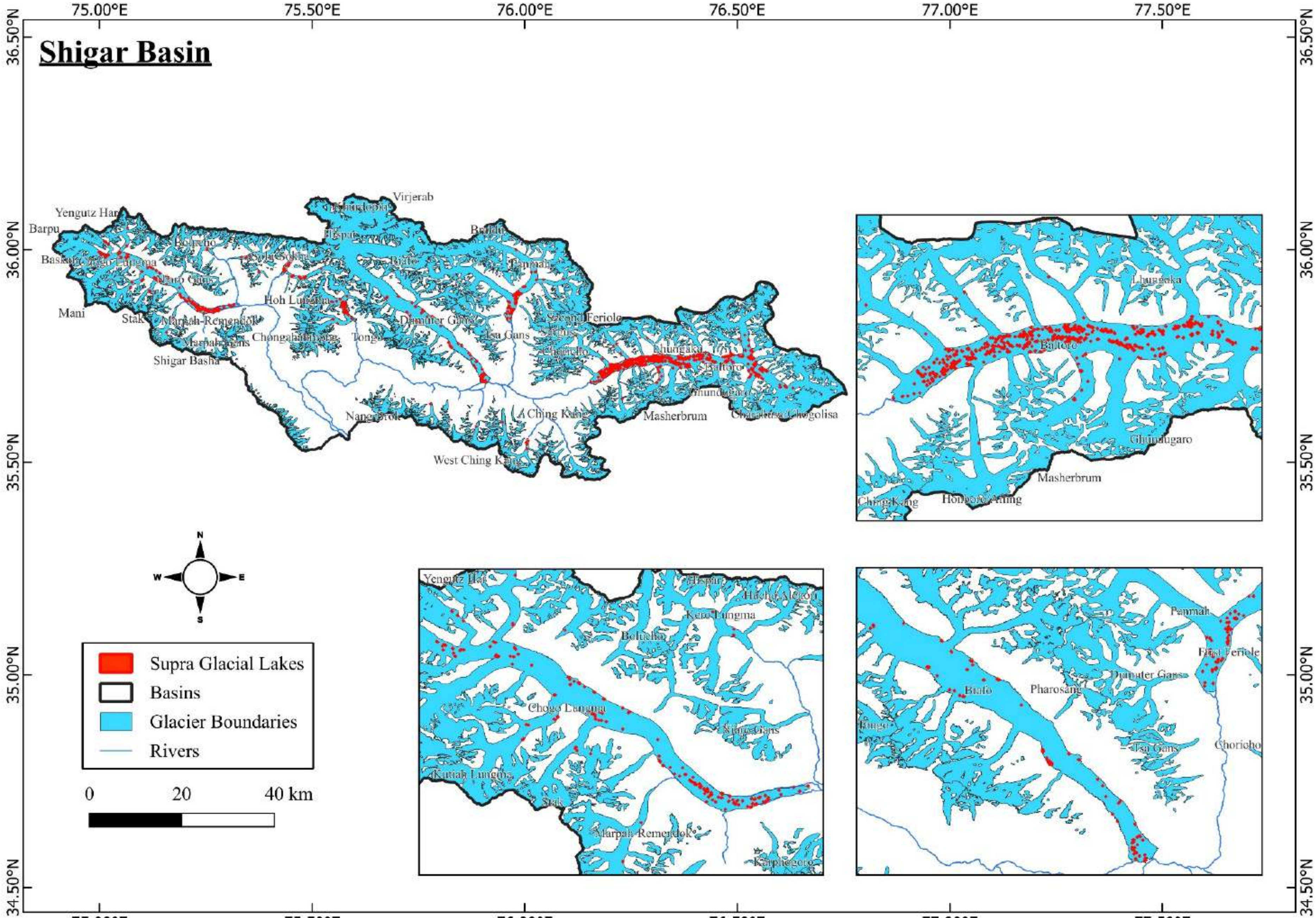
The Shigar Basin (1,336 km²) encompasses the lower Shigar River, merging with the Indus near Hussain Abad. Dominated by active alluvial fans fed by glacial debris flows, its arid climate supports sparse desert vegetation, with settlements like Shigar town situated on these fans.
A total of 856 glacial lakes were identified in the Shigar Basin on 10 glaciers. In term of lake surface this basin represents 31% of the whole region (1.62 km2); also, in terms of number of lakes this basin represents 31% of the whole region (856/2722).

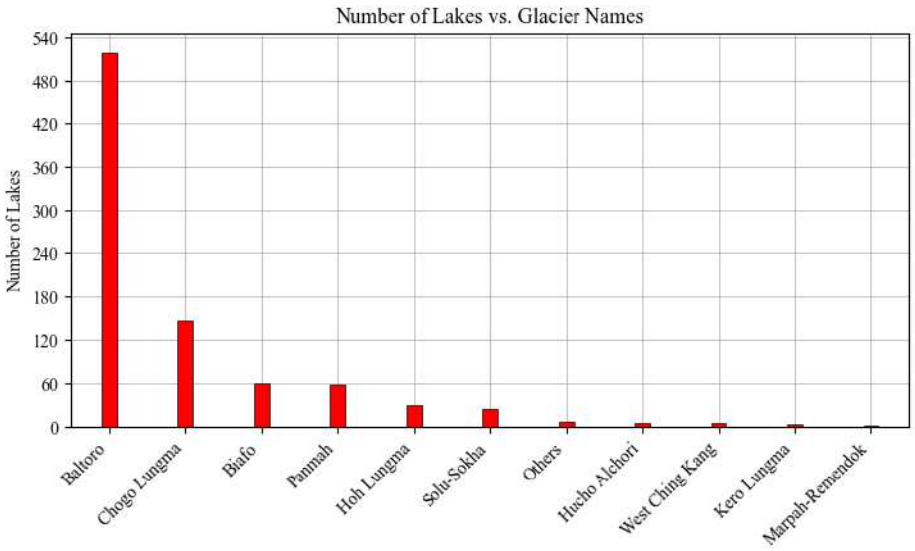


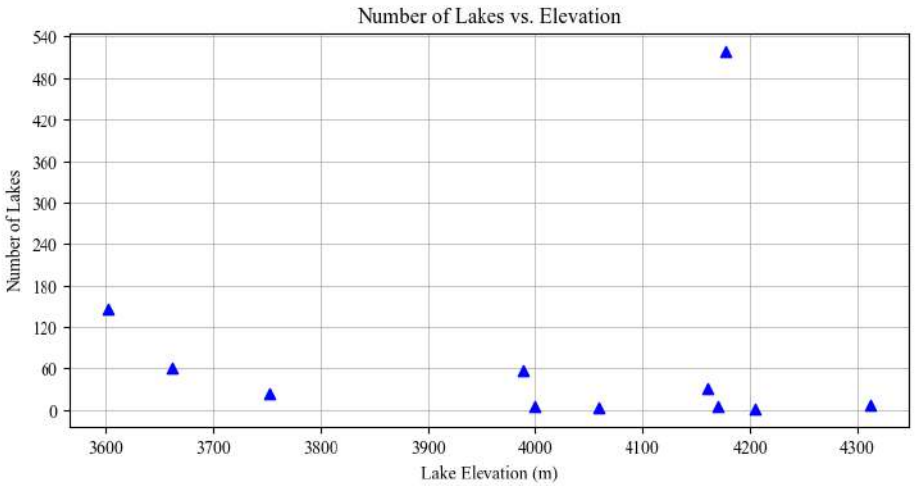
Glacial lakes in the Shigar Basin. Google Earth, Accessed March 2025

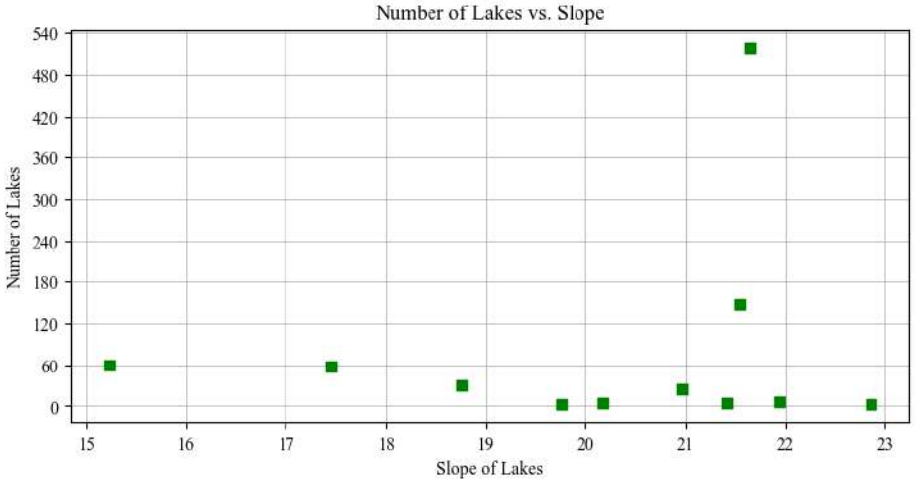
The glacier with the highest number of lakes is Baltoro Glacier (519 lakes) followed by the Chogo Lungma (147 lakes). Furthermore, we observe that in this basin the lakes are mainly located on glaciers with gentle slopes (15°-22°), while the elevation of glaciers, where the glacial lakes are located range from 3600 to 4300 m a.s.l.

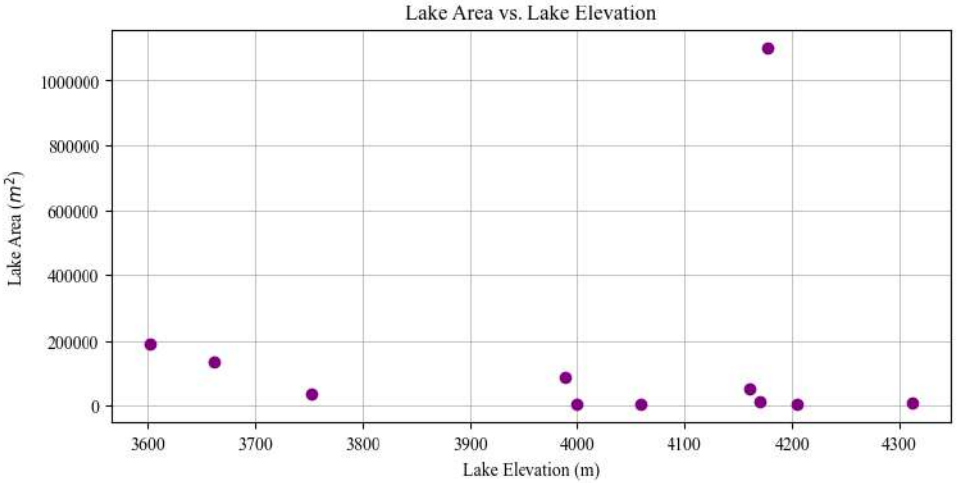
The Baltoro Glacier shows the highest lake density, therefore its morphological factors need to be studied in detail in the next future to develop predictive models of the of the glacial melting.


Shigar Basin
75.00°E
75.50°E
76.00°E
76.50°E
77.00°E
77.50°E
36.50°N
36.00°N
35.50°N
35.00°N
34.50°N
Yengutz Har
Barpu
Virjerab
Mani
Stak
Shigar Basha
Hoh Lungma
Tongo
Dumuter Gans
Tsa Gans
Baltoro
Lhungaka
Masherbrum
Ching Kang
West Ching Kang
Biafo
Panmah
Biafo
Pharosang
Dumuter Gans
Tsa Gans
Choricho
Panmah
Ghondugaro
Masherbrum
Chogo Lungma
Bolucho
Marpah Remendok
Kero Lungma
Stak
N
S
E
W
Supra Glacial Lakes
Basins
Glacier Boundaries
Rivers
0
20
40 km


Number of Lakes vs. Glacier Names
Number of Lakes
0
60
120
180
240
300
360
420
480
540
Baltoro
Chogo Lungma
Biafo
Panmah
Hoh Lungma
Solu-Sokha
Others
Hucho Alchori
West Ching Kang
Kero Lungma
Marpah-Remendok


Number of Lakes vs. Elevation
Number of Lakes
0
60
120
180
240
300
360
420
480
540
3600
3700
3800
3900
4000
4100
4200
4300
Lake Elevation (m)


Number of Lakes vs. Slope
Number of Lakes
0
60
120
180
240
300
360
420
480
540
15
16
17
18
19
20
21
22
23
Slope of Lakes

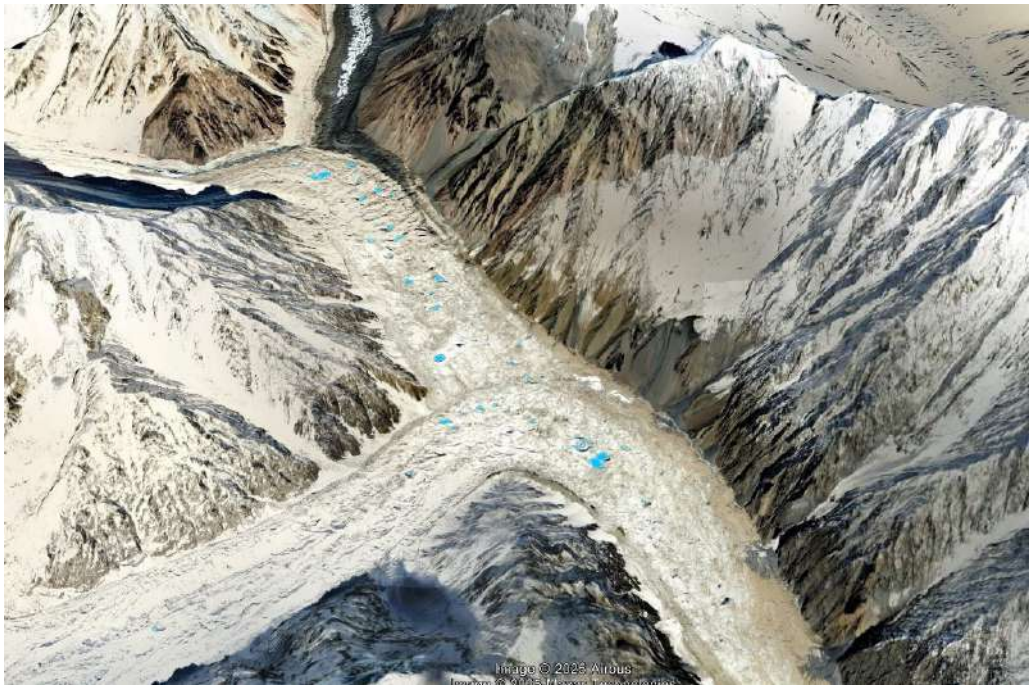

Lake Area vs. Lake Elevation
Lake Area (m^2)
0
200000
400000
600000
800000
1000000
3600
3700
3800
3900
4000
4100
4200
4300
Lake Elevation (m)

Chitral Basin

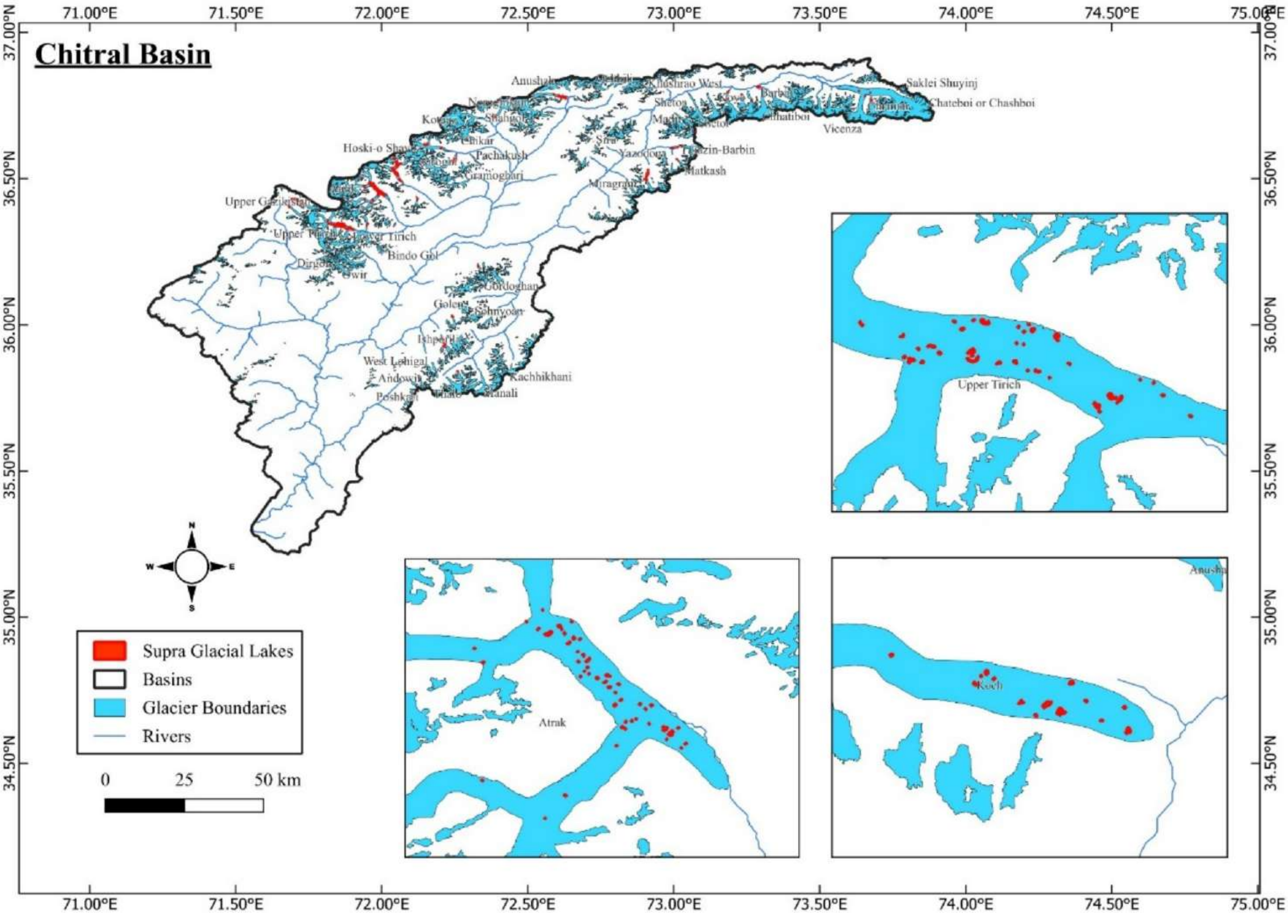
The Chitral Basin, comprising the Middle and Lower Chitral sub-basins, is a significant part of the Hindukush and Hindu Raj Mountain ranges, drained by the Chitral (or Kunar) River.

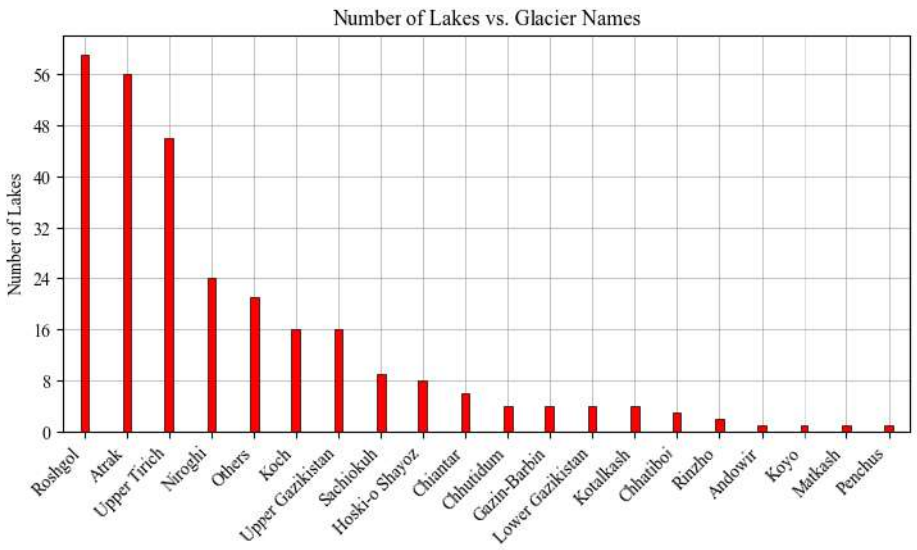
Chitral is the basin characterized by a higher presence of glacial lakes. A total of 423 glacial lakes were identified in the Chitral Basin on 16 glaciers. In terms of lake surface this basin represents 13% of the whole region (0.65 km^2), while in terms of number of lakes this basin represents 11% of the whole region (286/2722).

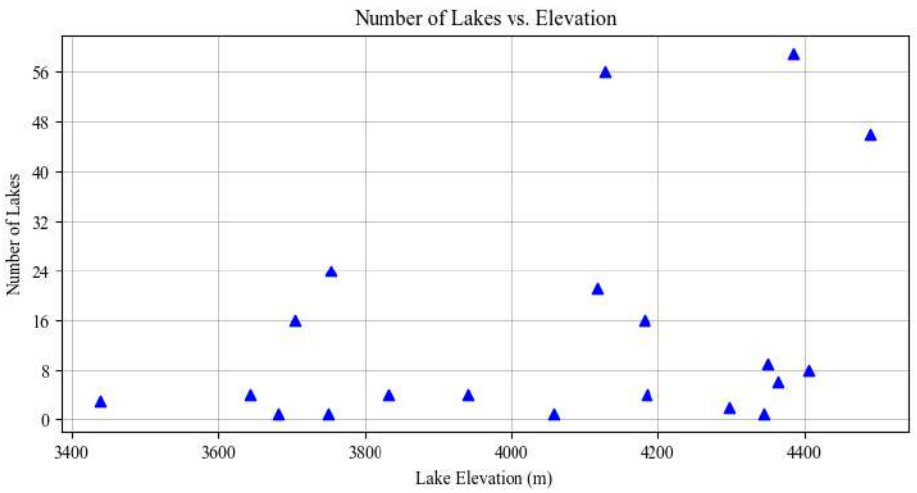
The glacier with the largest lake surface is Atrak Glacier (0.13 km^2) followed by the Roshgol (0.11 km^2). Furthermore, we observe that in this basin the lakes are mainly located on glaciers with gentle slopes (<19°) and that the mean elevation where lakes tend to develop is higher than 3400 m a.s.l..

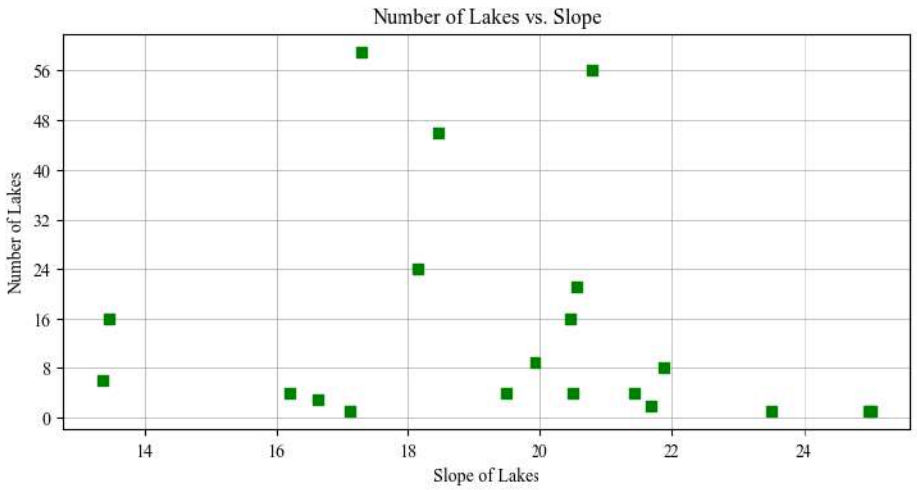


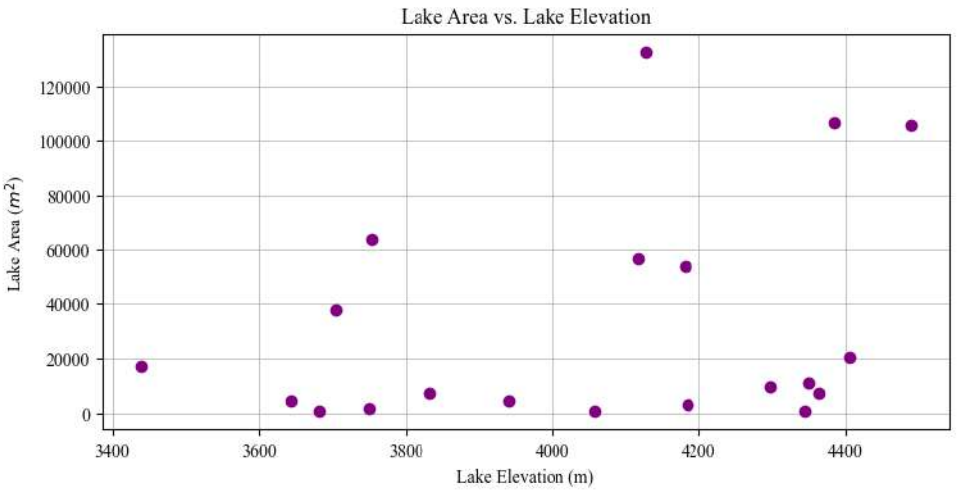
Glacial lakes in the Chitral Basin. Google Earth, Accessed March 2025


Chitral Basin
71.00°E
71.50°E
72.00°E
72.50°E
73.00°E
73.50°E
74.00°E
74.50°E
75.00°E
37.00°N
36.50°N
36.00°N
35.50°N
35.00°N
34.50°N
Anushah
Saklei Shuyinj
Chateboi or Chashboi
Vicenza
Koghi
Hoski-o Shay
Chikar
Pachakush
Gramoghari
Mjragram
Yazodora
Matkash
Upper Tirich
Lower Tirich
Bindo Gol
Owir
Gordoghan
Golen
Sohnyoan
West Lohigal
Andowir
Poshkari
Kachhikhani
Atrak
Koch
Supra Glacial Lakes
Basins
Glacier Boundaries
Rivers
0
25
50 km
N
S
E
W


Number of Lakes vs. Glacier Names
Number of Lakes
0
8
16
24
32
40
48
56
Roshgol
Atrak
Upper Tirich
Niroghi
Others
Koch
Upper Gazikistan
Sachiokuh
Hoski-o Shayoz
Chiantar
Chhutidum
Gazin-Barbin
Lower Gazikistan
Kotalkash
Chhatiboi
Rinzho
Andowir
Koyo
Matkash
Penchus


Number of Lakes vs. Elevation
Number of Lakes
0
8
16
24
32
40
48
56
3400
3600
3800
4000
4200
4400
Lake Elevation (m)


Number of Lakes vs. Slope
Number of Lakes
0
8
16
24
32
40
48
56
14
16
18
20
22
24
Slope of Lakes


Lake Area vs. Lake Elevation
Lake Area (m^2)
0
20000
40000
60000
80000
100000
120000
3400
3600
3800
4000
4200
4400
Lake Elevation (m)

Shyok Basin

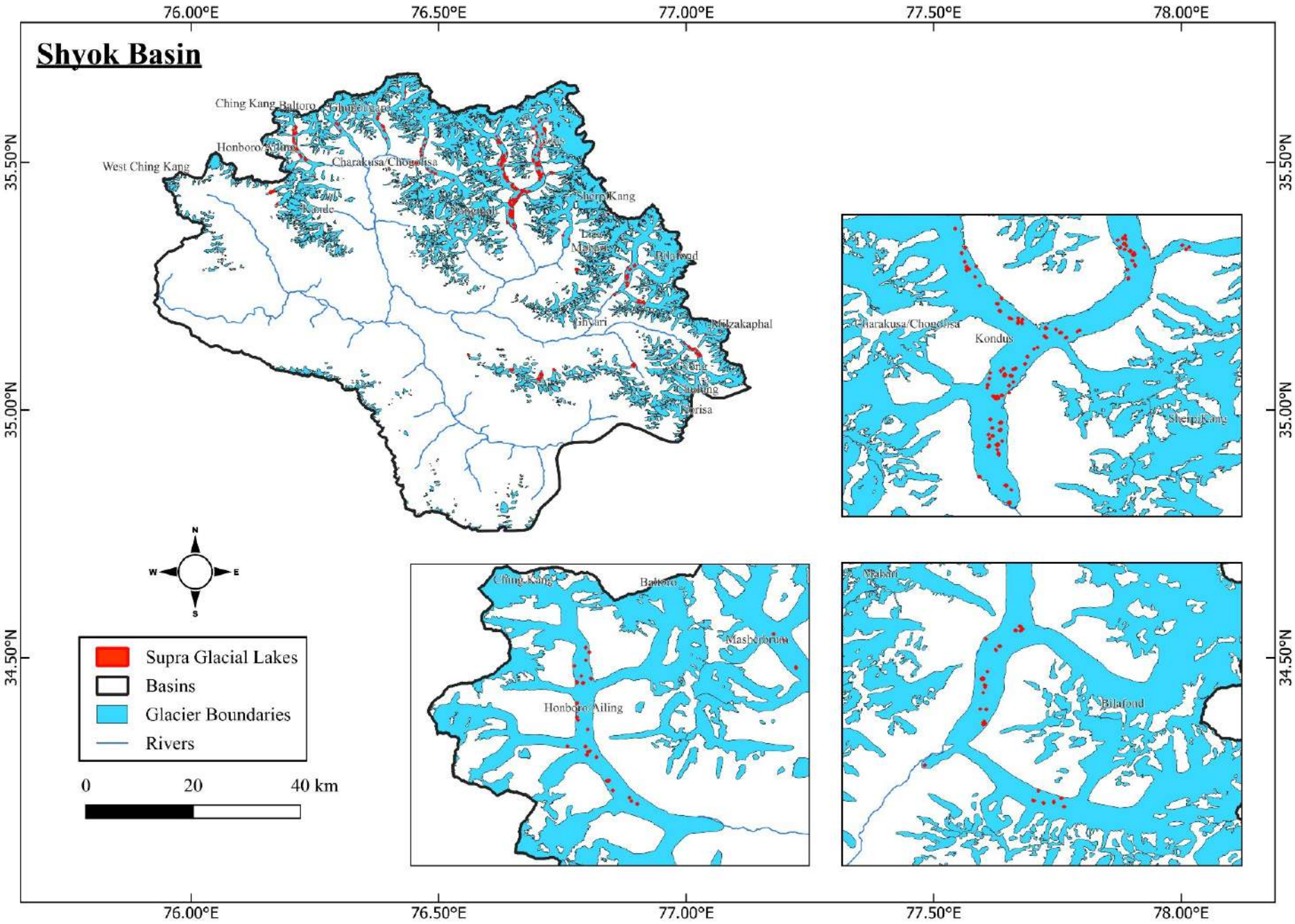
The Shyok Basin, a vital hydrological region in the Karakoram Range, is drained by the Shyok River, which originates from the Rimo Glacier and flows northwest before turning sharply southward near Diskit, forming the iconic “Shyok Loop”.

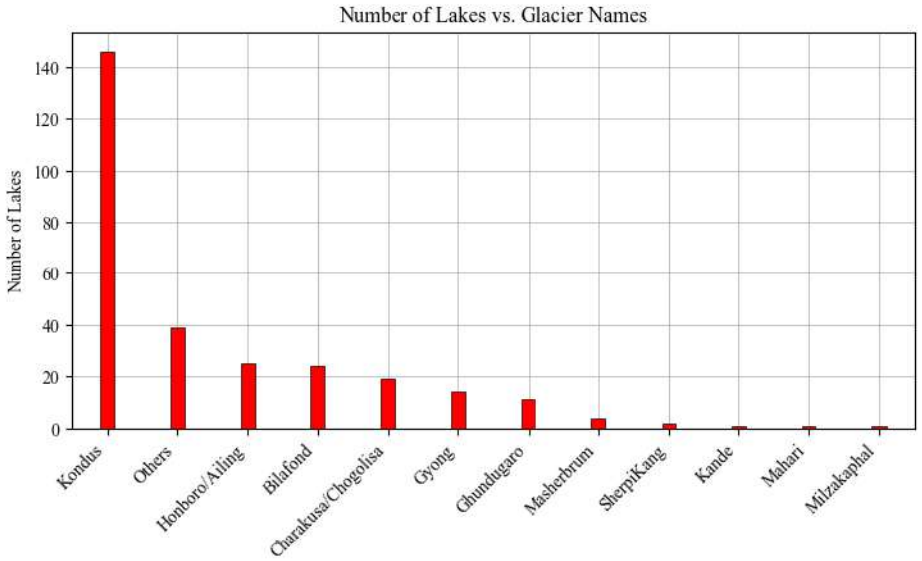
The basin is surrounded by towering peaks and hosts extensive glaciation, including the Chorbat Basin, which contains 197 glaciers covering 74.98 km².

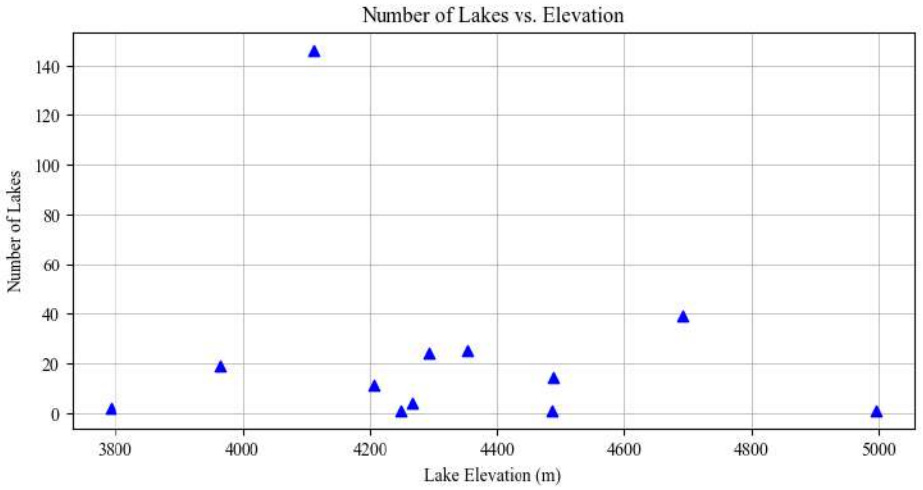
Shyok Basin is the fourth basin in term of total area (9%) and number of glacial lakes (11%). A total of 287 glacial lakes were identified in the Shyok Basin on 11 glaciers. The glacier with the highest number of lakes is Kondus Glacier (146 lakes) followed by the Honboro/Ailing (25 lakes).

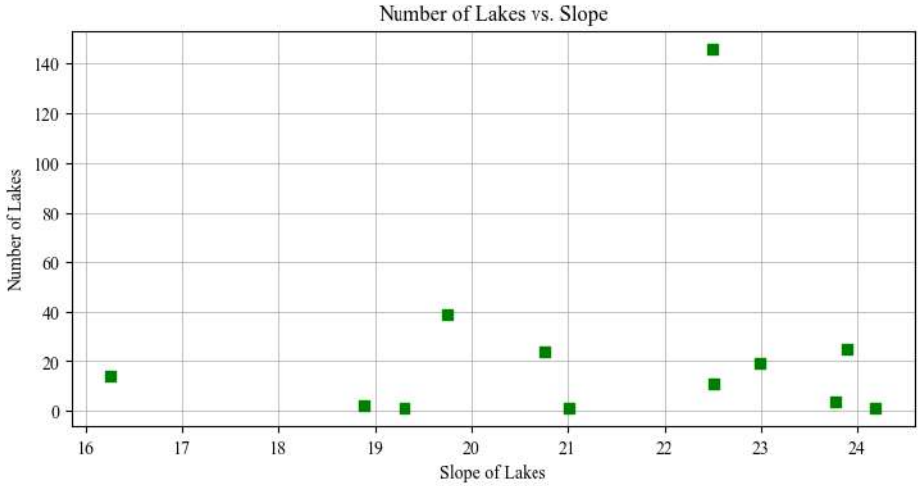
Glacial lakes in the Shyok Basin. Google Earth, Accessed March 2025

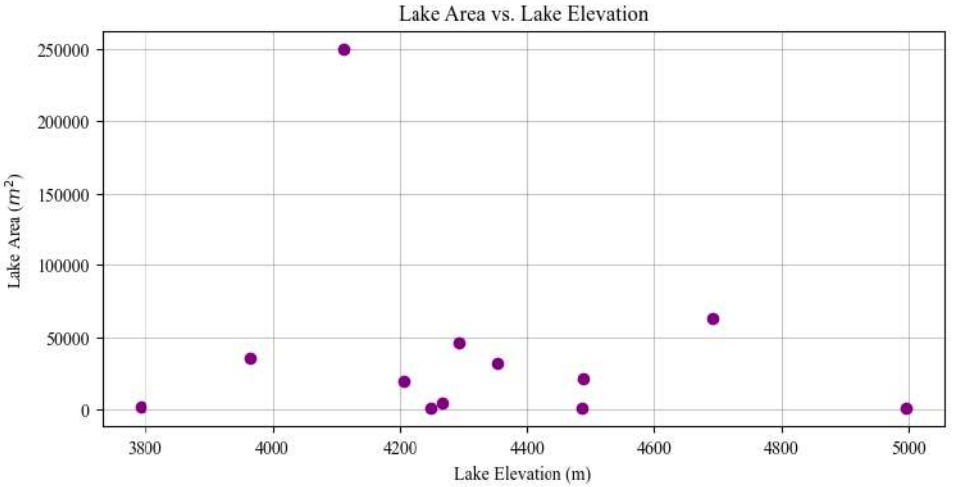
Furthermore, we observe that in this basin the lakes are mainly located on glaciers with gentle slopes (22°-23°), while the elevation of glaciers where the glacial lakes are located range from 3800 to 5000 m a.s.l..


Shyok Basin
76.00°E
76.50°E
77.00°E
77.50°E
78.00°E
35.50°N
35.00°N
34.50°N
Ching Kang
Baltoro
West Ching Kang
Honboro Ailing
Charakusa/Chogolisa
Sherpi Kang
Bilafond
Khyari
Korisa
Kondus
Mashabrum
Supra Glacial Lakes
Basins
Glacier Boundaries
Rivers
0
20
40 km
N
S
E
W


Number of Lakes vs. Glacier Names
Number of Lakes
0
20
40
60
80
100
120
140
Kondus
Others
Honboro/Ailing
Bilafond
Charakusa/Chogolisa
Gyong
Ghundugaro
Masherbrum
SherpiKang
Kande
Mahari
Milzakaphal


Number of Lakes vs. Elevation
Number of Lakes
0
20
40
60
80
100
120
140
3800
4000
4200
4400
4600
4800
5000
Lake Elevation (m)


Number of Lakes vs. Slope
Number of Lakes
0
20
40
60
80
100
120
140
16
17
18
19
20
21
22
23
24
Slope of Lakes


Lake Area vs. Lake Elevation
Lake Area (m^2)
0
50000
100000
150000
200000
250000
3800
4000
4200
4400
4600
4800
5000
Lake Elevation (m)

Gilgit Basin

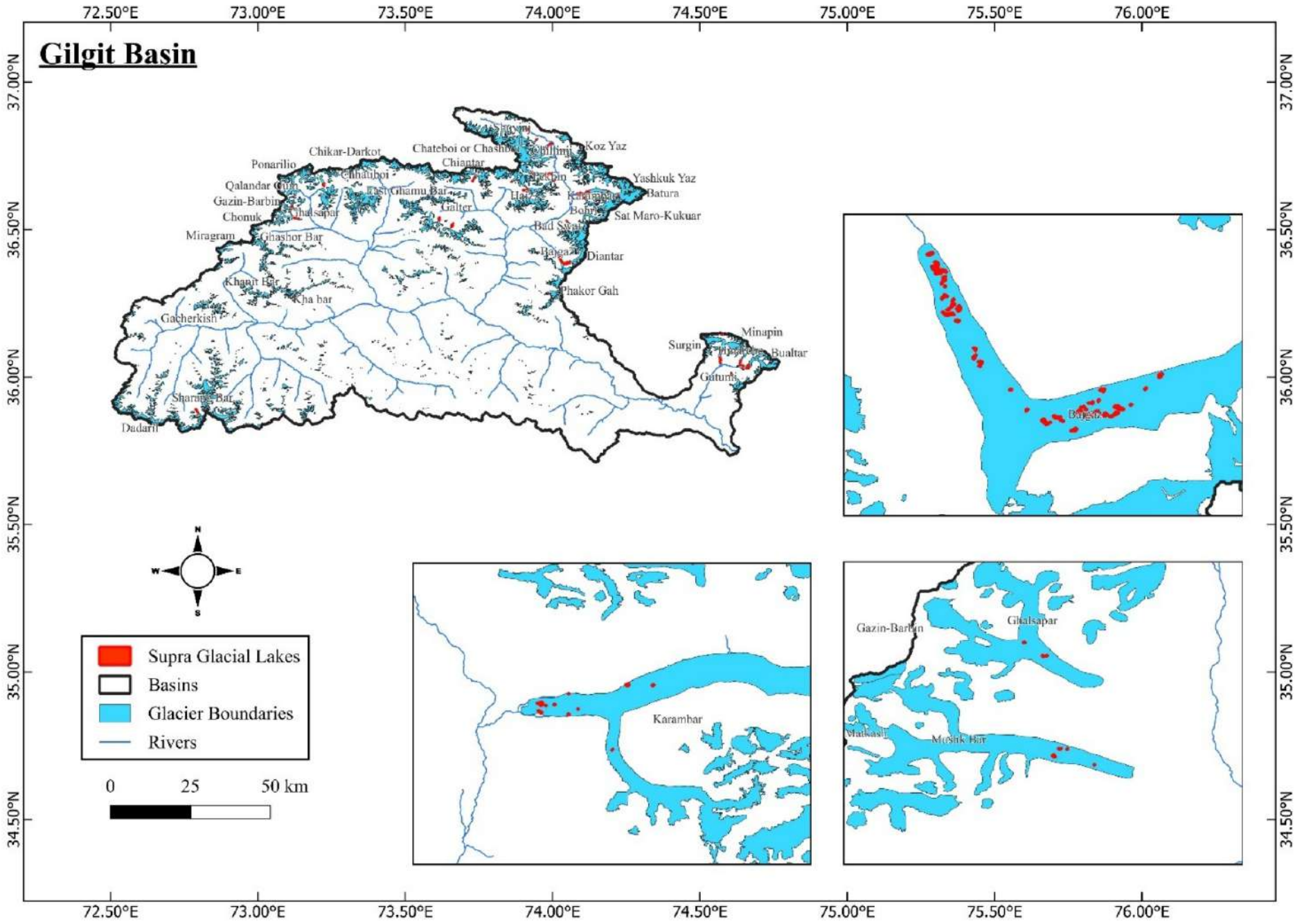
The Gilgit Basin (2,256 km²) spans the Gilgit River between the Ishkoman and Hunza River confluences, encompassing Gilgit city, the capital of Gilgit-Baltistan. Characterized by an arid climate, the basin receives 132 mm annual rainfall (1999–2008) and experiences extreme seasonal temperatures, ranging from -2.5°C in winter to 36.2°C in summer. Local livelihoods depend on agriculture and livestock, sustained by glacier and snowmelt from the Gilgit River.

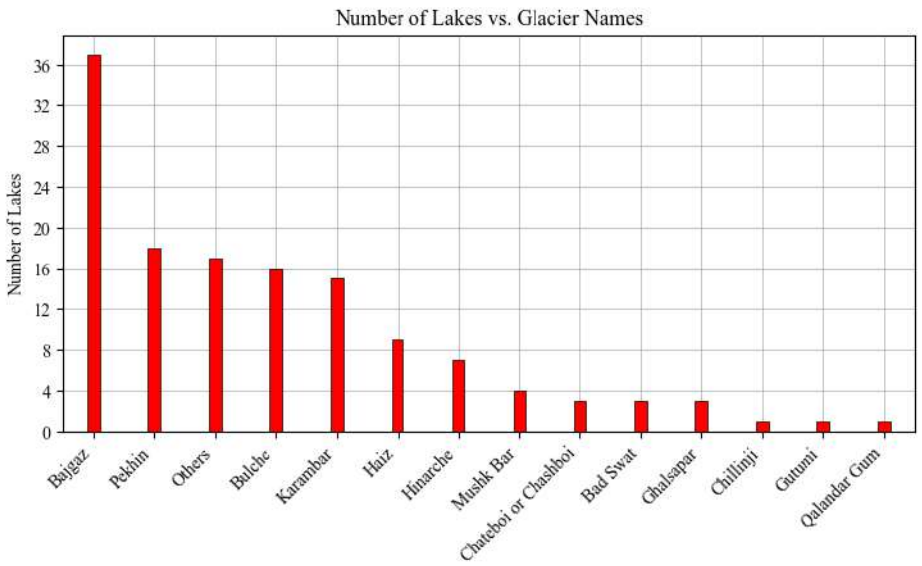
Gilgit Basin is the fifth basin in term of total area (5%) and number of glacial lakes (5%). A total of 135 glacial lakes were identified in the Shyok Basin on 13 glaciers.

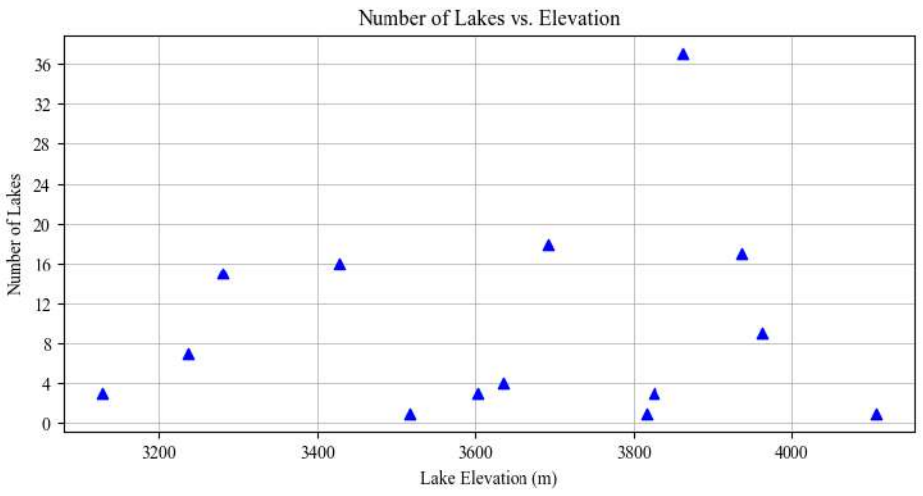
The glacier with the highest number of lakes is Bajgaz Glacier (37 lakes) followed by the Pekhin (18 lakes).

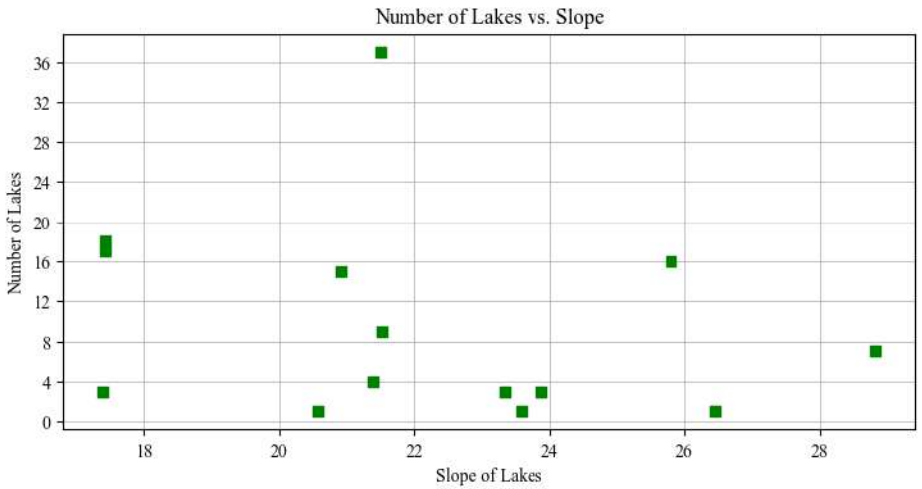
Glacial lakes in the Gilgit Basin. Google Earth, Accessed March 2025.

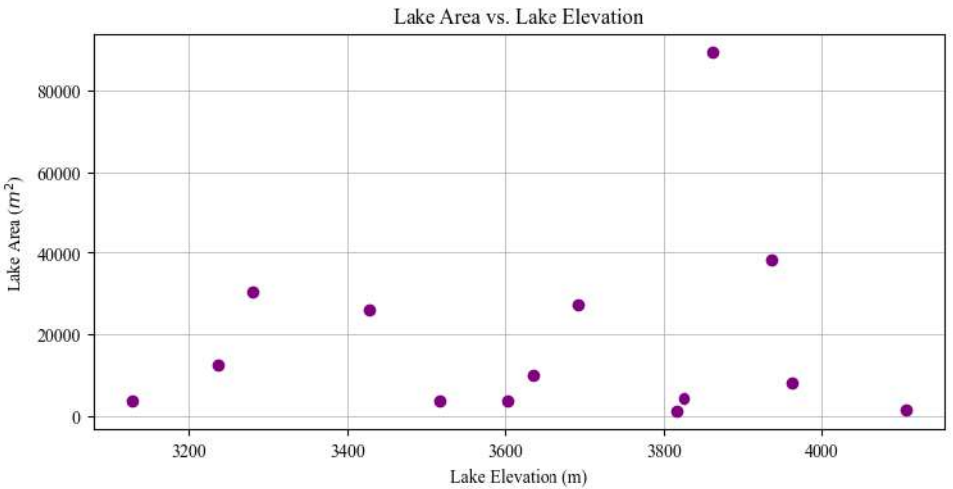
Furthermore, we observe that in this basin the lakes are mainly located on glaciers with gentle slopes (15°-29°), while the elevation of glaciers where the glacial lakes are located range from 3100 to 4100 m a.s.l..


Gilgit Basin
72.50°E
73.00°E
73.50°E
74.00°E
74.50°E
75.00°E
75.50°E
76.00°E
37.00°N
36.50°N
36.00°N
35.50°N
35.00°N
34.50°N
Chikar-Darkot
Chateboi or Chashm
Koz Yaz
Ponarilio
Chiantar
Yashkuk Yaz
Qalandar Gum
Batura
Gazin-Barbin
Ghulsapar
Chonuk
Sat Maro-Kukuar
Miragram
Ghashor Bar
Diantar
Khanit Bar
Phakor Gah
Kha bar
Gacherkish
Minapin
Surgin
Bualtar
Gutumi
Sharmi Bar
Dadarit
Karambar
Gazin-Barbin
Ghulsapar
Matkash
Mushk Bar
N
W
E
S
Supra Glacial Lakes
Basins
Glacier Boundaries
Rivers
0
25
50 km


Number of Lakes vs. Glacier Names
Number of Lakes
0
4
8
12
16
20
24
28
32
36
Bajgaz
Pekhin
Others
Bulche
Karambar
Haiz
Hinarche
Mushk Bar
Chateboi or Chashboi
Bad Swat
Ghalapar
Chillinji
Gutumi
Qalandar Gum


Number of Lakes vs. Elevation
Number of Lakes
0
4
8
12
16
20
24
28
32
36
3200
3400
3600
3800
4000
Lake Elevation (m)


Number of Lakes vs. Slope
Number of Lakes
0
4
8
12
16
20
24
28
32
36
18
20
22
24
26
28
Slope of Lakes


Lake Area vs. Lake Elevation
Lake Area (m^2)
0
20000
40000
60000
80000
3200
3400
3600
3800
4000
Lake Elevation (m)

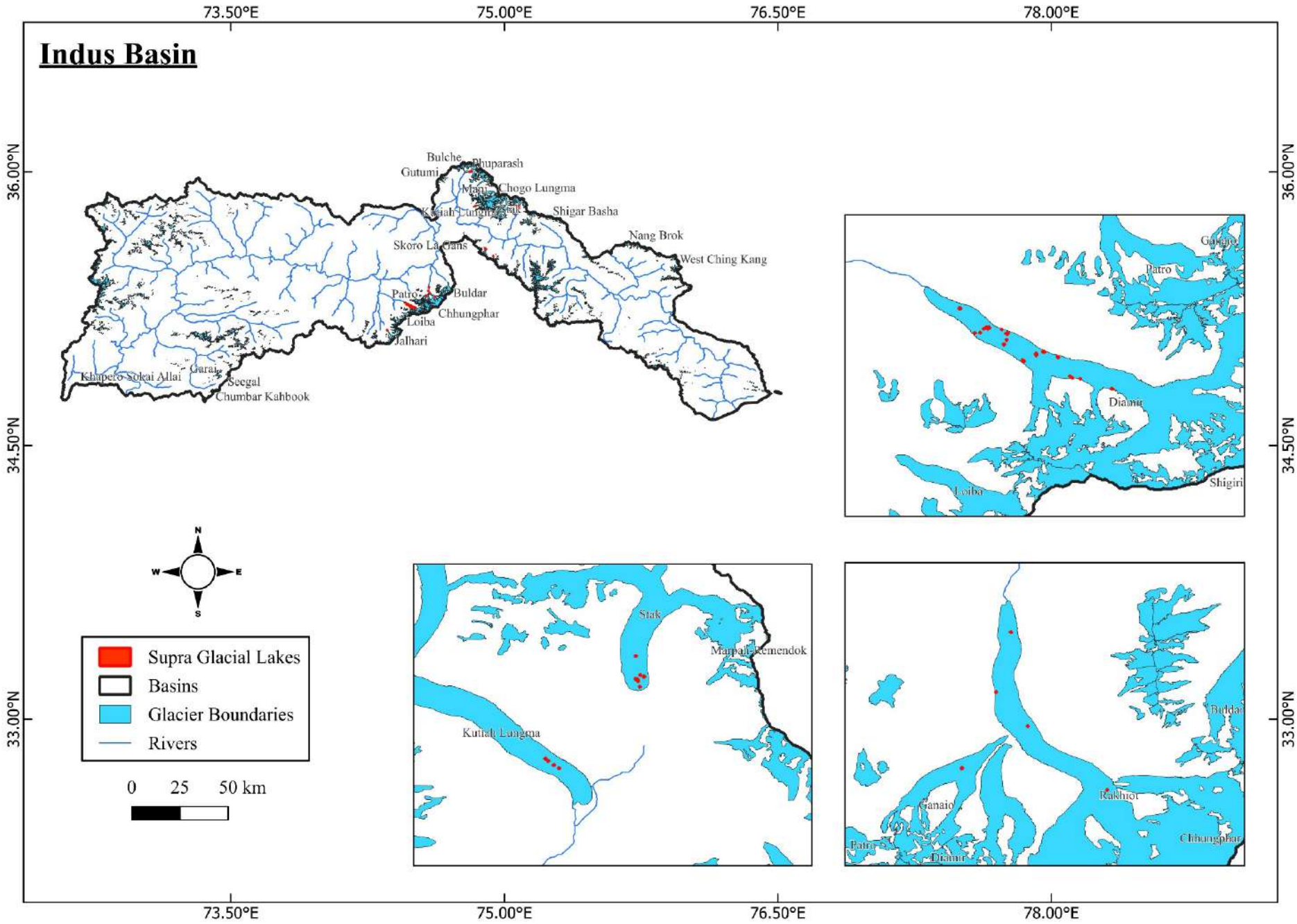
Indus Basin

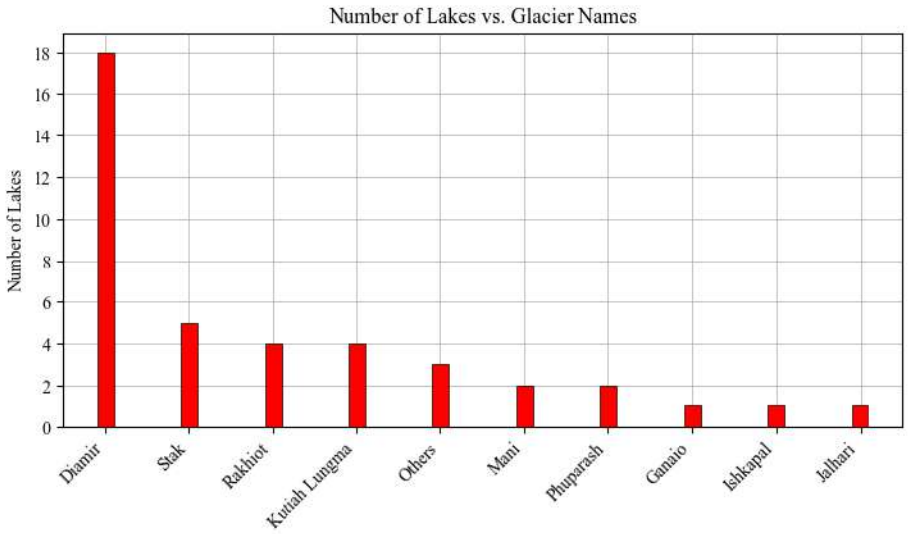
The Indus River Basin encompasses several significant sub-basins, including the Jaglot, Haramosh, and Tangir basins, each contributing uniquely to the region's hydrology and glaciation.

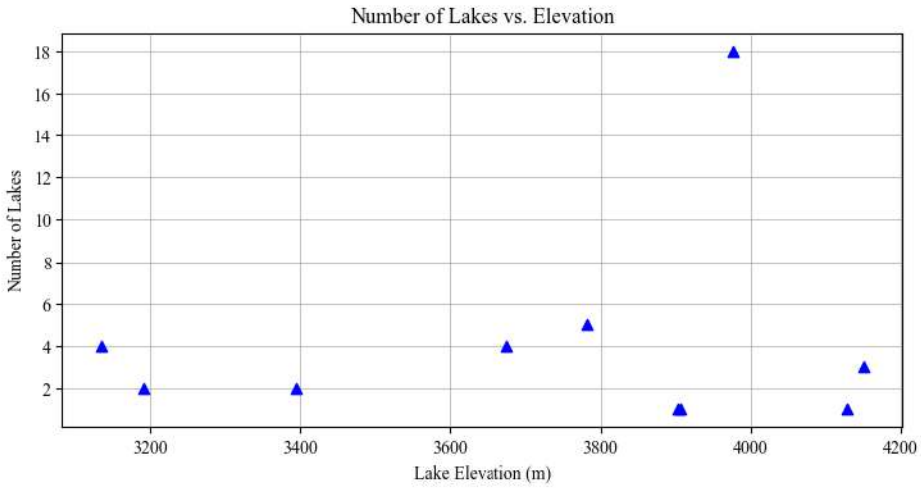
A total of 41 glacial lakes were identified in the Indu Basin, 18 of them are located on the Diamir Glacier and other 5 on the Stak Glacier.

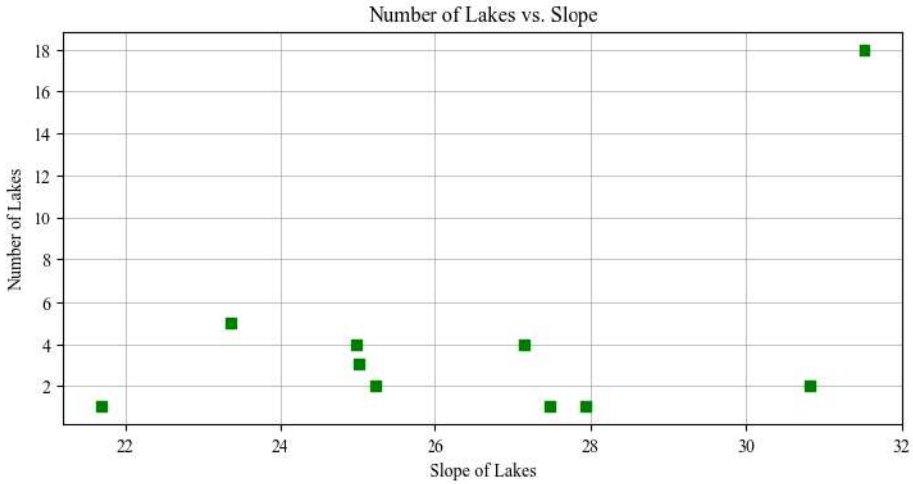
The total area of these lakes is 0.06 km^2. This glacier has a mean slope of around 20° ranging from 3100 and 4100 m a.s.l..

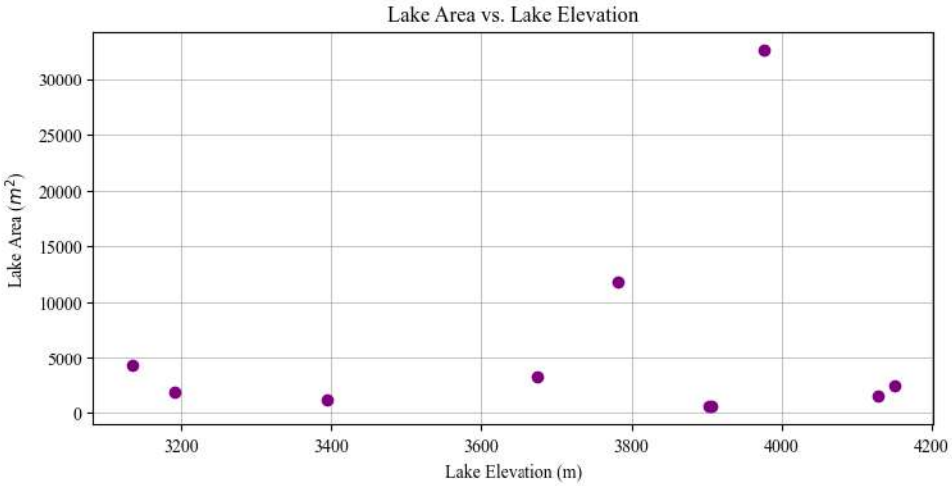
Glacial lakes in the Indus Basin. Google Earth, Accessed March 2025


Indus Basin
73.50°E
75.00°E
76.50°E
78.00°E
36.00°N
34.50°N
33.00°N
Bulche
Gutumi
Bhuparash
Mani
Chogo Lungma
Kutiah Lungma
Shigar Basha
Nang Brok
Skoro La Glans
West Ching Kang
Patro
Buldar
Chhungphar
Loiba
Jalhari
Khupero
Sokai Allai
Garai
Seegal
Chumbar Kahbook
Ganajo
Patro
Diamir
Loiba
Shigiri
Stak
Marpali-Kemendok
Kutiah Lungma
Budda
Rakhiot
Ganaio
Patro
Diamir
Chhungphar
N
W
E
S
Supra Glacial Lakes
Basins
Glacier Boundaries
Rivers
0 25 50 km


Number of Lakes vs. Glacier Names
Number of Lakes
Diamir
Stak
Rakhiot
Kutiah Lungma
Others
Mani
Phuparash
Ganaio
Ishkapal
Jalhari


Number of Lakes vs. Elevation
Number of Lakes
Lake Elevation (m)


Number of Lakes vs. Slope
Number of Lakes
Slope of Lakes


Lake Area vs. Lake Elevation
Lake Area (m^2)
Lake Elevation (m)

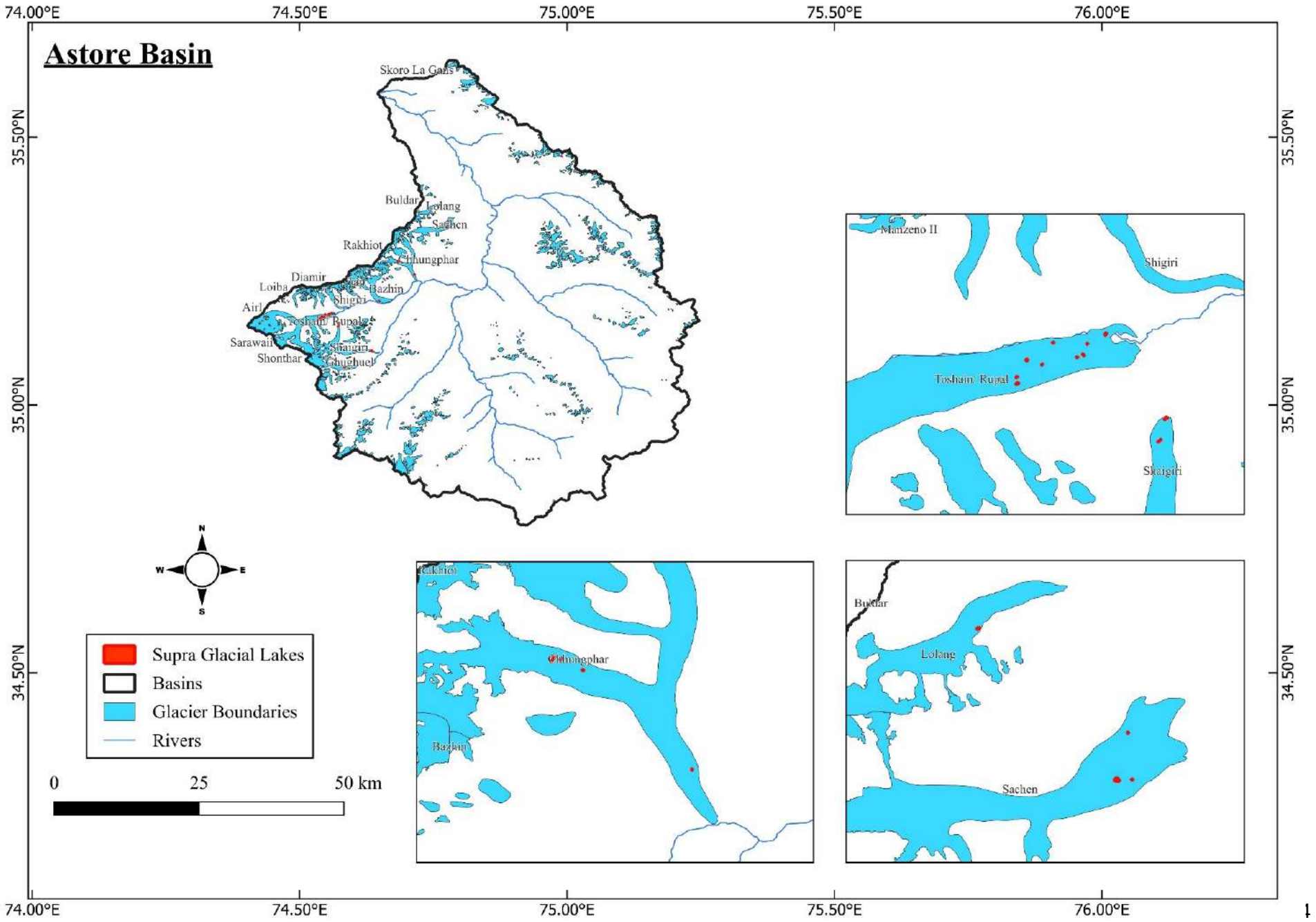
Astore Basin

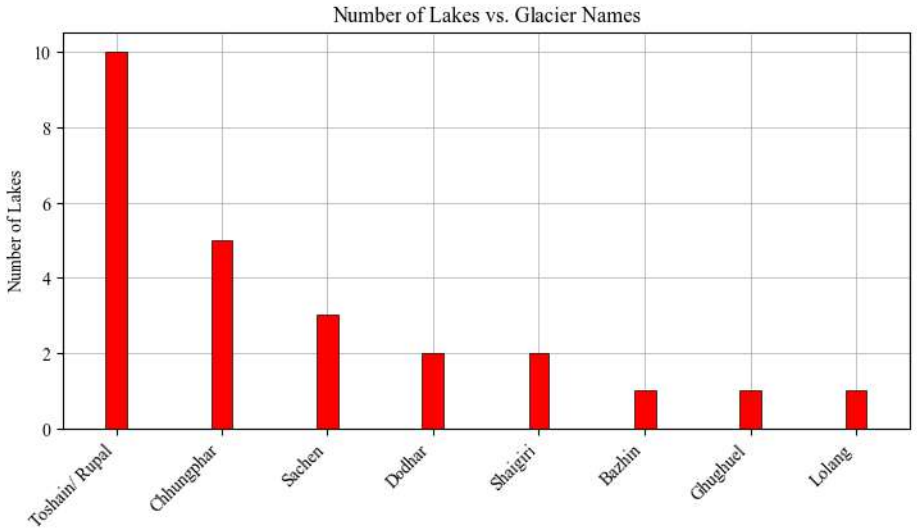
The Astore Basin (2,142 km²), east of the Diamir Range, is formed by the confluence of the Rupal and Astore rivers near Gehrak, with a southern branch extending toward the Deosai Plateau.

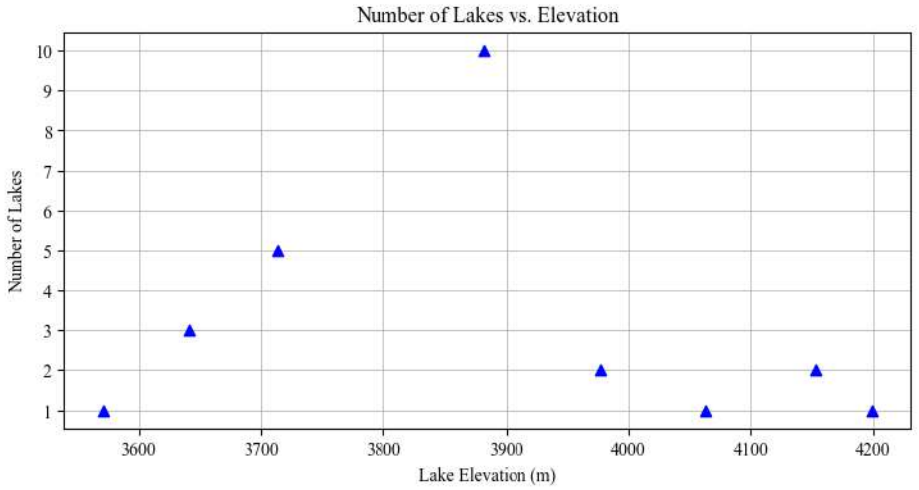
The Astore River flows north past Astore city into the Indus. Climate data (1961–2019) from Astore (2,167 m) show a 9.8°C mean temperature and 464 mm annual rainfall, while Burzil (4,030 m) averages -2.9°C and 870 mm precipitation (1980–2010).

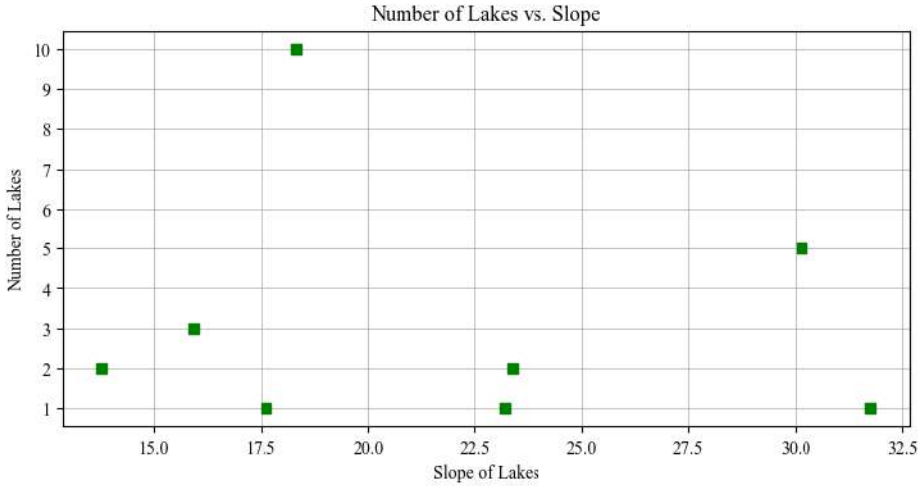
25 glacial lake were identified in the Astore Basin. The total area of these lakes is around 0.04 km². The glacier with the highest lake number is called Toshain/ Rupal with a slope 18° a 3800 m a.s.l..

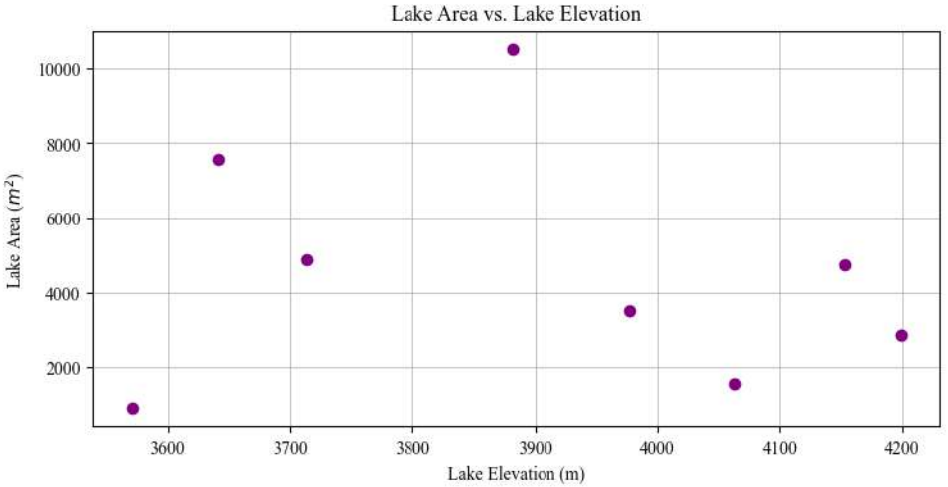
Glacial lakes in the Astore Basin. Google Earth, Accessed March 2025.


Astore Basin
74.00°E
74.50°E
75.00°E
75.50°E
76.00°E
35.50°N
35.00°N
34.50°N
Skoro La Gans
Buldar
Lolang
Sachen
Rakhiot
Chhungphar
Diamir
Loiba
Bazhin
Shigiri
Airl
Toshain Rupal
Sarawail
Shaigiri
Shonthar
Manzeno II
Bazhin
N
W
E
S
Supra Glacial Lakes
Basins
Glacier Boundaries
Rivers
0
25
50 km


Number of Lakes vs. Glacier Names
Number of Lakes
Toshain/ Rupal
Chhungphar
Sachen
Dodhar
Shaigiri
Bazhin
Ghughuel
Lolang


Number of Lakes vs. Elevation
Number of Lakes
Lake Elevation (m)


Number of Lakes vs. Slope
Number of Lakes
Slope of Lakes


Lake Area vs. Lake Elevation
Lake Area (m^2)
Lake Elevation (m)

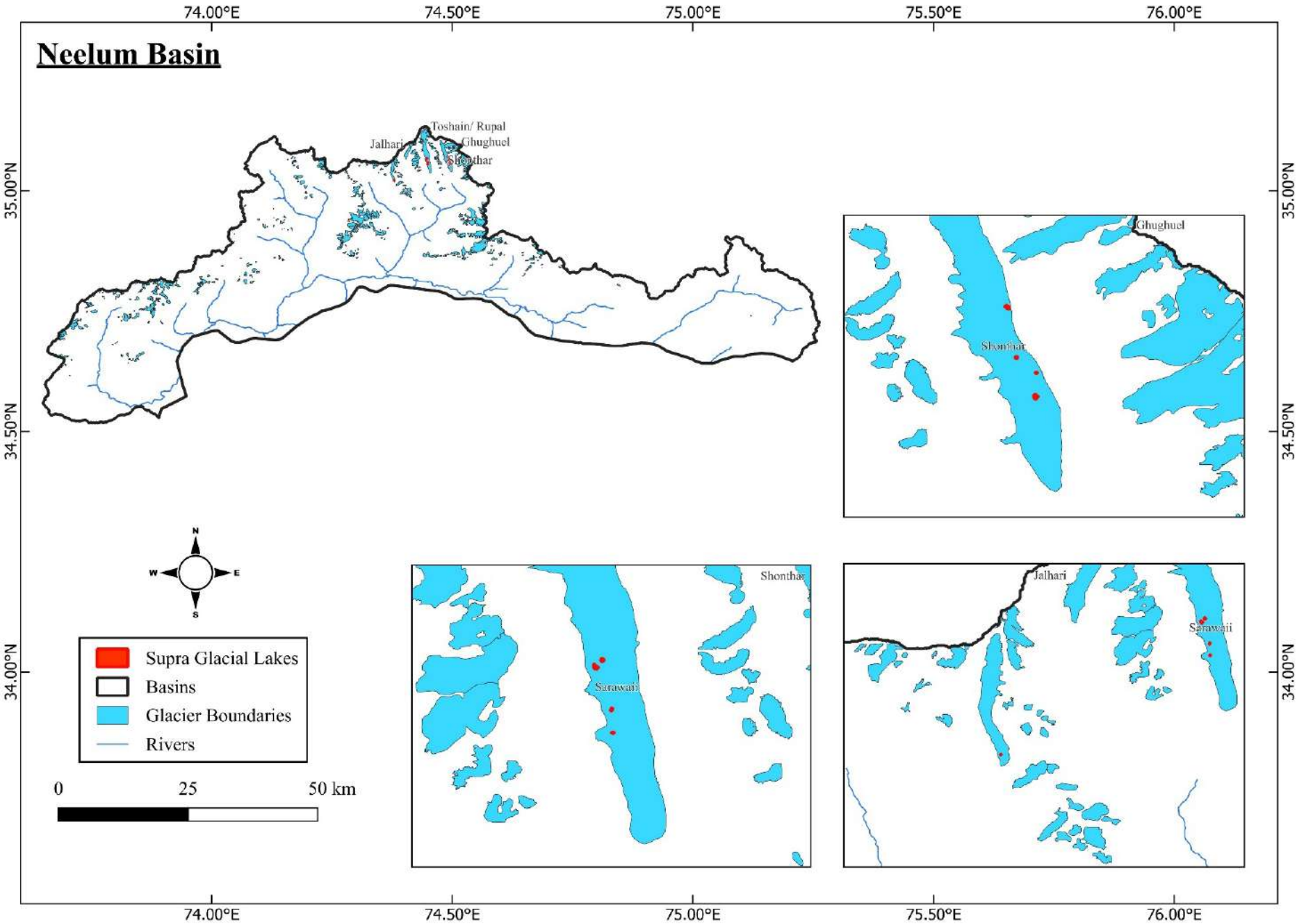
Neelum Basin

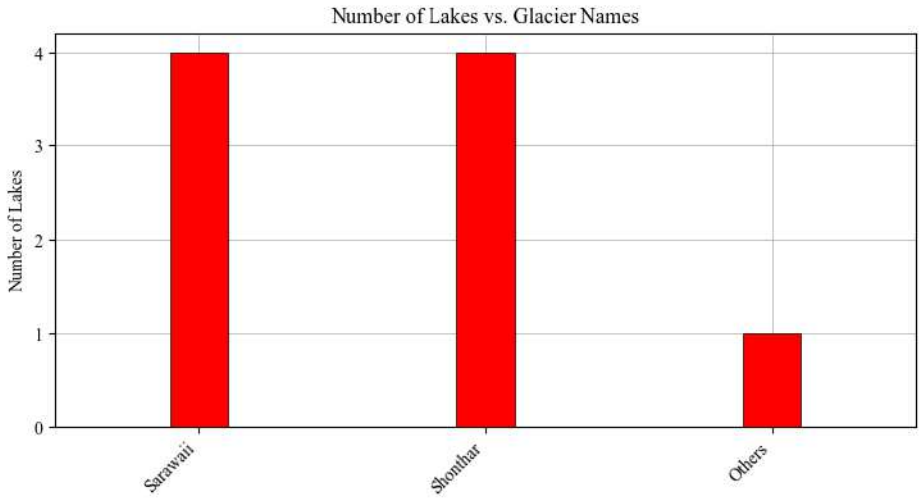
The Lower Neelum Basin (2,385 km²) spans the Neelum River downstream of Kel, including the Shounter sub-basin under Sarawali Peak (6,326 m). Major glaciers like Sarawali (8.78 km²) and Shonthar (6.81 km²) feature debris-covered tongues, while smaller glaciers cluster on the river's right bank.

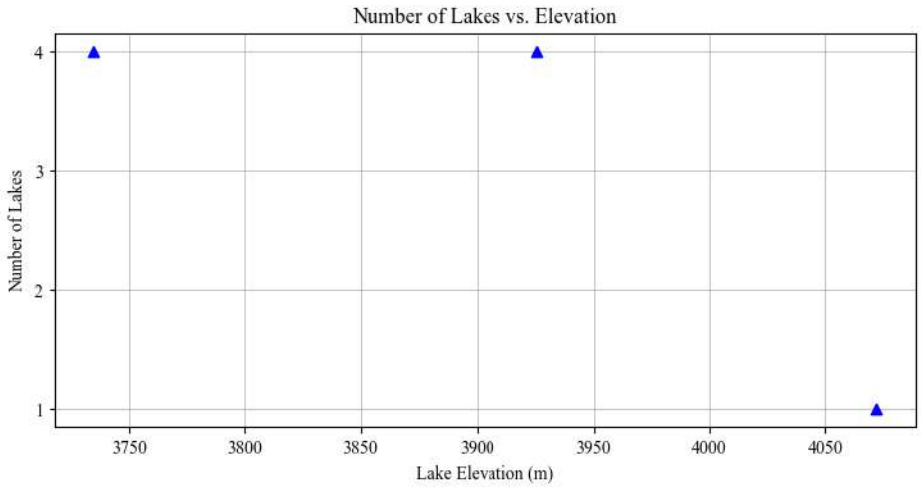
The region has a temperate climate (0–30°C) and 1,650 mm annual rainfall, supporting agriculture (corn, beans) and emerging tourism. Glaciers in the 0.1–0.5 km² class cover 25.84% of the total 125.17 km² area.

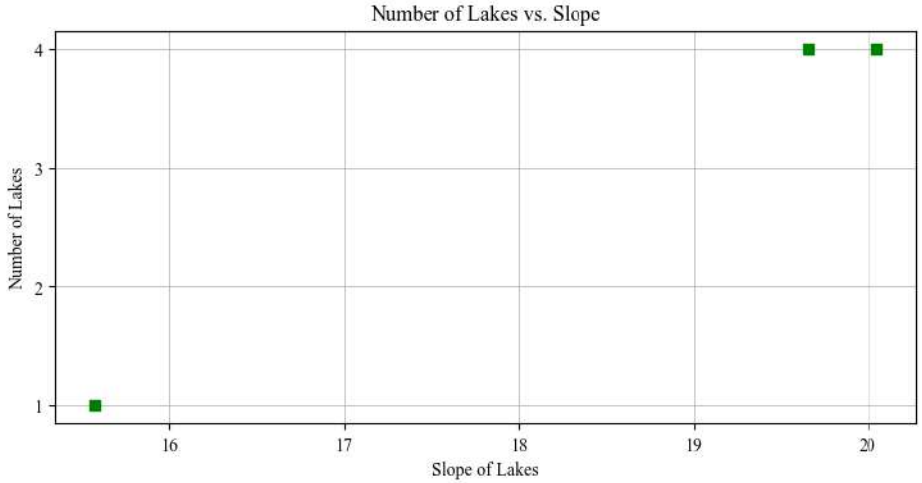
A total of 9 glacial lakes were identified in the Neelum Basin, 4 of them are located on the Sarawaii Glacier and other 4 on the Shonthar Glacier. The total area of these lakes is 0.02 km². This glacier has a mean slope of around 20° ranging from 3700 and 4000 m a.s.l..

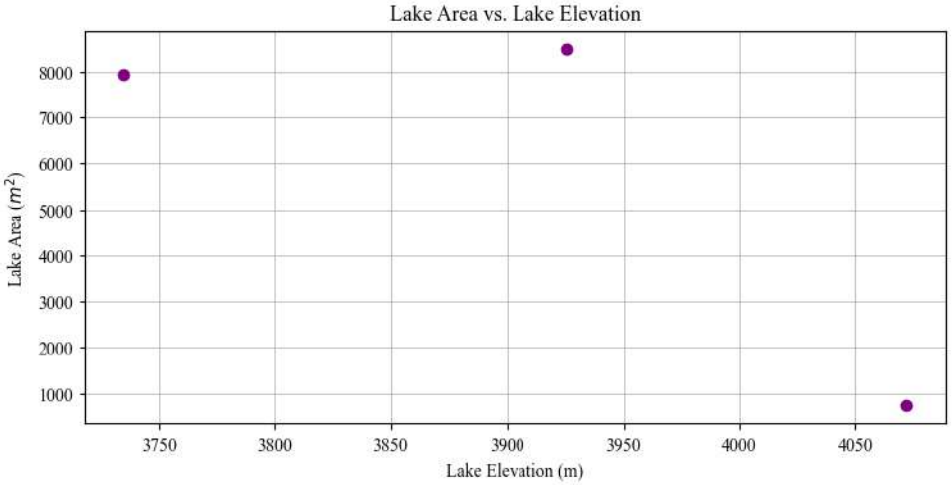
Glacial lakes in the Neelum Basin. Google Earth, Accessed March 2025.


Neelum Basin
74.00°E
74.50°E
75.00°E
75.50°E
76.00°E
35.00°N
34.50°N
34.00°N
Toshain/ Rupal
Jalhari
Ghughuel
Shonthar
Ghughuel
Shonthar
Shonthar
Sarawaii
Jalhari
Sarawaii
N
W
E
S
Supra Glacial Lakes
Basins
Glacier Boundaries
Rivers
0
25
50 km


Number of Lakes vs. Glacier Names
Number of Lakes
0
1
2
3
4
Sarawali
Shonthar
Others


Number of Lakes vs. Elevation
Number of Lakes
1
2
3
4
3750
3800
3850
3900
3950
4000
4050
Lake Elevation (m)


Number of Lakes vs. Slope
Number of Lakes
1
2
3
4
16
17
18
19
20
Slope of Lakes


Lake Area vs. Lake Elevation
Lake Area (m^2)
1000
2000
3000
4000
5000
6000
7000
8000
3750
3800
3850
3900
3950
4000
4050
Lake Elevation (m)

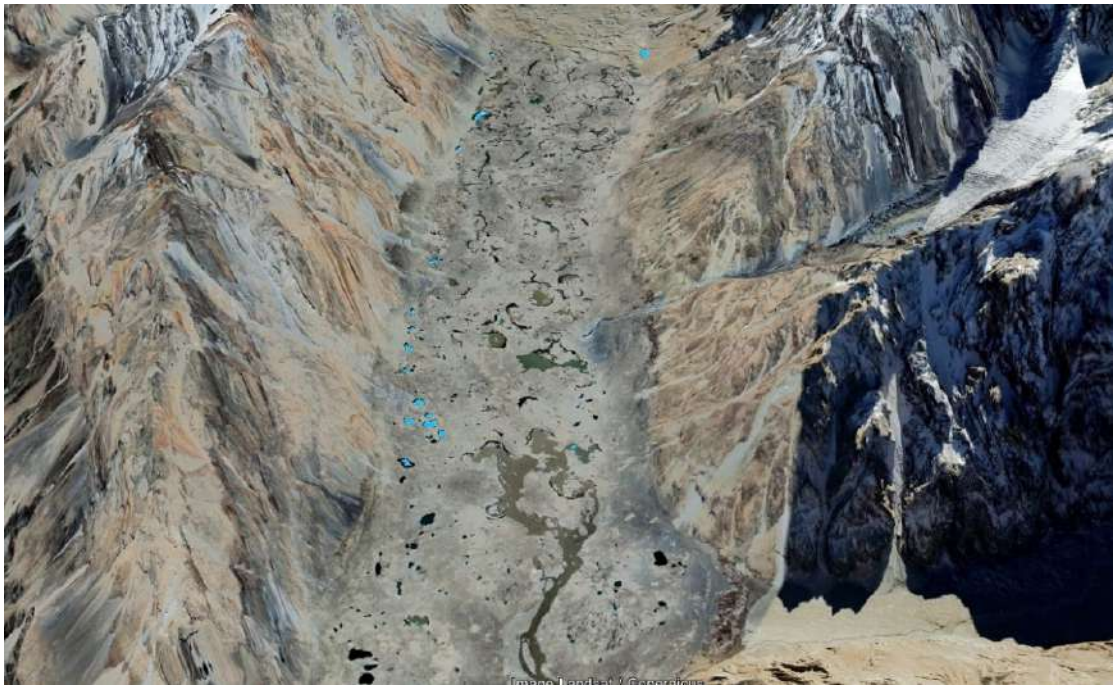
Shaksgam Basin

The Shaksgam Basin (757 km²), Pakistan's northernmost catchment bordering China, drains into Central Asia's Tarim River via the Shaksgam and Yarkand rivers.

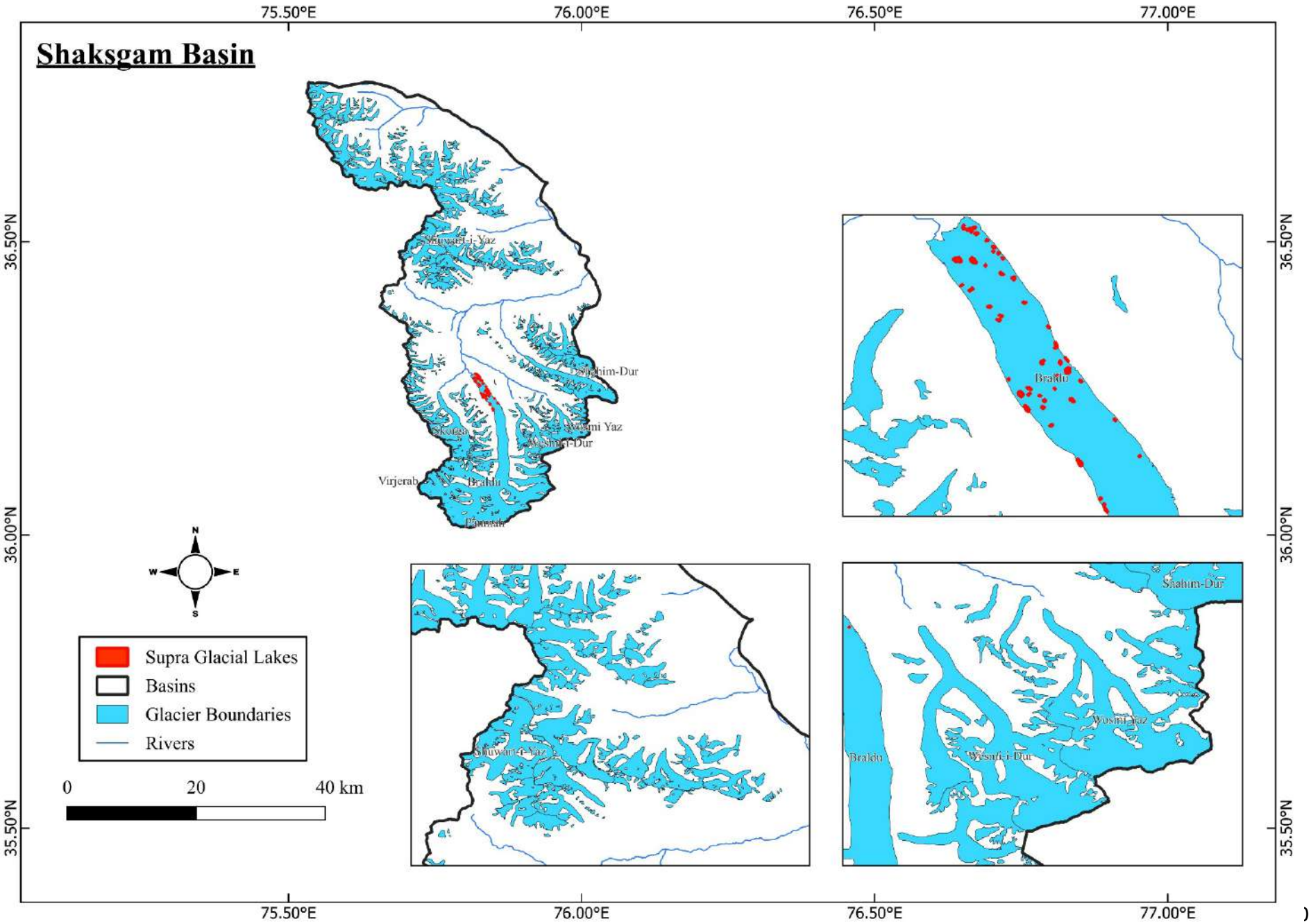
This remote region, historically explored in the early 20th century, serves as winter pasture for Shimshal villagers.

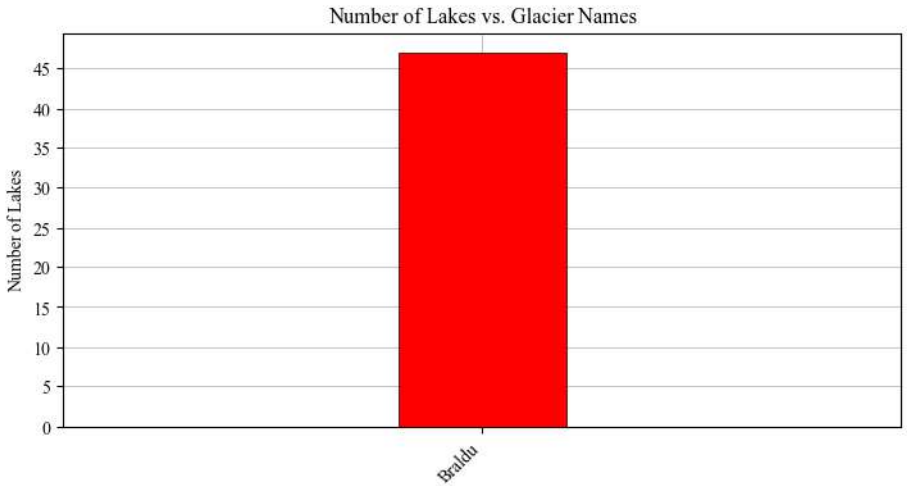
A total of 47 glacial lakes were identified in the Shaksgam Basin, all of them are located on the Braldu glacier.

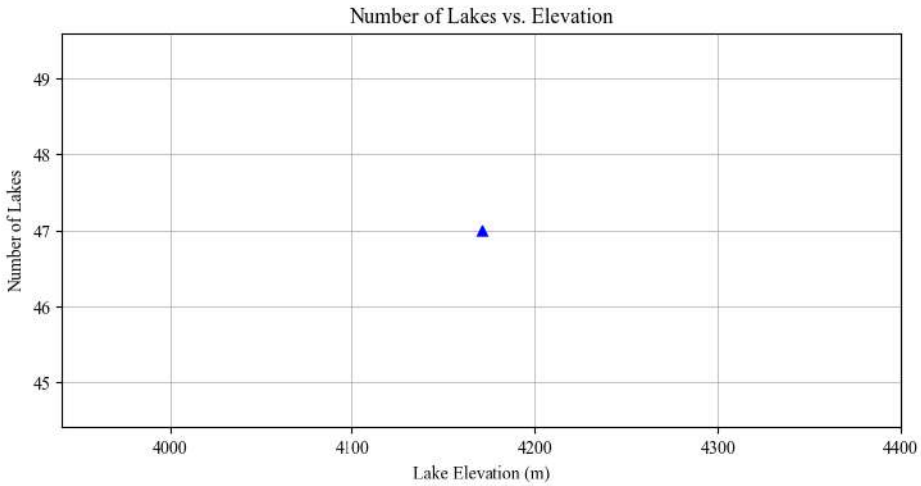
The total area of these lakes is 0.13 km². This glacier has a mean slope of 17° and a minimum elevation of 3991 m a.s.l.. The mean elevation of the 47 lakes is 4170 m a.s.l..

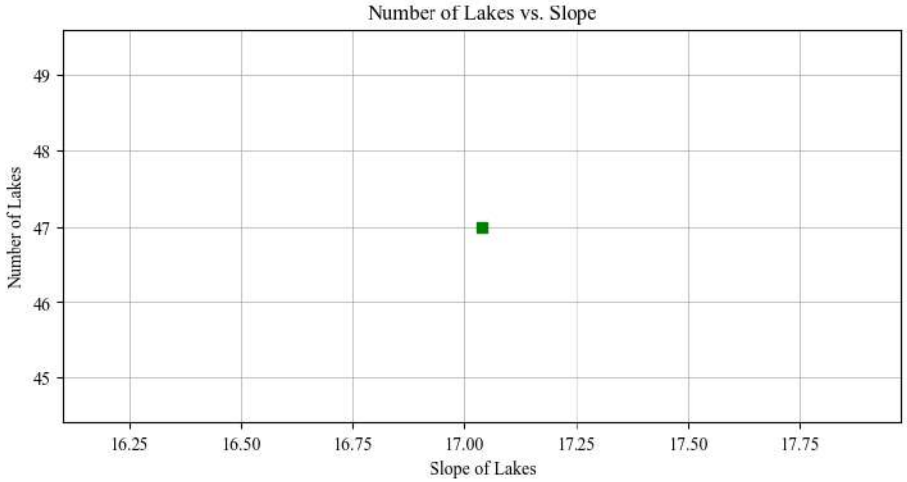


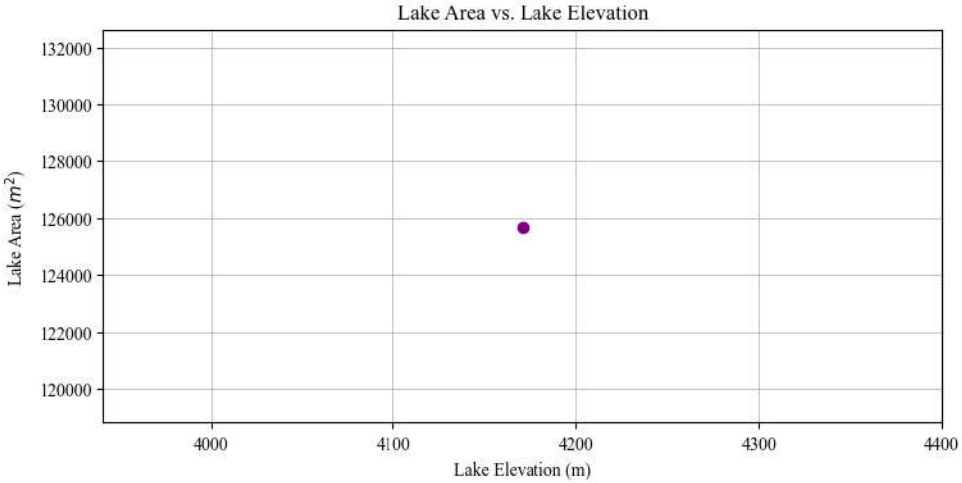
Glacial lakes in the Shaksgam Basin. Google Earth, Accessed March 2025


Shaksgam Basin
75.50°E
76.00°E
76.50°E
77.00°E
36.50°N
36.00°N
35.50°N
Shaahim-Dur
Braldu
Virjerab
N
W
E
S
Supra Glacial Lakes
Basins
Glacier Boundaries
Rivers
0
20
40 km


Number of Lakes vs. Glacier Names
Number of Lakes
0
5
10
15
20
25
30
35
40
45
Braldu


Number of Lakes vs. Elevation
Number of Lakes
45
46
47
48
49
4000
4100
4200
4300
4400
Lake Elevation (m)


Number of Lakes vs. Slope
Number of Lakes
45
46
47
48
49
16.25
16.50
16.75
17.00
17.25
17.50
17.75
Slope of Lakes


Lake Area vs. Lake Elevation
Lake Area (m^2)
120000
122000
124000
126000
128000
130000
132000
4000
4100
4200
4300
4400
Lake Elevation (m)

Future perspectives

Although lakes located at the glacier termini are observed increasing, we are not able to explain the underlying processes nor predict future risk. When the moraines fail, a glacier lake outburst flood (GLOF) can be generated, and GLOFs have caused thousands of fatalities and long-term economic damage. Flood wave triggered by a rock and ice avalanche generated by a GLOF can kill hundreds of people showing how relevant this research is.

In this project we created a large-scale satellite-based classification of existing glacial lakes in Pakistan, i.e, we created the knowledgebase of the GLOF risk in the region.

Future initiatives should implement the use of remotely sensed data, the new technologies as the Artificial intelligence (e.g., Machine Learning) and the access to "Satellite Big Data" to propose a dedicated framework to be considered for the GLOFs pre- Early Warning System in Pakistan.

We identified three main steps:

1) To generate a final inventory of glacial lakes
2) To address the GLOF susceptibility assessment
3) To create a Pre-Early-Warning assessment of the GLOF risk in selected valleys of Pakistan

Final inventory of glacial lakes

The inventory realized here is considered preliminary because, according to its aims, these analyses were carried out to develop a methodological framework in order to map correctly the supraglacial lakes in the entire regions. Particularly, this work allowed 1) analyzing the inter and intra-annual variability in the lake development; 2) detecting and mapping (semi-automatically) the supraglacial lakes; 3) managing and reducing the uncertainty related to the mapping.

The updated inventory will consider Proglacial and Lateral lakes mapped based on the same images and same period.

GLOF susceptibility assessment

A future initiative should determine the role of glacier lakes as a potential GLOF hazard using the GLACIAL LAKES INVENTORY created in this project as knowledge base. Furthermore, future initiatives should be addressed in understanding the role of glacier lakes as potential risk for safety of people in Pakistan.

Particularly, high resolution satellite imagery and field observations could be used to study the formation process of pro- and supra glacial lakes and consequently a regional scale hazard assessment based on mathematical modelling could be developed.

In the following we list some initiatives which could be implemented for a SUSTAINABLE MANAGEMENT OF THE GLOF RISK IN PAKISTAN.

Some key activities:

1. To quantify rates of change of glacial lakes in the last decades starting from this inventory
2. To identify possible mechanisms for lake formation based on field work and high-resolution satellite imagery
3. Develop a satellite-based regional hazard assessment

Early-warning assessment of the GLOF risk in selected valleys

A further phase could pilot the application of a GLOF pre-early warning in some selected valleys of Pakistan. A possible framework could rely on an innovative approach based on remotely sensed data, new technologies such as machine learning and access to "Satellite Big Data".

This system could be based on a dedicated Web-Platform for the access to data and maps from very high temporal and spatial resolution satellite imagery to monitor high risk glacial lakes. It could be also proposing the identification and definition, through a GEO database, of the mechanisms leading to glacial lake formation (from historic data) and the risk thresholds allowing relevant authorities to activate preventive measures such as field visits or glacial lakes drainage.

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