UNIVERSITÀ DEGLI STUDI DI MILANO

ITALIAN AGENCY FOR DEVELOPMENT COOPERATION

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EvK2CNR

Current behaviour of glaciers in Pakistan and implications for future water availability

Dr. Davide Fugazza, Glaciologist - EvK2CNR and University of Milan

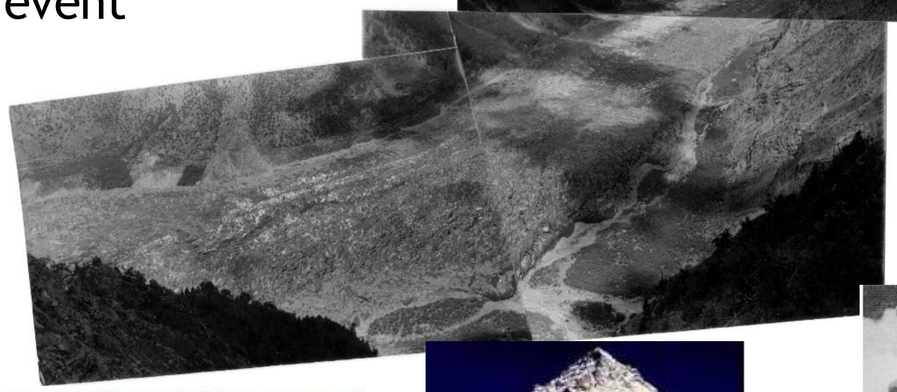


UNIMI Research in Pakistan

The Italian contribution to study the cryosphere of Pakistan started in 1954 with Ardito Desio and the K2 expedition….

The Kutiah Glacier which in 1954 experienced a surge type event









The expedition which performed the first ascent to K2 summit on the 31st of July 1954



www.arditodesio.it

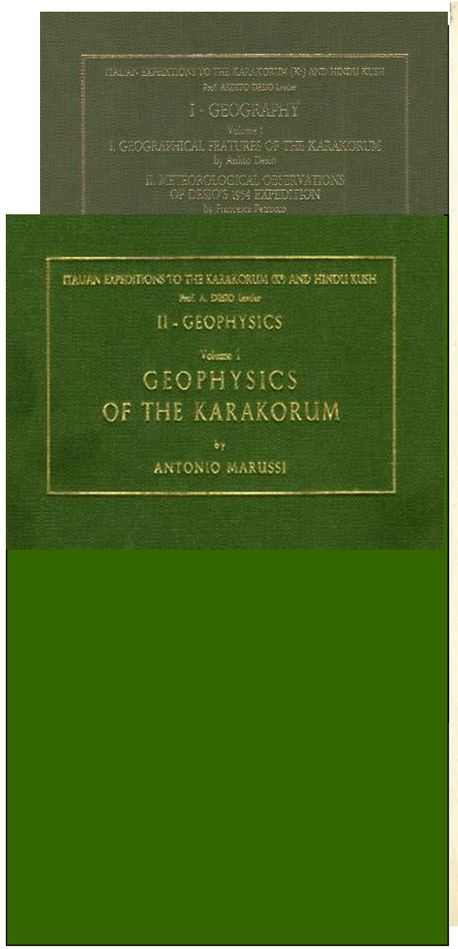


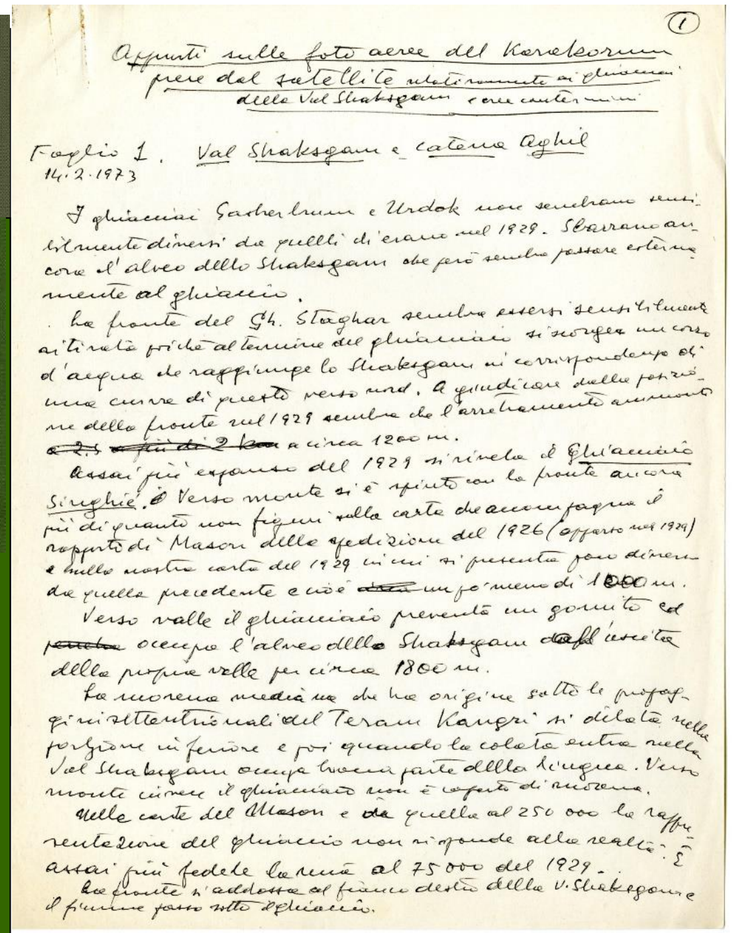
www.arditodesio.it



On the trails of Ardito Desio

A large amount of data have been collected since then providing a knowledge base on this important glacierized area





(1)

Appunti sulle foto aeree del Karakorum prese dal satellite relativamente ai ghiacciai della Val Shaksgam e aree contermini

Foglio 1. Val Shaksgam e catena Aghil
14.2.1973

I ghiacciai Gasherbrum e Urdok non sembrano sensibilmente diversi da quelli di erano nel 1929. Sbarrano ancora l'alveo dello Shaksgam che però sembra passare esternamente al ghiaccio.

La fronte del Gh. Staghar sembra essersi sensibilmente ritirata poiché al termine del ghiacciaio si scorge un corso d'acqua che raggiunge lo Shaksgam in corrispondenza di una curva di questo verso nord. A giudicare dalla posizione della fronte nel 1929 sembra che l'arretramento ammonti ~~a 2,5 ... più di 2 km~~ a circa 1200 m.

Assai più espanso del 1929 si rivela il Ghiacciaio Singhie. Il Verso monte si è spinto con la fronte ancora più di quanto non figuri sulla carta che accompagna il rapporto di Mason della spedizione del 1926 (apparso nel 1929) e sulla nostra carta del 1929 in cui si presenta poco diverso da quella precedente e cioè ~~...~~ un po' meno di 1000 m.

Verso valle il ghiacciaio prevente un gomito ed ~~...~~ occupa l'alveo dello Shaksgam dall'uscita della propria valle per circa 1800 m.

La morena mediana che ha origine sotto le propaggini settentrionali del Teram Kangri si dilata nella porzione inferiore e poi quando la colata entra nella Val Shaksgam occupa buona parte della lingua. Verso monte invece il ghiacciaio non è coperto di morena.

Nelle carte del Mason e da quella al 250 000 la rappresentazione del ghiaccio non risponde alla realtà. È assai più fedele la mia al 75 000 del 1929.

La fronte si addossa al fianco destro della V. Shaksgam e il fiume passa sotto il ghiaccio.



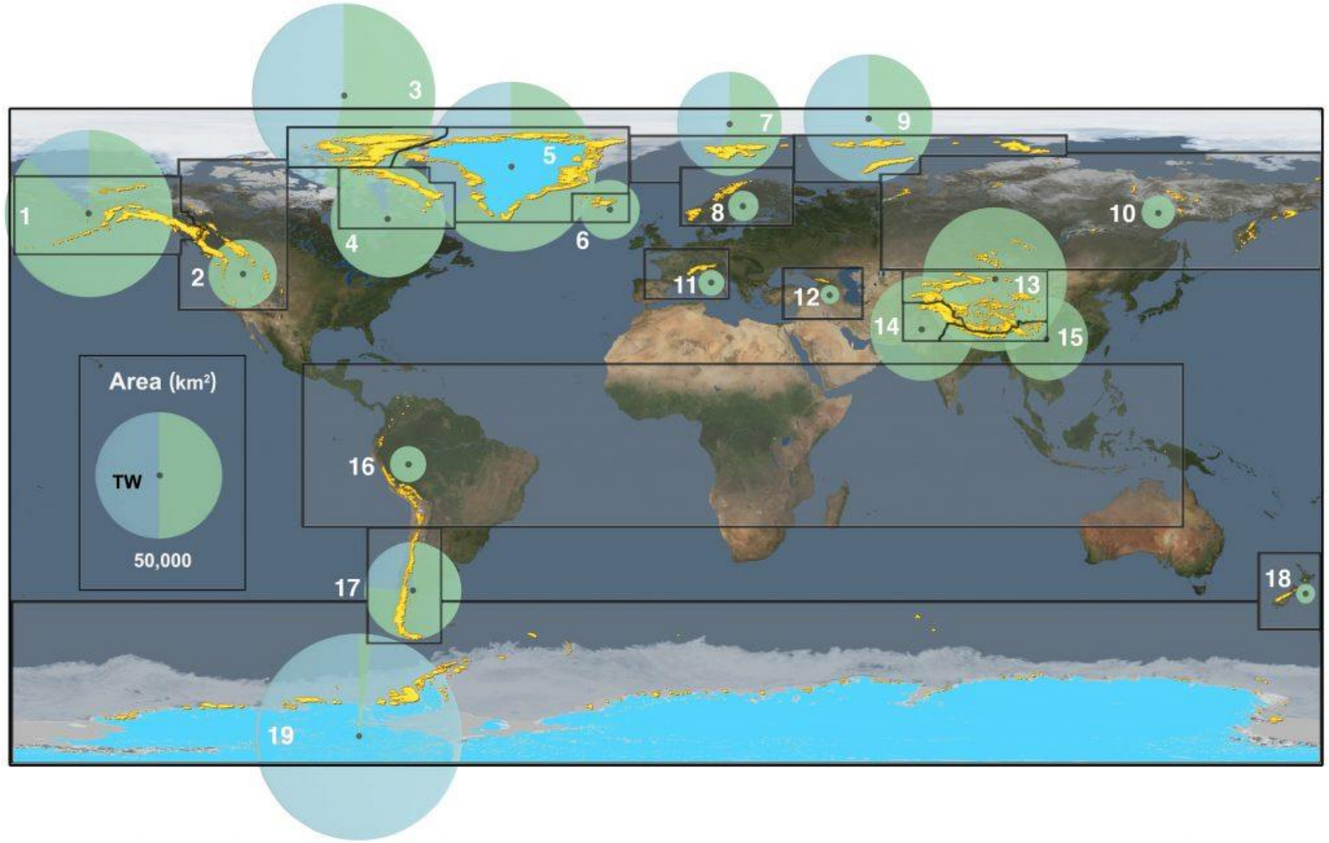


Glacier inventories

How many glaciers in the world??

198,000 glaciers worldwide (RGI estimate)

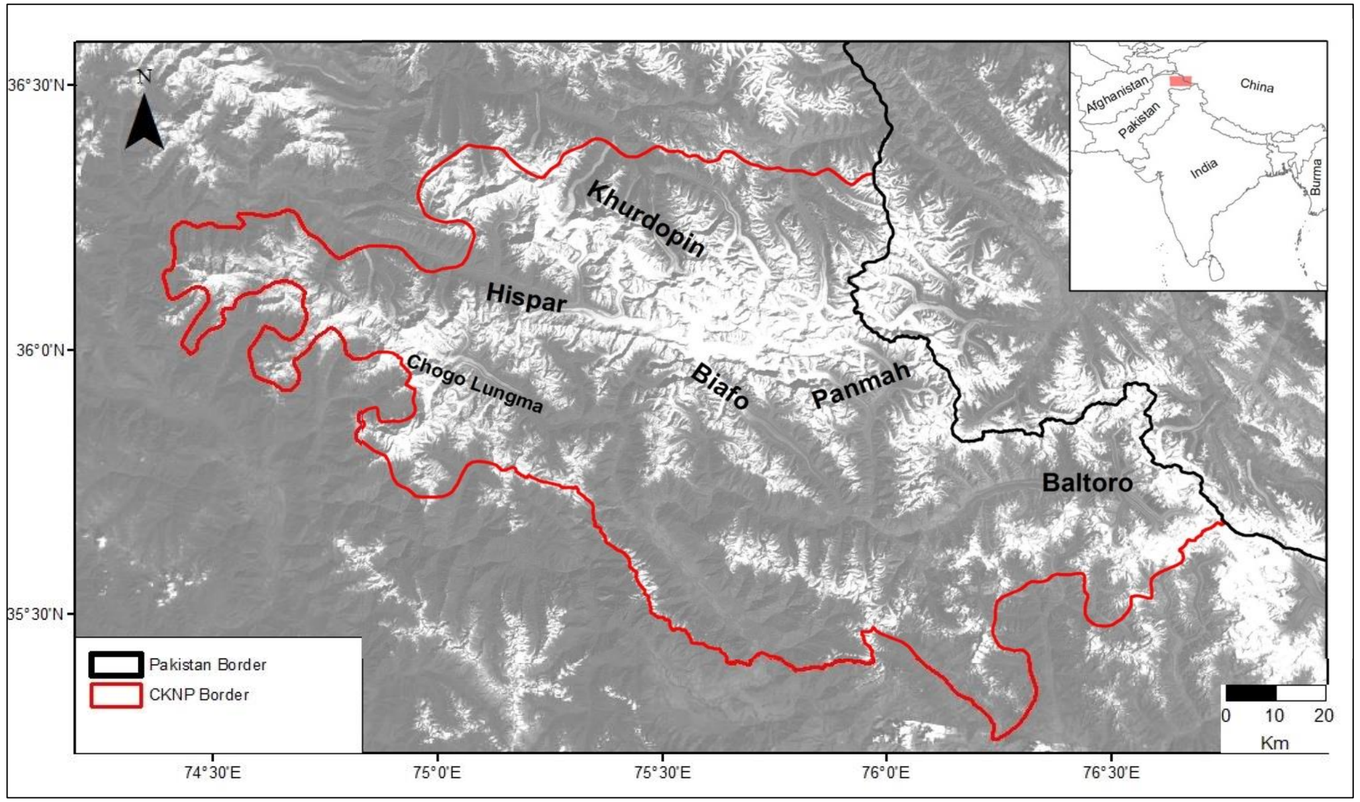
Total glacierised area: 726,000 km^2
- Subantarctic and Antarctic: 132,900 km^2
- Arctic Canada North: 104,900 km^2
- Asia: 62,606 km^2
- Low latitudes: 2346km^2
- 44 % is in Arctic regions, 18% in Antarctic & Subantarctic.



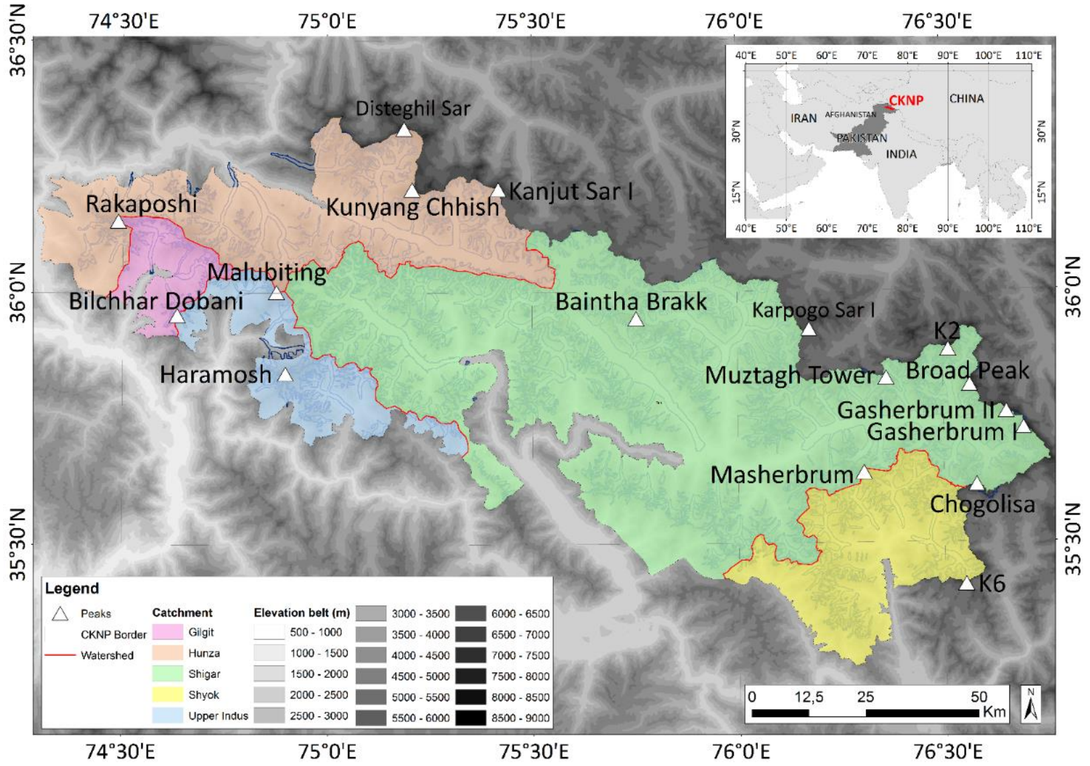
The CKNP glacier inventory

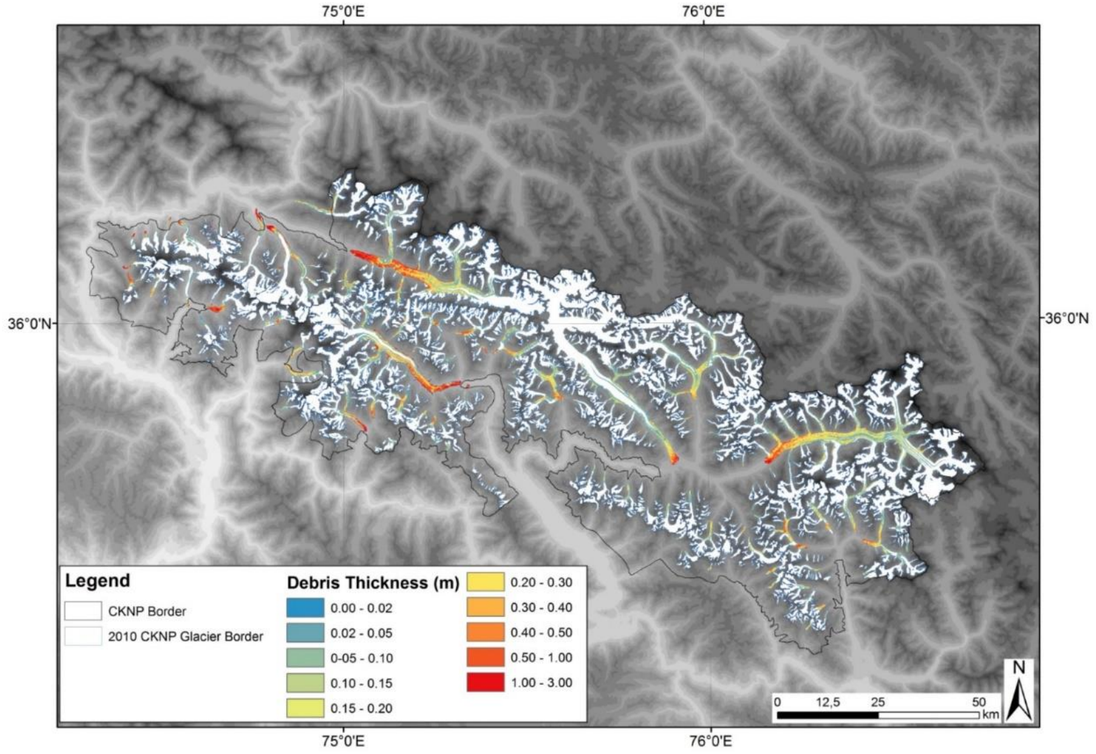
~30% of total glacier area of Pakistan (according to ICIMOD, 2005)

Most of the water in the Indus River originating from the Karakoram comes from snow and glacier melt (Immerzel et al., 2010)



The CKNP glacier inventory

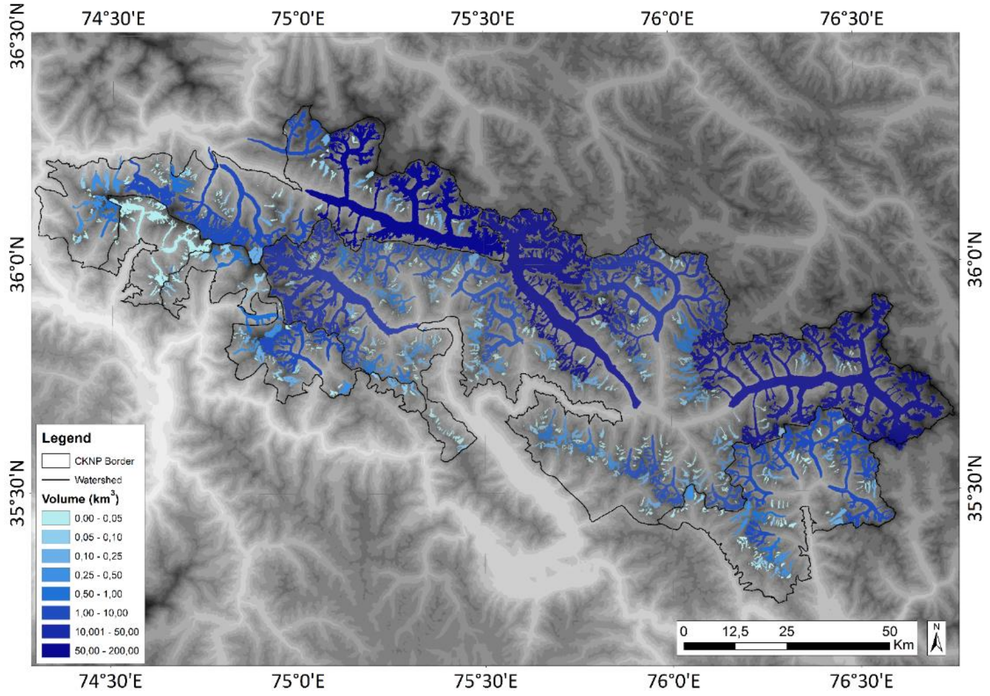




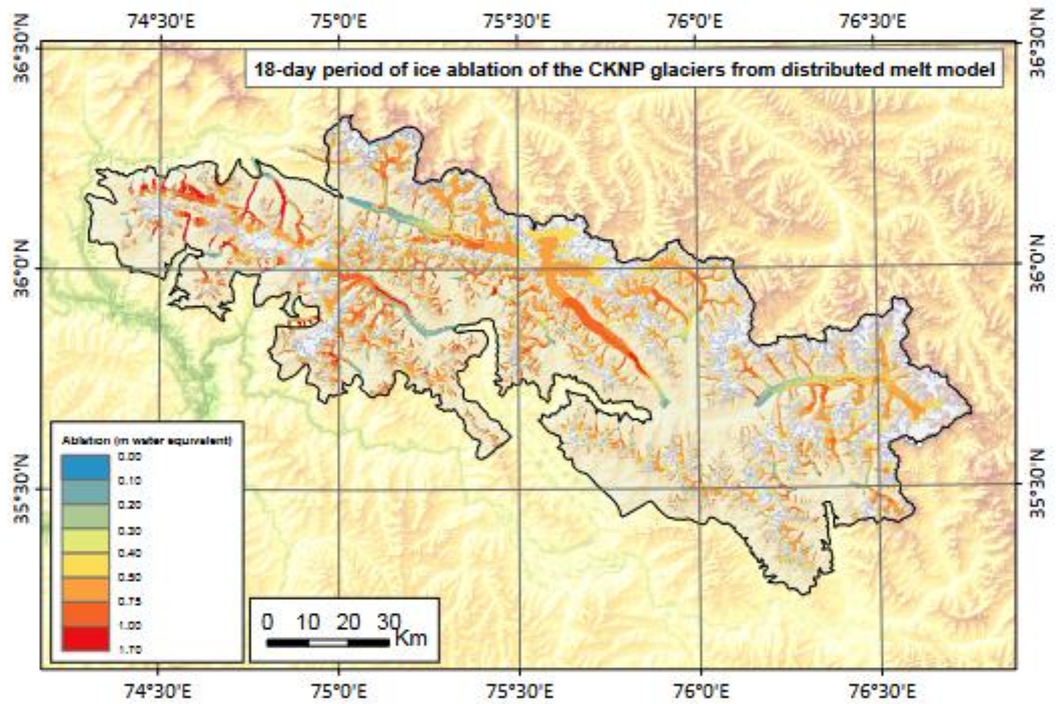
608 glaciers were found, covering c. 3700 km² (~35% of the CKNP area;
~24% of the glacier surface of the entire Karakoram Range within Pakistan)

The CKNP glacier inventory – volume and ablation

In total 532.37 km^3 (Baltoro Glacier → max volume, 128.79 km^3)
68.5% of all CKNP glaciers contains a volume of water < 0.05 km^3, contributing only to 0.98% of the total volume



In total 1.54 km^3 w.e. (daily average of 0.09 km^3 w.e. d^{-1}, 23 July–9 August 2011)



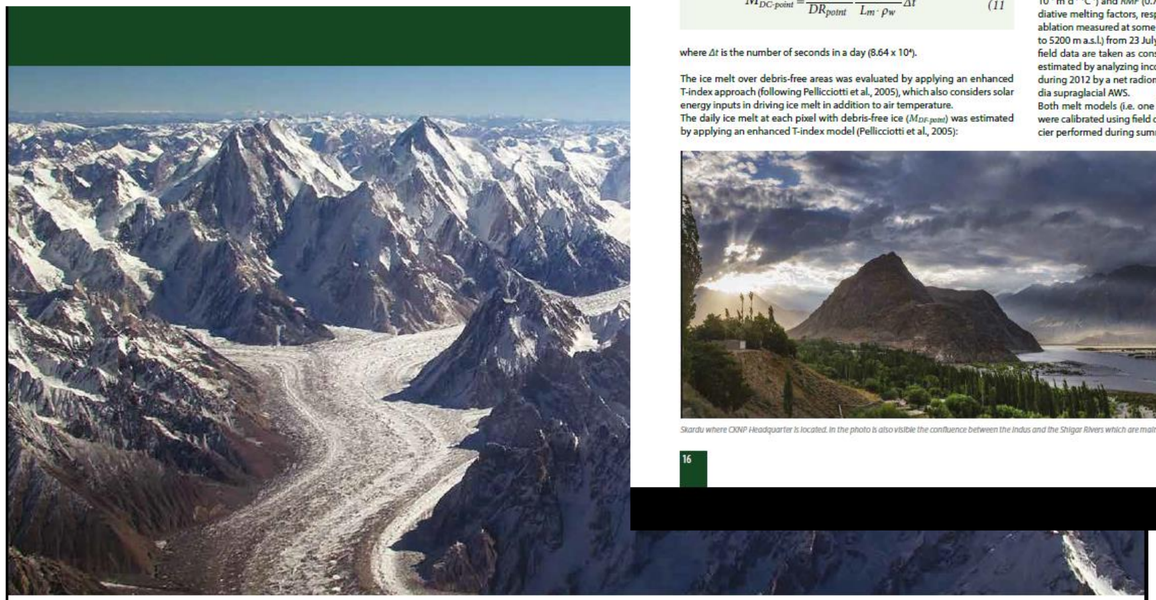
In total 1.54 km^3 w.e. (daily average of 0.09 km^3 w.e. d^{-1}, 23 July–9 August 2011)
→ ~11% of the reservoir capacity of the Tarbela Dam on the Indus River

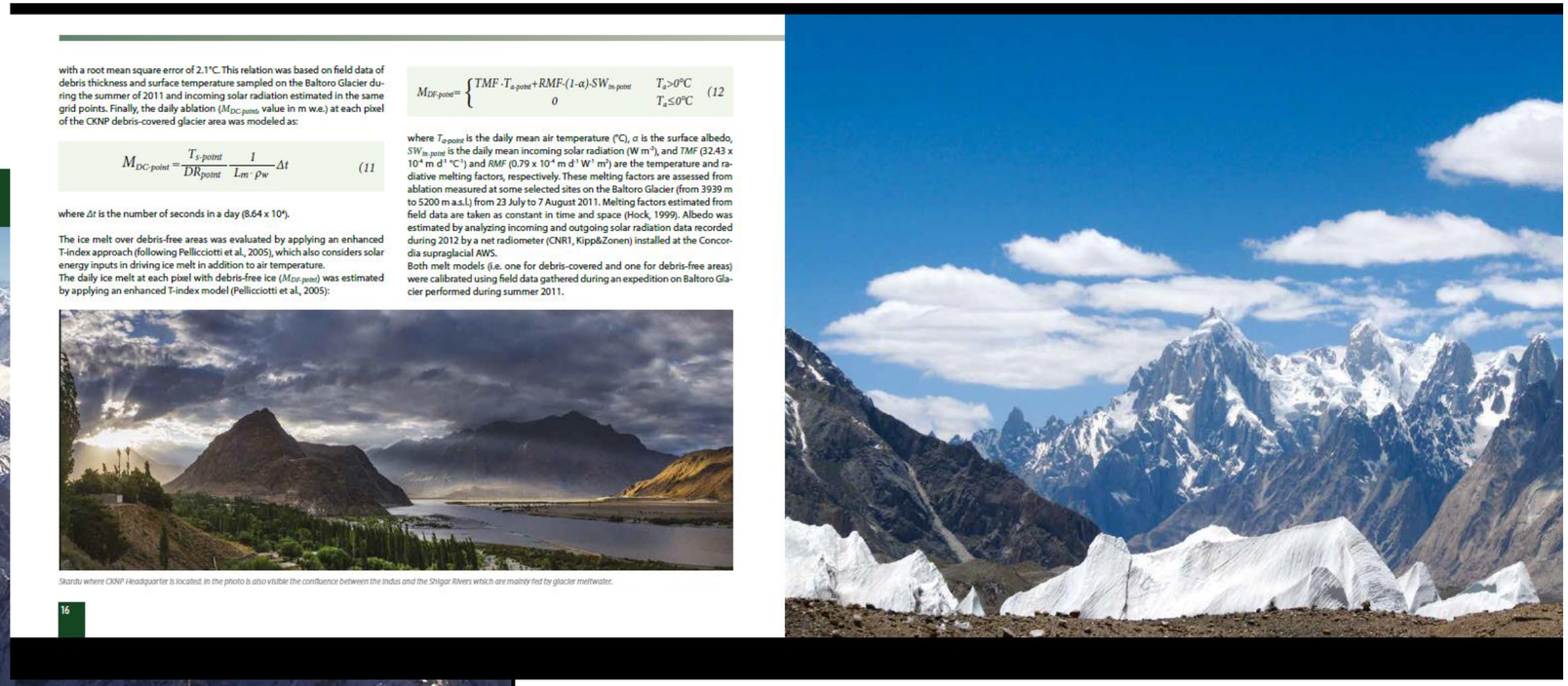




Tarbela Dam is a huge hydropower plant located in Pakistan (25,000 ha wide, 144 m high, 2743 m long and hosting a water volume of about 11x 10^9 m^3). This value gives an idea of the role played by glacier melt in providing freshwater for Pakistani people.

The CKNP glacier inventory book





with a root mean square error of 2.1°C. This relation was based on field data of debris thickness and surface temperature sampled on the Baltoro Glacier during the summer of 2011 and incoming solar radiation estimated in the same grid points. Finally, the daily ablation ($M_{DC\text{-}point}$, value in m w.e.) at each pixel of the CKNP debris-covered glacier area was modeled as:

$$M_{DC\text{-}point} = \frac{T_{s\text{-}point}}{DR_{point}} \frac{1}{L_m \cdot \rho_w} \Delta t \quad (11$$

where Δt is the number of seconds in a day (8.64 x 10^4).

The ice melt over debris-free areas was evaluated by applying an enhanced T-index approach (following Pellicciotti et al., 2005), which also considers solar energy inputs in driving ice melt in addition to air temperature.
The daily ice melt at each pixel with debris-free ice ($M_{DF\text{-}point}$) was estimated by applying an enhanced T-index model (Pellicciotti et al., 2005):

$$M_{DF\text{-}point} = \begin{cases} TMF \cdot T_{a\text{-}point} + RMF \cdot (1-\alpha) \cdot SW_{in\text{-}point} & T_a > 0°C \\ 0 & T_a \leq 0°C \end{cases} \quad (12$$

where $T_{a\text{-}point}$ is the daily mean air temperature (°C), α is the surface albedo, $SW_{in\text{-}point}$ is the daily mean incoming solar radiation (W m^{-2}), and TMF (32.43 x 10^{-4} m d^{-1} °C^{-1}) and RMF (0.79 x 10^{-4} m d^{-1} W^{-1} m^2) are the temperature and radiative melting factors, respectively. These melting factors are assessed from ablation measured at some selected sites on the Baltoro Glacier (from 3939 m to 5200 m a.s.l.) from 23 July to 7 August 2011. Melting factors estimated from field data are taken as constant in time and space (Hock, 1999). Albedo was estimated by analyzing incoming and outgoing solar radiation data recorded during 2012 by a net radiometer (CNR1, Kipp&Zonen) installed at the Concordia supraglacial AWS.
Both melt models (i.e. one for debris-covered and one for debris-free areas) were calibrated using field data gathered during an expedition on Baltoro Glacier performed during summer 2011.

Skardu where CKNP Headquarter is located. In the photo is also visible the confluence between the Indus and the Shigar Rivers which are mainly fed by glacier meltwater.

16

The Central Karakorum National Park Glacier Inventory

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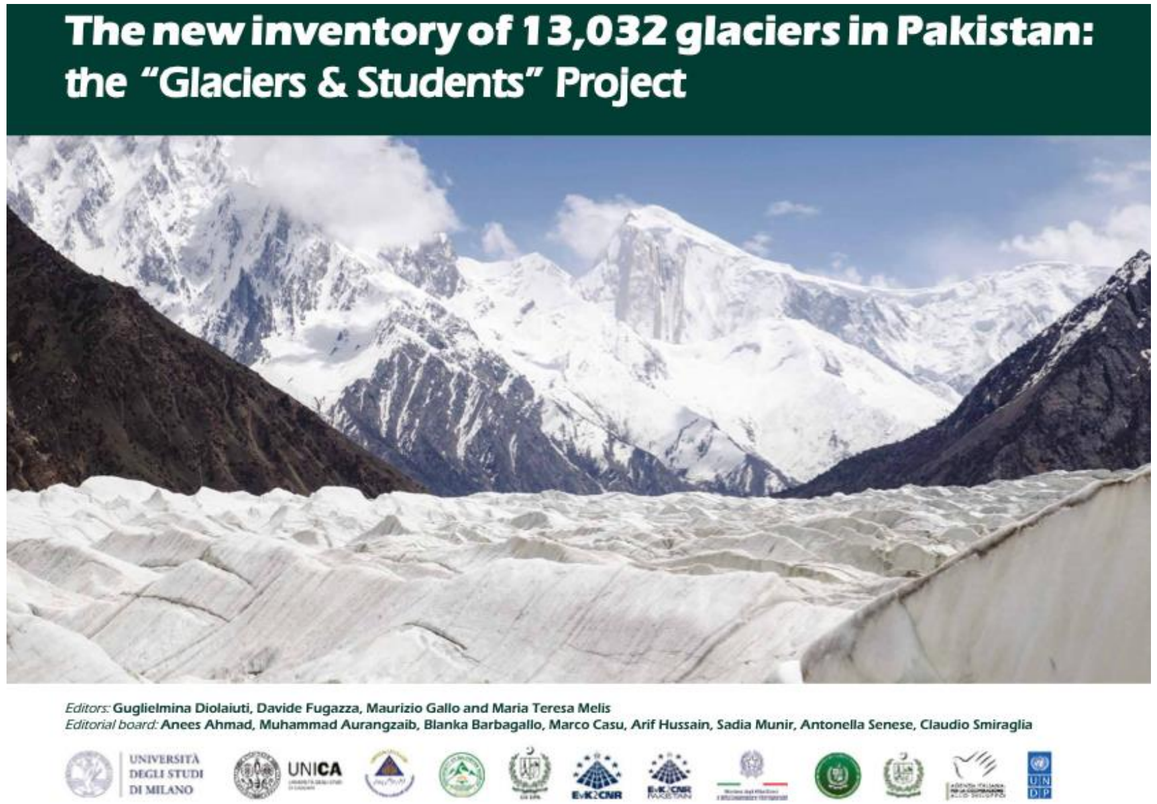
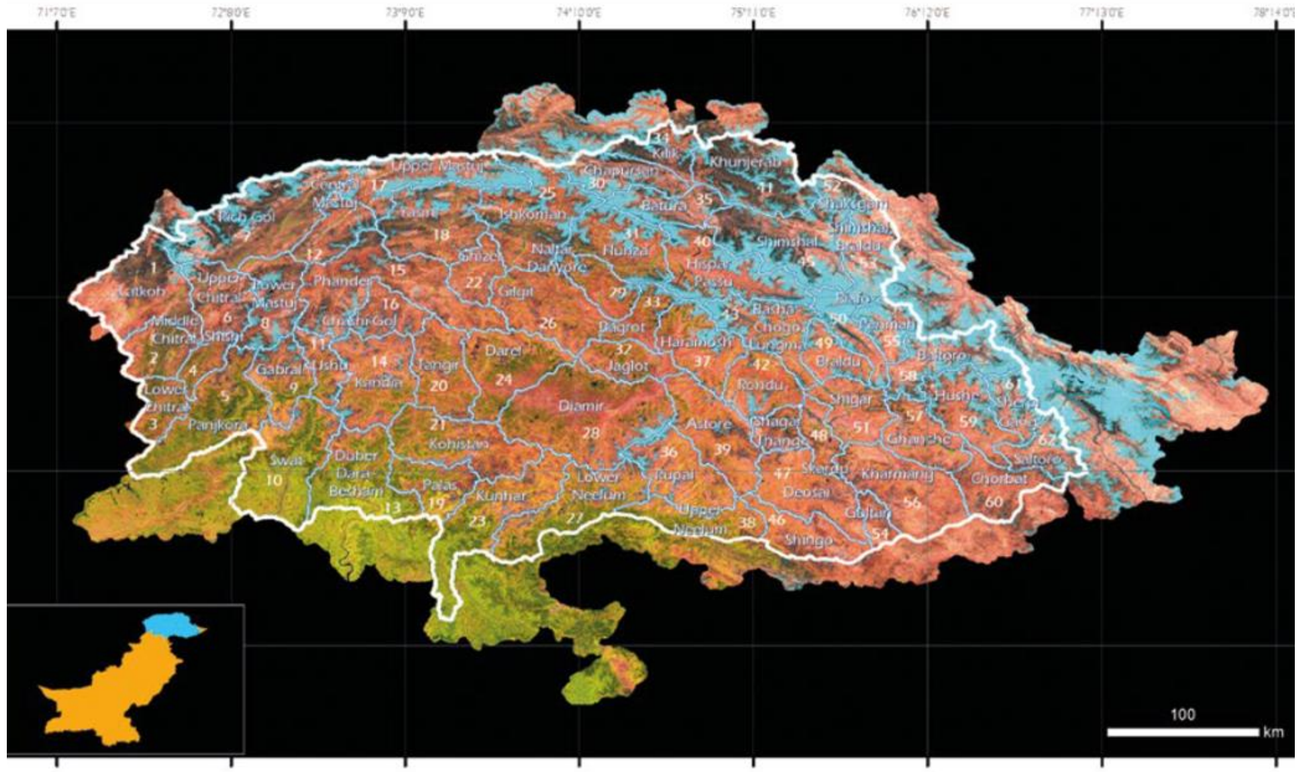
Freely available online at: https://sites.unimi.it/glaciol/wp-content/uploads/2019/02/CKNP-Glacier-inventory_2dic16.pdf

How many glaciers in Pakistan?





13,032
Number of glaciers

13,546.9 km²
Total glacier area

~ 1,500 km³
Total glacier volume

1,117
Satellite immages analysed

5,000 m
Average altitude

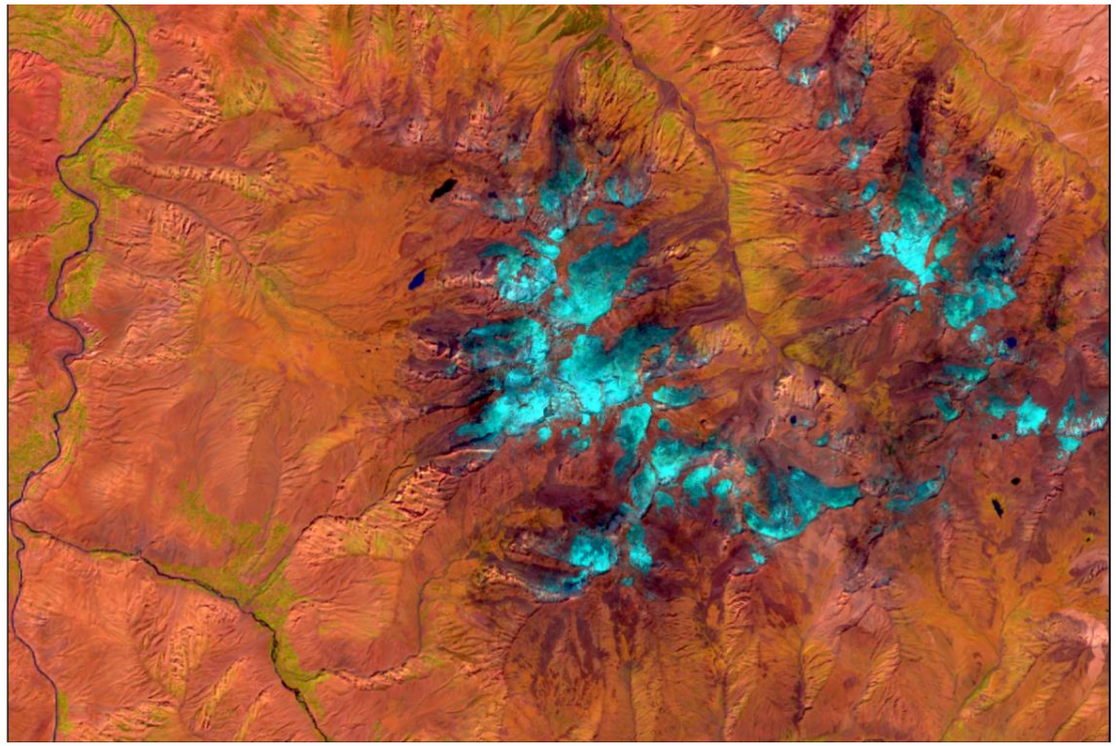
756 km²
Largest glacier: Baltoro

169,416
Glacier data reported

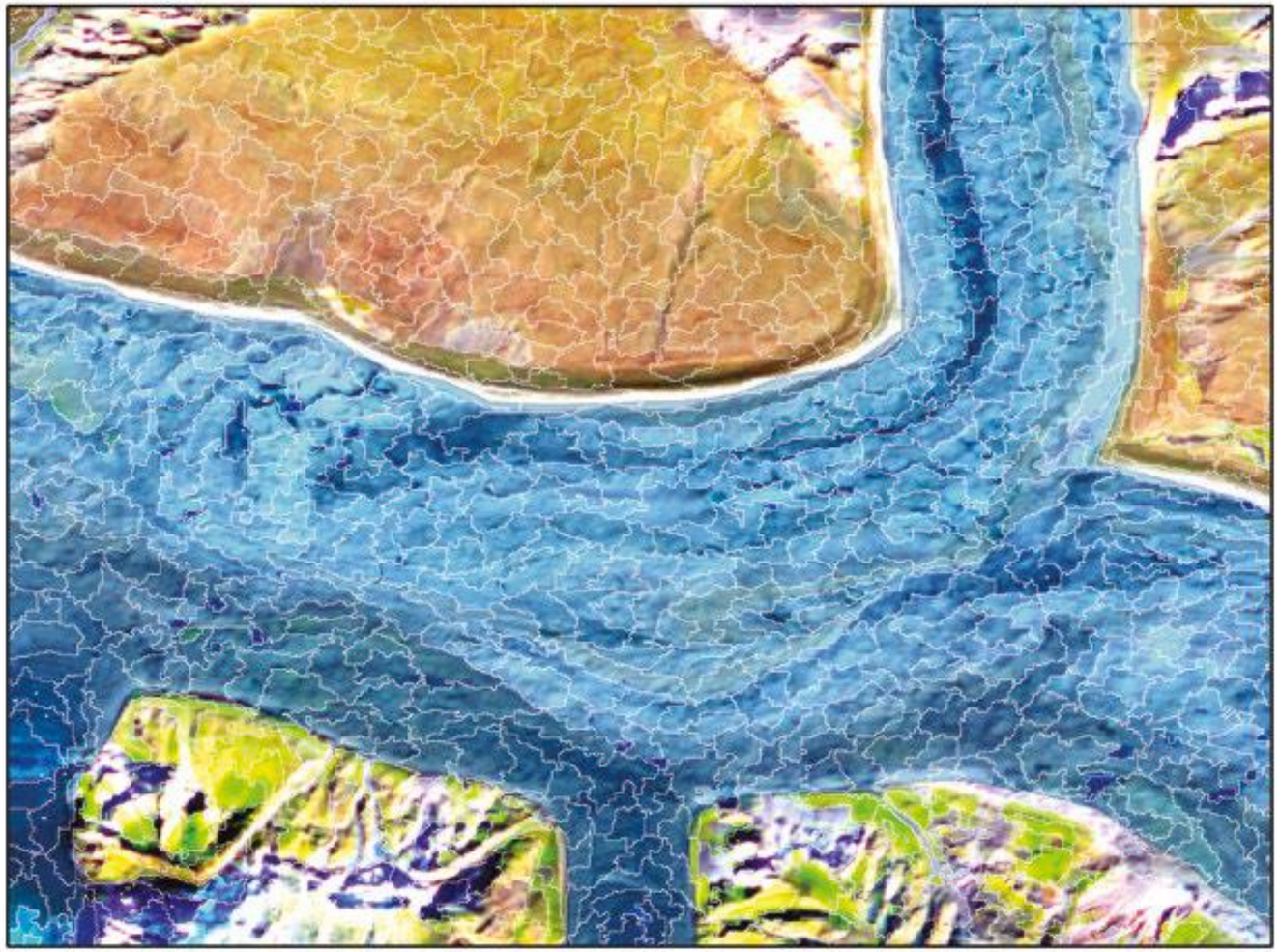
The new glacier inventory - Satellite images



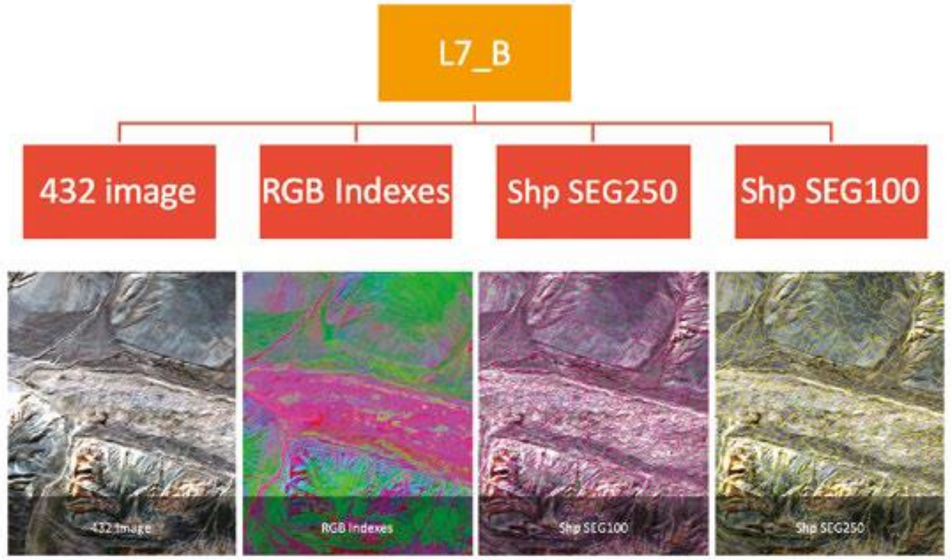
- Sentinel-2 images by ESA
- 10 m resolution
- Acquired over one summer season (2022)



The new glacier inventory - methodology



Hispar Glacier



How many glaciers in Pakistan?

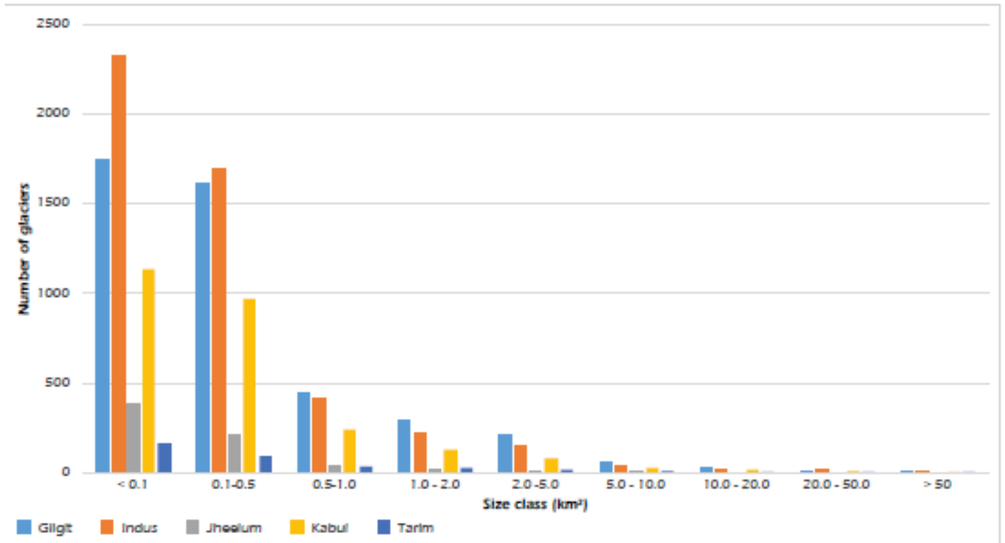


Figure 14: Number of glaciers in each size class for the 5 basins in the 1st order division

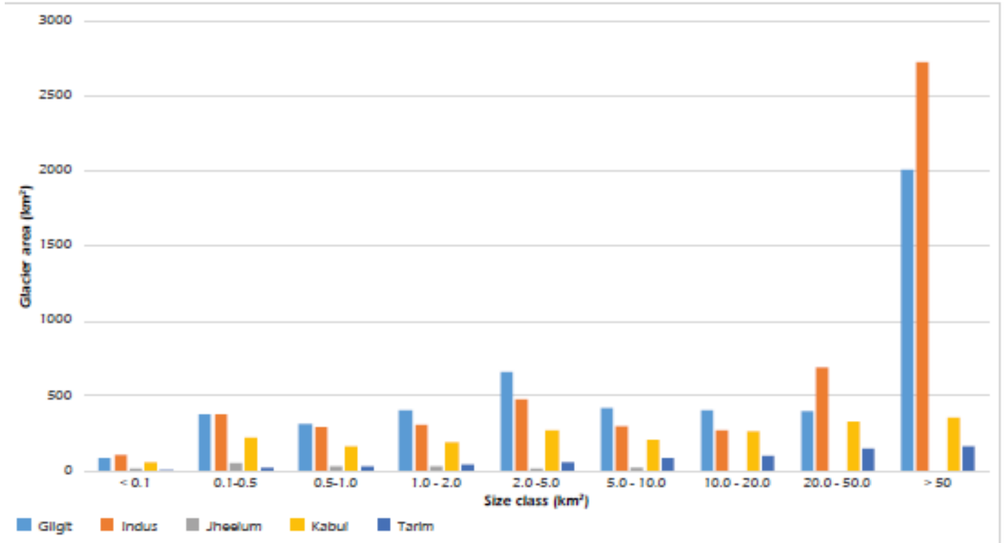
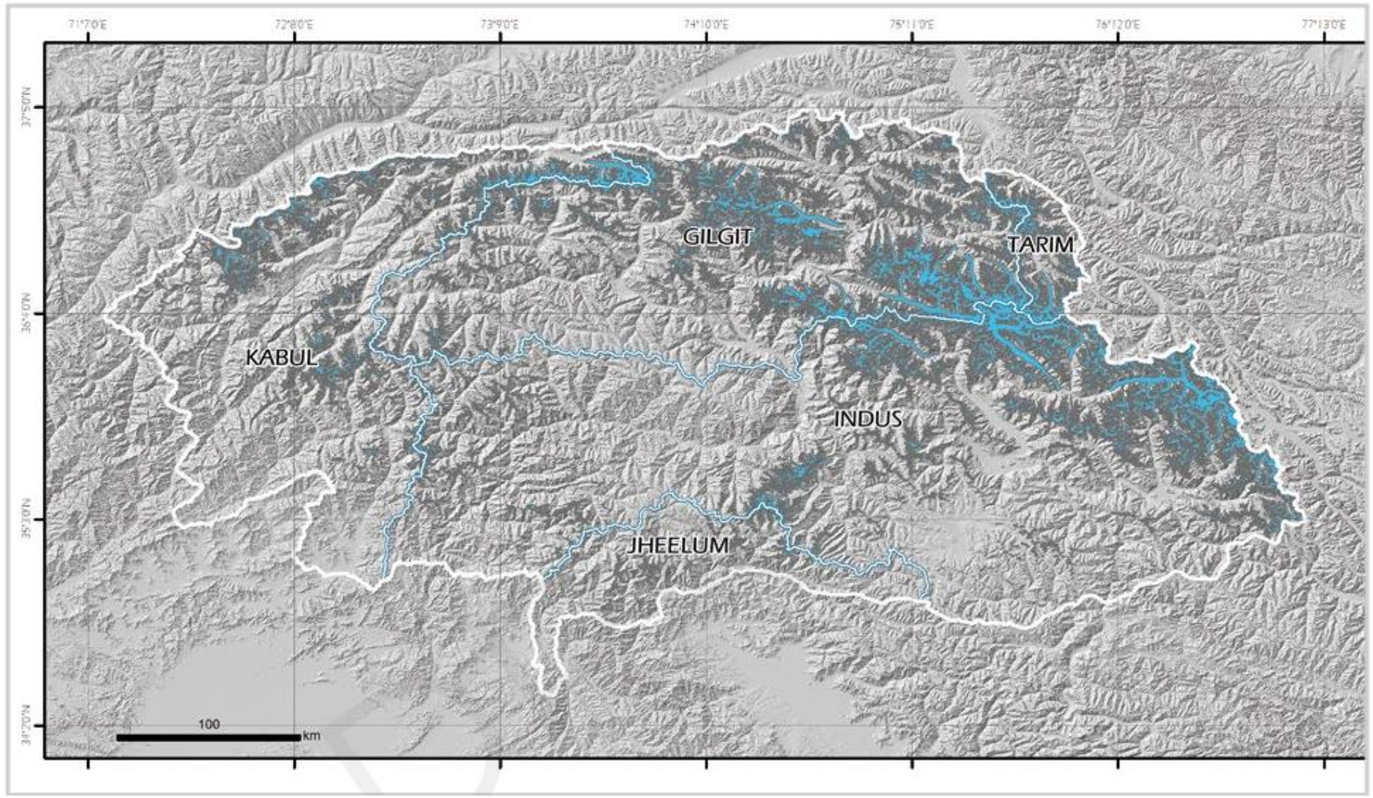


Figure 15: Area of glaciers in each size class for the 5 basins in the 1st order division

A large number of small glaciers (80% < 0.5 km²)

A small number of large glaciers! (32 > 50 km²)



How many glaciers in Pakistan?

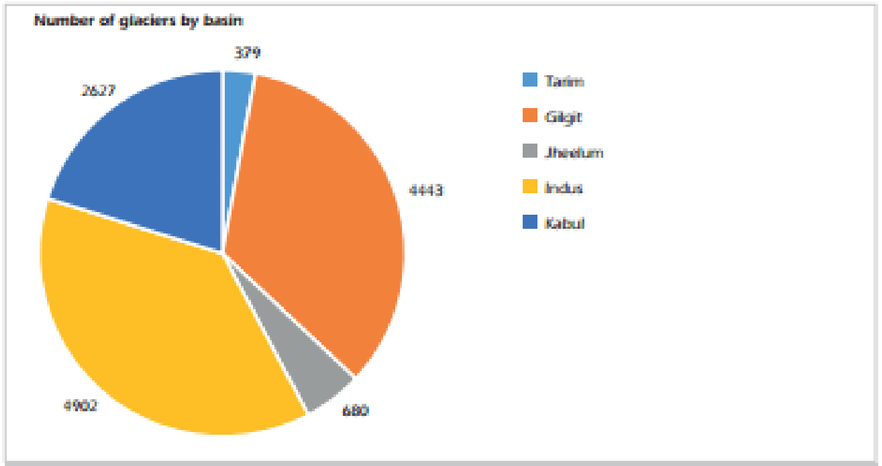


Figure 10: Number of glaciers in each basin of the 1st order.

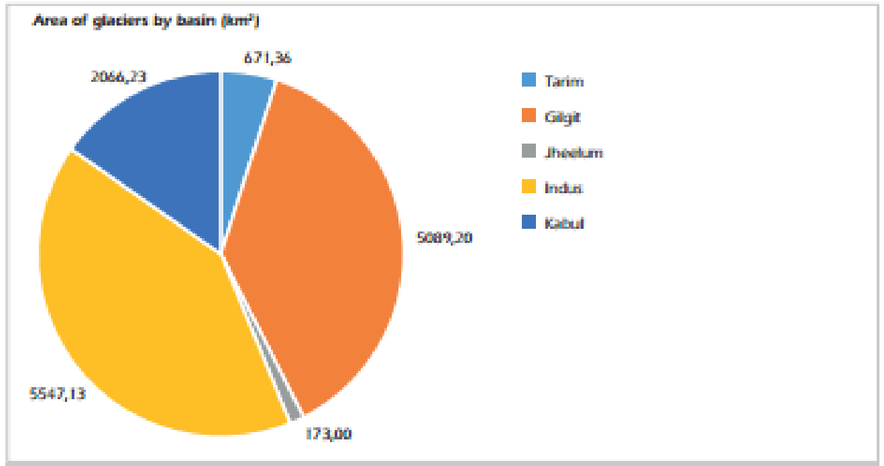


Figure 11: Area of glaciers in each basin of the 1st order.

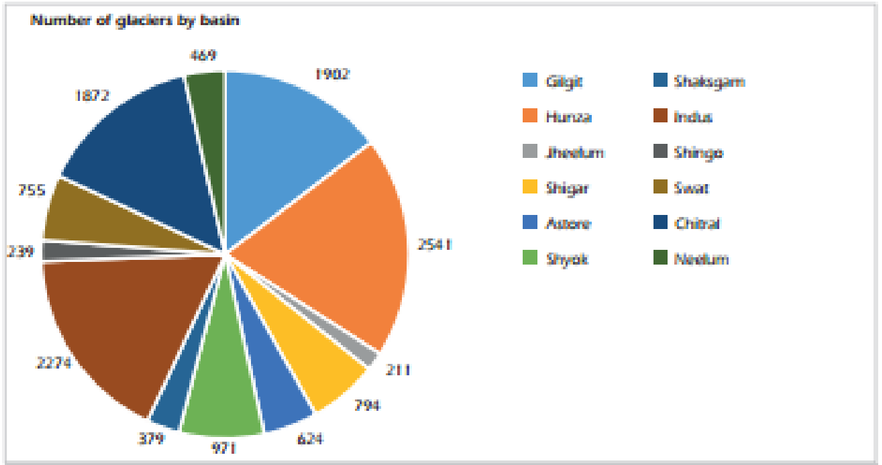


Figure 12: Number of glaciers in each basin of the 2nd order

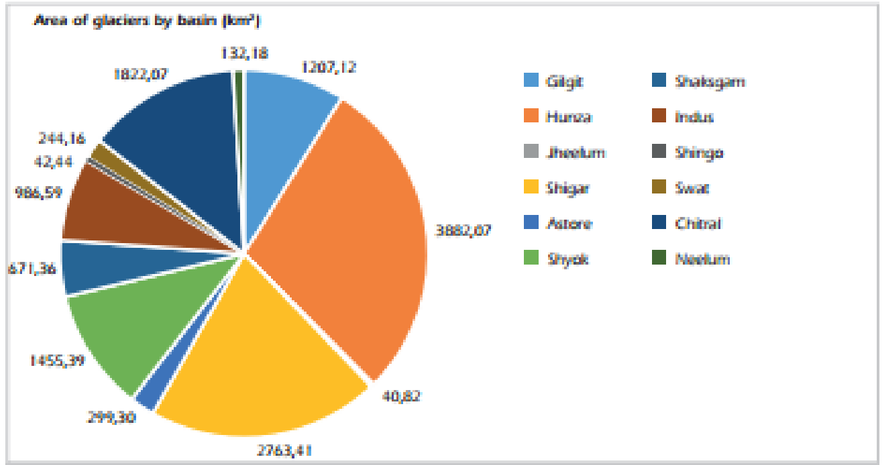


Figure 13: Area of glaciers in each basin of the 2nd order

How many glaciers in Pakistan?

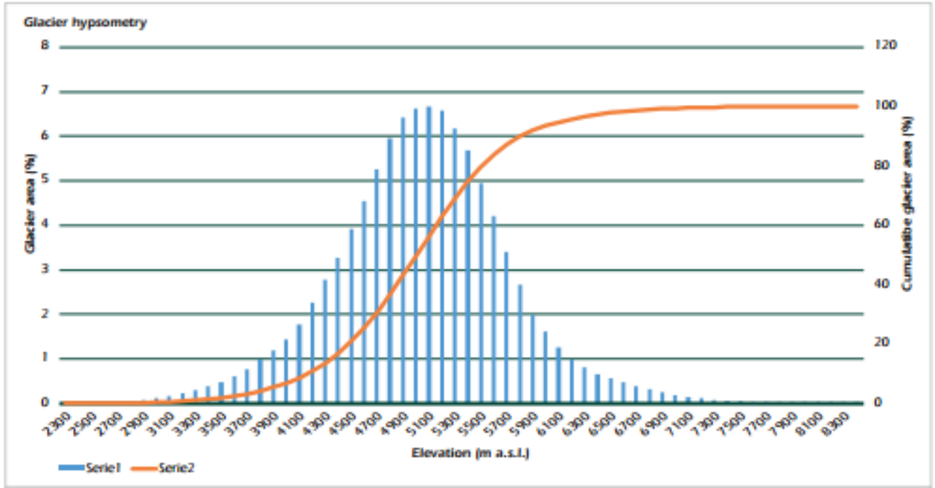


Figure 18: Hypsometric distribution of all glaciers in Pakistan in 100 m elevation bands.

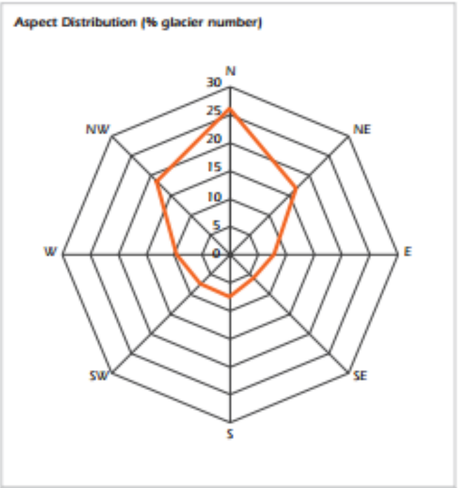


Figure 19: Percentage of glaciers in each aspect class (8 directions).

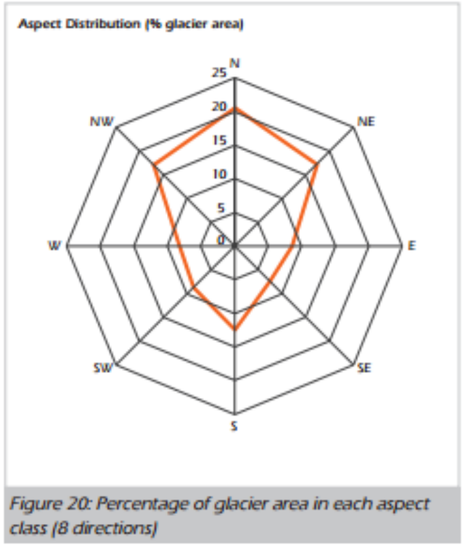


Figure 20: Percentage of glacier area in each aspect class (8 directions)

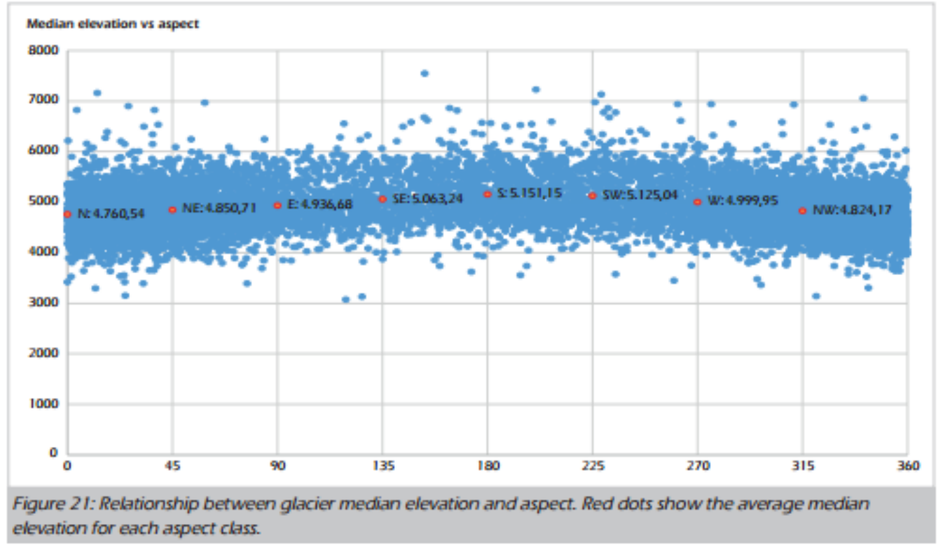


Figure 21: Relationship between glacier median elevation and aspect. Red dots show the average median elevation for each aspect class.

How many glaciers in Pakistan?

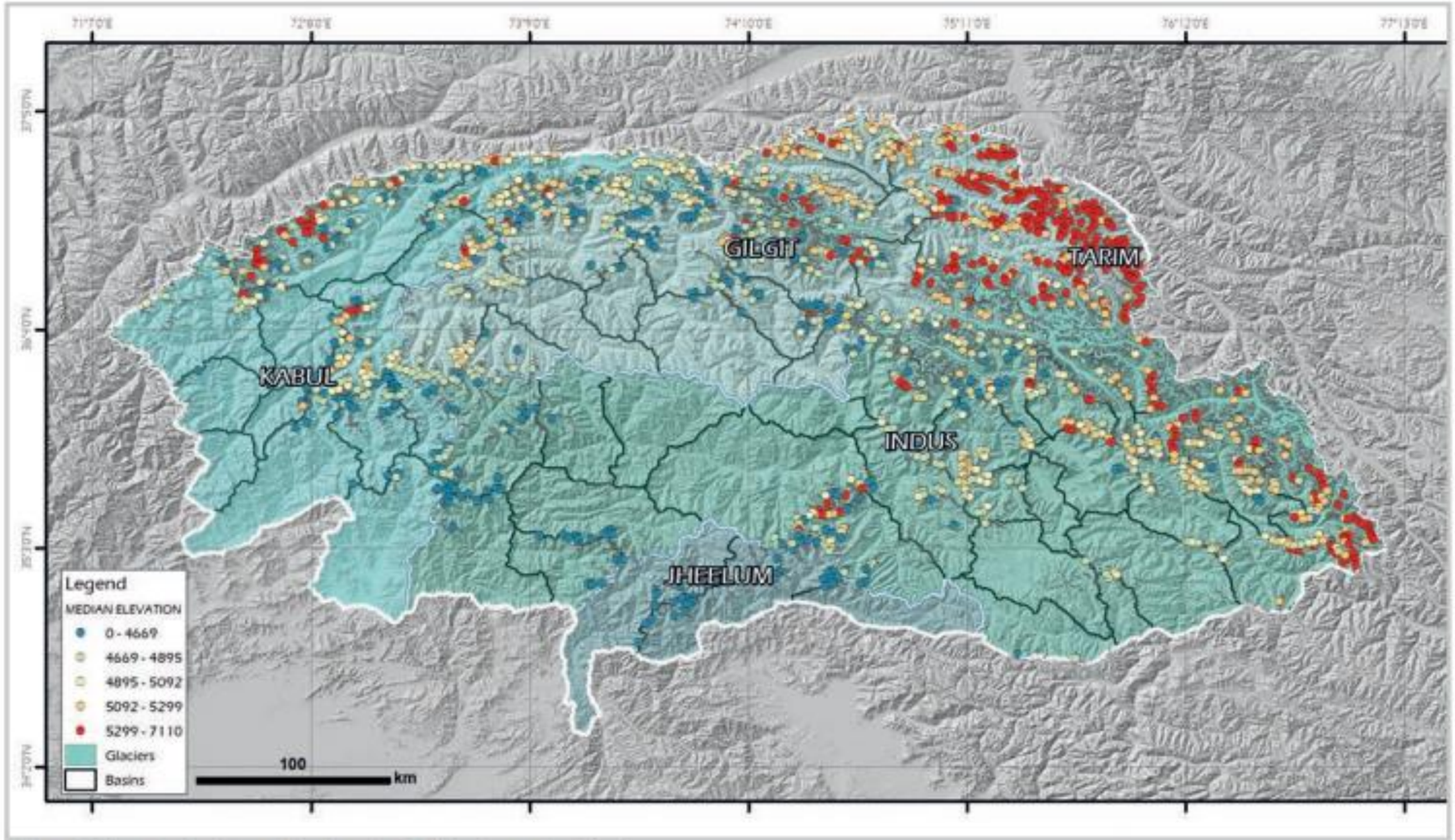
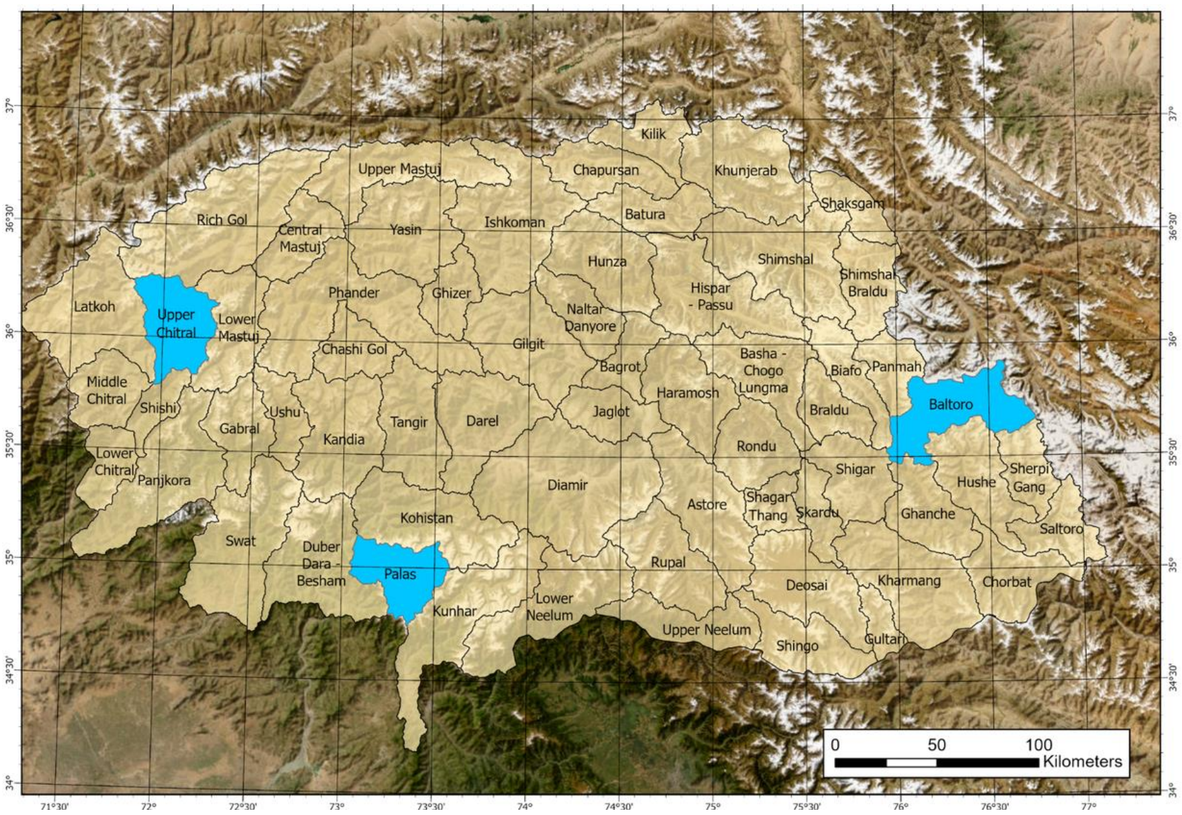
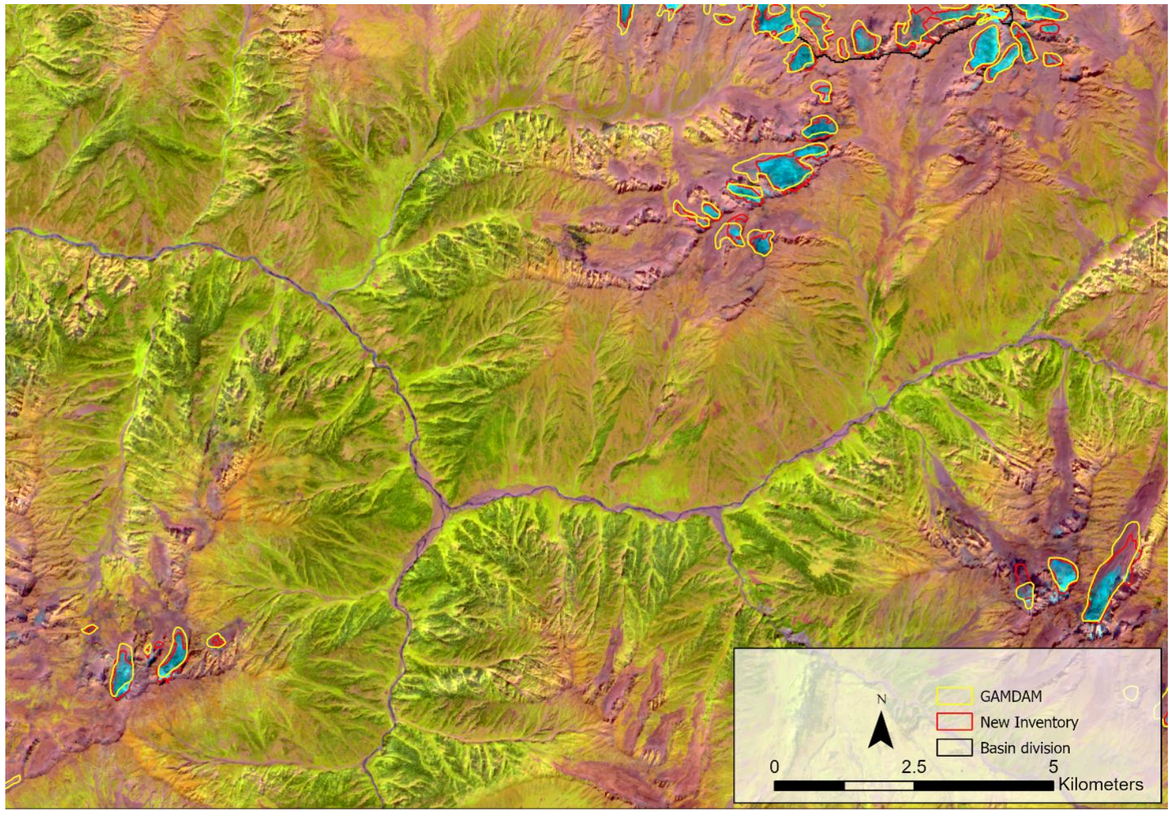


Figure 24: Map showing the median elevation of glaciers larger than 1 km²

Glacier recession in Pakistan





Comparison between the new inventory and
GAMDAM glacier inventory (~2000)
for Baltoro basin (Karakorum) and Palas basin (Himalayas)

There is evident retreat in the Himalayas
(e.g. Palas basin, -16% in ~ 20 years)
In the Karakorum, glaciers are more stable (0 / -2%)

The new glacier inventory - Capacity Building

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Abstract

This study aims to evaluate the effectiveness of a multi-phase educational model in geoscience training implemented within an international cooperation framework. In the framework of the Glaciers & Students project (2021–2024), funded by the Italian Ministry of foreign

Explore a research question

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How effective is a multi-phase educational model for geoscience training?

What are the broader impacts of international cooperation on geoscience education?



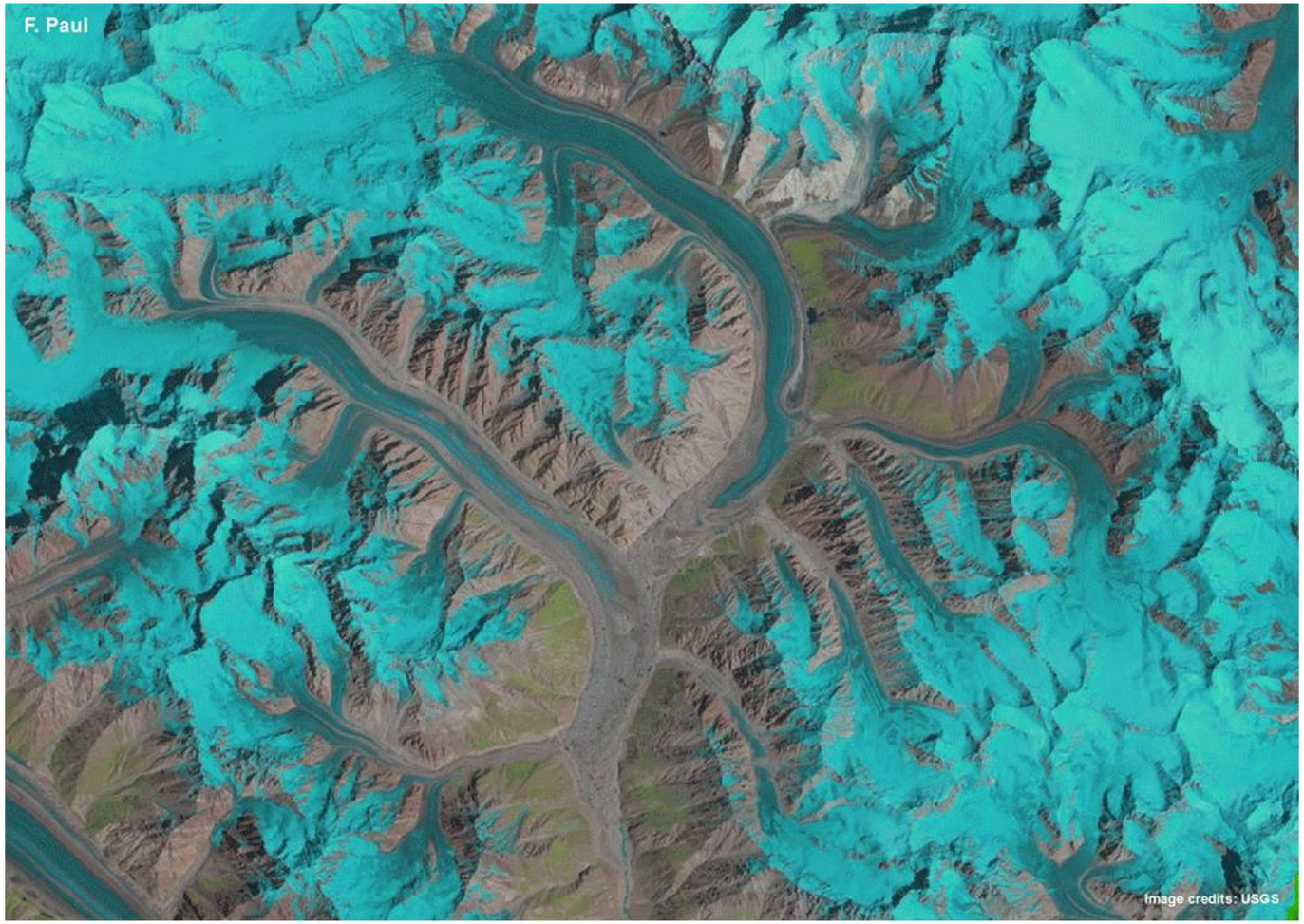
394 training beneficiaries

57% male

43% female



Glacier surges



- Sudden increase in the rates of glacier flow (kms over days to months)
- Higher frequency in Karakoram and Svalbard
- Still unknown causes, but likely caused by the efficiency of subglacial hydrological network, soft bed deformation and changes in the thermal regime
- Leaves clear traces (distorted/looped moraines, terminus advance, large changes in ice thickness)

The new glacier inventory - Surging glaciers and GLOFs

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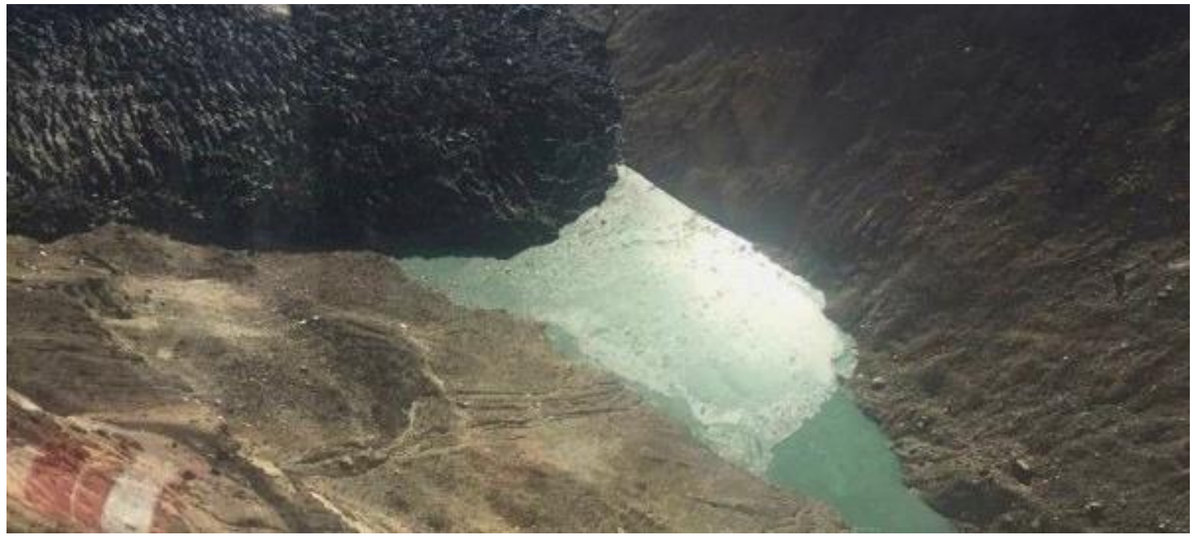
Satellite time series of Shishpar glacier and lake evolution

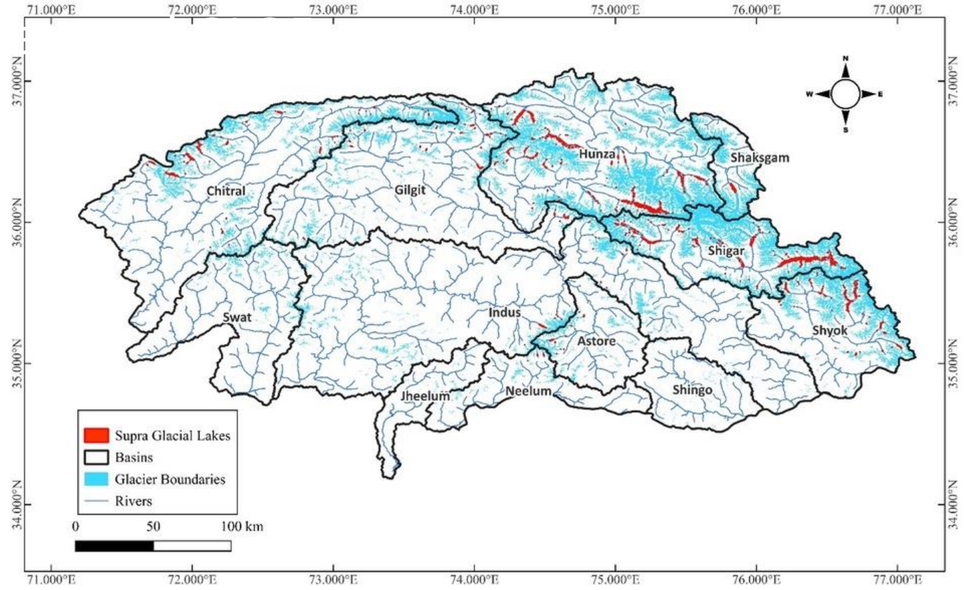


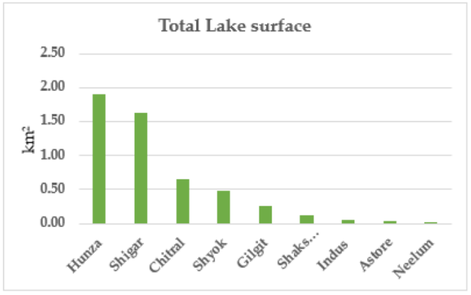


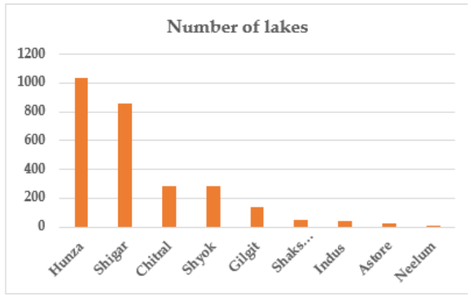


The new glacier inventory –

Glacier lake inventory: 2722 supraglacial lakes







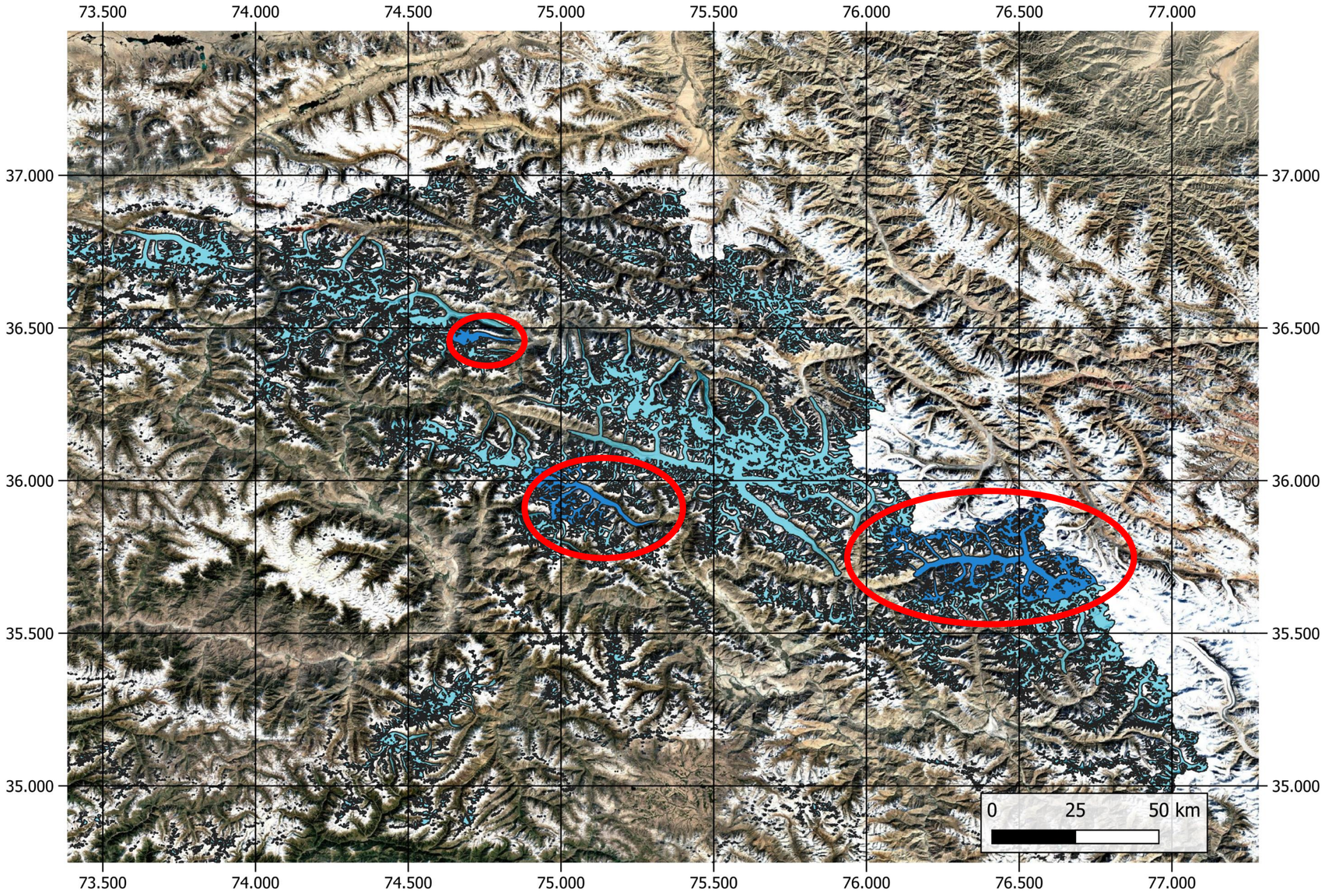
Basins	Total Lake Area km2	Number of Lakes
Hunza	1.91	**1036**
Shigar	1.62	**856**
Chitral	0.65	**286**
Shyok	0.48	**287**
Gilgit	0.26	**135**
Shaksgam	0.13	**47**
Indus	0.06	**41**
Astore	0.04	**25**
Neelum	0.02	**9**
TOTAL	**5.16**	**2722**

Inventory of all <u>supraglacial</u> lakes in 2022

Total: **2722 lakes**
Total area: **5.16 km²**
Hunza basin has the largest number and area of lakes

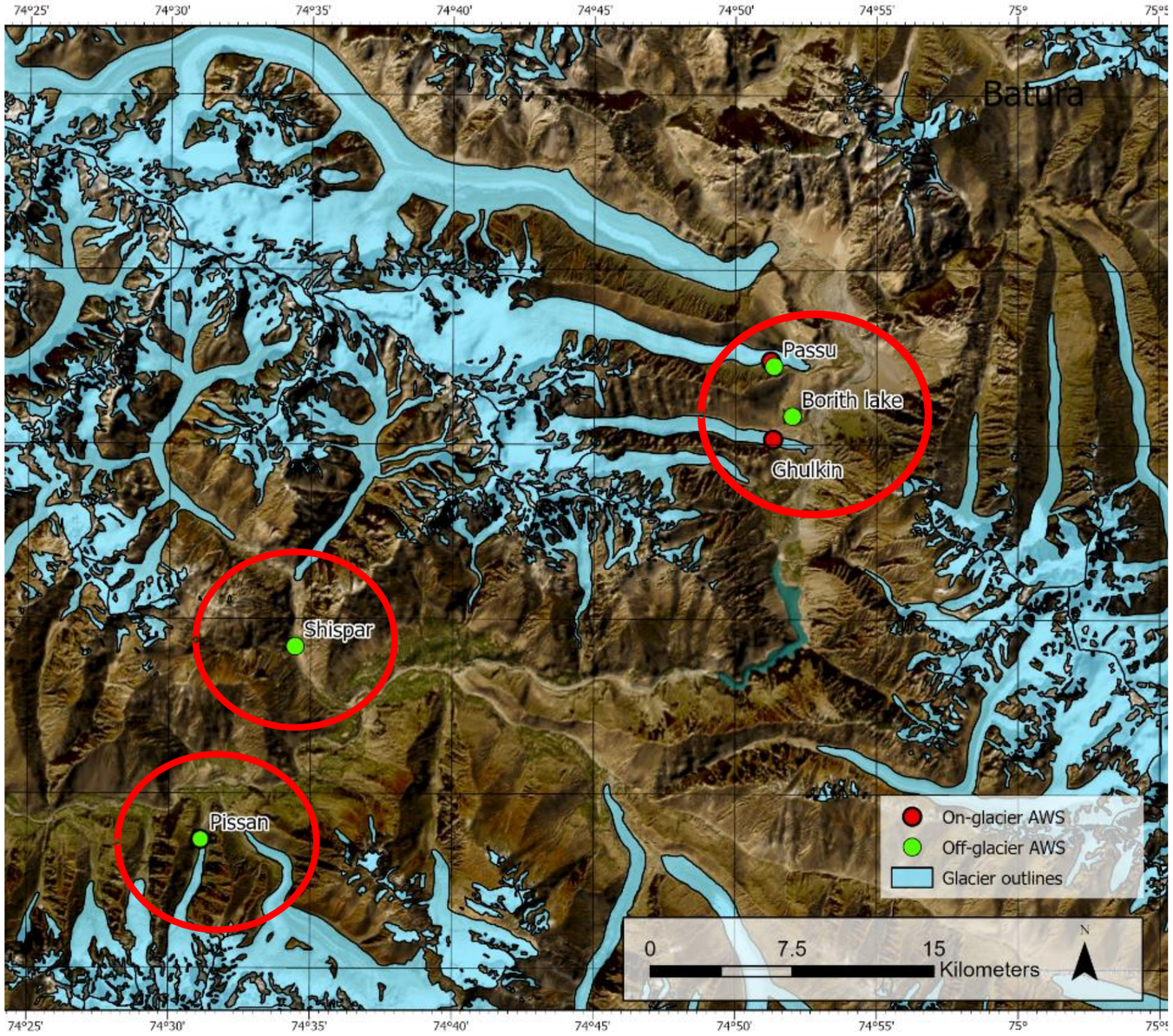


The three open air labs



- Passu Glacier (54 km^2) in Hunza Valley, Western Karakoram
- Chogo Lungma glacier (285 km^2) in Basha Valley, Central Karakoram
- Baltoro glacier (756 km^2), Braldu Valley, Eastern Karakoram

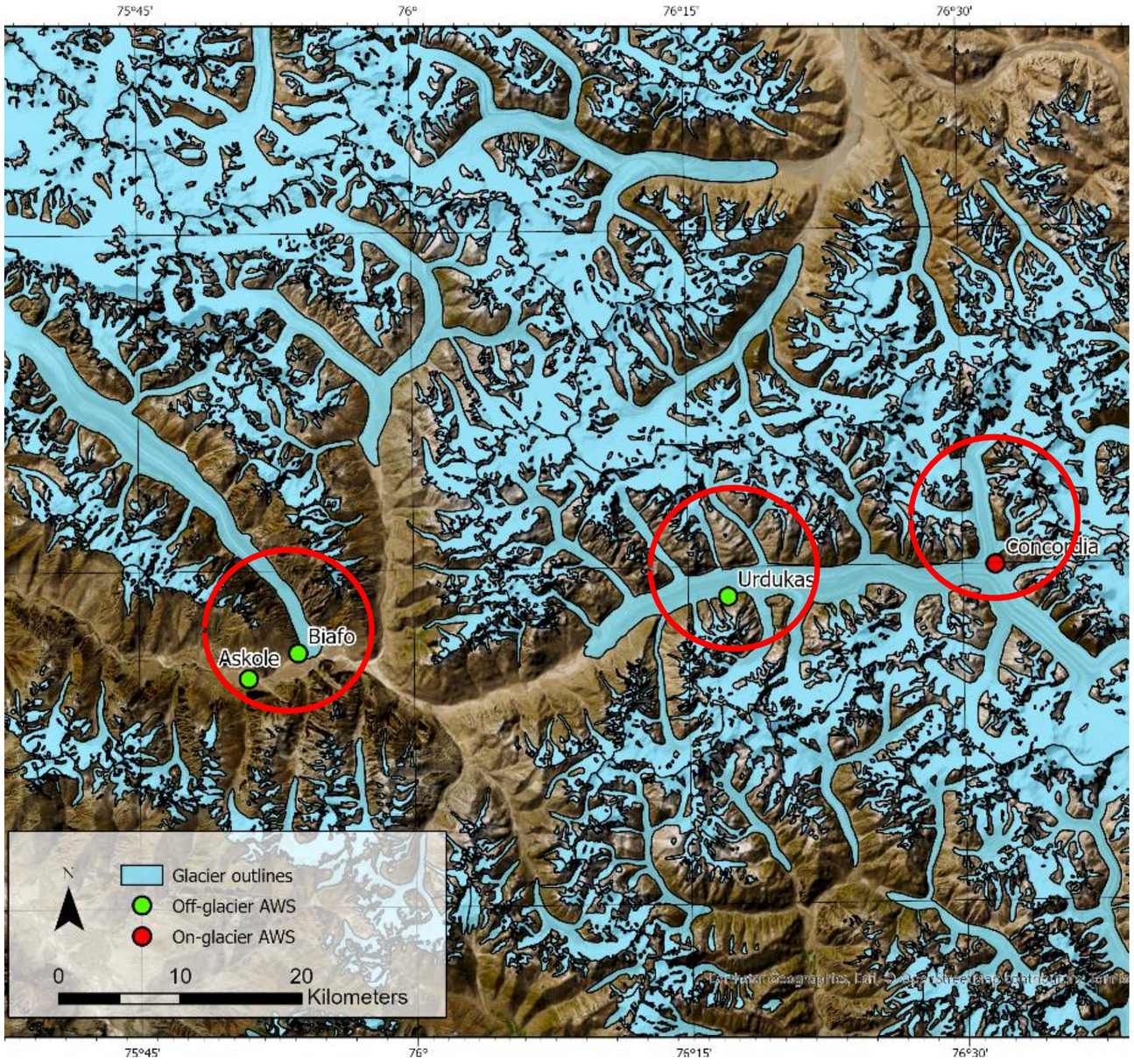
The new AWS network: Hunza

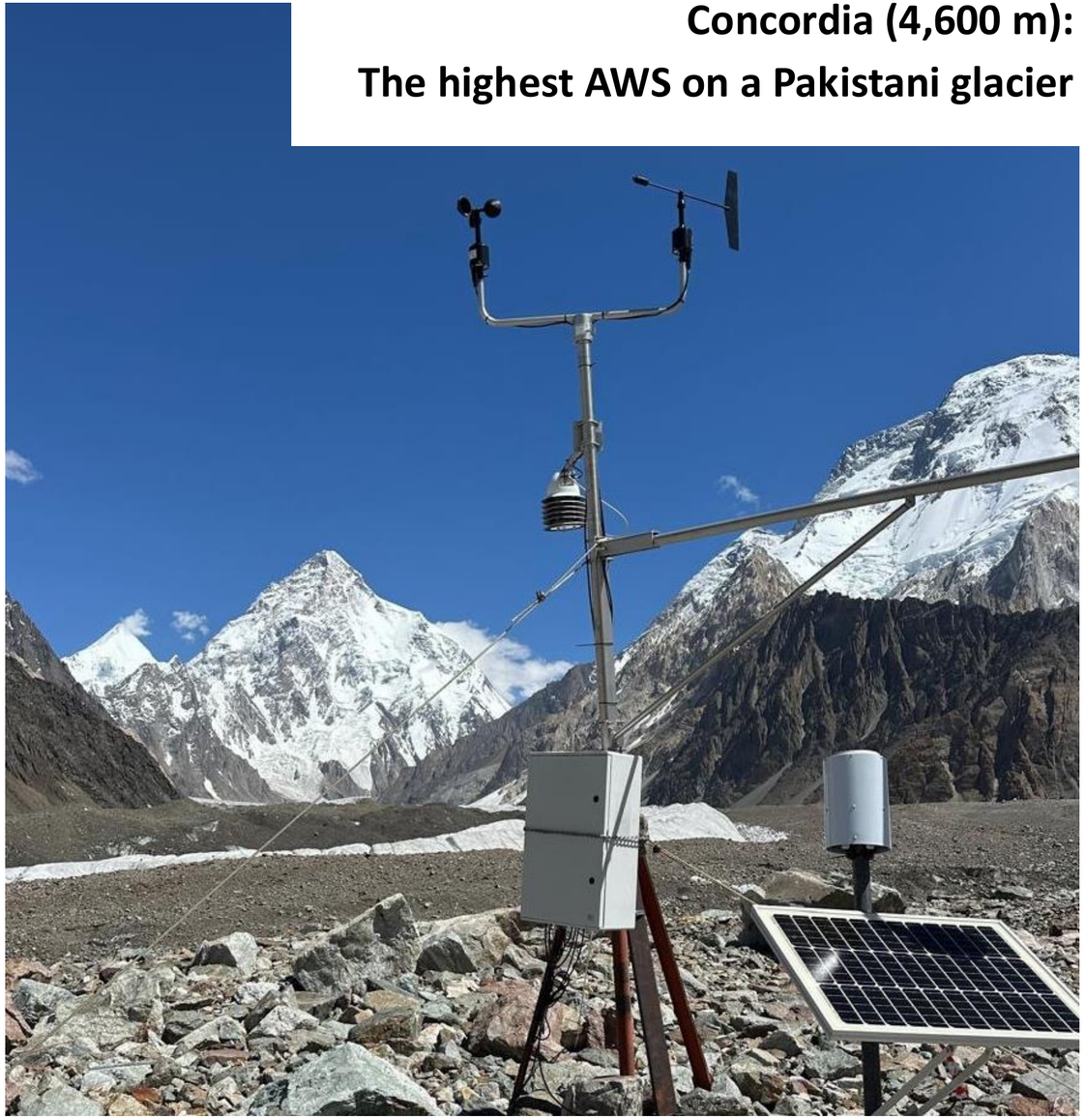


Borith Lake – 2900 m



The new AWS network: Baltoro

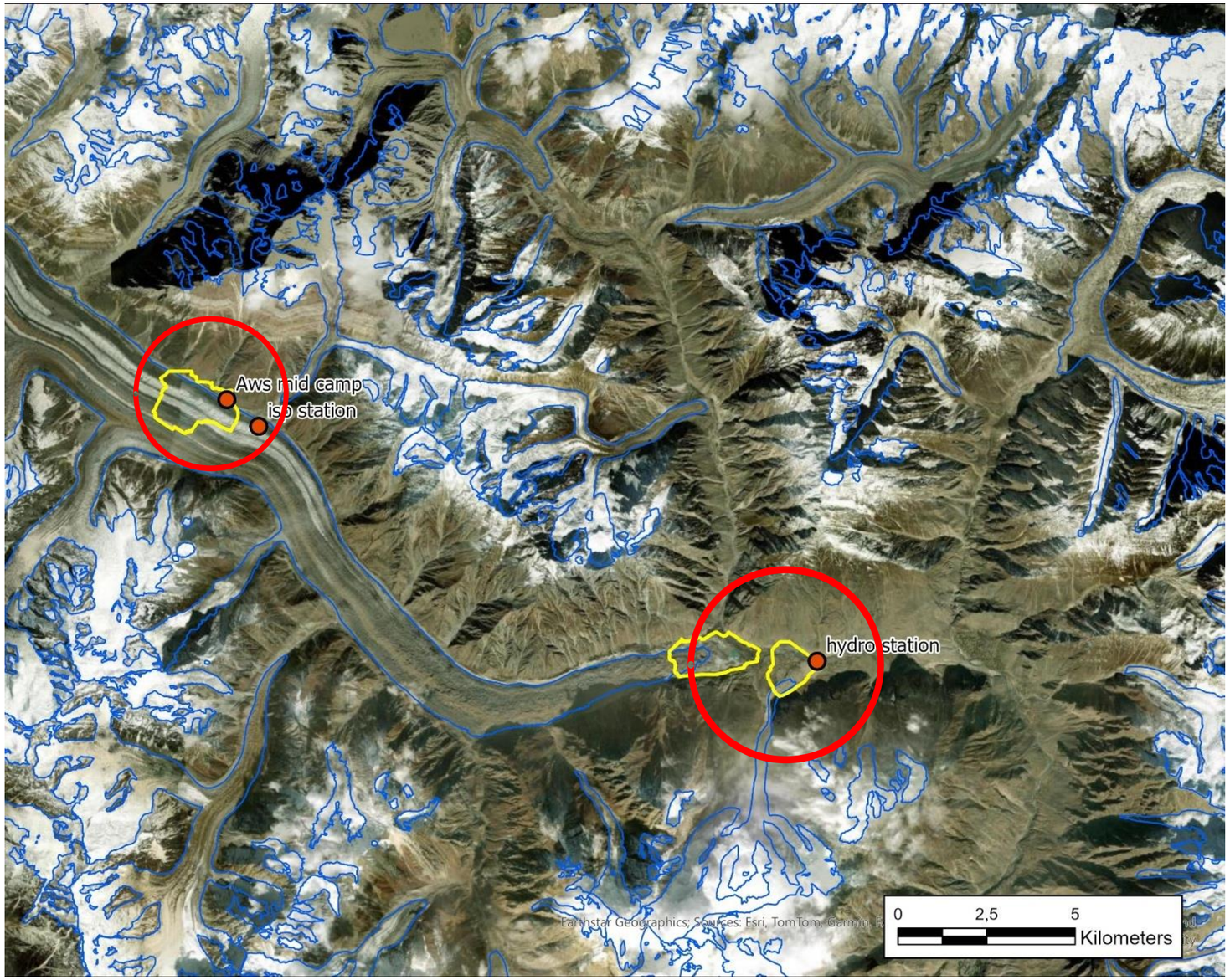




Concordia (4,600 m):

The highest AWS on a Pakistani glacier

The new AWS network: Spantik

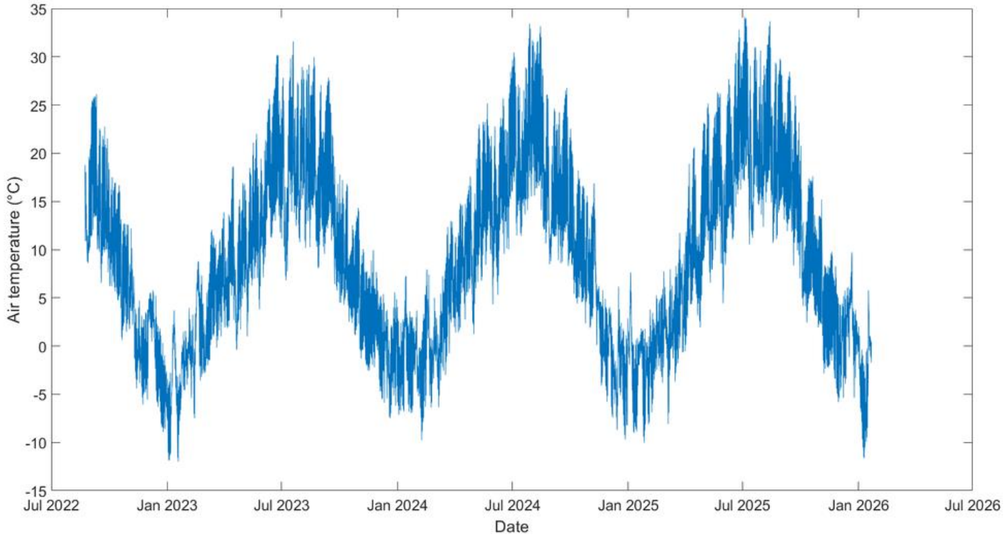




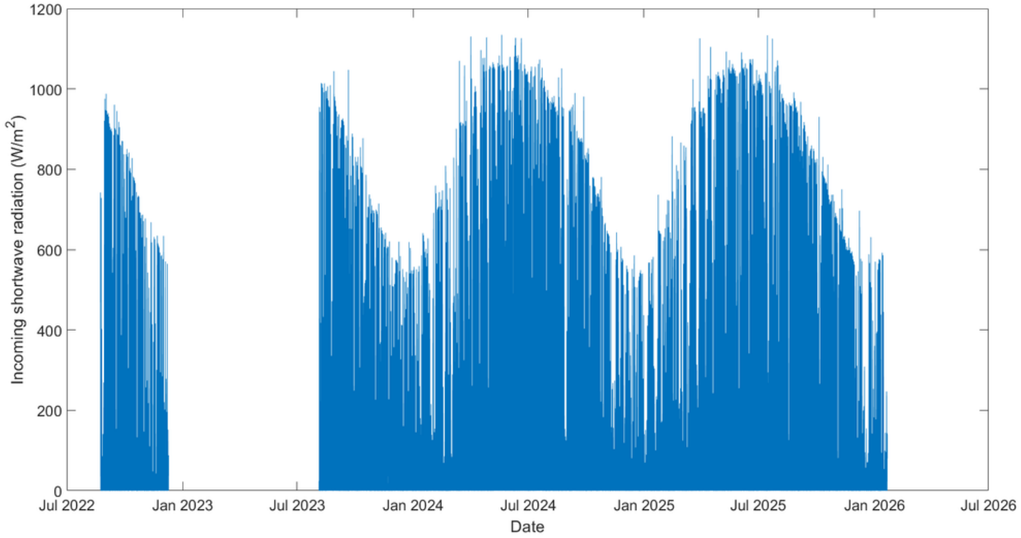
Chogo Lungma Glacier – 3.700 m

The new AWS network: Borith lake AWS data 2022-2026

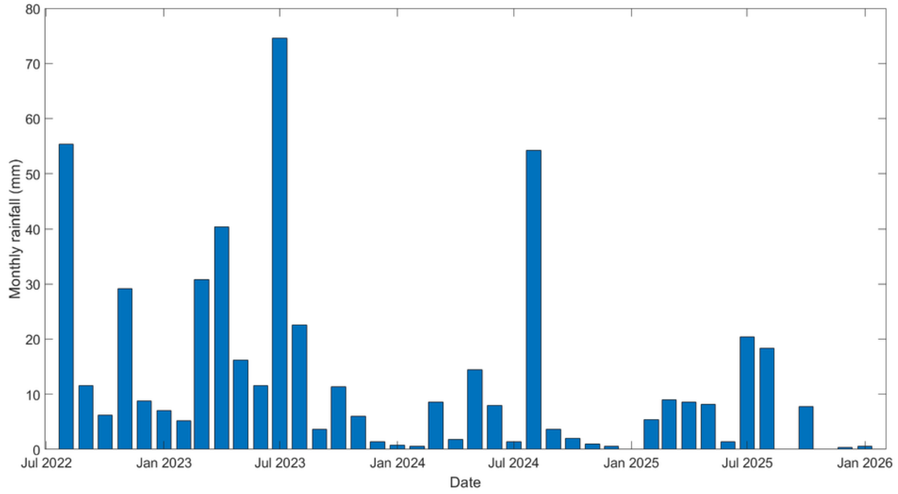
Air temperature



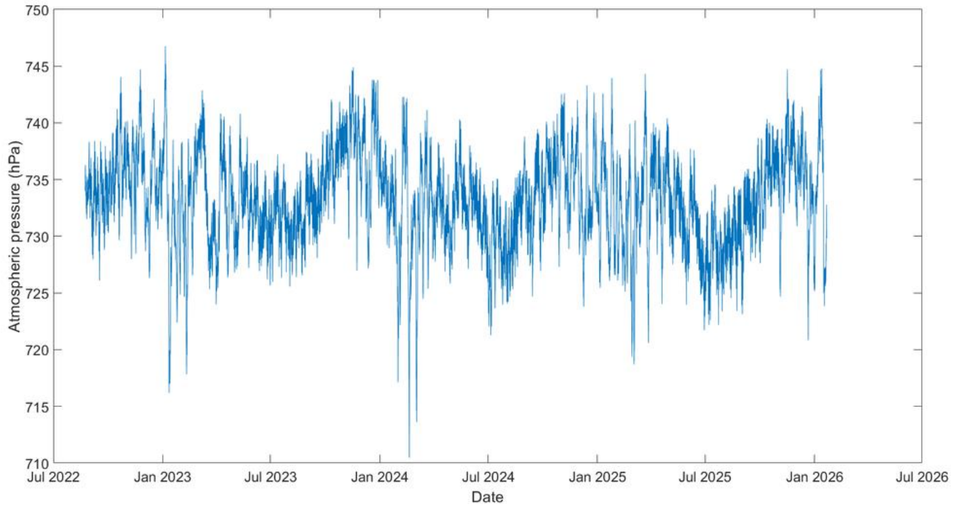
Solar radiation



Rainfall



Air Pressure



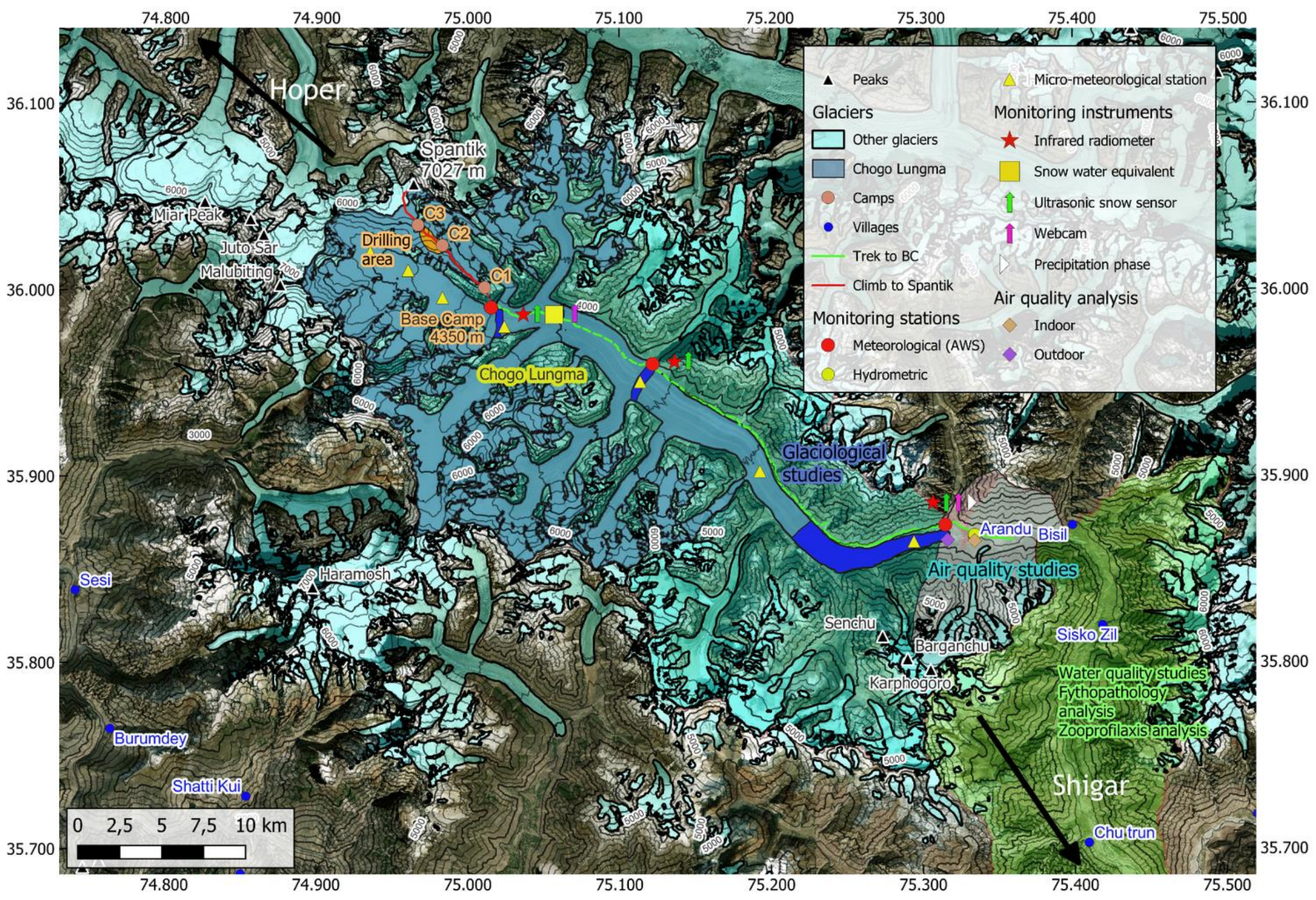
Glacier research in the ongoing W4D project

Starting the glacier inventory carried out in the Glaciers & Students project, we continue investigating the glaciers in relation to:

- Glacier mass balance
- Availability of freshwater downstream in the present and future
- Climate change impacts
- Hydrogeological risk phenomena



Spantik Lab


Peaks
Micro-meteorological station
Glaciers
Other glaciers
Chogo Lungma
Camps
Villages
Trek to BC
Climb to Spantik
Monitoring instruments
Infrared radiometer
Snow water equivalent
Ultrasonic snow sensor
Webcam
Precipitation phase
Air quality analysis
Indoor
Outdoor
Monitoring stations
Meteorological (AWS)
Hydrometric
Hoper
Spantik 7027 m
Miar Peak
Juto Sar
Malubiting
Drilling area
C3
C2
C1
Base Camp 4350 m
Chogo Lungma
Glaciological studies
Arandu
Bisil
Air quality studies
Sesi
Haramosh
Senchu
Barganchu
Karphogoro
Sisko Zil
Water quality studies
Fythopathology analysis
Zooprofilaxis analysis
Shigar
Chu trun
Burumdey
Shatti Kui
0 2,5 5 7,5 10 km
74.800
74.900
75.000
75.100
75.200
75.300
75.400
75.500
36.100
36.000
35.900
35.800
35.700





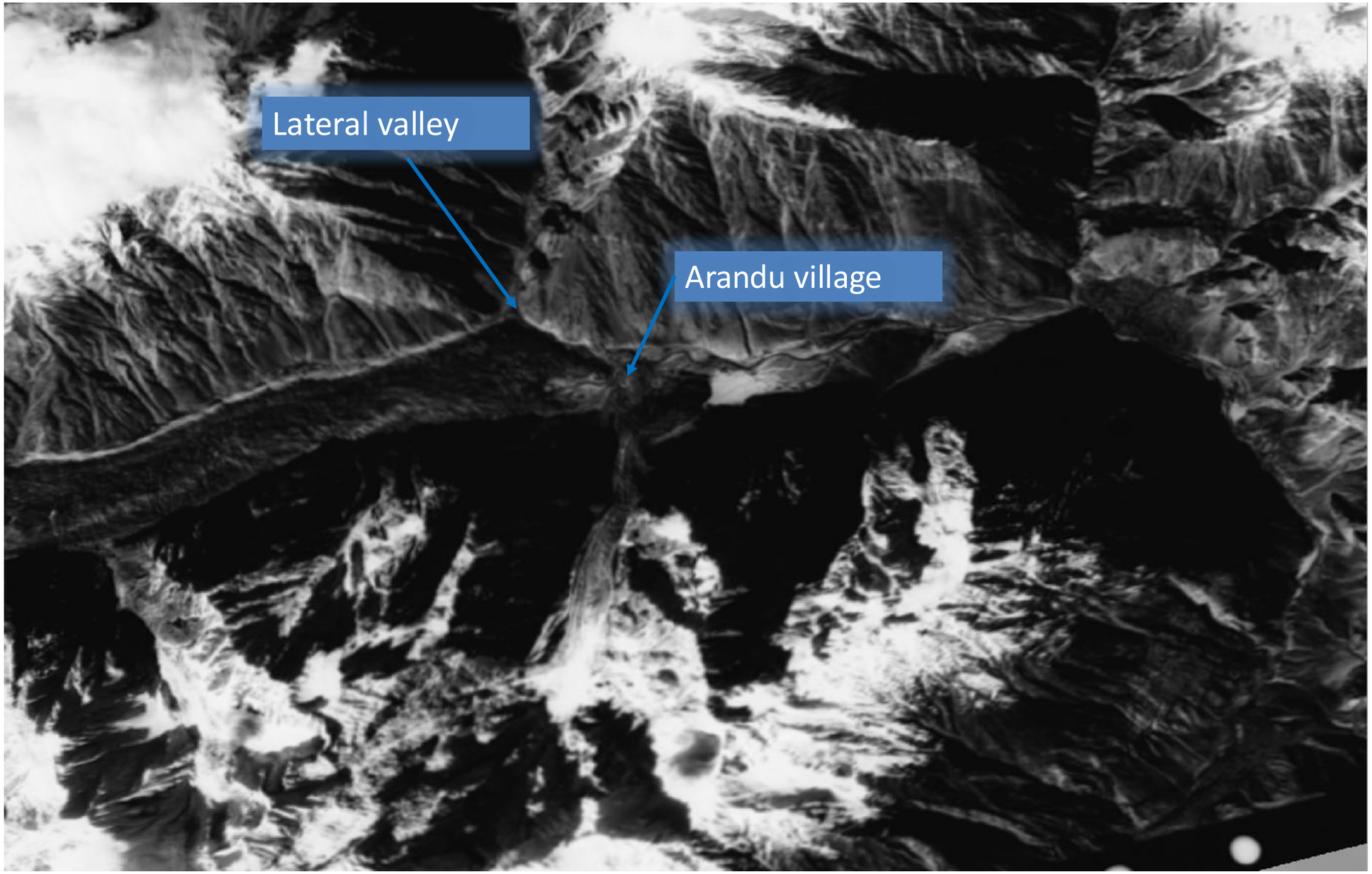
Spantik Lab: Chogo Lungma glacier

- One of the largest glaciers in Pakistan Karakorum (284 km²)
- The lower part of the glacier is almost entirely debris covered

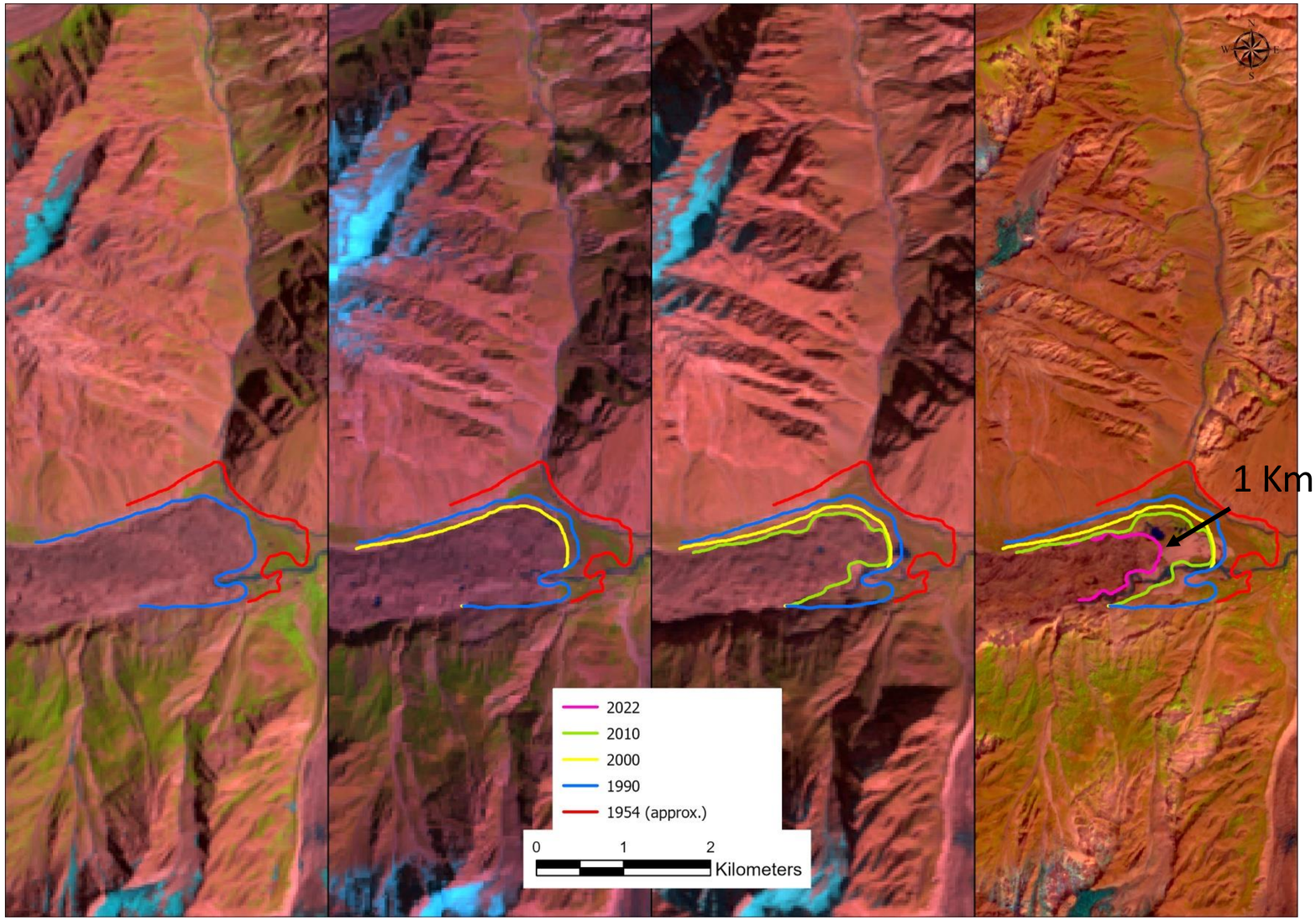
Investigation: enhance the understanding of the **Karakorum Anomaly** and the **future of Pakistani glaciers**



Spantik Lab: Chogo Lungma glacier



Chogo Lungma glacier retreat



Data sources:

Landsat 5 1990, 2010
Landsat 7 2000
Sentinel-2 2022

Spantik Lab: Glacier surveys in summer 2025



- Drone surveys over Chogo Lungma glacier
- Training on use of drone and GPS
- Installation of two AWS and a hydrometric station





Spantik Lab: Glacier surveys in summer 2026



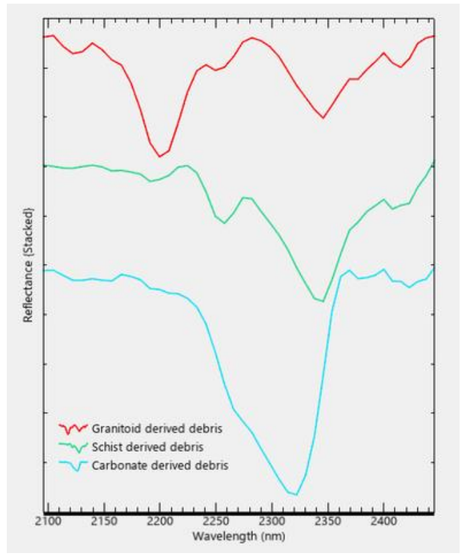


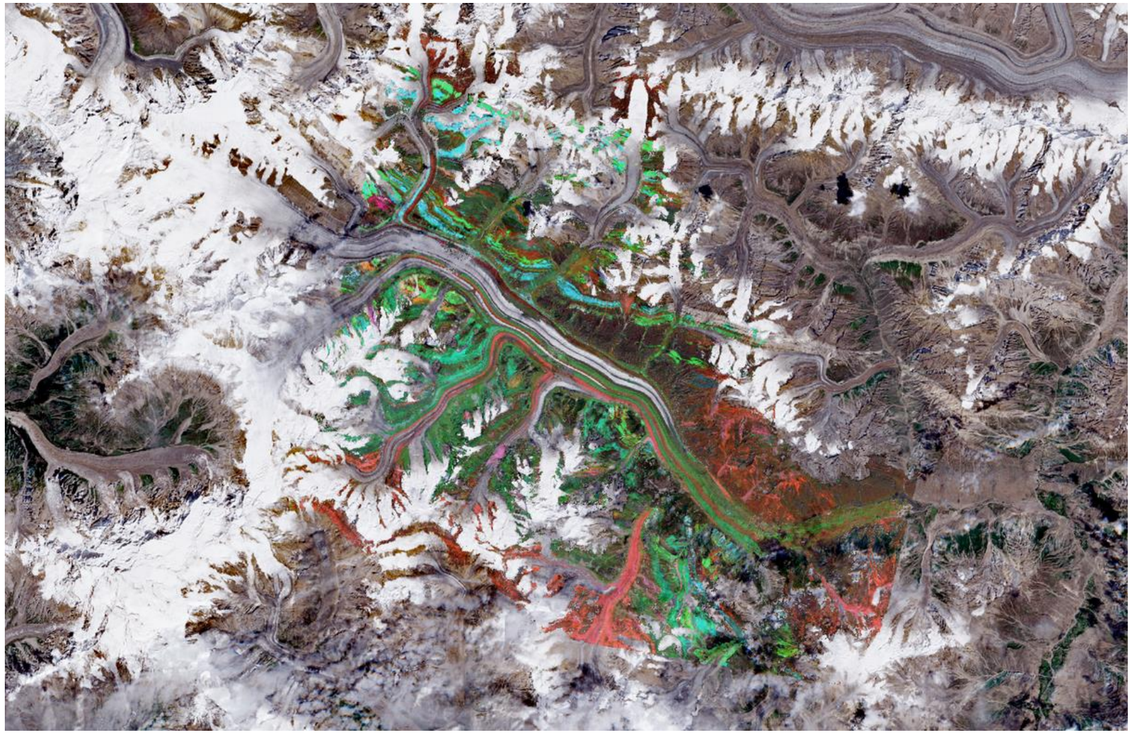
- Repeat drone surveys over Chogo Lungma glacier to estimate glacier mass balance of the terminal part
- Installation of ablation stakes and measurement of debris thickness
- Installation of AWS at base camp (4330 m a.s.l.)

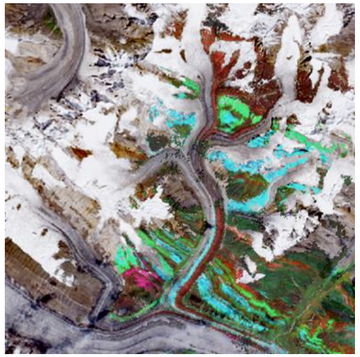
Spantik Lab: mineralogical mapping of supraglacial debris

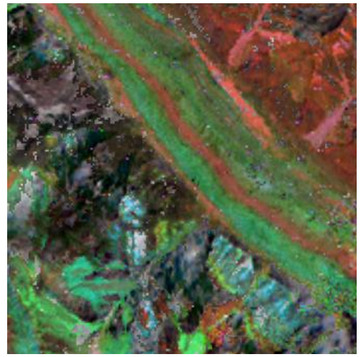
- Identification and **spatial delineation** of debris flows' **unique mineralogical signatures (granitoids, schists, carbonate rocks)**
- Discrimination of **debris provenance** zones, linking surface flows to specific source lithologies in the surrounding catchment
- Characterization of **debris mixing** and **flow evolution patterns** along the glacier tongue
- Production of **mineralogical maps** usable as input layers for describing debris-covered glacier flows





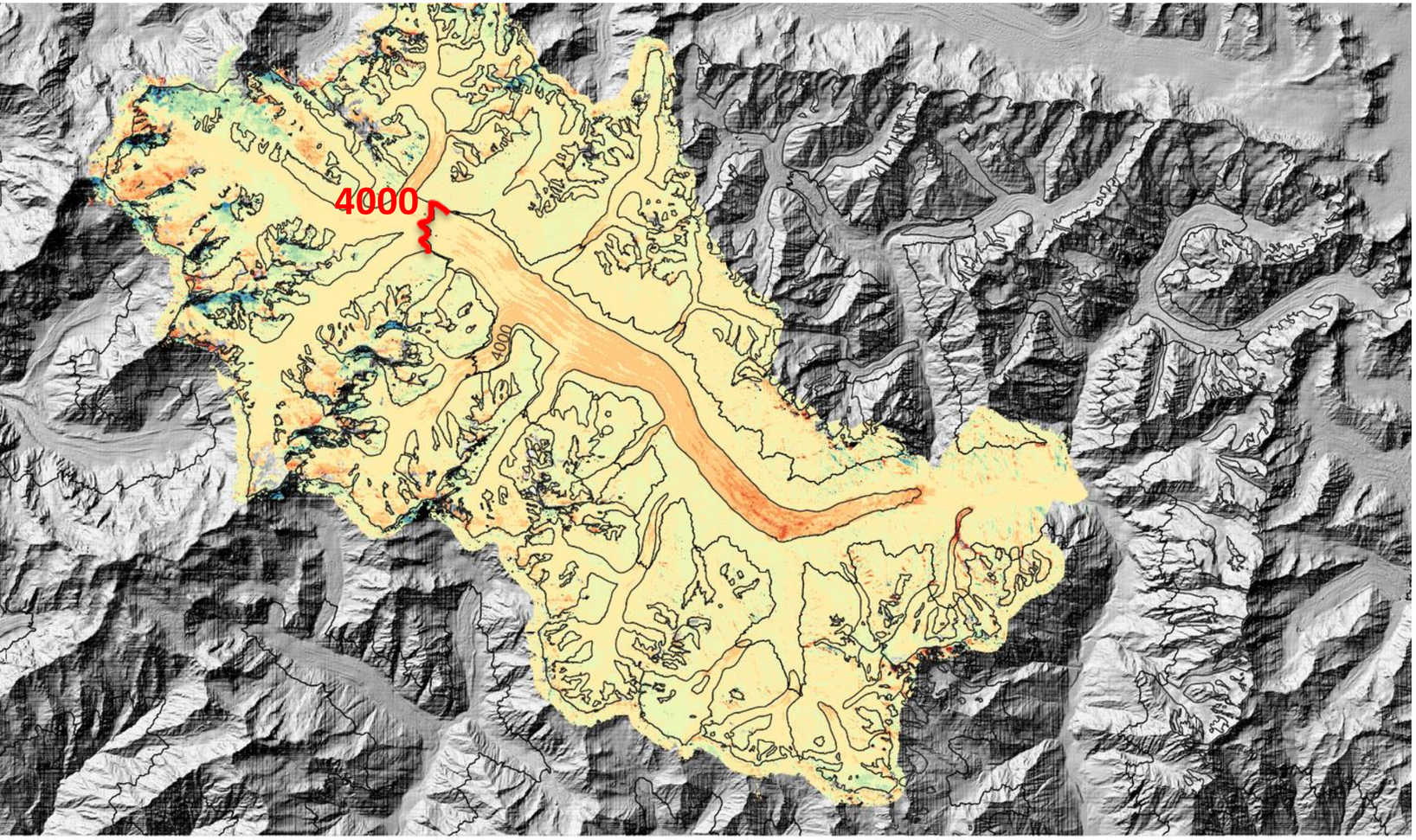








Spantik Lab: Chogo Lungma geodetic mass balance



Glaciers

Glacier thickness changes 2004-2025

<= -80,00

-80,00 - -60,00

-60,00 - -40,00

-40,00 - -20,00

-20,00 - 0,00

0,00 - 20,00

20,00 - 40,00

40,00 - 60,00

60,00 - 80,00

> 80,00

N

0 5 10 km

- Glacier area is **stable** (compared to -20% for Everest region)
- Glacier volume **stable above 4000 m** (compared to 6000 m for Everest region)
- Some areas above 4000 m show increase in glacier volume (in blue, under investigation)
- Loss of 60-80 m ice thickness on the glacier tongue below 4000 m

⬇

- Loss of 15% of glacier volume below 4000 m

Measuring ice melt: the surface energy budget

The term *surface energy balance* is specifically used to describe the balance between all surface energy inputs and outputs over a given interval of time. By calculating the surface energy balance, glaciologists can work out the change in temperature at a glacier surface and rate of glacier melt

The surface energy balance is the sum of all energy fluxes at the glacier surface, and is represented by the simple equation:

$$QM = SW + LW + QH + QE + QR$$

where ***QM*** is the energy available for melting ***SW*** is shortwave radiation, ***LW*** is longwave radiation, ***QH*** is sensible heat transfer, ***QE*** is latent heat transfer, ***QR*** is the energy supplied by rain.

Measuring melt: the surface energy budget





Deploying an automatic weather station (AWS) on a glacier allows measuring (potentially) all the necessary parameters for calculation of the surface energy budget at the point scale

These parameters then need to be distributed spatially and temporally to the glacier surface

Measuring melt: empirical models

Installing and maintaining an AWS on-glacier is complicated, so simpler forms of the energy budget are often used

Degree-day or T-Index: only takes air temperature into account

$$M = a\ T_a$$

Modified/enhanced T-Index: includes a factor for solar radiation (and albedo)

$$M = a\ SW\downarrow(1-\alpha) + b\ T_a$$

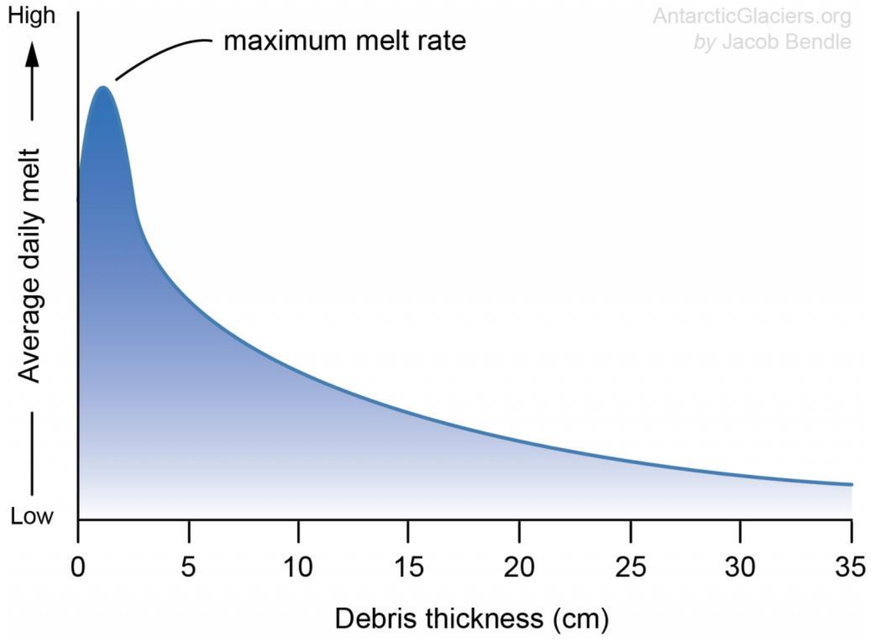
Drawbacks:

- they need to be calibrated with ablation stakes
- Melting factors are different for snow and ice

The role of debris cover

Depending on the thickness of the debris layer, the effect can be very different

- A thin layer of debris enhances melting, as the enhanced absorption of solar radiation owing to reduced albedo prevails
- A thick layer of debris reduced melting, as the debris insulates the ice

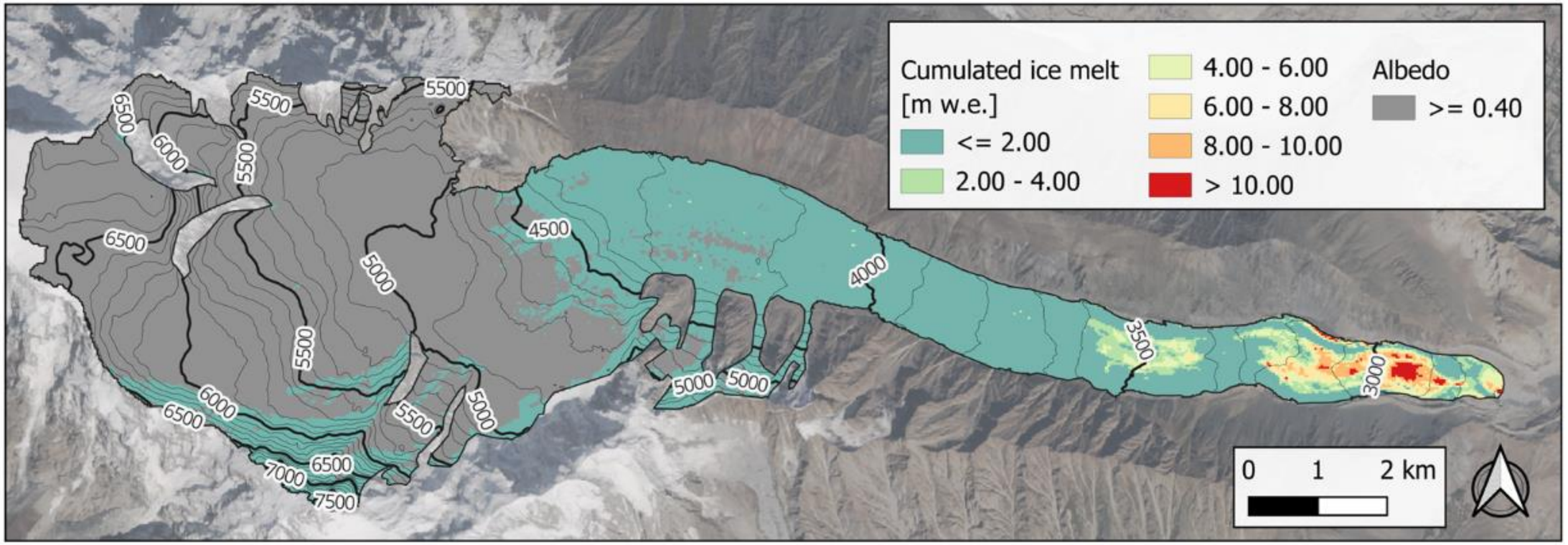


Q: What is the critical thickness?

A: It depends on the lithology. Usually 2-8 cm



Glacier melt modelling – Passu Glacier

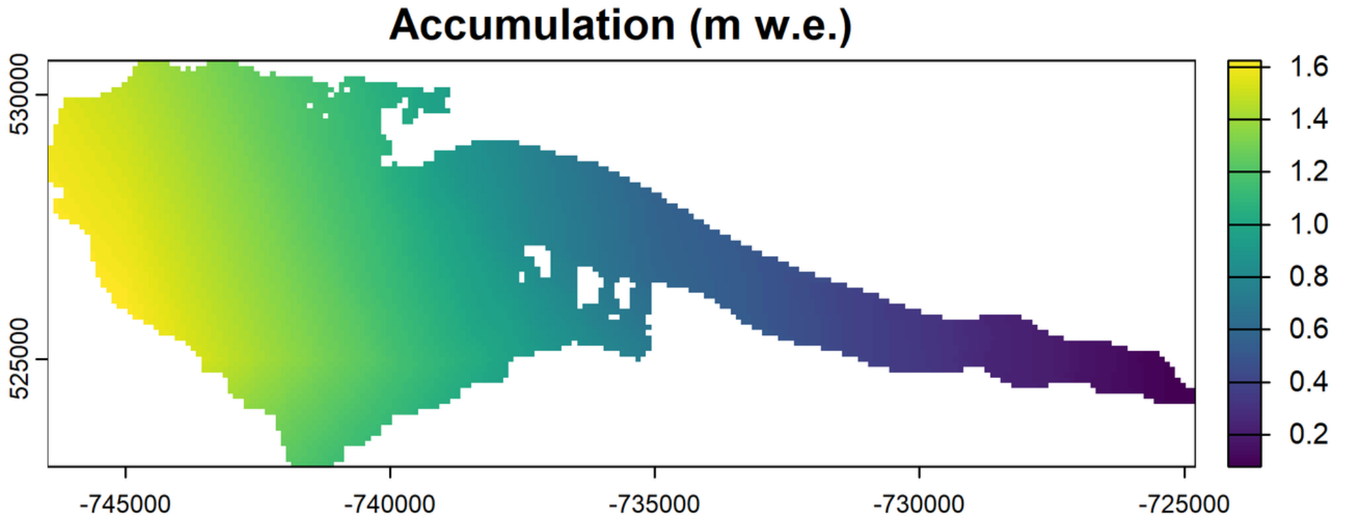


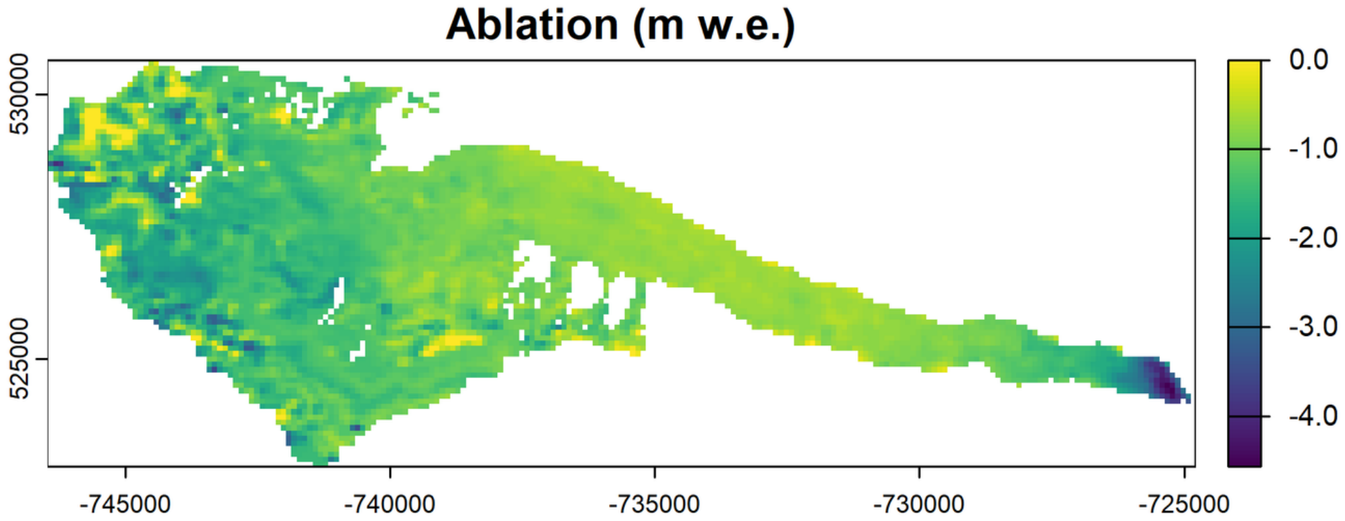
Barbagallo et al. (2025): Integrating Satellite and Field Data for Glacier Melt Modeling in High-Mountain Asia: A Case Study on Passu Glacier. Remote Sens. 2025, 17(23), 39077

Period: summer 2023 (August-October)

- Total ice melt : 16 million m³
- Average ice melt below 4500 m: 3.60 m

Glacier melt modelling – Passu Glacier





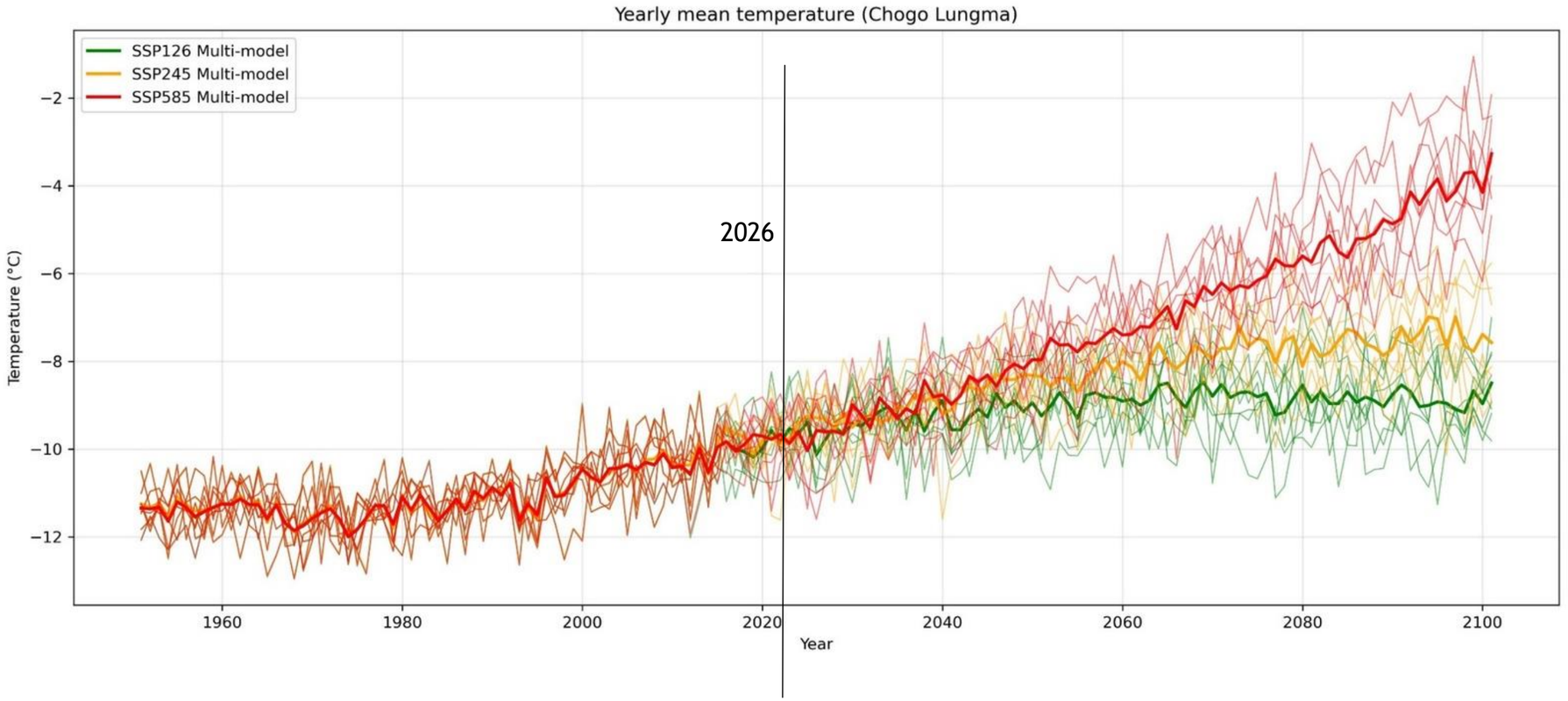
Glacier total volume: 7500 million m^3

Period 2023:

- Total ablation (ice and snow): 39 million m^3
- Total accumulation: 30 million m^3

Glacier mass balance for 2023: - 0.1%

Climate scenarios



Global climate models scaled to regional context

Red: higher emission scenario

Green: lower emission scenario

Yellow: moderate emission scenario

By end of the year: estimation of water availability from glaciers in relation to emission scenarios and temperature changes until 2100



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