DRAFT

The new inventory of 13200 Pakistani glaciers: the "Glaciers & Students" Project

Editors: **Guglielmina Diolaiuti, Maurizio Gallo and Maria Teresa Melis**
Editorial board: **Ahmad Anees, Muhammad Aurangzaib, Davide Fugazza, Arif Hussain, Sadia Munir, Antonella Senese, Claudio Smiraglia**

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UNICA UNIVERSITÀ DEGLI STUDI DI CAGLIARI
Karakoram International University
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GB EPA
EvK2CNR
EvK2CNR PAKISTAN
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Introduction

My experience on Pakistan's glaciers dates back to 25 years ago when I began to travel far and wide accompanying researchers, mainly geologists and geophysicists, who were studying the characteristics and thickness of the earth's crust in correspondence with the Karakoram range.
I have traveled across glaciers, even little frequented, in remote areas outside the classic itineraries and in those experiences, I have verified the complexity and size of Pakistan's glacial system and at the same time I have built a reference on their state and extent I have personally realized the intrinsic difficulty in visiting these glaciers, very crevassed and "troubled".
Since 2004 I have assiduously frequented the Baltoro glacier of which in these 20 years I have been able to personally see the changes in particular in the thickness of the glacial front and the continuous modification of the state of the surface with the presence of supraglacial lakes in continuous movement and streams always more difficult to cross and located in different areas of the glacier.
When I was presented with the possibility of a job as Project Manager of an analysis project on the updated state of the Pakistani glaciers, I was very honored and I carried out my job with satisfaction and, thanks to the support of many colleagues and local institutions, I believe that the expected results have been successfully achieved, overcoming a whole series of difficulties, above all the very short duration of the project.
The "Glaciers and Students" project acknowledges the urgency of addressing the impacts of climate change in the region. Through capacity building initiatives, the project aims to equip universities and local government institutes with the necessary skills and knowledge to address the environmental and water resource

Maurizio Gallo

implications of glacier retreat. As climate change accelerates, the changes in glaciers intensify, leading to the formation of glacial lakes and an increased risk of glacial lake outburst floods (GLOFs). These events can have devastating consequences for communities and infrastructure downstream. Therefore, building expertise in glaciology, remote sensing, and mapping is vital to effectively monitor and assess glacier changes, identify potential hazards, and develop appropriate mitigation strategies. By investing in capacity building and knowledge development, Gilgit Baltistan can strengthen its disaster preparedness and improve water resource management. Empowering local stakeholders with the necessary skills to navigate the challenges posed by climate change will contribute to sustainable development in the region. Through enhanced expertise in geomatics, weather stations, glaciological field activities, and avalanche risk assessment, the region will be better equipped to address the impacts of climate change on glaciers and water resources.
The main objective is to delineate the new inventory of all the glaciers of Pakistan that represent the third tower of water of the world, the biggest one excluding the poles. Totally there are 7200 glaciers in Pakistan in the three ranges of Himalaya, Karakoram and Hindukush. The analysis of the satellite images of 2021 gives a precise delineation of the surface of the glaciers and give the possibility to verify the trend that happened in the last 30 years comparing the previous inventory with the new one.
The Karakorum Anomaly, results of the studies conducted in 2011, show that the glaciers in the region are more stable compare the other parts of the world: nowadays is this result still true or the Pakistani glaciers are going to retreat as the others? From the first results we can suppose that there is a big difference between the western part of the mountain ranges and the ester one: in Hindukush and the right orographic of the Hunza River are melting much faster. The case of Shisper is a prove of this trend but also what is going on in Chitral in these days confirm this hypothesis.

The really unique approach of this project is the students involvement: students of the Italian Universities and Gilgit and Skardu Universities are working together sharing their steps and increasing their capacity building on glaciology studies: at the end of the project this awareness will remain and will create the basis for the development of a glaciology knowledge that has to be strengthened because in the situation of new era of climate change the study on the main resource of water of the Country has to become more important for the students and local institutions.
The expected result of creating an updated inventory of all Pakistan's glaciers was obtained through a very sophisticated analysis of satellite images from a methodological point of view thanks to the contribution of specialists from Italian universities: Milan, which has been studying the glaciers of the Karakorum for more than 70 years, Cagliari which developed the thematic maps used in the Management plans of the CKNP and Deosai. The glaciers have been divided by hydrological basins in order to allow in the future to estimate the water availability for use by local communities for agricultural use and for the overall availability of the entire Indus basin.
The methodological part and the analysis of the changes that have taken place in the last 20 years constitute the most relevant contributions included in volume 1, while the actual inventory is reported with graphs and maps in volume 2.
This work finds its natural continuation in the coming years through two fundamental tools: the database that is being built and above all that is made available to local institutions and the Universities of Gilgit Baltistan who will be able, indeed I would say will have to, update this register to correctly evaluate the evolution of the glacial system, the availability of water by basin and overall; secondly, the structuring of the glaciology center as a laboratory of excellence for the study of glaciers in close correlation with the water analysis laboratory to certify its potability.
In the mountains where I live in the Dolomites, a sudden collapse of the Marmolada glacier occurred last year which caused over a dozen deaths among hikers, the glacier is completely disappearing like most of the glaciers in the Alps: what happened for the Shisper glacier teaches us that glaciers are today a fundamental information base, a litmus test, of the progressive effects of climate change and oblige us to implement at least some adaptation strategies for the protection of the communities that live nearby of the glaciers and that only from their waters can they guarantee their survival.

Chapter 1.

The Project

Text by **Muhammad Aurangzaib** *and* **Sadia Maunir**

Project Introduction

The northern parts of Pakistan are home to some of the vast stretches of glaciers after the northern pole. The glacier reserves feed local livelihood systems and support unique ecosystems of global importance, in addition to serve as source of water for downstream areas. In face of the growing threat from global warming, these resources need assessment and monitoring through scientific technologies. The people living in mountain slopes of GB region are faced with risk of mountain hazards originating from glacier changes under the effect of climate change. The lack of information on climate change and assessment of glacial changes makes it difficult to predict the hazards. This project aimed at developing a consolidating program to establish monitoring of high-altitude climate and assessment of glacier changes, in support of environmental monitoring and natural resources management in Pakistan Mountains, Project activities will also contribute to improve risk assessment and prevention, dealing in particular with GLOFs and hydrogeological hazard, thanks to the application of remote sensing and GIS techniques and a dedicated web information system.
The project intended to actively involve Pakistan Universities and their students in the monitoring activities through a dedicated training and capacity building program in the field of glaciers monitoring activities and remote sensing analysis.

Development Challenge

Gilgit-Baltistan in the north of Pakistan, is home to unique geo-morphological set-up, hosting some of the precious ecological systems characterised by floral and faunal species of global importance. The vast glacier stretches on top of the Karakoram, Hindu Kush and Himalayan hills, classified as one of the largest glacier reserves after polar ice, serve as water towers for the productive and economic sectors of entire Pakistan.
The steep rocky slopes and wide green grassy meadows, as we come down the glaciers, provide a favourable habitat to rare wildlife species; Markhor, Ibex, Blue Sheep, Snow Leopard, Lynx, Eagle, Marmot, Flying Squirrel, are some to quote, in addition to a large number of plant species having scientific and economic significance.
The valley floors are habituated by local human

population, living there since long with their rich cultural heritage. The bond among humans, land, plants and wildlife for a mutually inter-dependent livelihood system is very strong and self-sustaining. It is further strengthened by flows of water from glaciers that irrigate their farmlands, nourish natural vegetation and fulfil human needs. An important element, since last few decades, has been the growing trend of nature tourism. Whereas the natural landscape, glaciers, wildlife and waterfalls attract a large number of national and international tourist, this becomes a source of employment and income for locals.

The ecosystem and natural resources, however, are not without risk and are taking the brunt of changing environmental and climatic patterns in the region. Whereas the reducing land cover, deforestation, over exploitation of land and wildlife species are directly linked to human interventions, the mountain disasters in the form of glacial lake outburst floods, landslides etc are the result of increased melting of glaciers. The number and frequency of these disasters has been increasing at fast pace, leaving behind damage to lives, property and infrastructure.

The mountain communities, already living in subsistence, are the most vulnerable to social and economic damage of these disasters. Women folks in mountain communities, who live behind at homes or work in their field while men are gone for business and labour, are at the forefront to take the damage of disasters. The economic impact of loss of livestock, houses, land and crops as a result of these disasters are felt life-long by the marginalized mountain population. The government agencies and institutions have been performing, at the most, a role of providing relief after disasters. Risk management and reduction, at source level, has been lacking because of insufficient information on glacier resources.

The huge glacier reserves in the Gilgit-Baltistan region, despite of their scientific and economic significance, have been one of the least monitored resources in this region, owing mainly to the lack of capacities, technology and accessibility. Due to lack of monitoring data and capacities, devising effective strategies to cope with the increased occurrence of disasters originating has not been accomplished so far. It is important to mention that glaciers management and monitoring, due to their ecological, social and economic importance, has been part of development frameworks in other parts of the world.

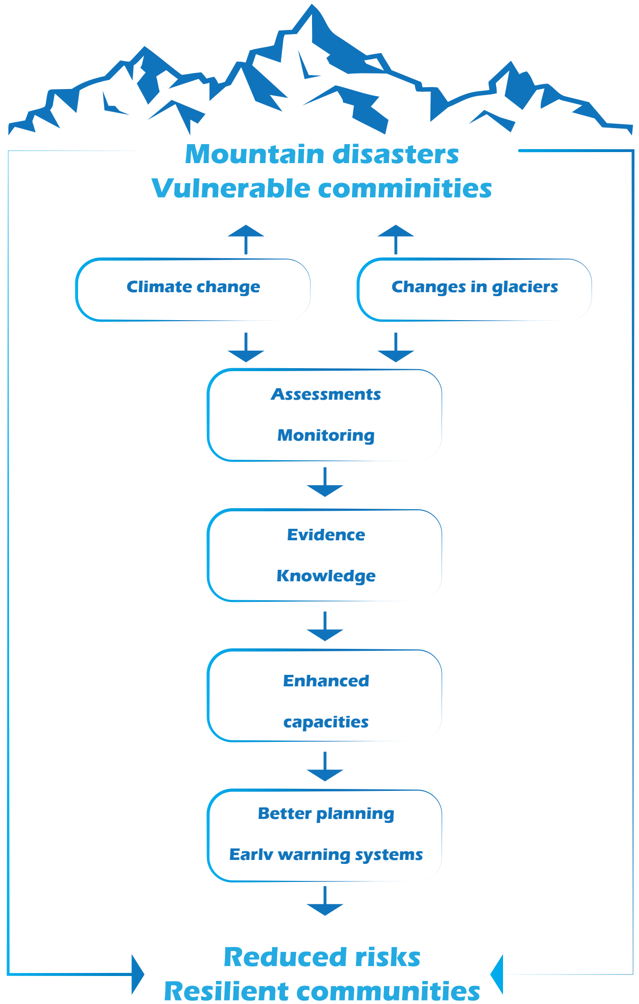
The role of glaciers in freshwater provision and regulation is proven in many other parts of the world, necessitating for us to monitor these precious resources. By providing baseline information on hydrological and hazard assessments, the observation of glaciers in mountain regions help us understand the changes occurring in glaciers. The measurements of changes in glaciers mass and length through in-situ methods and remote sensing in mountain ecosystems have indicated changes in climate patterns (Nussbaumer S.U. et al., 2017). This leads us to the conclusion also, that in order to better understand the root causes of glacier melting and other changes, and we must monitor meteorological factors in the glacier region.

The knowledge of the glacier "health state" is crucial for determining water availability, especially during the dry season. It is thus mandatory to collect information on specific, important glaciers, to determine their yearly contribution to river flow.

Glacial systems work through a delicate equilibrium between snow accumulation and snow ice melting. In Karakoram, this balance is complicated by the debris cover, widely present on most glacier surfaces. Baltoro Glacier, thanks to its dimensions (about 60 km long and more than 500 km2 wide) and the fact that it is the way to K2, is one of the symbols of Karakoram glaciers. Owing to the fact that its lower part is debris covered and its upper part is debris free, Baltoro can offer a wide spectrum of the different morphologies and typologies of Karakoram glaciers.

The glaciers of Gilgit-Baltistan provide 50.5 billion cubic meters of water to River Indus upon which country's 70 and 40 percent of agriculture and hydropower generation depends. This manifest that the food and energy security of Pakistan is highly dependent on this water tower, which is susceptible to global climate change phenomena. High altitude mountain glaciers of the region also serve as "Barometers of Climate Change" meaning that a slight change in the mean temperature

imparts drastic changes on the glacial mass. Increase in the mean annual temperatures are recorded in Gilgit-Baltistan and there is also seasonal shift in the precipitation increasing the frequency and ferocity of hydro-metrological disasters.
Remote mountain communities of Gilgit-Baltistan inhabit in valley bottoms along rivers and streams are highly vulnerable to the disasters triggered due to climate change. The response time is usually in minutes due to close proximity to the glaciers steep slopes.
To devise effective strategies for sustainable mountain development and monitoring, prevention and adaptation to climate change it is also fundamental to increase capacity both at local and institutional level in mountain regions. Previous experiences in other regions of Europe and South America demonstrate that a sound understanding of measurement techniques and of the purpose of measurements is necessary for successful glacier monitoring. In addition, establishing durable institutions, capacity-building programs, and related funding is necessary to ensure that glacier monitoring is sustainable and maintained in the long term.
The mountains and glaciers are highly sensitive to climate change and may have serious consequences downstream e.g. changes in sea level, effects on hydro-power planning for industries, and water management in agriculture sector. Systematic research into and long-term monitoring of cryosphere is therefore necessary. However, it is the complex environmental and geophysical setting in mountain regions that makes it difficult to conduct research and monitoring (Salzmann et al 2014; Strachan et al 2016).
The measurement of glacier resources and monitoring of climate factors in Gilgit Baltistan will generate knowledge that can be used for awareness raising, decision making and formulating long term strategies for disaster risk reduction and better management of sectors related to water. However, at the same time, this necessitates the building of capacities to generate, manage and share these knowledge resources for coordinated efforts. Better decisions and actions in these sectors will have positive impacts on the management of water and land resources,



ultimately enabling us to establish better responses to climate change and contribute in poverty reduction (Sustainable Development Goals No. 1, 6, 13 and 15).

Project Strategy

This project proposes an approach that will facilitate assessments, build capacities and hence reduce the risk of natural hazards originating from melting of glaciers under the effect of climate change. This approach consists of measuring the changes in glacier resources and the climate patterns at high altitude through advanced and proven scientific techniques using scientific equipment. The knowledge generated will be archived and shared through GIS based applications for scientific purposes, awareness raising, work planning and decision making at policy level. The same processes will be used to enhance local capacities in scientific institutions (i.e. universities) that will serve as an asset for longer term sustainability of the project initiatives. Apart from establishing, maintaining and monitoring a network of high-altitude meteorological observation system, changes in the glacier bodies will be monitored implying in-situ measurements and remote sensing techniques. The data trends generated over a period will be used to establish a link between climate variations and glacier changes. The same will also provide indication of disaster risks and hence favour better planning and timely decision making to reduce risks in dependent sectors e.g. agriculture, water management, power production, disasters etc.

General Objective:

Management of natural resources and mechanism for risk prevention in Pakistani Mountain Areas improved by enabling an evidence-based assessment and monitoring system for mountain glaciers in face of growing threat from global warming.

Specific Objectives/ Project Outputs

1. Assessment and monitoring system of mountain glaciers and climate improved in Pakistan contributing to improved planning and management of water and other natural resources including the sustenance of biological diversity.
2. Collaboration and sharing mechanism among Pakistani and international institutions and students strengthened to build capacities for longer term glaciers monitoring through innovative approaches and technologies.

Student Involvement

A dedicated training and capacity building program for local universities in Gilgit-Baltistan involved in the Glaciers &Students project. More than 160 students

Outputs	Output Indicators	Activities	Results
Assessment and monitoring system of mountain glaciers and climate improved in Pakistan mountain areas contributing to improved planning and management of water and other natural resources including the sustenance of biological diversity	1.A Number of climate monitoring stations in glacier region established and maintained to provide data on changing climate patterns for use by MET Deptt, GB Government (GB-EPA) and other concerned.	Install/improve and maintain climate monitoring network	8 climate monitoring stations installed and/or improved
	1.B Number of glacial bodies measured, monitored and documented to monitor changes over time that can provide early warning for natural hazards and contribute in reducing risks faced by mountain communities, particularly women and marginalized groups, in downstream valleys.	Study and monitoring of glaciers and glacial bodies	4 glaciers and glacial bodies monitored and studied
		Update the Pakistan Glacier Inventory	Updated Pakistan Glacier Inventory Report , and other scientific research articles published
Collaboration and sharing mechanism among Pakistani and international institutions and students strengthened to build capacities for longer term glaciers monitoring through innovative approaches and technologies	2.A Web based GIS climate and glaciers data archiving and sharing system developed and maintained to enable knowledge and data sharing among international institutions for scientific purposes, and the provincial and national authorities e.g. Met Deptt, GB-EPA, Water and Power Department GB, Disaster Management Authorities, Agriculture Deptt, and Water Mgt. Deptt.	Design and establish a web-based GIS information system Capacity building programme for faculties and students of Pakistani universities	Web-based GIS information system developed, and data archived
	2.B Number of students and faculty members of the local universities in Gilgit-Baltistan trained in glacier inventory and monitoring		169 (number of students and faculty members trained in glacier monitoring and related technologies with considerable representation of females

and faculty of Karakorum International University (KIU), University of Baltistan (UoB) and the personnel from EPAGB have been trained on the installation of AWS, data collectiona and their maintenance, GIS and remote sensing, and avalanche risk. The purpose of the involvement of KIU and University of Baltistan aims at importance of academia in carrying out environmental projects in GB with a focus on the students to strengthen the research and studies within the project and also in the future.International experts developed a dedicated learning program conducted through seminars and workshops at universities, in the field and through student involvement in the preparation of dedicated master's and PhD theses.

Gender Results

the Glaciers and Students Project in Gilgit Baltistan recognizes the importance of gender equality and takes steps to ensure that girls have equal access to education and training opportunities. By promoting gender equality and empowering girls, the project is helping to create a more just and sustainable society in the region. To address this issue, the project has implemented several measures to ensure that girls have equal access to education and training opportunities. This includes: Recruiting Female Researchers: The project has made a deliberate effort to recruit female researchers in the fields of GIS/RS and data science for the project. This helps to provide female students with role models and mentors who can inspire and guide them in their education.

Targeting Female Students: The project targets both male and female students, but there is a particular focus on reaching female students who may face additional barriers to the trainings.

In the project out of 169 students and researchers who were trained, 89 are female students and researchers. The students were involved and trained in monitoring stations installation, maintenance and data downloading, GIS and RS techniques, Avalanche risk prevention and rescue and generating classified maps for the glacier inventory while using various GIS software.

Involvement of institutions to access data base

Implemented a web GIS information system based on Ev-K2-CNR/SHARE GeoNetwork to collect and share the environmental information available in the area. The platform support concerned authorities, local stakeholders and beneficiaries to monitor the status and the evolution of glaciers, thus supporting the prevention of GLOF and hydrogeological risk. The system automatically elaborate satellite images and remote sending input in order to provide processed maps, data and metadata. This platform represented a unique data and information repository and could have several applications to support glacier and water resources management and risk assessment prevention. The information system interoperable and follow the international standards in terms of metadata and data format and QA/QC procedure, in order to guarantee the reliability of the information, facilitating the exchange of information at different level.

Project Partnetships

Thus relevant government departments responsible for monitoring climate (Met Deptt), disaster management (GB Disaster Management Authority), GB sectoral departments (Agriculture, Water), Gilgit-Baltistan Environmental Protection Agency and international development agencies (FAO, IFAD-ETI, WMO) will benefit from these platforms by gaining access to knowledge and data and mutual sharing of knowledge resources.

Gilgit-Baltistan Environmental Protection Agency (GB-EPA)

will be one of the key, beneficiary as the Agency has already started programme on glacier monitoring, climate reporting, climate change strategy and climate change adaptation action plan.
The GB Disaster Management Authority is the arm of National Disaster Management Authority responsible for managing the risks associated with natural hazards in the region. The GB-DMA will be one of the beneficiaries by getting access to real time and timely

data on climate factors and changes in the glaciers that could become source of hazards, enabling them to take timely decisions and strengthen their early warning system for disasters.

Karakoram International University (KIU): Through the EvK2CNR SEED project the KIU had received substantial support in several fields, as infrastructure development, furniture of equipment, including the installation of a Water Laboratory, scientific, such as the establishment of the Centre for Applied Mountain Studies (IMARC – Integrated Mountain Area Research Centre) and educational, with twenty students completing the PhD in Italian Universities. Thus, KIU is well acquainted in dealing with Italian partners. The faculty and students of the KIU will participate in monitoring and assessment activities in the field and will also benefit from exchange programmes with Italian universities. The project proposes to establish a Glaciology Centre in the University that can serve as knowledge repository and sharing platform for knowledge and experiences.

The University of Baltistan, Skardu:

UoBS is a public-sector university and the only higher education institution offering various degree programs in the region. The establishment of this university has multiplied prospects for the local, national, and international students. The geographical location of the university gives a strong foundation for the current and future programmatic activities. Baltistan is situated in the lap of the two largest mountain ranges, i.e., Himalaya and Karakoram, in the extreme north of Pakistan.

Chapter 2.

Italian research on Karakorum glaciers

Text by **Claudio Smiraglia**

K2 and Baltoro form an inseparable pair in the geography and history of Pakistan's mountains. K2 is the second highest peak in the World, but it is certainly the first one if we consider the grandiose fascination it exudes with its 8611 m altitude and its perfect pyramid shape. The Baltoro is one of the largest compound glaciers on Earth, 60 km long from the foot of K2 to the terminus where its melt waters flow, feeding the highlands of Baltistan before flowing into the Indus.
K2 is often referred to as 'the mountain of the Italians'. This name was given in reference the exploratory phases at the beginning and first half of the last century. It is hardly worth mentioning the pioneering exploits of the Duke of the Abruzzi in 1909 or those of the Filippo De Filippi expedition in 1913 or the expedition led by Aimone di Savoia in 1929. Moreover, K2 fully became the mountain of the Italians thanks to the widely described and discussed events that led to the first ascent of its peak in 1954 by the Italian expedition lead by Ardito Desio, professor at the University of Milan.
"Mountain of the Italians" is an appellation certainly deserved by the Italians who began a history of mountaineering, science and friendship with the Pakistani people more than a century ago, even though there were obviously numerous visits to carry out explorations and ascents by explorers and mountaineers from other countries of the World. Before the 1954 ascent, there was in fact the visit of the Englishman Martin Conway, for example, who in 1892 produced the first real topographical map of Baltoro, or the expeditions organised by the American Charles Houston in 1939 and 1953.
After 1954, when K2 had been climbed, a large number of mountaineers from many countries


Baltoro 1953

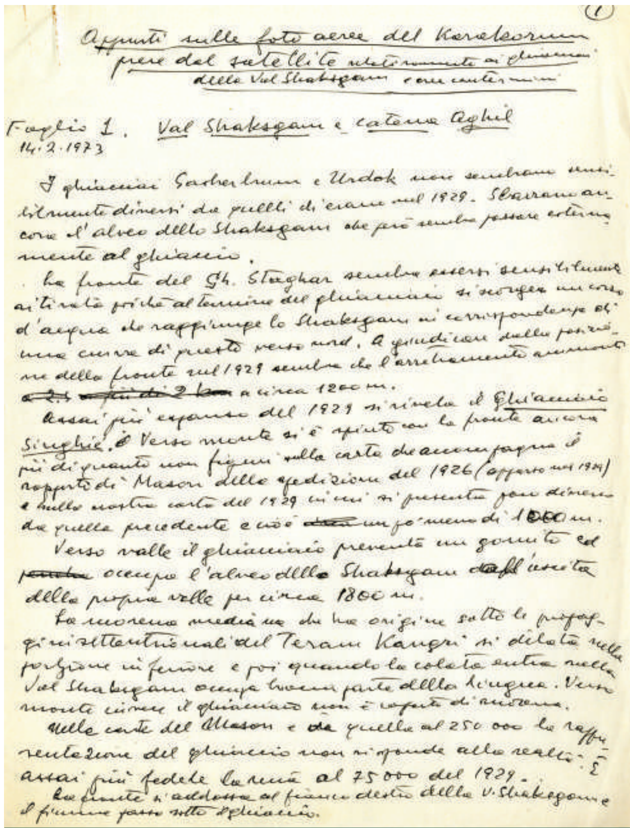

Baltoro 1954

attempted the summit. In this concise framework of historical references, we could attribute to Baltoro the qualification of "glacier of the Italians", both because it is located at the foot of K2, the "mountain of the Italians", and above all because Italian researchers have always played a significant role in the exploration and study of this immense mass of ice. Baltoro, with its surface area varying between about 600 km2 and about 850 km2 according to the different glacier inventories, covers a very limited percentage of the more than 22,000 km2 of the total glacial area of the Karakoram. However, it is the second largest glacier after the Siachen Glacier, and certainly one of the largest valley glaciers with compound basins on the entire Planet. All this justifies the interest and attraction it has always exerted on glaciological research in Italy and beyond.
Moreover, the Karakoram in terms of the presence, distribution and characteristics of glaciers is certainly one of the most interesting regions on Earth, not only for the total size of the glacier cover, but also for the socio-economic importance of these glaciers. In fact, they play a no negligible role with their melting waters to irrigation and hydropower production or they can drive GLOF-related hazards. Moreover in Karakoram glacier dynamics and surface conditions are often peculiar (e.g. surge and debris covered glaciers), thus making these glaciers unique and then subject of many international studies.
This chapter will therefore deal with the research carried out by Italian scientists on Baltoro and on other Pakistani glaciers, summarising the first phase, which can be defined as prevalently exploratory and which can be considered concluded with the researches performed by the staff of Prof. Ardito Desio during the expedition that reached the summit of K2 in July 1954. Then we will dedicate more space to describe the most recent studies performed after that historical event.


Baltoro 1958

The exploration phase

It is very difficult to describe the evolution of early Italian glaciological research in Karakorum without reducing it to a simple list of names. It must be added, that observations on the characteristics of the glaciers, on their evolution, and on the forms of the landscape modelled by them, have been carried out in practically all the expeditions, that can be defined generically as geographical ones. These geographical expeditions have been carried out since the end of the 19th century and have seen many Italian researchers, in particular topographers and cartographers, join organised groups of foreign scientists and mountaineers.
Among many, we should mention the topographer Cesare Calciati, who was part of the expeditions organised by Workman, an American couple (husband and wife) who organised and carried out missions to Pakistan in 1908 and 1911. It should also be noted that research in the glaciological field was certainly not undertaken by glaciologists in the modern sense; this qualification and specialisation would in fact only materialise many decades later (perhaps at the end of the 20th century!). Usually the first to take measurements on glaciers were geographers or naturalists or, more often, topographers, such as the aforementioned Calciati, who carried out field measurements on the great Hispar Glacier.
Many of the expeditions that have taken place since the beginning of the 20th century certainly had a predominant mountaineering objective, but they also combined scientific intentions. The same 1909 Duca degli Abruzzi expedition, which aimed at the ascent of K2, saw the topographer Federico Negrotto at work. Using photogrammetric methods for the first time, he produced a map of the middle-superior sector of Baltoro at a scale of 1:100,000, an important and useful initial moment for tracing the evolution of the glacier (De Filippi, 1912). This was followed in 1913-1914 by the great exclusively scientific expedition organised by Filippo De Filippi, in which a dozen researchers took part, including Giotto Dainelli and Olinto Marinelli, already experts in Alpine glaciation. Dainelli and


(1)
Appunti sulle foto aeree del Karakorum
prese dal satellite [illegible]
della Val Shaksgam [illegible]

Foglio 1. Val Shaksgam e catena Aghil
14.2.1973

I ghiacciai Gasherbrum e Urdok non sembrano [illegible] dimensioni da quelli di [illegible] nel 1929. Sbarravano [illegible] l'alveo dello Shaksgam che [illegible] mente al ghiaccio.
La fronte del Gh. Staghar sembra essere [illegible] [illegible] al termine del ghiacciaio si scorge un [illegible] 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 circa 1200 m.
[illegible] del 1929 si rivela il Ghiacciaio Assai più espanso del 1929 si è spinto con la fronte ancora Singhie. È Verso monte si è [illegible] 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 [illegible] da quella precedente e cioè un po' meno di 1000 m.
Verso valle il ghiacciaio presenta 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 [illegible] il ghiacciaio non è coperto di morena.
Nelle carte del Mason e da quella al 250 000 la rappresentazione del ghiacciaio non risponde alla realtà: è assai più fedele la nostra al 75 000 del 1929.
La fronte s'addossa al fianco destro della V. Shaksgam e il fiume passa sotto il ghiaccio.

Desio A. & Savoia Aosta, 1936

Marinelli explored, among other things, the Rimu Glacier in the eastern sector of the chain, producing a valuable map at a scale of 1:100,000 (Dainelli & Marinelli, 1928).
In 1929, a great scientific expedition to Karakorum took place. This was the expedition led by Aimone di Savoia duke of Spoleto, which initially had the primarily mountaineering objective of reaching the summit of K2. However, this objective was abandoned and the expedition took on the official name 'Italian Geographical Expedition to the Karakoram'. A young researcher, Ardito Desio, who was entrusted with the geographical, geological and glaciological surveys, took part. Since then, Desio's name will forever be linked to the study of these glaciers (Desio A. & Savoia Aosta, 1936). Desio carried out an extraordinary series of explorations, topographic surveys and barometric measurements on the glaciers on both sides of the chain. As part of the expedition, numerous topographic maps at a scale of 1:75,000 were drawn up, including that one of the Baltoro Glacier basin. From Desio's observations and from his comparisons with the older map surveyed by Conway in 1892, the front of the Baltoro glacier did not appear to show appreciable variations; the lack of frontal moraines and traces of collapse of the front itself confirmed this hypothesis. Desio emphasised that the use of the classical measurement methods applied in the Alps (i.e.: measurement of "terminus fluctuations" from fixed reference points –benchmarks- located outside the glacier body in the glacier forefield) did not seem suitable for this glacier, given its size. For this reason, he placed four signals in the glacier forefield, including the signal "T", which will play a significant role in the history of Baltoro. This signal is in fact located on a grandiose trapezoid-shaped gneiss boulder with a characteristic white transverse quartz vein, immersed in the fluvio-glacial debris, and about twenty metres far from the glacier ice covered by moraine material. The boulder had already been reported and described by Conway and Dainelli, but no measurements were taken.
The Second World War completely halted exploratory, scientific and mountaineering initiatives in the Karakoram. It was Desio again who planned and

coordinated the expedition that in 1954 not only led to the first ascent of K2, but also to an extensive series of scientific research in various fields, including glaciology. This expedition represents the conclusion of the exploratory phase and the beginning of what could be called the 'technological' phase (Desio et al., 1961). The 1954 expedition was preceded the year before by a reconnaissance, also carried out by Desio, which also marked an important page in the evolution of knowledge of the Karakoram glaciers.
Following an invitation from the government of Pakistan, Desio visited the Stak area where the inhabitants had reported that the entire valley was threatened by the extremely rapid advance of an ice body, the Kutiah Glacier. Desio, although initially doubtful, confirmed the unusual event: the glacier had actually moved towards the valley with an unimaginable speed, about 12 km in three months, 113 m per day. Desio described the glacier as "an immense flow all upset by pinnacles and crevasses, occupying, like a monstrous reptile, the bottom of the Kutiah valley'". He believed that the advance phase had ended and that a great landslide of ice and rock, which had filled the glacier's accumulation basin, caused this by forcing it with its weight to move rapidly downwards. This is one of the very first descriptions of a phenomenon, still being studied today, that characterises the glaciers of the Karakoram and a few other regions of the World (Svalbard and Alaska). This phenomenon is known today as "glacier surging"; Desio was one of the first to describe and study it and to share this information with the scientific community through an article published on the Journal of Glaciology, the most prestigious international glaciology journal (Desio, 1954). However, it was with the scientific missions of 1954, alongside and shortly after the epic mountaineering expedition, that knowledge of the Karakorum glaciers took decisive steps. It was above all the photogrammetric surveys carried out by Francesco Lombardi on the Baltoro, Biafo and Hispar glaciers that led to the creation of valuable large-scale maps (such as that one of Baltoro at the scale 1:100,000 and that of K2 at the scale 1: 12,500). These surveys constituted a milestone in the

Gasherbrum 1985

study of the evolution of these glaciers (Desio et al., 1991). Among other things, the geophysicist Antonio Marussi used gravimetric methods to measure the ice thickness of the Baltoro at Circo Concordia for the first time, obtaining a truly extraordinary maximum value of almost 900 m (Marussi, 1964). Measurements from the T-signal, known as 'Masso Desio', indicated that the Baltoro front had retreated by almost 300 m compared to 1929. The results of the scientific mission were published in nine volumes in English between 1964 and 1991, where glaciology is not fully exploited. In fact, the plan included a tenth volume dedicated to glacier evolution and to a detailed study of surging, as well as an inventory of the glaciers in the Braldo Valley. Objectives that engaged and still engage the scientists of the University of Milan who followed and follow the trails of Prof. Desio (Desio, 1977).

Between science and mountaineering

Between 1955 and 1975, Desio organised numerous other expeditions to the Karakorum with exclusively scientific objectives, particularly geological ones, while his contribution to knowledge of glaciers was limited to photographs and notes by a few mountaineers, members of the now numerous expeditions that frequented the Karakorum highlands. A significant example is the photograph of the Baltoro terminus taken in 1958 by Fosco Maraini, where the 'Masso Desio' is also clearly visible. A new, albeit brief, season of union between science and mountaineering took place in the early Eighties with the "Quota 8000" society founded by mountaineer Agostino Da Polenza, which aimed to link mountaineering at very high altitudes not only with the demands of

Liligo 1997

spectacularisation of the contemporary world, but also with its ancient cultural and scientific matrix. Prof. Desio had a young researcher, Claudio Smiraglia, joining the group with the task of repeating the measurements he had made on Baltoro. In the 1985 expedition, the 'Masso Desio' was found (the front of the glacier was advanced by about 130 m compared to 1954), a celerimetric survey of the front was carried out, and one of the first quantifications of differential ablation was carried out at 5100 m at the Gasherbrum base camp. It became evident that a thickness of rock debris of few centimetres tends to slow down ablation. On the Baltoro with ice buried by 20 cm thickness of rock debris it was observed an ablation equal to only 25% of that one experienced by debris free ice located at the same elevation. Differently, under a mantle of very fine and sparse debris (e.g.: 1 cm of rock debris with sand gran size) ice can experience an enhanced ablation, up to 6% more intense than the one of debris free ice at the same elevation. Other observations concerned the Liligo Glacier, which, on the basis of Vittorio Sella's 1909 and Ardito Desio's 1953 photographs, was classified as a surging glacier (Smiraglia, 1986; Smiraglia, 1987). Agostino Da Polenza, with the support of Ardito Desio, founded the Ev-K2-CNR Committee in 1987, later a recognised association, with the specific objective of promoting and organising scientific and technological research at high altitudes at a multidisciplinary level. Glaciology, of course, also found ample space through a series of agreements with the University of Milan and other Italian and European universities and research centres.

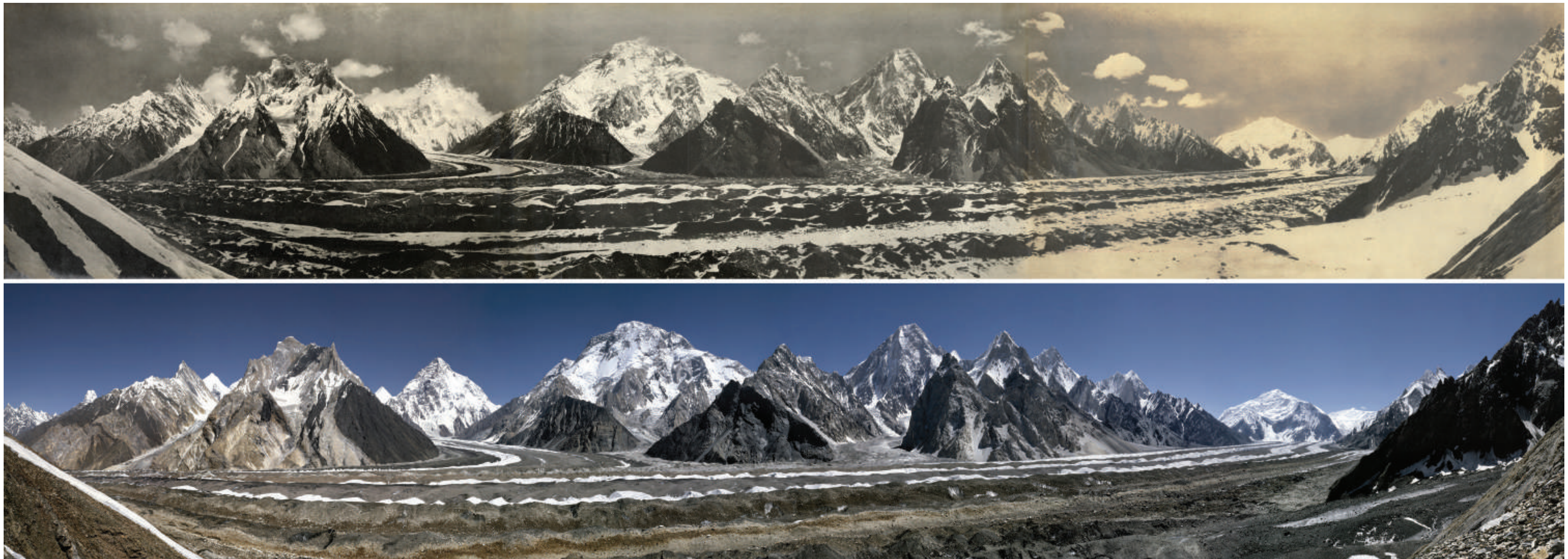
Decades of Italian glaciological studies in the Karakoram Karakoram glaciers continued to be one of the most important research topics, especially since 2004, when an expedition was organised to celebrate the 50th anniversary of the first ascent of K2. On that occasion, an expedition of researchers from the University of Milan and the Bavarian Academy of Sciences and Humanities carried out a series of surveys and observations on the Baltoro Glacier and its main tributaries. They also used advanced techniques and instrumentation, such as laser scanners and georadars, and took advantage from remote sensing investigations (Mayer et al., 2006; Smiraglia, et al., 2007). At that time, the first supraglacial Automatic Weather Stations (AWS) were also installed, which made it possible to collect the first supraglacial meteorological and energy data sets on a Pakistani glacier in the summer of 2004, and to calculate thermal lapse rate and radiative gradients that were indispensable for the calculation of the glacier's surface energy balance (Mihalcea et al; 2006, Mihalcea et al, 2008). This research, as well as the subsequent ones, is part of the specific issues that characterise Karakoram glaciation and distinguish it from other mountain ranges on our Planet. We refer in particular to the effects of surface debris cover (the largest debris-covered glaciers on Earth develop in Karakorum) and the phenomenon of the aforementioned surging glaciers. To these, has been added the so-called 'Karakorum Anomaly', a key issue to be investigated as an exception to the current rapid global glacier retreat. In fact, numerous investigations since the beginning of the 21st century have shown that for many Karakoram glaciers the retreat is much less intense than on other mountain ranges and that many are in a stable or even slightly advanced phase (Bocchiola & Diolaiuti, 2013; Minora et al, 2015; Minora et al, 2016).

Other important and topical issues, which will certainly require in-depth study in the future, are those of water resources represented by glaciers and possible risk phenomena.

With regard to the Baltoro Glacier, which has certainly been the glacier most studied by Italian glaciologists in Pakistan, the research objectives included the definition of the glacier's current dynamic phase, as well as the assessment of the magnitude of ablation in relation to the thermal characteristics of the debris and meteorological conditions. The field surveys carried out during several campaigns, integrated with the analysis of historic cartographic and iconographic documentation and supported by remote sensing, showed that the length and surface of the glacier have not undergone any significant variations. In the space of a century, the position of the front has in fact oscillated up and down by a couple of hundred metres. On the other hand, a reduction in thickness was evident in the lower sector, although to a lesser extent than in other mountainous areas. The scientists from the University of Milan found that the debris cover extends over about 40% of the glacier melting surface with a maximum thickness of more than 1.5 m in the frontal area (thicknesses were also assessed with georadar). Along the glacier up to about 5000 m asl, ablation measurements were taken on both debris free and debris covered ice ("stake farm" experiment, see Minora et al; 2015) which were then correlated with data from two automatic weather stations, the first one on a lateral moraine at Urdukas (about 4020 m asl), the second one is an ancillary station, temporary located at Concordia (abou 5033 m asl).

Furthermore, temperature measurements of the rock debris mantle have been carried out to calculate its thermal resistance, which is a crucial parameter for calculating the heat flow capable of passing through the debris and reaching the buried ice, promoting its melting. The relationships between ablation of the ice, debris thickness and altitude were investigated as well; the distribution of the physical and thermal characteristics of the debris over the entire surface of the glacier was also verified with remote sensing, in particular first using ASTER images (Mihalcea et al, 2008) then analysing Landsat images (Minora et al; 2015). In summary, the glacier energy budget was determined over the entire surface of Baltoro Glacier (Mihalcea et al; 2008) and then of the entire Central Karakoram National Park (CKNP, Minora et al; 2015) and the resulting ablation was calculated. The results obtained indicate that above a critical thickness threshold of about 5 cm, melting slows down considerably, and it becomes almost negligible with debris thicknesses greater than one metre. During a new mission to Baltoro carried out in 2013, Italian and German researchers found that ablation is also strongly influenced by other factors such as aspect, inclination and altitude. The superficial speed of the glacier between Urdukas and Concordia was calculated using land data (differential GPS measurements) and satellite data. Close to Concordia, a maximum speed of about 60 cm per day was measured, which extrapolated to the entire year would indicate an annual speed of just over 200 m, which decreases rapidly at Urdukas. It should be taken into account that the measurements were carried out during the summer season, when the occurrence of abundant melt water could influence the basal slip by reducing friction with the bedrock; the annual value could therefore be overestimated, as it is suggested by the comparisons made between Landsat and ASTER multi-temporal satellite images. The set of data collected also made it possible to determine the mass balance of the glacier close to Circo Concordia. The glacier is close to steady state conditions, with a balance in equilibrium or slightly positive (+0.34 km3 per year). In this area, formed by the confluence of the Godwin Austen Glacier and the Duca degli Abruzzi Glacier, the maximum thickness of the Baltoro resulted via georadar equal to about 800 m thus confirming the previous campaign performed under the umbrella of the missions organized and lead by Ardito Desio. In summary, the several field campaigns performed on the glacier, combined with the constant analysis of satellite images, have made it possible to highlight the physical and dynamic characteristics of what can truly be defined as the "Baltoro system", made up of seven main confluent glacier flows, which makes complicated any study of its mass balance. The upper part of the glacier,

Liligo 1909


Concordia 1929

close to Concordia, represents the greatest ice flow and dominates the dynamics of the glacier up to its front, with a balance, as mentioned, in equiibrium or even slightly positive, as confirmed by the frontal variations, which were minor throughout the previous century. This stability appears in contrast to numerous confluent glaciers, such as Liligo, which with repeated phases of intense advance and rapid retreat ranks among the surging glaciers. It is also in countertrend to the global regression of mountain glaciers, it can be placed in that framework which has been defined above as the "Karakoram Anomaly". Also on Baltoro, but also on Chogo Lungma, surface speeds were recently estimated by processing Sentinel-1 SAR (Synthetic Aperture Radar) satellite images, characterized by high repetitiveness (every week) and high resolution (5 m). In the period 2014-2015, the surface velocity for the Baltoro was about 100-120 m per year in its central sector, for the Chogo Lungma slightly higher (180-240 m per year) (Nascetti et al., 2016). The previously mentioned Liligo is a small glacier ("small" in a relative sense - it is 10 km long - compared to the large glaciers of the Karakoram), located in a transversal valley, which descends towards the Baltoro on its hydrographic left. Its location along the itinerary that leads to the K2 base camp and the ease of access have favoured the collection of documentation, especially photographs, by the various expeditions that pass through it. Using a wide variety of documentary sources, it has been ascertained that the glacier has had at least two notable stages of advance since the beginning of the last century. The first around 1909, as evidenced by a well-known photograph by Vittorio Sella, the second after 1954, with an acceleration between 1986 and 1997, when the advance was at least 1450 m (Pecci & Smiraglia, 2000; Diolaiuti et al., 2003). Further research, based both on land surveys and on the elaboration of images from Corona, Landsat and ASTER satellites, confirmed that Liligo advanced approximately 2 km between the early 1970s and the early 21st century (60 m per year), with an acceleration in the 90s (100 m per year) (Belò et al., 2008).
The rates of frontal advance of Liligo are certainly lower than in numerous other surging glaciers of the Karakoram. Nevertheless, some characteristic features of the front and of the lower sector of the glacier flow, in particular the intense crevasse area of the middle-lower part of the flow and the steep and swollen frontal cliff with its considerable thickness, are valid indicators that confirm Liligo's inclusion in the category of surging glaciers. Its phases of activity should last for a decade, while the phases of quiescence should last at least half a century. The absence of the typical folded and looped moraines, clearly evident in numerous small glaciers flowing into the Baltoro, indicate that in the advance phases mentioned above, the Liligo never flowed into the main flow of the Baltoro. The recent advancing phase ended at the beginning of the 21st century, when the thickness of the glacier significantly reduced in the frontal area, which was fragmented and covered with debris, creating favourable conditions for the development of many ephemeral proglacial lakes.
A very particular research topic is that one of glacier "mulins", vertical wells dug by melt waters, and subglacial and endoglacial cavities or caves, which are part of what is defined as "glaciospeleology" or

"glacial speleology". This is a sector that offers important information on the flow patterns of glaciers and on the ablation processes inside glacier bodies, which normally remain outside the experiences of "traditional" glaciology. On the Biafo Glacier and on the Batura Glacier between 1987 and 1993 some expeditions were organized by Italian speleologists, who explored the "mulins" up to about 140 m of depth, and horizontal caves that open on the front of the glaciers (Badino & Piccini, 1995).

Other researches mainly with applied purposes, in particular to determine the contribution of glaciers to the country's water resources, were also conducted in other areas of Pakistan, for example in the Bagrot Valley (Mayer et al., 2010). The valley opens north of Gilgit until it reaches its maximum altitude at 7788 m of Rakaposhi and is characterized by the presence of numerous glaciers certainly smaller in size than those of the Braldo Valley, where the Biafo and Baltoro glaciers are located. In the Bagrot Valley, research was carried out on the Hinarche, a medium-sized glacier (about 42 km2 of area), with the lower sector covered by debris, which may well represent this type of glacier for the whole of Pakistan. Ground measurements on glacier melt even in the presence of debris, information from remote sensing, meteorological data, have made it possible to estimate the contribution of the glacier to the river runoff; in summary, the annual outflow of the Hinarche can be estimated at 135 million m3. The snow-glacial melt water is characterized by a high sediment load and by a strong flow variability. For its more effective role in cropping, energy power and civil use, it is necessary to undertake further scientific and technological-application research. In the current phase of increased demand due to the increase in population and the improvement of living standards, it is clear that glaciological research must also contribute to careful planning and correct management of freshwater resources.

The fine-tuning of research not only in the glaciological field, but also in the sectors of climate change, hydrology and the ecosystems of the Karakoram, was also achieved with international meetings, among the others the one held in 2013 in Islamabad (Bocchiola et al., 2014). On this occasion, the state of the art of research coordinated by Ev-K2-CNR was presented, for example in the context of the SEED project (Socio Economic and Environmental Development), in collaboration with the Karakoram International University (KIU). As far as glaciology is concerned, the first data on the ongoing preparation of the CKNP Glacier Inventory and above all the first results of the 2011-2013 mission on the Baltoro glacier were presented. In summary it was confirmed the glaciers in Karakoram being more stable than in other regions; areal variations being mainly due to the advance of the surging glaciers; debris-covered glaciers losing mass mainly through reductions in thickness and not through reductions in surface area. Studies on the estimation of availability of freshwater deriving from glacier melting have also been carried out on larger surfaces, in particular in the Central Karakoram National Park (CKNP) area, where just under 700 glaciers are located (Minora et al., 2015). By applying a distributed model, calibrated with field data, it was possible to evaluate the ablation both on ice free from debris and on ice covered by rock debris. Over a period of approximately two weeks in mid-summer 2011, an ablation of approximately 0.22 km3 was estimated for glacier sectors with debris and approximately 1.74 km3 for glaciers without debris. In the indicated period, the CKNP glaciers would therefore have produced almost 2 km3 of water, corresponding to about 14% of the water contained in the large Tarbela dam, an artificial basin along the Indus river, of which all the CKNP glaciers are tributaries.

Hinarche 2008

Also for the CKNP we wanted to verify occurrence and magnitude of the already mentioned "Anomaly of the Karakorum", which means a widespread stability of the glaciers in this region at the beginning of the 21st century, in contrast with the regression observed almost everywhere in the rest of the World (Minora et al., 2016). With the elaboration of Landsat satellite images from 2001 and 2010, the areas for just over 700 glaciers were calculated, which as a total area showed a general stability (about 4606 km2, of which 31% covered by debris), stability that remains even if the advances of the surging glaciers are not considered in the calculation. The latter were eight, including the Shingchukpi Glacier, which advanced by 2.2 km, increasing its area by 1.7 km2. The cause of this anomalous evolution compared to what occurs on the glaciers of the other mountain ranges can be attributed to a combination of meteorological and climatic reasons and morphological reasons. In the first case, the analysis of MODIS (Moderate Resolution Imaging Spectroradiometer) satellite images showed an increase in snow cover between 2001 and 2011; moreover, the processing of data from some meteorological stations (Gilgit, Bunji, Astore), supplied by the Pakistan Meteorological Department (PMD), has shown a slight decrease in summer temperatures and an increase in snowfall, again between 2001 and 2011. Added to this are the particular morphological characteristics of the Karakorum glaciers, such as their sometimes grandiose dimensions, their exceptional altimetric distribution with differences in height of even kilometers between the fronts and the upper sectors, the accumulation basins surrounded by steep rock walls which not only favour accumulation of debris on glacier surfaces, but cause an orographic concentration of snow.

The study of the "Karakoram Anomaly" has been continued in more recent research (Gross et al., 2017), where the complexity of the phenomenon and the number of glaciological and meteorological parameters that determine it are not only underlined, but it is also analyzed its non-homogeneous distribution throughout the mountain range. These studies were aimed at setting up and calibrating a new Surface Mass Balance Model (SMBM) for the evaluation of the glacier mass balance of the entire mountain range. The model, which among the main objectives was to take into account the non-linear effect of supraglacial debris on the melting of the underlying ice, was calibrated with ground data from the summers 2010-2011, with observations from satellite images and with reanalysis of meteorological data. The results obtained from SMBM model suggest that the positive balances are not uniform, but are mainly concentrated in the central and northeastern sector of the chain. In any case, it is confirmed that the complex and non-uniform response of Karakorum glaciation cannot be ascribed to a single forcing factor. It is rather linked to a wide variety of local characteristics, such as more or less favourable meteorological conditions (in particular the effects of the westerly winter winds, which have recently acquired greater strength and frequency, bringing more snowfall) and the extensive supraglacial debris cover.

Urdukas 2011

Other recent studies by Italian researchers from the University of Milan in cooperation with scientists from University of Milano Bicocca have addressed innovative issues of an interdisciplinary nature, particularly in the biological field (Ambrosini et al., 2016). The results demonstrate that the studied glaciers, in particular the Baltoro, are unexplored reservoirs of biological functions with high biotechnological potential. In fact, there is growing evidence that the biological processes active in them can influence the energy flows taking place on the glaciers and therefore interfere with the weather and climate processes. On the Baltoro the "cryoconite cavities" were studied and sampled. These are small cavities filled with meltwater present on the surface of the glacier, which contain fine dark debris, the "cryoconite", rich in active ecological communities. For the Baltoro it has been verified that the prevalent bacterial communities are the Betaproteobacteria, with a notable abundance of the genus Polaromonas, probably due to its very versatile metabolism, and of the genus Limnohabitans,

probably favored by the presence of supraglacial lakes. The variations observed between the different sampling areas on the glacier could be attributed to selective processes deriving from spatial and temporal modifications of the environmental conditions, in particular the pH, the only environmental variable that can significantly influence the structure of the bacterial communities.

The CKNP Glacier Inventory

The need to have a picture as complete as possible of the extension of the glaciation of the Pakistani Karakoram prompted the first phase of compiling an inventory of perhaps the most significant area in the region, the Central Karakoram National Park (CKNP). It is the largest protected area in Pakistan (about 10,000 km2) and the highest national park in the World, where some of the largest glaciers in Pakistan, and among the largest valley glaciers with compound basins on Earth, are located. The Inventory is the result of a joint work of Italian and Pakistani researchers, CKNP managers and administrators who are managing this peculiar mountain territory and its resources (Smiraglia & Diolaiuti, edts, 2016; Senese et al., 2018). The Inventory is part of a research framework that aims to examine Pakistan glaciers as a strategic resource, which supplies water for civil uses, hydropower and agriculture (Bocchiola & Diolaiuti, 2013). An even more essential resource if we take into account the ongoing growth of the population and the intensification of agricultural activities and the fact that more than 50% of the runoff of the Indus from the Karakoram derives from snow and ice melting. The glaciation of Karakoram therefore appears as a key area for the study of the effects of climate change on the current and future regime of rivers and for a better understanding of the role of the cryosphere on the evolution of the regional hydrological network. The inventory examines the glaciers, first as a whole as a National Park, then in detail at the level of individual basins (i.e. Hunza, Shigar, Shyok, Upper Indus and Gilgit).
The identification of the individual glaciers and their basic parameters (in particular: location, type, size and characteristics of the surface, such as the presence and extent of the debris cover) was substantially based on remote sensing. More precisely the analysis of Landsat Thematic Mapper satellite images (TM) and Enhanced TM Plus (ETM+) of 2001 and 2010 was performed; in this way it was also possible to identify the variations during the first decade of our century. Furthermore, to obtain other parameters, such as glacier thickness and volume, fundamental for the determination of their water resource, an indirect approach was used, based on widely known parameterisations in glaciological research. The analysis of the data obtained indicates that in the CKNP there are 606 glaciers (2010 data), including the three largest in Pakistan (Baltoro, Biafo, Hispar) with very different types (in particular compound-basin valley glaciers, mountain glaciers, glacierets, hanging glaciers), just as the surface characteristics are differentiated (debris-free and debris-covered ice).
The comparison between the total areas had not revealed evident variations between 2001 and 2010, when it was 3682 km2 (about 35% of the entire surface of the CKNP and about 24% of the surface of the Pakistan); the total volume was about 532 km3.
The largest glacial body was the Baltoro with an area of 604.2 km2, while the average glacier area was 6.1 km2. The basin with the greatest extension and the greatest number of glaciers (as well as with the greatest volume of ice) was Shigar (where Baltoro is also located). Particular insights were devoted to the characteristics of the supraglacial debris, which appeared to cover approximately 920 km2, equal to 21% of the total glacial area.
Debris-covered glaciers are usually larger (Baltoro and Hispar belong to this typology) and descended to lower altitudes (even below 3000 m); on the contrary, debris-free glaciers were generally smaller and their front stopped at higher altitudes (around 4500 m). Despite the substantial stability of the total surface, some glaciers have shown significant changes; we refer to the surging-glaciers, many of which have recorded significant advances that have led them to flow into other glaciers (this is the case of the Shingchukpi, which has advanced by about 2200 m, until it flows into the Panmah).
The presence of lakes in a glacial environment was also taken into consideration in the inventory, in particular supraglacial lakes (202 in total with a total area of 4 km2, two of which have been identified as potentially dangerous).
From the previous pages it should have emerged on the one hand the commitment made in particular in recent decades by Italian glaciology in the study of the glaciers of the Karakorum, especially Pakistani (together with certainly satisfactory results), on the other hand the need for further insights aimed at clarifying some specific aspects of the evolution of these glaciers. We refer in particular to the glacier behaviour -meteoclimatic dynamics relationship, well represented by the well-known and still problematic "Karakoram Anomaly". On the causes of this phenomenon, recent publications by Swiss, Dutch and English authors underline the need for a more integrated approach that takes into consideration the entire chain of processes connected to the "Anomaly". In particular surface characteristics, atmospheric processes, climate change, which can lead to a reduction in summer temperatures, an increase in snowfall and a decrease in the energy available for glacial fusion. The effect of all this on the flow of glaciers and their hydrology could also influence the mechanism of surging glaciers, which however is still far from being understood. Whether this phenomenon will be observable in the future is currently unclear, but its long-term persistence seems unlikely in light of the scenarios of a significant future increase in temperatures (Farinotti et al., 2020). Surely in the first two decades of the twentieth century the "Karakorum Anomaly" is an indisputable reality, as also demonstrated by a recent publication by Chinese researchers (Lhakpa et al., 2022).
As can be seen, there are many themes and problems that remain to be explored; to these we could add the more applicative ones deriving from the reduction of water resources and the possible risks of glacier flood (GLOF-Glacial Lake Ouburst Flood). The hope is that the third generation students of prof. Desio in the near future will be able to offer a valuable contribution to the study of this phenomena thus contributing to forecast their occurrence and/or to mitigate their impacts.

The inventory methodology

Text by **Melis, Fugazza**

This Pakistan glacier inventory has been realized from optical data acquired by the European Space Agency Sentinel-2 twin satellites. This choice is dictated by the need to respond to the requirement to have homogeneous coverage of the entire territory under examination in terms of image acquisition dates, cloud cover and good spatial resolution, that allow the recognition of glaciers and their mapping.
Furthermore, particular attention in the selection of the data processing and mapping methods was given for the expected prospect activity of updating the glacial perimeters and monitoring changes in the future.

Existing inventories

As part of a number of different international projects, outlines of Pakistani glaciers were previously available. However, the most recent of these outlines refer to data acquired in 2009, when Sentinel-2 satellites had not been launched. Therefore, mapping efforts had to rely on data available from the Landsat Programme, managed by the United States Geological Survey (USGS), and mostly based on Landsat 5 TM and Landsat 7 ETM+ satellites. Landsat satellites have a lower revisit time than that of the Sentinel-2 satellites (3-5 days), which results in a limited availability of data, further reduced by cloud cover. Data quality of Landsat 5/7 is lower in terms of spatial, spectral and radiometric resolution, and Landsat 7 ETM+ suffered a technical failure of its scan line corrector in 2003, which resulted in striping across the images and further reduced quality. All these issues affect the temporal consistency of the inventories, as images from different years have to be considered to acquire information on all glaciers, while the reduced spatial resolution (30 m compared to 10 m for Sentinel-2) makes the recognition of landforms more complicated (Paul et al., 2016).

Inventory name	Geographic coverage	Acquisition dates	Image source	Spatial resolution (m)	Mapping methodology
GAMDAM v2	Asia	1993-2009	Landsat 5 TM/ Landsat 7 ETM+	30	Manual delineation
ICIMOD	Hindukush-Karkaoram-Himalaya	08/2005-09/2009	Landsat 5 TM/ Landsat 7 ETM+	30	Object-based image analysis
CKNP glacier inventory	CKNP (Central Karakorum National Park)	08/2010-10/2010	Landsat 5 TM/ Landsat 7 ETM+	30	Manual delineation

Table x: previously available glacier inventories for Pakistan

The following inventories are available for Pakistan (see Table x):

• The Randolph Glacier Inventory (RGI, Pfeffer et al., 2014), now in its 7th version (Maussion et al., 2023) is a global database of glacier outlines; the goal of the RGI is to map glaciers for a specific time period (as close as possible to the year 2000), and the data used in this inventory are in fact taken from other datasets: the last version of the RGI uses the GAMDAM version 2 outlines for Pakistan, while previous versions used the first version of that inventory.

• The GAMDAM (Glacier area mapping for discharge from the Asian mountains) glacier inventory also has a wide scope, covering all high mountain Asia; this inventory is mostly based on Landsat ETM+ images acquired between 1999 and 2003 and glaciers were mapped manually based on a false-colour composite of the Landsat images (Nuimura et al., 2015). Version 2 of the inventory added several images from Landsat 5/7 spanning a wide range (1993-2009) to improve coverage of all glaciers in their accumulation area (Sakai et al., 2018)

• The ICIMOD (International Centre for Integrated Mountain Development) inventory used images acquired by Landsat 5 TM and Landsat 7 ETM+ between 2005 and 2009 for Pakistan. Compared to GAMDAM, the ICIMOD inventory used an object-based segmentation approach (Bajracharya and Shreshta, 2011).

• The CKNP (Central Karakorum National Park) inventory, produced by the University of Milan (Senese et al., 2016), is also based on manual delineation of Landsat 5 TM acquired in 2010 for glacier mapping, with additional images from 2009-2010 acquired by Landsat 7 ETM+ as cross-check. This inventory satisfies time consistency, as the images were acquired in August-October 2010. However, it offers limited coverage, only including glaciers in the park.

Methods

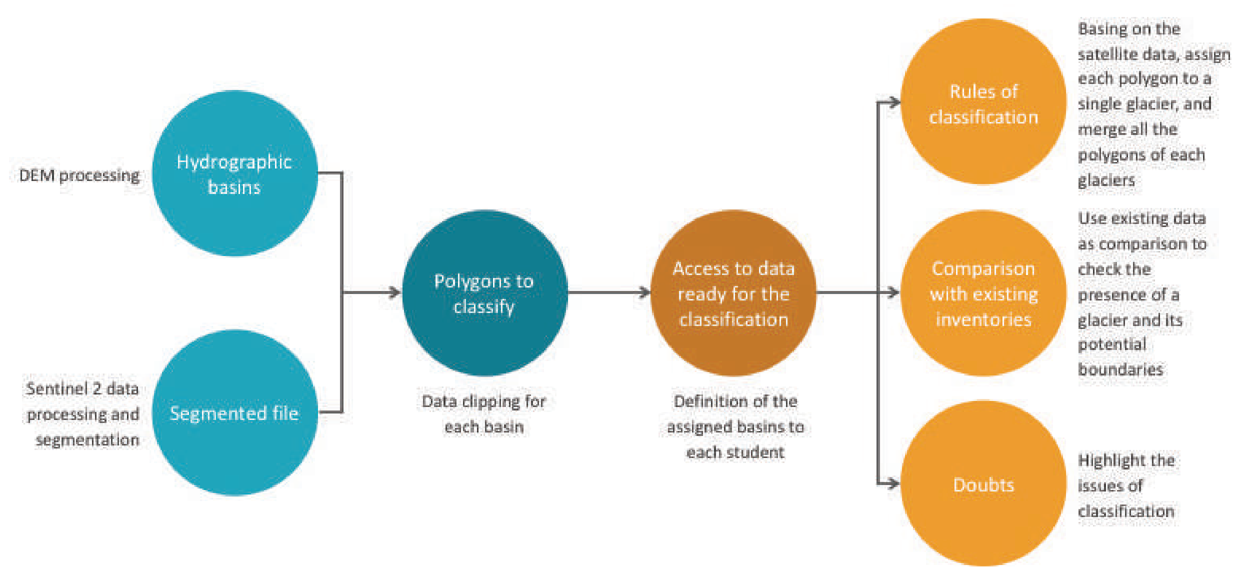


Figure 1: Schema of the approach with the steps of the adopted methodology

Methods

As part of the Pakistan New Glacier Inventory project, in order to reduce the subjectivity of the human interpretation, a new proposal for a semi-automated process of classification of glacier boundaries from Sentinel-2 data was implemented. Optical satellite data have been widely used for the glacier mapping, starting from the first Landsat imagery in the '70s. The revisit time and the availability of these data can be regarded as the most important characteristics the researchers considered to create the first existing glacier inventories based on the photointerpretation of the satellite data. Multispectral data allowed to propose algorithms, like the spectral indexes, for the masking of the cloud cover and the recognition of snow and ice and then map the glacier extent (Paul et al., 2005). The resulting new images can support the mapping, but two main concerns arise: i) a unique threshold of the adopted spectral index is inclined to give a good result only locally with homogeneous geomorphological, slope and aspect conditions; ii) multispectral indexes based on optical data cannot clearly identify the debris-covered or partially covered glaciers, which are confused with the surroundings moraines or rock outcrops. This latter is one of the main and well-known issues, mainly considering the identification of glacier snouts. Researchers propose different methods based on thermal data or the integration of optical and topographic data, to compare the landforms due to the presence of debris, using data with high spatial resolution (Kraaijenbrink et al., 2016; Mölg et al., 2020). Moreover, the application of automatic classification of spectral data, supported by high performance of digital processing systems has been applied in limited areas suggesting that for the analysis of a very large region, a step-by-step procedure has to be applied with a detailed check of the results. For this reason, in this project the automatic extraction of the glacier boundaries using a pattern recognition technique has been controlled by human interpretation.

Sentinel-2 twin satellites acquire data through an optical multispectral sensor with 10 meters of spatial resolution in the visible and Near-Infrared and 20 meters in the Short-Wave Infrared, allowing to apply the useful algorithms for the spectral recognition of the glaciers (Kääb et al., 2016; Paul et al., 2016).
Starting from the expected outputs, and considering the new technical performance that can be obtained with satellite data, the strategy of this project aims to achieve two main goals:

− Developing a new methodological approach to map the glaciers;
− Involving the Pakistani and Italian students in the process of recognition of the glacier boundaries.

The applied methods can be divided in two main sections, as in Figure 1:

- Satellite data arrangement
- Glacier recognition (classification) and mapping

The first section is dedicated to the preparation of

the base data that was used by the researchers and students for the classification: recognition and mapping of the glacier boundaries. The second section of the methodology includes the activities of mapping, based on a semi-automatic procedure of classification.
The final phase, once the glacier outlines are mapped and validated, consists in the creation of a database which lists for each glacier its attributes, both geometric (coordinates, area), descriptive (glacier name) and morphometric (related to the glacier topography).
Two main typologies of geo-data have been considered: a Digital Elevation Model (DEM) and satellite optical imagery.
The DEM has been used to divide the Gilgit Baltistan region in hydrographic basins to allow each user to focus the analysis and the glacier classification in a limited area. In the following paragraph, the applied procedure to extract the basins from the DEM is explained.
The second phase is dedicated to the Sentinel-2 data processing. In this paragraph, the specific steps to create the composite image used to spectrally discriminate the glacial bodies and extract their limits will be described. The output of these functions is a file in polygonal vector format (shapefile), where each feature belongs to a glacier.

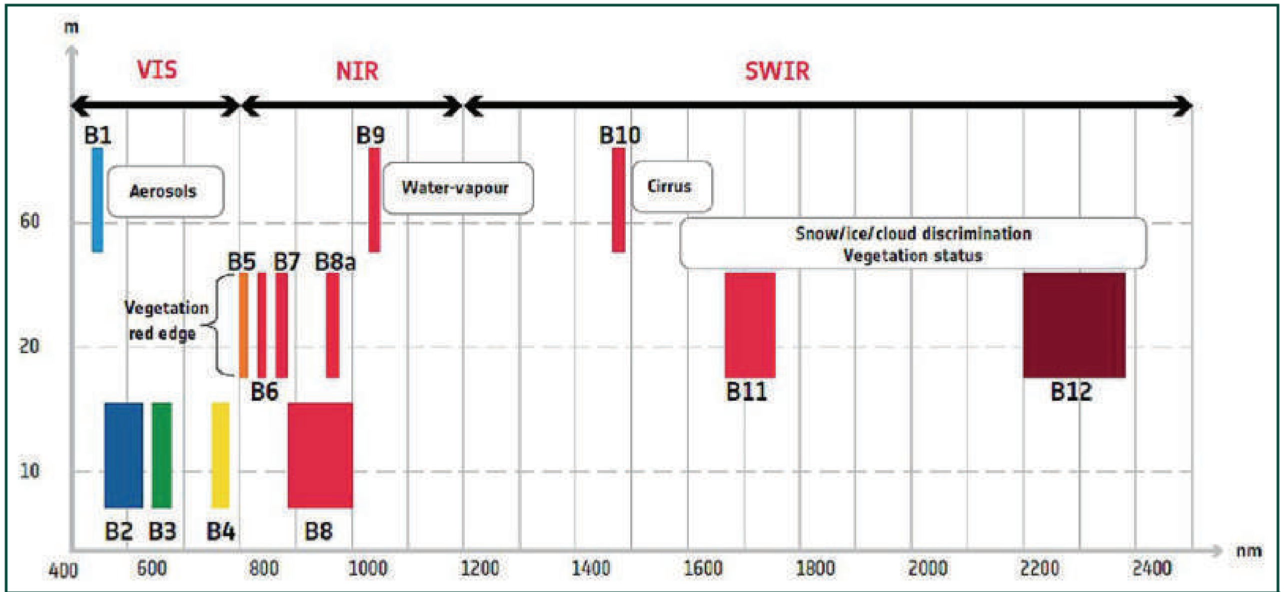


Figure 2: **MSI spatial resolution versus wavelength: Sentinel-2's span of 13 spectral bands, from the visible and the near-infrared to the shortwave infrared at different spatial resolutions ranging from 10 to 60 m on the ground, takes land monitoring to an unprecedented level (image credit: ESA)**

Digital elevation model (DEM) processing: Hydrographic Basins

The first step in the creation of the basins was the choice of a suitable digital elevation model (DEM), which was used to automatically extract basins within Pakistan containing glaciers. The ALOS AW3D30 global DEM, at 30 m spatial resolution, was used for this purpose. This product was generated by photogrammetric processing of stereo pairs of the ALOS PRISM sensor, at 5 m spatial resolution, with scenes acquired between 2006 and 2011 (Tadono et al., 2014). The relevant tiles covering the north of Pakistan (1° x 1° in size) were downloaded from the AW3D30 website https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm, mosaicked together and converted from the geographic coordinate system based on the WGS84 datum to a projected coordinate system based on the UTM grid and WGS84 datum, to ease further processing (especially calculation of areas and slope parameters). To extract the basins of the study area, we used the tool r.watershed, available from the GRASS GIS software. This tool allows to automatically extract the stream network and hydrological basins based on a DEM. It uses a single flow direction or multiple flow direction algorithm to extract the flow direction of each cell of the DEM, followed by generating a flow accumulation raster indicating accumulated flow to every raster cell. Finally, the tool is able to extract the river network by identifying maxima in flow accumulation and the topographic ridges by identifying accumulation minima. The basin is then identified by input of a minimum area.
To extract the basins of interest, we used the single flow direction algorithm and input a minimum basin size of 1000000 cells. We also flagged the options to exclude topographic sinks, which would be recognized as low elevation points and confound the analysis. The final result was then vectorised to generate polygons of the basins. Parts of the basins located outside of the Pakistani borders were excluded. Since the basins extracted in this way were too small for the analysis, we aggregated them at different levels, using the Hydrosheds definition as a guide. Hydrosheds (https://www.hydrosheds.org/) is a global database of river basins; version 1 was generated from resampled SRTM data at 500 m spatial resolution, where river basins are defined using the Pfafstetter coding system. We therefore generated levels up to 8 maintaining the same scheme as in Hydrosheds, while using a different DEM for improved level of detail. Finally, to perform the glacier analysis, and distribute the work among the different participants, mostly level 7 of the coding system was used. However, in some cases were basins were too large they were split in their level 8 sub-basins, to allow for a faster processing. The final basins are therefore mostly based on level 7 of the Hydrosheds definition, with a few exceptions.

Sentinel-2 data processing and segmentation

SATELLITE DATA

The inventory of the glaciers has been realized analyzing the satellite data acquired in the framework of the European Space Agency (ESA) Copernicus Program.
In particular, imagery acquired by the SENTINEL-2 twin satellites have been chosen.

SENTINEL-2

These satellites fly in the same sun-synchronous orbit at a mean-altitude of 786 km but phased at 180°, to give a high revisit frequency of 5 days at the Equator. Each of the satellites in the SENTINEL-2 mission (SENTINEL-2A and SENTINEL-2B) carries a single payload: the Multi-Spectral Instrument (MSI), an optical instrument that samples 13 spectral bands with different spectral and spatial resolution (Figure 2), four bands at 10 m, six bands at 20 m and three bands at 60 m spatial resolution. The orbital swath width is 290 km.
The MSI works passively, by collecting sunlight reflected from the Earth. New data is acquired by the instrument as the satellite moves along its orbital path (www.esa.int).
The 13 spectral bands of SENTINEL-2 range from the Visible (VNIR) and Near Infra-Red (NIR) to the Short Wave Infra-Red (SWIR):
– 4 x 10 meter Bands: the three classical RGB bands ((Blue (~493nm), Green (560nm), and Red (~665nm)) and a Near Infra-Red (~833nm) band;
– 6 x 20 meter Bands: 4 narrow Bands in the VNIR vegetation red edge spectral domain (~704nm,~740nm, ~783nm and ~865nm) and 2 wider SWIR bands (~1610nm and ~2190nm) for applications such as snow/ice/cloud detection, or vegetation moisture stress assessment;
– 3 x 60 meter Bands mainly focused towards cloud screening and atmospheric correction (~443nm for aerosols and ~945nm for water vapour) and cirrus detection (~1374nm).

Copernicus • https://www.copernicus.eu

Copernicus is the Earth observation component of the European Union's Space Programme, looking at our planet and its environment to benefit all citizens. It offers information services that draw from satellite Earth Observation and in-situ (non-space) data.
International Cooperation is of significant importance to Copernicus; data policy provides full, open and free-of-charge access to Copernicus data and information, in line with the international data sharing principles.
The Copernicus component of the EU Space Programme is served by a set of dedicated satellites and contributing missions.
The Sentinel satellites are specifically designed to meet the needs of the Copernicus information services and their users.
Since the launch of Sentinel-1A in 2014, the European Union has initiated a process to place a complete constellation of almost 20 satellites in orbit before 2030. Today, there are eight Sentinel satellites in orbit, of five different types.
Each Sentinel mission is based on a constellation of satellites to fulfil revisit and coverage requirements. They carry a range of technologies, such as radar and multi-spectral imaging instruments for land, ocean and atmospheric monitoring:

- **Sentinel-1** is a polar-orbiting, all-weather, day-and-night radar imaging mission for land and ocean services. Sentinel-1A was launched on 3 April 2014 and Sentinel-1B on 25 April 2016.
- **Sentinel-2** is a polar-orbiting, multispectral high-resolution imaging mission for land monitoring. It provided imagery in the present project on the glaciers inventory in Pakistan. Sentinel-2 can also deliver information for emergency services. Sentinel-2A was launched on 23 June 2015 and Sentinel-2B followed on 7 March 2017.
- **Sentinel-3** is a multi-instrument mission to measure sea-surface topography, sea- and land-surface temperature, ocean colour and land colour with high-end accuracy and reliability. Sentinel-3A was launched on 16 February 2016 and Sentinel-3B joined its twin in orbit on 25 April 2018.
- **Sentinel-5 Precursor** – also known as Sentinel-5P – is the forerunner of Sentinel-5 to provide timely data on a multitude of trace gases and aerosols affecting air quality and climate. Sentinel-5P was taken into orbit on 13 October 2017.
- **Sentinel-4** is a payload devoted to atmospheric monitoring that will be embarked upon a Meteosat Third Generation-Sounder (MTG-S) satellite in geostationary orbit.
- **Sentinel-5** is a payload that will monitor the atmosphere from polar orbit.
- **Sentinel-6** carries a radar altimeter to measure global sea-surface height, primarily for operational oceanography and for climate studies. The first satellite was launched into orbit on 21 November 2020.

Looking to the future, ESA is developing six Copernicus Sentinel Expansion missions. These high-priority missions will address gaps in Copernicus user needs, expanding the current capabilities of the Copernicus programme.
The Copernicus services transform the wealth of satellite and in situ data into timely and actionable information by processing and analysing it. The services deliver datasets and time series that are comparable and searchable, ensuring that trends and changes are monitored. Maps are derived from imagery, features and anomalies are identified and statistical information is extracted.
These value-adding activities are streamlined through six thematic streams of Copernicus services:

- Copernicus Atmosphere Monitoring Service (CAMS)
- Copernicus Marine Environment Monitoring Service (CMEMS)
- Copernicus Land Monitoring Service (CLMS)
- Copernicus Climate Change Service (C3S)
- Copernicus Emergency Management Service (CEMS)
- Copernicus Security Service

The vast majority of the information services, as well as the data from which they are derived, are accessible on a free, full and open basis by anyone. These data and information are used by service providers, public authorities and international organizations to improve the quality of life for citizens of Europe and around the world, to monitor and mitigate climate change, and to preserve our fragile environment.

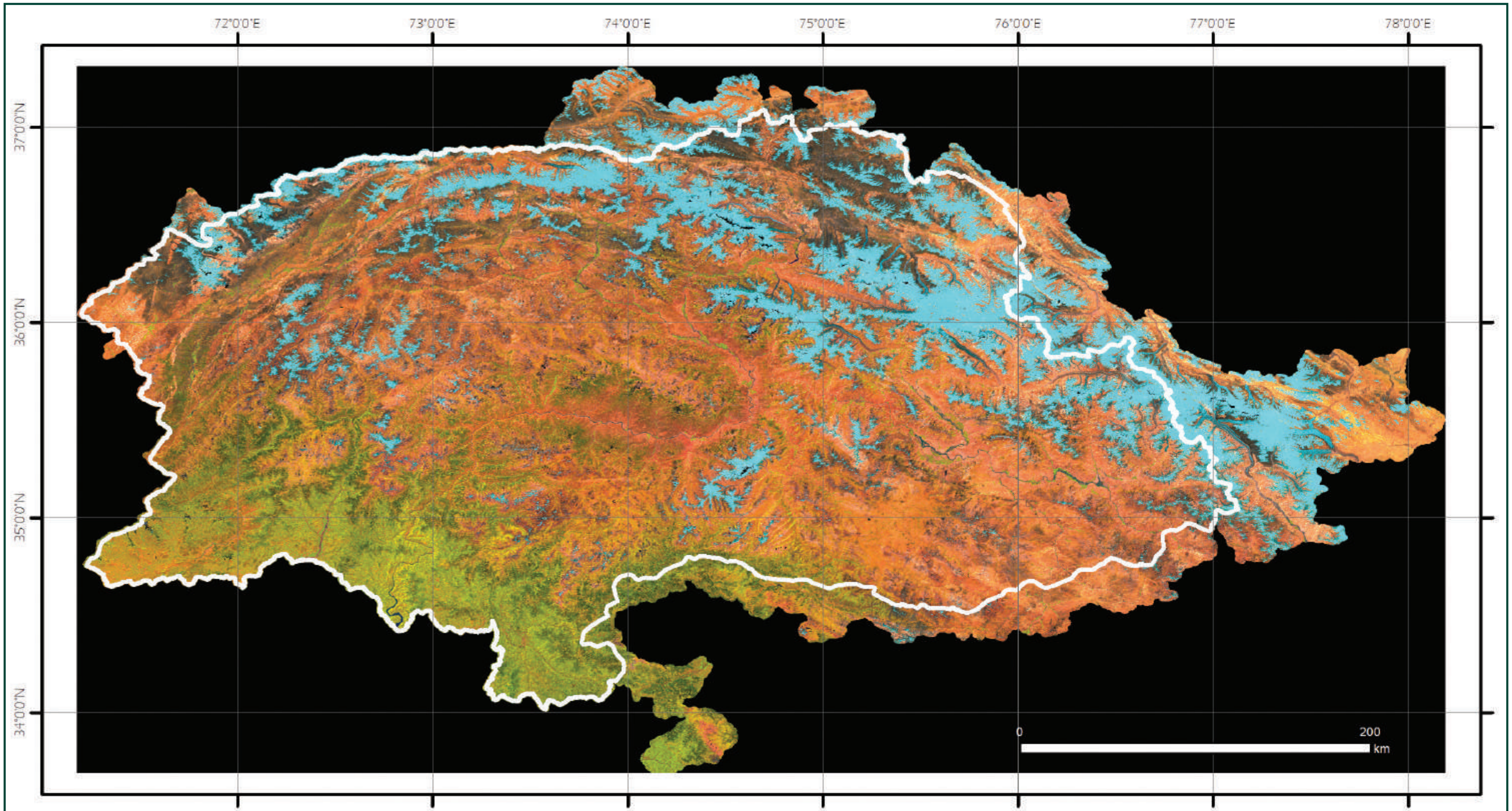


Figure 3: Sentinel-2 RGB composite image of the Pakistan region used in this inventory. This image is the synthesis of all the images acquired by the Sentinel-2 satellites in the period "2022-07-31" -"2022-10-01. In the Red, Green and Blue channels the SWIR, NIR and Red bands are represented. The main land cover types can be identified: in bright blue the snow, in dark blue the ice, in bright and dark tones of red the bare soils and rocks, and in green the vegetated areas.

Approach

The workflow in the applied procedure is composed by three main steps:

- Satellite data acquisition and composite;
- Spectral Index extraction;
- Data classification and segmentation.

Satellite data acquisition and composite

The first step aims at the production of a single/mosaic multi-spectral dataset reproducing the mountain range in northern Pakistan free of clouds, cloud-shadows and haze. A large number of Sentinel-2 data are needed to cover this area and to guarantee the cloud-free observations. Considering the swath of each image and the temporal resolution of these data, the possibility to use the cloud platform Google Earth Engine has been adopted for the creation of a unique multispectral dataset for the whole region. As well-known, it is very difficult to find in this region all cloud-free images for the whole region. So, the approach

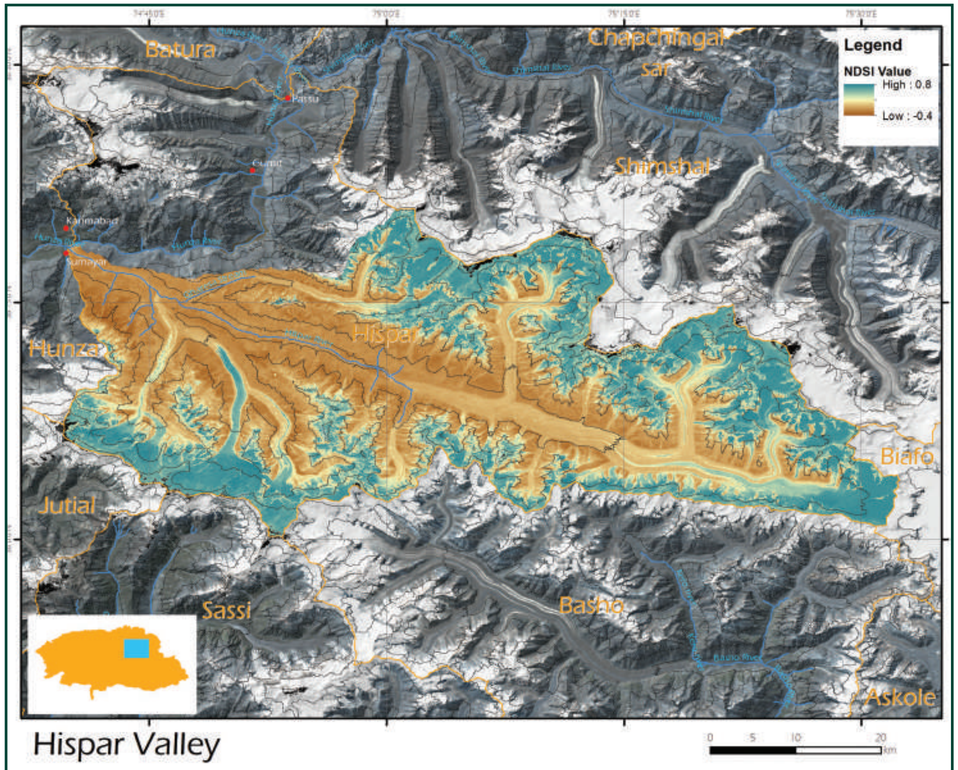


Figura 4: NDSI

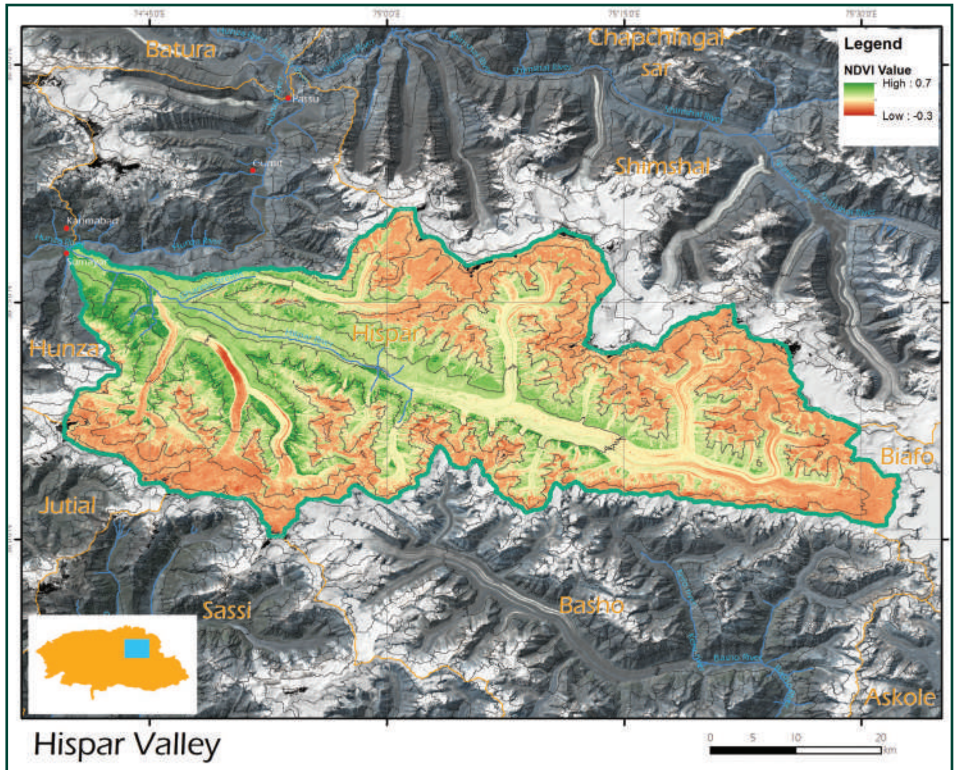


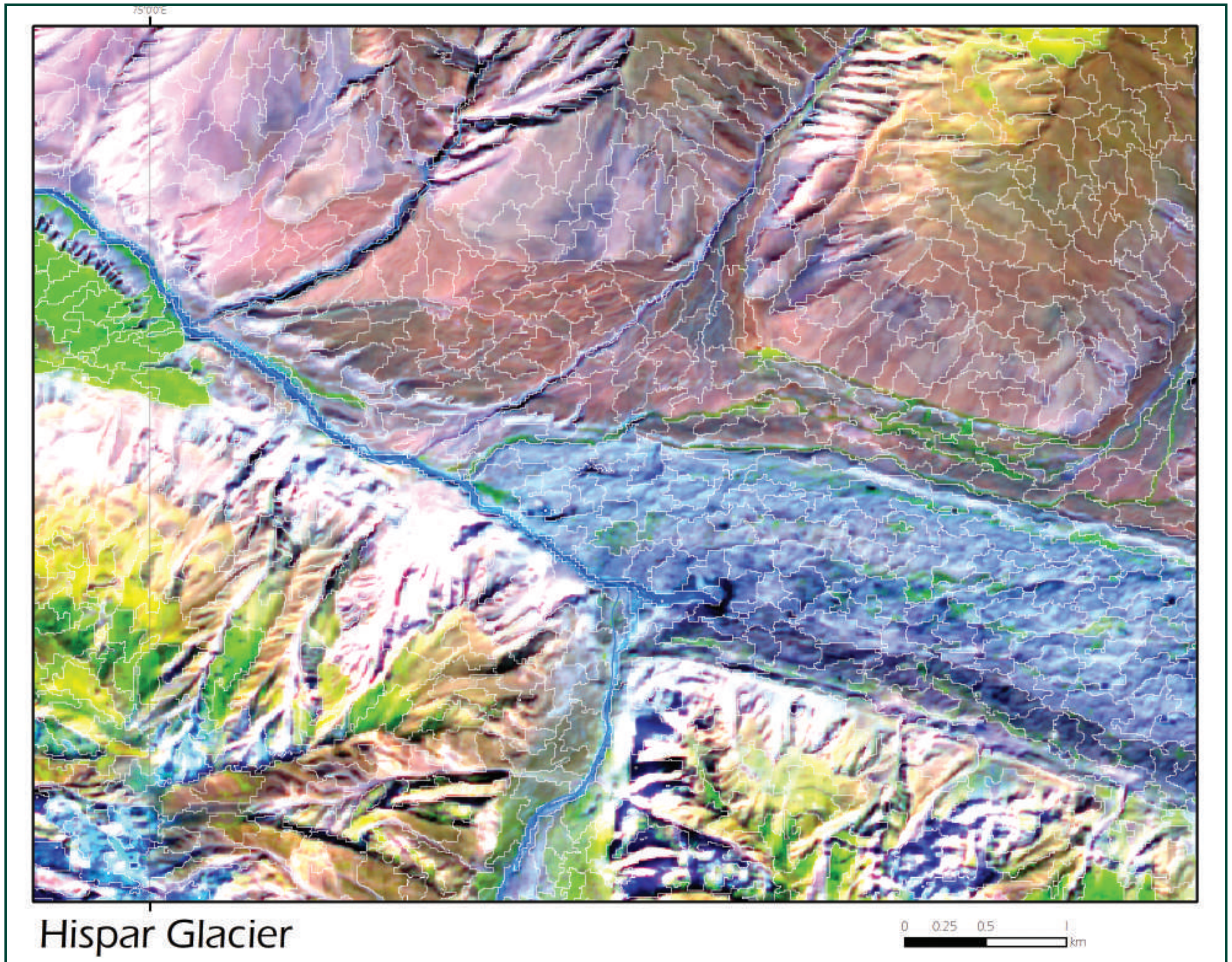
Figura 5: NDVI

GOOGLE EARTH ENGINE

https://earthengine.google.com)

Google Earth Engine -GEE is a web portal providing global time-series satellite imagery and vector data, cloud-based computing, and access to software and algorithms for processing such data. The data repository is a collection of over 40 years of satellite imagery for the whole world, with many locations having two-week repeat data for the whole period, and a sizeable collection of daily and sub-daily data as well.
Technically, Google Earth Engine is a cloud computing platform created in 2001 for processing satellite images and other geospatial and observation data. It provides access to a large database of images and has the computing power necessary to analyze those images: thanks to these innovations, the software allows the observation of changes in agriculture, natural resources and the climate of specific places, using the geospatial data from the Landsat and Copernicus satellite programmes.
While Google Earth lets you travel, explore, and learn about the world by interacting with a virtual globe, GEE, on the other hand, is a tool for analyzing geospatial information.
GEE is an incredibly powerful tool for monitoring the environment. The tool has been designed for geographers, scientists and researchers to allow them to quickly access and analyze more than 600 remote sensing datasets, including satellite imagery spanning from the 1970's to today.

in this project has been based on the creation of a single multi-band composite cloud-free image, starting from the selection of acquisitions during the summer season.
The cloud-filtering technique applied in this project is based on the PINO cloud mask image processing procedure, applied in JavaScript code through the Google Earth Engine platform to create multi-temporal data composites (Simonetti et al., 2021). The PINO function returns the same Sentinel-2 image received as input after replacing every pixel classified as clouds or shadows with no-data. Filtering the annual image collection before extracting the median value of each pixel increases the probability of obtaining a cloud-free composite in cloud-prone areas or whenever the atmospheric contaminations affect more than 50% of the acquisitions. For each pixel of the resulting



Segmentation

image, and for each band, the most frequent pixel value (median) at the correspondent position in the given time series is assigned. For the computation of median digital numbers, pixel values recognized as belonging to clouds, cloud-shadows or haze by the PINO cloud mask algorithm are automatically skipped, resulting in a data composite clean from atmospheric contaminants. The time series of Sentinel-2 L1C data in the acquisition period from "2022-07-31" to "2022-10-01" was processed. The resulting image composite is a cloud free Sentinel-2 multiband dataset, time-centered at the end of August (Figure 3).

Spectral Index extraction

The second step of the approach is focused on the enhancement of the spectral differences among objects composing the scene, and the spectral investigation was focused on the distinction of glaciers ice/snow, glaciers debris and rocky slopes. The normalized-difference snow index (NDSI) was adopted (Dozier, 1989):

$$\text{NDSI} = (\text{B3(green)} - \text{B11(SWIR1)}) / (\text{B3(green)} + \text{B11(SWIR1)})$$

In order to distinguish the glacier debris (not covered by ice or snow) from rocky slopes, it is hypothesized that the vegetation has a discriminating role, being present in the second (especially during the summer, such as the acquisition period chosen for the synthetic composite), even if sparse and low, and is almost absent in the first, because of the slow but constant friction, movement and tilling of sediments in the dynamics of the glaciers. According to this hypothesis, the normalized-difference vegetation index (NDVI) was calculated as follows:

$$\text{NDVI} = (\text{B8(NIR)} - \text{B4(Red)}) / (\text{B8(NIR)} + \text{B4(Red)})$$

Since the best contrast strategy to distinguish the landforms of interest is based on the spectral indices mentioned above, a new dataset was prepared using NDSI, NDVI and Band4 (red), creating a new multiband image stack. For each one of these new dataset bands, the segmentation classification algorithm was applied, in order to aggregate pixels on the base of the proximity and of the similarity in the response of the NDSI, NDVI and Red reflectance Figure 4 e 5.

Data classification and segmentation

The third step in the workflow regards the data classification. In this project we adopted the methodology of image segmentation, aimed at the partitioning of the dataset into multiple polygons (segments) based on spectral, geometric or texture properties, calculated in conjunction with user-defined parameters describing size, shape and similarity to adjacent segments.

The following parameters have to be considered in the classification process:

- bands and weights: raster bands and associated weight values to use;
- scale factor: factor that controls the spectral heterogeneity of the objects in the image and is therefore related to their average size, the low value of which allows obtaining a high number of objects and vice versa;

Segmentation 2

• color: spectral component of the Baatz algorithm [0,0; 1.0] (Baatz et al., 2000);
• compactness: morphological component of the Baatz algorithm [0,0; 1.0];
• Euclidean distance: minimum distance (expressed in DN values) to set for the merging of the segments that cross two adjacent links; high values will allow the aggregation of heterogeneous objects between the meshes, while low values will preserve the sharp boundaries of the meshes;
• MMU: minimum map unit, i.e. the spatial resolution in meters per pixel of the segmentation layer; for the images collected by Sentinel-2, 1 MMU corresponds to an area of 100 m2, i.e. a surface of 10 x 10 m on each side, the spatial resolution of Sentinel-2 being 10 m, (Simonetti et al., 2015).

In this project, the segmentation process was applied through the functionality available in the JRC IMPACT free software, which is based on the Baatz-Schape open source segmenter libraries (Inpe's TerraAIDA Operators). The NDSI-NDVI-B4 multiband dataset was processed adopting the settings proposed by the application as optimal ("majority" as aggregation rule, 0.8 as compactness, 0.9 as similarity in a scale 0-1, 0.9 as color). The minimum map unit (MMU) parameter was empirically tested by setting two different values: 250 and 100.

Applying the first value, the segmentation process produces a reduced number of aggregations, distinguishing landforms quite correctly. However, in some cases (e.g. where the slope shadow affects the scene) the detail of the output is not accurate enough to precisely perimeter the landforms as efficiently as the MMU parameter 100 does. On the other end, the output of the segmentation achieved by setting 100 as the MMU parameter returns a number of aggregation blocks considerably higher, less easy to analyze for a photo-interpreter.

Glaciers recognition (classification) and mapping

This section of the methodology has been implemented in a Geographic Information System (GIS) environment. Subsets of the composite have been created for each basin. All the data have been uploaded in a dedicated cloud server, allowing each researcher and student to access an assigned basin in a folder. For each basin, four thematic data were available, as in Figure 6.

- The composite Sentinel-2 multiband image with the bands
- The spectral indexes
- The shapefile with the polygons of the segmentation with the MMU of 250
- The shapefile with the polygons of the segmentation with the MMU of 100.

Starting from these data, the methodology followed the workflow in Figure 6 The steps were driven by an initial training activity and periodic online meetings which allowed the working group to discuss and share the classification procedures. An example of the classification is in Figure 7; As can be seen in this last figure, the polygons created with the segmentation follow the limit of the glacial tongues with a good accuracy, allowing them to be identified very precisely.

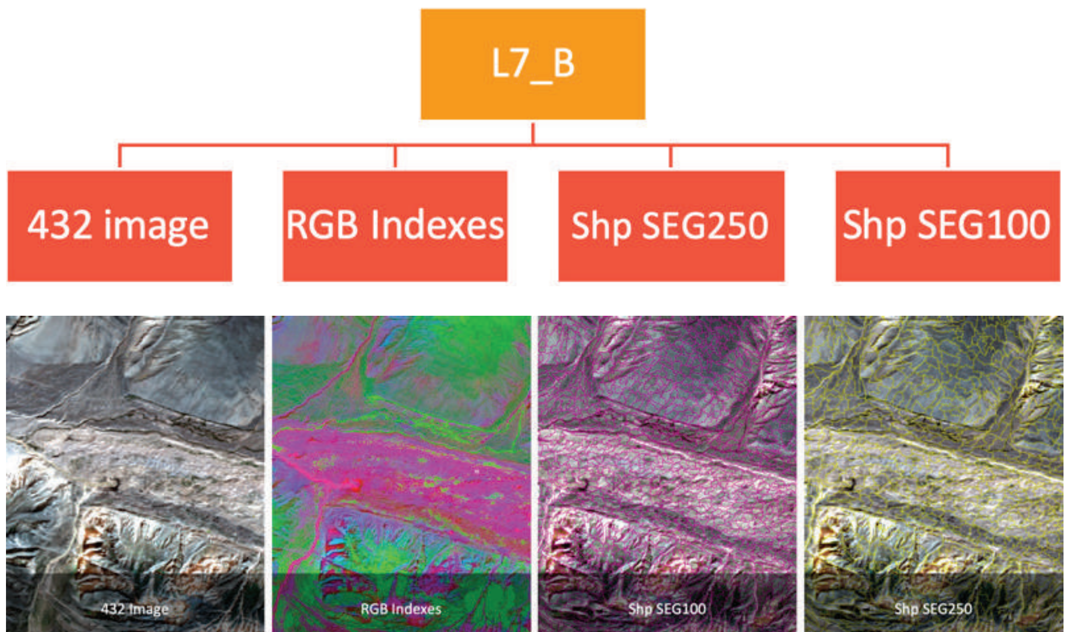


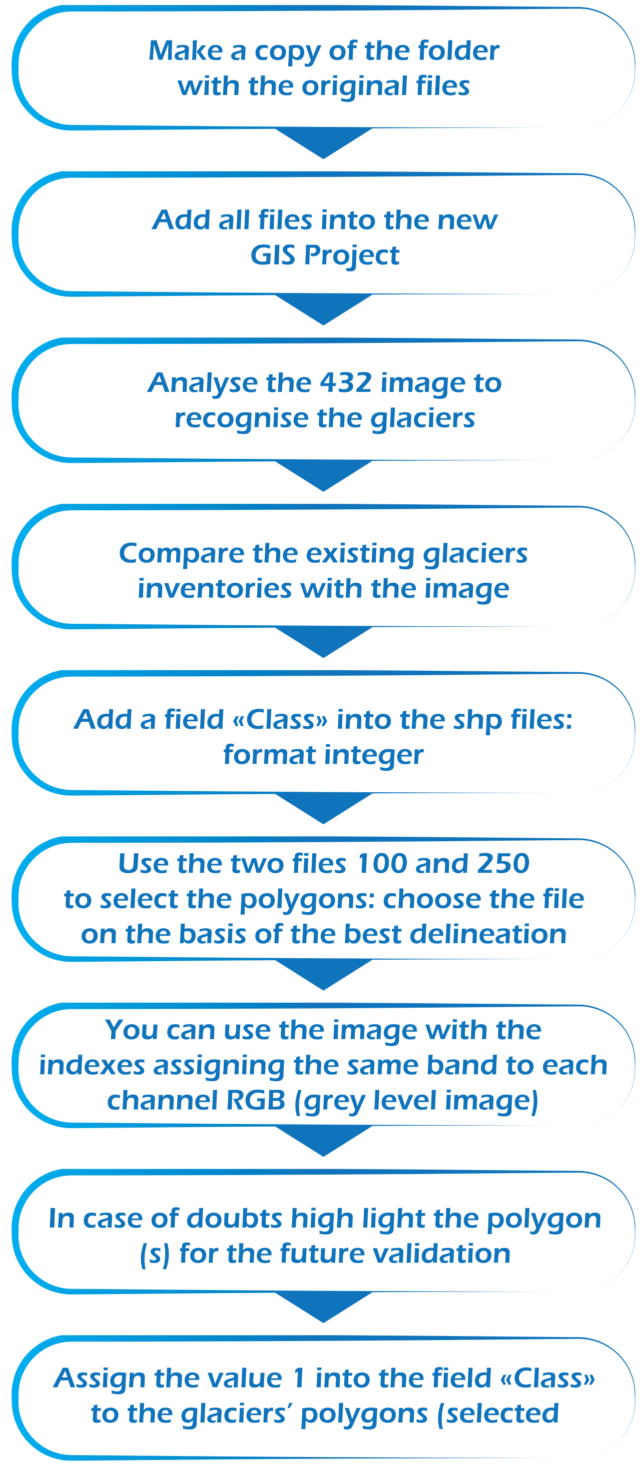
Figura 6: Contents of the working folders for each basin

The process of identification of the polygons has been supported by accessible datasets, like the existing glacier inventories, the very high-resolution satellite data of Google Earth and Bing aerial maps, and the base map available in the GIS software. However, the final decision and the final limit was drawn based on the Sentinel image, thus ensuring homogeneity of the detection date.
A specific activity of comparison of each glacier with the available high-resolution imagery has been carried out in the final phase of validation, considering their acquisition date.

DB and morphometric analysis

The validation phase led to the generation of a shapefile for each basin including all the glaciers mapped in that basin. For each basin, the attributes of the glaciers were then extracted to generate a glacier database, which includes the following parameters (see Figure 8):

1. Glacier ID. This was generated automatically by considering the basin code and glacier code. Both are progressive numbers (2 digits for the basin and 3 for the glaciers in each basin), starting from 1 and moving west to east for the basin and north to south for glaciers (first glacier has the northernmost latitude, last lacier the southernmost in the basin). The letters B and G are added to separate basin and glacier in the ID, which is thus coded as BxxGyyy where xx is the basin code and yyy the glacier code.
2. Latitude and longitude, in decimal degrees, which represent the coordinates of the centroid of each glacier
3. Glacier name, where available.
4. Glacier area, in m2
5. Morphometric parameters. These include elevation-specific parameters, slope and aspect and are used to identify the glacier topography and relationship with the area. For each glacier we reported



a. Minimum, maximum, average and median elevation, and elevation range (in m).
b. Average slope (in °)
c. Average aspect (In °). Aspect goes from 0 to 360° and 0 represents north.
d. Aspect sector, based on the 8 possible cardinal points (N, NE, E, SE, S, SW, W, NW).

The morphometric parameters are based on the same DEM used in the generation of the basins. For each basin, we also calculated the glacier hypsography to further analyse the patterns of glacier area in different elevation bands. This was done by first reclassifying the DEM into 100 m elevation bands, then combining the glacier shapefile and reclassified DEM to identify the glacier area in each elevation band.

Id	Name	Alias	Type	Type name	Length	Precision	Comment
abc 0	Glacier_ID		Text (string)	String	20	0	
1.2 1	Latitude		Decimal (double)	Real	12	8	
1.2 2	Longitude		Decimal (double)	Real	12	8	
abc 3	Name		Text (string)	String	30	0	
1.2 4	Area		Decimal (double)	Real	15	3	
1.2 5	min_ele		Decimal (double)	Real	6	2	
1.2 6	max_ele		Decimal (double)	Real	6	2	
1.2 7	range_ele		Decimal (double)	Real	6	2	
1.2 8	mean_ele		Decimal (double)	Real	6	2	
1.2 9	median_ele		Decimal (double)	Real	6	2	
1.2 10	mean_slope		Decimal (double)	Real	6	2	
1.2 11	mean_asp		Decimal (double)	Real	6	2	
abc 12	asp_sector		Text (string)	String	10	0	

Figure x: Structure of the glacier database. The first column "Id" represents the order of the attribute and the data type (number or alphanumeric); the second column "Name" is the name of the attribute; "Type" and "Type name" describe the data type in detail; "Length" is the total length of the field (how many numbers or characters) and "Precision" is the number of decimal digits for a decimal type field.

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Chapter 6.

Students training and work

Text by **Melis, Fugazza, Anees, Arif Hussain, Sadia Munir, Aurangzaib**

In the face of climate change, which poses a significant threat to glaciers and water resources, the importance of capacity building, skill development and knowledge sharing in Northern Pakistan particularly in Gilgit Baltistan has become even more pronounced. This region, with its vast concentration of glaciers after the poles, is particularly vulnerable to the impacts of a changing climate. Hence, it is crucial to emphasize on the significance of training programs and capacity building initiatives also involving the students as a future generation who can severe as a work force required skills and knowledge in dealing with such emerging threats.

The "Glaciers and Students" project acknowledges the urgency of addressing the impacts of climate change in the region. Through capacity building initiatives, the project aims to equip universities and local government institutes with the necessary skills and knowledge to address the environmental and water resource implications of glacier retreat. As climate change accelerates, the changes in glaciers intensify, leading to the formation of glacial lakes and an increased risk of glacial lake outburst floods (GLOFs). These events can have devastating consequences for communities and infrastructure downstream. Therefore, building expertise in glaciology, remote sensing, and mapping is vital to effectively monitor and assess glacier changes, identify potential hazards, and develop appropriate mitigation strategies.

By investing in capacity building and knowledge development, Gilgit Baltistan can strengthen its disaster preparedness and improve water resource management. Empowering local stakeholders with the necessary skills to navigate the challenges posed by climate change will contribute to sustainable development in the region. Through enhanced

expertise in geomatics, weather stations, glaciological field activities, and avalanche risk assessment, the region will be better equipped to address the impacts of climate change on glaciers and water resources.

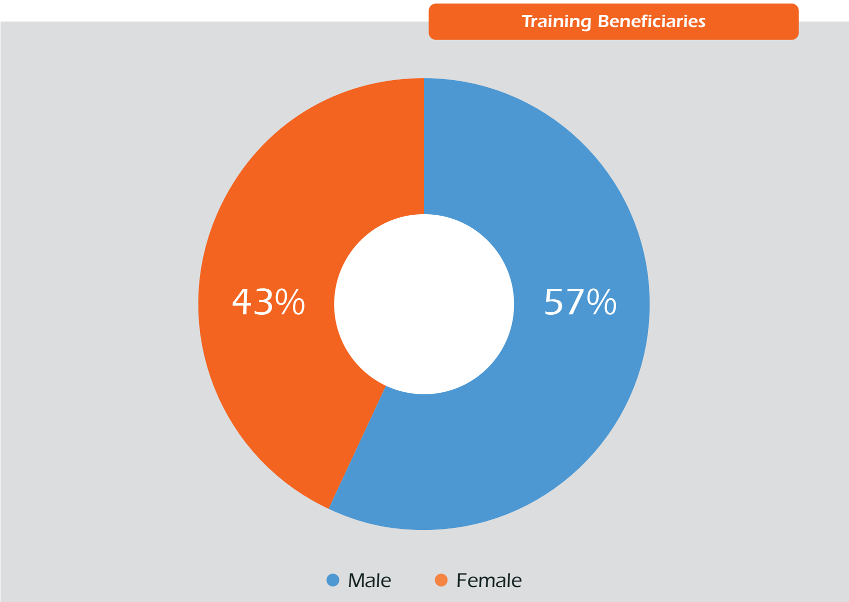
Introduction

Training is a significant tool in any organization that can help to improve performance, efficiency, better decision-making, and enhanced skill development whether in the sector of education, business, technology or any other domain. In the present era, which is dominated by digital advancement, the empowerment of youth is necessary to enhance through capacity building and skills development programs. For instance, educational institutions and organizations can encourage the enthusiastic younger generation by offering opportunities and engaging in technology innovation, contests and other productive activities.

GIS & RS is one of such an emerging sector that is highly demanded globally. These tools can play a major role in every sector, including education, environment, business, industry, agriculture, economic development, natural resource management, transportation and many others. Geographical Information System is a computer-based system for capturing, analyzing and interpretation data particular, it is essential to provide this training opportunity to students to equip them with the skills and knowledge needed in every sector that is currently in demand.

In view of this perspective, trainings related to the glaciology, avalanche risk, geometric, installation of weather stations, GIS &RS were arranged under the project ''Student and Glaciers'' at Karakoram International University. One of the primary objectives of this project is the empowerment of youth and stakeholders through training programs leading to develop the capacities to address the impact of climate change on various ecosystems including glacier ecosystem.

Students from Karakoram International University, the University of Baltistan, and various stakeholders from different organizations participated in these training sessions. These stakeholders included the Environmental Protection Agency (EPA), Gilgit-Baltistan Disaster Management Authority (GBDMA), Rescue 1122, the Forest Department, GB Police,



Pakistan Air Force, and Aga Khan Agency for Habitat. The total number of participants in these training sessions was 394, which encompassed both students and stakeholders. A significant proportion of female participants was actively engaged. Trainees expressed their deep appreciation for the training programs and recommended the continuation of such programs in the future.

Training Beneficiaries

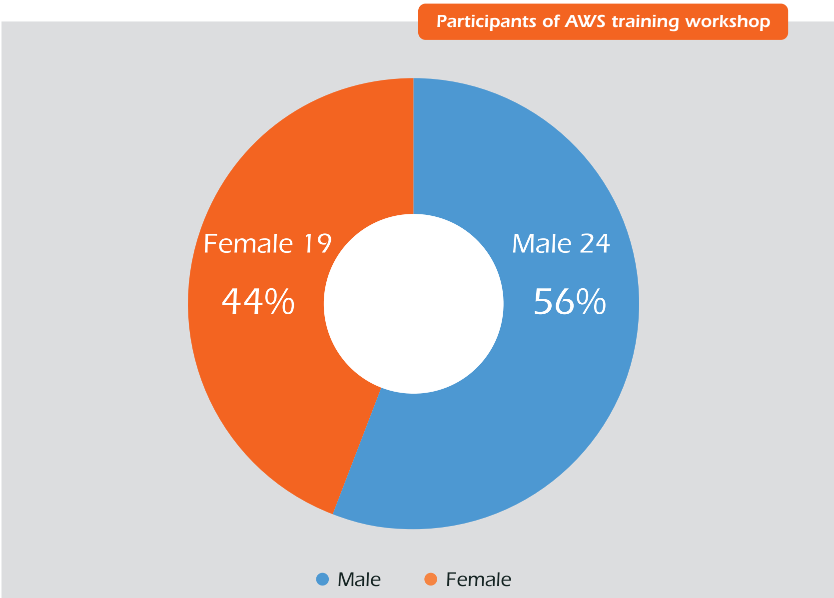
One of the most distinguishing features of the G&S project has been its inclusive approach, bringing all stakeholders on board to achieve each project objective. This strategy encompassed institutions mandated to address climate change and environmental conservation in Gilgit-Baltistan (GB), making it imperative to enhance the capacity of partner organizations in various critical areas. This comprehensive effort included training on AWS installation, maintenance, and data collection, as well as extensive sessions on GIS and RS to facilitate the development of Pakistan's glacier inventory. In this regard, the pivotal role played by the Gilgit-Baltistan Environmental Protection Agency (EPA GB) was instrumental in extending these initiatives beyond the project timeline, ensuring their long-term sustainability. Furthermore, the active involvement of Karakoram International University (KIU) and the University of Baltistan (UOB) in this research-oriented journey is poised to make glacier studies an integral and enduring part of future initiatives.

The establishment of a dedicated training program was a fundamental component of this project, with the overarching goal of preparing students to address the pressing challenges of climate change and glacier preservation. Students, viewed as the vanguards of the future, hold the potential to become catalysts for safeguarding our natural heritage. Equipped with enhanced knowledge and skills, they can play a pivotal role in the scientific exploration of core issues. As a result, a total of 394 beneficiaries were enriched through comprehensive training sessions spanning GIS and RS, Geomatics, Glaciology, AWS installation and maintenance, and Avalanche Rescue. Within this diverse cohort, 171 participants (constituting 43% of the total) were women, while the remaining 223 participants (57% of them) were men, demonstrating a balanced representation across all training sessions. This inclusive and skill-enhancing approach underscores the project's commitment to nurturing a new generation of researchers and conservationists to address the urgent challenges of our times, particularly in the context of glaciers and climate change in GB.

Training Missions

Pakistan being a glacier resource rich country, the necessity for comprehensive monitoring, mapping, and estimation has always been paramount for effective planning and decision-making. This is particularly crucial, considering the significant coverage of glaciers in the country and its heavy reliance on water resources.

Hence, the Glaciers and Students (G&S) project was conceived with a primary objective of sharing knowledge. This involved active participation from local academia, students, government line departments, and dedicated researchers in the realm of glacier analysis. The project placed a significant emphasis on generating and disseminating knowledge, as well as best practices in glacier and climate monitoring, with a particular focus on their applications for environmental risk assessment.



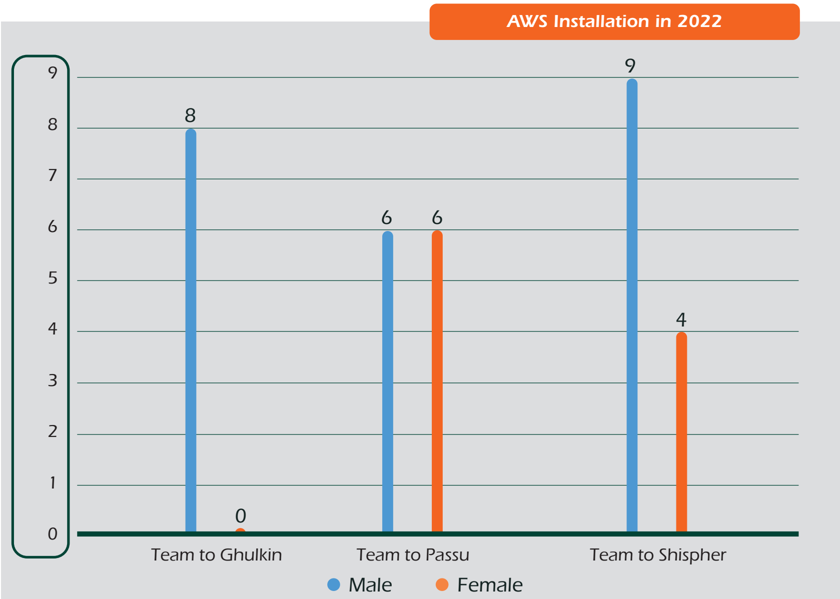
Through a series of dedicated training missions within the project, participating institutions, students, and specialized staff were equipped with new skills and expertise in the domain of environmental monitoring and glacier inventory development. Ev-K2-CNR hopes that even after the project's conclusion, these elevated levels of knowledge will persist and serve as a valuable resource for similar initiatives in the future. This collective wealth of expertise stands as an enduring testament to the project's lasting impact.

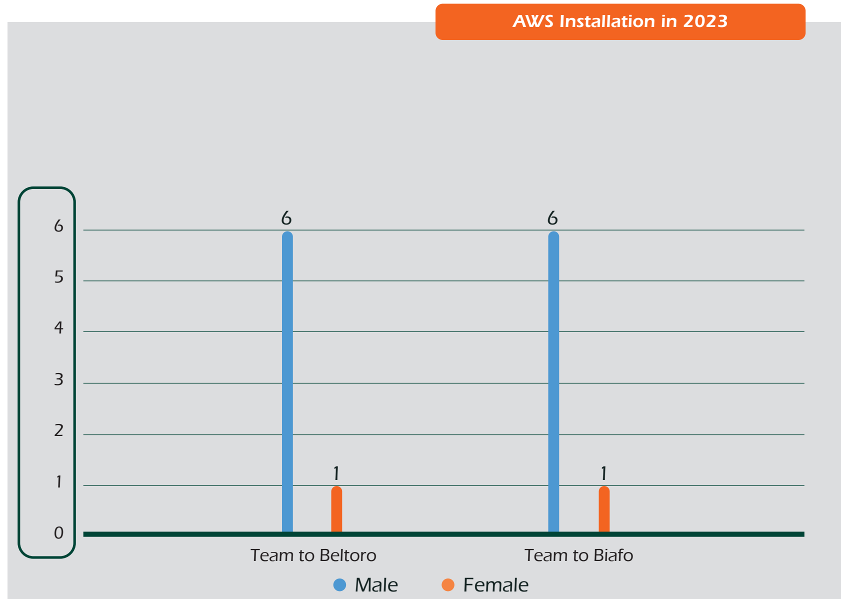
Workshop on AWSs Installation and Sustainability

Prior to the AWS field interventions, it was necessary to organize a session which could bring together all the stakeholders, students and G&S project staff.). This first training session functioned as an informative session for both instructors and students, offering insights into the project and upcoming field trips. The workshop provided comprehensive information about the Automatic Weather Stations, including their components, functions, data, parameters, and data collection procedures. Apart from the selected students, the representatives from EPA, Forest & Wildlife Department, KIU and UOB were the participants, with a total of 43 attendees, consisting of 19 females and 24 males.

Training for WS Installation on Glaciers

AWS installation has been one of the major goals of the "Glaciers and Students" project, using cutting-edge technology to investigate climate change effects and to adopt measures accordingly in the future. In the practical and field trainings, technical personnel EPA, students and faculty of KIU, UOB and field staff CKNP were involved. Various teams were composed for various project locations and they worked in collaboration with the joint effort of Ev-K2-CNR and the University of Milan to install AWSs at various glacier sites including Shisper, Ghulkin, Passu, Minapin, Askole, Biafo, Urdukas and Concordia.
International experts shared their knowledge with training participants, illustrating how Automatic Weather Stations (AWS) play a pivotal role in assessing long-term climate trends while monitoring critical meteorological data. Participants received comprehensive information about various meteorological parameters, including temperature, barometric pressure, humidity level, wind speed and direction, precipitation, and solar radiation. They were also trained on data storage in loggers and retrieval methods, which could be executed either through a cellular network or on-site, using computers or mobile





devices. This data is instrumental for modeling and informed decision-making.

The training sessions comprised a total of 41 participants, with a gender-diverse composition of 12 females and 29 males. To facilitate an optimized learning experience, the participants were subdivided into three distinct groups. These teams effectively harnessed the power of collaborative efforts, with the valuable support and guidance of both Ev-K2-CNR and the University of Milan. This approach allowed for a more comprehensive and enriched understanding of the subject matter, ensuring that each participant could contribute to the collective knowledge and skill development.

The installation of AWS on glaciers brings a multitude of advantages, primarily bolstering glacial research efforts. It empowers scientists and researchers to delve into the intricate effects of climate change on glacial retreat, mass balance, and melt rates. Furthermore, AWS systems serve as early warning tools for potential glacial hazards, offering critical protection to vulnerable communities downstream.

The data collected by AWS will be made accessible to researchers and policymakers through the Gilgit-Baltistan Environmental Protection Agency, which will assume the role of custodian for AWS and the amassed data. The installation of eight AWS on various glaciers within Gilgit Baltistan represents a groundbreaking step in advancing climate research and deepening our comprehension of glacial environments. These AWSs will continuously monitor real-time meteorological data, providing invaluable insights into weather conditions and their influence on glacial dynamics.

The active involvement of academia and the Gilgit-Baltistan Environmental Protection Agency in the project, along with their responsibilities as custodians of AWS and its data, is integral to ensuring the project's success and long-term sustainability.

Training on Glaciological Field Activities

The glaciological field trainings in Gilgit-Baltistan are instrumental in providing a holistic and comprehensive understanding of the region's glacial landscapes. Covering a spectrum of vital subjects, including glacier dynamics, field techniques, safety protocols, ablation stake installation for glacial melt measurement, micro plastics analysis, carbon deposits, data collection and analysis, and environmental considerations, these trainings equip participants with a multifaceted skill set. This knowledge empowers individuals to engage in meaningful research and practical initiatives related to glaciology and climate change, thereby fostering a deeper connection to the region's environment. The beneficiaries of these training sessions, comprising a total of 33 trainees, including 10 females and 23 males, were drawn from KIU, UOB and GB-EPA, all operating under the aegis of the Glaciers and Students Project. It's noteworthy that these participants had previously been involved in the installation of Automatic Weather Stations (AWS) in the upper Hunza region, showcasing their commitment to enhancing their skills and understanding in glaciology and environmental research. This integrated approach seeks to develop a

Glaciological Field Activities Training Content

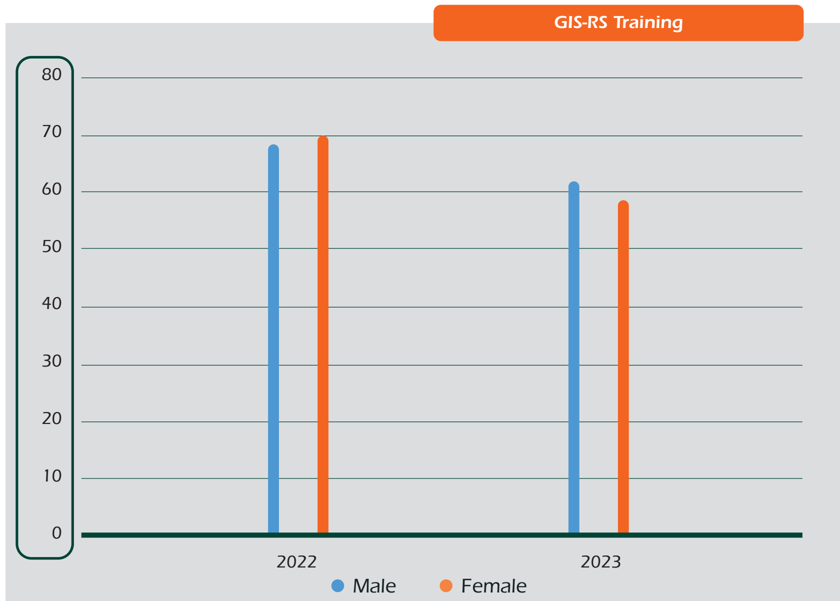
- Introduction to the AWS
- AWS Installation
- Data Collection from AWS
- Data storage

cadre of experts capable of contributing significantly to glaciological research, environmental conservation, and glacier management in this unique and fragile region.

Training on GIS-RS

The GIS and RS training programs hold immense significance for students, researchers, and the Gilgit-Baltistan Environmental Protection Agency (EPA) in the context of glacier studies and glacier inventory development. Equipping students and researchers with the knowledge and skills to harness Geographic Information Systems (GIS) and Remote Sensing (RS) technologies is a vital step towards advancing glaciological research. These tools enable in-depth analysis, monitoring, and modeling of glaciers, providing invaluable insights into glacial dynamics, changes, and their impact on the environment. Furthermore, the EPA's involvement in this training fosters local expertise and empowers the agency to effectively manage and protect the region's fragile glacial ecosystems. With an increasingly urgent need to understand and mitigate the effects of climate change on glaciers, GIS and RS training is a cornerstone in promoting sustainable practices and informed decision-making, essential for safeguarding vulnerable communities and the environment in Gilgit-Baltistan.

Throughout the course of the Glaciers and Students (G&S) project, four (04) comprehensive training sessions were conducted on Geographic Information Systems (GIS) and Remote Sensing (RS), tailored for students and faculty from Karakoram International University (KIU) and the University of Baltistan (UOB). These sessions were attended by a diverse array of participants, encompassing not only students but also representatives from critical organizations such as the Gilgit-Baltistan Environmental Protection Agency (GB EPA), the GB Disaster Management Authority, GLOF-II, and the Central Karakoram National Park. These training endeavors marked the active engagement of 119 female participants and 131 male participants in the acquisition of both theoretical and practical knowledge and experience related to GIS and RS, underlining the inclusive approach of the project towards fostering expertise in glacier studies and inventory development.



GIS-RS Training Content

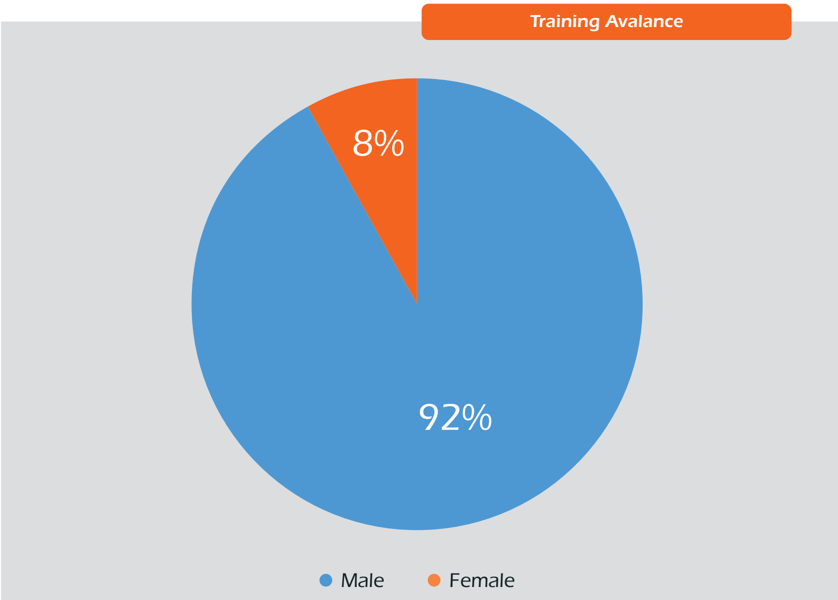
- Knowledge and comprehension of Glacier Inventory
- Monitoring techniques
- Understanding of GIS-RS
- Components of RS
- Data supply and users
- Characteristics and Resolution of RS
- Software tools and installation
- Spectral-based classification
- Object-based image analysis
- Image classification and validation

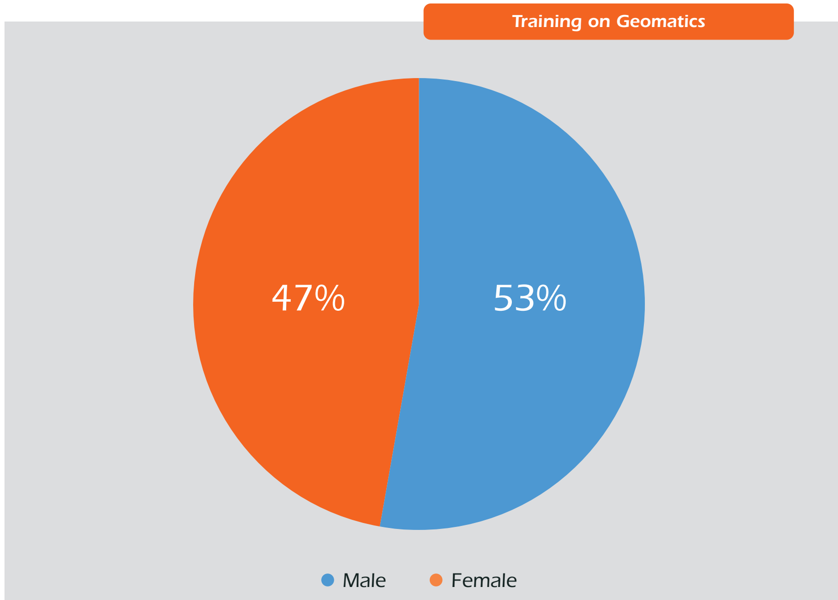
Training on Avalanche prevention and Rescue

Avalanches are unquestionably recognized as one of the foremost challenges confronting the rugged landscapes of Gilgit-Baltistan. The region's unique amalgamation of towering mountain peaks, precipitous slopes, and substantial snowfall during winter months gives rise to a complex avalanche hazard that requires earnest attention. To address this formidable menace, a concerted effort was undertaken to enhance the capacity of pertinent institutions. Leveraging the extensive international experience of trainers from Italy, a comprehensive 10-day training program on Avalanche Rescue was meticulously orchestrated by Ev-K2-CNR. This vital initiative attracted participants from a spectrum of relevant departments within Gilgit-Baltistan, including the GB Tourist Police, the Aga Khan Agency for Habitat, Rescue 1122 GB, Karakoram International University (KIU), and the University of Baltistan (UOB). While the invitation was extended to both men and women, the challenging practical segments of glacier training in Naltar valley did somewhat limit the participation of women in this critical endeavor, with a total of 02 females (8%) and 22 males (92%) in attendance. Nevertheless, this training endeavor epitomizes a proactive step toward mitigating the perils posed by avalanches in this geographically distinctive and challenging terrain.

Training on Geomatics

Geomatics training holds pivotal importance for students, researchers, and the Gilgit-Baltistan Environmental Protection Agency (EPA) within the context of glacier studies and glacier inventory development. By imparting essential skills in surveying, mapping, and geospatial data management, Geomatics equips individuals with the capacity to accurately measure and analyze the dynamic nature of glaciers. For students and researchers, this proficiency is a catalyst for advancing their





Training Objectives

- Prepare a group of skilled rescuers for GB who will handle avalanche disasters
- Make participants aware of the usage of technology during avalanche disasters
- Prepare master trainers to raise awareness in the community
- Use of tools and equipment during avalanche rescue

Training Content

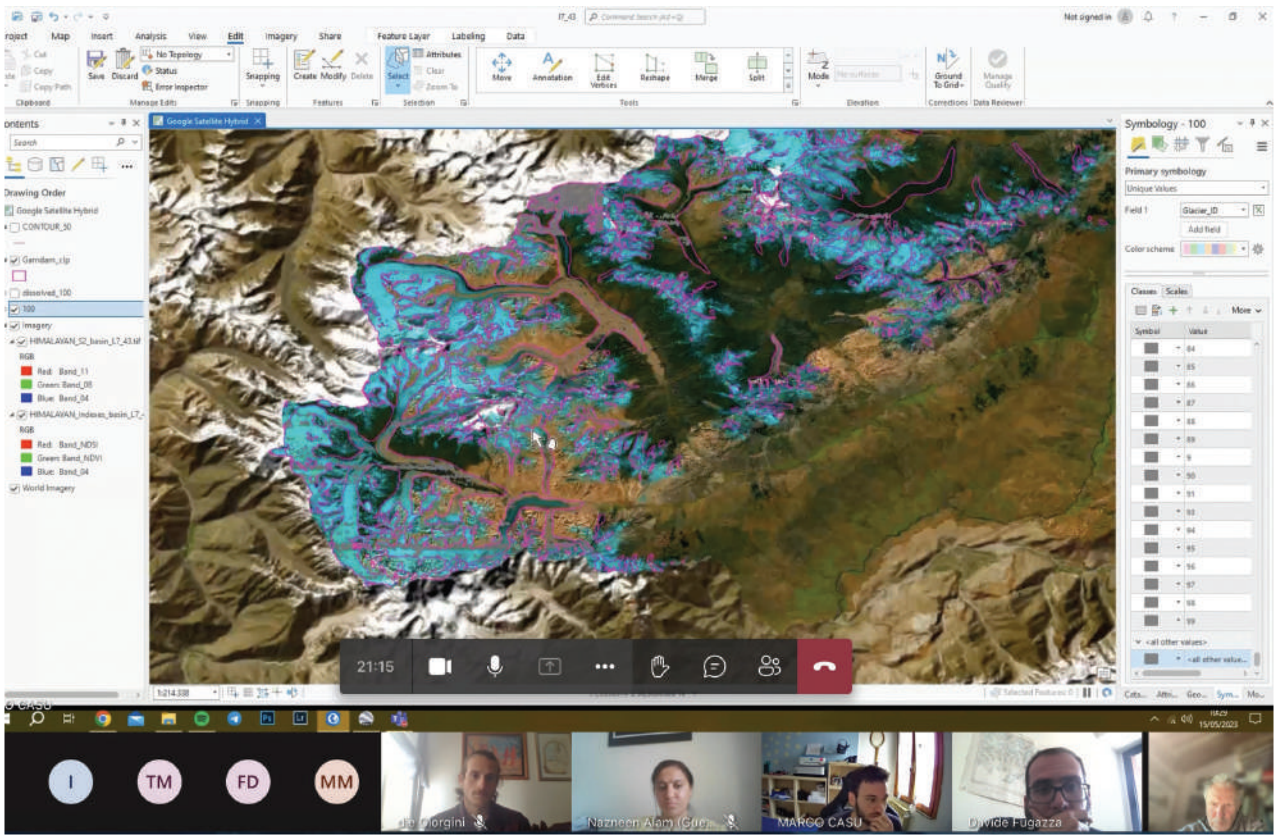
- Snow and snowpack definitions and characterization
- Avalanche phenomenon description and classification
- Avalanche defense systems
- Avalanche search and rescue methods and technologies

Geomatics Training Content

- Introduction to glaciers
- Knowledge and comprehension of Glacier Inventory
- Monitoring techniques
- Understanding of GIS-RS
- Components of RS
- Data supply and users
- Characteristics and Resolution of RS
- Software tools and installation
- Spectral-based classification
- Object-based image analysis
- Image classification and validation

scientific inquiries, enabling comprehensive glacier assessments, and offering invaluable insights into the effects of climate change. For the EPA, this knowledge serves as a base for effective environmental management, aiding in the protection of vulnerable ecosystems and communities while fostering data-driven decision-making. The long-term impact of Geomatics training is felt through the sustainable preservation of Gilgit-Baltistan's unique glacial landscapes and their vital contributions to the region's ecosystem.

The Geomatics training sessions conducted as part of the project, participants from Karakoram International University (KIU), the University of Baltistan (UOB), the Gilgit-Baltistan Environmental Protection Agency (EPA), and the United Nations Development Programme (UNDP) converged to enhance their expertise in this critical field. University of Milan, played a pivotal role in facilitating the session, ensuring that participants received a comprehensive understanding of Geomatics. This endeavor underscores the project's dedication to equipping students, researchers, and EPA representatives with the knowledge and practical skills needed to engage in glacier studies and contribute to the development of a robust glacier inventory. The acquired Geomatics proficiency empowers them to make informed decisions, safeguard vulnerable ecosystems, and effectively manage the unique glacial resources of Gilgit-Baltistan, thereby fostering sustainability and the preservation of this vital natural heritage.



Training Impact and Reviews of Beneficiaries

One of the key components of the G&S project has been the active involvement of researchers and students at every project stage, commencing with the installation of AWSs on glaciers, followed by capacity building through training and workshops. This participation has culminated in students contributing to the achievement of significant project milestones, including AWS installation and the development of a glacier inventory.

The GB-EPA and GB-DMA researchers, university students and faculty found the GIS and RS training to be exceptionally valuable for their learning and research endeavors. GIS and RS offer applications across diverse fields and study areas, proving essential in analyzing data related to glaciers, lakes, plants, streets, buildings, and more. The ability to visualize this multifaceted data on a single map greatly enhances the quality and significance of research. It empowers individuals to discern, assess, and comprehend complex patterns and relationships, thereby amplifying the overall understanding and value of their work.

Mr. Ejaz Ali, a Scientific Officer at the GB Environmental Protection Agency, lauded the training as exceptionally well-designed, offering valuable insights into the fundamentals of GIS, ""The training was exceptionally well-designed for anyone seeking to grasp the fundamentals of GIS. The delivery of knowledge and skills during the training was highly effective."

Ms. Palwasha from the Disaster Management Department expressed her thoughts, stating, "The course was truly remarkable in enhancing one's understanding of GIS and RS. It provided a solid foundation and highlighted their practical applications as invaluable research tools."

Ms. Zubaida, a student from KIU, participated as a team member in the field visit to Passu Glacier for AWS installation. She shared her thoughts on the training and field visit, stating, "Ev-K2-CNR adopted an incredible approach by actively involving students in the entire project. This allowed us to bridge the gap between our theoretical knowledge of AWSs and the practical aspects of their installation, functioning, and data processing. Working on the glaciers was certainly challenging, but being on Passu Glacier provided me with the most remarkable experience of my life. The beauty of nature and the awe-inspiring Passu Cones left me breathless. It made me truly appreciate the dedication of researchers who work in such harsh environments to conduct studies in these extreme climatic conditions."


Ms. Nazneen Alam


Ms. Sabrina Khan

Statements from Interns/Research Fellows

Ms. Nazneen Alam, a dedicated M.Phil./MS student specializing in Climate Change and GIS-RS, discovered Ev-K2-CNR. Over the past year, she became an intern and research fellow with the Ev-K2-CNR family, immersing herself in the world of Geographic Information Systems (GIS) and Remote Sensing (RS). Here are her reflections as both a student and researcher about her journey with Ev-K2-CNR and the Glaciers and Students Project.

"In an enriching year-long journey as an intern and research fellow at Ev-K2-CNR, I delved into GIS and RS. The initial excitement and apprehension I felt on my first day were soon replaced with determination, hard work, and collaboration. The Ev-K2-CNR family, a community of experts, played a crucial role as mentors, guiding me towards GIS-RS proficiency. A pivotal moment came when I gained expertise in glacier inventory, a daunting task made achievable through unwavering support. International collaborations with experts from Pakistan and Italy expanded our horizons. Becoming trainers ourselves, my colleagues and I imparted knowledge to eager students, witnessing their growth with immense pride. Reflecting on this transformative journey, I'm profoundly grateful. I've not only evolved as a student but as an individual. My quest for knowledge is far from over, and I'm eager to explore GIS-RS in-depth to contribute meaningfully to climate change research. My time at Ev-K2-CNR marks just the beginning of a lifelong adventure in learning, growth, and discovery."

Ms. Sabrina Khan, an intern and project research fellow, shares her experiences and gratitude for her time with the Glaciers and Students Project. With an undergraduate background in Space Science from the University of the Punjab, Lahore, she reflects on her experience and role within the remarkable team of Glaciers and Students Project.

During my tenure as an Intern/Research Fellow at Ev-K2-CNR Pakistan, I contributed to the "Glaciers and Students" project, focusing on scientific-based monitoring of climate and glaciers in Pakistan's mountainous regions to support hydrological risk prevention. My responsibilities included identifying and classifying glaciers within a designated hydrological basin, using satellite data and GIS. I also worked on classifying polygons in assigned shape files to establish their connections with specific glaciers. Collaborating with a skilled team, I actively participated in meetings and shared diverse ideas, enriching our research. I'm grateful for Ev-K2-CNR Pakistan's trust and support. Being part of a team dedicated to advancing scientific knowledge and environmental conservation was a source of pride. This project significantly enriched my career, and I look forward to future accomplishments in studying the climate and glaciers of Pakistan's mountains."

Testimonials from Volunteers who worked on Glacier Inventory

The project involved a team of six dedicated volunteers who made substantial contributions to the inventory development under specialist supervision. Additionally, three interns were selected from the G&S training recipients, all of whom were students from KIU and UOB. They displayed exceptional professionalism and effectiveness in meeting their targets

The volunteers played a pivotal role in the development of the glacier inventory, aligning their efforts with the Ev-K2-CNR team. Guided by the capable leadership of the G&S project manager and fostering close collaboration with UNIMI and UNICA, they embarked on this challenging mission. Their journey to contribute to the inventory was preceded by extensive training and capacity-building sessions focused on GIS and Remote Sensing. In the subsequent passages, these dedicated individuals will share their first-hand experiences, shedding light on their involvement in inventory development and their field visits dedicated to the installation of Automatic Weather Stations (AWSs). Their accounts offer a unique perspective on the intricacies of this multifaceted project, showcasing the intersection of training, fieldwork, and tangible contributions to the scientific community.


Zaheer Ul Islam

Zaheer Ul Islam a student from the department of Earth Sciences- KIU: Over the past three months, I've undergone GIS training, an enlightening and rewarding experience. As a student passionate about Earth science and spatial analysis, this training expanded my horizons and equipped me with valuable skills. GIS's versatility across disciplines, from urban planning to agriculture, was striking. It's an indispensable tool for analyzing spatial data, capable of addressing real-world challenges. Hands-on experience creating a glacier inventory deepened my understanding and showcased GIS's ability to provide actionable insights. Mentors' exceptional support and guidance were pivotal. Their expertise and willingness to share knowledge were invaluable. I explored various GIS software, including Snap and QGIS, boosting my confidence. Reflecting on this transformative journey, I'm excited about the opportunities ahead. GIS opens possibilities, and I'm eager to apply my skills to address environmental challenges, contribute to sustainable development, and make a positive impact.

Nouman Karim a student from the department of Computer Sciences- KIU: "My experience with GIS and RS has broadened my understanding of their vast applications, extending beyond traditional inventory management. These technologies have empowered me with essential skills that will undoubtedly shape my future academic pursuits. GIS has emerged as a pivotal tool in numerous sectors, such as public


Nouman Karim


Sher Karim


Aziz Aman


Danish Murad


Mujahid Ali


Iqra Saeed

health and environmental research, owing to its prowess in integrating and analyzing geographical data. It facilitates a comprehensive grasp of complex interrelationships among various factors, enabling data-driven decision-making. My proficiency in data collection, analysis, and visualization has significantly improved through RS and GIS. I've acquired the ability to work with spatial data, employ geospatial algorithms, and extract valuable insights from satellite imagery. This knowledge equips me to advance my future studies and contribute to cutting-edge research and practical applications in my chosen field."

Sher Karim a student from the department of Computer Sciences- KIU: "Currently, I work with EVK2CNR, focusing on Glacier Inventory. I've successfully completed work on three glacier basins, enriching my GIS skills significantly. GIS holds immense potential for advancing future studies by offering essential data and insights for environment understanding and management, aiding informed decision-making for our planet's future. The prospects of GIS in the coming years are incredibly exciting. These technologies have the power to create a tangible global impact, and I take pride in being a part of this dynamic field."

Aziz Aman a student from the department of Environmental Sciences- KIU: "I recently completed training program with Ev-K2-CNR's Glaciers & Students Project, where I gained hands-on experience in GIS and RS technologies. This training offered me a strong foundation in these tools' principles and applications, which are particularly relevant in environmental research. GIS, in my view, is an essential skill for my future studies, as it empowers me to assess land use, habitat fragmentation, and climate change impacts. The versatility of GIS is striking, extending its benefits to urban planning, disaster management, agriculture, and various other fields. Its spatial analysis capabilities are particularly valuable when studying glaciers and their response to climate change. My work on the glacier inventory project has provided practical experience and deepened my understanding of how GIS can be applied in environmental research. I'm enthusiastic about the potential of GIS in my future studies and research, appreciating the opportunities I've had so far and looking forward to further exploration in this field."

Danish Murad a student from the department of Forestry range and Wildlife- KIU: "GIS (Geographic Information System) and RS (Remote Sensing) offer extensive applications beyond inventory management. During my two-month affiliation with institutions, particularly my volunteering with Ev-K2C-NR, I've gained valuable knowledge on the practical applications of GIS and RS. This exposure has made me an expert in glacier inventory, enhancing my capabilities for future studies and research. GIS, as an emerging technology, will undoubtedly be instrumental in my academic and analytical pursuits, and I'm immensely grateful for the knowledge and experience I've gained through this project."

Mujahid Ali a student from the department of Earth Sciences- KIU: "My affiliation with Ev-K2-CNR has significantly broadened my understanding of Q-GIS and RS, areas I had limited prior knowledge of these subjects. This newfound expertise is a valuable asset for my future studies, particularly in the domain of hazard predictions. The collaborative environment at Ev-K2-CNR, featuring regular meetings with Italian specialists and local experts, has enriched my learning experience. The supportive teamwork within our group has further facilitated my learning journey. I extend my sincere thanks to the Project Manager and experts from UNIMI and UNICA for their continuous guidance, which has been instrumental in my professional growth. I believe the work I'm engaged in will be pivotal for future GLOF (Glacial Lake Outburst Floods) research and Alpine glacier inventory. It's an honor to contribute to such important work with implications for natural hazard management. My heartfelt appreciation to the entire Ev-K2-CNR team for this invaluable volunteer opportunity."

Iqra Saeed a student from the department of Plant Sciences- KIU: "The RS & GIS training conducted by Ev-K2-CNR at Karakoram International University was a remarkable experience, introducing me to Italian researchers. Although initially unfamiliar with Q-GIS & RS, the advanced software knowledge became vital for my data analysis as a researcher. I incorporated RS & GIS into my thesis work, focusing on land conversion and vegetation estimation. This training allowed me to apply modern, accessible methods to replace traditional complex approaches in assessing vegetation and ecosystem services. The curriculum emphasized glacier mapping and equipped me with Q-GIS skills to process Sentinel and Landsat data efficiently. If presented with another opportunity, I eagerly look forward to advancing my knowledge further."

The students


Anees Ahmad


Irtiza Ahmed


Irtiza Ahmed


Mujahid Ali


Sajjad Ali


Aziz Aman

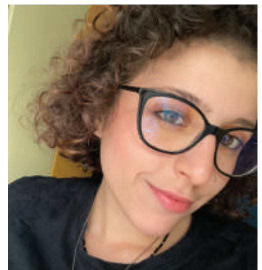

Fernando Benini

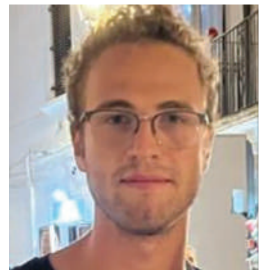

Blanka Barbagallo


Sara Bonomelli


Silvia Case


Marco Casu


Chiara Condò


Luca Facchinetti


Diego Giorgini


Syed M. Hussain

Nouman Karim


Sher Karim


Ms. Sabrina Khan


Zaheer Ul Islam


Tommaso Maero


Lorenzo Meggetto


Danish Murad


Marco Obialero


Mirko Panzeri


Francesco Pinna


Ms. Iqra Saeed

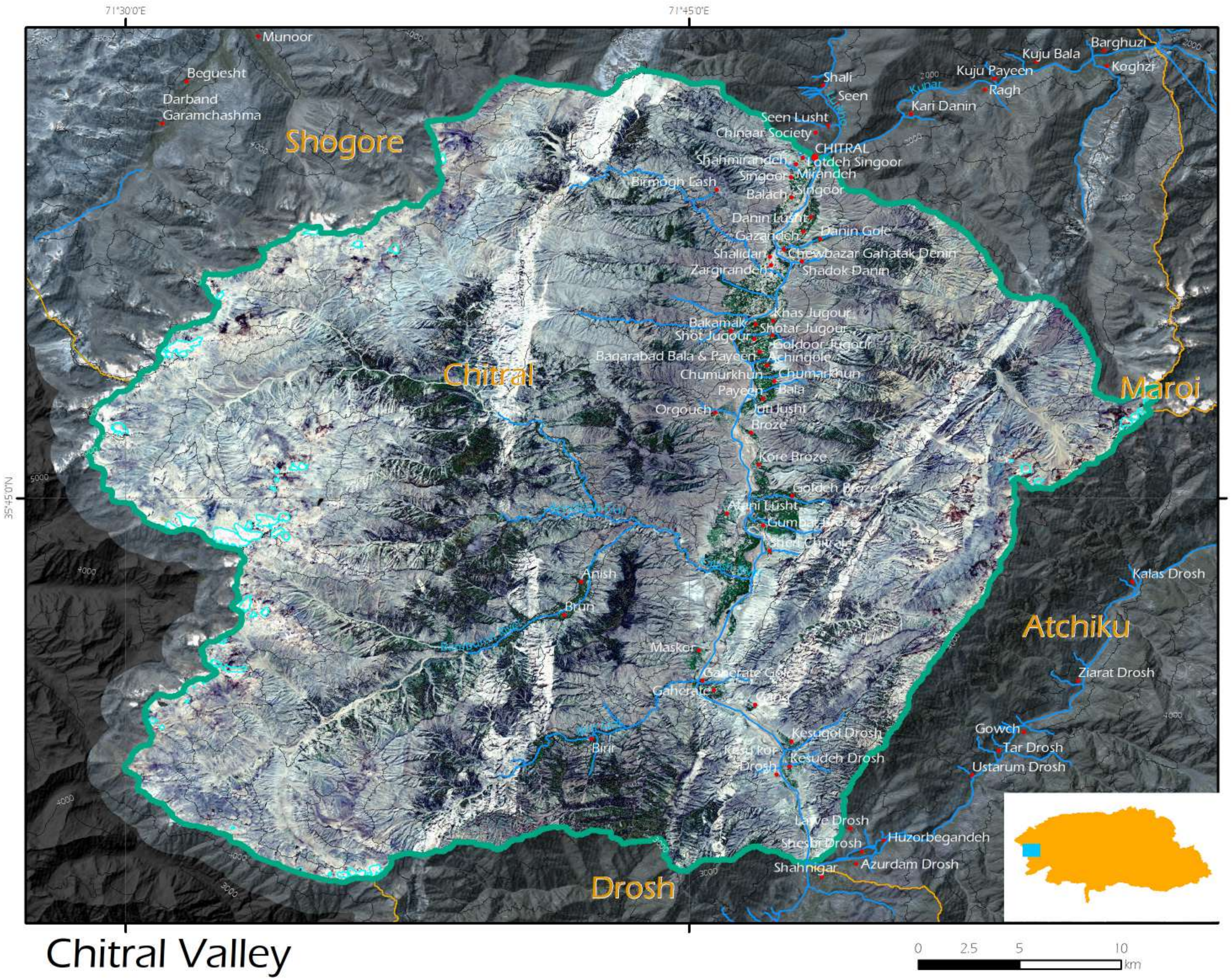

Giacomo Traversa


Ms. Irene Trovalusci

Chitral

Chitral basin (1111 km2) was named after the Chitral (or Kunar) River, receiving water from the slopes of the Hindukush and Hindu Raj mountains. It shares its name with the town of Chitral, which is also the capital of the eponymous district, now split into upper and lower Chitral.
This basin is among the smallest by glacier number in Pakistan; 48 glaciers were mapped within its boundaries, with glacier areas ranging from fewer than 0.1 km2 to 0.83 km2. Most of these glaciers (31) are in fact smaller than 0.1 km2, while only two are larger than 0.5 km2. The largest share of the area however is included in the size class 0.1-0.5 km2 (53%).
In view of their small size, glaciers of this basin do not show a clear dependence with elevation, which ranges between 4451 m a.s.l. and 5416 m a.s.l. The largest elevation range for an individual glacier is 788 m, which is found in the second largest glacier, whereas the largest has an elevation range of only 395 m.
As common for very small glaciers, most of them face north (16 glaciers or 33%), north-east (13 glaciers or 27%) and north-west (10 glaciers or 21%), with a very limited amount of glaciers in the other aspect classes, and none of them facing south or south-west. The picture is similar when considering the glacier area, with only a slightly larger share of north-west facing glaciers (30%).
The glacier hypsography shows a bi-modal distribution, with a small peak between 4200 and 4300 m a.s.l. (7%) and the largest one centered around 4600-4700 m a.s.l. (28% of glacier area). Very little glacier area is found above 5000 m a.s.l. (3% in total).

Laglar Pit. Google Earth. September 03, 2013. Accessed November 2023. Data SIO,NOAA, U.S. Navy, NGA, GEBCO ©



Chitral Valley

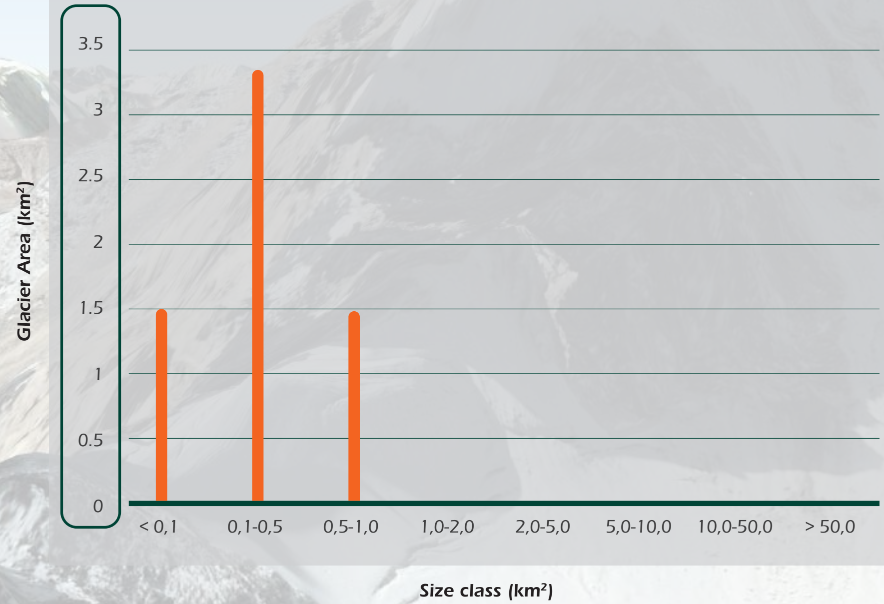
Chitral

Summary table

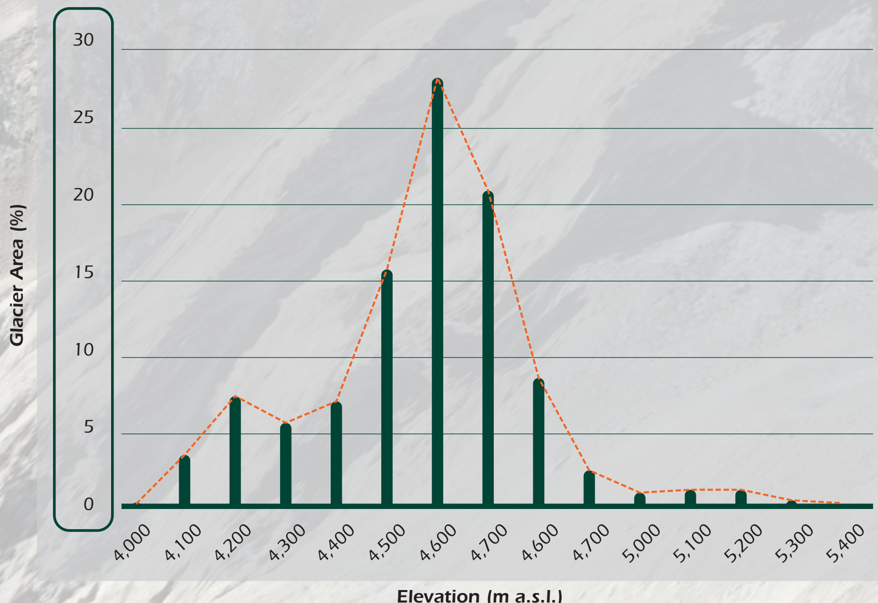
Number of glaciers	Glacier Area	Mean Elevation
48	6.24 km^2	4598.16 m a.s.l.

North-East sector of Chitral. Google Earth. September 24, 2013. Accessed November 2023. Data SIO,NOAA, U.S. Navy, NGA, GEBCO ©

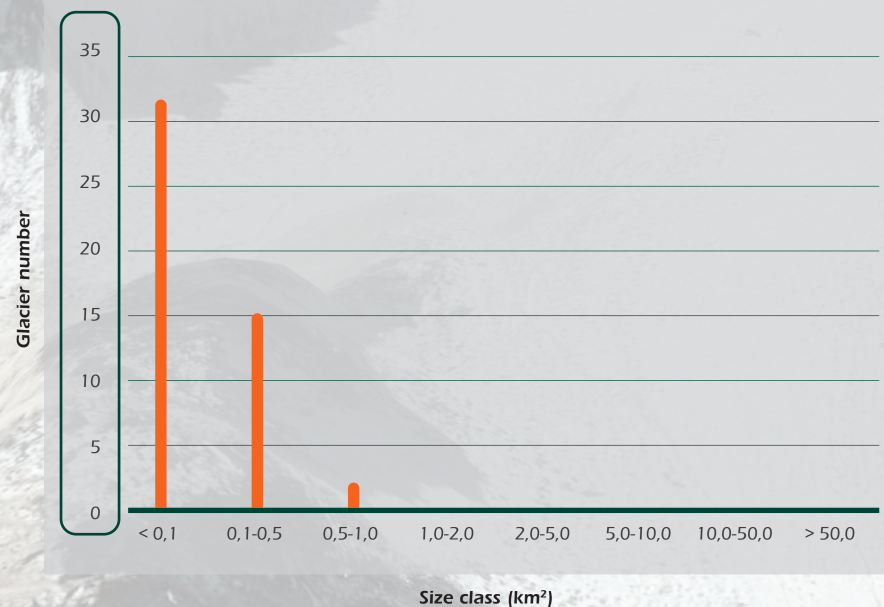
Glacie Area distribution



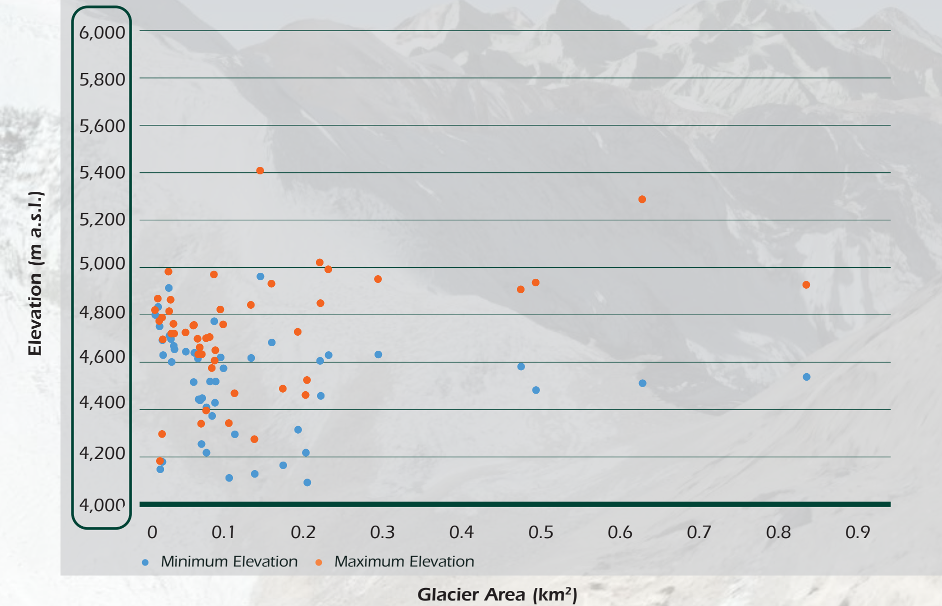
Glacier Hypsometry



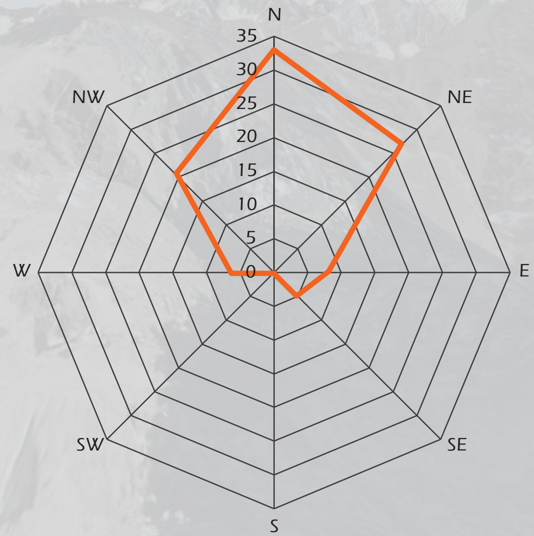
Glacier Number distribution



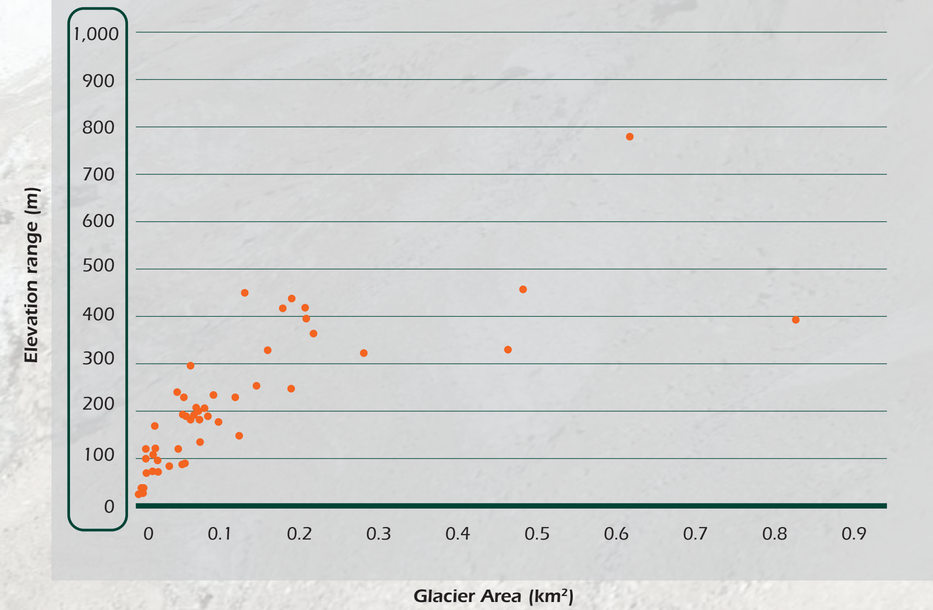
Glacier Min/Max Eleveation - Area



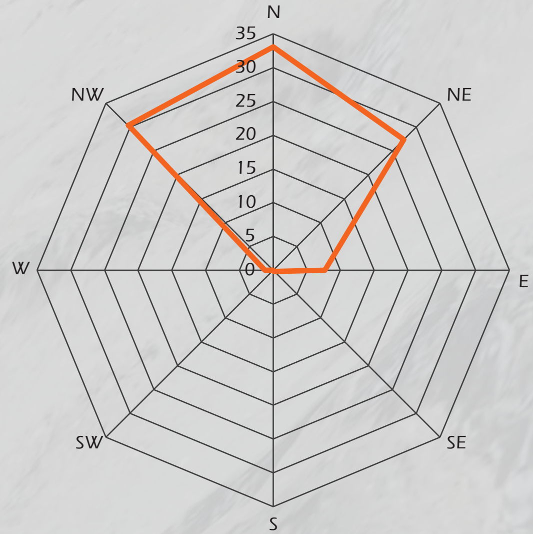
Aspect Distribution (% Glacier number)



Glacier Elevation range - Area

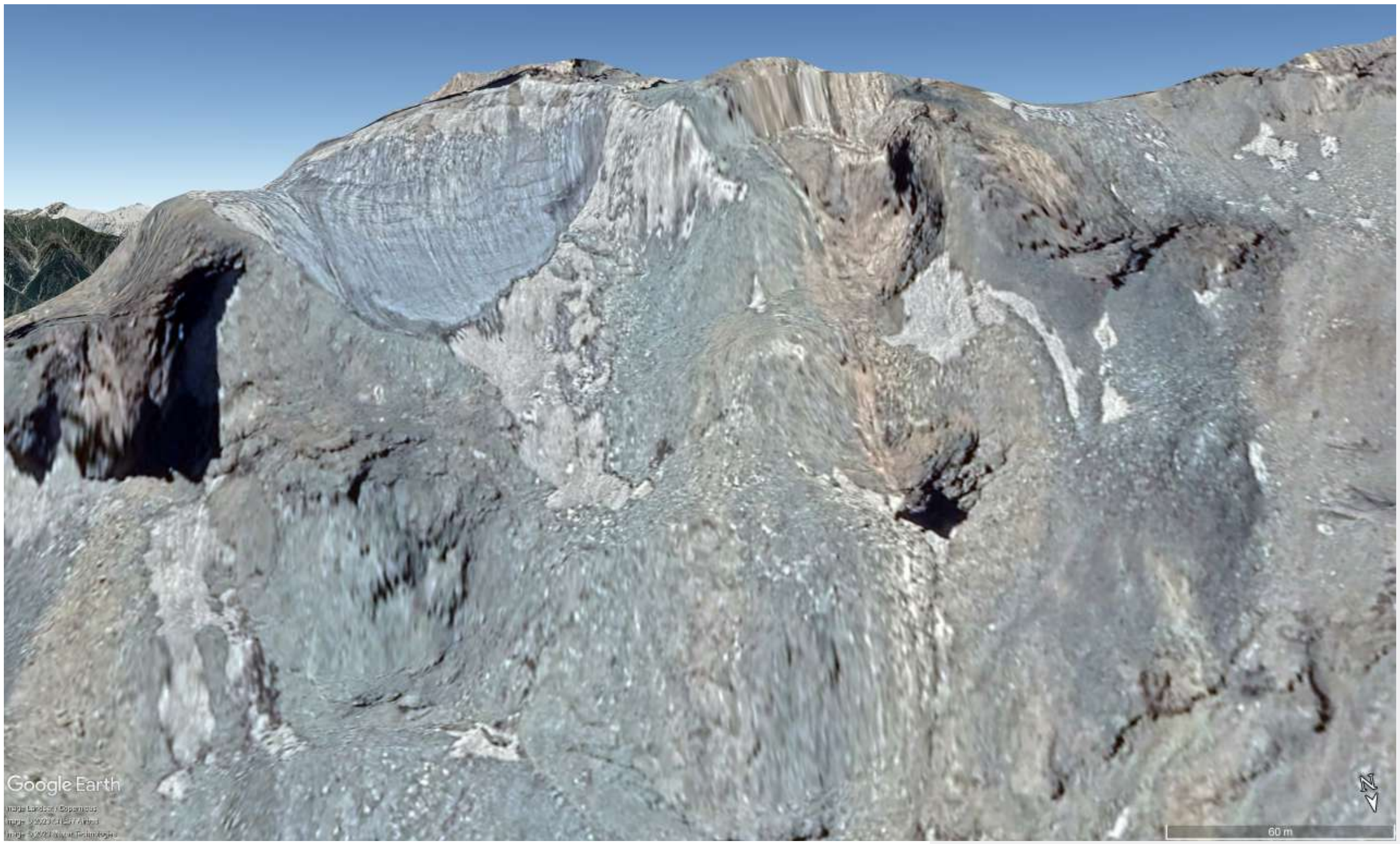


Aspect Distribution (% Glacier Area)

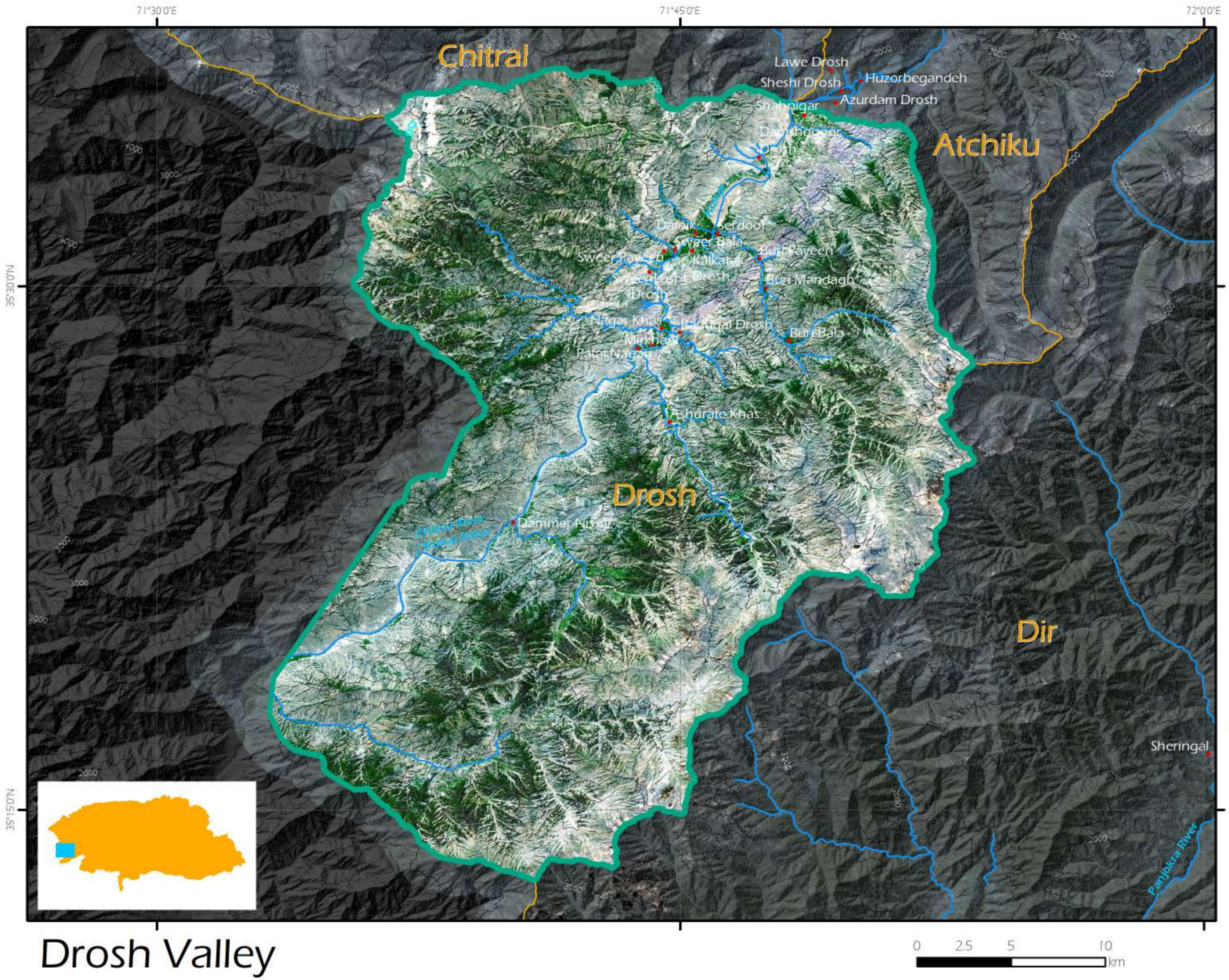


Drosh

Drosh basin (843 km2) is part of lower Chitral district. The main river of the basin is Chitral River, of which this basin forms the southern continuation. Chitral River also receives waters from many tributaries, including Bashgal river upon whose banks lies the town of Drosh. This is the smallest basin by number of glaciers within Pakistan. Only two very small glaciers are found here, both with areas lower than 0.1 km2, reaching 0.12 km2 combined. The elevation of these glaciers ranges between 4110 m a.s.l. and 4408 m a.s.l., and the largest of them has an elevation range of 154 m. As the two glaciers are small and at relatively low elevations, their survival is granted by the north-facing orientation, creating shadow conditions limiting melt. Debris cover does not appear to be large, so snow accumulation from solid precipitation, avalanching and wind redistribution likely plays a role in providing nourishment to these glaciers.



North-western sector of Drosh. Google Earth. July 17, 2019. Accessed November 2023. Data SIO,NOAA, U.S. Navy, NGA, GEBCO ©



Drosh Valley

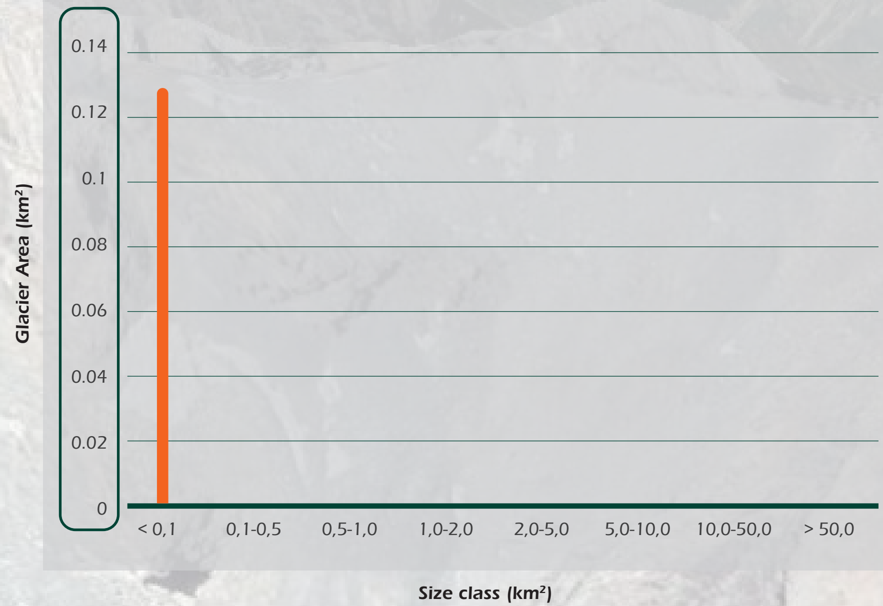
Drosh

Summary table

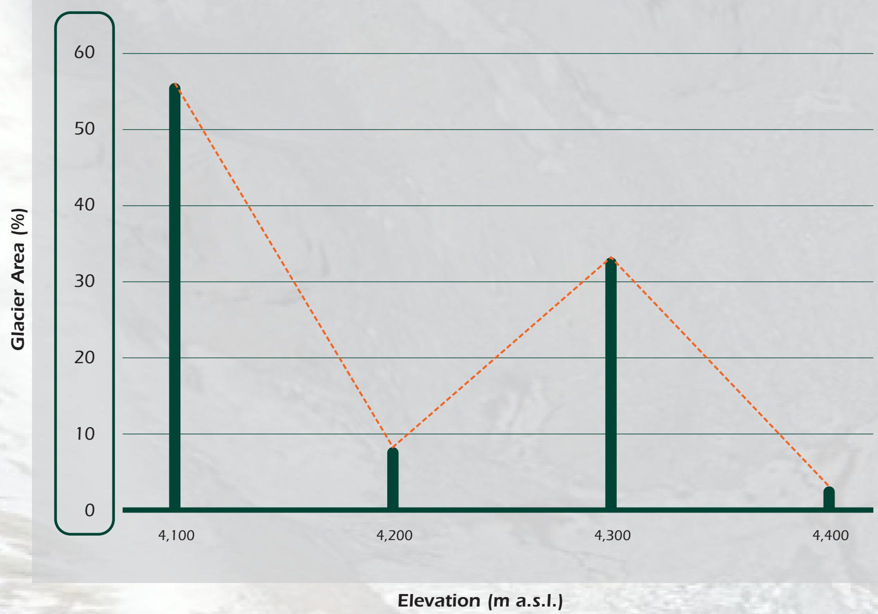
Number of glaciers	Glacier Area	Mean Elevation
2	0.13 km²	4244.47 m a.s.l.

North-western sector of Drosh. Google Earth. July 11, 2019. Accessed November 2023. Data SIO,NOAA, U.S. Navy, NGA, GEBCO ©

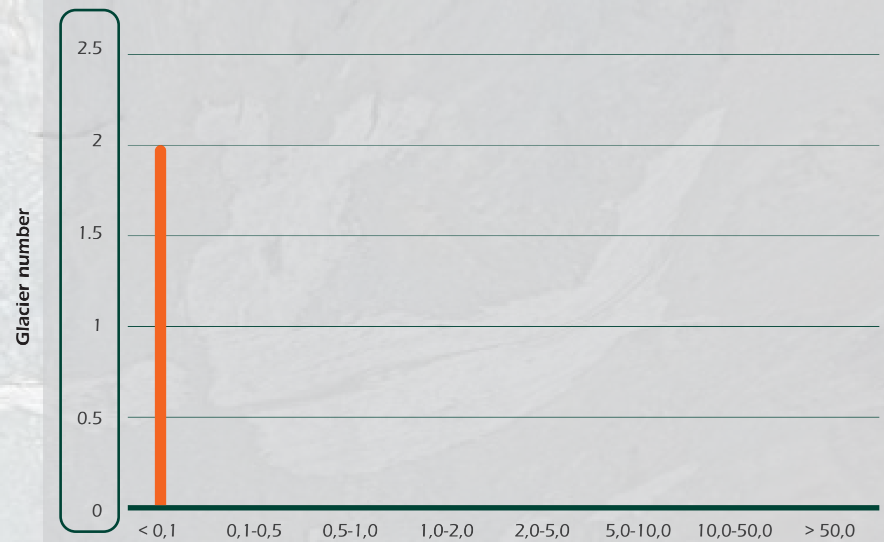
Glacie Area distribution



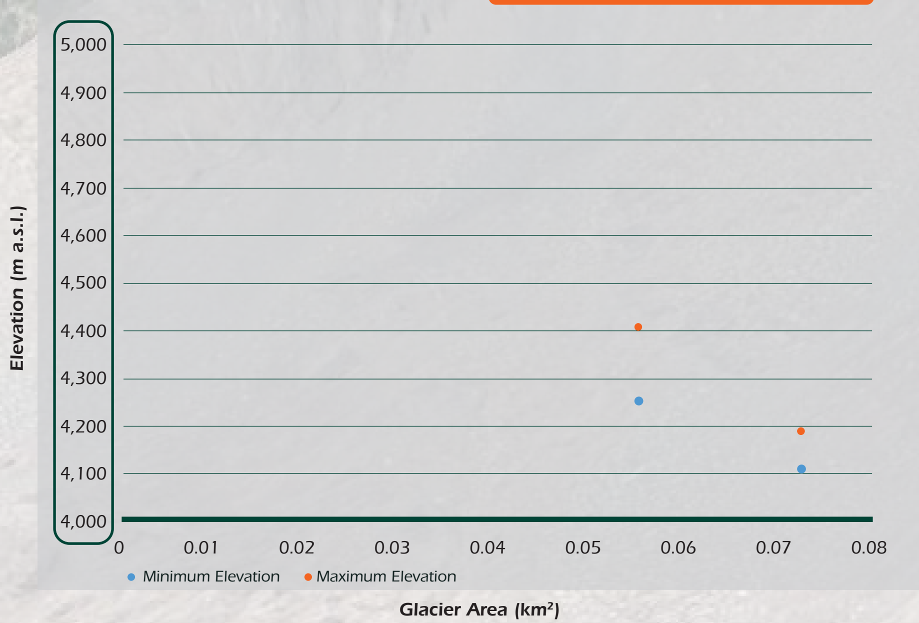
Glacier Hypsometry



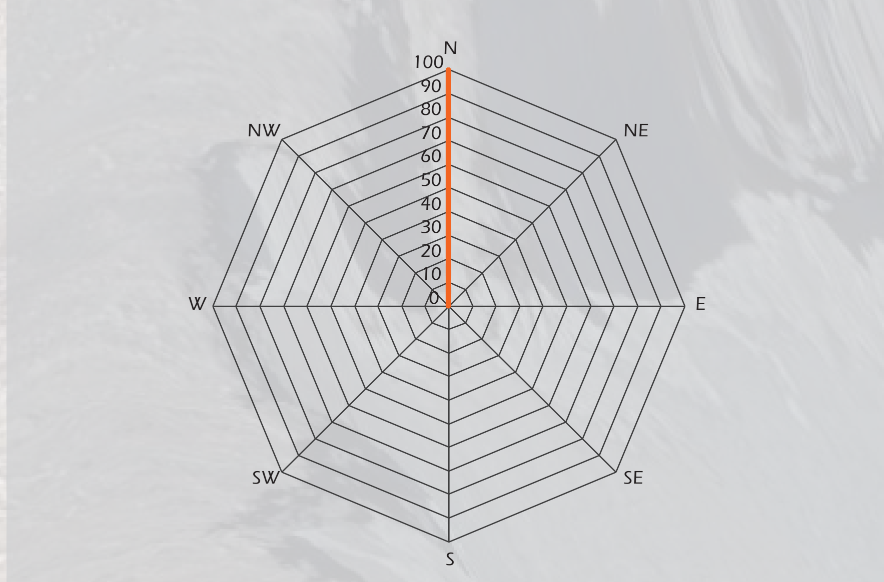
Glacier Number distribution



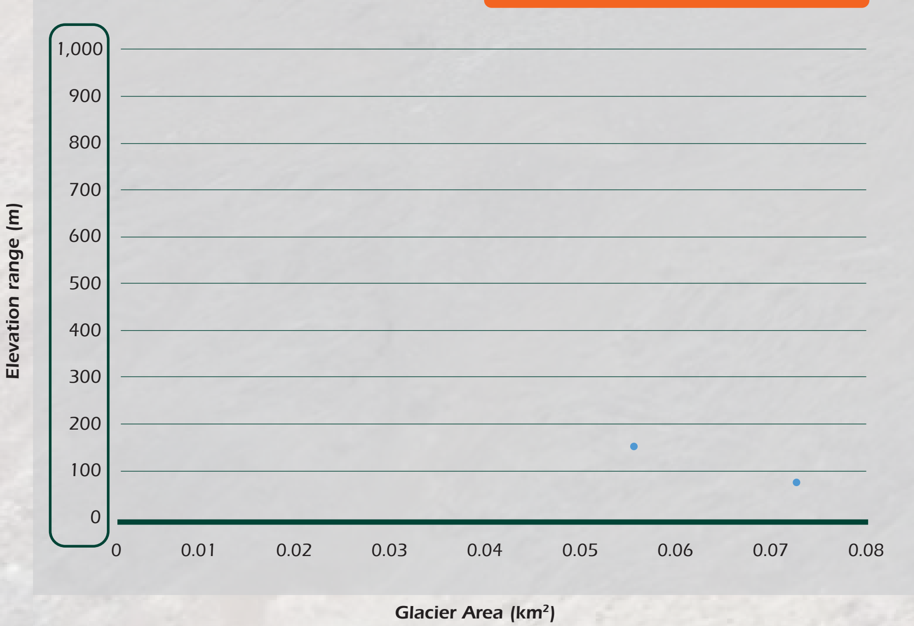
Glacier Min/Max Eleveation - Area



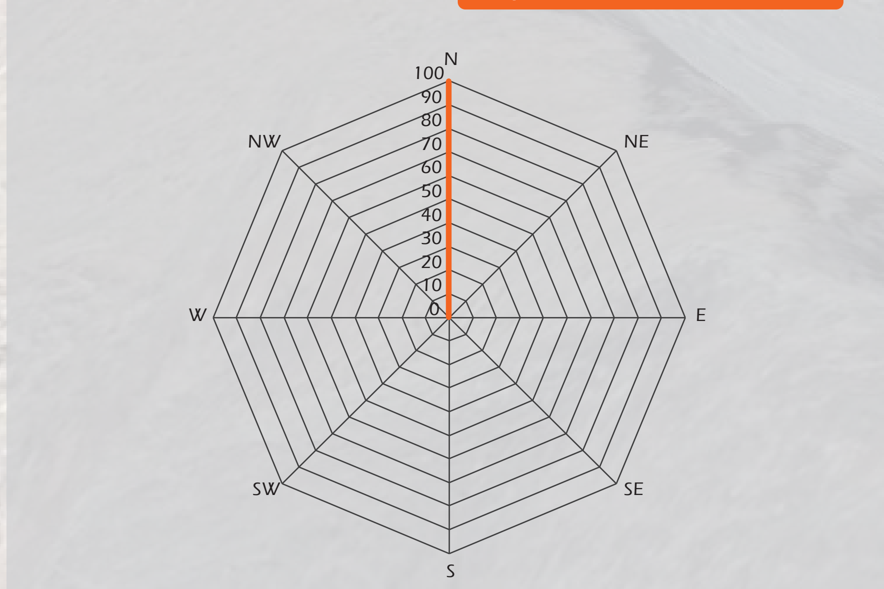
Aspect Distribution (% Glacier number)



Glacier Elevation range - Area

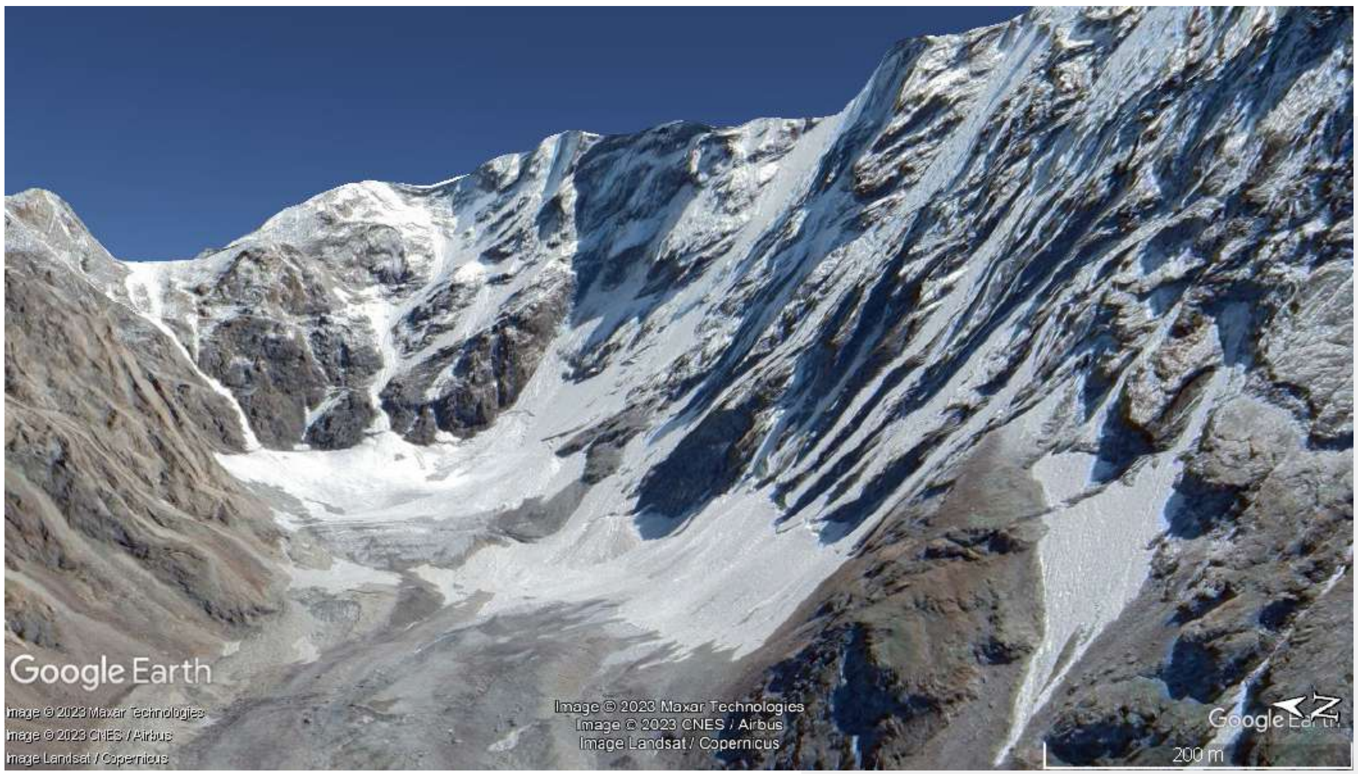


Aspect Distribution (% Glacier Area)

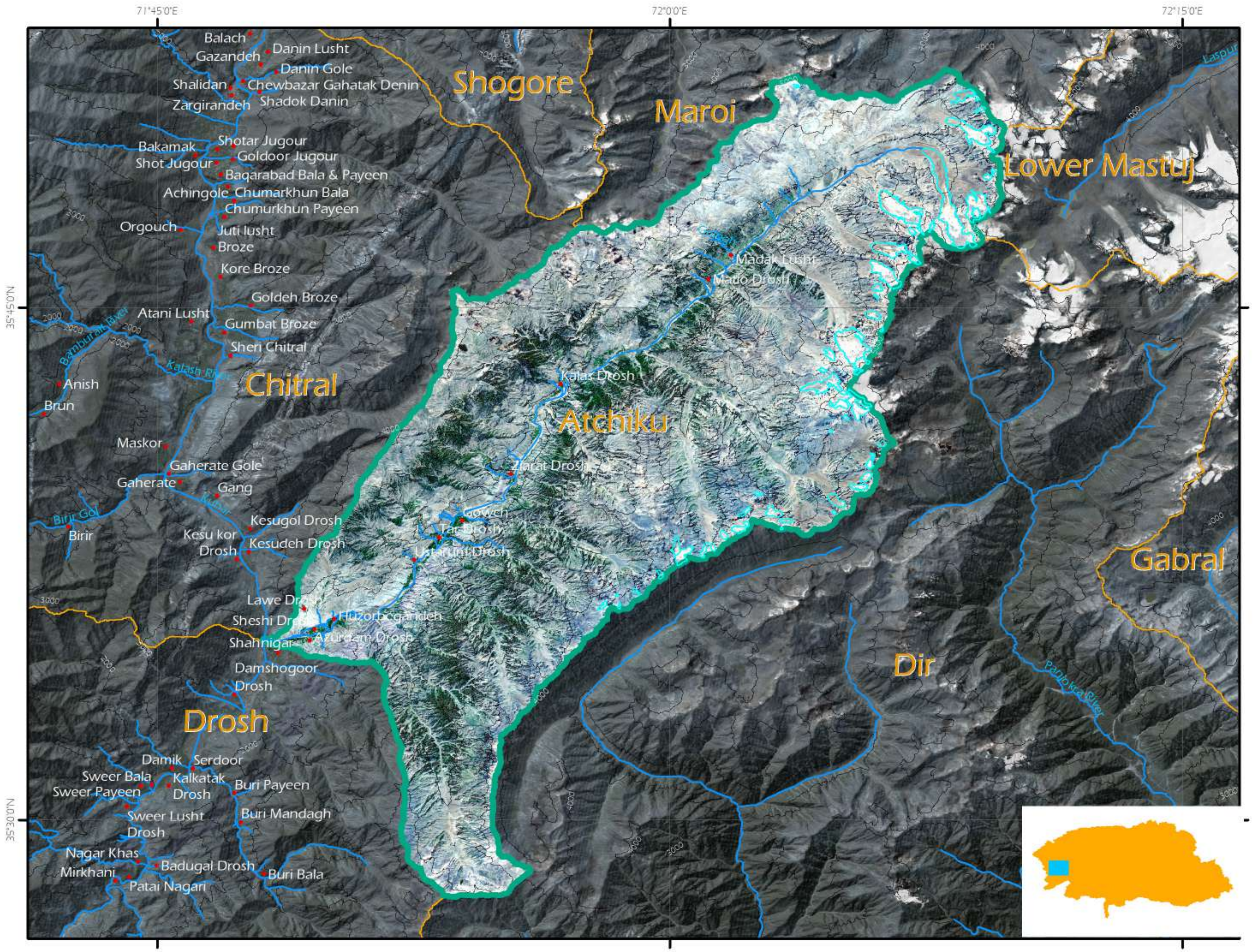


Atchiku

The basin takes its name from Shishi river, originating on the northern slopes of the basin and receiving the waters of many glacier-fed tributaries on the eastern side of the basin. The river flows past the towns of Atchiku and Tar before joining the Chitral river just north of the city of Drosh, in the Khyber Pakthunkhwa province.
The basin hosts 54 glaciers, the largest of which is 3.16 km2. Most glaciers in the basin (29) are smaller than 0.1 km2, and their area combined makes up 1.31 km2, or 7.81% of the total of the basin (16 .76 km2). The largest share of glacier area comes from the size class 1-2 km2, where three glaciers sum up to 4.43 km2 or 27.20% of the total. While the amount of glaciers in each size class decreases with size, the area increases up to the size class 1-2 km2.
In view of the relatively small size of the glaciers, their elevation is also rather high: the minimum is 3652 m a.s.l., and the maximum 5636 m a.s.l., with an average of 4564 m a.s.l. There is no clear relationship between glacier area and minimum/maximum elevation, as small glaciers tend to cover a wide range of elevations, although for minimum elevation, a general tendency for lower values with increasing area can be observed. The elevation range follows a clearer pattern of increase with area, although the highest elevation range (1580 m) is attributed to a relatively small glacier (0.97 km2).
Glacier aspect is dominated by the northern orientation, a 74% of glaciers face N, NE or NW, with the largest number facing NW (38.89%). In fact, all glaciers in this basin are located on the hydrographic left side, where these orientations prevail, as opposed to the hydrographic right, where orientations would be mostly SE. No glaciers in fact have this orientation, while 3 of them (5.55%) face S and a very small one (0.06 km2) faces SW. Considering the area of glaciers, a larger amount is found in the N orientation (40.10%) compared to NW (33.50%) and NE (4.17%).
The glacier hypsometry shows a rather asymmetric curve, with an equal share of glacier area between 4400-4500 and 4500-4600 m a.s.l. (14.91%). The curve tails to the right with a small peak around 5100-5200 m a.s.l. (2.43%) and a low share of glacier area above 5000 m a.s.l. (7.73%) compared to elevations below 4000 m a.s.l. (12.07%).



East sector of Atchiku. Google Earth. September 09, 2020. Accessed November 2023. Data SIO,NOAA, U.S. Navy, NGA, GEBCO ©



Atchiku Valley

0 2.5 5 10 km

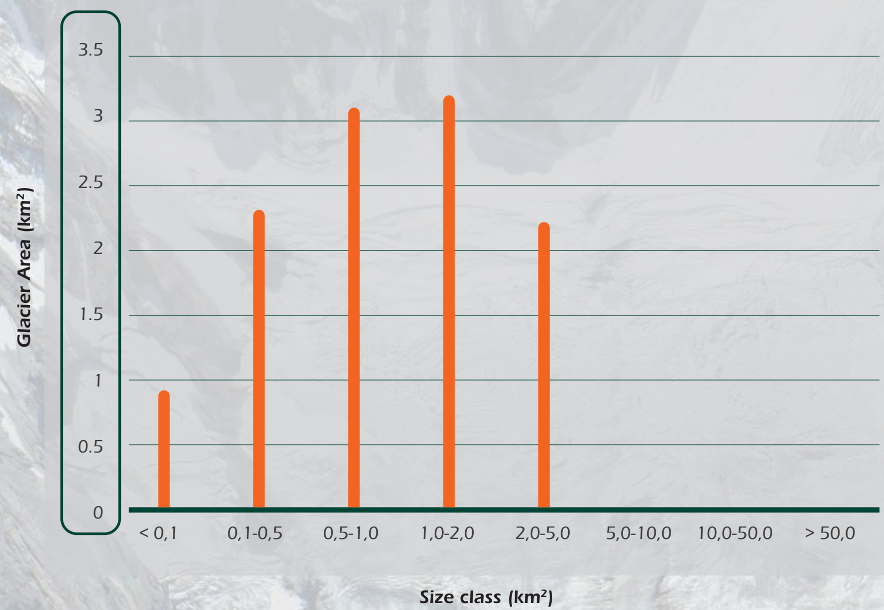
Atchiku

Summary table

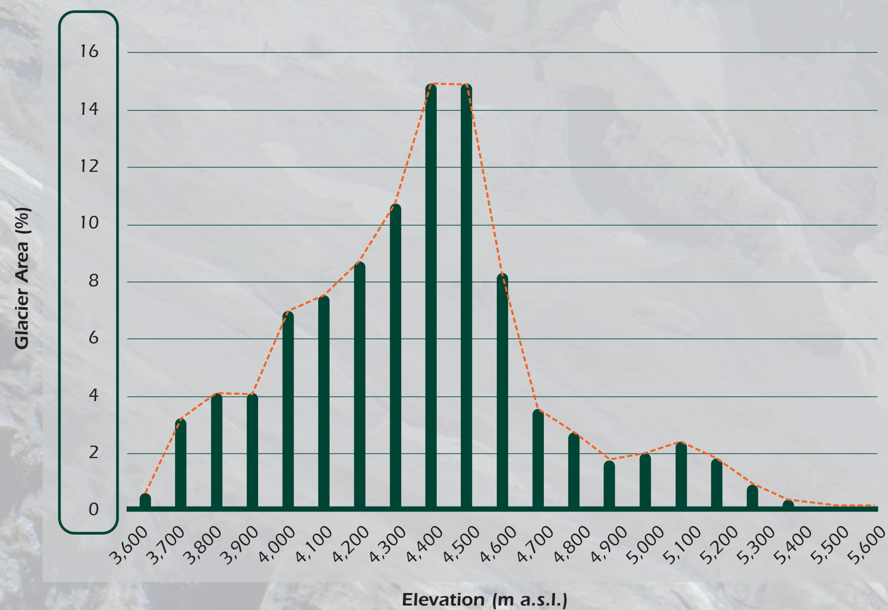
Number of glaciers	Glacier Area	Mean Elevation
54	16.76 km²	4564.24 m a.s.l.

North-East sector of Atchiku. Google Earth. December 03, 2016. Accessed November 2023. Data SIO,NOAA, U.S. Navy, NGA, GEBCO ©

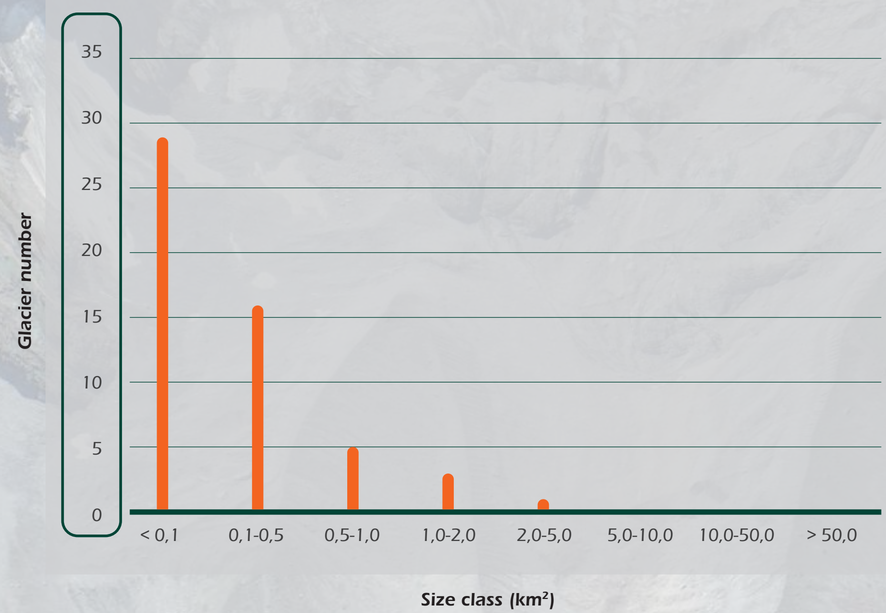
Glacie Area distribution



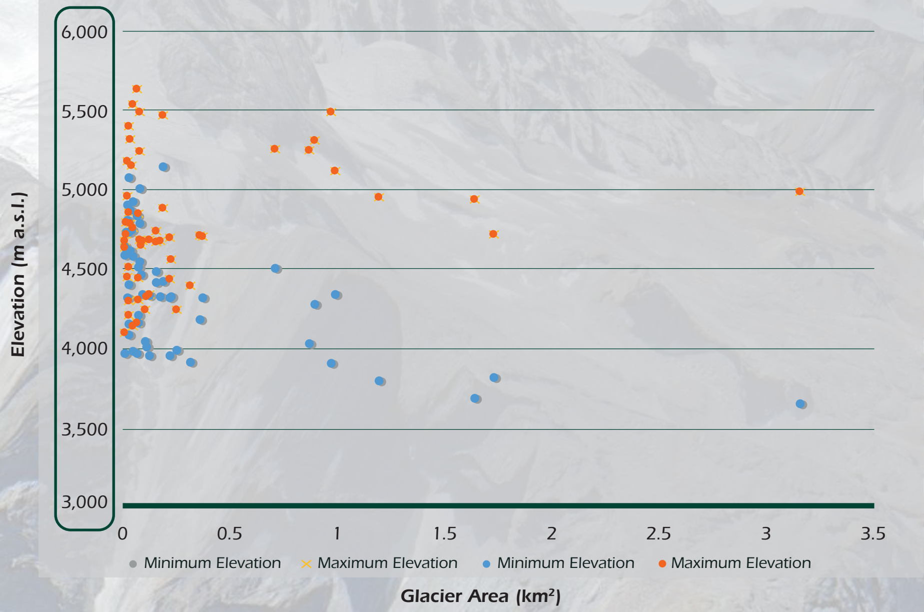
Glacier Hypsometry



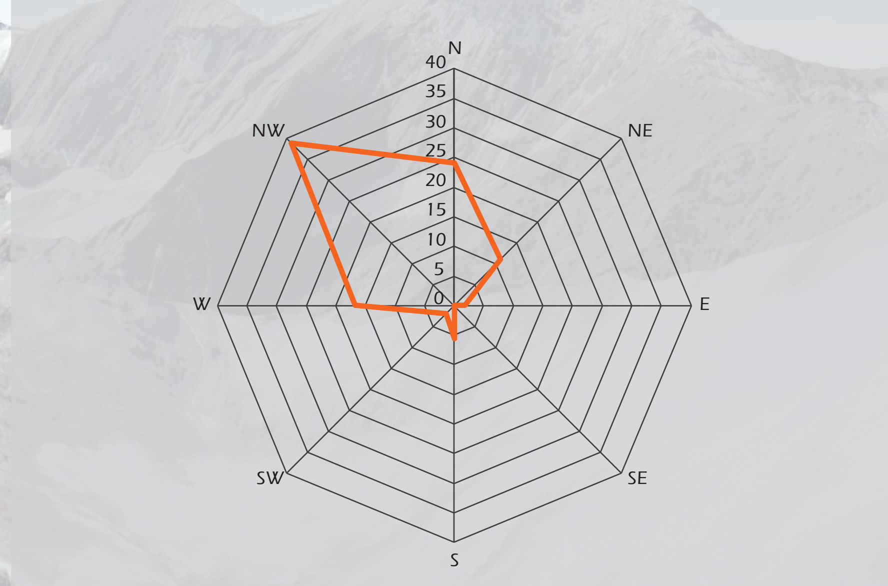
Glacier Number distribution



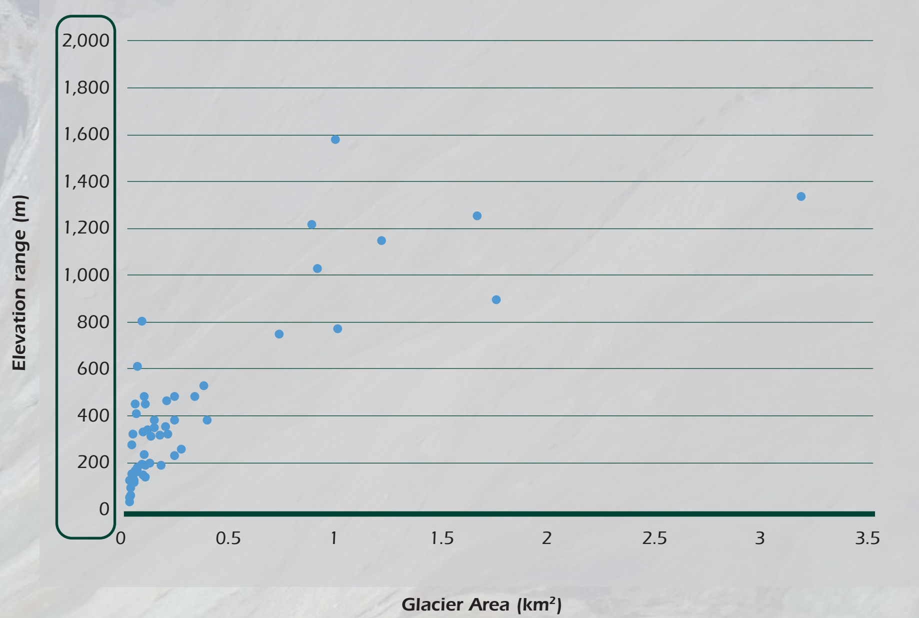
Glacier Min/Max Eleveation - Area



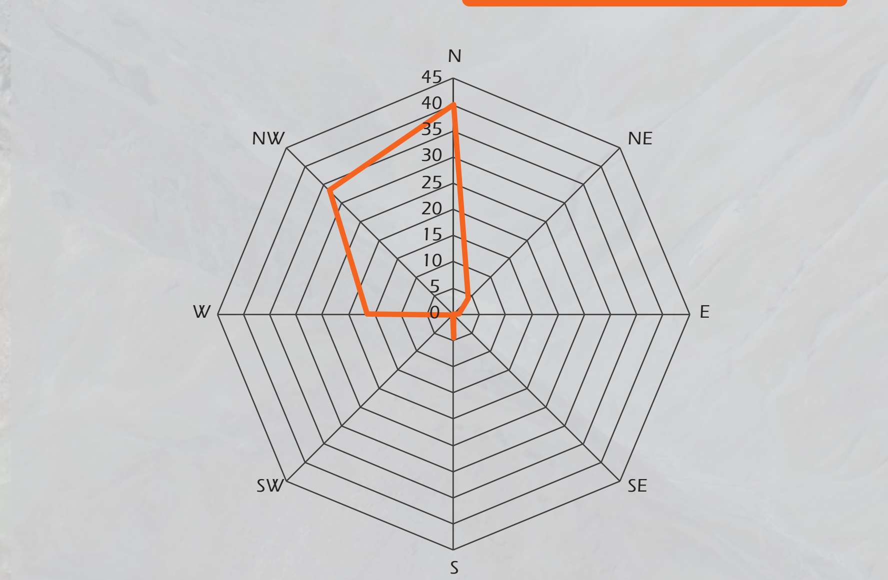
Aspect Distribution (% Glacier number)



Glacier Elevation range - Area



Aspect Distribution (% Glacier Area)



Hispar

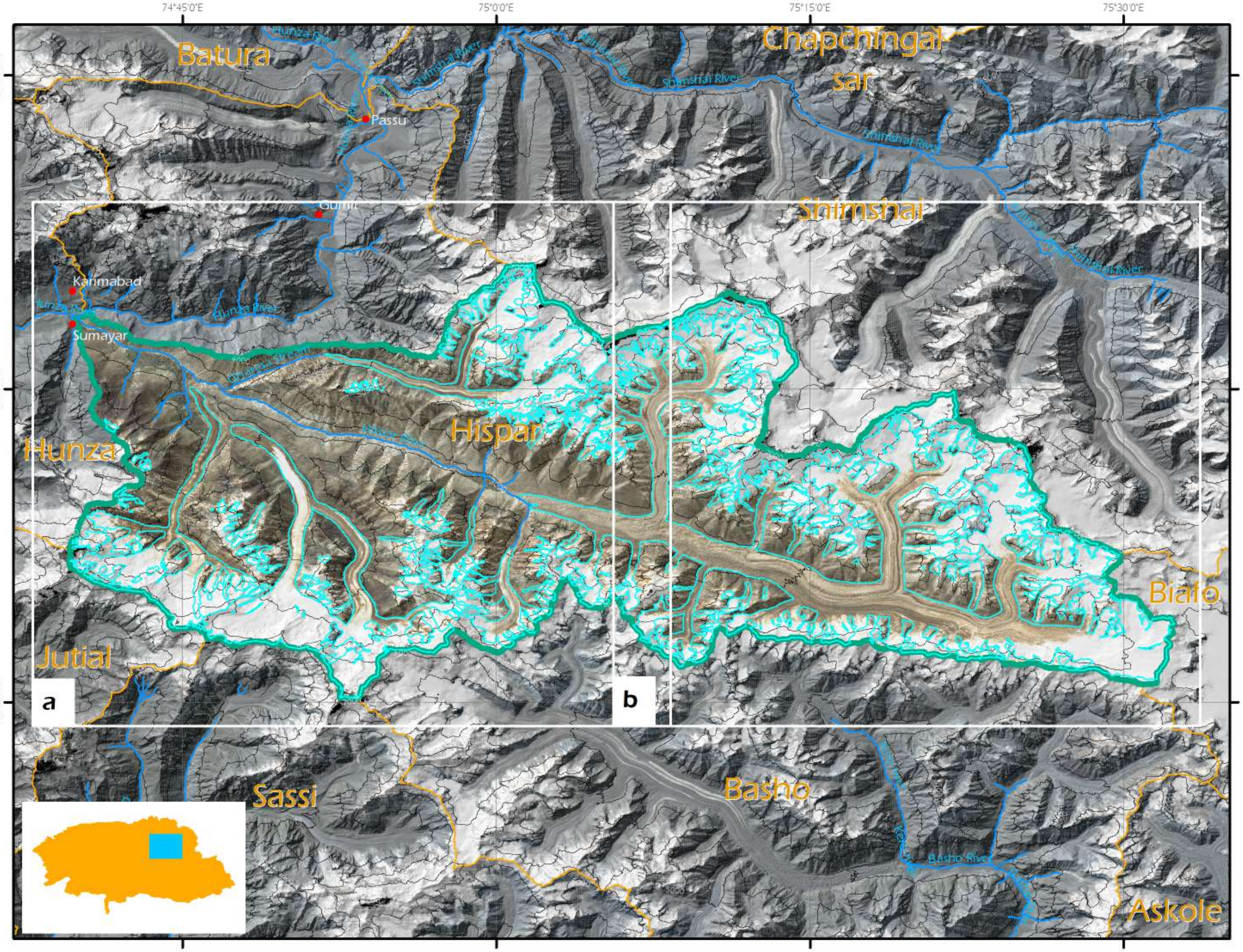
Hispar basin is a large basin (1783 km2) with a prevalent NW-SE orientation, taking its name from the Hispar glacier, the largest of the basin (664.01 km2) featuring a wide, elongated debris covered tongue and several tributaries. The river originating from the glacier passes the villages of Hopar, where it is also joined by water coming from Barpu and Bualtar (Hopar) glaciers, and Nagar Khas before flowing into the Hunza river. In its upper reaches, the basin is separated from that of Biafo basin to the east by Hispar Pass, at 5128 m a.s.l. The Hispar Muztagh range towers over the glaciers to the north, featuring several peaks above 7000 m a.s.l.; the highest peak is Disteghil Sar at almost 7900 m a.s.l. On the southern side of the basin, notable peaks above 7000 m a.s.l. include Diran and Malubiting, separating the basin from Haramoosh valley.

Hispar basin hosts 116 glaciers, with a mean area of 6.57 km2 and a total area of 761.64 km2. The glacier distribution by size class is very uneven, with a large cluster of small glaciers and only a few large ones. 55 glaciers have an area between 0.1 and 0.5 km2, while only four belong to the largest size class, i.e. Hispar, Barpu (98.27 km2), Bualtar (60.97 km2) and Gharesa glacier (72.23 km2). The sum of the area of these four glaciers dwarves the contribution from all the other 112 in the basin, making up 87% of the total. Like Hispar, Bualtar and Gharesa glaciers are heavily debris covered on their tongue, and all these glaciers show evidence of the formation of supraglacial ponds and collapses, pointing to the present downwasting. Hispar glacier has three major tributaries to the north (Kunyang, Yutmaru and Khani Basa), each of them hosting its small basin and with its own tributaries. As the surrounding rock walls have a high relief, these tributary glaciers supply most of the debris reaching the glacier tongue; tributaries on the southern side are in contrast numerous (about a 12) and smaller (Paul et al., 2017). The glacier also show signs of past surge events, marked by the presence of looped and distorted moraines in its tributaries (Paul et al., 2017; Wu et al., 2020). Barpu glacier consists of two major tributaries, and while the right hydrographic tributary is debris covered the left one is mostly clean except for the terminus and features a long series of ogives (alternating bands of white and dark ice formed by the movement of the ice through a serac). Both Bualtar and Barpu have also been affected by surge events in the past (Gardner and Hewitt, 1990; Hewitt, 2013).

Considering the glacier topography, there is a large spread of almost 5500 m between the minimum (2271 m a.s.l.) and maximum elevation (7735 m a.s.l.). Both minimum and maximum elevation as well as the elevation range show a clear relationship with the glacier area. The maximum elevation range is that of Bualtar glacier, with almost 4900 m between the highest point and the glacier terminus. The glacier hypsometry is dominated by elevations between 4000 and 6000 m a.s.l., making up 80% of the total, with the remaining share almost equally split between elevations below 4000 m a.s.l. and above 6000 m a.s.l. Median elevation by glacier ranges between 4439 m a.s.l. and 6866 m a.s.l.. The aspect distribution by glacier area shows the clear importance of Hispar glacier, whose tongue mainly faces west. In contrast, aspect distribution by glacier number reveals a more balanced picture, with an almost equal share of glaciers facing north, north-east and north-west (15.51%,15.51% and 13.79%, respectively), the largest number facing south-west (18.97%) and smaller contributions from the other sectors. This is caused by the main orientation of the valley and the presence of several small glaciers on either slopes perpendicular to the valley direction, sheltered by the high peaks.

The comparison between the new inventory and the GAMDAM inventory shows stability of the debris covered tongues. Hispar glacier itself shows very little change over more than 10 years, and in fact, the glacier terminus position is considered to have remained stable for the past 100 years (Paul et al., 2017). An exception to this behaviour is that of Gharesa glacier, whose tongue is at a lower elevation in the new inventory compared to the GAMDAM inventory, as a result of three recent surge events, the last of which occurred between 2015 and 2017 (Wu et al., 2020). For Barpu and Bualtar, apparent changes in the glacier outlines are more likely caused by varying interpretation of the debris covered tongue, also in view of the different data sources and their spatial resolution.

Gharesa Glacier, Google Earth. July 24, 2020. Accessed November 2023. Data SIO,NOAA, U.S. Navy, NGA, GEBCO ©



Hispar Valley

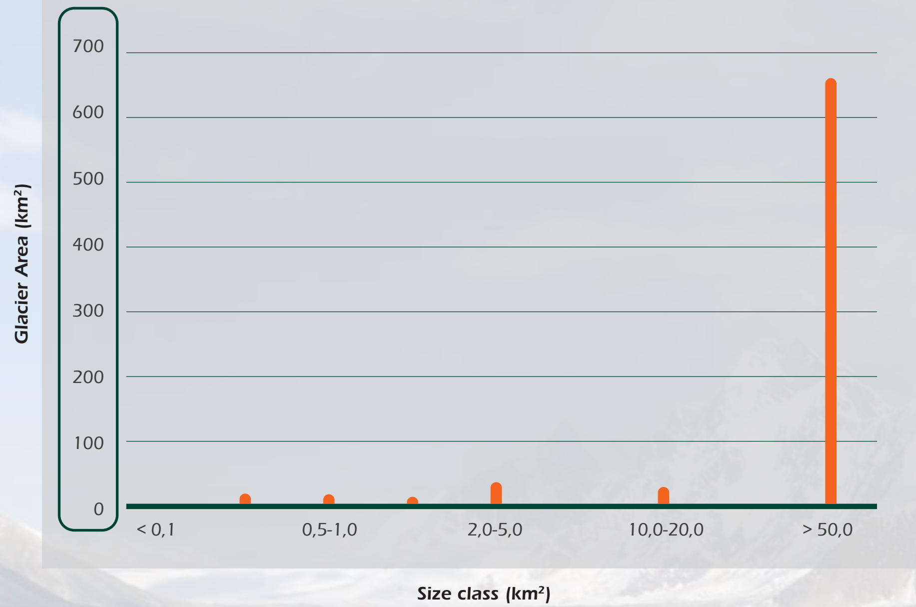
Hispar

Summary table

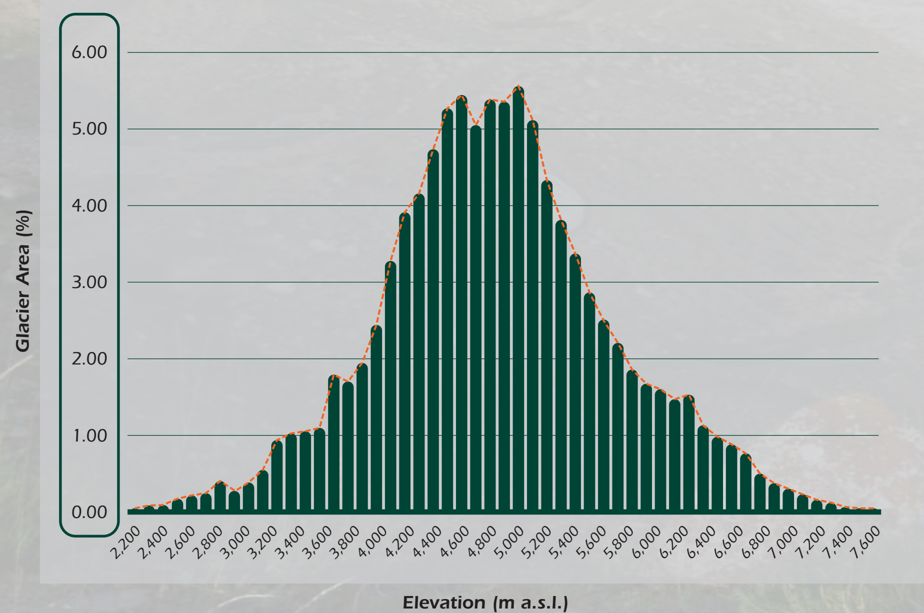
Number of glaciers	Glacier Area	Mean Elevation
116	761.64 km^2	5215.70 m a.s.l.

Hispar Glacier, Google Earth. July 24, 2020. Accessed November 2023. Data SIO,NOAA, U.S. Navy, NGA, GEBCO ©

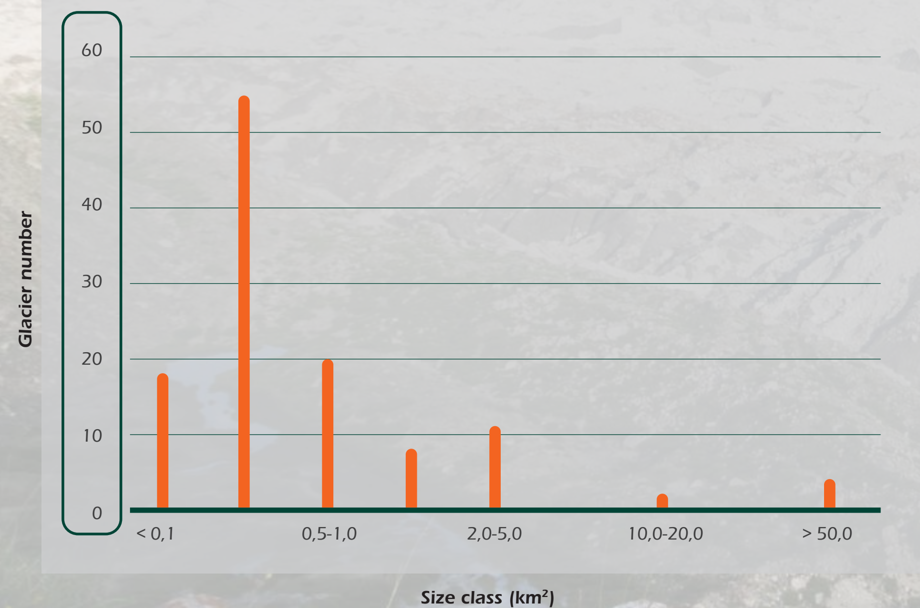
Glacie Area distribution



Glacier Hypsometry

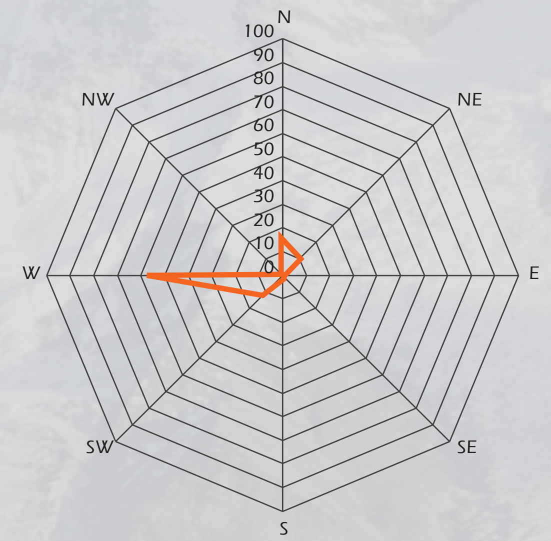


Glacier Number distribution

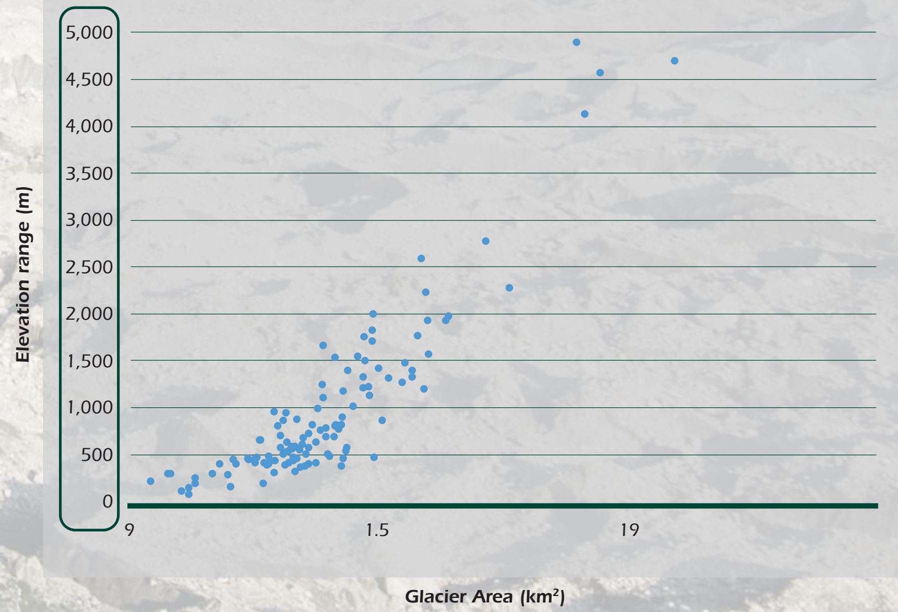


Glacier Min/Max Eleveation - Area

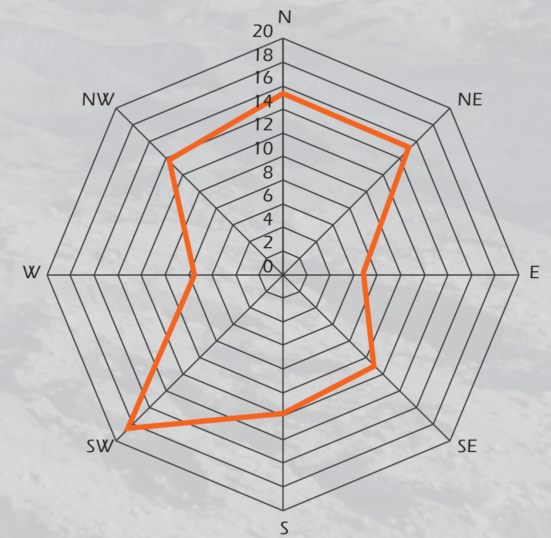
Aspect Distribution (% Glacier number)



Glacier Elevation range - Area

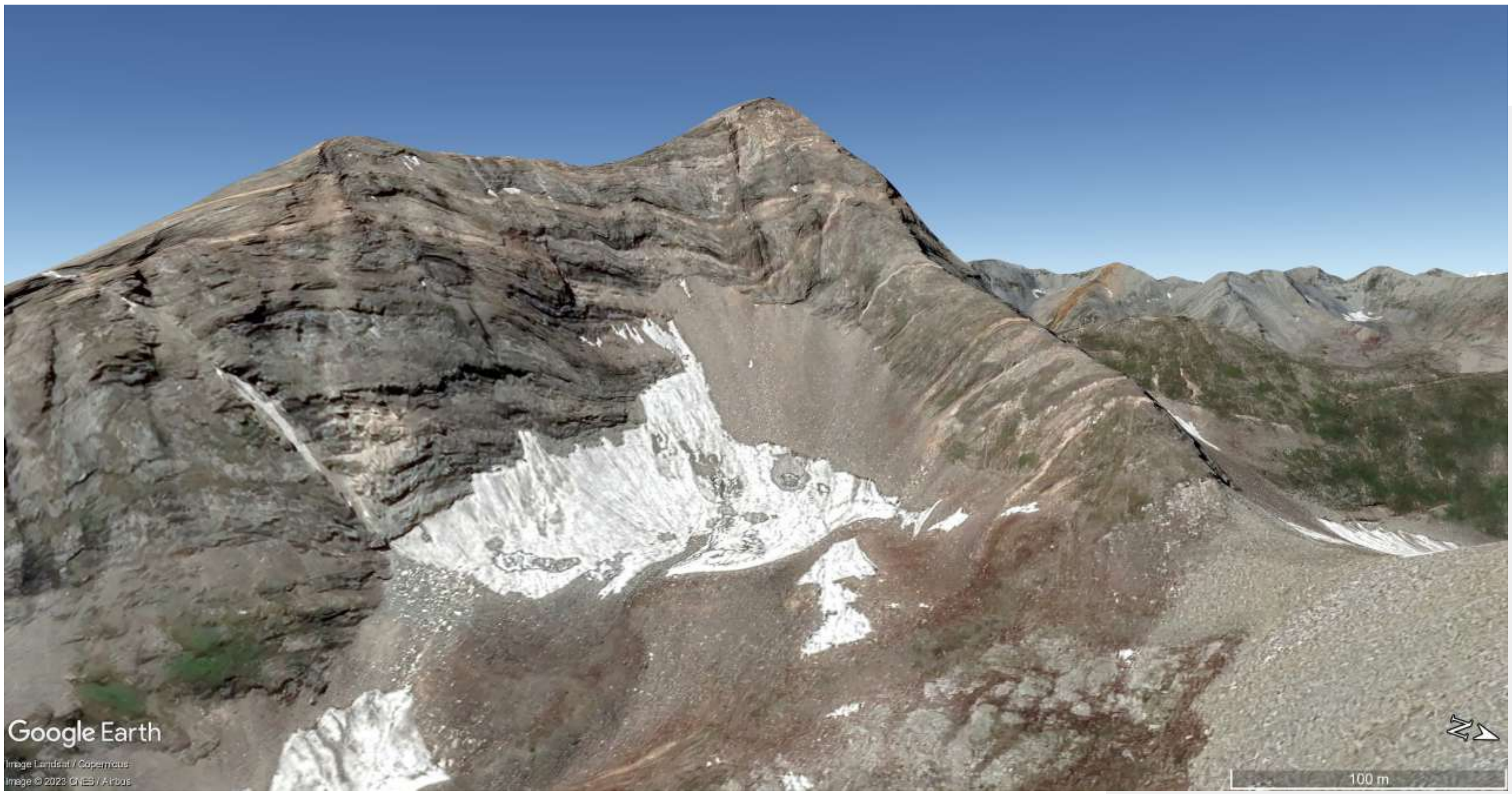


Aspect Distribution (% Glacier Area)

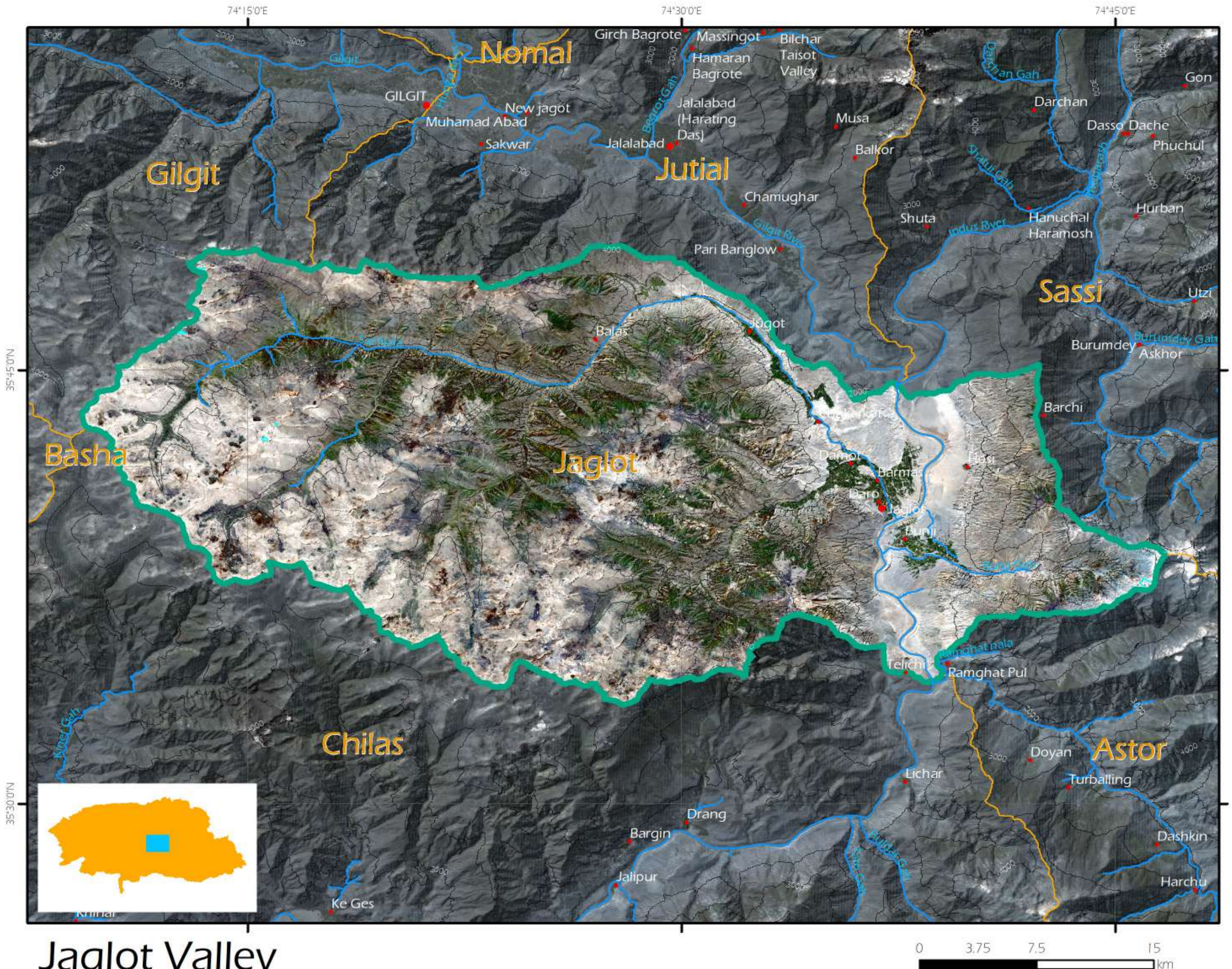


Jaglot

Jaglot basin is the second smallest basin by glacier number in Pakistan. Located at the junction between the three mountain ranges of the Hindukush, Karakorum and Himalaya, and south of the confluence of the Indus and Giglit Rivers. It is a sub-basin of the Indus River, and takes its name from the district and town of Jaglot.
This basin contains 6 small glaciers, the largest of which is only 0.28 km2. All other glaciers are smaller than 0.10 km2, and the total area of all 6 glaciers combined is 0.48 km2. These glaciers are located at the western and eastern borders of the basin, four in the Hindukush and two in the Himalayas. They range in elevation between 4399 and 5327 m a.s.l., and given their small number it is difficult to ascertain a relationship between area and minimum and maximum elevation. The glacier area however is linearly related to the elevation range, which lies between 30 m and more than 500 m.
As concerns the glacier aspect, these glaciers show a clear predominance of a NW orientation, both in relation to the number of glaciers (33%) and their size (66%). The hypsometric curve shows a highly skewed distribution, with a high frequency of glacier area around 4500-4600 m a.s.l. (31.01%), and very little glacier area above 5000 m a.s.l (1.69%).



North-western sector of Jaglot. Google Earth. June 08, 2018. Accessed November 2023. Data SIO,NOAA, U.S. Navy, NGA, GEBCO ©



Jaglot Valley

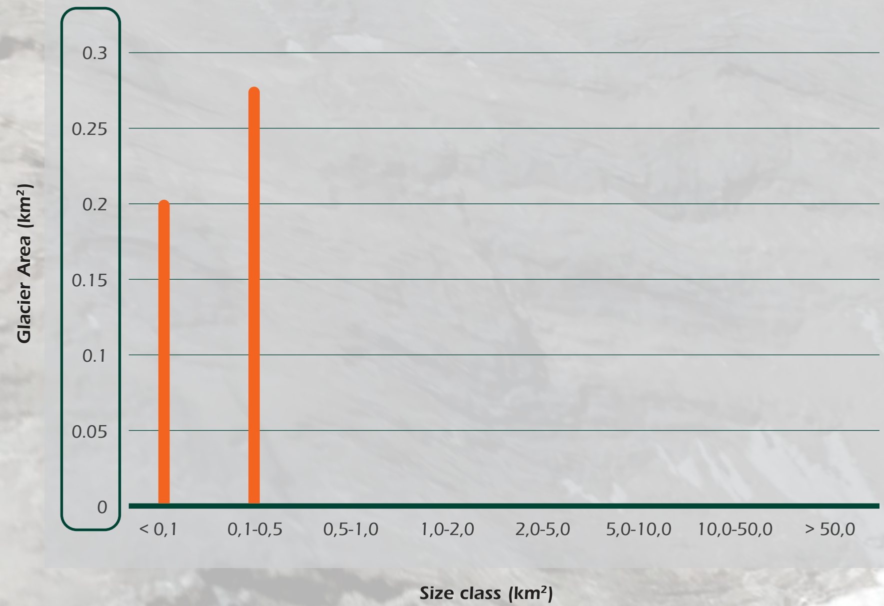
Jaglot

Number of glaciers	Glacier Area	Mean Elevation
6	0.48 km²	4680.54 m a.s.l.

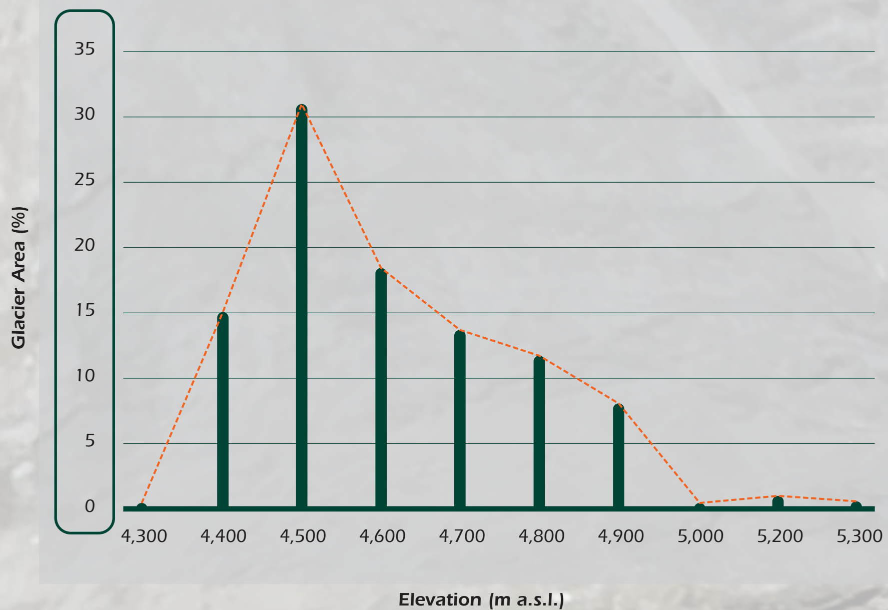
Summary table


South-eastern sector of Jaglot. Google Earth. August 10, 2013. Accessed November 2023. Data SIO,NOAA, U.S. Navy, NGA, GEBCO ©

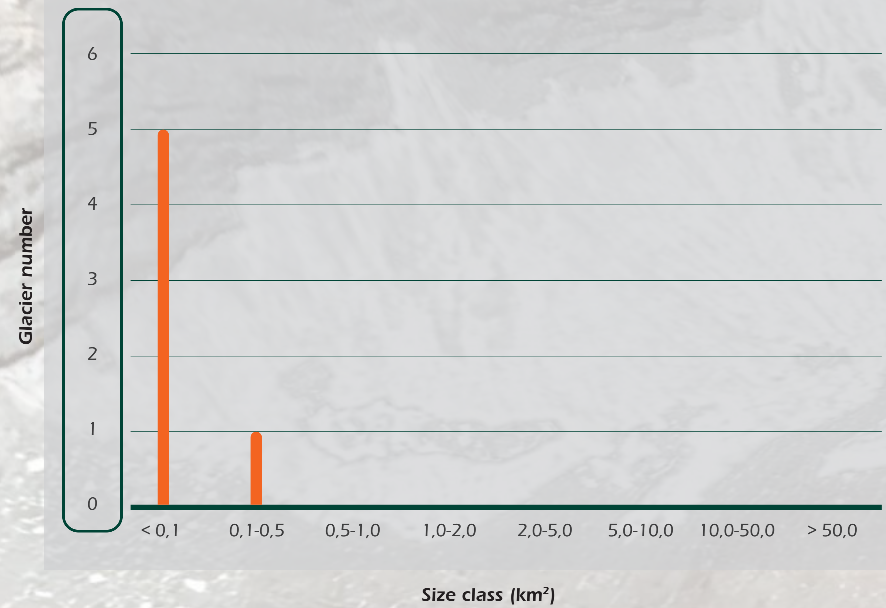
Glacie Area distribution



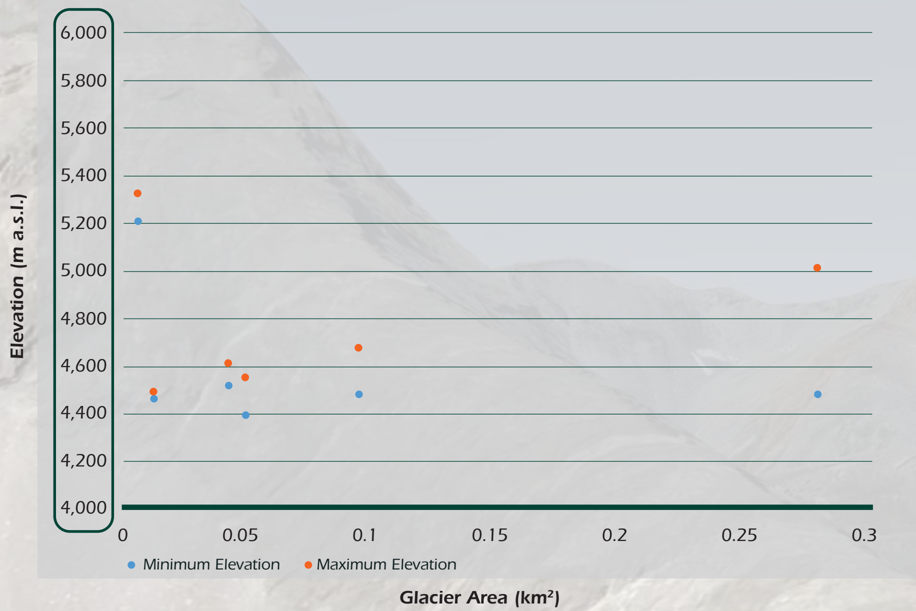
Glacier Hypsometry



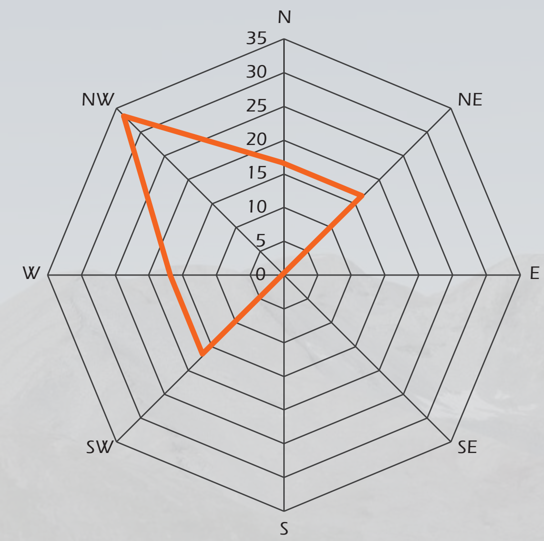
Glacier Number distribution



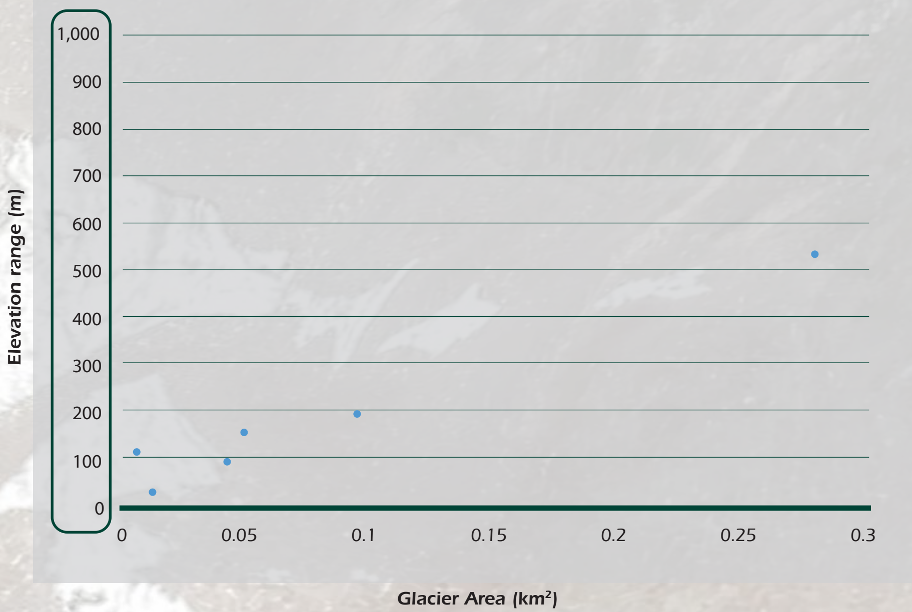
Glacier Min/Max Eleveation - Area



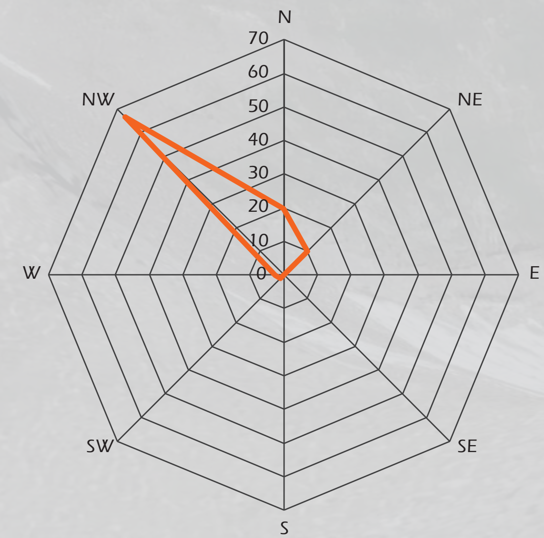
Aspect Distribution (% Glacier number)



Glacier Elevation range - Area

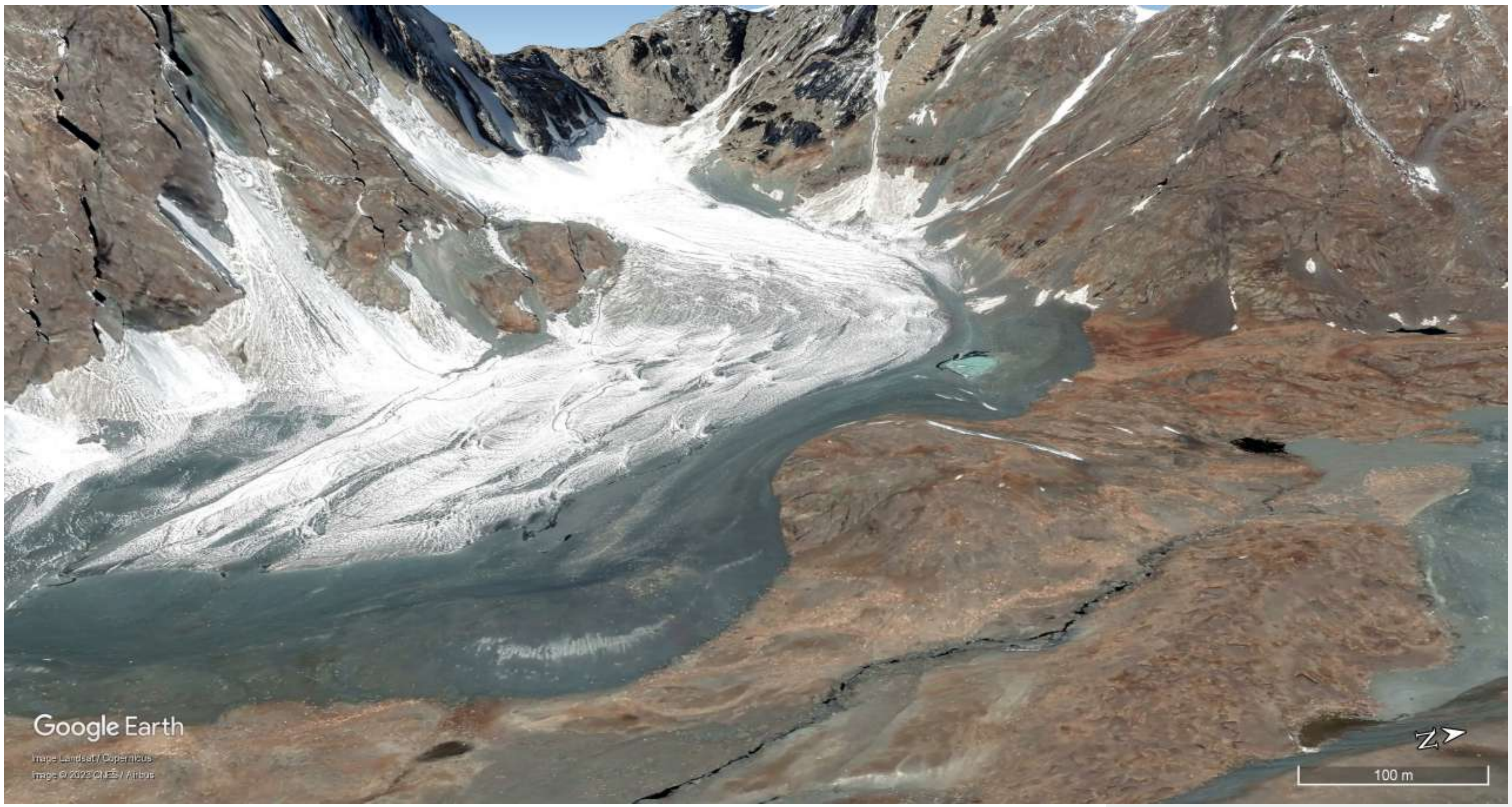


Aspect Distribution (% Glacier Area)

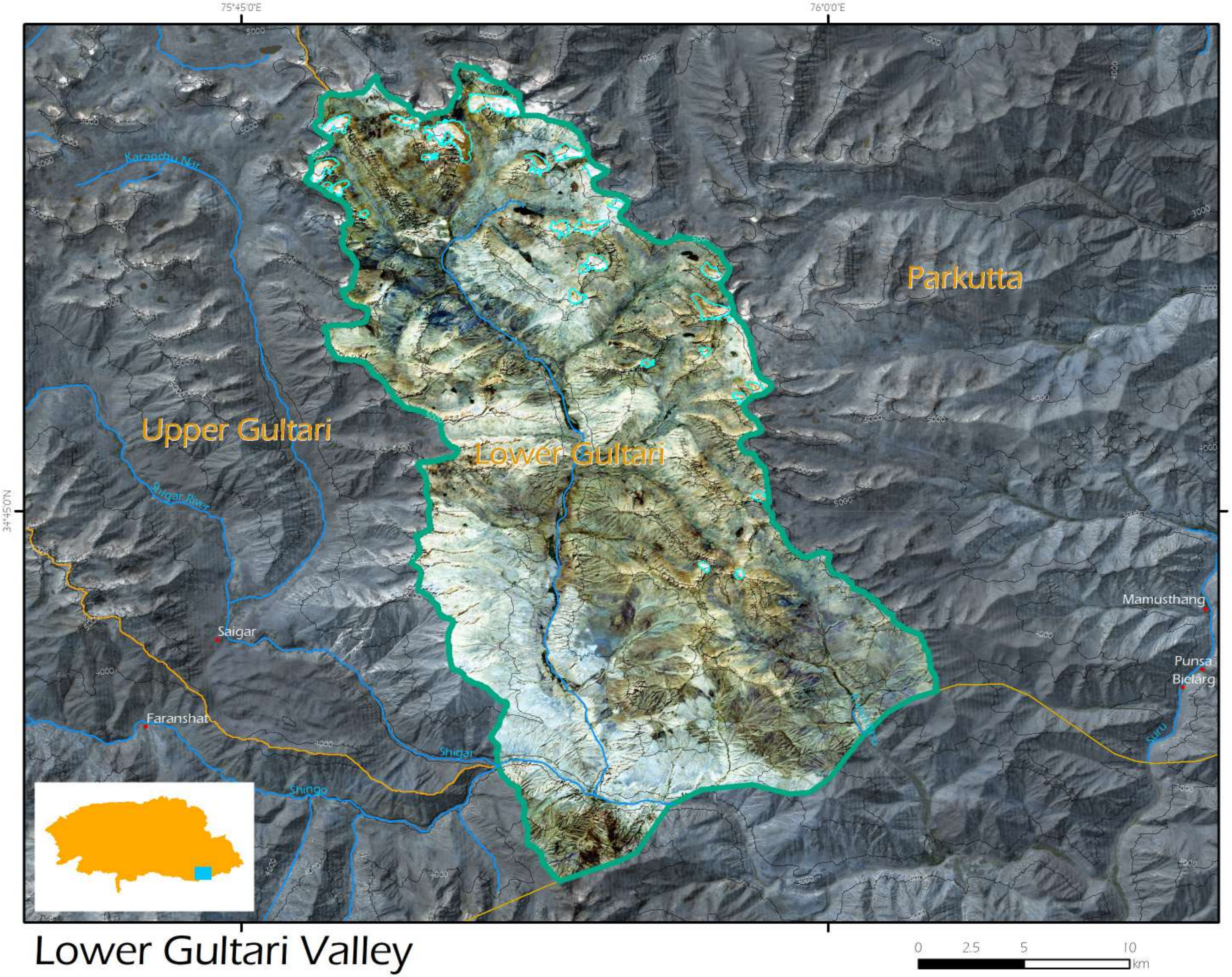


Lower Gultari

The Lower Gultari basin includes a small portion of Gultari Valley in the Baltistan region of Pakistan, specifically the course of the Shingo River before the Pakistani border; here, the Shingo River also receives water from the Phultukus River, more than 30 km long, to its North. There are no major towns in the basin.
The basin hosts 35 glaciers, two of which are larger than 1 km2. The largest glacier is 1.67 km2, while most glaciers (17) have an area between 0.1 and 0.5 km2 and 11 are smaller than 0.1 km2. The size class 0.1-0.5 km2 also contributes the largest share to the total glacier area, i.e. 4.41 km2 or 40% of 11.16 km2.
Glaciers of this basin range in elevations between 4627 m a.s.l. and 5646 m a.s.l., and the maximum elevation range of a glacier is 868 m, while the minimum is below 50 m. A logarithmic relationship is evident between minimum elevation and glacier area, as the smaller glaciers tend to have higher minimum elevations, where lower temperatures are found and therefore more favourable conditions for glacier survival. A similar relationship is also observed between glacier area and elevation range, as larger glaciers tend to have greater elevation ranges increasing asymptotically.
Another condition favouring the glacier survival in this basin is the orientation: most glaciers face northwest (43%), and in general 66% of glaciers face north, north-west or north-east, compared to only 11% of glaciers facing south or south-west. No glacier faces south-east. A similar pictures is observed when considering the orientation in relation to the glacier area, with an even larger share of glaciers in the north-west facing aspect (49% of glacier area).
The glacier distribution by elevation class is highly skewed, with a majority of glacier area between 4900 and 5000 m a.s.l. (30%), but also a relevant share between 5000 and 5300 m a.s.l. (32%), and between 4600 and 4900 m a.s.l. (33%), and a residual small amount above 5300 m a.s.l. (5%).



North-western sector of Lower Gultari. Google Earth. September 09, 2017. Accessed November 2023. Data SIO,NOAA, U.S. Navy, NGA, GEBCO ©



Lower Gultari Valley

Lower Gultari

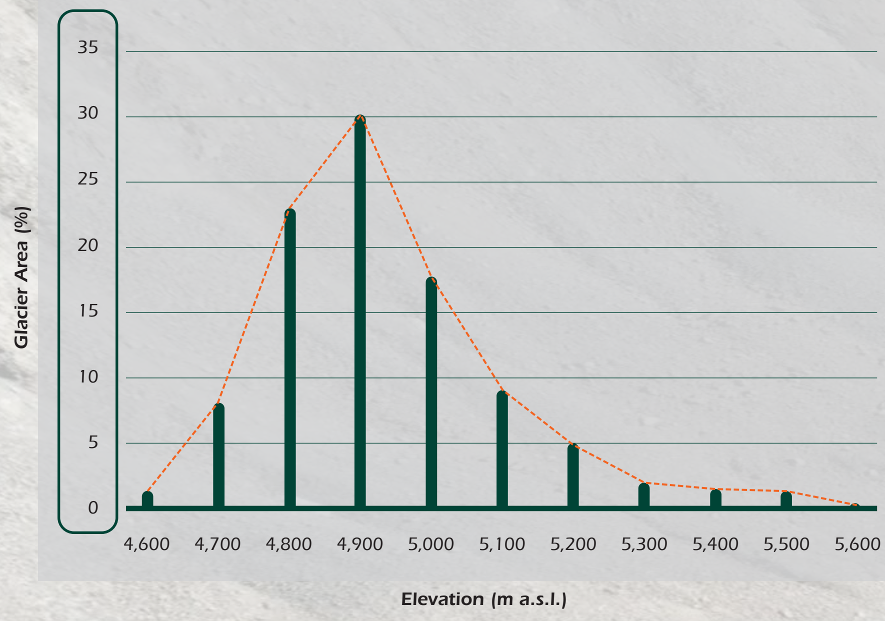
Summary table

Number of glaciers	Glacier Area	Mean Elevation
35	11.16 km²	5066.90 m a.s.l.

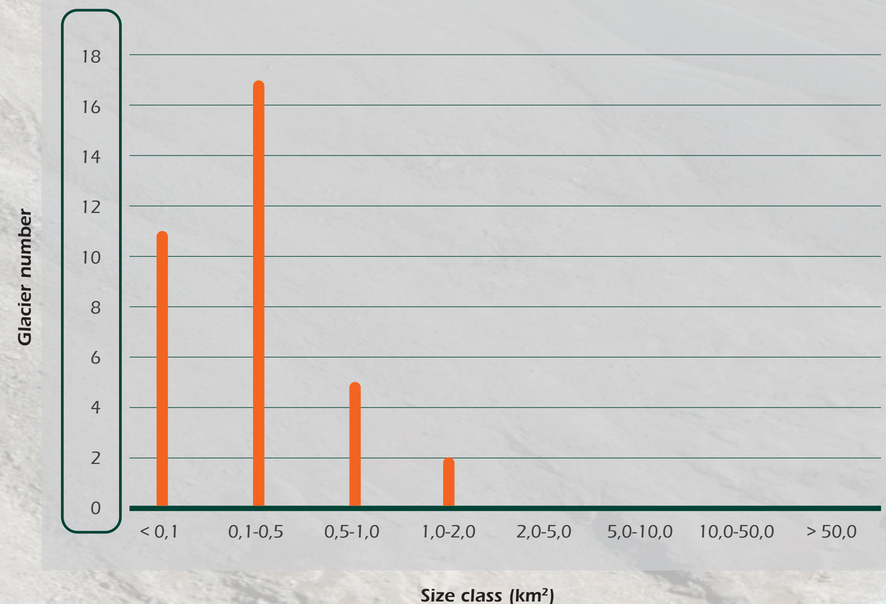
Northern sector of Lower Gultari. Google Earth. September 10, 2020. Accessed November 2023. Data SIO,NOAA, U.S. Navy, NGA, GEBCO ©

Glacie Area distribution

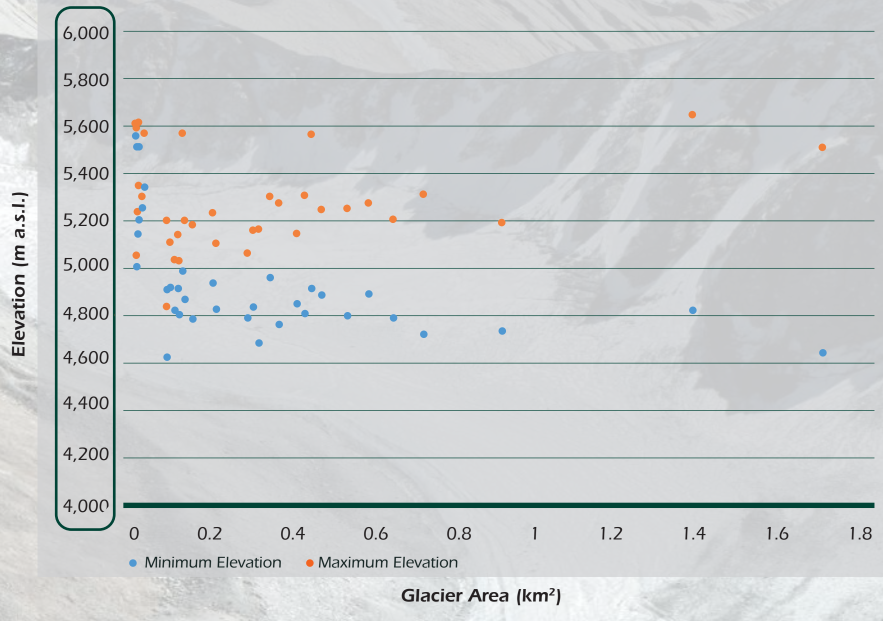
Glacier Hypsometry



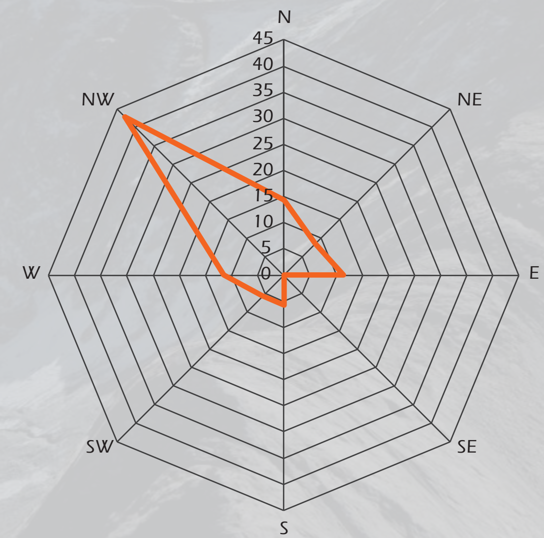
Glacier Number distribution



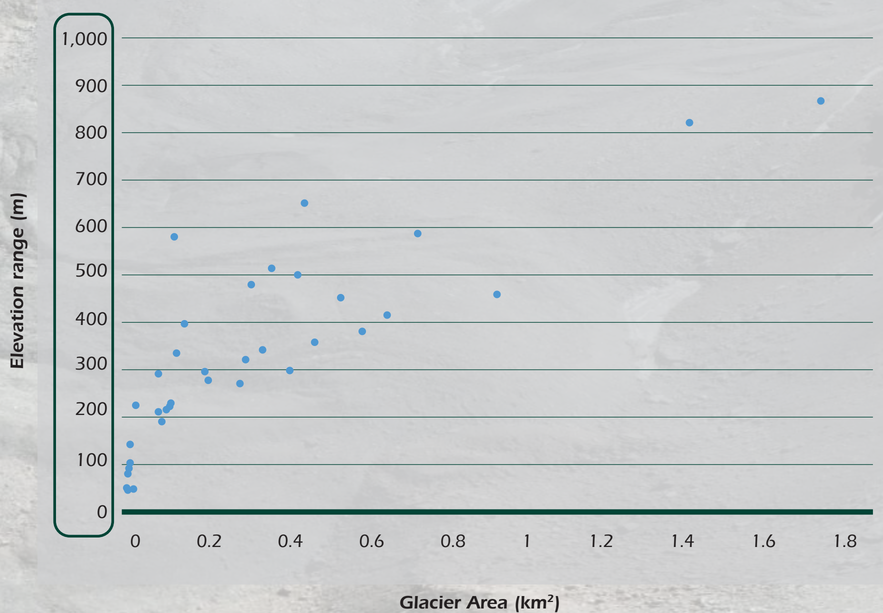
Glacier Min/Max Eleveation - Area



Aspect Distribution (% Glacier number)



Glacier Elevation range - Area



Aspect Distribution (% Glacier Area)

Skardu

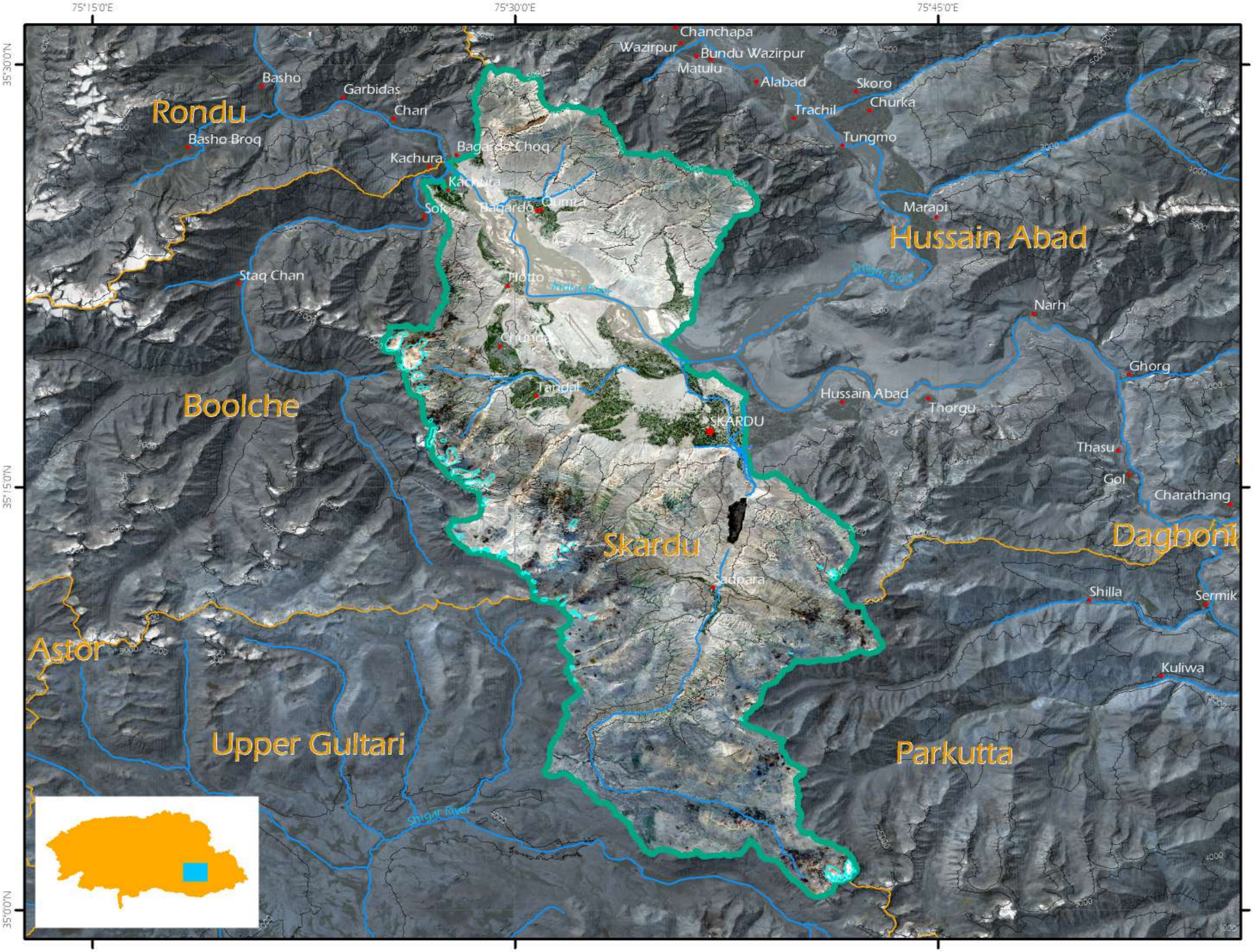
Skardu basin (721 km2) is named after the city and district of Skardu, a populated city (26000 inhabitants) and capital of the Baltistan division of Pakistan. The basin hosts 46 glaciers, most of which lie close to Skardu city, on the western slopes of the basin. Meltwater from these glaciers feeds the Indus River, but in spite of their closeness to the city, little is known about them, probably owing to their small size in comparison with other much larger glaciers in Baltistan. The glacier distribution by size class shows a high prevalence of very small glaciers (34 < 0.1 km2), compared to the other size classes. Only one glacier is larger than 1 km2. However, 4 glaciers between 0.5 and 1 km2 make up the largest share of the area (2.44 km2 or 35%).

Considering the glacier elevation, there is a general tendency for higher maximum and minimum elevation with increased area, but owing to the large percentage of small glaciers, there is also a large spread: small glaciers (< 0.1 km2) are found across a wide range of elevations, with a maximum elevation ranging from 4600 to 5200 m a.s.l. A clearer relationship is seen between glacier area and elevation range, with a logarithmic pattern. The glacier with the largest area (1.64 km2) however has the second largest elevation range of the basin (753 m); the glacier with the largest elevation range (775 m) instead has an area of only 0.32 km2.

For glaciers in this basin, aspect also plays an important role: no glacier has a south or south-westerly aspect, while only one has a south-easterly aspect. In contrast, 86.96% of glaciers have a north, north-easterly or north-westerly aspect, with the first two being the most common, while for most other basins the prevalent aspect is north-west. This is caused by the prevalent aspect of the tributary valleys in this basin, which are mainly oriented south-west to north-east.

The glacier hypsometric curve shows a peak at 4700-4800 m a.s.l. (26% of glacier area); compared to other basins, the curve is rather symmetric, tailing above 5000 m a.s.l., as these elevations contribute little (5.97%) to the total glacier area.

Gang Senge Peak. Google Earth. August 11, 2017. Accessed November 2023. Data SIO,NOAA, U.S. Navy, NGA, GEBCO ©



Skardu Valley

Skardu

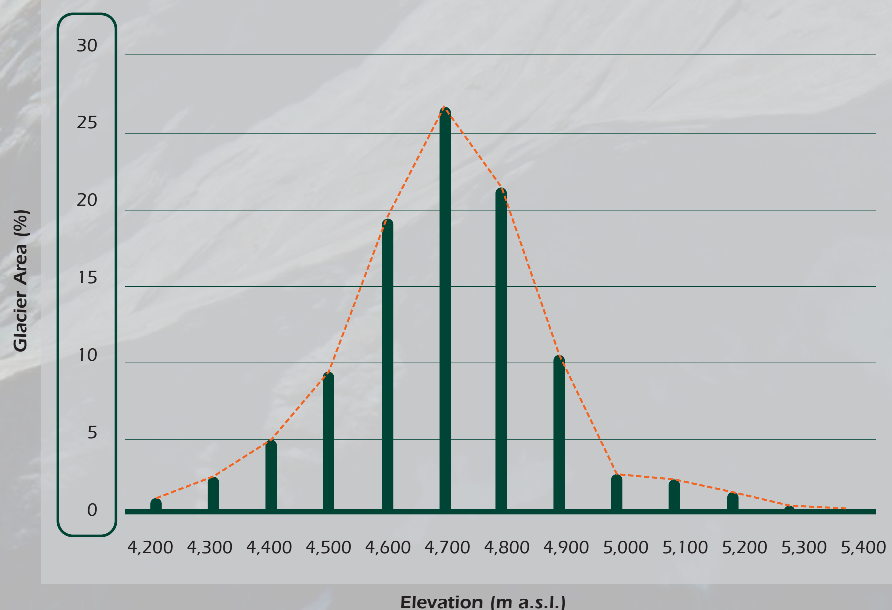
North-western sector of Skardu. Google Earth. August 11, 2018. Accessed November 2023. Data SIO,NOAA, U.S. Navy, NGA, GEBCO ©

Summary table

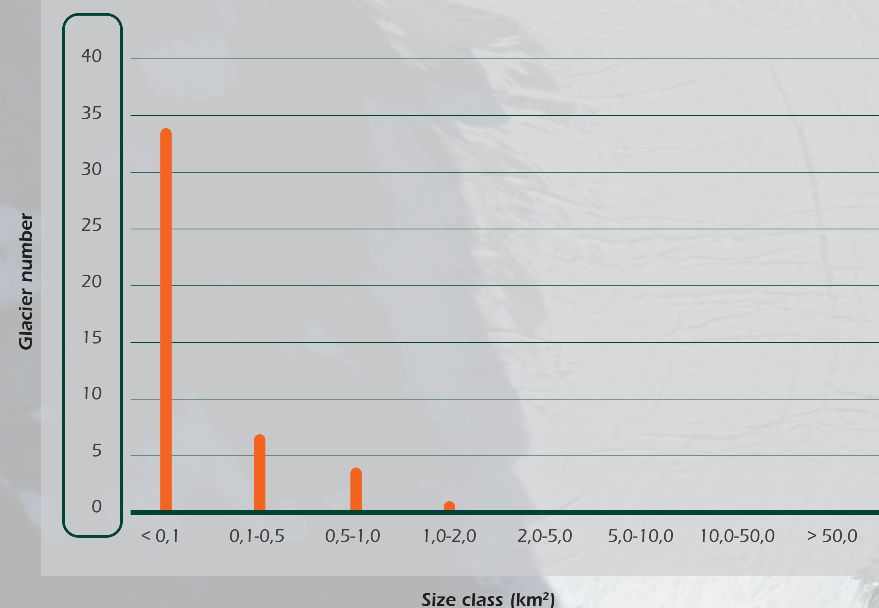
Number of glaciers	Glacier Area	Mean Elevation
46	6.97 km²	4758.99 m a.s.l.

Glacie Area distribution

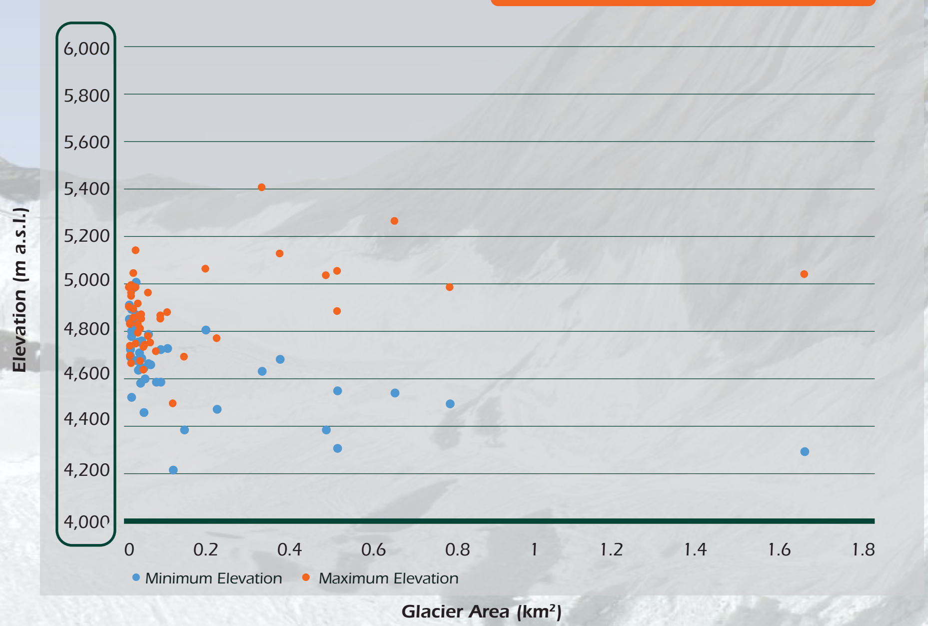
Glacier Hypsometry



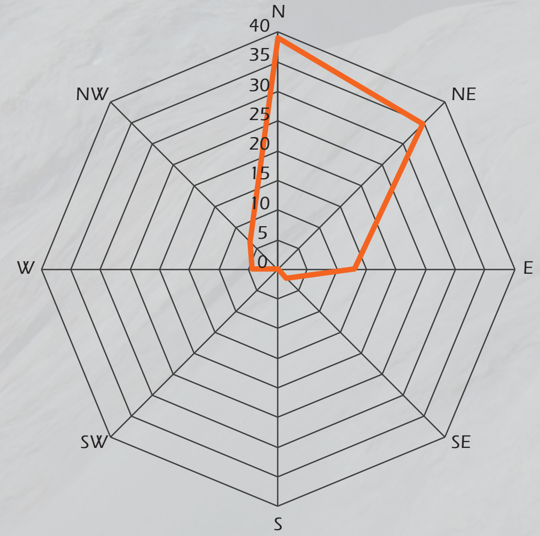
Glacier Number distribution



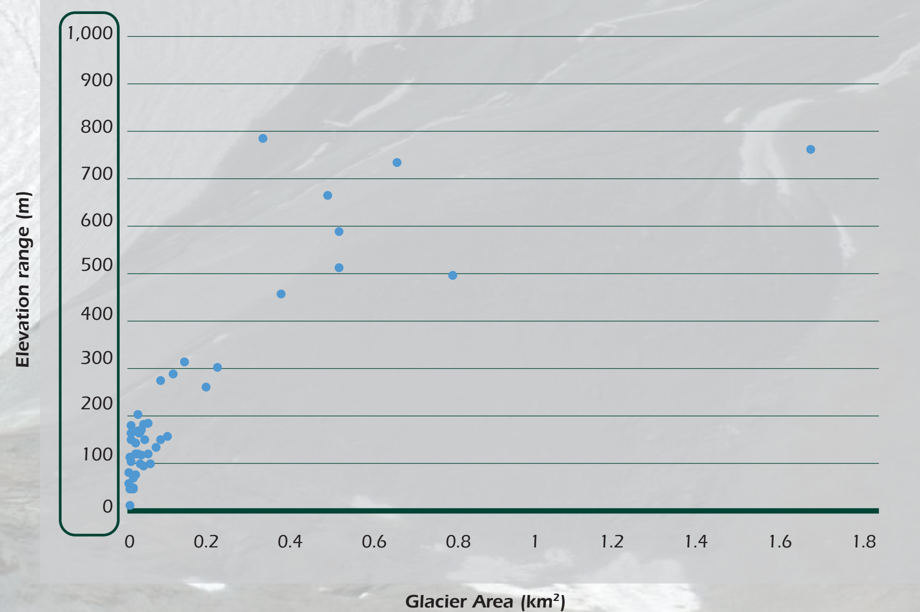
Glacier Min/Max Eleveation - Area



Aspect Distribution (% Glacier number)



Glacier Elevation range - Area



Aspect Distribution (% Glacier Area)