Selected pilot sites Central Asia

by Martin Barandun[1], Tomas Saks[1], Enrico Mattea[1], Joel Fiddes[2], Serikzhan Atanov[1], Martin Hoelzle[1]

[1] Department of Geosciences, University of Fribourg, Fribourg, Switzerland

[2] Mountain Futures GmbH, Switzerland

The World Meteorological Organization (WMO) has highlighted that there are currently major gaps in the global climate observation system, particularly in high mountain environments. Developing and emerging countries lack observations on climate variables. In the mountains of the Central Asian Tien Shan and Pamir where the cryosphere is one of the main water resources for the region, data is very scarce. This data however is essential for planning for future mitigation and development strategies regarding climate change impacts. There is a need for long-term improvements in the understanding of cryosphere dynamics in the Central Asian mountains, particularly of processes related to snow, glaciers and permafrost. These processes eventually govern the water availability in downstream countries, where water quality and quantity problems become more acute, and potential negative impacts of accelerated cryosphere degradation become reality.

Central Asia has a rich history of cryospheric observation. The systematic cryosphere monitoring network was discontinued between the early 1990s and 2000s for various reasons. Around 2010, initial efforts were made to re-establish the glacier monitoring network in Central Asia. These efforts have continued in collaboration between Central Asian and international scientists to (i) collect high quality data, and (ii) exchange knowledge and train capacities of young scientists and students (Hoelzle et al., 2017). Cryosphere monitoring in the Tien Shan and Pamir has progressed considerably since these early efforts.
As of today, glacier observations in the region provide a relatively dense network and data is shared with the scientific community through open-access data centers. Over the past five years, the long-term and continuous monitoring efforts have been expanded to include snow and permafrost observations, as well as an improved network of automated weather stations. Like the glaciological measurements, this complementary and extensive dataset is made available to the international scientific community. With this development and following the ideas of the monitoring strategy of a dense network of observations at selected sites (e.g. Abramov glacier) during Soviet times, it is now possible to create so-called "super-sites". A cryospheric monitoring supersite integrates observations of multiple cryosphere components across temporal scales within a strategically selected location, providing representative essential climate variables for a broader geographical region, such as a mountain range. This approach ensures a more sustainable way of cryosphere monitoring and allows for a better process understanding of each cryosphere component and its interaction across the domain. In the following we describe the monitoring strategy for super-sites and describe in detail three pilot sites in Central Asian's main mountain ranges.

Introduction

The UN General Assembly agreed on 17 Sustainable Development Goals (SDGs) and related targets at the 21st Conference of the Parties to the UN Framework Convention on Climate Change (UNFCCC), which provides an overarching framework for the implementation of the Paris Agreement. However, major efforts are needed to achieve the SDGs and the 2°C atmospheric warming target within a timeframe that avoids major disruptions for humanity. Therefore, strategies to enforce climate resilience, mitigation, and adaptation must be based on sound baseline climate observation (Bojinski et al., 2014), and the monitoring of Essential Climate Variables (ECVs) defined by the Global Climate Observing System (GCOS, 2022). ECVs include snow, glaciers and permafrost. As noted by the World Meteorological Organization (WMO), there are currently large gaps in the global climate observing system, particularly in high mountain environments (WMO, 2019). Developing and emerging countries lack essential baseline data, needed for future planning and mitigation of climate change impacts. One region where climate change is projected to have a major impact is Central Asia (SDC, 2012). Recent assessments by Brocard et al., (2021) as part of a MeteoSwiss evaluation of Kyrgyz Hydromet concluded that the existence of climate services is rated at the lowest possible level, showing that these services within the Hydromet agencies in Central Asia need to be improved for all planned future activities. Since then, with international support, Hydromet agencies have stepped up their efforts to improve climate services. There remains a need for long-term improvements in the understanding of cryosphere dynamics, particularly those related to snow, glaciers and permafrost, in the Tien Shan and Pamir and related water availability in downstream countries, as water related issues become more acute, and negative impacts of accelerated cryosphere degradation become more frequent and severe (Barandun et al., in press).

The hydrometeorological observations in Central Asia have been recorded since 1879 (Williams and Konovalov, 2008). Central Asia has also a rich history of cryosphere monitoring spanning research on all cryosphere components (e.g. Ermolin et al., 1989, Gorbunov, 1978; Gorbunov and Nemov, 1978, Vilesov & Fedulov, 1968; Makarevich & Fedulov, 1968; Makarevich et al., 1969; Fedulov & Shultz, 1989; Makarevich, 1964; Makarevich & Shabanov, 1965; Tokmagambetov et al., 1977; Cherkasov, 2004; Severskiy et al., 2008; Kotlyakov & Severskiy, 2006, Marchenko et al., 2007) and reaching far back to the end of the 19th century, when pioneering explorers visited the high mountain areas of Central Asia (Mergili et al., 2012). Cryosphere research and systematic monitoring intensified under the programmes of the International Geophysical Year 1957-1959 and the International Hydrological Decade from 1965 to 1974, then continued in the International Hydrological Programme (IHP), which is still in operation today under the auspices of UNESCO. However, the systematic cryosphere observational network was interrupted for various reasons in the early 1990s to 2000s.

During Soviet time, many manually controlled monitoring stations for meteorological, cryospheric and hydrological observations were operated for extended periods of time. Measurements were clustered at selected locations to understand the interaction of the atmosphere, snow, glaciers and permafrost. These networks have inspired the creation of today's super-sites. Specifically, the river discharge data were used to infer the meltwater of the snow-covered mountains of Tajikistan and Kyrgyzstan (Bernauer and Siegfried, 2012). After the collapse of the Soviet Union, these observations were partially reduced, especially those involving substantial funding e.g. helicopter flights for snow height observations and similar. Rather than being systematically grouped to provide an understanding of the cryosphere as a whole, the measurements focused on individual components of the cryosphere and hydrosphere.

Since the late 1990-ies hydrometeorological network has been upgraded through various international efforts with additional automatic hydrometeorological stations, such as remotely operated multi-parameter stations network installed within the regional research network Water in Central Asia (CAWa) funded by the German Federal Foreign Office (Zech et al., 2021). In 2010, the first efforts were made to re-establish cryosphere monitoring networks in Central Asia (Hoelzle et al., 2017). These efforts have continued in collaboration between Central Asian and international scientists to (i) provide high quality and modern scientific observations, (ii) exchange knowledge and train young scientists and students, and (iii) rebuild the community in cryosphere sciences throughout the region (Barandun, 2018). These efforts created a denser network of cryosphere monitoring across components, but systematic coordination and a coherent strategy for monitoring different components at the same sites were still lacking. It was only in the last three years, under the Cryosphere project of UNESCO/UNDP/GEF and the CROMO-ADAPT project, which was funded by the Swiss Cooperation and Development Office, that a strategy for supersite monitoring emerged.

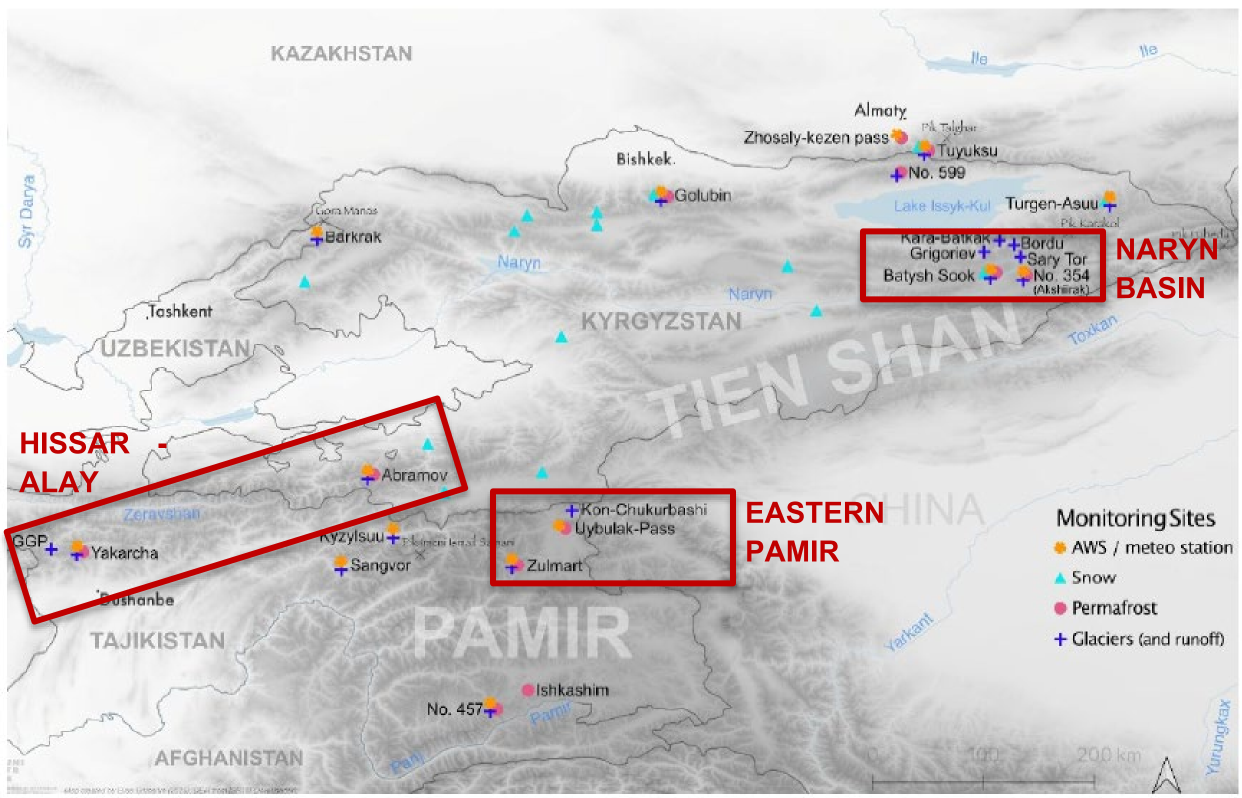


Figure 1. Cryosphere monitoring sites in Central Asia. AWS and meteorological stations that are linked to cryosphere monitoring are shown with orange stars. All AWSs measure atmospheric variables and snow height. Light blue triangles are snow monitoring sites with unmanned aerial vehicle (UAV) surveys, blue crosses are glacier monitoring sites combined mostly with runoff and discharge measurements, red circles highlight the permafrost monitoring sites coupled with geophysical surveys. Red squares highlight the pilot super-sites. For more details on measurements at each site see Table1.

Table 1: Cryosphere monitoring network in Central Asia in 2024. AWS = Automatic Weather Station; SMB = Surface Mass Balance, GPR = Ground Penetrating Radar, UAV = Unmanned Aerial Vehicle, dL = gl. length change, dV = gl. volume change, ERT = Electrical Resistivity Tomography, RST = Refraction Seismic Tomography, BR = Borehole temperatures; GST = Ground Surface Temperature.

country	site	Meteo Station / $AWS_{off\ glacier}$	$AWS_{on\ glacier}$	cameras	snow monitoring	SMB_{annual} / $SMB_{seasonal}$	$SMB_{sub\text{-}seasonal}$	ice / firn temperature	GPR	$UAV_{on\ glacier}$	dL	glacier $dV_{high\ res.}$	ice velocity	water level & discharge	ERT	RST	borehole	GST
Kazakhstan	Tuyuksu	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]					
	Shumsky					[illegible]	[illegible]		[illegible]		[illegible]							
	Zholsaly-kezen Pass	[illegible]			[illegible]										[illegible]	[illegible]	[illegible]	[illegible]
Kyrgyzstan	Akshiirak	[illegible]			[illegible]				-	-		-			[illegible]	[illegible]	[illegible]	
	Abramov	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
	Batysh Sook	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]		[illegible]
	Bordu	[illegible]	[illegible]			[illegible]			[illegible]	[illegible]	[illegible]	[illegible]						
	Grigoriev		[illegible]			[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]						
	Golubin	[illegible]		[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]		[illegible]
	Kara-Batkak	[illegible]	[illegible]			[illegible]			[illegible]	[illegible]	[illegible]	[illegible]						
	Sary Tor	[illegible]				[illegible]			[illegible]	[illegible]	[illegible]	[illegible]						
	Turgen Aksuu	[illegible]			[illegible]	[illegible]				[illegible]	[illegible]			[illegible]				
	#354	[illegible]		[illegible]		[illegible]	[illegible]		[illegible]		[illegible]	[illegible]		[illegible]				
	#599			[illegible]		[illegible]					[illegible]			[illegible]	[illegible]			[illegible]
	additional snow monitoring sites since 2023	[illegible]																
Tajikistan	GGP					[illegible]			[illegible]	[illegible]								
	Kyzylsuu	[illegible]	[illegible]	[illegible]		[illegible]			[illegible]	[illegible]				[illegible]				[illegible]
	Sangvor (Glacier catchment Nissai)	[illegible]		[illegible]	[illegible]	[illegible]			[illegible]					[illegible]				[illegible]
	Uybulak Pass	[illegible]													[illegible]	[illegible]	[illegible]	
	Yakarcha	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]				[illegible]	[illegible]	[illegible]			[illegible]
	Kon-Chukurbashi							[illegible]	[illegible]									
	Zulmart	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]		[illegible]	[illegible]	[illegible]		[illegible]
	Ishkashim														[illegible]		[illegible]	[illegible]
	#457	[illegible]				[illegible]	[illegible]		[illegible]	[illegible]				[illegible]	[illegible]	[illegible]		[illegible]
Uzbekistan	Barkrak	[illegible]		[illegible]		[illegible]					[illegible]			[illegible]				[illegible]

A cryospheric supersite provides a strategic framework to address anticipated future challenges associated with cryosphere degradation by integrating long-term observations of glaciers, snow, permafrost, hydrometeorology, and hydrology within representative benchmark catchments. Such sites generate consistent Essential Climate Variables (ECVs) required under the Global Climate Observing System (GCOS) while enabling simultaneous monitoring of coupled climate–cryosphere–hydrology processes across temporal and spatial scales. By combining in situ measurements, automated monitoring systems, geophysical surveys, remote sensing validation, and hydrological observations within one coordinated infrastructure, super-sites provide a scientifically robust and operationally efficient basis for climate services, early warning systems, and adaptive water management for the whole region. Concentrating technical expertise, maintenance capacity, and long-term institutional investment into a limited number of highly instrumented reference sites also offers a more sustainable monitoring model, and the foundation of a comprehensive process understanding at the atmosphere-cryosphere-hydrosphere nexus for Central Asia, supporting both national hydrometeorological services and transboundary scientific cooperation. In the following the cryosphere monitoring strategy is outlined and the 3 pilot sites acting as super-sites described in detail, followed by a perspective and recommendations for the continuation of supersite monitoring.

2. Cryosphere monitoring strategy

In order to adapt to and ultimately mitigate climate change, we need more accurate information on the interactions between the atmosphere, the ocean and the land. A multitude of climate observation networks cover our entire planet. Together, these networks form the Global Climate Observing System (GCOS), which monitors all relevant Earth Climate Variables (ECVs) in order to improve our understanding of the climate system, enhance climate services, and enable us to prepare for future changes more effectively (GCOS, 2022). This network is subdivided into thematic groups. Two of these are the Global Terrestrial Network for Glaciers (GTN-G) and the Global Terrestrial Network for Permafrost (GTN-P), which cover temporal and spatial information on the states and changes of ECVs at scales ranging from local to global, with varying levels of accuracy and uncertainty (WGMS, 2024; Streletskiy, 2021; Biskaborn et al., 2019). These two networks and their strategies form the basis for designing the cryosphere monitoring network across Central Asia. The envisaged monitoring programme is organised around key super-sites, including long-term measurements with different temporal and spatial resolutions, as well as individual measurement campaigns. These super-sites include a comprehensive monitoring of all cryosphere components: snow, glacier and permafrost as well as the atmospheric variables driving the cryosphere changes. 3 super-sites were established as pilot sites within the GEF/UNDP/UNESCO cryosphere project: Supersite: Tien Shan, Hissar-Alay and Pamir. The sites were chosen to best reflect the main mountain ranges of Central Asia, their morpho-topographic characteristics as well as their different climatic settings (Fig. 1).

At each supersite, important in-situ, airborne and space-based information on snow, glaciers and permafrost are systematically collected and follows the recommendation in Barandun et al., in press. The following ECVs are identified for a comprehensive cryosphere monitoring and are carried out at the super-sites:

Long-term measurements: Snow:

- Snow depth, SWE, snow cover extent and duration at the snow monitoring sites
- Local avalanche surveys at selected sites
- Remote sensing-based snow cover monitoring over larger regions

Long-term monitoring: Glaciers:

- Mass balance change (seasonal to annual)
- Snowline (seasonal)
- Length change (annual)
- Volume and area change (annual to decadal)
- Glacier inventories (quinquennial to decadal)
- Ice flow velocities (annual to pluriannual)
- Englacial temperatures (annual to pluriannual)

Individual measurements: Glaciers:

- Ground penetrating radar measurements to determine the thickness of the glacier and the corresponding total volume
- Ground penetrating radar measurements to determine spatial accumulation rates and distribution

Long-term monitoring: Permafrost:

- Near surface ground temperature measurement below different surface types (hourly to daily)
- Temperature monitoring in boreholes including active layer depth (hourly to daily to annually, depending on measured depth)
- Near surface geophysical measurements to determine the change of ground ice content (annual)
- Velocities of moving landforms such as rock glaciers (annual to pluriannual)

Individual measurements: Permafrost:

- Different geophysical measurements (e.g. GPR, ERT, RST) to characterize the different surface and subsurface characteristics

Important additional variables measured within the alpine catchments:

- Meteorological data (hourly to daily)
- Runoff (hourly to daily)

Methods used aim to always be a combination of in situ measurements, remote sensing data and numerical models to achieve highest accuracy and largest reduction in uncertainties. In addition, climate model output is necessary to drive relevant cryospheric models to obtain sound scenarios of future snow, glacier and permafrost change. Uncertainties related to the global cryosphere monitoring strategies are summarized in e.g. Irrgang et al. (2025), Zemp et al. (2009), Noetzli et al. (2021).

The super-sites form part of the Central Asian cryosphere network that is described in Barandun et al., in press as the following (update from Barandun et al., in press):

2.1. Snow monitoring network in Central Asia

Snow processes at high altitudes play an important role in the annual water balance. The establishment of snow monitoring is therefore closely linked to hydrological research and has a long history in Central Asia (Shultz 1965). The emphasis on research into the various components of the water balance led to the initiation and expansion of the snow monitoring network in the 1940s. In the 1960s, a permanent network of snow stakes was established in the Tien Shan and Pamir and monitored annually until 1990 (monthly in some years; Bedford and Tsarev, 2001). In the 1970s and 1980s, much scientific attention was devoted to the quantification of SWE, complemented by optical satellite data in the late 1980s (Bedford and Tsarev, 2001). The extensive snow observations provided the information for an empirical scheme to derive snow accumulation at regional scales, which is still used by many hydrometeorological agencies. After the break-up of the Soviet Union in the early 1990s, many ground-based snow measuring stations were abandoned and the renewal of the observation network in the region has been slow, especially in remote high-altitude areas. While snow observations have been relatively continuous in Kazakhstan, in both Kyrgyzstan and Tajikistan snow monitoring is still far below the coverage during the Soviet era. However, since the beginning of the 21st century, quantification of snow resources has increasingly relied on remote sensing (e.g. Gafurov et al., 2013). This also enabled the development of a first operational tool such as MODSNOW to provide snow cover maps based on MODIS satellite data (Gafurov et al., 2016). This was a first and very important step towards accurate snow cover mapping by hydrometeorological services across Central Asia for improved water management (e.g. Tillakarim et al., 2023, Mamaraimov et al., 2022). The new snow monitoring strategy combines traditional field observations and modern technologies to generate continuous spatial and temporal estimates of seasonal snow water resources. The integrated approach includes satellite observations, UAV surveys, manual snow measurements, automatic weather stations, and airborne monitoring platforms (Fig. 2).

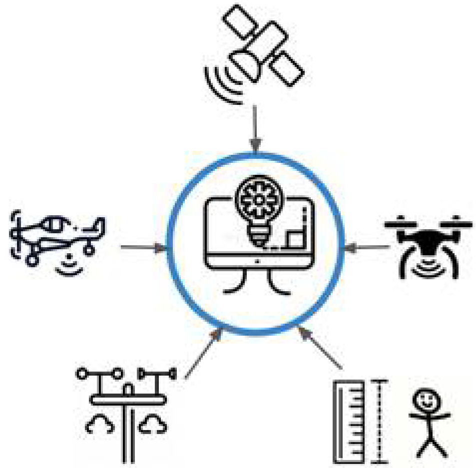


Figure 2. The snow monitoring strategy utilizes new and traditional observation data together with model-based estimates of the snowpack to obtain spatio-temporally continuous estimates of water resources contained in the seasonal snowpack. These include satellites, drones, manual measurements, automatic weather stations and manned airborne platforms. Figure from Barandun et al., in press.

UAV snow surveys

The CROMO-ADAPT drone snow survey archive (apps.mountainfutures.ch/drone-map) consolidates 53 photogrammetric missions flown across 17 sites in the Kyrgyz Tien Shan between April 2023 and March 2026, in collaboration with KyrgyzHydromet and CAIAG (Table 2. Fig. 2). The network spans a representative cross-section of Kyrgyz mountain catchments — from Talas and Suusamyr in the north, through the central Naryn syrts (Ara-Bel, Dolon, Kyzylbel), to Sary-Tash and Isfaram-Sai in the south and the Issyk-Kul tributaries (Jyrgalan, Kyzyl-Suu, Chon-Ashuu) in the east (Fig. 3). The campaign design combines a snow-free reference campaign (September 2023) covering all primary sites with repeat snow-on campaigns at peak accumulation each winter (March-April 2023, February–March 2024, February–March 2025, February–March 2026); snow depth is derived by differencing each snow-on digital surface model against the bare-earth reference. Surveys combine a PPK-equipped senseFly fixed-wing platform for large-area coverage with an RTK-corrected DJI multirotor for work over terrain where landings are difficult or smaller targets, with positioning referenced to a locally established base station and processed following methodology adapted from SLF Davos practice, applied here for the first time at this scale in Central Asia. In total the archive holds over 25,000 aerial images and approximately 331 GB of imagery, DEMs, and orthomosaics (Fig. 4). Raw and processed data are archived on an FTP server hosted at CAIAG in Bishkek, with inventory and access provided through the web platform linked above. Each campaign is co-located with manual ground truth (snow probe transects and SWE pits) used to validate the drone-derived depth fields and to constrain the density assumptions needed to convert depth to snow water equivalent. The resulting dataset provides a transferable reference for evaluating the SnowMapper operational product and for characterising sub-grid snow depth variability in mountain catchments where conventional gauge networks are sparse.

Table 2: Overview of UAV snow survey campaigns.

Campaign	Type	Missions	Photos	Volume
April 2023	Snow-on	4	1,981	19.0 GB
September 2023	Snow-free	14	6,122	75.4 GB
February–March 2024	Snow-on	11	4,405	68.2 GB
February–March 2025	Snow-on	12	6,623	84.3 GB
February–March 2026	Snow-on	12	6,623	84.3 GB
Total		**53**	**25,754**	**331.2 GB**

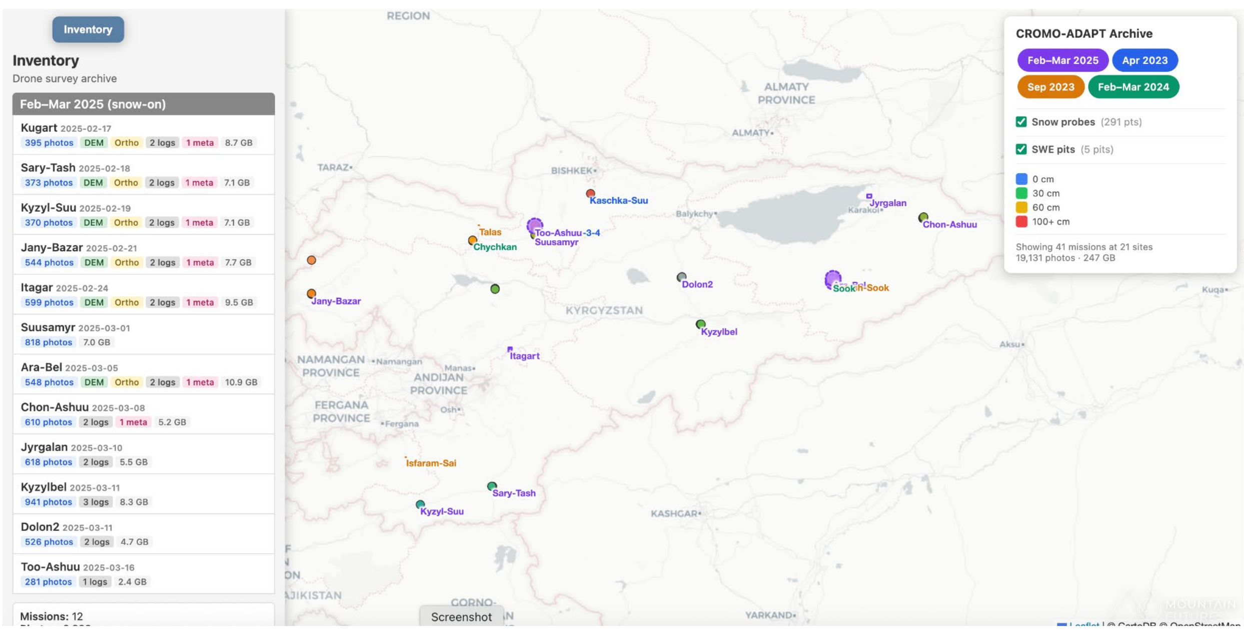


Figure 3. The interactive visualisation and access platform for the CAIAG hosted datasets available at apps.mountainfutures.ch/drone-map.

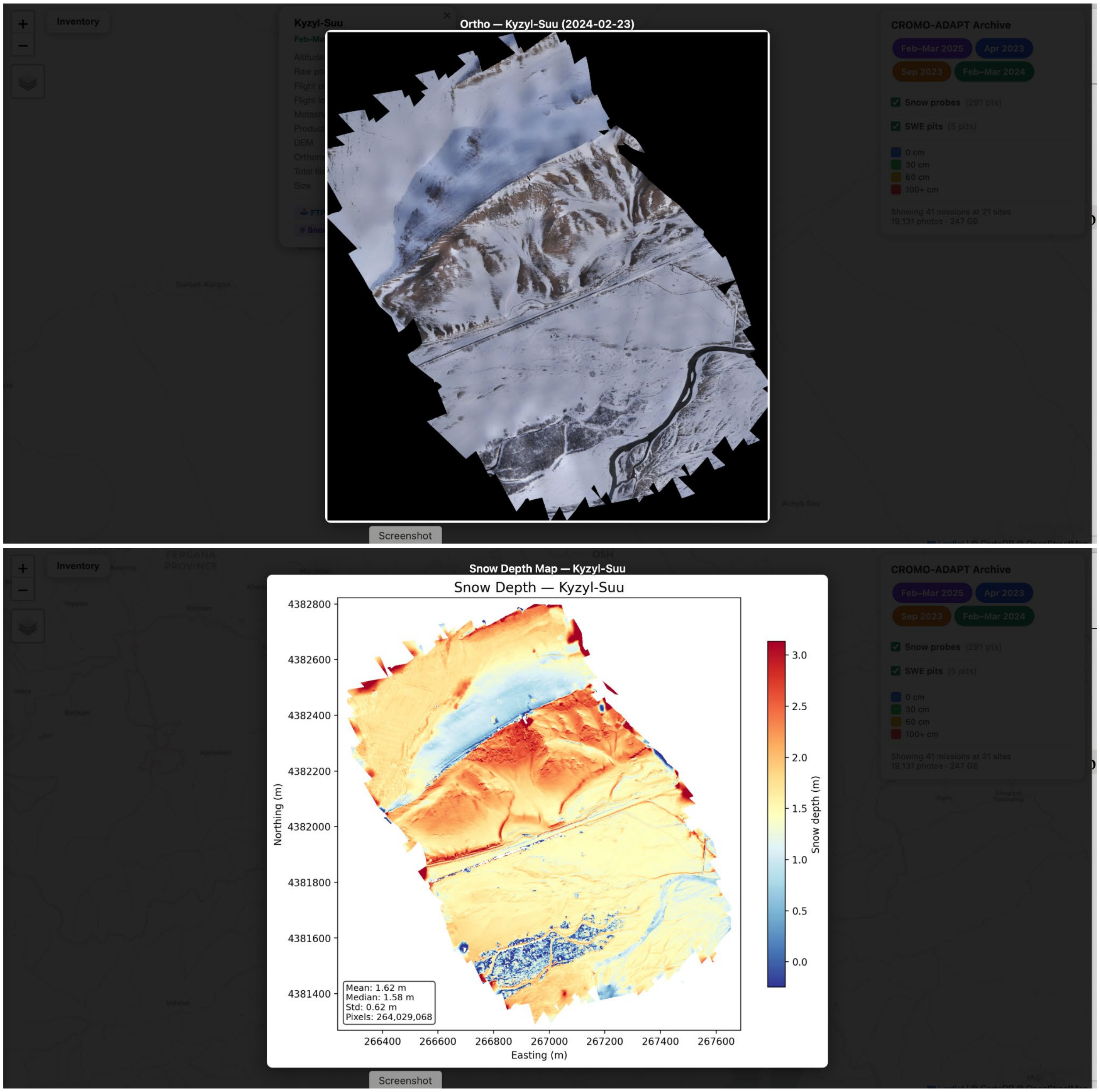


Figure 4. Ortho photo (above) and snowdepth (bottom) from 2024 campaign in Kyzyl-Suu accessed via the platform apps.mountainfutures.ch/drone-map.

2.2. Glacier monitoring network in Central Asia

A first region-wide glacier mapping initiative was launched in the region in 1946, and aerial photographs were taken with the aim of cataloguing glaciers across the region. These first efforts were complemented by the analysis of a series of aerial photographs taken in 1971 (Kotlyakov, 1975). An extensive system of glacier monitoring was initiated under the auspices of the USSR Committee for the International Hydrological Decade (1965 to 1974), and measurements were intensified in the following decades (Dyurgerov et al., 2002; Kuzmichenok, 2006). The first in situ measurements of glacier mass balance however date back to the 1950s in Kazakhstan and

Kyrgyzstan. Glacier research in Uzbekistan commenced in the early 1960s. A significant boost of cryosphere research was the establishment of the Central Asian Research Institute of Hydrometeorology in 1957 in Uzbekistan. Studies on glacier dynamics and area changes intensified in the late 1960s to 1970s and included, for example, ice surface velocity measurements, meteorological, and mass balance observations (Vinogradov et al., 1966; Glazirin et al., 1985, 1988). Three comprehensive glacier inventories were compiled by the Uzbekistan State Hydrometeorological Service (Shchetinnikov & Podkopaeva, n.d.). During the Soviet period, systematic mapping of glaciers in Tajikistan was carried out from 1968 to 1973 as part of the Soviet Glacier Inventory (Kotlyakov, 1980). As a result of all of these efforts, some of the best monitored glaciers worldwide with particularly detailed observations and time series longer than 30 years are located in Central Asia: Central Tuyuksu and Shumskii Glacier in Kazakhstan, Abramov, Kara-Batkak, Sary-Tor and Golubin Glaciers in Kyrgyzstan, Yakartsha, Vanch-Yakh (former Fedshenko) and GGP Glacier in Tajikistan and Paktakor Glacier in Uzbekistan (e.g. Kotlyakov & Severskiy, 2006, Pertziger et al., 1996, Aizen et al., 1995, 1996).

Most of these in situ monitoring programs were, however, discontinued with the collapse of the USSR (Fig. 5). Most of the data are not digitally available, and access to archives is often restricted. Only on two glaciers in the Tien Shan monitoring activities are nearly continuous since the mid-1950s: Central Tuyuksu Glacier in Kazakhstan and Urumqi Glacier (Glacier No. 1) in China (Kapitsa et al., 2020, WGMS, 2024). Glacier observations on Shumsky and Vanch-Yakh Glacier (no mass balance) were never resumed and comprehensive cryosphere research in Central Asia has slowly been revived for the past 2 decades (Lv et al., 2019; Hoelzle et al., 2019; Barandun, 2018). Since around 2010, efforts were made by the international community to resume glacier monitoring (Hoelzle et al., 2017) and later to establish new glacier monitoring sites, mainly in the Pamir (Barandun et al., 2020). The modern monitoring strategy follows the international frameworks of the Global Terrestrial Network for Glaciers (GTN-G). In Kazakhstan, several glaciers of the Tuyuksu complex are measured (WGMS, 2024). In Kyrgyzstan, glacier mass balance monitoring covers the glacial systems of the Northern, Inner, Central Tien Shan and the Issyk-Kul Basin. These include glaciers (1) No. 354 on the northwestern slope of the Akshiirak mountain range, (2) Batysh Sook on the northern slope of the Zhetim-Bel ridge (Inner Tien Shan), (3) Golubin on the northern slope of the Kyrgyz Alatau ridge (Ala-Archa river basin), (4) Abramov, located on the southern slope of the Alai Range; (5) No. 599 on the southern side of the Kungey Alatau range, and (6) Kara-Batkak and (7) Turgen-Aku-Suu on the northern flank of the Terskey Alatau range within the Issyk-Kul basin (Fig. 1). Currently (8) Barkrak Middle is the only continuously monitored glacier in Uzbekistan (Umirzakov et al., 2024, Fig 1). Long term mass balance measurements in Tajikistan were reinitiated in 2018-2021. Currently the mass balance of (9) Yakartsha, (10) GGP, (11) Nissai (Sangvor), (12) Zulmart and (13) Glacier No. 457 are monitored (Fig. 1).

To address the gap of direct glaciological observations from the 1990s to the onset of the current monitoring program and to extend the coverage to a regional scale, comprehensive monitoring programmes in Central Asia include periodical geodetic surveys of changes in glacier surface elevation. These are based on topographic maps and space or airborne digital elevation models for glacier to catchment scale (e.g., Aizen et al., 2007; Bolch et al., 2011, Bolch, 2015; Goerlich et al., 2017; Holzer et al., 2015; Li et al. 2017; Pieczonka and Bolch 2015, Denzinger et al., 2021; Mattea et al., 2025), as well as for regional assessments (e.g., Brun et al., 2017; Gardelle et al., 2013; Gardner et al., 2013; Lin et al., 2017; Wang et al., 2017, Hugonnet et al., 2021). The incorporation of periodic validation and calibration of annual glaciological time series with decadal geodetic estimates has been demonstrated to significantly enhance the robustness and uncertainty estimates of long-term series (e.g., Thibert and Vincent, 2009; Andreassen and Engeset, 2016). Zemp et al., (2013) proposed a systematic re-analysis of glaciological mass balance series in conjunction with geodetic assessments, as a standard procedure for all glacier monitoring programmes. In the context of the Tien Shan and Pamir, the geodetic method has been widely applied for regional assessments (e.g. Gardner et al., 2013; Gardelle et al., 2013; Brun et al., 2017) and it complements the in-situ glacier monitoring network. Most geodetic mass balance calculations are constrained by a decadal to semi-decadal temporal resolution, which precludes the capture of seasonal to annual mass balance variations. The combination with glaciological observations provides a robust glacier monitoring network with high spatial and temporal resolution. Recent advancements in the field have enabled the utilisation of Pléiades high-resolution optical images to accurately estimate annual to seasonal geodetic mass balances (see Falaschi et al., 2023; Beraud et al., 2023). There is much potential to further improve the combined efforts of remote sensing and in-situ observations, with ever-improving satellite missions and growing long-term in situ glacier observations in Central Asia.

Today, glacier mass balance monitoring in the Tien Shan and Pamir is principally led by Central Asian researchers. The data are submitted annually to the World Glacier Monitoring Service (WGMS, 2024) and regional databases. The currently established glacier monitoring network is relatively well distributed throughout the different subregions of Central Asia (Fig. 1). It covers most of the geographical and climatic zones. However, some regions, with unique regional climatic conditions are not monitored, e.g. Dzungarstky Alatau, Eastern Pamir (Barandun et al., 2021). The systematically collected data significantly improves our knowledge of processes governing the glacier response on the effects of atmospheric warming regarding glacier mass change, discharge and glacier-related hazards. The re-established long-term glacier monitoring provides further the basis for accurate gap-filling to create long-term mass balance time series as a climate change indicator and allows, in combination with numerical modelling, better future projections for glacier changes in the Tien Shan and Pamir. Based on the combination of *in situ* measurements (glaciological surveys, runoff and discharge), remote sensing (e.g. geodetic surveys, snowline monitoring) and numerical modelling at these valuable long-term monitoring sites, the region-wide assessments have become more accurate (Barandun et al., 2021). In recent years, near-real time melt monitoring stations in combination with hourly meteorological and hydrological observations collect important data on sub-daily time scale. A better understanding of the temporal dynamics of glacier mass loss has important implications for assessment of water availability in mountain ranges around the world and thus for future water management.

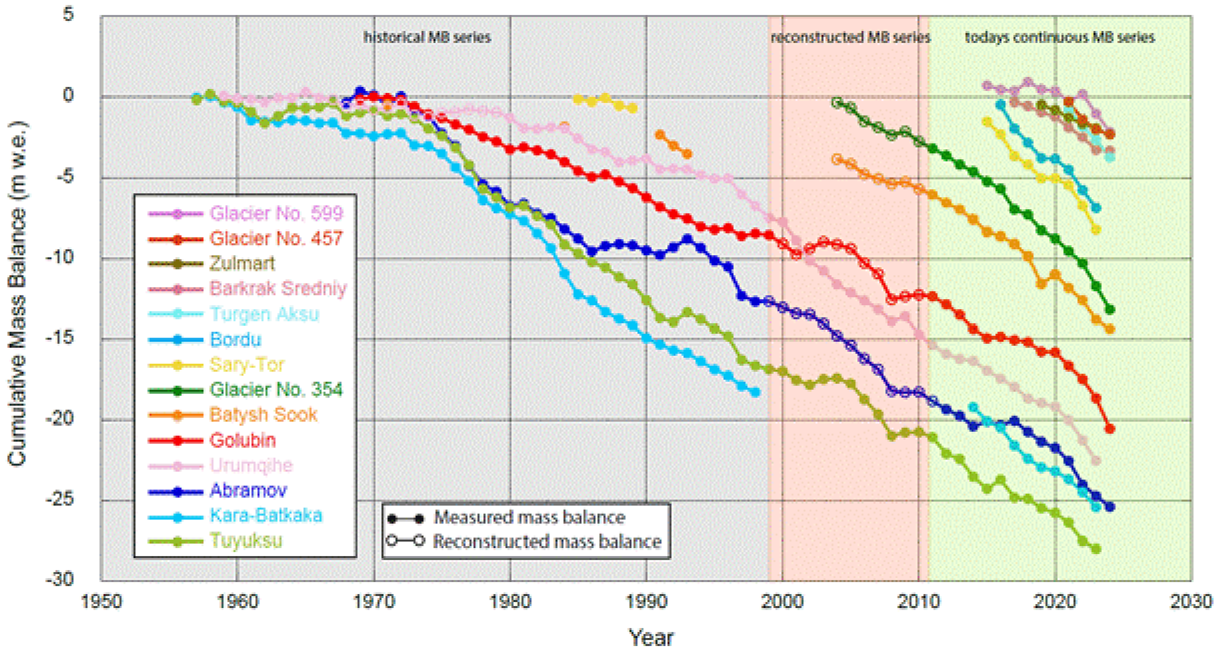


Figure 5. Re-established glacier mass balance observations in meter water equivalent (m w.e.) in Central Asia. Reconstructed values in the figure are based on the following studies: Urumqi (Li et al. 2008), Abramov (Barandun et al. 2015), Bathys Sook (Kenzhebaev et al. 2017), Glacier No. 354 (Kronenberg et al. 2016) and on WGMS (2024). Source: Barandun et al., in press.

2.3 Permafrost monitoring network in Central Asia

Extensive areas in cold mountain regions of the Tien Shan and Pamir mountains are in a permafrost condition. Permafrost is present when the subsurface remains below 0 °C throughout the year and permafrost soil can contain considerable amounts of ice. Changes in the permafrost thermal regime can have significant impacts on local and regional hydrological processes, land surface energy and moisture balances, land-atmosphere carbon exchange, ecosystems and engineering infrastructure (Haeberli & Whiteman., 2024; Noetzli et al., 2024, Hoelzle et al., 2001; Gruber & Haeberli, 2007; Krautblatter et al., 2012). As climate change continues, permafrost is warming and thawing in many regions of the world (Haeberli & Whiteman 2024). The process of permafrost thawing is associated with a variety of hazards, including the destabilization of rock walls, increased sediment loads in rivers, subsidence of the ground surface, and changes in subsurface hydrology (Daanen et al., 2011; Haeberli et al., 2017; Ravanel et al., 2017, Magnin et al., 2017). However, the potential impact of atmospheric warming on mountain permafrost and the influence on slope stability in alpine terrain was hardly recognised worldwide before the 1990s (Haeberli, 1992). The expansion of tourism and the construction of infrastructure in permafrost terrain has influenced the awareness of permafrost phenomena. There has been a demand for increased knowledge of (1) the distribution of mountain permafrost, (2) the thermal state and thickness of permafrost, and (3) the future response of permafrost to a changing climate. These questions led to Central Asian and European permafrost research initiatives (Harris et al., 2009; Marchenko, 2003; Marchenko et al., 2007). Main objectives were to monitor soil temperatures in borehole transects, to develop methods for mapping and modelling mountain permafrost (Marchenko 2001) and to assess hazards following potential permafrost degradation (Allen et al., 2022).

Permafrost today is recognized as an ECV within the Global Climate Observing System (GCOS) of the WMO. GTN-P has formulated an international strategy dedicated to long-term monitoring of permafrost. The core mission of the GTN-P is to provide a sustained, comprehensive long-term monitoring network to collect consistent, representative, and high-quality long-term data series of indicator variables (ECV products) at globally distributed key sites, and to assess the state and change of permafrost over time.

The presence of permafrost in the Tien Shan was first confirmed in 1914 by Bezsonov and Glinka (1914). More detailed studies began later, with borehole surveys at the Kazakh Cosmostation, established in the late 1940s primarily to study high-energy physics through cosmic radiation. Research on high mountain permafrost intensified in the late 20th century, and since then considerable progress has been made in understanding mountain permafrost processes in Central Asia (Gorbunov, 1978). In the northern Tien Shan, the first ground temperature observations were initiated in the 1960s at the Zhosaly-Kezen Pass in the Ili Alatau range, Kazakhstan (Fig. 1; Marchenko & Gorbunov 1997; Marchenko 1999, 2001; Gorbunov et al., 2004) and continued into the 21st century (Gorbunov, 1978; Marchenko, 2003; Seversky, 2017). The first systematic monitoring of permafrost temperatures in the northern Tien Shan began in 1973 (Gorbunov & Nemov, 1978).
However, direct (in situ) observations or data on permafrost in the rest of the Tien Shan and especially in the Pamir are very limited (Barandun et al., 2020). In the 1980s, permafrost ground temperatures were monitored in the Akshiirak Massif, Kyrgyzstan, with several boreholes and later with additional ground surface temperature measurements (Marchenko et al., 2007, Duishonakunov, 2014). Sporadic observations and some first modelling results of the presence of permafrost have been made in other regions of the Tien Shan and Pamir (e.g. Gorbunov et al., 2000, Marchenko, 2001, Marchenko et al., 2007). Knowledge of the state, depth and distribution of permafrost is currently largely unknown and relies strongly on modelling results (e.g. Gruber et al., 2012). Projections for the extended Tibetan Plateau include parts of the Pamir in most studies (Guo et al., 2012; Bolch et al., 2019). However, existing permafrost distribution maps are often based on simplified models that overlook key factors influencing permafrost occurrence (e.g. Gruber & Mergili, 2013; Gruber, 2012).

Since the early 2020s, a new strategy for systematic permafrost monitoring in Central Asia has been implemented (Hoelzle et al., 2019, 2025). These efforts have helped to reintroduce permafrost monitoring into the new cryosphere network of Central Asia (Fig. 1 and Table 1). These efforts follow the international frameworks of the Global Terrestrial Network for Permafrost (GTN-P) and the WMO Global Cryosphere Watch (GCW) programme. The primary goal of the new monitoring network is to revive and continue observations at existing sites with long records and, where necessary and possible, to upgrade instrumentation. Expanding the network to include sites in regions with little or no data will fill critical data gaps and help improve our understanding and modelling capabilities of permafrost response to climate change (Hoelzle et al., 2019; Barandun et al., 2020). Particularly for modelling purposes, the additional acquisition of complementary and systematically repeated observations of active geomorphic surface processes (e.g. slope deformation and movement, thermokarst and lake development) will be of high value.

2.4. Hydrological monitoring network in Central Asia

Hydrometeorological datasets in the different climate zones within the high mountain domain of Central Asia are sparse and therefore limit our hydrological process understanding of these heterogeneous mountain landscapes. Recent efforts to compile existing hydrometeorological data (Marti et al., 2023) provide, for the first time, a comprehensive dataset combining geolocated river gauge locations (295 sites in mountainous Central Asia) with actual river discharge time series for 135 of those stations and long-term norm discharge for all of them, alongside basin characterization and hydrometeorological variables. However, a lack of time-series data for many high-altitude catchments and especially for individual glacier catchments prevails. Differences in cryosphere response to climate change are apparent but an understanding of underlying processes in glacier dynamics and meltwater generation linked to meteorological forcing is limited (e.g. Barandun and Pohl, 2023). The severe lack of both hydrometeorological and cryosphere data prevents robust modelling of relevant cryo-hydrological processes, and therefore, the formulation of sound future predictions of cryosphere evolution and water availability.

The systematic hydrological monitoring in Central Asia began in the former Soviet Union at the start of the 20th Century and became more widespread in the 1950s and peaked in the 1980s. Some of the gauging stations were located in the high-altitude mountainous terrain, providing invaluable hydrological data. After the collapse of the Soviet Union, the number of active gauging stations was reduced. Starting from the 2000s, with international support, several automatic gauging stations have been installed, including some at high elevations (e.g. Zech et al 2021; World bank lead initiatives such as CAHMP, CAWEP and others). The most complete observation network with short gaps and earliest re-initialisation after the Soviet era exists in Kazakhstan (e.g. Shahgedanova et al., 2018). Access to the historical discharge data through national hydrometeorology services is, however, often limited and depends on the purchasing power of potential users. The beforementioned freely accessible data compilations (Marti et al., 2023) provide valuable long-term monthly average data for the critically important high-altitude catchments – important for the validation of model upscaling and model application (e.g. Siegfried et al., 2024); but they often lack time-series data for these high alpine catchments, crucially needed to investigate the physical processes leading to meltwater generation. An installation of a pro-glacial stream monitoring network (Pohl et al., 2024) aims at getting insights into glacier dynamics at high temporal resolution to pinpoint specific interactions between meteorological forcing and glacier response, in particular meltwater generation. The choice of locations follows the (re-)established trans-boundary network of glaciological measurement sites in Central Asia (Fig. 1 and Table 1). This provides the benefit of having access to long-term glaciological and meteorological observations, existing field logistics, and expert knowledge from scientists in Central Asia. Currently, eight glacier sites in Kyrgyzstan, Tajikistan and Uzbekistan have now been instrumented with hydrological monitoring stations consisting of water level gauges that are calibrated twice per year (at the beginning and end of the field season) to discharge with multiple fluorescence dye tracer experiments.

The combined dataset of glacier mass balance, meteorological, and hydrological observations will ultimately allow identifying and improving glacio-hydrological models that are able to accurately represent the hydrological cycle in the different climate zones of Central Asia. These data will thus provide the basis for improving basic knowledge of process representations and their scaling and transferability, which are important for regional-scale water assessment studies. They also provide a dataset for improving and validating large-scale remote sensing approaches.

2.5 Transboundary cooperation

The collected data of the re-established cryosphere monitoring network is aimed to be entirely accessible in national as well as international data centres such as GTN-P, GTN-G (WGMS) or GCW. The current glacier monitoring data is already openly accessible by the international database structure. However, the establishment of an overall national cryospheric monitoring system with several comprehensive cryospheric sites is still not fully addressed and should be further developed (development of web-based access of data). Such systems are today available at other international monitoring sites such as GLAMOS and PERMOS in Switzerland, addressing the need to provide open access to high quality data on transboundary level to the research community and stakeholders.

The transboundary nature of water resources in Central Asia highlights the need for cohesive and coordinated efforts on water resource monitoring among the countries in the Central Asia region (Sehring et al., 2019). Each country faces unique challenges and relies on diverse water sources, making collaborative cryosphere monitoring and data sharing critical to understanding and addressing dynamic changes in the region's cryosphere. Given the diverse challenges Central Asian countries are facing, a collaborative approach to cryosphere monitoring is essential. The establishment of a unified cryosphere monitoring network, building on existing strategies presented before (GTN-G, GTN-P), can facilitate the exchange of expertise and resources (Hoelzle et al., 2019). Jointly managed observing stations across national boundaries would improve the sustainability as well as the accuracy and reliability of data and provide a comprehensive understanding of cryospheric dynamics across the region.
To ensure the effectiveness of transboundary cooperation (Krasznai, 2019), there must be a commitment to open data exchange and standardization of measurement protocols. A centralized data repository accessible to all participating countries could streamline the exchange of information. Standardized measurement techniques and reporting formats will improve the comparability of data, enable a more accurate assessment of regional trends and promoting a common understanding of the state of the cryosphere.
Recognizing the heterogeneity of water-related challenges in each country, transboundary cooperation should include targeted initiatives to address specific issues (Cassara et al., 2019). For example, Kazakhstan, with its large lakes and rivers, faces uneven spatial water distribution and external dependencies (Karatayev et al., 2017). Kyrgyzstan relies heavily on cryospheric resources for hydropower and irrigation (Hill et al., 2017; Saks et al., 2022; FAO, 2016), while snow and glacier melt in the Tien Shan and Pamir provide almost 90% of necessary water for irrigation in Uzbekistan (Zhumaeva, 2021). Turkmenistan faces water scarcity problems that are exacerbated by climate change, with a high dependence on the Amu Darya (Zonn, 2012).

Tajikistan, a major contributor to the Amu Darya, is predominantly dependent on its extensive cryosphere as main water resource (Dukhovny et al., 2014).
Transboundary cooperation and knowledge exchange are crucial for disaster preparedness (e.g. Petrakov et al., 2020). Many potential mountain hazards are transboundary by nature, therefore timely and accurate, science-based, information exchange is crucial. Additionally, the capacities in various fields of cryosphere research are uneven between Central Asia countries, therefore efforts should be made to support the regional exchange of best practices and knowledge among various institutions.

3. Pilot sites: 3 Super-sites

3.1 Hissar Alay

The Hissar-Alai is a major mountain system located at the south-western margin of the Tien Shan, stretching approximately 600 km from west to east across Kyrgyzstan, Tajikistan, and Uzbekistan. The range is bounded by the Fergana Valley to the north and the Alay Valley to the south, with its highest peaks reaching 5600 m a.s.l. in the central area. Precipitation in this region is governed by winter and spring westerly and south-westerly circulation, yielding relatively moist conditions compared to the surrounding ranges: values increase from 350–700 mm yr^{-1} in the lowlands to more than 1500 mm yr^{-1} above 3000 m a.s.l., with a marked west-to-east decreasing gradient (Mattea et al., 2026). According to the Randolph Glacier Inventory version 7.0 (RGI7.0, corresponding to approximately year 2000), the Hissar-Alai encompasses 5058 glaciers with a total surface area of approximately 1912 km^2, representing a significant reduction from the 2184 km^2 mapped in the late 1950s (Mattea et al., 2026).

The focal point of the Hissar-Alai supersite is the Abramov glacier (39°37'N, 71°33'E; Fig. 7), a valley glacier situated on the southern slope of the Alai Range in Kyrgyzstan, within the Vakhsh river catchment that drains into the Amu Darya (Fig. 6). Covering 21 km^2 as of 2024 (Mattea et al., 2025), Abramov is one of the longest-monitored glaciers in Central Asia, with an in situ observation record beginning in 1967. Its exceptional observational dataset, together with renewed international monitoring efforts since 2011 (Hoelzle et al., 2017), makes it uniquely suited as a reference site. The Hissar-Alai supersite also encompasses the Yakarcha and GGP glaciers in the Tajik portion of the mountain range, which extend the spatial coverage of cryospheric observations across this transboundary territory.

The monitoring strategy at the Hissar-Alai supersite follows the comprehensive approach outlined in Chapter 2, combining systematic in situ measurements at point locations with remote sensing instruments and high-resolution modelling to achieve superior spatio-temporal resolution and coverage.

Snow monitoring

Dedicated snow monitoring at the Hissar-Alai supersite is currently limited. Precipitation and air temperature data from the off-glacier AWS since 2011 provide an indirect record of snowfall at a single point near the glacier. The firn core study of Kronenberg et al., (2021) found evidence of an increase of snow accumulation rates in recent decades, observed at two point locations in the upper area of the Abramov glacier. However, no dedicated snow stake network, continuous measurement of Snow Water Equivalent (SWE), or systematic snow density surveys are currently operational at the site. Regional-scale snow cover extent is monitored through remote sensing (MODIS, Sentinel-2) as part of the broader monitoring described in Chapter 2.

Two permanent UAV monitoring sites have been established in the Chon Alai region since 2024: Kyzyl-Suu and Sary-Tash. Both lie within the Alay Valley, an east–west tectonic depression at around 3,000 m flanked by the Alay range to the north and the Trans-Alay — the northern wall of the Pamir — to the south, and feed the Kyzyl-Suu river, a transboundary headwater of the Vakhsh and ultimately the Amu Darya, making the snowpack monitored here directly relevant to downstream water supply in Tajikistan and Uzbekistan (Fig. 6). Sary-Tash (~3,170 m) sits at the M41 junction on the open valley floor, with Kyzyl-Suu in the adjacent western Alay, both sampling a continental, semi-arid high-mountain regime in which snowpack is thin but spatially highly variable, driven by topography and strong wind redistribution

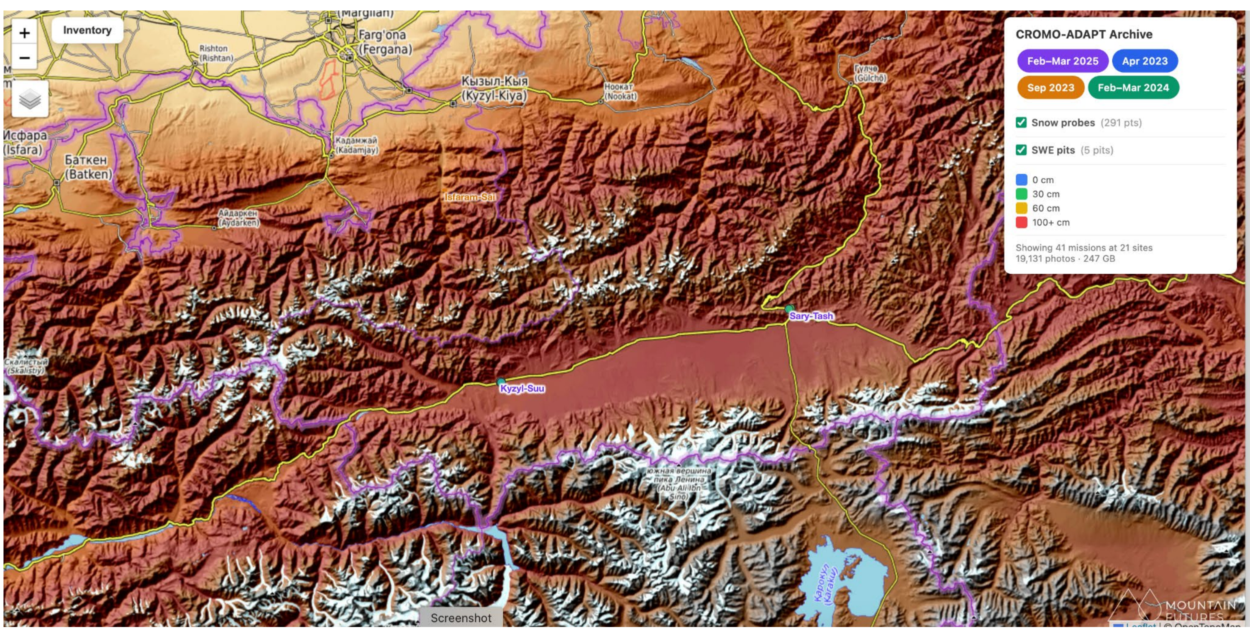


Figure 6. UAV based snow monitoring sites within the Hissar-Alai supersite.

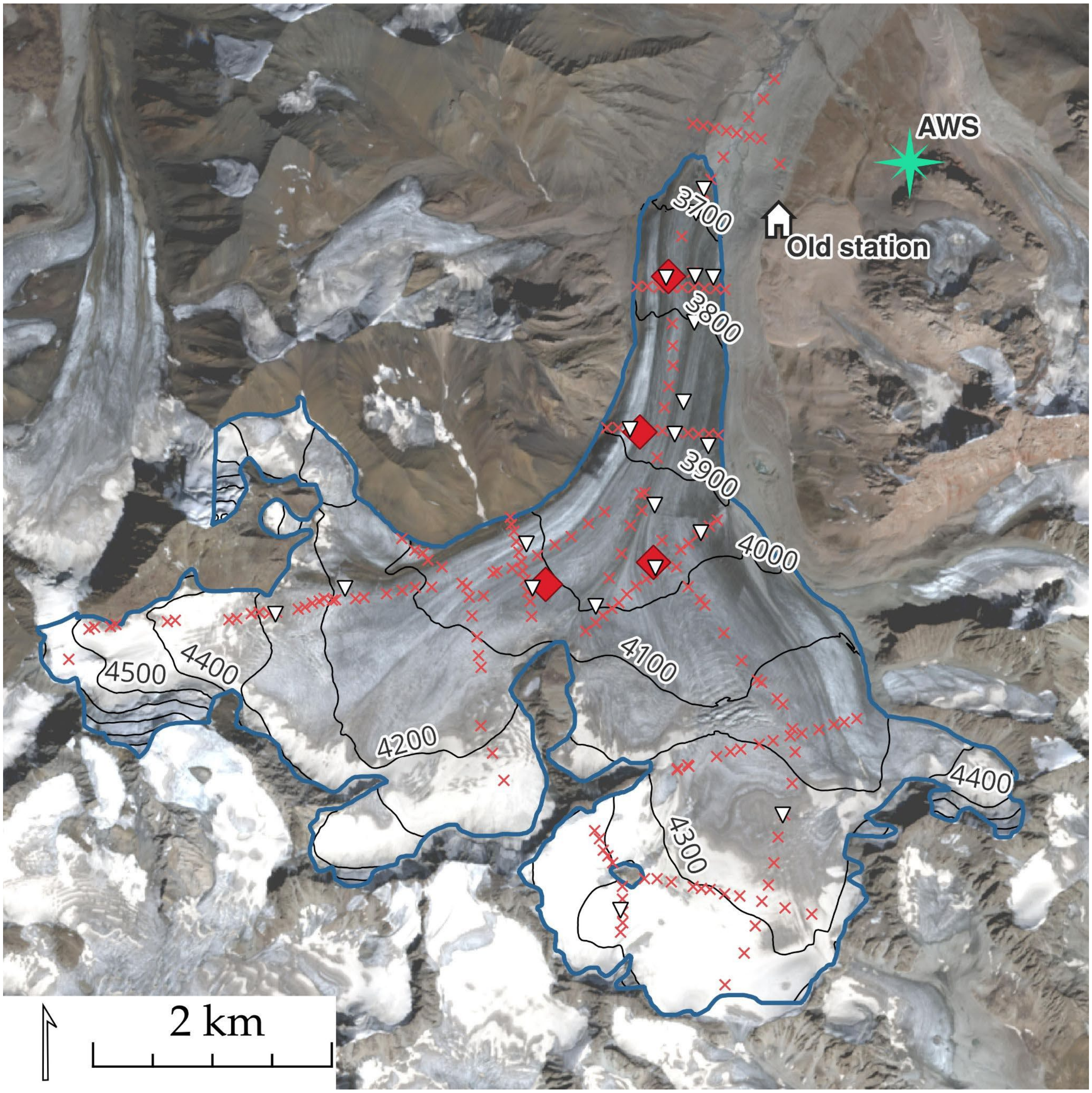


Figure 7. Map of the Abramov glacier. Red crosses: Soviet-era monitoring network. White triangles: present-day mass balance network. Red diamonds: glacier velocity instruments. Background: Sentinel-2 true colour image.

Glacier monitoring

Systematic glaciological observations at the Abramov glacier were initiated in 1967 under the Soviet monitoring program, establishing a comprehensive measurement network with approximately 150 points surveyed year-round (Suslov et al., 1980; Glazirin' et al., 1993; Pertziger, 1996). This program was discontinued when the resident research station was abandoned in 1999, leaving a gap of twelve years. Monitoring was resumed in 2011 through collaboration between the University of Fribourg (Switzerland), the Central Asian Institute for Applied Geosciences (CAIAG, Kyrgyzstan), the Geoforschungszentrum Potsdam (GFZ) and partner institutions (Fig. 7).

Meteorological monitoring. An automatic weather station (AWS) has been operating since 2011, at approximately 4050 m a.s.l. in the immediate vicinity of the glacier. It provides continuous high-frequency records of air temperature, precipitation, humidity, wind speed and direction, and incoming solar radiation, collecting the essential meteorological data to drive glacier energy and mass balance models. An additional on-glacier AWS was installed between 2018 and 2021 but was not maintained beyond that period.

Surface mass balance. Annual glaciological measurements have been conducted continuously since 2011, connecting to the historical series of 1967–1998 (Barandun et al., 2015). Mass balance observations are collected at a network of ablation stakes and snow pits distributed across the glacier. Since 2022, continuous measurement of ice ablation at the point scale has been added with an innovative design (SmartStake by A2 Photonic Sensors), enabling observations at sub-hourly time resolution (Fig. 8).

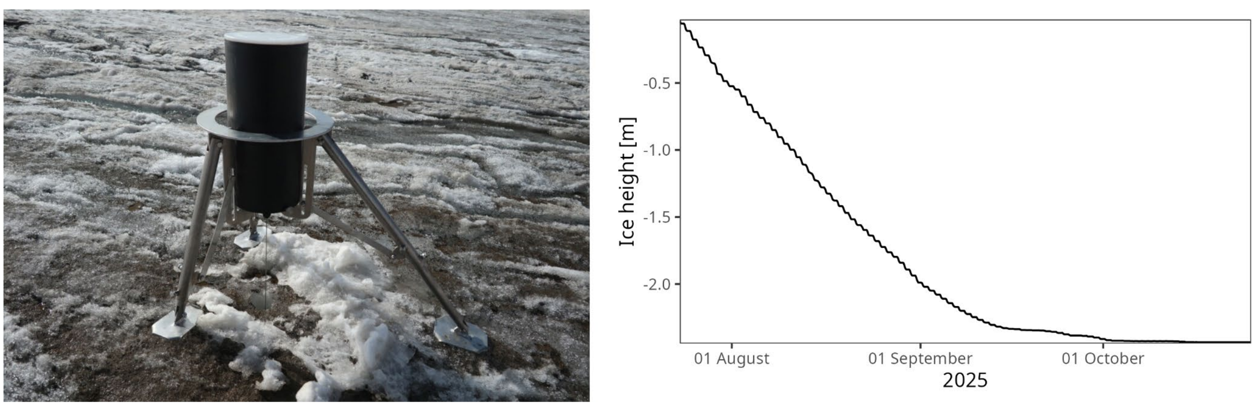


Figure 8. SmartStake instrument for continuous measurement of ice melt on the Abramov glacier (left). The right panel shows the measured sub-daily ice melt at a point location in the ablation area in summer 2025.

Geodetic surveys and remote sensing. At the Abramov glacier, a geodetic mass loss of −0.36 ± 0.07 m w.e. a^{-1} was derived from aerial photographs and high-resolution satellite imagery for the period 1975–2015 (Denzinger et al., 2021). This result was extended by Mattea et al. (2025) with a multi-sensor approach, which provided time-resolved estimates of geodetic change over a 55-year period. Data from the Pléiades satellite constellation, acquired in 2015, 2020, and twice annually since 2022, provide high-resolution Digital Elevation Models for the assessment of recent surface elevation change (Fig. 9). Evolution of the on-glacier snow cover (snowline elevation and snow-covered area fraction) is monitored through satellite imagery (Landsat and Sentinel) and a time-lapse camera as a proxy for glacier mass balance. Drone-based surveys of the glacier terminus have been conducted since 2022, providing high-resolution data on frontal retreat and thickness change.

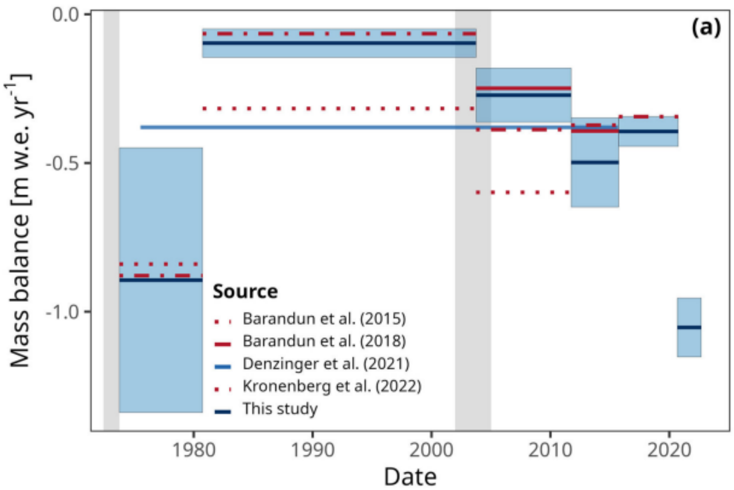


Figure 9. Recent estimates of multi-decadal mass balance at the Abramov glacier, from geodetic (blue) and model-based (red) assessments. Source: Mattea et al. (2025)

Ice thickness. A ground-penetrating radar (GPR) campaign was conducted in January 2018 along 24.6 km of profiles across the lower portion of the glacier (Saks et al., 2024). This survey enabled mapping of the current ice thickness distribution and, by comparison with a 1986 radio-echo sounding dataset, quantification of thickness loss over three decades. The topography of the glacier bed over the full glacier extent had previously been compiled by Kuzmichenok et al., (1992) from 1986 radio-echo sounding data.

Ice flow velocity. Continuous in situ monitoring of ice surface velocity was initiated in July 2022, with the installation of four autonomous GNSS loggers in the ablation area of the Abramov glacier. These stations provide a daily record of three-dimensional ice movement – the first of its kind in Central Asia. The dataset has revealed the seasonal cycle of velocities as well as short-term fluctuations. Historical velocity measurements from the Soviet network (1967–1990), recently digitised from archived Russian-language publications and technical reports, are exceptionally available to provide crucial long-term context of the ice dynamics at the site (Mattea et al., preprint). Annual surface velocity fields are also derived from satellite data via image correlation, complementing the point-based in situ measurements (Fig. 10).

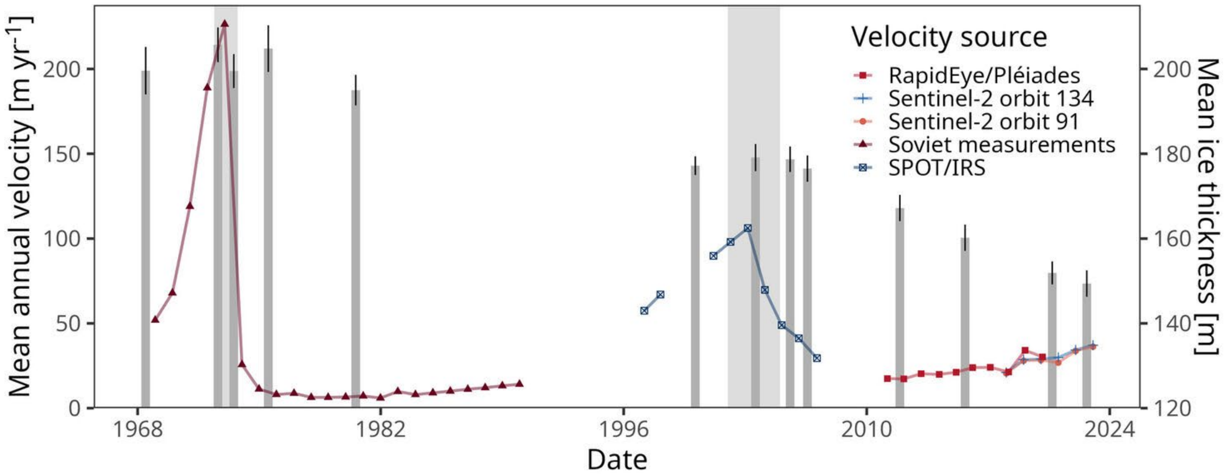


Figure 10. Mean annual ice surface velocity in the central part of the Abramov glacier. Grey bars indicate the corresponding evolution of ice thickness. Source: Mattea et al., (2025).

Hydrological monitoring. Water level and discharge at the glacier outlet have been monitored since 2019, providing continuous records of proglacial streamflow linked to glacier melt and groundwater contributions.

Other glaciers in the supersite. In the Tajik portion of the Hissar-Alai, annual glaciological mass balance measurements have been established at Yakarcha glacier since 2019 and at GGP glacier since 2020 (Fig. 1). Time-lapse cameras have been operating at Yakarcha since 2021. These sites extend the spatial representativeness of the supersite into Tajikistan and contribute to the transboundary character of cryospheric monitoring across the Hissar-Alai.

Permafrost monitoring

Permafrost monitoring at the Hissar-Alai supersite is described in Mathys et al., (2025). Ground surface temperature (GST) loggers have been installed in the Abramov catchment since 2011, providing continuous records of near-surface ground thermal conditions. With a mean annual air temperature of −4.6°C at 4100 m a.s.l., permafrost is expected to be widespread above approximately 3800 m a.s.l. in this part of the Pamir-Alay.

Geophysical surveys to characterise permafrost distribution and ground ice content have been conducted at the Abramov site since 2021. A total of 10 electrical resistivity tomography (ERT) profiles and 8 refraction seismic tomography (RST) profiles have been measured on different landforms in the catchment, including rock glaciers, talus slopes, fine-grained sediments, and the glacier's lateral moraine (Mathys et al., 2024). The collected data have been processed using the petrophysical joint inversion (PJI) approach, for quantitative estimation of volumetric ground ice content across these landforms. At the Yakarcha study site (western Pamir-Alay, Tajikistan), 2 ERT profiles have been measured on a large rock glacier, extending permafrost geophysical investigations to the Tajik portion of the super-site.

Monitoring gaps and needs

Despite the significant progress achieved since 2011, important monitoring gaps remain across all cryospheric components at the Hissar Alai supersite.

For snow monitoring, the present-day configuration does not enable reliable quantification of solid precipitation at the site. The AWS at the vicinity of Abramov glacier, is affected by systematic undercatch. Moreover, currently there are no continuous measurements of snow water equivalent (SWE), as in other super-sites. As a result, the total seasonal snow storage and its spatial distribution across the supersite – both on and off the glacier – remain poorly constrained. This is a fundamental limitation for hydrological forecasting as well as regional mass balance modelling.

Currently glacier mass balance is determined from annual field surveys conducted near the end of the hydrological year, which constrains the temporal resolution of observations and limits the ability to resolve intra-annual variability and the processes governing seasonal glacier surface mass exchange (e.g., Huss et al., 2009, Huss & Hock 2015; Zemp et al., 2019). The thermal regime of Abramov glacier is monitored only for the upper 12 m which limits our understanding of glacier dynamics and for projecting future changes. The monitoring of ice flow velocity, while pioneering in the Central Asian context, is currently limited to four GNSS stations all located in the ablation area, and the record spans only three years. Accumulation-zone dynamics remain unobserved, and the short duration of the record is insufficient to characterise the full spectrum of dynamical behaviours, including the cyclical velocity oscillations (Mattea et al., 2025). The monitoring of glacier dynamics should be maintained and expanded: the GNSS velocity network should be extended into the accumulation area, and the record should be sustained over multiple years to characterise the full arc of the current pulsation cycle and detect its eventual termination. Finally, a long-term installation for monitoring englacial temperatures should be established at Abramov glacier, to characterise the glacier thermal regime and its evolution under continued atmospheric warming.

For permafrost monitoring, no rock glacier velocity monitoring currently exists at the supersite. Rock glacier flow is one of the most accessible and informative indicators of permafrost dynamics, yet the numerous rock glaciers located in the supersite have not been tracked for surface displacement.

The geophysical survey programme – which has provided the only available characterisation of ground ice distribution in the Pamir-Alay – was conducted within the framework of individual research projects. The continuation of repeat surveys beyond these projects is not guaranteed, and without repeated measurements at the same profiles, temporal changes in permafrost conditions cannot be detected. This sustainability problem is compounded by the limited number of local scientists who have been trained to conduct independent geophysical surveys in Central Asia.

At the catchment scale, while discharge has been monitored since 2019, the record is still short and the separation of glacier melt, snowmelt, and permafrost contributions to total runoff has not been formally attempted.

3.2 Naryn basin

The Naryn River (see Fig. 1) constitutes the primary tributary of the Syr-Darya River, originating from the confluence of the Big and Small Naryn Rivers further upstream. The upper Naryn basin is bordered by the southern slopes of the Kyrgyz Alatoo and Terskey Alatoo ranges to the north, the Akshiirak massif to the east, and the Ferghana, At-Bashi, and Borkoldoy ranges to the south. The river flows into the Toktogul Reservoir in Kyrgyzstan, providing water for the important agricultural area of the heavily irrigated Ferghana Valley in Uzbekistan. Approximately 8% of the total area of both catchments is glacierised. The total glacierised area is 779 km2, with 462 km2 for the Big Naryn and 317 km^2 for the Small Naryn.
The Small and Big Naryn catchments are located within the inner ranges of the Tien Shan mountains, a geographical location that results in a precipitation shielding from western, northwestern and northern air flow, and a drier continental climate in comparison to the outer ranges (Sorg et al., 2012). Precipitation maxima usually occur later in the year, specifically in the late spring to summer months, in comparison to the winter months when precipitation is dominant in the outer ranges of Pamir and Tien Shan (Schiemann et al., 2008; Sorg et al., 2012; Pohl et al., 2015). The annual precipitation range is between 280 and 450 mm (Aizen et al., 1995). Whereby glacier melt water contribution into the river system becomes crucial in the dry summer months (Saks et al., 2022). Permafrost is critical due to its extensive distribution and role in influencing slope stability and related natural hazards in the region rather than as a water resource (Barandun et al., in press). It mainly affects road stability.

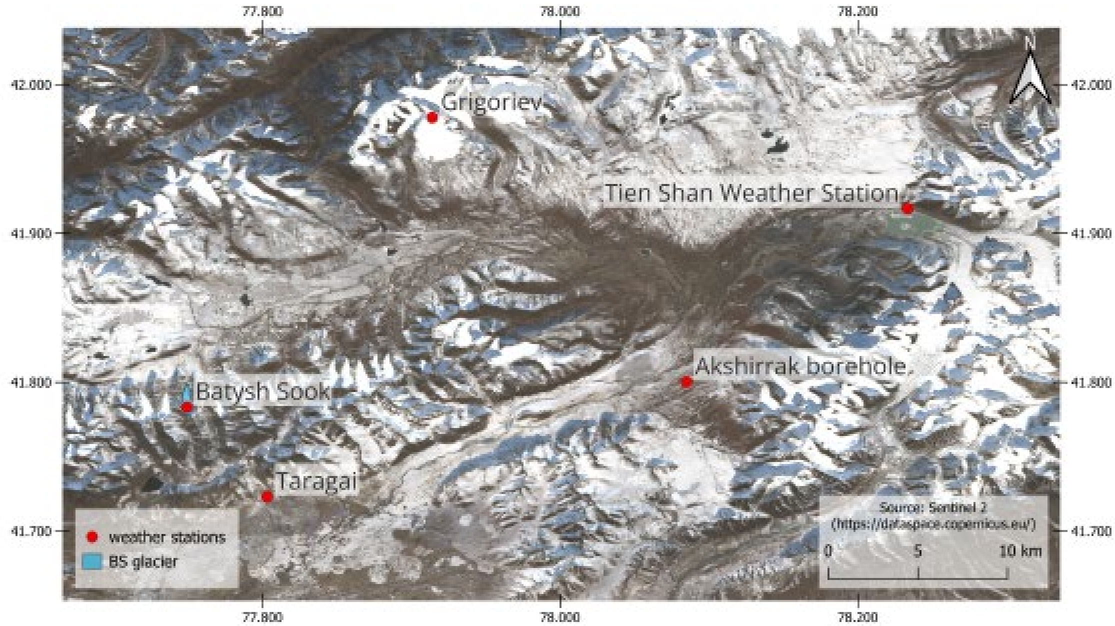


Figure 11. A general map of BS glacier and the main weather stations for meteorological monitoring in the super-site. Source: B. Boehm.

The Naryn supersite include extensive snow, glacier and permafrost monitoring as well as comprehensive monitoring of atmospheric variables (Fig. 11 and 12). The monitoring strategy employed at the Naryn supersite aligns with the comprehensive approach described in Chapter 2, integrating systematic in situ measurements at designated points with remote sensing instruments and high-resolution modelling to achieve superior spatio-temporal resolution and coverage of all three cryosphere components.

The monitoring in the Naryn supersite includes snow height and snow water equivalent distributed throughout the Arabel Plateau, glacier monitoring on Batysh Sook, Glacier 354, Sary-Tor, Bordu and Grigoriev glaciers and permafrost monitoring including: geophysical ERT and RST surveys distributed through the Arabel Plateau, an autonomous ERT installation as well as hydrological and meteorological observations.

Snow monitoring:

All automated weather stations are now equipped with a snow height sensor (Fig. 12). This provides important data for model validations such as complex energy balance model applications. Systematic in situ snow height measurement however remains sparse. Complementary, terrestrial snowline cameras help to evaluate current snow cover conditions at glacier 354. This data is complemented with remote sensing applications.

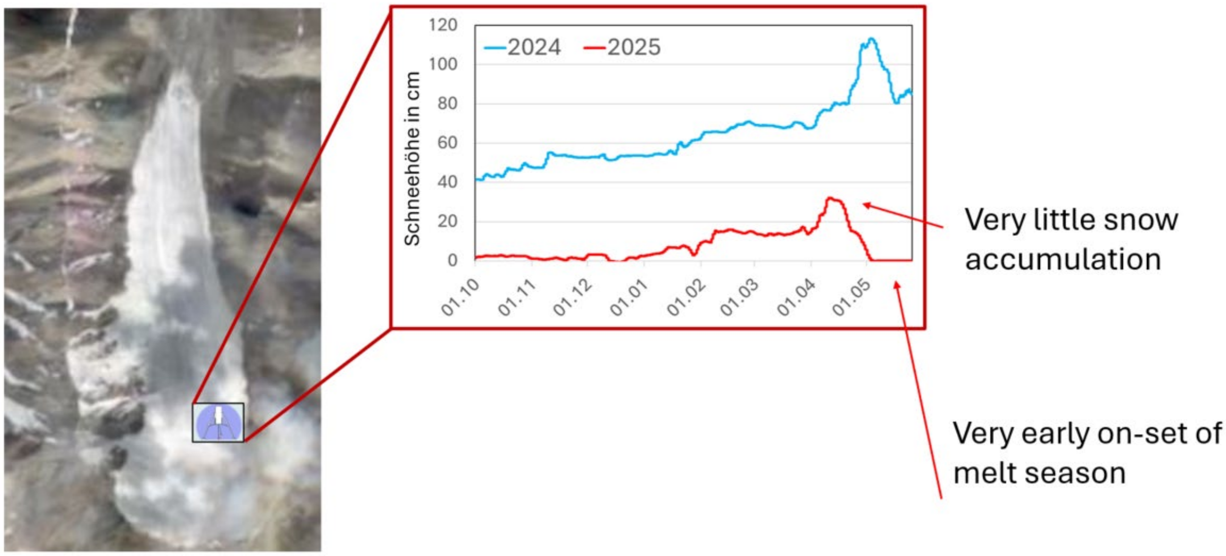


Figure 12: Snow height observations at automatic weather station at Batysh Sook, comparing an extreme snow poor year 2025 with the winter season for 2024.

Efforts are currently underway to address the observational gap in winter snowpack data, which is a critical factor in determining seasonal runoff in Central Asia at higher resolution. A new spatio-temporal snow observation strategy, utilizing Autonomous Vehicle surveys (UAVs), has been developed to generate high-resolution snow depth maps at the catchment scale (Bühler et al., 2015) and has recently been implemented in Kyrgyzstan. All monitoring sites are in the source areas of key rivers or in particularly water-stressed catchments, which are crucial to both local and regional economies. The sampling strategy focuses on capturing the climatic variability between major basins and the snow distribution heterogeneity within basins due to elevation differences. These new data products will be integrated with traditional observations from rehabilitated snow stake sites (currently ongoing), automatic weather stations (Fig. 12), and satellite data (Fig. 13). Combined with forecast models, it enables the production of spatio-temporally continuous estimates of SWE - the most critical snow variable needed by water managers for hydrological forecasting and modelling (Fig. 13).

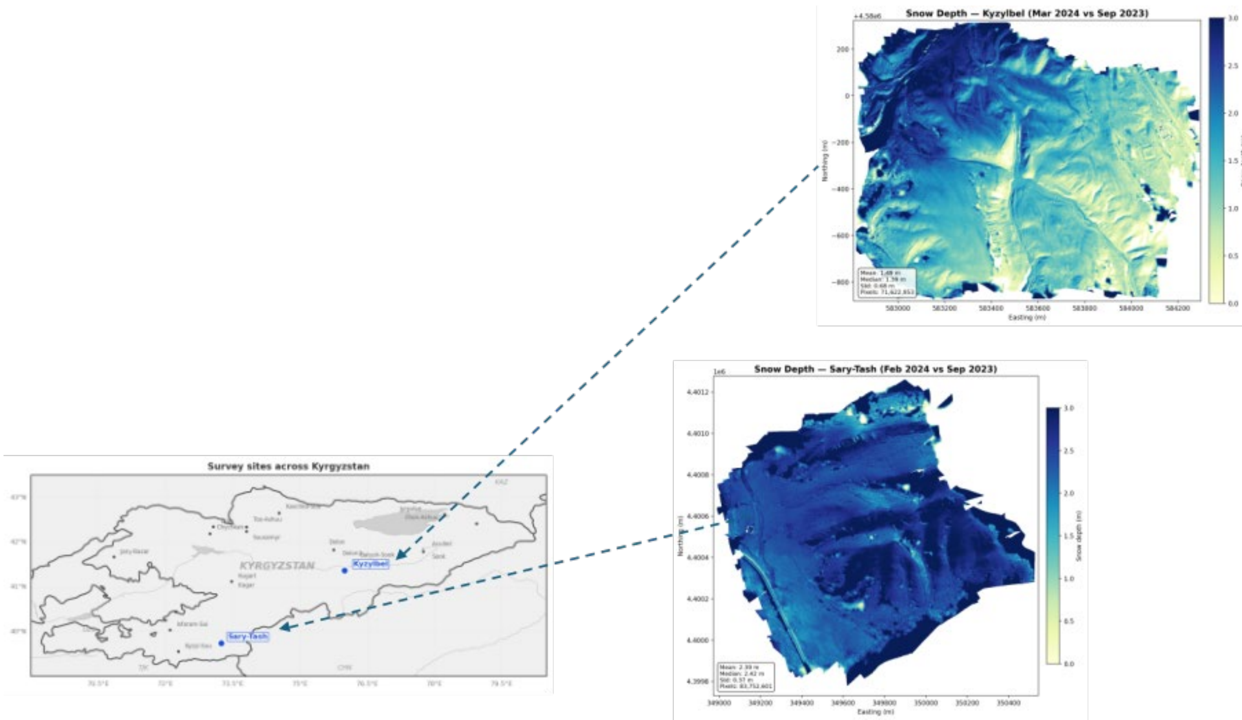


Figure 13. Example distributed assessments of snow depth from UAV surveys in Kyrgyzstan.

Three permanent UAV monitoring sites have been established in the Naryn basin since 2024: Dolon (south side of the Dolon Pass), Kyzyl-Bel, and the Ara-Bel plateau (Fig. 14). The Naryn is the principal headwater of the Syr Darya and feeds the Toktogul cascade, making the snowpack of its central Tien Shan headwaters a primary control on regional hydropower generation and on downstream irrigation supply to the Fergana Valley and beyond. The three sites are positioned along the dominant elevation and climate gradient of the basin — from the moisture-receiving northern threshold at Dolon Pass (~3,030 m a.s.l.), to the high, cold, semi-arid syrt landscape of the interior at the Ara-Bel plateau (~3,800–4,000 m a.s.l.) — sampling the thin, long-lived, wind-redistributed snowpack characteristic of the Tien Shan high plateaux.

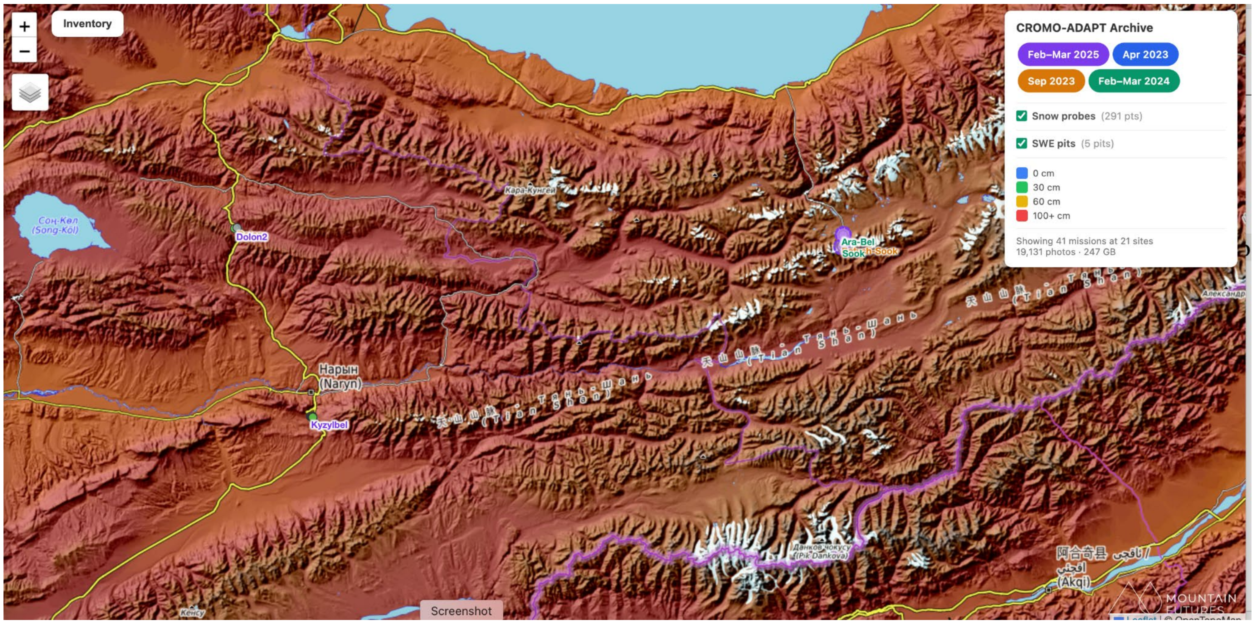


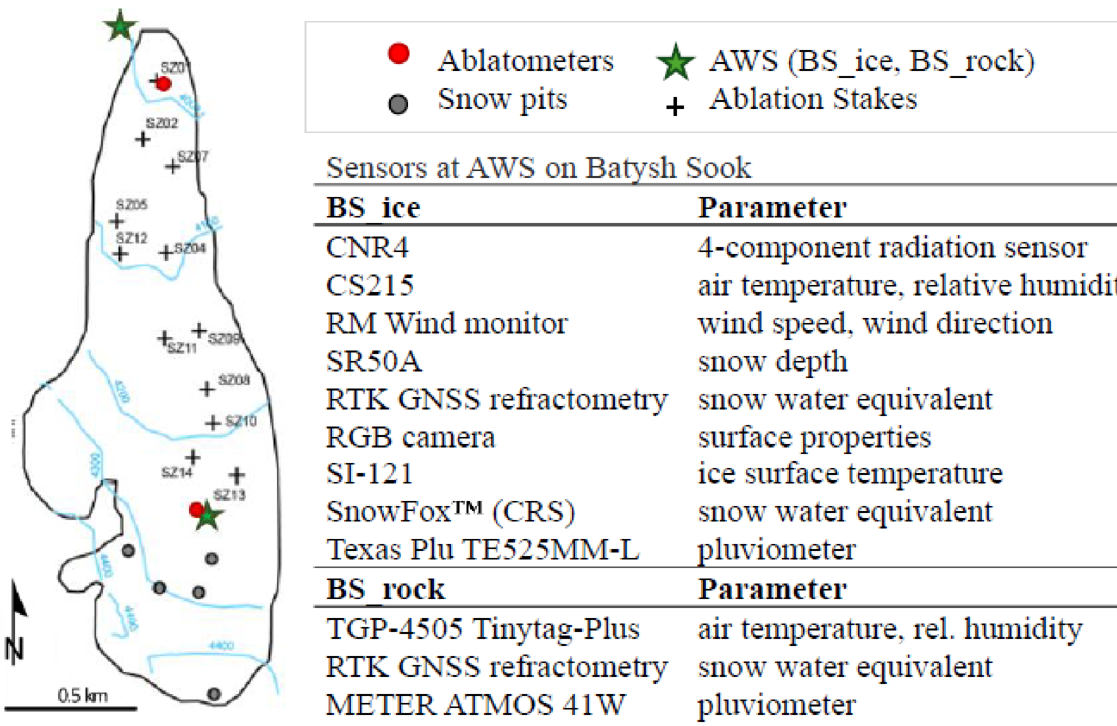
Figure 14. UAV based snow monitoring sites within the Naryn supersite.

Glacier monitoring:

Figure 15. On and off weather stations at the Batysh-sook glacier.

Surface mass balance. Annual glaciological measurements have been conducted continuously since 2010 on glacier 354 and Batysh Sook glacier (Kronenberg et al., 2016; Kenzhebaev et al., 2017). Mass balance observations are collected at a network of ablation stakes and snow pits distributed across the glaciers. At glacier 354, an automatic snowline camera provides a proxy for sub-seasonal mass balance. In addition to the annual mass balance observations, an extended campaign in 2014, provided data on the winter balance and important data on snow distribution on the glacier Batysh Sook and Glacier 354.

Field laboratory Batysh Sook: The focal point of the supersite is Batysh Sook glacier (41° 46.668′N, 77° 45.071′E). This is a small and well-accessible valley glacier situated in Terskey Alatoo mountain range in Kyrgyzstan (Kenzhebaev et al., 2017). In addition to the annual surface mass balance programme the glacier provides the perfect site for a " field laboratory" for all three cryosphere components (Fig. 16). The glacier benefits from an extensive atmospheric, cryospheric and hydrospheric glacier monitoring network (Fig. 15 and 16) and serves as an optimal field laboratory for high-temporal resolution studies of surface processes. The availability of multi-sensor atmospheric, hydrological and glaciological data at sub-daily to annual scales provides a unique framework for analysing short-term dynamics and investigating key processes governing surface energy balance and mass loss in a data scarce region.



Sensors at AWS on Batysh Sook

BS_ice	Parameter
CNR4	4-component radiation sensor
CS215	air temperature, relative humidity
RM Wind monitor	wind speed, wind direction
SR50A	snow depth
RTK GNSS refractometry	snow water equivalent
RGB camera	surface properties
SI-121	ice surface temperature
SnowFox™ (CRS)	snow water equivalent
Texas Plu TE525MM-L	pluviometer
BS_rock	**Parameter**
TGP-4505 Tinytag-Plus	air temperature, rel. humidity
RTK GNSS refractometry	snow water equivalent
METER ATMOS 41W	pluviometer

Figure 16: Batysh Sook monitoring network (modified from Hoelzle et al., 2017). Red dots mark the ablatometers locations, while green stars indicate AWS BS_ice and BS_rock as of 2024.

Continuous surface mass balance: Since 2023, continuous measurement of ice ablation at the point scale has been added with an innovative design (SmartStake by A2 Photonic Sensors), enabling observations at sub-hourly time resolution. The primary function of the SmartStake s is to measure glacier ice ablation continuously. Previously, ablation on the region's glaciers was measured using wooden or plastic stakes that were drilled into the ice and whose exposed length was measured as they melted out (Kenzhebaev et al., 2017). Although it is a very effective method, the temporal resolution is very low, with only a few measurements taken per year. This results in a lack of information especially on melting behaviour during the ablation season. SmartStake s are designed to close this gap, as they are equipped with a sensor that measures changes in ice height continuously (A2PhotonicSensors, 2023). Combining SmartStake data with data from nearby weather stations enables the analysis of single weather events or small changes in temperature, albedo and precipitation on the glacier's melt response (Fig. 17). The continuous information available on glacier melting behavior makes it possible to observe the impact of changes on an hourly to daily scale. This approach to glacier ablation research is just at the beginning due to the novelty of the SmartStake device. The collected data contributes to a better idea of how the glacier mass balance and its contribution to the river discharge will be affected by the changing climate on extremely high temporal resolution (Barandun et al., 2020).

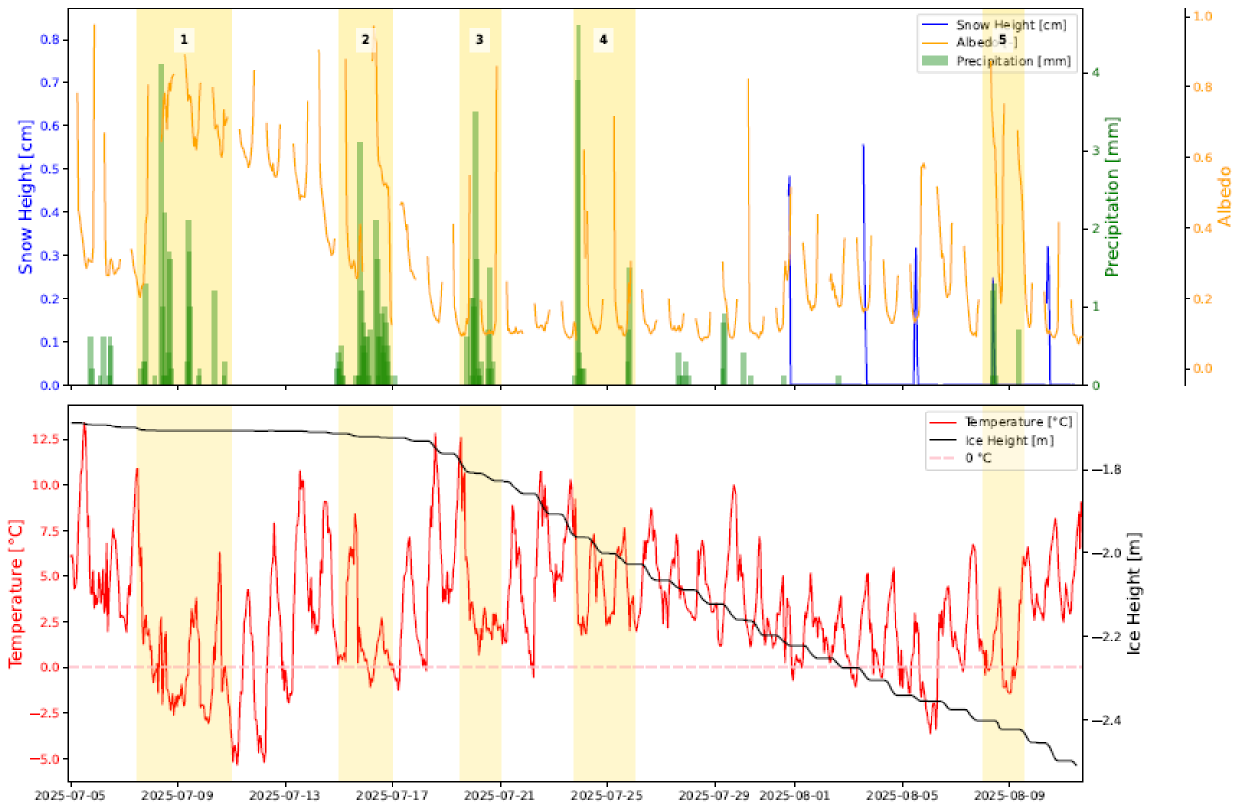


Figure 17. Corrected SmartStake data and meteorological data from the BS_ice weather station, visualizing the interaction between temperature, albedo, precipitation, snow height and ice loss. Source: M. Karrer

Meteorological monitoring: A detailed and unique high mountain atmospheric monitoring has been put in place in the Naryn catchment. The table below highlights the current automatic weather station network. Meteorological data are available since 1997 from the Tien Shan Kumtor Automatic Weather Station (AWS), located 32 km to the east from Batysh Sook (Kenzhebaev et al. 2017) and 10km to the west from Glacier 354. As part of the WE-ACT and GEF-UNDP-UNESCO Cryosphere projects, an AWS (BS_ice) was installed in July 2023 close to the long-term equilibrium line at 4242 m a.s.l, providing data at hourly resolution (Fig. 18). A second AWS (BS_rock) was installed on bedrock at the glacier terminus (3950 m a.s.l.). Both stations feature the sensors listed in Table 1. Two automated ablatometers were installed in 2023, one near the AWS and another one at the glacier tongue, to continuously measure ablation along the glacier's elevation profile. Two all in one weather stations (ATMOS 41) complement the existing network with a focus of improving precipitation observations in the region. The first ATMOS 41 weather station was installed near Lake Arabel at an elevation of 3,793.57 m a.s.l. above sea level (coordinates: 41° 51.67′ N, 77° 44.38′ E41.8612383° N, 77.7397004° E). The site represents an open area with minimal terrain influence, ensuring reliable measurements of wind characteristics, solar radiation, and precipitation. The second ATMOS 41 weather station was installed on the Arabel Plateau at an elevation of 3,717.163 m a.s.l. (coordinates: 41.8911336° N, 77.9116947° E) (Table 3). The location is characterized by flat terrain and an open horizon, allowing the collection of representative meteorological data for the plateau area. With the current setup extreme events and years can be identified almost in real-time. This helps to better prepare for the summer conditions with for example with extreme melt rates due to high spring and summer temperature.

Table 3. Summary of the most important weather stations in the super-sites area.

Station name	Distance from BS [km]	Altitude [m. a.s.l.]	Years of Activity	Parameters measured
Batysh Sook Rock	0	3'908	2023-2025	Air Temperature Relative Humidity
Taragai	8	3'557	2010-2025	Air Temperature Precipitation Relative Humidity Incoming SW Radiation Wind Speed
Grigoriev Ice Cap	25	4'600	2022-2025	Air Temperature
Akshiirak Borehole	28	3'553	2023-2025	Air Temperature Relative Humidity Wind Speed
Tien Shan Weather Station	43	3'614	2001-2015	Air Temperature Precipitation Relative Humidity Incoming SW Radiation Wind Speed
Batysh Sook Ice	0	4'242	2023-2025	Air Temperature Relative Humidity Incoming SW Radiation Wind Speed Snow Height

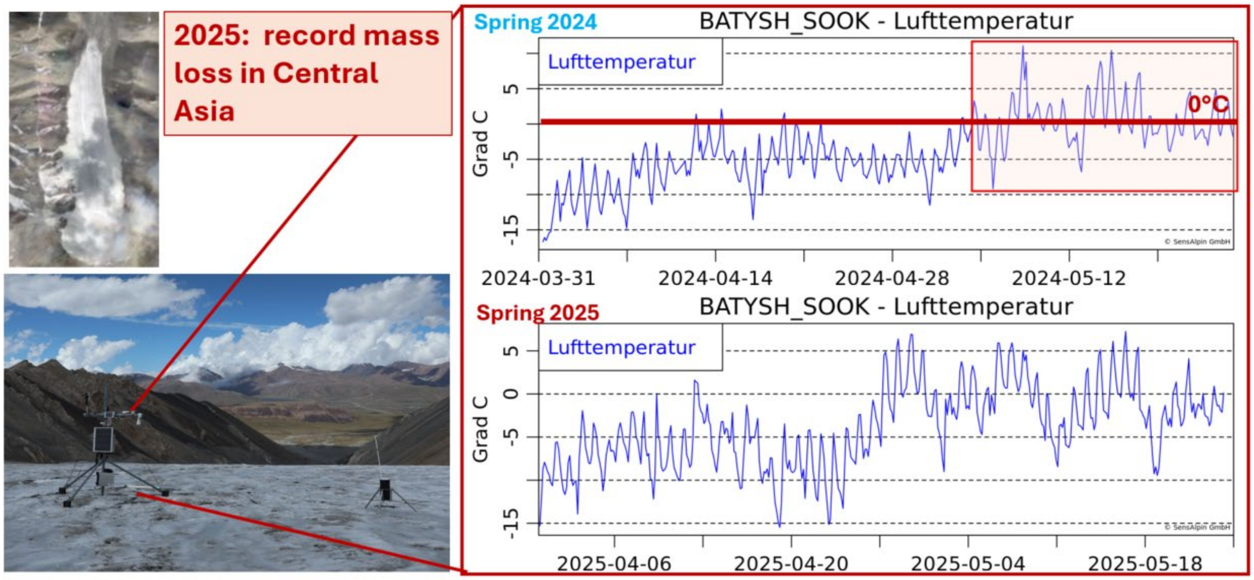


Figure. 18. Comparison of air temperature measured at Batysh Sook at 4242 m a.s.l. for spring 2024 and the extreme year 2025.Source.

Hydrological monitoring. At glacier terminus of glaciers 354 and Batysh Sook, hourly discharge data is derived from a calibrated, automatic water level gauge since 2023. In spring 2025, rain gauges were installed at the AWS BS_ice (Table 1).

Geodetic surveys and remote sensing. For glacier 354, several studies provide estimates on glacier mass change based on high resolution geodetic surveys (e.g. Kronenberg et al., 2016, Barandun et al., 2018, Petrakov et al., 2014; Pieczonka et al., 2015). For Batysh Sook glacier high resolution digital elevation models are available from drone flights. Evolution of the on-glacier snow cover (snowline elevation and snow-covered area fraction) is monitored through satellite imagery (Landsat and Sentinel) and a time-lapse camera at glacier 354 as a proxy for glacier mass balance (Fig. 19). Drone-based surveys of the glacier terminus have been conducted since 2022, providing high-resolution data on frontal retreat and thickness change. Remote sensing based snowline observations improve extrapolation of in situ mass balance observations to glacier scale for both glaciers (Fig. 20, Kim et al., 2025).

Figure 19. Terrestrial snowline cameras for monitoring snow cover conditions at glacier 354.

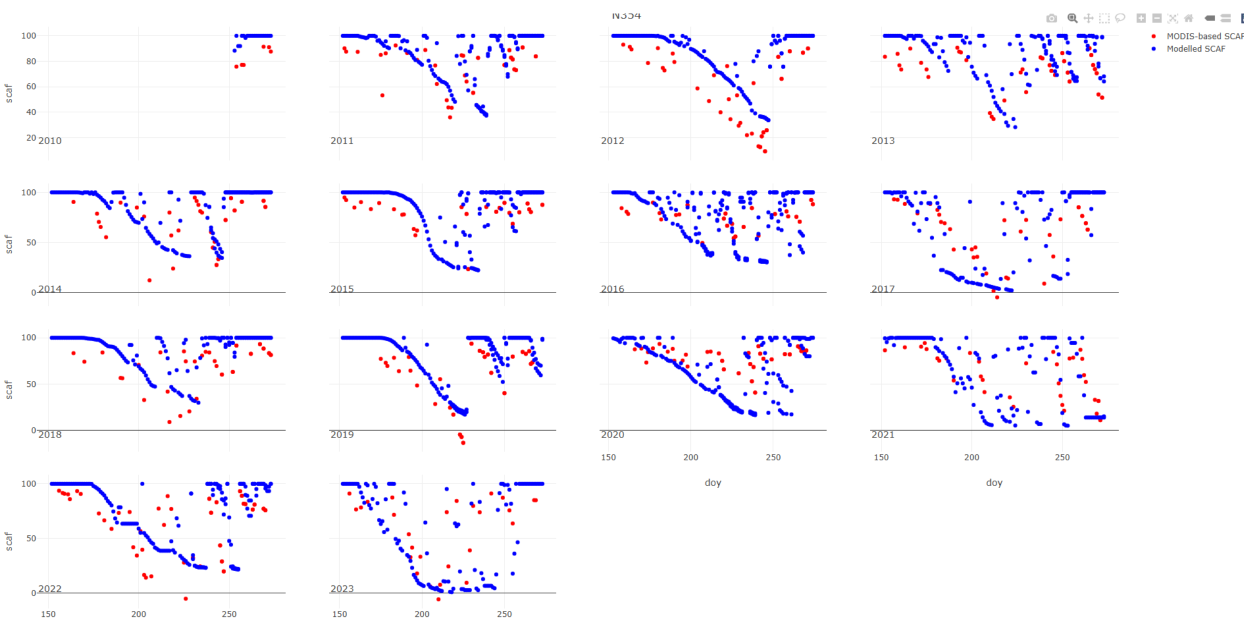


Figure 20. Comparison of extrapolated in situ observation on glacier scale and to daily resolution since the onset of measurements in 2010 with close-to-daily snowline observations based on remote sensing for glacier 354. Source: Kim et al 2025

Ice thickness. Ground-penetrating radar (GPR) campaign was conducted repeatedly in the region (e.g. Hagg et al. 2013; VanTricht et al., (2021); Petrakov et al., 2014).

Firn temperature monitoring: Grigoriev Ice Cap, situated in the Terskey Ala-Too mountain range of Kyrgyzstan, boasts a long-standing tradition of firn and ice core drilling, with the practice having commenced as early as 1962. In this study, the record was extended with the addition of a new 18-metre firn core, which was drilled in February 2018 (Fig. 21). Furthermore, continuous firn temperature measurements were taken on the summit of Grigoriev ice cap, at an altitude of 4600 m a.s.l. (Machguth et al., 2024). However, apart from lateral runoff evidence, the firn's thermal regime appears to have undergone no significant changes. In 2018, the lowest recorded temperatures were observed to be -1.6°C at a depth of approximately 17 m. However, the temperature in 2023 is comparable to the early 2000s, with a similar mean temperature of -2.5°C (Machguth et al., 2024). Moreover, there has been negligible change in net accumulation since the 1980s (Machguth et al., 2024). This new data facilitates the observation of climate change-induced feedbacks, including the potential stabilisation of firn temperatures by the removal of latent heat through lateral meltwater runoff, and a compensatory increase in accumulation due to enhanced mass loss (Machguth et al., 2024). The hypothesis is further substantiated by data from a nearby weather station.

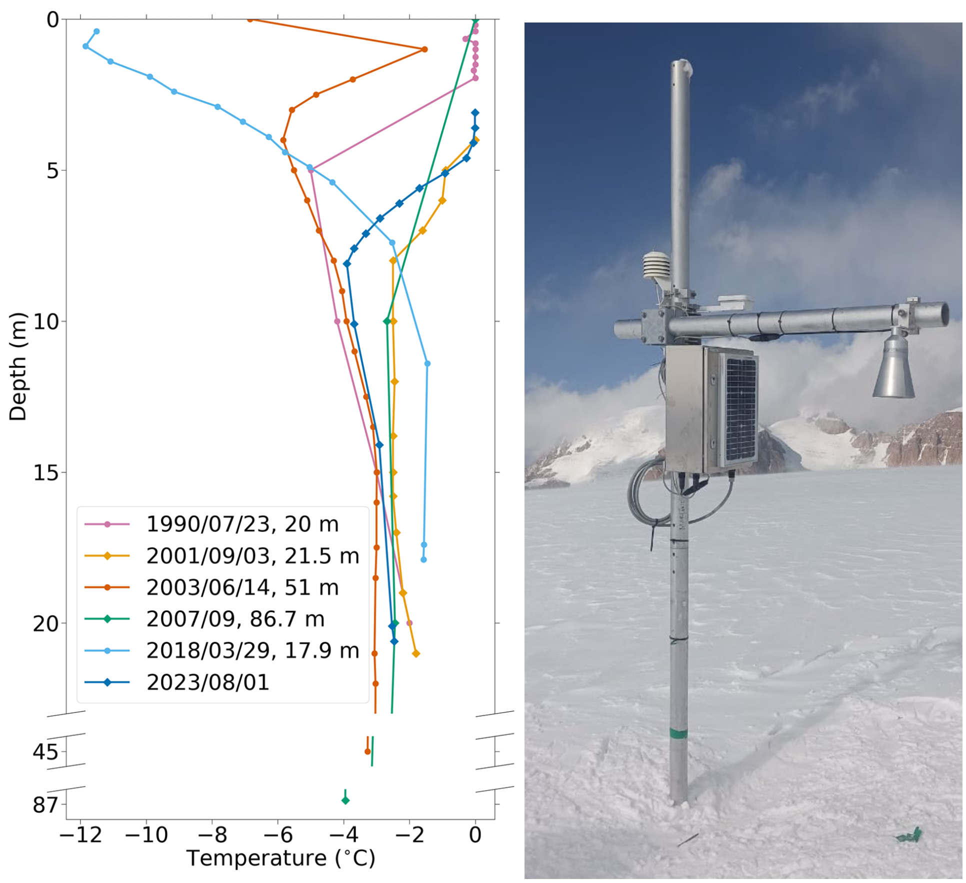


Figure 21. Left Firn temperatures measured on or near the summit of Grigoriev ice cap, 1990 to 2018. Date and depth of the borehole are indicated for each measurement (Figure from Machguth et al., 2024). **Right**: picture of the AWS and firn temperature station.

Permafrost monitoring:

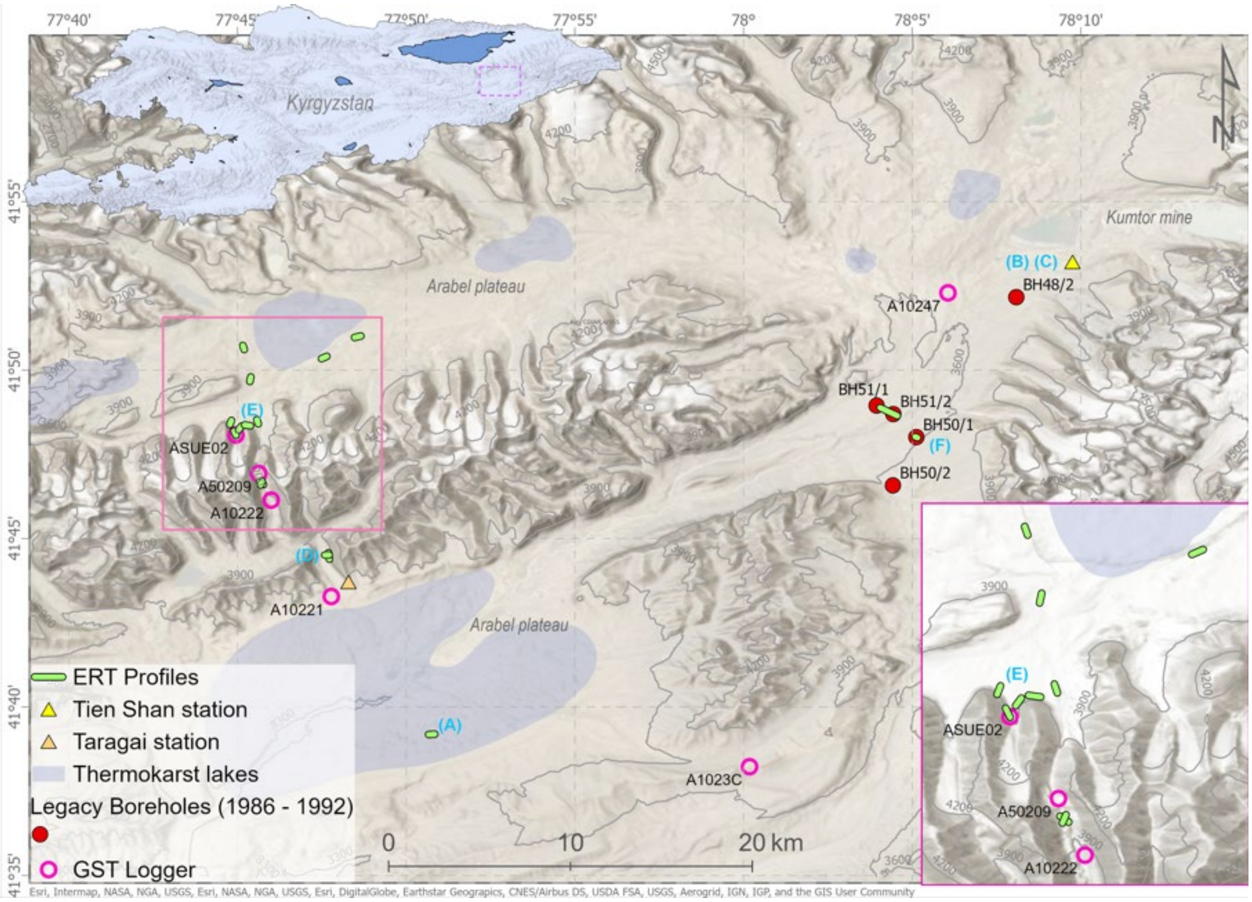


Figure 22. An overview of all permafrost monitoring sites.Source: Mathys et al 2024.

An overview of all permafrost monitoring sites across the supersite Naryn is shown in Fig.22. In the Akshiirak massif (3500–4200 m a.s.l., Kyrgyzstan), over 30 permafrost temperature monitoring boreholes were established. These revealed permafrost thicknesses of up to 350 m in bedrock and 270 m in moraines, with ground temperatures as low as –6.7^{o} C (Ermolin et al., 1989; Gorbunov 1996). These results laid the foundation for understanding the regional distribution and physical properties of high-mountain permafrost.
A new permafrost temperature monitoring borehole and the revived existing borehole are now continuously monitoring ground temperatures to a depth of approx. 30 m. in the Akshiirak region (Fig. 23 and 24; e.g. Marchenko et al., 2007, Hoelzle et al., 2025). Ground surface temperature monitoring network spans across all cryosphere monitoring sites is providing essential data for validating permafrost distribution maps.

These geophysical measurements have been carried out systematically since 2021 around the cryosphere monitoring sites (Mathys et al., 2024). A total of 12 ERT profiles, out of which 3 profiles were measured also with RST. Additionally, a permanent automatic ERT monitoring profile has been installed, providing continuous daily ground resistivity data (Fig. 23).

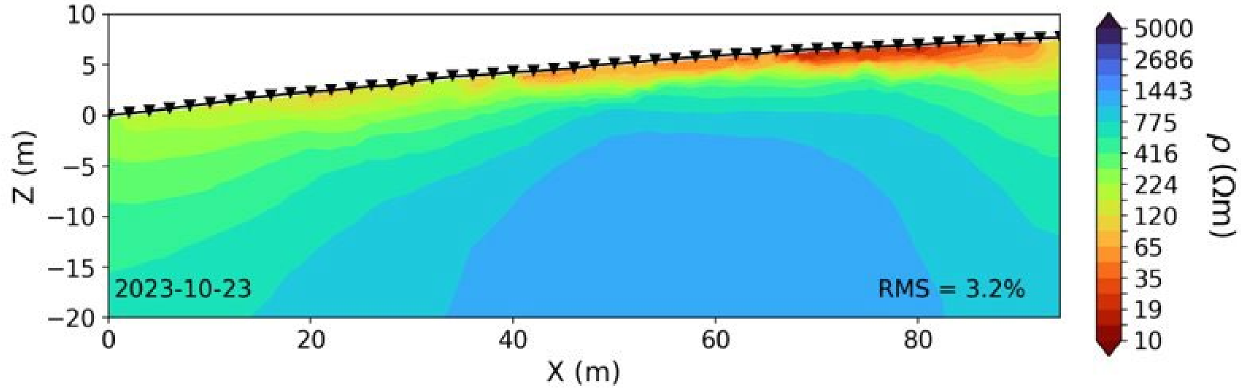


Figure 23. Automatic ERT profile in the Ak-Shiirak massif region, in the vicinity of the newly installed borehole**.** Source: Hoelzle et al., 2025

With the new borehole, direct comparison of historical (Marchenko et al., 2007) and recent borehole temperatures in the Akshiirak massif indicated a warming of up to 0.9°C at a depth of 18-20 m from 1986 to 2024 (Fig. 24, Hoelzle et al., 2025). The ground ice content of the newly drilled borehole in the Akshiirak massif was estimated to be as high as 40% (Hoelzle et al., 2025). Electrical resistivity tomography (ERT) surveys conducted in the northern Tien Shan in 2013 and 2017 identified high resistivities indicative of ice-rich permafrost (Severskiy, 2017). To complement the borehole temperature monitoring, numerous geophysical surveys were carried out across the basin (Mathys et al., 2025). This data helps on the one hand to estimate the ground ice content and its correlation to landform types and on the other hand to calibrate a permafrost model.

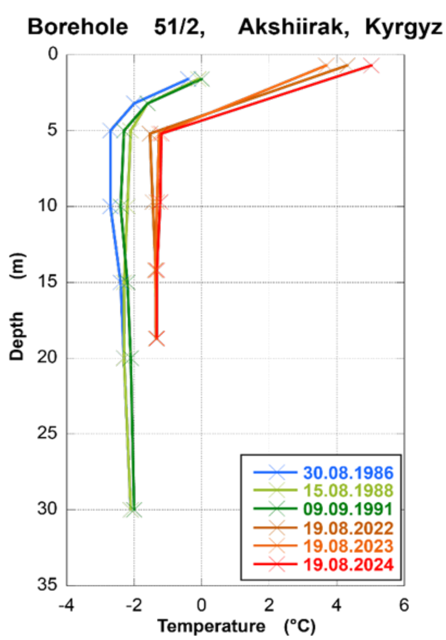


Figure 24. Comparison of historical permafrost temperatures recorded in the borehole 51/2 in Akshiirak, Kyrgyzstan with recent temperatures measured in the same borehole. The temperature profiles clearly reveal a strong warming of around 0.9°C in 20 m depth. Source: Barandun et al., in press.

Monitoring gaps and needs

Despite the significant progress achieved since 2011, some important monitoring gaps remain across all cryospheric components at the Naryn supersite.

Currently glacier mass balance is determined from annual field surveys conducted near the end of the hydrological year, which constrains the temporal resolution of observations and limits the ability to resolve intra-annual variability and the processes governing seasonal glacier surface mass exchange (e.g., Huss et al., 2009; Zemp et al., 2019). The monitoring of ice flow velocity is currently lacking, restricting the critical insights into glacier dynamics and overall glacier response to climate change in this region. Accumulation-zone dynamics remain unobserved, and the short duration of the record is insufficient to characterise the full spectrum of dynamical behaviour. Compared to snow and permafrost monitoring, glacier monitoring is well advanced, with measurements now focusing on detailed process understanding. Glacier monitoring is more advanced than snow and permafrost monitoring, and measurements can now focus on detailed process understanding. The next step is to use firn stratigraphy, densification and surface characteristics, such as detailed albedo and surface roughness observations, to improve our understanding of how glaciers respond to extreme weather conditions, as observed in recent years.

For permafrost monitoring, no rock glacier velocity monitoring currently exists at the supersite. Rock glacier flow is one of the most accessible and informative indicators of permafrost dynamics, yet the numerous rock glaciers located in the supersite have not been tracked for surface displacement.

While snow monitoring at the site is relatively well established, current operations still rely heavily on international technical and financial support, raising concerns regarding long-term sustainability. In addition, only a fraction of the former Soviet-era snow stake observation network remains operational, substantially limiting the spatial representativeness of snow observations in the region. To ensure sustainable long-term monitoring, targeted investments are required both for the rehabilitation and expansion of the national snow monitoring network and for strengthening operational capacities for modern snow observation techniques, including UAV-based snow depth mapping and remote sensing-supported monitoring approaches. Recent initiatives in Kyrgyzstan have demonstrated the strong potential of UAV-supported snow monitoring for improving high-elevation snow observations and operational cryosphere services.

At the catchment scale, while discharge has been monitored since 2019, the record is still short and the separation of glacier melt, snowmelt, and permafrost contributions to total runoff has not been formally attempted.

3.3 Eastern Pamir

The Eastern Pamir is a high-elevation plateau-like mountain region located at the eastern margin of Tajikistan, forming part of the Pamir orogenic system and extending towards the western

Kunlun and Tian Shan ranges. The region is characterised by broad intermontane basins separated by mountain ranges exceeding 5000–6000 m a.s.l., with mean elevations above 3500–4000 m a.s.l. The Karakul Basin is one of the largest of these intramontane depressions, centred on Lake Karakul at ~3900 m a.s.l., and forms a closed (endorheic) hydrological system within the eastern Pamir plateau (Fig. 1)

Climatically, the Eastern Pamir is characterised by cold-arid conditions with strong continentality, low precipitation, and high evaporation. Moisture supply is primarily controlled by mid-latitude westerly circulation, with annual precipitation generally below 100–150 mm yr^{-1} in basin floors and increasing with elevation (Barandun et al in press). In contrast to the more humid western Pamir and Hissar-Alai ranges, the Eastern Pamir exhibits a pronounced rain-shadow effect (Mischke et al., 2010; Heinecke et al., 2017). Permafrost is widespread and exerts a strong influence on hydrological processes, slope stability, and sediment transport across the region.
Glaciers in the Eastern Pamir (Murghab and Karakul basins) are generally smaller and cold-based compared to those in the more humid western ranges, reflecting the limited precipitation supply (Savoskul et al 2013; Kabutov et al 2022). According to the Glacier Atlas-Catalogue of Tajikistan (In preparation, ~year 2018), the Eastern Pamir hosts more than 1600 glaciers with a total area of ~ 1090 km^2.
The focal point of the Eastern Pamir supersite is the Zulmart (No 139) glacier (38° 52′ N, 73° 01′ E ; Fig. 25 and. 26), a valley glacier situated on the southern slope of the Zulmart Range in Tajikistan, within the closed Karakul Lake basin. Covering 3.7 km^2 as of 2018 (Kabutov 2025). Glacier mass balance monitoring on the glacier was initiated in 2018 (Barandun et al., in press). These are the first ever direct glacier mass change observations in the eastern Pamir region. The Eastern Pamir supersite also encompasses Kon-Chukurbashi (No 3) glacier, and a permafrost monitoring borehole, situated to the north from the Karakul lake as well as several geophysical permafrost surveys and ground surface temperature measurements. Combined these sites provide crucial data on cryosphere response to atmospheric warming.
The monitoring strategy at the Eastern Pamir super-site follows the comprehensive approach outlined in Chapter 2, combining systematic in situ measurements at point locations with remote sensing instruments and high-resolution modelling in order to achieve superior spatio-temporal resolution and coverage.

Snow monitoring

Dedicated snow monitoring at the eastern Pamir supersite is currently limited. Snow height sensor on the on and off AWS provide high resolution now height data in two points, however, no dedicated snow stake network, continuous measurement of Snow Water Equivalent (SWE), or systematic snow density surveys are currently operational at the site. Regional-scale snow cover extent is monitored through remote sensing (MODIS, Sentinel-2) as part of the broader monitoring described in Chapter 2.

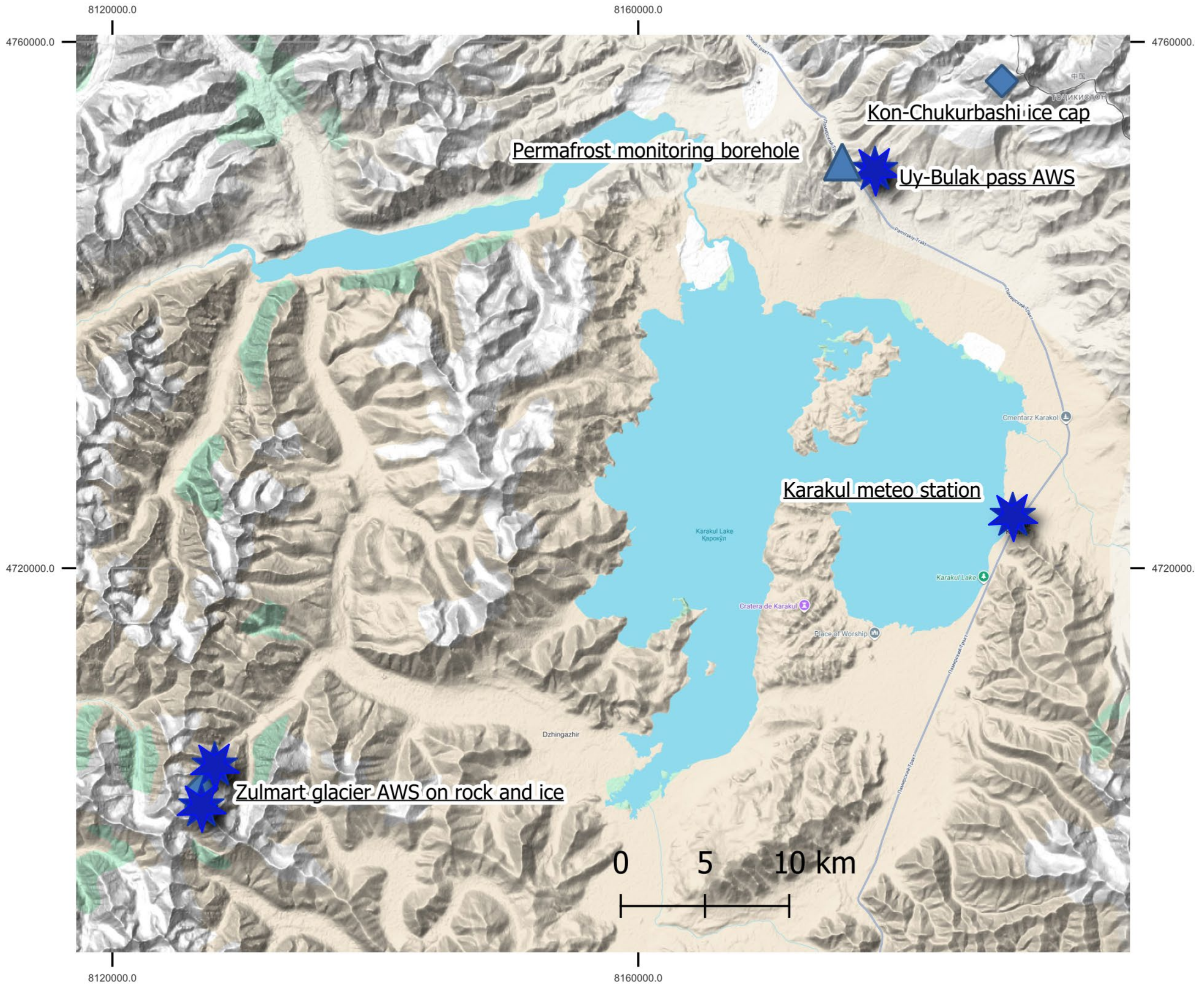


Figure 25. Overview of monitoring network at the eastern Pamir monitoring super site.

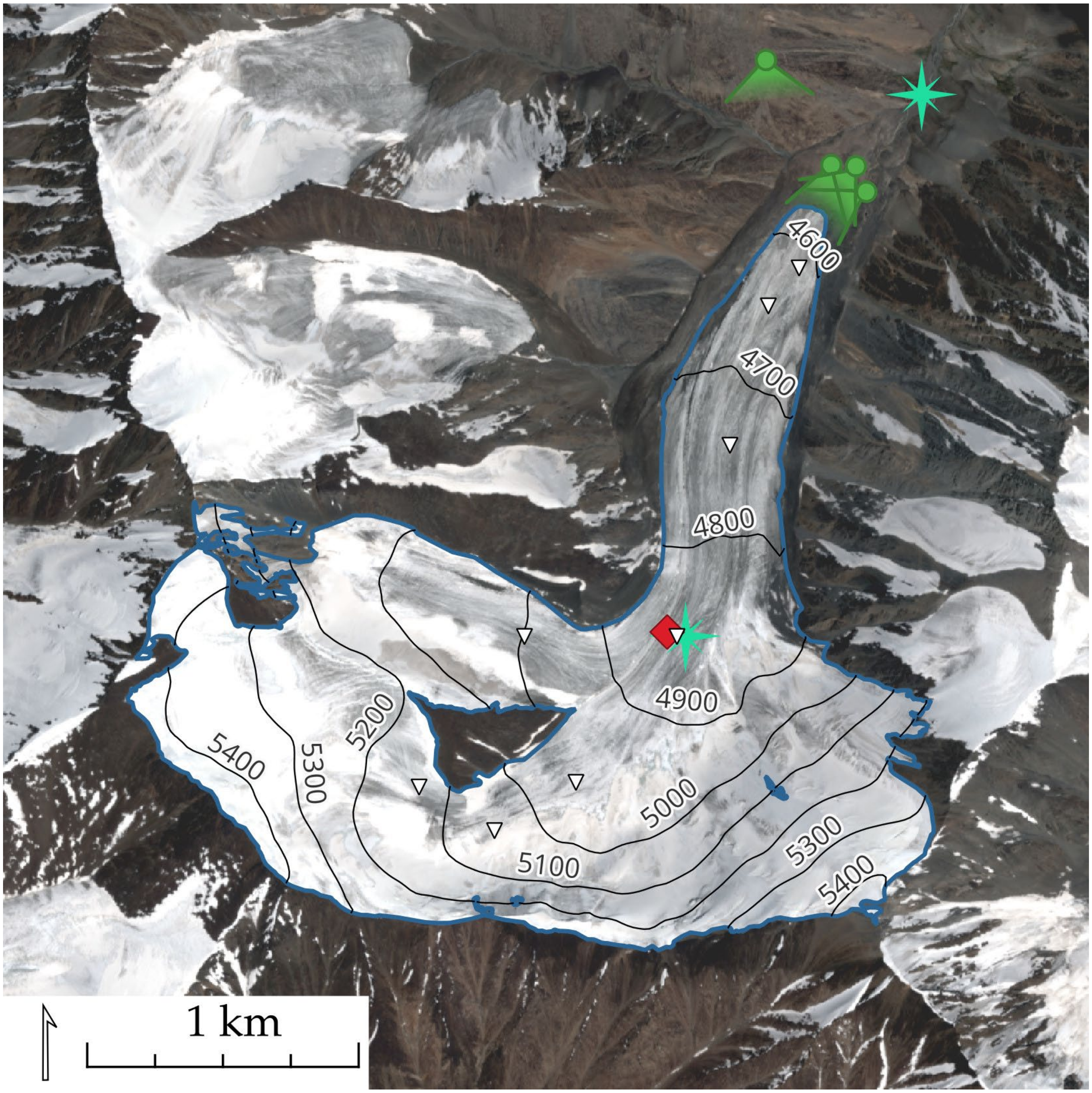


Figure 26. Map of the Zulmart (No 139) glacier. White triangles: present-day mass balance network. Red diamond: SmartStake continuous ablation measurement device. Green stars: automatic weather stations. Green dots: timelapse cameras. Background: Pléiades © CNES 2019, Distribution AIRBUS DS.

Glacier monitoring

Systematic glaciological observations at the Zulmart (No 139) glacier were initiated in 2018 in collaboration between the University of Fribourg and The State Scientific Institution "Center for Glacier Research of the National Academy of Sciences of Tajikistan" (CGR) establishing a monitoring network of 8 observation points (Fig. 26). On glacier Kon-Chukurbashi a network of 7 ablation stakes was established in 2025.

Meteorological monitoring. An automatic weather station (AWS) has been operating since 2019, at 4591 m a.s.l. in the immediate vicinity of the glacier. It provides continuous high-frequency records of air temperature, precipitation, humidity, wind speed and direction, snow height and incoming solar radiation, collecting the essential meteorological data to drive glacier energy and mass balance models. An additional on-glacier AWS was installed in 2023 (Fig. 27). Additionally, since 2024, a thermistor chain near the AWS on ice, logging englacial temperature up to depth of 12 m, has been installed.

Figure 27. Automatic weather station on Zulmart glacier, installed in 2022.

Surface mass balance. Annual glaciological measurements have been conducted continuously since 2018 (Barandun et al., in press). Mass balance observations are collected at a network of ablation stakes and snow pits distributed across the glacier. Since 2022, continuous measurement of ice ablation at the point scale has been added with an innovative design (SmartStake by A2 Photonic Sensors), enabling observations at sub-hourly time resolution.

Geodetic surveys and remote sensing. Data from the Pléiades satellite constellation, acquired in 2015, 2020, and twice annually since 2022, provide high-resolution Digital Elevation Models for the assessment of recent surface elevation change. Evolution of the on-glacier snow cover (snowline elevation and snow-covered area fraction) is monitored through satellite imagery (Landsat and Sentinel) and a time-lapse camera as a proxy for glacier mass balance. Drone-based surveys of the glacier terminus have been conducted since 2023, providing high-resolution data on frontal retreat and thickness change. Additional time lapse cameras observe glacier front change and penitentes growth since 2023.

Ice thickness. A ground-penetrating radar (GPR) campaign was conducted in August 2023 on the Zulmart Glacier and in September 2024 and 2025 on the Kon-Chukurbashi glacier, On Zulmart glacier, a total length of 8.3 km of GPR profiles were measured providing detailed ice thickness distribution data for the lower part of the glacier (Fig. 28). GPR measurements on the glacier Kon-Chukurbashi, with profile length exceeding 10 km, provided data on glacier thickness distribution and internal structure.

Ice core. In 2025 two ice cores were extracted from the top of the glacier Kon-Chukurbashi (approximately 5800 m a.s.l.), in collaboration with the Pamir project, with the aim of reconstructing past climate variability and past atmospheric composition. In the coming future these efforts will improve our understanding of westerly circulation dynamics in Central Asia and provide long-term context for current glacier retreat.

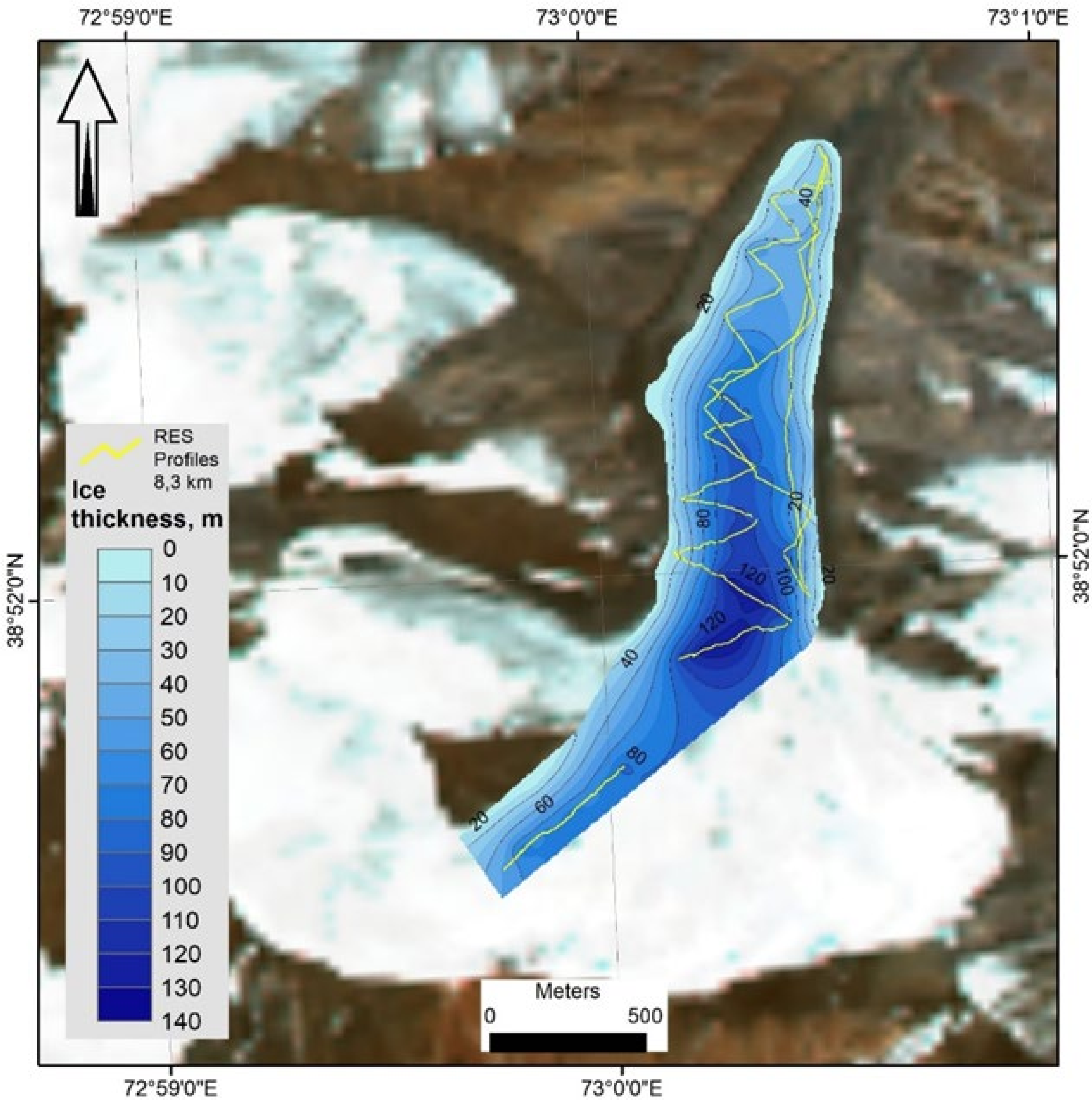


Figure 28. Ice thickness distribution for Zulmart glacier, according to 8.3 km GPR measurements in 2023.

Hydrological monitoring. Water level and discharge at the glacier outlet have been monitored since 2020, providing continuous records of proglacial streamflow linked to glacier melt and groundwater contribution.

Permafrost monitoring

In 2024 a permafrost monitoring borehole was installed at the Uy-Bulak Pass (coordinates N39.203017, E73.442117) at an elevation of 4264 m a.s.l., north of Lake Karakul in Tajikistan, which is providing essential ground temperature data (Fig. 29). The borehole was equipped with the thermistor chain, logging temperature up to 25 m depth. This is the first permafrost monitoring borehole in the Pamir mountains.

Figure 29. Permafrost temperature monitoring site at Uy-Bulak pass, eastern Pamir super-site.

Ground surface temperature (GST) loggers have been installed in the Zulmart glacier catchment since 2023, providing continuous records of near-surface ground thermal conditions. Geophysical surveys to characterise permafrost distribution in different surface types (e.g. talus slopes, rock glaciers) and ground ice content (Hilbich et al., 2009) have been conducted at the Zulmart glacier site and wider eastern Pamir since 2023. Electrical resistivity tomography (ERT) and refraction seismic tomography (RST) are invaluable tools for detecting and characterizing permafrost conditions, delineate active layer and taliks, and in case of repeated measurements, assess the changes in ground properties (Mathys et al., 2024). Four ERT profiles and 1 RST profile have been measured on different landforms in the catchment, including rock glaciers, talus slopes, fine-grained sediments, and the glacier's lateral moraine (Mathys et al., 2025). In 2025, 6 additional ERT profiles were measured across Karakul lake, aiming to further characterize permafrost conditions in the area as well as ice content. The collected data have been processed using the petrophysical joint inversion (PJI) approach, for quantitative estimation of volumetric ground ice content across these landforms.

Monitoring gaps and needs

Despite the significant progress achieved since 2018, important monitoring gaps remain across all cryospheric components at the Eastern Pamir supersite.

Snow monitoring remains particularly limited. Although automatic weather stations provide valuable meteorological observations, reliable quantification of solid precipitation is still challenging due to undercatch and the scarcity of high-elevation measurements. Continuous observations of snow water equivalent (SWE) are currently absent, and systematic snow density surveys are lacking. Consequently, the seasonal snow storage and its spatial variability across glacierized and non-glacierized terrains remain insufficiently constrained, limiting the accuracy of hydrological forecasting and regional water balance assessments. Expanding the snow monitoring network through additional SWE observations, rehabilitation of historical snow stake sites, and sustained UAV-based surveys would substantially improve process understanding and operational forecasting capabilities.

Glacier monitoring in this supersite was established in 2018 (Barandun et al., in press) and has advanced considerably in recent years, yet several key limitations persist. Glacier mass balance is still primarily derived from annual field campaigns conducted near the end of the hydrological year, restricting the temporal resolution of observations and limiting the ability to resolve intra-annual variability and seasonal surface mass exchange processes (e.g. Huss et al., 2009; Huss and Hock, 2015; Zemp et al., 2019).

So far, the thermal regime of the Zulmart Glacier has only been monitored in the ice part. The firn temperature, hydrology and strategy remain unknown, resulting in a significant knowledge gap regarding internal ablation and accumulation processes (e.g. superimposed ice formation). The glacier is highly dependent on incoming shortwave radiation and turbulent heat fluxes, which have not yet been adequately quantified. The next step is to use the AWS ice data to constrain different heat fluxes in order to assess the influence of turbulent and latent heat fluxes such as sublimation and refreezing processes.

Due to its dependency on radiation, the glacier is subject to penitentes, which result in very high surface roughness. Despite initial attempts to monitor penitentes growth using stereo imaging time-lapse cameras, the impact of high surface roughness on the mass balance remains unclear.

Future efforts should therefore focus on expanding continuous monitoring of ice flow velocities and expanding high-temporal-resolution measurements of albedo, sublimation and firn stratigraphy to better understand glacier response under increasingly extreme climatic conditions.

For permafrost monitoring, no rock glacier velocity monitoring currently exists at the supersite. Rock glacier flow is one of the most accessible and informative indicators of permafrost dynamics, yet the numerous rock glaciers located in the supersite have not been tracked for surface displacement.

The geophysical survey programme – which has provided the only available characterisation of ground ice distribution in the supersite – was conducted within the framework of individual research projects. The continuation of repeat surveys beyond these projects is not guaranteed, and without repeated measurements at the same profiles, temporal changes in permafrost conditions cannot be detected. This sustainability problem is compounded by the limited number of local scientists who have been trained to conduct independent geophysical surveys in Central Asia.

At the catchment scale, while discharge has been monitored since 2020, the record is still short and the separation of glacier melt, snowmelt, and permafrost contributions to total runoff has not been formally attempted. Nevertheless, at regional scale, cryospheric data from the super-sites were used to validate climate impact studies on Naryn and Vaksh catchments (Naryn and Hisar-Alay super-sites) (Huan 2025, a and b). Such studies should be reproduced also for other catchments to link the different cryosphere components with the hydrosphere.

4. Perspectives and Recommendations

The following recommendations address the gaps identified above and outline a path towards more comprehensive and sustainable cryospheric monitoring at the Central Asian super-sites.

Across all super-sites, the snow monitoring strategy for Central Asia now needs to prioritize re-establishing the formerly operational snow stake network once maintained by national hydrometeorological services. A critical gap exists in high-altitude observations - precisely where the majority of seasonal snow storage is concentrated. This network should be complemented with modern technologies, including UAV-based surveys, remote sensing products, and in-situ, online sensors. Together, these approaches can significantly improve estimates of SWE while reducing the costs and logistical demands of traditional airborne campaigns. Furthermore, enhancing avalanche hazard mapping and early warning systems remains vital. This involves maintaining and upgrading existing avalanche monitoring stations and integrating advanced tools for real-time observation and alerting capabilities. Moreover, for snow monitoring, SWE should be introduced as a continuously measured variable. A promising low-cost approach suitable for the remote high-mountain environment is the monitoring of lake level fluctuations using pressure transducers: as demonstrated by Pritchard et al. (2021), lake-level time series can be used to infer SWE evolution with good accuracy, requiring only simple instrumentation. In parallel, point-wise snow height measurements at sub-daily frequency could be introduced using time-lapse camera setups at individual locations within the catchment; these are low-cost, easy to deploy, and have already proven effective at glacier monitoring sites in Central Asia. Further, the suitability of the super-site for the installation of more advanced SWE monitoring technologies – including cosmic ray sensors and snow pillows – could be formally evaluated. These instruments provide continuous SWE estimates that would substantially reduce the current uncertainties in water resource management and forecasting.

The sustainability of glacier mass balance monitoring on a long-term basis is of highest priority. Efforts are now underway to modernize the instrumentation and to complement the basic infrastructure with novel and more experimental set-ups. These efforts include GPS stations to monitor glacier dynamics, high-resolution remote sensing applications, reprocessing of historical satellite and aerial photographs as well as in situ monitoring of atmospheric variables at the glacier surface at sub-daily time scales. This will help to better understand the past and current behaviour of glaciers, and ultimately their future response in a changing climate, including changes in vital meltwater contribution to total river discharge in summer. Furthermore, for glacier monitoring, an improved, spatially extended, continuous monitoring of mass changes should be a priority. This could include both the installation of additional devices for sub-hourly measurement of ice ablation, and SWE monitoring as outlined in the previous section. Dedicated measurement and modelling of the spatial distribution of snowfall under different meteorological conditions would also be beneficial, to overcome the current limitations in the understanding of snow accumulation variability. In this context, characterising and monitoring snow avalanche deposition on the glacier surface is an important and currently neglected aspect: avalanche redistribution can substantially modify the spatial pattern of accumulation, and its magnitude and frequency should be quantified to improve annual mass balance estimates. The fusion of in situ observations with satellite-derived products – including Sentinel-2 snow line tracking, Pléiades geodetic surveys, and image-based velocity mapping – should be advanced towards near-real-time, glacier-wide and catchment-wide products, building on the methodological frameworks already developed for the site (Barandun et al., 2018; Mattea et al., 2025; Kim et al., 2025). The monitoring of glacier dynamics should be maintained and expanded and a long-term installation for monitoring englacial temperatures should be established at the focal points of each super-sites, to characterise the glacier thermal regime and its evolution under continued atmospheric warming.

Permafrost research in Central Asia is still in its infancy. Ongoing collaborative activities between Central Asian and international scientists will greatly improve our understanding of the state and distribution of permafrost in the Tien Shan and Pamir. However, capacity building of local researchers and national research institutions is urgently needed, and awareness must be raised about the risks associated with permafrost degradation in Central Asian countries. One of the most pressing issues at present is the sustainability of permafrost research in Central Asian countries. Therefore, a long-term government commitment for the monitoring strategy is needed for each Central Asian country. For permafrost monitoring across the super-sites, operational satellite-based monitoring of rock glacier velocity should be introduced, using interferometric SAR (InSAR) or optical image correlation to track surface displacements across the rock glaciers of the catchment at multi-annual to seasonal intervals. This would provide a spatially comprehensive and sustainable indicator of permafrost dynamics. The geophysical survey programme should be supported through the training of local scientists capable of independently conducting ERT and RST measurements and processing the resulting data. Ensuring that annual repeat surveys at selected reference profiles are locally managed — rather than dependent on visiting international teams – is essential for the long-term continuity of the permafrost observational record. The new collected data is integrated into global permafrost network databases such as the Global Terrestrial Network for Permafrost (GTN-P) (Biskaborn et al., 2015). These observations provide: (i) monitoring of the most important variables according to international standards, (ii) data, which is permanently and openly accessible in the target countries and (iii) data, which is available at the designated international data centres (Noetzli et al., 2021) and are the cornerstone of sustainable and comprehensive permafrost monitoring in the region. The next steps are to gradually establish a new permafrost infrastructure and data storage for systematic observations of permafrost changes in the Tien Shan and Pamir.

Across all monitoring domains, a fundamental enabling condition is strengthened transboundary cooperation and local awareness. The Hissar-Alai super-sites spans three countries, and the full value of the observations can only be realised through coordinated data collection, open sharing, and joint analysis. Moving towards nationally funded, locally managed observation programmes — supported by but not dependent on international projects — is the only path to long-term sustainability. In this light, it is also worth recalling that a substantial body of detailed observations from the Soviet era — covering not only mass balance but also meteorology, hydrology, ice dynamics, and accumulation distribution — remains largely inaccessible, stored in printed archives held by institutions in Tashkent, Bishkek, and elsewhere in the region. As highlighted by Mattea et al., (2026), these archives represent an irreplaceable scientific resource whose recovery and reanalysis, in close collaboration with local partners, could significantly extend the observational baseline available to current research and monitoring.

5. Conclusion

Over the last two decades, a substantial progress has been achieved in re-establishing glacier mass balance observations, automated weather station networks, permafrost monitoring, UAV-based snow surveys, and high-resolution hydrological measurements. In several domains, Central Asia now hosts observational infrastructures of international significance, including some of the longest glacier monitoring records worldwide and newly emerging high-frequency monitoring systems capable of resolving sub-daily cryosphere processes. The integration of in situ observations with remote sensing products, geophysical surveys, and numerical modelling has substantially improved the capacity to assess regional cryosphere change and associated impacts on downstream water resources. Importantly, many of these monitoring activities are now increasingly led by Central Asian scientists and institutions, strengthening regional scientific ownership and technical capacity.

Despite this progress, significant observational and institutional gaps remain. Snow monitoring networks remain sparse compared to the former Soviet-era system, long-term monitoring of glacier dynamics related variables is still limited, and systematic observations of permafrost deformation and ground ice evolution are only beginning to emerge. Many monitoring activities continue to depend heavily on short-term international project funding, raising concerns regarding long-term sustainability, maintenance, and institutional continuity. In addition, major geographical gaps persist in climatically distinct regions such as the Eastern Pamir and Dzungarian Alatau. Addressing these challenges will require sustained national investment, stronger integration of cryosphere monitoring into operational hydrometeorological services, expansion of open-access data infrastructures, and continued regional cooperation in scientific training, technical development, and standardized observation protocols.

The supersite concept offers a practical and scalable pathway toward a sustainable regional cryosphere observing system. Concentrating resources and expertise into strategically selected, highly instrumented reference catchments enables efficient long-term monitoring while simultaneously supporting process understanding, model development, and operational climate services across the cryosphere components and atmo-, cryo- and hydrosphere. Beyond scientific value, the super-sites provide critical infrastructure for transboundary water cooperation, early warning systems, hydropower planning, agricultural water management, and climate adaptation across Central Asia. As atmospheric warming accelerates cryosphere degradation throughout the region, sustained investment in integrated cryosphere monitoring clustered within selected super-sites will become increasingly essential for ensuring water security, reducing climate risks, and supporting evidence-based decision-making for the mountain societies and downstream populations that depend on the water towers of Central Asia.

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