Climate-Driven Glacier Dynamics in the Upper Amu Darya Basin, Tajikistan

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Abstract. The Amu Darya River basin, particularly its Khingov and Surkhob sub-basins in Tajikistan, is an important headwater area in Central Asia. Glaciers in this region play a critical role in sustaining freshwater resources for agriculture, hydropower, and livelihoods. Together, the two basins account for 13.9% of Tajikistan's glacier coverage and 9.1% of Central Asia's total glacier area. This study assessed glacier changes using the USSR Glacier Inventory (1971, 1978), satellite remote sensing, GIS analysis, and hydroclimatic records (1961–2022). We quantified glacier area changes, identified surge-type glaciers, and examined the implications of climate change for regional hydrology. In the lower reaches and right-bank parts of the Khingov River Basin included in the comparative assessment, glacier area decreased from 164.6 km² in 1978 to 150.7 km² in 2022, representing an overall reduction of 13.9 km² (8.4%). In the Surkhob basin, glacier area declined from 401.1 km² in 1971 to 348.6 km² in 2022, a loss of 52.5 km² (13.1%). Glacier losses were particularly severe (20–39%) in the Yarkhich sub-basin. The mean air temperature increased by 1.5°C during 1961–2022, contributing to glacier retreat and changes in runoff generation. Below 3300 m, runoff is predominantly snowmelt-driven (60–64%), whereas above 3500 m, glacier meltwater contributes up to 23% of total runoff. A total of 143 surge-type glaciers (26% of the total) were identified in the two basins, approximately 20% of which show signs of recent activity with potential hydrological implications. These findings highlight the need to strengthen glacier monitoring and implement adaptive water management strategies to support regional water security under ongoing climate change.

Keywords: climate change impacts, glacier monitoring, pamir mountains, remote sensing, water security.

1. Introduction

Climate change has become one of the major drivers affecting global hydrological systems, especially in glacier-fed mountain regions such as the Himalayas, Pamir, and Tien Shan mountains. Variations in temperature, precipitation, and snow cover strongly influence glacier dynamics and water availability across High Mountain Asia (HMA) (IPCC, 2022; Wang et al., 2025). Global mean temperature increased by approximately 0.85°C between 1880 and 2012 due to anthropogenic greenhouse gas emissions, and future warming in HMA is projected to exceed 2°C by 2100 under moderate climate scenarios, with even higher increases under high-emission pathways (Kraaijenbrink et al., 2017; Stocker et al., 2013). Such warming accelerates glacier retreat and mass loss, as confirmed by satellite observations, field measurements, and climate-model simulations (Hugonnet et al., 2021; Davaze et al., 2020).

Recent studies indicate that glaciers in HMA may lose more than one-third of their total mass by the end of the century, while glacier systems in some regions could lose the majority of their present ice volume under extreme climate scenarios (Hugonnet et al., 2021). Glacier degradation also increases debris cover, destabilizes mountain slopes, and enhances the risk of Glacial Lake Outburst Floods (GLOFs), threatening hydropower infrastructure, irrigation systems, freshwater availability, and mountain ecosystems (Compagno et al., 2022; Zemp et al., 2019; McColl, 2012). These challenges highlight the importance of integrated glacier and hydrological monitoring using remote sensing, climate modeling, and runoff analysis (Rounce et al., 2020; Huss & Hock, 2018).

Central Asia has been recognized as one of the region most vulnerable to climate change impacts (Chen et al., 2024; Nasrulloev et al., 2026a; 2026b). In Tajikistan, glaciers cover nearly 6% of the national territory and represent a major freshwater source for the Amu Darya and Syr Darya river basins (Chen et al., 2026; Immerzeel et al., 2010). Glaciers in Tajikistan contribute more than 60% of the total water resources of Central Asia and play a key role in supporting downstream agriculture, hydropower generation, and ecosystems (Nasrulloev et al., 2026b; Xu et al., 2026). The upper Amu Darya basin is particularly dependent on glacier and snow melt originating from the high mountains of Tajikistan and Afghanistan.

Climate-model projections suggest that many glacier-fed river basins, including the Amu Darya, could experience runoff reductions exceeding 10% by 2100, with peak runoff expected between 2030 and 2050 (Huss & Hock, 2018). Modern remote sensing techniques and GIS technologies provide effective tools for monitoring glacier extent, velocity, surface conditions, and debris cover (Paul et al., 2020; Brun et al., 2017). However, glacier monitoring in Tajikistan remains limited because of sparse

observational records, difficult access to high-mountain regions, and the reduction of monitoring stations after the 1990s (Kotlyakov et al., 2020).

Historical glacier inventories and regional studies documented significant glacier retreat, fragmentation of glacier systems, and the disappearance of small glaciers in the Pamir-Alay region during the twentieth century (Halimov et al., 2026). These changes confirm the high sensitivity of tributaries within the Vakhsh River basin to climatic warming (Nasrulloev et al., 2026a). Long-term Landsat archives, Digital Elevation Models (DEMs), and hydrological models now allow reconstruction of glacier dynamics and assessment of their hydrological impacts (Scherler et al., 2018; Liang et al., 2023).

The aim of this study is to comprehensively assess the current state and dynamics of glaciers in the upper Amu Darya River basin (the Khingov and Surkhob river basins) under the influence of global climate change. To achieve this goal, remote sensing data and GIS analysis were employed, enabling: (1) the evaluation of glacier area changes over the period from 1971–1978 to 2022; (2) the identification of spatial patterns of glacier degradation, including differences between the upper and lower parts of the basins and the influence of slope aspect; (3) the analysis of the relationship between glacier changes and climatic factors; (4) the assessment of the contribution of glacial meltwater to the runoff of the Vakhsh river basin (Khingov and Surkhob) and the risks of water resource deficits amid the ongoing reduction of snow cover. The results of this study aim to improve glacier monitoring programs and develop recommendations for sustainable water resource management under conditions of climate instability.

2. Materials and Methods

2.1. Study Area

This study focuses on the high-mountain basins of the Surkhob and Khingov rivers, located in the upper reaches of the Amu Darya one of the most important water arteries of Central Asia. These basins are characterized by a high degree of glaciation and play a significant role in maintaining the regional water balance and hydrological processes.

The Khingov River basin, the largest tributary of the Vakhsh River, is recognized as one of the most glaciated regions of the Pamirs. Glaciers cover approximately 11% of its total area (6660 km²). The valley extends approximately 180 km from west to east and more than 70 km from north to south. It is bounded by the Peter the First Range to the north, the National Academy of Sciences Range to the east, and the Darvoz Range to the south, which collectively define its distinctive topographic and climatic characteristics (Fig. 1) (USSR Glacier Inventory, 1978).

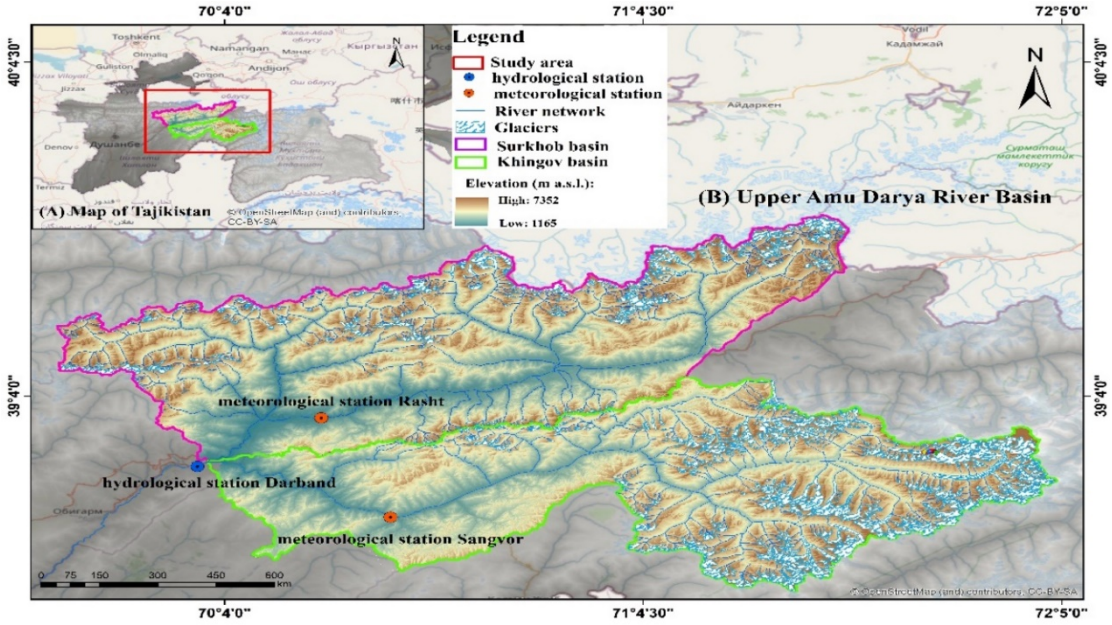


Figure 1. Study area (Upper Amu Darya, Khingov and Surkhob river basins)

The Surkhob River basin, with an area of about 7286 km², extends in an east–west direction. It is formed by the confluence of the Surkhob (Kyzylsu) and Mughob (Muksu) rivers, and upon merging with the Khingov River, it gives rise to the Vakhsh River. The northern boundary of the basin is delineated by the Alay and Zarafshon ranges, while the southern boundary is defined by the Peter the First Range. Glacier-fed tributaries in the northern part of the basin are notably longer (~40 km) than those in the southern part (~10–15 km). The Surkhob valley itself extends approximately 150 km in length (USSR Glacier Inventory, 1971).

2.2. Data Sources

To assess the spatial and temporal changes in glacier extent, multispectral satellite images from Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI with a spatial resolution of 15–30 meters were utilized. The primary source of satellite data was the United States Geological Survey (USGS) EarthExplorer platform (USGS, n.d.). The images were predominantly acquired at the end of the ablation season (August – early September), ensuring minimal seasonal snow cover and optimal conditions for delineating glacier boundaries.

For terrain analysis, a Digital Elevation Model (DEM) derived from Shuttle Radar Topography Mission (SRTM) data was employed, enabling the extraction of elevation, slope, and aspect information. Additional data sources included historical glacier inventories (USSR Glacier Inventory, 1971, 1978), the GLIMS glacier boundary

database (GLIMS, n.d.), scientific articles, monographs, satellite imagery from Google Earth, and field observations collected during scientific expeditions.

Hydrological data on mean monthly discharge at the Darband hydrological station for the period 1961-2022, located in the upper reaches of the Vakhsh River basin, were provided by the Agency for Hydrometeorology under the Committee for Environmental Protection of the Government of the Republic of Tajikistan. Climate data, including mean annual temperature for the period 1961-2022 and annual precipitation for the period 1970-2022, were also obtained from this agency.

Among the operating meteorological stations located within the upper reaches of the Vakhsh River basin, three stations were selected for analysis: two within the Surkhob River basin - Lakhsh (central part of the basin) and Rasht (eastern part), and the Sangvor (Tavildara) station, located in the Khingov River basin.

2.3. Methods

2.3.1. Glacier Mapping and Digitization

Initial image preprocessing, including geometric correction, georeferencing, and composite generation, was performed using ArcGIS 10.8 and QGIS 3.28 software packages. For topographic analysis, the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) with a 30 m spatial resolution was utilized, enabling the extraction of morphometric characteristics such as mean elevation, slope, and aspect of glacierized areas.

Glacier outlines were manually delineated through visual interpretation of false-color composites (Landsat 5/7/8 bands 5-4-3), supported by the Global Land Ice Measurements from Space (GLIMS, https://www.glims.org/maps/glims) glacier database. This approach ensured high accuracy in capturing glacier extents and facilitated temporal comparisons with historical inventories. Special attention was paid to debris-covered glaciers and shadowed zones, where manual adjustments were required to refine boundaries.

The accuracy assessment accounted for spatial resolution and the complexity of glacier geometry. The shape complexity (or sinuosity) of glacier boundaries was evaluated using the formula:

$$f = \frac{P^2}{4\pi S} \qquad (1)$$

where P is the perimeter and S is the area of the polygon. This coefficient indicates the degree of boundary irregularity, which correlates with the potential error (Berlyant, 1978). The number of pixels (N_p) within the reference area was calculated as:

$$N_p = \frac{S}{L^2} \quad (2)$$

where L is the spatial resolution. The raster-based measured area was determined by:

$$S_n = N_n + L^2 \quad (3)$$

and the relative error of area estimation was calculated using the empirical formula:

$$\delta = a * (\frac{S_n}{L^2})^b \quad (4)$$

where *a* and *b* are empirical coefficients. Atmospheric conditions such as cloud cover, sensor noise, and processing errors were also considered as potential sources of uncertainty (Kupriyanov et al., 2018). Based on the spatial resolution of Landsat imagery and the complexity of glacier boundaries, the uncertainty in glacier area estimates was considered to be approximately ±2–5% for debris-free glaciers and ±5–10% or higher for debris-covered and small glaciers. These uncertainty ranges were taken into account when interpreting the estimated glacier area changes.

The processed and reconstructed time series were analyzed and visualized using ArcGIS and Microsoft Excel**,** enabling a comprehensive assessment of water balance dynamics in conjunction with glacial changes.

2.3.2. Glacier Inventory and Area Estimation

A detailed inventory of glaciers in the Khingov and Surkhob river basins was compiled based on the processed Landsat satellite imagery for 2022. This inventory provides updated glacier outlines, areal measurements, and classification by size categories and morphological types, including surge-type glaciers. The historical USSR Glacier Inventories (1971 and 1978) were used as reference datasets to establish baseline glacier areas and support temporal comparisons. The 2022 glacier outlines were independently delineated from Landsat imagery using a consistent manual digitization procedure, ensuring methodological consistency in the updated inventory.

For the Khingov River Basin, the comparative assessment of glacier area changes between 1978 and 2022 was restricted to the lower reaches and right-bank parts of the basin. Other sectors were excluded from this comparison due to the presence of surge-type glaciers, which exhibit dynamic behavior that may complicate direct comparisons of glacier outlines between different observation periods. Therefore, the reported glacier area values for 1978 and 2022 represent only the two assessed sectors and should not be interpreted as the total glacier area of the entire Khingov River Basin. The combined glacier area of these sectors was calculated by summing their respective areas.

The analysis revealed that the glacierized area constitutes approximately 11% of the total basin area, primarily concentrated in the higher elevations of the surrounding

mountain ranges. This substantial degree of glaciation is attributed to the favorable orientation of the basin relative to prevailing moisture-bearing westerly and southwesterly airflows. In contrast, the lower parts of the basin, representing about one-quarter of its total area, are entirely devoid of glacier cover.

Glacier boundaries were digitized manually in ArcGIS, resulting in polygon layers saved in Shape file format. Each polygon includes spatial and attribute information: a unique glacier identifier, names corresponding to entries in the (USSR Glacier Inventory, 1971, 1978), and updated area values derived from the 2022 remote sensing data. This research provides a critical basis for detecting and quantifying glacier changes over recent decades and evaluating their influence on river runoff and water resources management.

3. Results

3.1. Glacier Changes in the Khingov River Basin

3.1.1. Spatial Distribution and Characteristics

The main glacier masses are concentrated in the upper part of the Khingov River basin, predominantly within the valleys of its major tributaries - the Garmo and Kargasrud rivers - as well as in the basin of the left tributary, the Bohud River (Fig. 3). The meridional segment of the Academy of Sciences Range, enclosing the headwaters of the Garmo River valley, is characterized by absolute elevations ranging from 5600 to 6800 m. In the vicinity of the Siston Glacier, at the junction of the National Academy of Sciences Range and the Peter the First Range, rises Ismoil Somoni Peak - the highest point in Tajikistan (7485 m). The eastern section of the Peter the First Range reaches elevations of 5800–6500 m, where its highest summit, Moscow Peak (6785 m), is located. The southwestern spur of this range, known as the Garmo Range, separates the valleys of the Garmo and Kargasrud rivers, gradually descending from 6000 to 5000 m. Overall, the Khingov River basin is characterized by extensive glaciation, covering an area of more than 700 km². A distinctive feature of this region is that the glaciers do not form isolated masses but instead extend along the valley slopes in nearly continuous chains. For a more detailed analysis of the spatial differentiation of glaciation, the territory was conventionally divided into four major regions Figure 2.

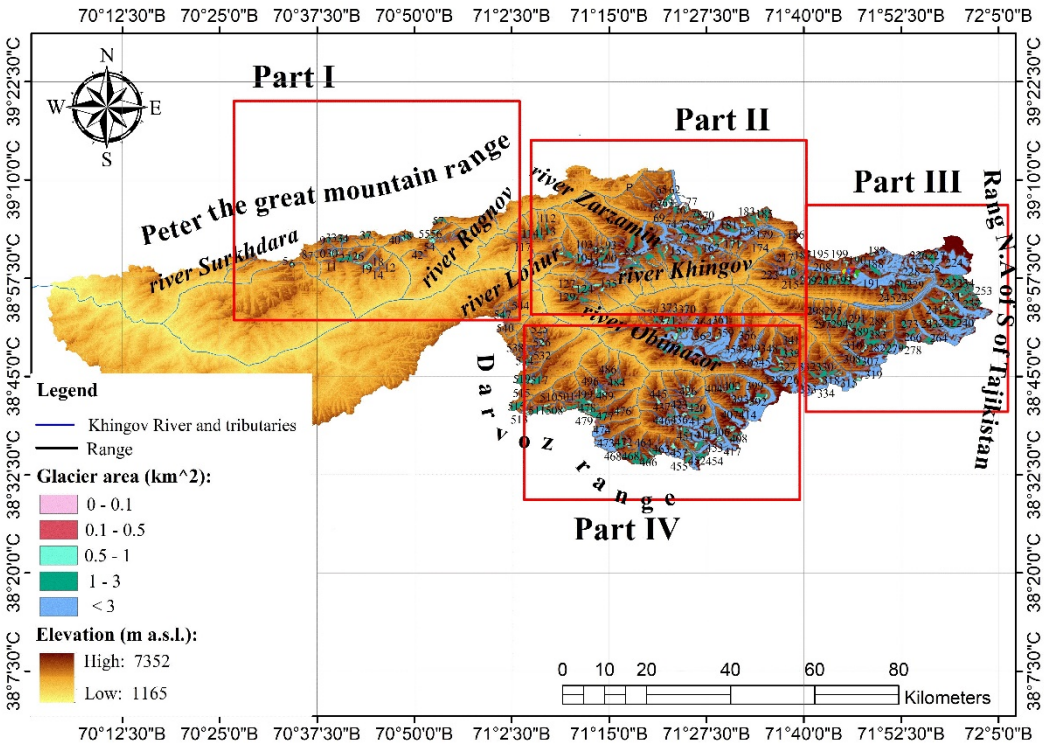


Figure 2. Schematic map of glacierized regions in the Khingov River basin

Within the Khingov River basin, 549 glaciers with an area greater than 0.1 km² have been identified, with a total glaciated area of 701.9 km². In addition, 207 smaller glaciers (with an area less than 0.1 km²) have been recorded, covering a combined area of 10.5 km² (USSR Glacier Inventory, 1978).

The lower reaches of the Khingov River (part I) encompass the southern slopes of the Peter the First Range in the lower part of the basin. This area includes the catchments of the right-bank tributaries, characterized by relatively small glacier formations (No. 1–61). A total of 85 glaciers are identified here, covering an area of 27.4 km², of which 61 glaciers have an area ≥ 0.1 km² (total glaciated area of 25.9 km²), and the remaining 24 glaciers are smaller than 0.1 km², occupying a combined area of 1.5 km². The glacier cover in the lower basin is predominantly composed of small ice bodies: 78.2% of glaciers (24) have an area less than 0.1 km², and 48.3% (41 glaciers) fall within the range of 0.1–0.5 km². Glaciers with an area of 0.5–1.0 km² are rare and account for only 14.1% (12 glaciers). No glaciers exceeding 1 km² in size occur in this sector. The largest glacier in the lower reaches covers 2.6 km². The mean glacier area is only 0.3 km², the smallest value among all sectors of the basin. This glacial pattern indicates degradation processes and the dominance of small glacier forms in the lower valley. The right bank of the Khingov River (part II) encompasses the central part of the

Peter the First Range, including its southern branch and extending from the northern part of the Tuda Plateau in the west to the basin of the Devlokh Glacier in the east. The main glacier massifs of this sector are concentrated within the Ragnov River basin (No. 62–186). A total of 200 glaciers have been identified in this area, covering a combined surface of 137.6 km². Of these, 125 glaciers have an area ≥ 0.1 km², accounting for a total glaciated area of 134.2 km², while the remaining 75 glaciers, each with an area < 0.1 km², together occupy 3.4 km². Small glaciers dominate the region's glaciation structure: 41.4% (75 glaciers) are smaller than 0.1 km². Glaciers ranging from 0.1 to 0.5 km² represent 33.7% (61 glaciers), and 11.5% (21 glaciers) are between 0.5 and 1.0 km². Medium-sized glaciers (1–5 km²) constitute 9.9% (18 glaciers) of the total count. Among the larger glaciers, three glaciers fall within the 5–10 km² range and another three within the 10–20 km² range, representing 1.7% of each class. Glaciers larger than 20 km² are absent in this sector. The largest glacier in the right-bank region, the Peter the First glacier, has an area of 24.2 km². The average glacier size in the right-bank sector is approximately 0.8 km², which is the lowest among all major regions of the basin and reflects the predominance of small-scale glacial forms.

The Upper Khingov River (part III) represents the largest glaciated area, situated between the ranges of the National Academy of Sciences, the eastern segments of the Peter the First Range, the Darvoz Range, and the Mazori Range. This sector encompasses the catchments of the Gando, Garmo, Bohud, Batrut, and Bijov rivers (No. 187–377). Within this territory, there are 270 glaciers with a total area of 356.4 km². Of these, 191 glaciers have an area ≥ 0.1 km² (collectively covering 352.4 km²), while the remaining 79 glaciers with areas < 0.1 km² account for only 4 km². The glacier system of the upper Khingov River basin is characterized by the highest concentration of large glaciers. Specifically, 35.3% (79 glaciers) are smaller than 0.1 km², 37.9% (85 glaciers) range from 0.1 to 0.5 km², 11.1% (25 glaciers) have areas between 0.5–1.0 km², and 9.4% (21 glaciers) are medium-sized, ranging from 1–5 km². The largest glaciers of the eastern sector include six glaciers with areas of 10–20 km² (2.7%) and two glaciers larger than 20 km² (0.9%). The Garmo Glacier, the largest in this region, covers 114.6 km², making it not only the largest in the Khingov basin but also one of the largest in Central Asia. The average glacier size in this area is 1.6 km², significantly exceeding the basin-wide mean. This high degree of glaciation is attributed to the region's location in the most elevated parts of the basin and favorable conditions for snow accumulation. The left-bank area of the Khingov River (part IV) encompasses glaciers located on the northern slopes of the Darvoz Range and the catchments of the left tributaries of the Khingov River below the confluence of the Obimazor River, as well as one tributary above the confluence containing two glaciers

(No. 378–549). In total, this sector hosts 201 glaciers covering an area of 191 km², of which 172 glaciers have an area ⩾ 0.1 km² (total glaciated area of 189.4 km²), while the remaining 29 smaller glaciers (< 0.1 km²) account for only 1.6 km².

Within the catchments of the left-bank tributaries of the Khingov River (part III), glaciers smaller than 0.1 km² represent 15.8% (29 glaciers) of the total number (184). The majority of glaciers in this sector (51.1%, or 94 glaciers) fall within the 0.1–0.5 km² size class. Glaciers of 0.5–1.0 km² are less common, comprising 10.3% (19 glaciers), while medium-sized glaciers (1–5 km²) are represented by 37 glaciers (20.1%). Large glaciers are rare in this area, with only 2 glaciers of 5–10 km² (1.1%) and 3 glaciers in the 10–20 km² range (1.5%). Glaciers exceeding 20 km² in area are absent. The largest glacier in the southern sector covers 27.8 km². The average glacier area in this region is 1.0 km², which is close to the mean value for the basin; however, excluding the largest glaciers reduces the average to 0.8 km². This distribution indicates a predominance of small and medium-sized glaciers with a relatively low proportion of large ones.

Analysis of the glacier size distribution reveals that the vast majority (72.4%) of glaciers have areas less than 1 km², with 30.7% of them being smaller than 0.1 km². In contrast, large glaciers exceeding 10 km² (accounting for only 2% of the total number) contribute nearly half of the total glaciated area within the basin. The mean glacier area in the Khingov River basin is 1.0 km²; however, this average is significantly influenced by the presence of the largest glaciers in the upper reaches and left-bank sectors.

3.1.2. Area Changes and Slope Aspect

A comparative analysis conducted for the Lower and Right-Bank sections of the Khingov River basin using data from the (USSR Glacier Inventory, 1978) and satellite imagery from 2022 revealed a reduction in glacier area in these zones from 164.6 km² to 150.7 km² over a 40-year period. This represents an approximate decrease of 10% in glacier coverage. It should be noted that the majority of surge-type glaciers in the Khingov River basin are concentrated mainly in the Upper and Left-Bank sections. Therefore, a comparative analysis of glacier area changes was not performed for these parts of the basin. The results of the comparative assessment of glacier numbers and areas are summarized in Table 1, which presents changes based on 1978 data and updated outlines derived from 2022 satellite imagery.

Table 1. Glacier Area Changes in the Khingov River Basin for the Period 1978–2022

Glaciated Area	Glaciers (>0.1 km²)	ID Range	Glaciers (<0.1 km²)	Min elev. (m)	Max elev. (m)	Area 1978 (km²)	Area 2022 (km²)	ΔS (2022–1978), km²	Change, % (2022–1978)
Lower reaches	61	1–61	24	2700	4700	27.4	21.9	5.5	20
Right bank	125	62–186	75	2900	5500	137.2	128.8	8.4	6.1
Upper reache	191	187–377	79	2980	6350	356.4	the main body of surging glaciers		
Left bank	172	348–549	29	3380	5800	191.0	the main body of surging glaciers		
Total	549	1–549	207	2700	6350	712.4 (164.6)	150.7	13.9	8.4

An analysis of the spatial distribution of glaciers by slope aspect revealed a pronounced asymmetry in their distribution. Glaciation predominantly develops on slopes with northern, northeastern, and northwestern orientations. These aspects provide more favorable conditions for snow accumulation and reduced ablation due to lower solar radiation and increased shading. Specifically, slopes facing north (N), northeast (NE), and northwest (NW) account for 61.9% of the total number of glaciers (549 glaciers) and 67.1% of their cumulative area (712.4 km²) (USSR Glacier Inventory, 1978) (Fig. 3).

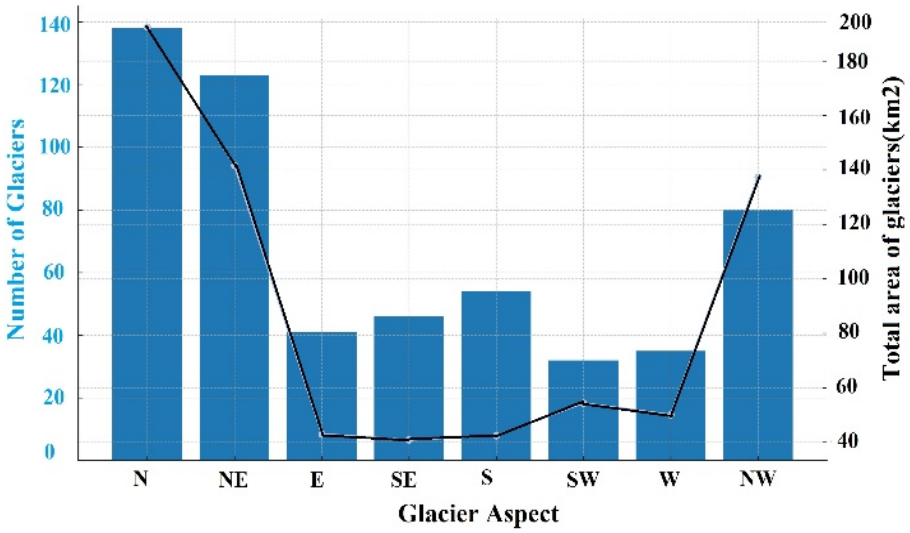


Figure 3. Distribution of glaciers by exposure in the Khingov River basin (The left diagram shows the number of glaciers in different directions of exposure. The right diagram shows the total area of glaciers for each direction)

Conversely, southern and southeastern slopes are less favorable for glaciation: only 18.2% of glaciers are located here, occupying merely 11.8% of the total glacierized area. Glaciers with western and eastern aspects exhibit intermediate values in both number and area, confirming the significant influence of slope aspect on the distribution and dynamics of glacier cover in the Khingov River basin.

3.2. Glacier Changes in the Surkhob River Basin

3.2.1. Spatial Distribution and Characteristics

Glaciation in the Surkhob River Basin is located in the western part of the Pamir-Alay, a transitional zone between two major mountain systems of southern Central Asia: the southern Tian Shan (Alay and Zarafshon ranges) and the Pamir (Peter the First and Kabudreg ranges). The orographic boundary between these systems is defined by the latitudinally oriented Surkhob River valley. The northern part of the basin comprises the southern slopes of the Alay and Zarafshon ranges, while the southern part includes the northern slopes of the western section of the Peter the First Range, which is approximately 1000 m lower than its eastern extension. The Surkhob watershed is formed by runoff from the opposing slopes of these mountain systems, with the right-bank territory being highly dissected by a dense network of tributaries. Within the basin, four orographic zones are distinguished, corresponding to the catchments of major tributaries: the Kabudrud, Yarkhich, Sorbog, and the left-bank tributaries of the Surkhob (Fig. 4).

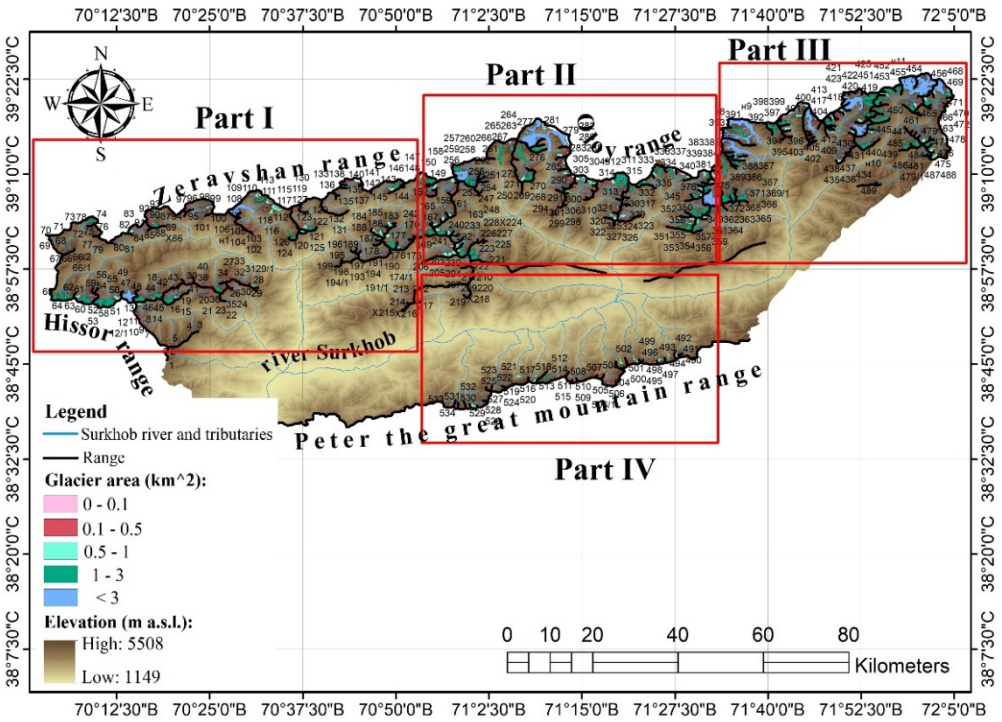


Figure 4. Schematic map of glacierized regions in the Surkhob River basin

The right-bank mountain slopes, which host the majority of the glaciers, are influenced by moist southwesterly winds. As these air masses move eastward, their moisture content decreases, affecting the elevation of the firn line. In the Sangikar River basin, the firn line averages 3780 m a.s.l., in the Sorbog and Yarkhich basins it rises to 3880 m, and in the Kabudrud basin it reaches approximately 3990 m. The left-bank glaciers, situated on the leeward slopes, experience less favorable snow accumulation conditions. However, due to their northern exposure and the specific morphology of the ridges, their firn line lies at a lower average elevation of 3630 m. Overall, the firn line on north-facing slopes is 220–240 m lower than on south-facing slopes.

According to the (USSR Glacier Inventory, 1971)**,** the Surkhob basin contains 534 glaciers larger than 0.1 km², with a total area of 393.3 km², and an additional 148 smaller glaciers covering 7.8 km². The mean glacier size is 0.6 km² (or 0.74 km² excluding the smaller glaciers). The majority of the glaciation (295.4 km²) is concentrated on the slopes of the Alay and Zarafshon ranges. Glaciers of the Rashton Range cover 85.3 km², those on the northern slopes of the Peter the First Range account for 19.4 km², and the Kabudreg Range host only 1.0 km² of ice. Large glaciers are rare and are mainly found in the upper reaches of major valleys. Notable among them is the Said Nafisi (Baralmos) Glacier on the northern slope of the Peter the First Range, which contributes to the runoff of both the Surkhob and Khingov rivers.

3.2.2. Sub-basin Analysis

In the sub-basins of Sangikar, Sorbog, Yarkhich, Kabudrud, and the left-bank tributaries of the Surkhob River, a particularly high concentration of glacierized areas is observed. Their spatial distribution, especially in the Sangikar and Sorbog sub-basins, is shown in Figure 5(part I) and is influenced by both natural topographic conditions and historical dynamics of glacier coverage.

Specifically, within the Sorbog sub-basin, 285 glaciers have been identified, with a total glacierized area of 114.8 km². Small and medium-sized glaciers dominate the region: the largest share (49.5%, or 141 glaciers) consists of glaciers with an area between 0.1 and 0.5 km². These are followed by glaciers smaller than 0.1 km² (23.9%) and those between 0.5 and 1.0 km² (16.8%). Glaciers larger than 1 km² represent only 9.8% of the total number, with only one glacier exceeding 5 km², having a maximum area of 5.2 km². The average glacier size in the sub-basin is 0.40 km². The Sangikar and Sorbog river basins (part I) encompass glacier termini positioned at elevations ranging

from 2900 to 4850 meters above sea level, reflecting the significant vertical distribution of glacial features within these catchments. The aspect of slope exposition in this area shows a pronounced orientation of glaciers toward the northeast (22.7%), north (18.0%), and northwest (18.0%), collectively accounting for 55.4% of all glaciers. This dominant northern exposure is associated with reduced solar radiation, which contributes to more effective preservation of the snow and ice cover. A comparative analysis of changes in glacierized area in the Sorbog sub-basin between 1971 and 2022 indicates a decrease from 114.8 km² to 103.0 km², corresponding to a reduction of 11.8 km² or approximately 10%. This trend reflects ongoing glacier retreat in the region, albeit at a lower rate compared to other sub-basins.

Within the Yarkhich sub-basin (part II), 177 glaciers have been identified with a total glacierized area of 106.8 km². The majority are small to medium-sized glaciers: the largest share (45.7%) consists of glaciers ranging from 0.1 to 0.5 km², while 22.2% of glaciers are smaller than 0.1 km². Glaciers with an area between 1 and 5 km² account for 14.9% of the total, with one large glacier exceeding 10 km² (0.6%), reaching a maximum area of 21.5 km². The average glacier size in this sub-basin is 0.60 km², which is larger than the corresponding value for the Sorbog sub-basin.

Between 1971 and 2022, the glacierized area in the Yarkhich sub-basin decreased from 106.8 km² to 82.0 km², representing a loss of 24.8 km², or 23%. This rate of degradation is the highest among the studied sub-basins and can be attributed to the relatively small glacier sizes and low-altitude ablation zones, which make the glacier cover more vulnerable to climatic changes. The Kabudrud sub-basin (part III) contains 168 glaciers with a total glaciated area of 160.1 km² , making it the largest among the right-bank tributaries of the Surkhob River in terms of glacier coverage. This sub-basin is characterized by a relatively high proportion of large glaciers: 21.6% of glaciers have areas ranging from 1 to 5 km² , and 1.8% have areas between 5 and 10 km² . The largest glacier in the sub-basin covers 15.7 km² , while the mean glacier size is 0.98 km² , which is nearly twice as large as the average glacier size in the Sorbog sub-basin. The glaciers are situated across a wide altitudinal range, from 2400 m to 4800 m above sea level, with larger glaciers mainly concentrated at higher elevations.

Between 1971 and 2022, the total glacier area in the Kabudrud sub-basin decreased from 160.1 km² to 151.8 km², corresponding to a reduction of 8.3 km² or 5.1%. This rate of shrinkage is the lowest among all investigated sub-basins, suggesting more favorable conditions for glacier preservation. Such resilience may be attributed to their higher altitudinal positions and local topographic features that mitigate glacier mass loss.

The left-bank tributaries of the Surkhob River (part IV) exhibit the lowest degree of glaciation among all sub-basins, with only 52 glaciers covering a total area of 19.4 km² . The glacier cover in this region is dominated by small glaciers: 13.5% of them have an area of less than 0.1 km² , and 48.1% range from 0.1 to 0.5 km² . Glaciers between 0.5 and 1.0 km² account for 36.5% of the total, while only one glacier (1.9%) falls into the medium-sized category of 1–5 km² . The largest glacier in this sub-basin reaches an area of 1.9 km² , and the mean glacier size is 0.37 km² , which is considerably smaller than the average for the right-bank sub-basins. The terminus elevations of glaciers in this sub-basin range from 2320 to 4600 m a.s.l. During the study period (1971–2022), the total glacier area decreased from 19.4 km² to 11.8 km², representing an absolute loss of 7.5 km² or 38% of the original glacier extent. This rate of degradation is the highest among all sub-basins within the Surkhob River basin. Such substantial losses are likely attributable to the relatively low elevations of these glaciers and insufficient snow accumulation, which together make them more vulnerable to climatic changes.

These spatial differences in glacier dynamics underscore the pronounced heterogeneity in glacier responses to climatic and topographic factors across the Surkhob River basin. The findings emphasize the need for detailed, localized glaciological studies to accurately assess the current state and predict future changes in glacier systems. These sub-basin-scale variations demonstrate the heterogeneity of glacier responses within the Surkhob River basin, underscoring the importance of localized glaciological analysis.

3.2.3. Area Changes and Slope Aspect

The glacier systems of the Surkhob River basin are distributed across a wide range of elevations and slope aspects. According to the (USSR Glacier Inventory, 1971) and satellite data from 2022, glacier termini in the region occur at elevations ranging from 2320 to 5100 meters above sea level**,** reflecting significant vertical zonation. The total glaciated area in the basin was 401.1 km² in 1971 (USSR Glacier Inventory, 1971), decreasing to 348.6 km² by 2022, which represents a net loss of 52.5 km²**,** or approximately 13% of the original glacier coverage (Table 2). This reduction underscores the ongoing degradation of the cryosphere in response to climatic and morphometric drivers.

Table 2. Glacier Area Changes in the Surkhob River Basin for the Period 1971–2022

Glaciated Area	Glaciers (>0.1 km²)	ID Range	Glaciers (<0.1 km²)	Min elev. (m)	Max elev. (m)	Area 1971 (km²)	Area 2022 (km²)	ΔS (2022–1971), km²	Change, % (2022–1971)

Sangikar and Sorbog Basins	217	1-217	68	2900	4850	114.8	103	11.8	10.3
Yarkhich Basin	138	218-355	39	2720	5100	106.8	82	24.8	23.2
Kabudrud Basin	134	356-489	34	2400	4800	160.1	151.8	8.3	5.2
Left-bank tributaries	45	490-534	7	2320	4600	19.4	11.8	7.6	39.2
Total	534	1-534	148	2320	5100	401.1	348.6	52.5	13.1

The results confirm a pronounced and spatially variable trend of glacier degradation within the Surkhob River basin during the period 1971–2022. The most significant reductions in glaciated area (20–38%) were recorded in the Yarkhich sub-basin and the left-bank tributaries, with important implications for seasonal water availability, particularly during the summer months when meltwater serves as a critical hydrological resource. Conversely, lower glacier retreat rates observed in the Kabudrud sub-basin may reflect the influence of topographic features and microclimatic buffering effects. The spatial orientation of glaciers within the Surkhob River basin is a key factor determining their resilience to contemporary climate change. Analysis of aspect distribution revealed similar patterns in the right-bank sub-basins of Sorbog, Yarkhich, and Kabudrud: the majority of glaciation is concentrated on northeast-facing (22.7 %), north-facing (18.0%), and northwest-facing (18.0%) slopes, which together account for more than half (55.4%) of all glaciers. Eastern (11.7%) and southeast-facing (9.7%) aspects occupy a smaller area, which can be attributed to higher insolation and, consequently, increased rates of ablation.

In the left tributaries of the Surkhob River, glaciers predominantly occur on north-facing (53.3%), northeast-facing (22.2%), and northwest-facing (24.5%) slopes. This pattern further highlights the critical role of cold-exposure slopes in preserving the snow and ice cover under conditions of increasing climatic instability. Glaciers in the Surkhob and Khingov basins currently account for approximately 13,94% of Tajikistan’s total glacier area and about 9,06% of Central Asia’s glaciation.

3.3. Causes of glacial change

Climate change is a primary driver of glacier dynamics in the Vakhsh River basin, particularly in its major sub-basins - Surkhob and Khingov. The most prominent indicators of climate change in this region include a persistent increase in air temperature and alterations in the established precipitation regimes. To quantitatively

evaluate the influence of these climatic variables, an integrated approach was applied, combining long-term meteorological records, satellite remote sensing data, and snow cover modeling. This study analyzed data from the Rasht (Surkhob River basin, 39°00′ N, 70°18′ E), Lakhsh (Surkhob River basin, 39°16′ N, 71°31′ E), and Sangvor (Khingov River basin, 38°42′ N, 70°28′ E) meteorological stations Fig. 5(A). Mean annual air temperature was calculated based on monthly observations from 1961 to 2022, while total annual precipitation was assessed for the period 1970–2022. The results reveal a clear warming trend and a shift in the seasonal distribution of precipitation, both of which directly affect the hydrological and glacial regimes of the region.

Analysis of mean annual air temperature between 1961 and 2022 reveals clear evidence of warming across all three sites: (1) Khingov Basin (Sangvor station): The linear trend equation y = 0.011x – 12.958 (R^2 = 0.0172) suggests a weak but steady rise in air temperature, although the low R^2 reflects strong interannual variability, likely modulated by local topographic and atmospheric factors. (2) Surkhob Basin – Rasht station: The trend here is more pronounced (y = 0.0276x – 43.509, R^2 = 0.1337), indicating a more consistent and sustained warming that likely accelerates glacier ablation and causes an upward shift in the snowline and equilibrium line altitude (ELA). (3) Surkhob Basin – Lakhsh station: A modest warming signal is also evident in the Surkhob basin, particularly at the Lakhsh meteorological station (y = 0.0101x – 13.513, R^2 = 0.0662). Although the coefficient of determination suggests a weak linear relationship (6.6% of variance explained), the upward trend in mean annual temperature remains apparent (Fig. 5).

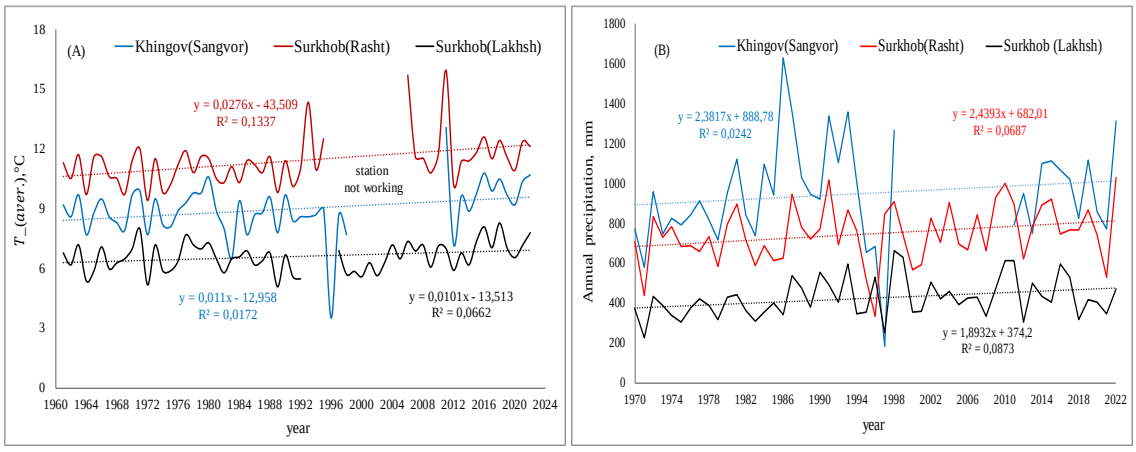


Figure 5. Dynamics of air temperature and precipitation in theupper Amu Darya River basin (Khingov and Surkhob): (A) Trends of mean annual air temperature at Sangvor (Khingov basin, blue), Rasht (Surkhob basin, red), and Lakhsh (Surkhob basin, black) meteorological

stations for the period 1961-2022; (B) Trends of annual precipitation in the Khingov (blue), Surkhob (red), and Lakhsh (Surkhob basin, black) river basins for the period 1970–2022.

Since the 1960s, the average annual temperature has increased by approximately 1.5°C. In high-altitude glaciated basins, even moderate warming can lead to intensified glacial melt due to low baseline temperatures and high sensitivity of the cryosphere to temperature fluctuations. Even a slight increase in temperature causes noticeable changes in the snow cover according to the model: the melting season becomes longer, the volume of meltwater increases, and the glacier mass decreases. In mountainous regions such as the Vakhsh River basin, warming leads to an upward shift of the boundary between the accumulation and ablation zones of snow, which significantly affects glacier dynamics.

Precipitation trends from 1970 to 2022 demonstrate weak but generally positive linear trends, accompanied by high interannual variability: (1) Khingov (Sangvor): The equation $y = 2.3817x + 888.78$ ($R^2 = 0.0242$) suggests a slight increase in annual precipitation (~2.38 mm/year). Despite high variability, the relatively high baseline (average ~920 mm/year) may sustain some glacier accumulation under current climatic conditions. (2) Surkhob (Rasht): The trend $y = 2.4393x + 682.01$ ($R^2 = 0.0687$) shows a similar increase, but with a lower baseline (~740 mm/year). This lower snow input could exacerbate glacier mass loss in response to warming, especially if the precipitation shift includes more rain and less snow. (3) Surkhob (Lakhsh): The lowest baseline precipitation (~420 mm/year) and weakest trend ($y = 1.8932x + 374.2$, $R^2 = 0.0873$) suggest that this basin is the most vulnerable to climate-induced glacier loss. Limited snowfall, combined with high variability, results in irregular accumulation, making it difficult for glaciers to sustain mass balance.

Despite a slight increase in precipitation over time, this growth is likely insufficient to offset the impact of rising temperatures. Moreover, changes in the form of precipitation - specifically, an increased proportion of rainfall instead of snowfall, particularly in spring and autumn — reduce the snow accumulation period and, consequently, lead to a decrease in glacier mass.

3.4. Impact of glacial change on water resources

For assessing the impacts of glacier retreat on water resources in the Surkhob and Khingov River basins, long-term meteorological and hydrological datasets from 1961 to 2022 were analyzed. Specifically, mean annual air temperature records from the Lakhsh meteorological station (39°16′ N, 71°31′ E) and mean annual river discharge data from the Darband hydrological station on the Vakhsh River (38°41′ N, 69°59′ E) were utilized. The Darband station integrates runoff from the tributary basins studied

(Fig. 6). In addition, glacier area changes in the study region were assessed using data from the (USSR Glacier Inventory, 1978) and for the Surkhob River basin (USSR Glacier Inventory, 1971).

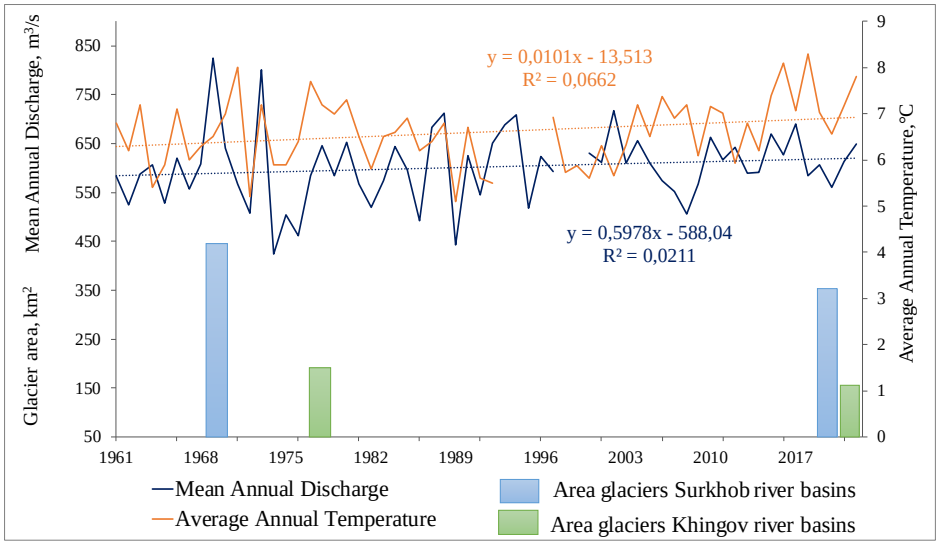


Figure 6. Trends in glacier area, air temperature, and discharge changes in the upper basin of the Amu Darya River (Khingov and Surkhob river basins) during 1961-2022.

The positive trend in mean annual air temperature directly affects the hydrological regime of glaciated basins. According to observations at the Lakhsh meteorological station, the temperature has increased by approximately 1.5°C since the 1960s. Although the coefficient of determination is relatively low ($R^2 = 0.0662$), this warming contributes to accelerated glacier melt and, consequently, a short-term increase in runoff. However, in the long term, it may lead to a reduction in water resources due to the depletion of glacial reserves.

Analysis of long-term hydrological data on mean annual river discharge reveals a weak but positive linear trend: $y = 0.5978x - 583.63$; $R^2 = 0.0211$; where y is the mean annual discharge (m^3/s), and x is the year of observation. Although the coefficient of determination ($R^2 = 2.1\%$) indicates a low degree of statistical explanation of discharge variability, the presence of a positive trend may reflect the combined influence of climatic factors.

Amid rising mean annual air temperatures and ongoing glacier retreat, a slight yet consistent increase in average annual river discharge has been observed, particularly over the past few decades. This trend likely reflects enhanced glacial melt, which temporarily augments summer runoff. However, as glacier reserves continue to diminish, a long-term decline in summer discharge is anticipated, potentially disrupting sustainable water supply and exacerbating water resource vulnerabilities. The clear linkage between regional climate warming, glacier shrinkage, and altered hydrological

regimes in the Vakhsh basin suggests that current increases in water availability are a transient phenomenon driven by accelerated ablation, with future reductions in glacier-fed runoff expected due to continued ice mass loss.

4. Discussion

4.1. Spatial Patterns and Drivers of Glacier Area Change

The transformation of glaciers in the headwaters of the Amu Darya River reflects a complex interplay between climatic dynamics and anthropogenic influences, with direct consequences for regional water resources, sustainable agriculture, hydropower generation, and the preservation of natural ecosystems. In the upper Amu Darya River basin, particularly in the Khingov and Surkhob river basins, our analysis revealed substantial glacier area reductions between the historical inventory periods and 2022. In the Surkhob River Basin, glacier area decreased from 401.1 km² in 1971 to 348.6 km² in 2022, representing a reduction of 52.5 km² (13.1%). In the Khingov River Basin, the comparative assessment of the lower reaches and right-bank parts showed a decrease from 164.6 km² in 1978 to 150.7 km² in 2022, corresponding to a reduction of 13.9 km² (8.4%). These findings are broadly consistent with (Konovalov, 2012), who reported an 8.3% decrease in glacier extent during 1980–2000 and projected a 13% loss by 2020 relative to the (USSR Glacier Inventory, 1971, 1978). Our study further revealed a mean annual temperature increase of 0.05°C per year during 2000–2020, coinciding with continued glacier retreat. Although Konovalov (2012) reported a lower summer warming rate of 0.017°C per year for 2001–2020, a comparable degree of glacier area loss was reported. This discrepancy in warming rates may reflect differences in datasets (meteorological station observations, satellite observations, and reanalysis products), temporal intervals, seasonal focus (annual versus summer mean temperatures), and regional climatic conditions. These results highlight the sensitivity of glaciers to rising temperatures and their vulnerability to continued climate change.Variations in glacier loss magnitude across studies also reflect methodological differences, including data resolution, temporal coverage, and the handling of debris-covered glaciers and seasonal snow. Such uncertainties are particularly significant in inner mountain ranges with complex glacier morphologies. The in the upper basin of the Amu Darya River, extending across the Pamir and Alay mountain systems, exhibits pronounced regional contrasts due to diverse climatic and topographic conditions. Elevations range from 1100 to 7450 m a.s.l., with an average altitude of ~3500 m, and a strongly continental climate characterized by sharp seasonal variability in temperature and precipitation (Siegfried et al., 2012). Precipitation peaks

in winter and spring, with southern areas receiving substantially more moisture than northern and northeastern regions near the Kyrgyz border.

Future climate projections indicate continued warming under RCP4.5 and RCP8.5 scenarios, with summer temperatures in the Vakhsh basin expected to rise by 1.96–10.34°C by the late 21st century (Petrov & Normatov, 2010). Changes in precipitation patterns are also anticipated, with increases of 6–20% in winter across much of the Northern Hemisphere but possible reductions in southern parts of the basin. These trends will likely accelerate glacier retreat, particularly in high-altitude sub-basins such as the Mughob River, where glacier melt currently contributes over 54% of annual runoff (Wagner & Hoelzle, 2010).

The Khingov and Surkhob sub-basins have experienced substantial glacier area and volume reductions throughout the 20th century. Between 1935 and 1985, total ice volume losses were 79.9×10^6 m³ and 27.2×10^6 m³, respectively (Kotlyakov et al., 2008). These changes reflect not only regional warming but also altered atmospheric circulation, diminished snow accumulation, and enhanced ablation. The progressive glacier loss reduces their buffering capacity against hydrological variability, posing serious challenges to water security in drought years and amplifying the impacts of ongoing climate change.

4.2. Hydrological Impacts on Regional Water Resources

The hydrological regime of the Vakhsh River is primarily driven by snowmelt and glacier melt, contributing about 63% of the annual runoff: 37% from seasonal snow and 26% from glaciers. During the summer months (June-September), this contribution rises to 71%, acting as a natural buffer against precipitation deficits (Huang et al., 2022; Aizen et al., 2006). However, climate change-manifested as an increase in mean annual temperature by 0.4-0.7°C and precipitation growth of 7-9% by the mid-21st century (Sorg et al., 2012)-may disrupt this balance. Projections indicate accelerated glacier retreat and a shift in seasonal runoff distribution, with an initial increase (“peak water”) expected until around 2060, followed by declining runoff volumes towards 2080 due to depletion of glacier reserves (Hock et al., 2019).

Nevertheless, the complex orography of the Pamir-Alay and underdeveloped hydrometeorological infrastructure introduce significant uncertainties in projections (Kure et al., 2013). Effective water resource management thus requires integrated strategies that balance energy, agricultural, and ecological demands under changing climatic and socio-economic conditions.

The runoff formation in the Surkhob and Khingov basins is predominantly snow-fed. At elevations of 2900–3300 m, snowmelt contributes 60–64% of runoff,

while above 3500 m the importance of glacier melt increases (up to 23%), and rainfall contribution remains minimal (<1%). In the Surkhob Basin, groundwater contributes up to 40% of runoff in certain sections. In the upper Khingov basin, glacier melt contribution reaches up to 44%, whereas in the lower reaches snowmelt dominates (48%) (USSR Glacier Inventory,1971,1978).

4.3. Study Limitations and Future Research Directions

Current research on glacier dynamics and hydrological responses in the upper Amu Darya basin (Khingov and Surkhob basins) faces several limitations. The scarcity of high-resolution and long-term hydrometeorological data, especially in high-altitude zones, constrains the accuracy of existing models and limits our ability to fully understand glacier–runoff interactions (Kure et al., 2013). The rugged topography of the Pamir-Alay system further complicates field measurements, leading to significant spatial and temporal gaps in monitoring glacier mass balance and ice thickness. Moreover, uncertainties in precipitation projections from global climate models (GCMs) (Petrov & Normatov, 2010), add to the difficulty of developing reliable hydrological forecasts. The weak observed correlation (0.1–0.3) between precipitation and river discharge suggests that glacier melt and subsurface water contributions may play a more dominant role than previously assumed (Mernild et al., 2013).

In addition, assessments of glacier area change are often based on heterogeneous data sources and are therefore susceptible to methodological inconsistencies. For example, in the (USSR Glacier Inventory, 1971, 1978), glacierized areas were partly overestimated, likely due to misinterpretation of seasonal snow cover in aerial imagery. Consequently, studies that have used this inventory as a baseline tend to overestimate glacier retreat, particularly in the outer ranges (USSR Glacier Inventory, 1971, 1978; Sorg et al., 2012). Similar discrepancies are noted for the Surkhob and Khingov river basins in the inner ranges (Aizen et al., 2006), where misidentification of fresh snow and failure to account for debris-covered glaciers may have led to biased results.

Future research should focus on expanding and sustaining glacier monitoring programs to include mass balance and ice thickness measurements on key reference glaciers, such as Vanjyakh (Fedchenko) and Garmo (Sorg et al., 2012). Enhancing observational networks in high-altitude areas and integrating satellite remote sensing with in situ measurements will improve the spatial and temporal resolution of available datasets. Additionally, the development of basin-specific hydrological models that incorporate the region’s complex orography and climatic variability is necessary to reduce uncertainties. Particular attention should be given to the role of surge-type

glaciers in the hydrological cycle, as their episodic behavior could have significant implications for river discharge and hydrological extremes.

Finally, future investigations should address the socio-economic impacts of changing runoff patterns, particularly in relation to hydropower production and irrigation demands. Including small glaciers (<1 km²), which make up a substantial proportion of the glacierized area in the upper Amu Darya basin (Khingov and Surkhob basins) (Barnett et al., 2005), will provide a more comprehensive understanding of the regional hydrological system. Equally important is the consideration of anthropogenic factors, such as the influence of hydropower infrastructure, and the combined effects of climatic and hydrological changes on regional water security.

5. Conclusions

This study assessed glacier changes in the upper Amu Darya River basin using historical inventories (1971 and 1978) and satellite observations from 2022. In the assessed lower and right-bank parts of the Khingov River Basin, glacier area decreased from 164.6 to 150.7 km² (8.4%) between 1978 and 2022. In the Surkhob River Basin, it declined from 401.1 to 348.6 km² (13.1%) between 1971 and 2022. The most pronounced losses (20–39%) occurred in the Yarkhich sub-basin. The study identified more than 143 surge-type glaciers (26% of the total), approximately 20% of which showed signs of recent activity. Mean air temperature increased by 1.5°C during 1961–2022. Hydrological analysis showed that snowmelt accounts for 60–64% of runoff below 3300 m, while glacier melt contributes up to 23% of discharge above 3500 m. The two basins contain approximately 13.9% of Tajikistan's glacier cover and 9.1% of Central Asia's total glacier area.

Despite these findings, limited high-altitude hydrometeorological observations and differences between historical and modern datasets remain important sources of uncertainty. Future research should combine satellite observations with field monitoring, glacier mass-balance and ice-thickness measurements, and basin-specific hydrological modelling, particularly to improve the assessment of surge-type and small glaciers. The results provide a scientific basis for improving regional water-resource management, hydropower planning, and climate adaptation in glacier-dependent areas of Central Asia.

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