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Estimating changes in the Khisar glacier, using remote sensing data and GIS technologies for the assessment of water use in agriculture (Surkhandarya valley, Uzbekistan)

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Abstract: Climate change is speeding up the melting and retreat of glaciers, which is a big threat to water security in dry and semi-dry areas like Uzbekistan. To understand how glaciers affect regional hydrological systems and to come up with adaptive water management strategies, it is important to keep an eye on how they change over time. This study examines the temporal changes of the Khisar Glacier in the Surkhandarya Basin by combining remote sensing data from different times with a GIS-based spatial analysis. We looked at Landsat images from 1990, 2000, 2010, and 2024 to see how the size of the glaciers has changed and how that relates to weather and water variables. The results show that the glacier area has shrunk significantly, from 8.6 km^2 in 1990 to 5.1 km^2 in 2024, a 40.7% decrease over the past three decades. The mean annual temperature in the basin rose by about 1.9 °C during the same time, and the Surkhandarya River's average summer discharge fell by about 22%. These results show how closely rising temperatures, melting glaciers, and lower river flow are linked. They also show how vulnerable glacier-fed water systems are to climate change. Combining satellite observations with climate and hydrology data is a good way to keep an eye on glaciers and assess water resources over time. The GIS-based monitoring framework created in this study provides useful tools for planning how to adapt to climate change and manage water resources in a way that is good for the environment in the Surkhandarya region and other glacier-dependent basins in Central Asia.

Keywords: agriculture; climate change; gis analysis; glacier retreat; khisar glacier; remote sensing; water resources

Mountain glaciers, especially those in dry and semi-arid areas, are very important for keeping freshwater supplies, controlling the flow of rivers during different seasons, and supporting farming

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and ecological systems. Glaciers are an important part of the cryosphere. There are natural water reservoirs that let out meltwater during dry seasons, which keep rivers flowing and help people make a living. However, glaciers are melting faster than ever before due to the effects of global climate change. This is a serious threat to the availability of water downstream and the stability of the environment in the region. In Uzbekistan, where farming relies heavily on seasonal meltwater, glacier retreat has become a major national issue with serious effects on the food and water security.

The Surkhandarya Valley, which is in southern Uzbekistan, is one of the country's most productive farming areas. The Surkhandarya River, which starts in the High Khisar mountain range, is the main source of its water. The Khisar Glacier, which is in this range, is an important source of meltwater that feeds the river. It is especially important for irrigation, groundwater recharge, and household water supply during the hot and dry summer months. About three million people depend on this water system for drinking water and growing crops (Abdurakhmonov et al. 2021). Recent evidence, however, shows that the Khisar Glacier is melting quickly because the air is getting warmer and snow is falling less, which could upset the delicate water balance of the Surkhandarya Basin.

Previous studies have investigated glacier dynamics and alterations in water resources in Central Asia (Conrad et al. 2007; Mamatkulov et al. 2021); however, a significant deficiency persists in comprehensive research that concurrently examines glacier fluctuations, climatic influences, and river discharge within a cohesive geospatial framework. Utilising remote sensing and Geographic Information System (GIS) technologies effectively addresses this gap by providing spatial and temporal accuracy for monitoring glacial changes, quantifying hydrological responses, and facilitating adaptive water management strategies.

This study employed multi-temporal satellite imagery from the Landsat series to evaluate alterations in the extent of the Khisar Glacier from the early 2000s to 2024. We used Geographic Information System (GIS) tools to analyse, visualise, and combine glacier, climate, and hydrological datasets in space. We looked at long-term weather records (temperature and precipitation) and river discharge data to find links between the glacier retreat, climate change, and water availability. The findings indicate a persistent trend of glacier retreat over the preceding twenty years, with the most significant reductions observed in the last decade. This retreat coincides with a significant increase in the average summer temperatures and a decrease in the snow accumulation, resulting in diminished meltwater flow during the peak irrigation season (July–September). As a result, the productivity of water-intensive crops like cotton and wheat has gone down, putting more stress on the region's agricultural system (Mamatkulov et al. 2021). Additionally, a Normalised Difference Vegetation Index (NDVI)-based vegetation analysis reveals changes in land cover patterns linked to increasing water stress.

These results highlight the wider effects on the environment and economy of glaciers melting in the High Khisar range. The decline in meltwater jeopardises the food security, agricultural sustainability, and local economies in the Surkhandarya Valley, while also signalling ecological shifts, including biodiversity loss and diminished ecosystem resilience (Goibberdiev et al. 2023; Gerts et al. 2024). Using remote sensing in water management planning can make irrigation much more efficient, encourage the use of crops that can survive drought, and help people adapt to climate change in a way that is good for the environment (Bishop et al. 2007). The region could fall into a cycle of resource depletion, lower productivity, and greater vulnerability to environmental stressors if timely interventions are not made.

The primary aim of this research is to examine the alterations occurring in the Khisar Glacier due to climate variability and to evaluate the subsequent implications for water availability in the Surkhandarya Valley. The study specifically seeks to: (*i*) Quantify the temporal retreat of the Khisar Glacier utilising multi-temporal satellite imagery; (*ii*) Investigate the correlation between glacier loss, temperature trends, and seasonal river discharge; (*iii*) Assess the socioeconomic and agricultural ramifications of diminished meltwater supply; and (*iv*) Recommend pragmatic adaptation and water management strategies informed by the geospatial analysis.

This integrated approach offers an evidence-based framework for the surveillance of glacier-fed water systems and the formulation of sustainable water management policies in southern Uzbekistan and analogous areas throughout Central Asia.

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MATERIAL AND METHODS

Study area

This study centres on the Khisar glacier, situated in the elevated Khisar mountain range within the Surkhandarya river basin in southern Uzbekistan (Figure 1). The study area covers about 140 km^2, and the glaciers mostly cover areas between 2 500 m and 4 200 m above sea level (m a.s.l.). The terrain has steep slopes, a lot of changes in elevation, and is hard to get to, which makes ground-based measurements difficult and makes remote sensing techniques necessary. The area is in a continental semi-arid climate zone, which means that most of the rain falls in the winter and spring. The summers are dry and hot, which speeds up the melting of the glaciers and increases the need for irrigation downstream.

Data sources

The glacier change analysis was conducted using multi-temporal satellite data from the following sources:

- Landsat 5 TM, Landsat 7 ETM+, and Landsat 8/9 OLI/TIRS: Images from the United States Geological Survey (USGS) Earth Explorer archive were used for the years 1993–2024, focusing on cloud-free scenes during the ablation season (July–September).
- SRTM DEM (30 m) was used to extract elevation profiles, slope, aspect, and to delineate glacier boundaries.
- Meteorological data (temperature and precipitation) for the region were obtained from the Uzhydromet stations at Denov (690 m), Sariasia (1 180 m), and Boysun (1 520 m), covering the period from 1993 to 2024.
- River discharge data for the Surkhandarya River were obtained from the Uzbek Hydrometeorological Service and used to correlate glacier melt with seasonal flow dynamics (Figure 2).

Methods

Satellite images were corrected for atmospheric effects using LEDAPS (for Landsat) and the MODIS Reprojection Tool for MODIS imagery. All the datasets were reprojected to WGS84/UTM Zone 42N. Cloud and shadow masking were applied using the QA band in the Landsat and MODIS products. Image subsets were clipped to the glacier catchment area using manually digitised polygons.

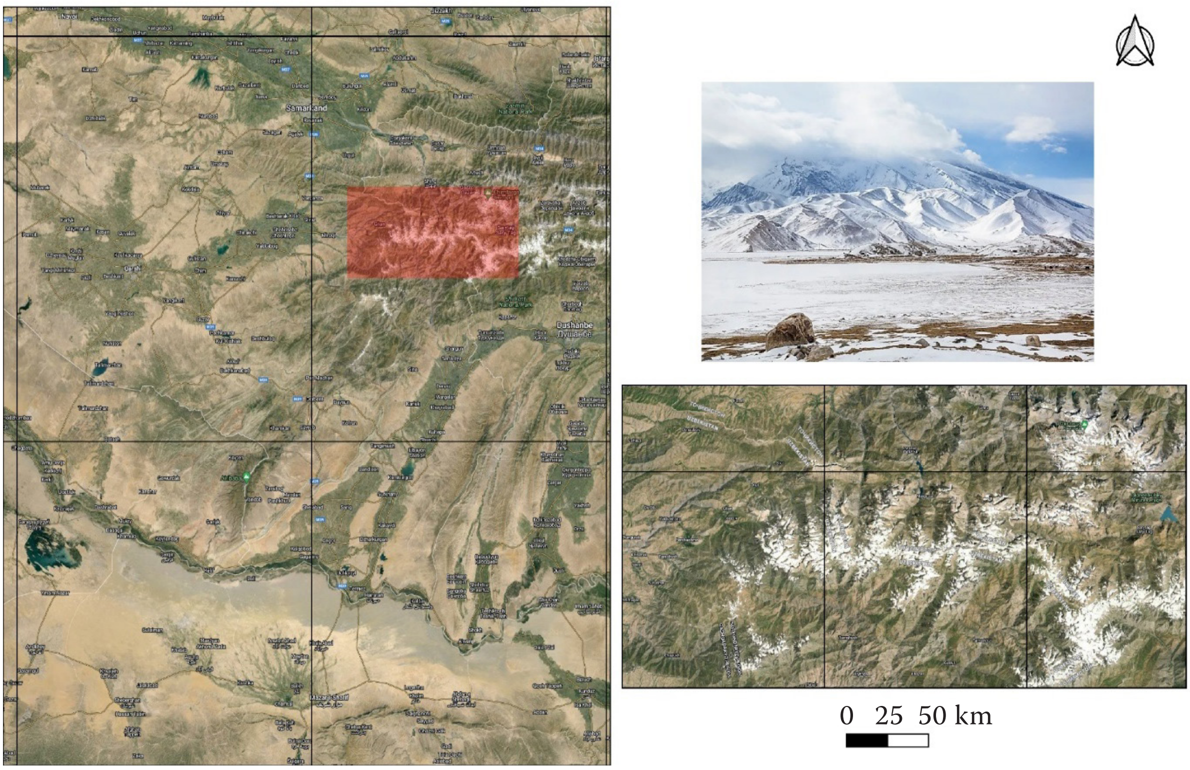

Figure 1. Study area, high Khisar range glacier
Source: Google Earth

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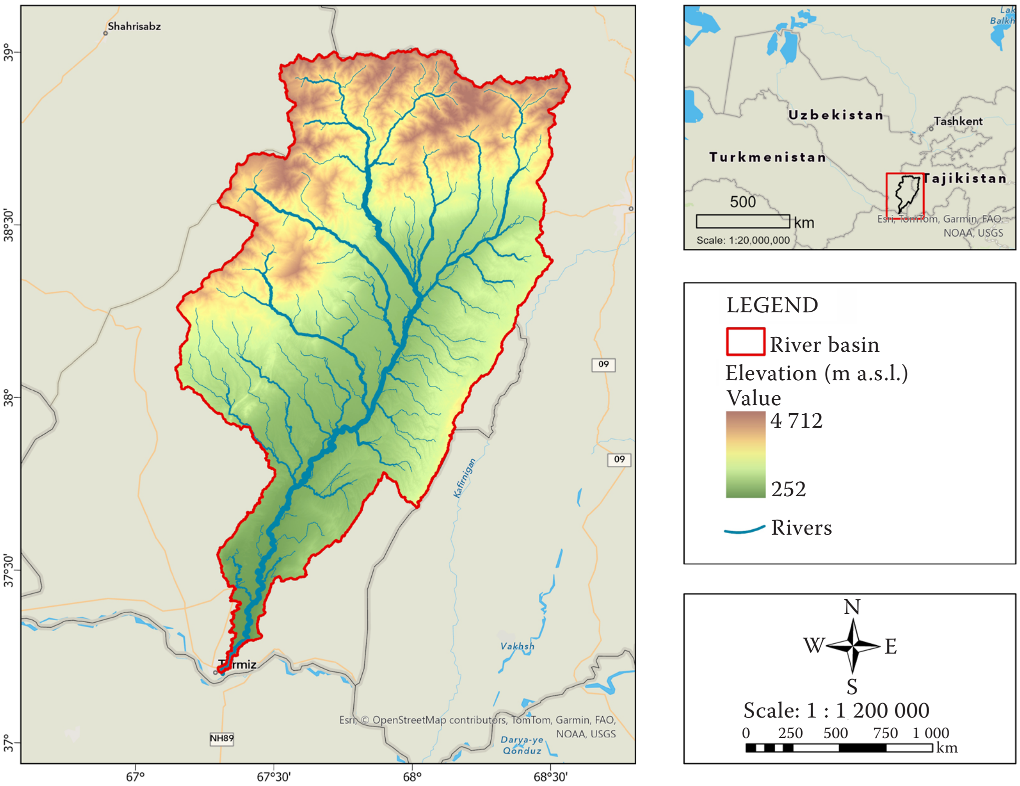

Figure 2. Water basin of the Surkhandarya River
Source: Heberger (2022)

Using semi-automated band ratio techniques like the Normalised Difference Snow Index (NDSI) and the Band 5/Band 4 ratio, we were able to draw the outlines of glaciers. We did thresholding in Google Earth Engine (GEE) and then made manual changes in QGIS.

We measured the changes in the glacier area for each time point (2000, 2010, 2020, 2022, and 2024) and used post-classification comparison to find the changes.

NDSI and Snow over analysis

Of the snow cover changes direct effects to the water stress in the Surkhandarya valley were assessed using a Landsat time-series. Seasonal averages for June–September were calculated to evaluate trends in the vegetation health under decreasing meltwater conditions. The snow cover extent was derived using Landsat data and used to assess temporal snow line fluctuations and their relationship with air temperature trends.

$$NDSI = \frac{Green - SWIR}{Green + SWIR} \qquad (1)$$

where: NDSI – Normalised Difference Snow Index; Green – spectral reflectance measured in the green wavelength band (approximately 0.52–0.60 μm); SWIR – spectral reflectance measured in the shortwave infrared band (approximately 1.55–1.75 μm).

Typical value range:
- NDSI values range from –1 to +1;
- Snow pixels: NDSI > 0.4 (common threshold);
- Non-snow pixels (like vegetation, water, or clouds) usually have lower or negative values.

Climatic and hydrological correlation. To investigate the relationship between the glacier retreat and water availability, we examined long-term temperature and precipitation trends using Pearson's correlation and statistical tools in R Studio. These climatic patterns were then compared with changes in the glacier area and river discharge volumes through Pearson's correlation analysis in R.

GIS-based spatial analysis

Topographic characteristics of the glacier and surrounding terrain (elevation, slope, aspect) were

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extracted from SRTM DEM and analysed using ArcGIS pro. Spatial overlays were used to identify zones of high ablation risk and to visualise glacier retreat boundaries over time. This study integrates multi-source datasets and remote sensing techniques to analyse the snow cover dynamics and assess the climate change impacts over the study area. The methodology is structured around three primary data categories: satellite imagery, vector data, and meteorological information. Each dataset contributes to a specific analytical objective within the research framework (Figure 3).

Landsat 5–9 satellite images were used to keep an eye on the amount of snow and glaciers. We got the optical remote sensing images from the USGS EarthExplorer portal (https://earthexplorer.usgs.gov/). We used these pictures to figure out how much snow was on the ground and how it changed over time by calculating the Normalised Difference Snow Index (NDSI). NDSI is a well-known spectral index that uses the way snow reflects light in the green and shortwave infrared (SWIR) bands to find it. Simultaneously, vector data from 1993 to 2024 was used to show how far the research area went in space. The MGHydro database (https://mghydro.com/watersheds/) is where the data came from. It has reliable datasets for watersheds and hydrographic boundaries. The vector layers were used to pull out the study area from the larger dataset and hide it, making sure that all the analyses were focused on the geography and were consistent over time and across data types. We also got weather data from the NASA POWER project platform (https://power.larc.nasa.gov/). This dataset contained daily and monthly records of climate variables like the temperature and precipitation, which are important for figuring out how climate change is affecting the world. The same time frame as the remote sensing data was used to look at the variables to find links between changes in the snow cover and changes in the weather. The combination of satellite, vector, and meteorological datasets made it possible to fully understand how the snow cover changes and how the climate changes in the study area. We used a Geographic Information System (GIS) to process and analyse each dataset. This made it possible to make spatially explicit assessments and made sure that the temporal and spatial resolution was the same for all of the assessments.

RESULTS AND DISCUSSION

The analysis reveals significant reductions in glacier size and mass over the 31-year period, with an accelerated meltdown starting in 2008, leading to the loss of 60% of the glacier by 2024.

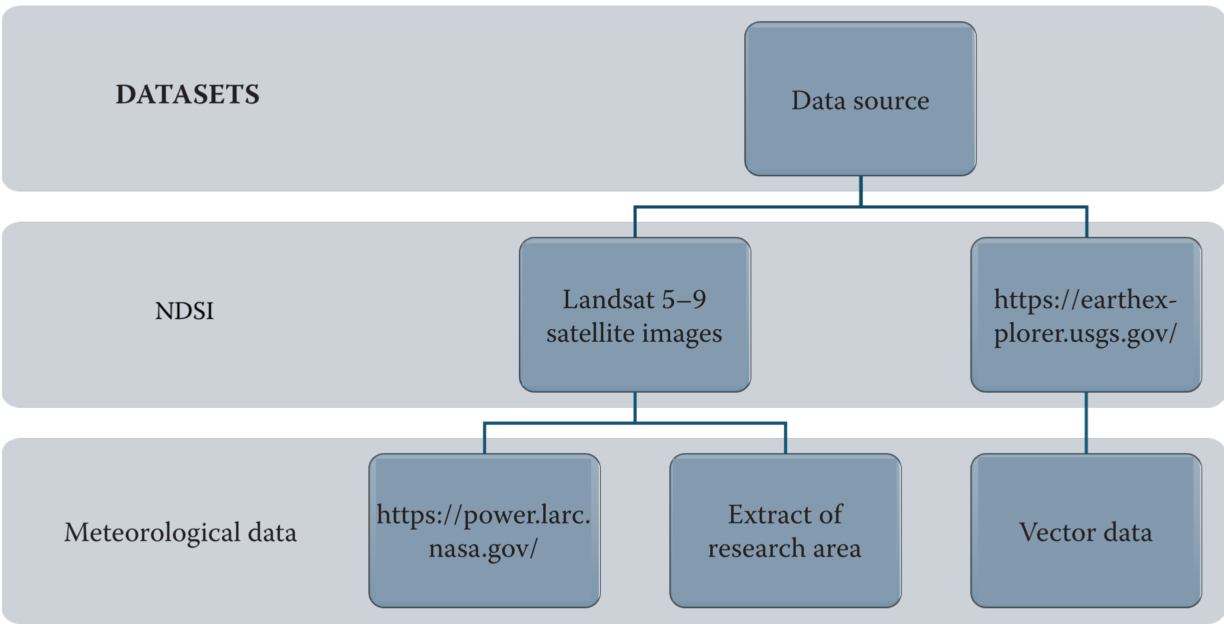

Figure 3. Data analysing flow chart
Source: Created by authors

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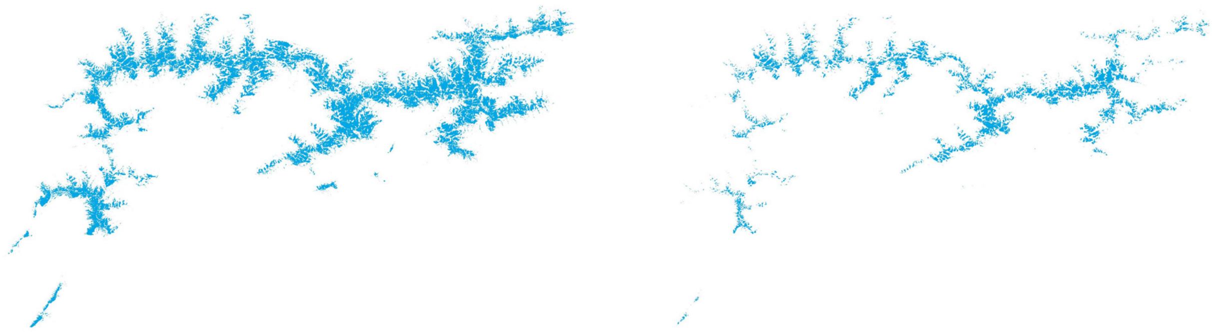
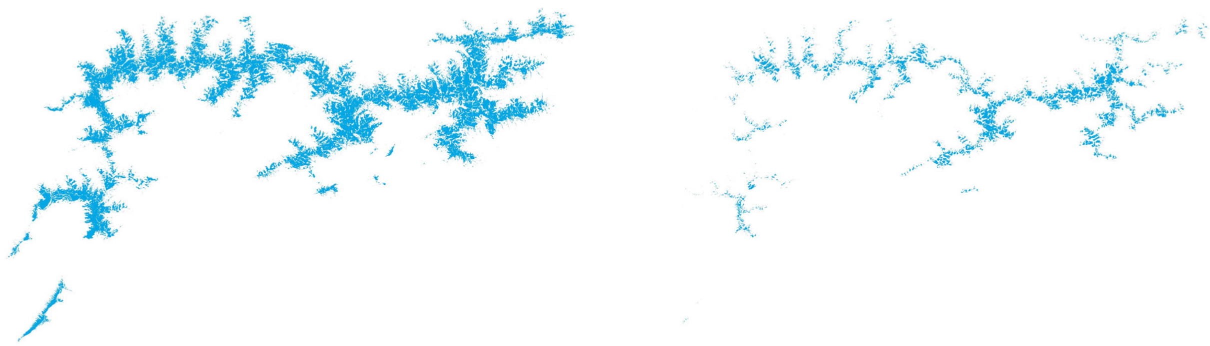
Between 1993 and 2008, the Khisar Glacier showed signs of retreat, but the changes were moderate compared to the rapid loss observed in the subsequent years. Remote sensing data from this period indicate a reduction in the glacier surface area of approximately 15% over the 15-year span (Figures 4–7). Analyses had shown that the glacier had lost approximately 20% of its ice volume. During this period, the retreat was primarily attributed to rising temperatures and fluctuating precipitation patterns, which were less extreme than those experienced in later years. However, the



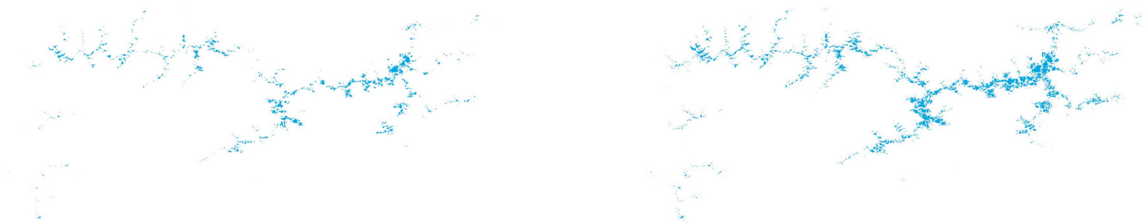
1993 1998

Figure 4. Illustration of NDSI index of the Landsat TM: 01-07-1993 scene (left) and Landsat ETM+: 29-06-1998 (right)



2002 2008

Figure 5. Illustration of NDSI index of the Landsat ETM+: 26-07-2002 scene (left) and Landsat ETM+: 10-07-2008 (right)



2013 2018

Figure 6. Illustration of NDSI index of the Landsat OLI: 24-07-2013 scene (left) and Landsat OLI: 22-07-2018 (right)

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2021 2023

Figure 7. Illustration of NDSI index of the Landsat OLI: 28-06-2021 scene (left) and Landsat OLI: 12-07-2023 (right)

relatively steady glacier retreat already suggested potential long-term impacts on the hydrological cycle, raising concerns about future water availability for agriculture.

From 2008 onward, the rate of glacier loss accelerated drastically, with 60% of the glacier melting away by 2024, where there was a significant loss of the glacier mass and area. By 2024, the total glacier area had shrunk to less than half of its size in 1993. The rapid melting during this period coincides with the rising temperatures in the region, which saw an increase of 1.5 °C on average over the past decade. The glaciers have responded to these warming trends by thinning significantly, with some areas losing as much as 50 metres in thickness. The increased rate of melt has also shifted the glacier's accumulation and ablation zones, altering the timing of meltwater flows into the valley's river systems.

NDSI analyses were employed to integrate the remote sensing data on the glacier change with hydrological models and agricultural water use patterns in the Surkhandarya Valley. These models estimate that the Khisar Glacier contributed up to 30% of the valley's total irrigation water during peak melt seasons in the 1990s. However, by 2024, this contribution had dropped by more than half, leading to significant stress on the water resources. The reduction in glacier meltwater has been particularly detrimental during the critical growing seasons for water-intensive crops like cotton, which dominate the agricultural production in the valley. The GIS-based spatial analysis of the irrigation zones indicates that regions downstream from the Khisar Glacier, which were once reliably fed by glacier meltwater, have experienced increasingly frequent water shortages since 2010. As the glacier meltwater diminished, the dependence on groundwater sources and river systems increased, placing additional pressure on the region's water infrastructure.

Figure 8 shows where two hydrological monitoring points, Points 1 and 2, were set up to measure the flow of the Surkhandarya River system. These points line up with known hydroposts, and the Denau Climate Station is the closest hydrometeorological station to the area being studied. Figures 9 and 10 demonstrate, through scientific means, the impact of climate change on the water flow regime in the Surkhandarya Basin. Long-term observations at these two monitoring points show that the volume of discharge has been steadily decreasing since 2000, with a bigger drop after 2010. Figure 9 shows that the flow of water at Point 1 has

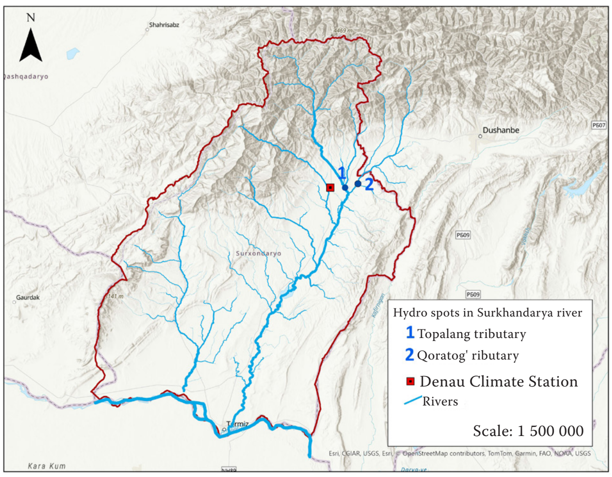

Figure 8. Location of the hydrological monitoring points and Denau Climate Station

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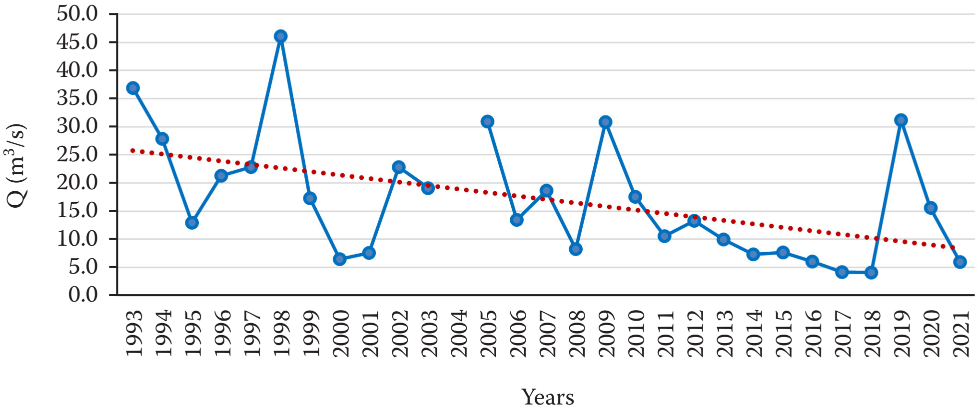

Figure 9. Dynamics of the measured water flow at Point 1

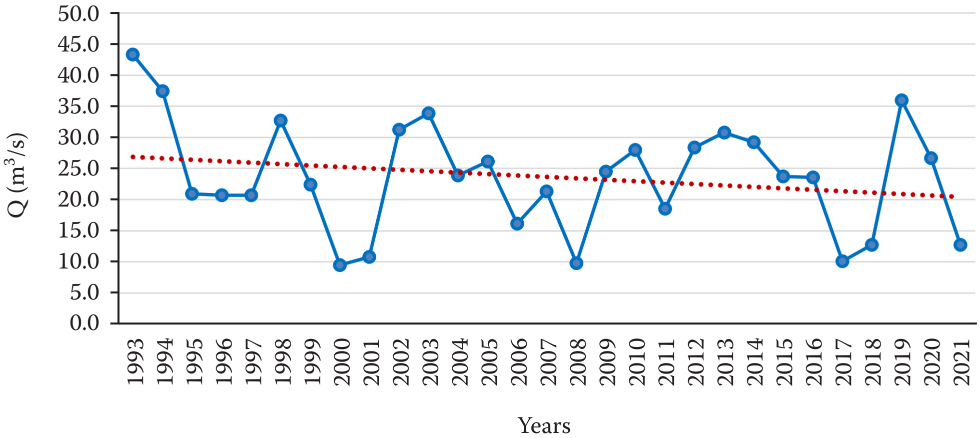

Figure 10. Dynamics of the measured water flow at Point 2

slowed down. This is because the air temperature is higher, which means that melting happens earlier, but lasts for a shorter time. Figure 10 shows that the decrease in glacier meltwater and the increase in irrigation withdrawals at Point 2 (downstream) have made the discharge more variable all year round. Due to this, the river's average yearly flow has decreased a great deal.

Figure 11 shows how the average summer temperature (June, July, and August) has changed over the years. The data were obtained from the Denau Climate Station (Figure 8). The graph shows that the average summer temperature increased from about 28 °C to 29.5 °C between 1991 and 2023. This means that the temperature has increased by about 1.5–2 °C over the past thirty years. This

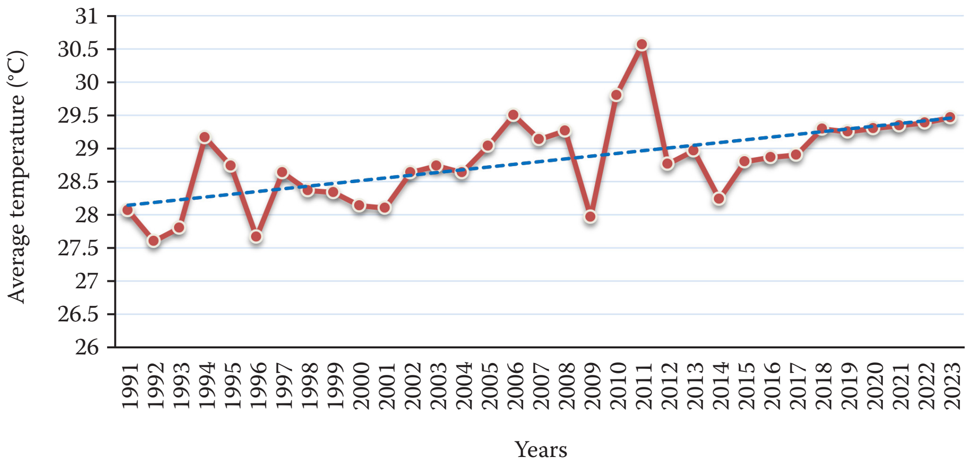

Figure 11. Dynamics of the average summer temperature (June–August) based on data from the Denau Climate Station

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clearly shows that the region is still getting warmer. The trend line shows that the summer seasons are getting hotter over time, in addition to the yearly changes. The Denau Climate Station data show that the summer temperatures in the Surkhandarya Basin have been rising steadily over the past few decades.

The results of this study highlight the urgent need for adaptive water management strategies in the Surkhandarya Valley. The 60% loss in glacier volume and the associated decline in meltwater supply present significant challenges for sustaining the agricultural productivity. As the glacier melt continues to decrease, the reliance on meltwater for irrigation will become increasingly untenable, especially as climatic trends predict further warming and glacial retreat in the coming decades. GIS-based projections suggest that if the current trends persist, the Khisar Glacier could lose an additional 20% of its remaining mass by 2040, which would further exacerbate water shortages in the valley. This could lead to reduced crop yields, increased competition for water, and a shift towards less water-intensive crops, which may not be as economically viable for local farmers.

This study's results show that glaciers are retreating quickly and that there is less meltwater available in the Khisar Range of southern Uzbekistan. The glacier area shrank by almost 60% from 1993 to 2024, while the average summer temperature rose by about 1.9 °C. This means that warming in the area is having a bigger effect on cryospheric systems in Central Asia. These findings align with those of Khan et al. (2024), who documented significant glacier retreat and velocity reduction in the Pamir–Karakoram–Hindu Kush regions utilising multi-temporal Landsat data. Both that study and the current research validate that the increasing temperatures, rather than alterations in the precipitation, are the primary catalyst for the glacier melt in this region.

The study also shows that climate change speeds up the melting of glaciers and changes when the meltwater flows during the year. The average summer temperature in the Surkhandarya Basin has increased by 1.5–2 °C over the past 30 years. This has caused the annual river discharge to drop by about 25%. Similar trends have been noted in other glacier-fed basins of Central Asia (Ruan et al. 2023), where abbreviated melt seasons and premature runoff peaks have diminished the water availability during essential irrigation periods. The NDVI-based analysis corroborates the findings of Aslanov et al. (2023) and Goibberdiev et al. (2023), indicating a decline in vegetation and desertification in irrigated areas post-2015, attributed to diminished meltwater inflow.

The comparative results show that the rates at which glaciers are melting differ from one mountain system to another. Nurakynov et al. (2023) reported an average glacier loss of 0.6 km^2 per decade in the Zhetysu Alatau Range; however, the Khisar Glacier exhibited a higher loss rate of approximately 1.1 km^2 per decade, likely attributable to variations in the elevation, albedo, and atmospheric dynamics.

The observed decrease in glacier-fed runoff presents significant threats to the agricultural sustainability in the Surkhandarya Valley, underscoring the necessity for integrated management of water, energy, and agriculture (Saidmamatov et al. 2023) and the integration of remote sensing technologies into national water monitoring and adaptive planning systems.

CONCLUSION

The analysis of Khisar Glacier's changes from 1993 to 2024 using remote sensing and GIS technologies reveals a stark decline in glacier mass and volume, with 60% of the glacier having melted by 2024. This rapid meltdown, particularly after 2008, has had profound implications for the water availability in the Surkhandarya Valley, where agriculture relies heavily on consistent water supplies. The integration of glacier data with GIS models of water use demonstrates that the future agricultural sustainability in the region will depend on more efficient water use practices, improved irrigation technologies, and strategic planning to cope with the diminishing glacier-fed water sources. Adaptive management strategies will be crucial to ensure the long-term viability of agricultural practices in the face of continued climate change and glacier retreat.

The research has shown that using remote sensing data and analysing it with GIS technologies yields good results in the long-term monitoring of mountain glaciers. The data and methods applied for the continuous monitoring of mountain glaciers can also be used to monitor other glaciers.

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