CLIMATE CHANGE IMPACT ON GLACIERS OF CENTRAL ASIA: WATER SCARCITY IN THE AMU DARYA AND SYR DARYA RIVER BASINS

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Abstract

The Tien Shan and Pamir glaciers, located in the high mountainous regions of Central Asia, serve as the primary water source for the Amu Darya and Syr Darya river basins. These glaciers ensure the long-term runoff of the rivers and play a vital role in supporting agriculture, hydropower generation, and drinking water supply across the region. However, rapid temperature increases driven by global climate change are causing intensive glacier melting. While this process may temporarily increase river runoff in the short term (2020–2040), it will lead to a sharp decline in water resources and a severe deepening of water scarcity in the long term (after 2050).

This article provides a comprehensive analysis of glacier degradation in Central Asia, changes in the hydrological cycle, and the resulting water scarcity problem in the Amu Darya and Syr Darya basins. The analysis is based on scientific studies from the Scopus database (2020–2026), including hydrological modeling, satellite monitoring, and bibliometric analyses, as well as international reports from the IPCC, UNESCO, UN Water, and the World Bank.

The findings show that the Tien Shan glaciers have lost 20–30% (approximately 27% according to some estimates) of their volume over the past 50 years. Projections indicate a further reduction of 30–50% by 2040–2050 and 60–90% by 2100. In the short term, glacier melt increases summer river runoff, but in the long term, annual runoff is expected to decrease by 10–35%. Seasonal changes are also significant: winter and spring flows are increasing, while summer flows are sharply declining. These shifts are exacerbating water scarcity in the Aral Sea basin, leading to reduced agricultural productivity, decreased irrigation efficiency, lower hydropower potential, and heightened risks of transboundary water conflicts.

The results of the article highlight the need to strengthen integrated water resources management (IWRM), real-time glacier monitoring, climate adaptation strategies, and international cooperation in the region.

Keywords: *climate change, Tien Shan and Pamir glaciers, Amu Darya, Syr Darya, water scarcity, hydrological changes, sustainable management, Aral Sea basin.*

Introduction

The water resources of Central Asia are primarily formed by the melting of glaciers and snow cover in the Tien Shan and Pamir mountain ranges. These high-altitude areas are known as the “Water Towers of Central Asia” because they provide 50–80% of the long-term runoff of the Amu Darya and Syr Darya rivers. These two rivers are of critical importance for the region’s agriculture, hydropower, drinking water supply, and overall economic development.

Due to climate change, global and regional temperatures are rising 1.5–2 times faster in Central Asia than the global average, accelerating the intensive melting of glaciers. This process is fundamentally altering the hydrological cycle and changing both seasonal and long-term dynamics of river runoff.

Studies in the Scopus database (2020–2026) demonstrate a sharp increase in scientific interest regarding the impact of global warming on Central Asian glaciers. Currently, most glaciers in the region are in a state of regression. The Tien Shan glaciers have lost approximately **27% ± 15%** of their volume over the past 50 years (1961–2012 and subsequent periods). This rate is four times higher than the global average.

In the short term (2020–2040), rapid glacier melt is expected to increase river runoff, particularly in summer. However, in the long term (after 2050), glacier volume is projected to decrease by an additional 30–50% (and up to 60–80% in some models). This will lead to a 10–35% reduction in the total annual runoff of the Amu Darya and Syr Darya rivers, significant seasonal shifts (increased winter-spring flows and sharply decreased summer flows), and a deepening water scarcity crisis in the Aral Sea basin.

These changes are expected to result in declining agricultural productivity, reduced irrigation efficiency, decreased hydropower potential, drinking water supply problems, and increased risks of transboundary water conflicts.

This article, based on the latest research from Scopus and other scientific databases (Web of Science, Google Scholar), as well as international reports (IPCC, UNESCO, UN Water, World Bank), provides a comprehensive analysis of the impact of climate change on Central Asian glaciers, its hydrological consequences, and water scarcity issues in the Amu Darya and Syr Darya basins. Recommendations on sustainable water resource management and climate adaptation strategies are also provided.

Materials and Methods

This study was conducted using the **Systematic Literature Review (SLR)** method. The main objective was to comprehensively analyze the impact of climate change on glaciers in Central Asia and the resulting water scarcity in the Amu Darya and Syr Darya river basins based on scientific sources.

Data Sources The following sources were used:

- Scopus and Web of Science (primary sources for scientific articles);
- Google Scholar (additional publications and reports);
- Official reports from international organizations: IPCC, UNESCO, UN Water, World Bank, Central Asia Regional Economic Cooperation (CAREC), and national regional reports.

The search period covered 2020–2026 (up to June 2026).

Search Strategy Keywords and combinations: “climate change” OR “global warming” AND (“glaciers” OR “glacier melt” OR “cryosphere”) AND (“Central Asia” OR “Tien Shan” OR “Pamir”) AND (“Amu Darya” OR “Syr Darya” OR “Aral Sea basin”) AND (“water scarcity” OR “water resources” OR “hydrological change” OR “runoff”).

Boolean operators, truncation, and phrase search were applied. Over 120 scientific works and reports were identified.

PRISMA guidelines were strictly followed for inclusion and exclusion criteria. As a result, **55** of the most relevant and high-quality sources were selected.

Analysis Methods

- Hydrological and geographical analysis using GIS technologies, satellite data (MODIS, Sentinel), and hydrological models (SWAT, HBV, VIC).
- Climate scenarios: IPCC RCP 4.5 (moderate) and RCP 8.5 (high).
- Trend analysis: Mann-Kendall test, statistical analysis, and bibliometric analysis.
- Regional synthesis with special focus on the Amu Darya and Syr Darya basins, distinguishing short-term and long-term impacts.

Data reliability was ensured through peer-reviewed sources and independent verification by multiple authors. Ethical issues (plagiarism and bias) were strictly observed.

Results

The study results, based on recent Scopus studies and international reports (IPCC, UNESCO, UN Water), reveal the main trends in the impact of climate change on Central Asian glaciers and hydrological changes in the Amu Darya and Syr Darya basins.

1. Glacier Degradation The Tien Shan and Pamir glaciers in Central Asia are melting 3.5–4 times faster than the global average. Over the past 50–60 years (1960–2020), the total glacier

volume in the region has decreased by 20–30% (approximately 27% ± 15% according to some estimates).

- Degradation is particularly intense in the Tien Shan, where small glaciers (area < 1 km²) are disappearing faster.
- By 2050, glacier volume is projected to decrease by 30–50%, and by 2100 by 60–90% (under RCP 8.5).
- Along with the reduction in number and area, ice thickness is also decreasing, leading to the long-term loss of the glaciers' "water tower" function.

2. Hydrological Changes Glacier melt creates a two-phase dynamic in river runoff:

- **Short-term (2020–2040)**: Summer runoff of the Amu Darya and Syr Darya may increase by 10–20%.
- **Long-term (after 2050)**: Annual runoff is expected to decrease by 10–35%. The change is more pronounced in the Amu Darya due to its higher glacial contribution (30–40%).

Seasonal changes are significant: winter and spring flows increase, while summer flows sharply decline. Flow variability is also rising. These trends are confirmed by SWAT, HBV models and satellite data.

3. Impact on Water Scarcity Glacier degradation is one of the main drivers of water scarcity in the Aral Sea basin. It negatively affects agriculture (potential yield loss of 15–30%), hydropower generation, drinking water supply, and increases the risk of transboundary conflicts between upstream and downstream countries.

Discussion

Climate change is fundamentally transforming the traditional "water tower" role of glaciers in Central Asia. In the short term, rapid glacier melt provides additional water volume to rivers, offering temporary relief for the current generation. However, in the long term, the disappearance of glaciers will lead to a sharp reduction in sustainable water resources for the region. The results of this study, based on Scopus data and international reports (IPCC AR6, UNESCO), show that the degradation of the Tien Shan and Pamir glaciers is causing profound changes in the hydrological system of the Amu Darya and Syr Darya river basins.

Socio-economic and Ecological Impacts The reduction in glacier volume and changes in seasonal river runoff have a significant impact on the region's key economic sectors. In agriculture, where more than 80% of irrigated lands in the region depend on the Amu Darya and Syr Darya rivers, summer water scarcity may lead to a 15–30% decrease in crop productivity. This poses a serious threat to food security and the income of the rural population.

A negative trend is also observed in the hydropower sector. The generation capacity of large hydropower plants in mountainous Kyrgyzstan and Tajikistan is declining, which limits energy supply and export opportunities. The ecological situation in the Aral Sea basin is deteriorating further, with increased soil degradation, dust storms, and public health problems (particularly respiratory diseases).

The issue of transboundary water sharing remains highly relevant. The risk of conflicts over water resources between upstream countries (Kyrgyzstan, Tajikistan) and downstream countries (Uzbekistan, Turkmenistan, Kazakhstan) is increasing. This may affect regional stability and the geopolitical situation.

Global Context The rate of glacier melt in Central Asia significantly exceeds the global average and shows similarities with the Himalayas and the Andes. According to IPCC reports, in cases of warming above 1.5°C, changes in high-mountain areas may reach an "irreversible" level.

Limitations of the Study The main limitations of this study are as follows:

- Insufficient number of glacier and hydrological monitoring stations in the region;
- Uncertainties in some models (especially regarding the dynamics of small glaciers);
- Incomplete modeling of the interaction between climate and anthropogenic factors (excessive water withdrawal, inefficient irrigation).

Future Directions and Recommendations Taking into account the urgency of the problem, the following measures must be implemented:

- Strengthen real-time satellite and automated monitoring of glaciers and river runoff;
- Fully implement Integrated Water Resources Management (IWRM) systems;
- Widely adopt water-saving technologies in agriculture (drip irrigation, precision agriculture);
- Enhance transboundary cooperation and improve international legal mechanisms;
- Develop targeted programs for Central Asia within the framework of COP conferences and the UN Sustainable Development Goals (SDG 6 and SDG 13).

This discussion demonstrates that strategies for combating climate change and adapting to it will become a decisive factor in ensuring the long-term sustainability of the Central Asian region.

Conclusion and Recommendations

Climate change is causing rapid degradation of the Tien Shan and Pamir glaciers in Central Asia, and this process has become the main driver of water scarcity in the Amu Darya and Syr Darya river basins. Recent studies from the Scopus database and international reports (IPCC, UNESCO, UN Water) confirm that the reduction in glacier volume leads to a temporary increase in river runoff in the short term, followed by a 10–35% decrease in the long term, along with increased seasonal variability and overall water resource scarcity in the region.

As a result, a decline in agricultural productivity, reduced hydropower potential, further deterioration of the ecological situation in the Aral Sea basin, and heightened risks of transboundary water conflicts are observed. The loss of the glaciers' "water tower" function poses a serious threat to the long-term sustainability of the Central Asian region.

Key Recommendations Considering the urgency of the problem, the following comprehensive measures must be implemented:

- **Strengthening glacier and hydrological monitoring**: Organize real-time monitoring of glaciers using satellite technologies (Sentinel, MODIS), GIS systems, and automated meteorological stations. This will enable timely forecasting of future changes.
- **Integrated Water Resources Management (IWRM) and transboundary cooperation**: Improve joint water management mechanisms in the Amu Darya and Syr Darya basins, update international agreements, and develop a regional water convention.
- **Water conservation and efficiency improvement in agriculture**: Widely introduce drip irrigation, smart irrigation, and precision agriculture technologies, and optimize water consumption on cultivated lands.
- **Climate adaptation and sustainable development projects**: Develop national climate change adaptation strategies, implement programs for glacier protection and restoration, and attract additional funding through international financial mechanisms (Green Climate Fund, World Bank).
- **Enhancing scientific research and public awareness**: Strengthen scientific cooperation in the region, train young researchers, and conduct awareness campaigns among the population on the importance of climate change and water resources.

Protecting glaciers and ensuring sustainable water resource management is not merely an environmental issue, but the key to the socio-economic stability, food security, and geopolitical stability of the Central Asian region. Only through timely, scientifically grounded, integrated, and internationally collaborative measures can we preserve water resources for future generations.

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