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Glacial Retreat and Water Security: What Are the Long-Term Implications of Glacier Melt in the Tien Shan and Pamir Mountains for Downstream Water Availability in Uzbekistan and Turkmenistan?

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ABSTRACT

The Tien Shan and Pamir mountains serve as critical water towers for Central Asia, supplying meltwater to major rivers like the Amu Darya and Syr Darya, which are vital for downstream countries such as Uzbekistan and Turkmenistan. This review synthesizes recent literature on glacier retreat, revealing substantial mass losses of 14–30% since the mid-20th century, with projections of 45–81% area reduction by the end of the century under high-emission scenarios. Initial melt increases river flows, but long-term declines—potentially 5–31% in annual streamflow by mid-century—threaten irrigation-dependent agriculture, hydropower, and water security in these arid nations. Qualitative impacts include heightened risks of food insecurity, economic losses up to 1.3% of regional GDP annually, and potential geopolitical tensions over transboundary resources. Adaptation strategies, such as improved irrigation efficiency and regional cooperation, are essential but face implementation challenges. This review highlights the urgency for integrated policy responses to mitigate these implications.

INTRODUCTION

Central Asia's hydrological systems are profoundly influenced by the cryosphere in the Tien Shan and Pamir mountains, which span Kyrgyzstan, Tajikistan, and Uzbekistan. These glaciers act as natural reservoirs, releasing meltwater during dry seasons to sustain the Amu Darya and Syr Darya rivers, providing over 90% of water resources for approximately 22 million people in the region (Zou et al., 2019). Downstream nations Uzbekistan and Turkmenistan, characterized by arid climates and heavy reliance on irrigated agriculture, are particularly vulnerable to changes in upstream glacier dynamics (Luo et al., 2018). The impending glacier retreat, driven by atmospheric warming, poses a significant threat to water availability, agricultural productivity, and overall water security in these already water-stressed regions (Hoelzle et al., 2017). Specifically, these mountain systems contribute significantly to the watersheds feeding the densely populated oases of the arid lowlands (Cariou, 2021), making them indispensable for regional water supply. A general warming trend of 1–2 °C has been observed in Central Asia since the beginning of the 20th century, potentially impacting regional temperature, evaporation, and precipitation regimes (Rakhmatullaev et al., 2010). This warming has already led to a notable decrease in Tajikistan's glaciated area, from 6.0% in the mid-20th century to approximately 4.8% by 2014, signaling substantial cryospheric changes that directly influence riverine systems (Gulakhmadov et al., 2020).

Climate change has accelerated glacier melt, with observed retreats four times the global average in the Tien Shan, leading to a 27% mass loss from 1961 to 2012 (Muccione & Cassara, 2019). Consequently, this ongoing glacial retreat poses significant threats to regional water security, food production, and ecological stability in Central Asia (Fu et al., 2017) (Kattakulov et al., 2021). Specifically, the rapid warming has altered precipitation patterns, shifting from snow to rain and diminishing the overall snow cover, especially in the Middle Tien Shan Mountains (Chen et al., 2016). These shifts are critical because the Tien Shan's glacial meltwater is integral to the freshwater supply, irrigation, and hydropower generation for transboundary regions highly susceptible to climate change (Kaliyeva et al., 2021) (Ahmad et al., 2025). As a result, the scarcity of water resources is emerging as a primary constraint on regional development in Central Asia, exacerbating existing vulnerabilities (Kattakulov et al., 2021). Compounding these challenges are issues such as low water use efficiency and rapid population growth, which intensify the demand for dwindling water resources (Kulmatov & Khasanov, 2023). Moreover, poor water management practices, including infrastructure issues like sedimentation and inadequate operation of hydraulic systems, further exacerbate water scarcity, particularly in downstream countries like Uzbekistan (Rakhmatullaev et al., 2010).

This review examines the long-term implications for water availability in Uzbekistan and Turkmenistan, drawing on recent studies to analyze quantitative projections and qualitative socio-economic effects. By synthesizing data from hydrological models, climate reports, and regional analyses, it identifies key trends, risks, and adaptation needs.

Glacier Dynamics and Melt Trends

Glaciers in the Tien Shan and Pamir have undergone significant retreat due to rising temperatures and altered precipitation patterns. Historical data indicate a 20–30% reduction in glacier extent over the past 50 years, with 97% of Tien Shan glaciers retreating between the 1960s and 2010s, and some small ones vanishing entirely. In Kyrgyzstan alone, over 16% of glaciers have been lost in the last 50 years, exacerbating regional drought risks. This accelerated shrinkage is projected to continue, with some models forecasting a 43% to 81% decrease in glacier coverage in parts of the Pamirs and Himalayas by 2100, which will significantly impact future water availability in Central Asia (Narama et al., 2009). This rapid glacial melt initially augments river flows, leading to an immediate increase in water availability, but this phenomenon is transient, as it presages a longer-term decline in water resources once the ice reserves are significantly depleted (Shahgedanova et al., 2020). The continued reduction in glacial volume is anticipated to decrease overall water flow in critical river systems, with projections indicating potential reductions of 2–5% in the Syr Darya basin and 10–15% in the Amu Darya basin by 2050 if current trends persist (Kulmatov & Khasanov, 2023). Such declines are particularly concerning for Central Asia, a region already grappling with increased water consumption, rapid population growth, and the complex impacts of climate change on water resources (Wang et al., 2022) (Berndtsson & Tussupova, 2020). The interdependencies between upstream and downstream countries in Central Asia further complicate water management, as upstream nations like Kyrgyzstan and Tajikistan prioritize hydropower, while downstream nations such as Uzbekistan and Turkmenistan depend on water for agricultural irrigation (Didovets et al., 2021). This dichotomy frequently results in political tensions and necessitates robust, regionally coordinated water management strategies (Fallah et al., 2024).

Projections under Representative Concentration Pathway 8.5 scenarios forecast severe losses: 52–93% of glacier area on the eastern slopes and 70–81% on the western slopes by 2095, with corresponding ice-water storage reductions of 46–94%. Furthermore, a 2015 study warns that an additional 2°C summer temperature rise could halve the Tien Shan's ice volume by the 2050s. These trends are driven by increased melt rates and a higher frequency of extreme events, such as glacial lake expansions at rates exceeding 3% per year. The average glacier melt contribution to total runoff is estimated at 30–37%, with an imbalance contribution of 8–16%, indicating that current melt rates exceed accumulation (Bolch et al., 2021). Compounding this issue, models suggest that by the end of the century, glaciers in High Mountain Asia could lose between 29 ± 12% and 67 ± 10% of their total mass relative to 2015, with considerable regional variability (Rounce et al., 2020). These projections underscore the urgent need for adaptive water management strategies, especially given that glaciers serve as crucial water storage systems on seasonal, mid-term, and long-term scales (Gan et al., 2015).

Impacts on Streamflow and Water Availability

Glacier melt initially augments river flows, contributing 4–61% to streamflow in major basins, with ice melt alone accounting for 1–22% historically. However, as glaciers diminish, long-term streamflow declines are anticipated, particularly on the western slopes feeding Central Asia. For the Amu Darya and Syr Darya, projections indicate a 5% overall reduction by 2066–2095 under RCP8.5, with seasonal shifts including earlier peak flows by 42 days and 15–21% drops in high-flow volumes during summer irrigation periods. These changes are particularly critical given that glacial meltwater sustains streamflow during drought conditions and provides essential water resources for drinking, irrigation, and hydropower generation in regions like the Hindu Kush Himalaya (Shokory et al., 2025).

In Uzbekistan and Turkmenistan, these changes could result in 13–31% flow reductions by 2041–2050, compounded by potential diversions like Afghanistan's Qosh Tepa Canal, which may siphon up to 30% of Amu Darya water. The UN World Water Development Report 2025 projects a 30% loss of freshwater resources by 2050 if unchecked, threatening the rivers' average annual flows of 74 km^3 (Amu Darya) and 37 km^3 (Syr Darya). Contrasting regimes show eastern slopes (e.g., Tarim River) gaining 28% in flow, while western slopes face deficits of 0.8–5.3 billion cubic meters annually (Carleton et al., 2024; Vanham et al., 2022). These regional disparities in hydrological response necessitate differentiated adaptation strategies, emphasizing the urgent need for transboundary water governance frameworks to mitigate potential conflicts and ensure equitable resource distribution across Central Asia.

Socio-Economic Implications

Uzbekistan and Turkmenistan's economies, dominated by agriculture (e.g., cotton production), allocate 88–92% of water to irrigation, much of which is lost through inefficient systems like Turkmenistan's Karakum Canal. Reduced water availability could lead to yield declines, food insecurity, and annual GDP losses of 1.3% regionally, with up to five million people displaced by 2050 due to water stress. Qualitatively, communities face heightened vulnerability, with experts warning of a shift from water abundance to scarcity post-2050 peak melt, necessitating agricultural diversification away from water-intensive crops (KC et al., 2022). These shifts are further exacerbated by climate change, which is projected to decrease annual average snow-covered area and river flow, thereby altering high-altitude stream sources and reducing downstream water availability, particularly in the mid to late 21st century (Azizi & ASAOKA, 2020). Moreover, declining water resources in the Amu and Syr Darya basins are anticipated to increase reliance on rainfall runoff, even as glacier ice and seasonal snow diminish, further stressing already vulnerable hydrological systems (Su et al., 2022).

Health and livelihood impacts are pronounced in rural areas, where erratic flows increase flood risks initially and drought thereafter, exacerbating poverty and migration. In Uzbekistan, heatwaves and reduced irrigation water disrupt crop cycles, while Turkmenistan contends with desertification amplified by local methane emissions.

Geopolitical and Environmental Consequences

As downstream users consuming 83% of basin water, Uzbekistan and Turkmenistan depend on upstream cooperation with Kyrgyzstan and Tajikistan for equitable sharing. Declining flows may intensify transboundary disputes, especially with hydropower dams altering seasonal releases. Environmentally, the Aral Sea's ongoing shrinkage—already 90% lost—worsens dust storms and ecosystem degradation, affecting biodiversity and human health (Berndtsson & Tussupova, 2020; Chen et al., 2018). This situation is compounded by rapid population growth and climate change impacts, which are projected to further exacerbate the precarious water management situation in the region, potentially leading to increased conflict over water resources (Berndtsson & Tussupova, 2020). Effective transboundary water management strategies are crucial to mitigating these conflicts, particularly given the historical context of poor water management causing significant economic losses in Central Asia (Rakhmatullaev et al., 2010). The vulnerability of Central Asian water resources is further underscored by the historical susceptibility to environmental shortages, where any increase in water consumption intensifies the frequency and severity of these shortages (Boer et al., 2021). A lack of collaboration among Central Asian nations in managing shared water resources further exacerbates these challenges, potentially leading to substantial economic repercussions (Azimov & Avezova, 2022). Furthermore, the degradation of water infrastructure and ongoing land reforms also contribute to the complexity of water management in Central Asia, requiring comprehensive regional approaches to address these multifaceted issues (Stucker et al., 2012).

Adaptation Strategies and Challenges

Initiatives like the GEF-UNDP-UNESCO project in Uzbekistan focus on cryosphere monitoring, knowledge platforms, and policy integration to build resilience. Recommendations include drip irrigation, reservoir expansion, and drought-resistant crops, alongside regional forums for data sharing. Challenges persist due to aging infrastructure, political fragmentation, and insufficient funding, underscoring the need for interdisciplinary research and international support (Abou-Shady et al., 2023; Zin et al., 2025).

CONCLUSION

The melting of glaciers in the Tien Shan and Pamir mountains presents a profound and urgent challenge to water security in Central Asia, particularly for downstream nations like Uzbekistan and Turkmenistan. While initial melt temporarily increases river flows, this phenomenon is transient, foreshadowing significant long-term declines in water availability. Projections indicate substantial reductions in annual streamflow, threatening the agricultural backbone, hydropower generation, and overall water security of these arid regions.

The implications extend beyond mere hydrological changes, encompassing severe socio-economic impacts such as heightened risks of food insecurity, potential economic losses up to 1.3% of regional GDP annually, and the displacement of millions due to water stress. Geopolitically, the diminishing water resources exacerbate existing tensions over transboundary rivers, making effective regional cooperation critical. Environmentally, the ongoing shrinkage of the Aral Sea and increased desertification underscore the cascading ecological consequences.

Addressing these multifaceted challenges necessitates immediate and integrated adaptation strategies. These include improving irrigation efficiency, developing drought-resistant crops, expanding water storage infrastructure, and fostering robust regional water governance frameworks. Despite these efforts, significant obstacles remain, including aging infrastructure, political fragmentation, and insufficient funding. Ultimately, safeguarding regional stability and ensuring sustainable water resources requires not only continued scientific research and localized modeling but also a concerted, collaborative effort among Central Asian nations and international partners to implement effective and equitable solutions.

REFERENCES

1. Abou-Shady, A., Siddique, M. S., & Yu, W. (2023). A Critical Review of Innovations and Perspectives for Providing Adequate Water for Sustainable Irrigation [Review of A Critical Review of Innovations and Perspectives for Providing Adequate Water for Sustainable Irrigation]. Water, 15(17), 3023. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/w15173023
2. Ahmad, Z., Altaf, F., Kamp, U., Rahman, F., & Malik, S. M. (2025). Glacier Recession and Climate Change in Chitral, Eastern Hindu Kush Mountains of Pakistan, Between 1992 and 2022. Geosciences, 15(5), 167. https://doi.org/10.3390/geosciences15050167
3. Azimov, U., & Avezova, N. R. (2022). Sustainable small-scale hydropower solutions in Central Asian countries for local and cross-border energy/water supply. Renewable and Sustainable Energy Reviews, 167, 112726. https://doi.org/10.1016/j.rser.2022.112726
4. Azizi, A. H., & ASAOKA, Y. (2020). Assessment of the Impact of Climate Change on Snow Distribution and River Flows in a Snow-Dominated Mountainous Watershed in the Western Hindukush–Himalaya, Afghanistan. Hydrology, 7(4), 74. https://doi.org/10.3390/hydrology7040074
5. Berndtsson, R., & Tussupova, K. (2020). The Future of Water Management in Central Asia. Water, 12(8), 2241. https://doi.org/10.3390/w12082241
6. Boer, T. de, Paltán, H., Sternberg, T., & Wheeler, K. (2021). Evaluating Vulnerability of Central Asian Water Resources under Uncertain Climate and Development Conditions: The Case of the Ili-Balkhash Basin. Water, 13(5), 615. https://doi.org/10.3390/w13050615
7. Bolch, T., Duethmann, D., Wortmann, M., Liu, S., & Disse, M. (2021). Declining glaciers endanger sustainable development of the oases along the Aksu-Tarim River (Central Asia). International Journal of Sustainable Development & World Ecology, 29(3), 209. https://doi.org/10.1080/13504509.2021.1943723
8. Cariou, A. (2021). Spatial Impacts of Melting Central Asian Glaciers: Towards a “Water War”? 187. https://doi.org/10.1002/9781119817925.ch9
9. Carleton, T., Crews, L., & Nath, I. (2024). Is the World Running Out of Fresh Water? AEA Papers and Proceedings, 114, 31. https://doi.org/10.1257/pandp.20241008

10. Chen, Y., Li, W., Deng, H., Fang, G., & Li, Z. (2016). Changes in Central Asia's Water Tower: Past, Present and Future. Scientific Reports, 6(1). https://doi.org/10.1038/srep35458
11. Chen, Y., Li, Z., Fang, G., & Li, W. (2018). Large Hydrological Processes Changes in the Transboundary Rivers of Central Asia. Journal of Geophysical Research Atmospheres, 123(10), 5059. https://doi.org/10.1029/2017jd028184
12. Didovets, I., Lobanova, A., Krysanova, V., Menz, C., Babagalieva, Z., Nurbatsina, A., Gavrilenko, N., Khamidov, V., Umirbekov, A., Qodirov, S., Muhyyew, D., & Hattermann, F. F. (2021). Central Asian rivers under climate change: Impacts assessment in eight representative catchments. Journal of Hydrology Regional Studies, 34, 100779. https://doi.org/10.1016/j.ejrh.2021.100779
13. Fallah, B., Didovets, I., Rostami, M., & Hamidi, M. (2024). Climate change impacts on Central Asia: Trends, extremes and future projections. International Journal of Climatology, 44(10), 3191. https://doi.org/10.1002/joc.8519
14. Fu, B. H., Guo, Q., Yan, F., Zhang, J., Shi, P., Ayinuer, M., & Xue, G. (2017). Glacier retreat of the Tian Shan and its impact on the urban growth and environment evaluated from satellite remote sensing data. IOP Conference Series Earth and Environmental Science, 74, 12022. https://doi.org/10.1088/1755-1315/74/1/012022
15. Gan, R., Luo, Y., Zuo, Q., & Sun, L. (2015). Effects of projected climate change on the glacier and runoff generation in the Naryn River Basin, Central Asia. Journal of Hydrology, 523, 240. https://doi.org/10.1016/j.jhydrol.2015.01.057
16. Gulakhmadov, A., Chen, X., Gulahmadov, N., Liu, T., Anjum, M. N., & Rizwan, M. (2020). Simulation of the Potential Impacts of Projected Climate Change on Streamflow in the Vakhsh River Basin in Central Asia under CMIP5 RCP Scenarios. Water, 12(5), 1426. https://doi.org/10.3390/w12051426
17. Hoelzle, M., Azisov, E., Barandun, M., Huss, M., Farinotti, D., Гафуров, A., Hagg, W., Kenzhebaev, R., Kronenberg, M., Machguth, H., Merkushkin, A., Moldobekov, B., Petrov, M., Saks, T., Salzmann, N., Schöne, T., Tarasov, Y., Usubaliev, R., Vorogushyn, S., … Zemp, M. (2017). Re-establishing glacier monitoring in Kyrgyzstan and Uzbekistan, Central Asia. Geoscientific Instrumentation, Methods and Data Systems, 6(2), 397. https://doi.org/10.5194/gi-6-397-2017
18. Kaliyeva, K., Punys, P., & Zhaparkulova, Y. (2021). The Impact of Climate Change on Hydrological Regime of the Transboundary River Shu Basin (Kazakhstan–Kyrgyzstan): Forecast for 2050. Water, 13(20), 2800. https://doi.org/10.3390/w13202800
19. Kattakulov, F., Artikbekova, F., Gafurov, Z., Jumabaeva, G., & Musulmanov, F. (2021). Consideration of climatic factors in the operating mode of hydraulic facilities in the Amudarya river basin. E3S Web of Conferences, 264, 3068. https://doi.org/10.1051/e3sconf/202126403068
20. KC, K. B., Tzadok, E., & Pant, L. P. (2022). Himalayan ecosystem services and climate change driven agricultural frontiers: a scoping review [Review of Himalayan ecosystem services and climate change driven agricultural frontiers: a scoping review]. Discover Sustainability, 3(1). Springer Nature. https://doi.org/10.1007/s43621-022-00103-9
21. Kulmatov, R., & Khasanov, S. (2023). Contemporary climate change problems in Central Asia. E3S Web of Conferences, 413, 5013. https://doi.org/10.1051/e3sconf/202341305013
22. Luo, Y., Wang, X., Piao, S., Sun, L., Ciais, P., Zhang, Y., Ma, C., Gan, R., & He, C. (2018). Contrasting streamflow regimes induced by melting glaciers across the Tien Shan – Pamir – North Karakoram. Scientific Reports, 8(1). https://doi.org/10.1038/s41598-018-34829-2
23. Muccione, V., & Cassara, M. (2019). The climate-cryosphere-water nexus in central Asia. 8. https://doi.org/10.5167/uzh-181502
24. Narama, C., Kääb, A., Duishonakunov, M., & Abdrakhmatov, K. (2009). Spatial variability of recent glacier area changes in the Tien Shan Mountains, Central Asia, using Corona (~ 1970), Landsat (~ 2000), and ALOS (~ 2007) satellite data. Global and Planetary Change, 71, 42. https://doi.org/10.1016/j.gloplacha.2009.08.002
25. Rakhmatullaev, S., Huneau, F., Coustumer, P. L., Motelica-Heino, M., & Bakiev, M. (2010). Facts and Perspectives of Water Reservoirs in Central Asia: A Special Focus on Uzbekistan. Water, 2(2), 307. https://doi.org/10.3390/w2020307

26. Rounce, D. R., Hock, R., & Shean, D. (2020). Glacier Mass Change in High Mountain Asia Through 2100 Using the Open-Source Python Glacier Evolution Model (PyGEM). Frontiers in Earth Science, 7. https://doi.org/10.3389/feart.2019.00331
27. Shahgedanova, M., Afzal, M., Hagg, W., Kapitsa, V., Kasatkin, N., Mayr, E., Rybak, O., Saidaliyeva, Z., Severskiy, I., Usmanova, Z., Wade, A. J., Yaitskaya, N., & Zhumabayev, D. (2020). Emptying Water Towers? Impacts of Future Climate and Glacier Change on River Discharge in the Northern Tien Shan, Central Asia. Water, 12(3), 627. https://doi.org/10.3390/w12030627
28. Shokory, J. A. N., Horton, P., Schaefli, B., & Lane, S. N. (2025). Glacier-influenced hydrological regimes in the Afghanistan Hindu Kush Himalaya under current and future climate. Hydrology Research. https://doi.org/10.2166/nh.2025.082
29. Stucker, D., Kazbekov, J., Yakubov, M., & Wegerich, K. (2012). Climate Change in a Small Transboundary Tributary of the Syr Darya Calls for Effective Cooperation and Adaptation. Mountain Research and Development, 32(3), 275. https://doi.org/10.1659/mrd-journal-d-11-00127.1
30. Su, F., Pritchard, H. D., Yao, T., Huang, J., Ou, T., Meng, F., Sun, H., Li, Y., Xu, B., Zhu, M., & Chen, D. (2022). Contrasting Fate of Western Third Pole's Water Resources Under 21st Century Climate Change. Earth s Future, 10(9). https://doi.org/10.1029/2022ef002776
31. Vanham, D., Alfieri, L., & Feyen, L. (2022). National water shortage for low to high environmental flow protection. Scientific Reports, 12(1). https://doi.org/10.1038/s41598-022-06978-y
32. Wang, X., Chen, Y., Fang, G., Li, Z., & Liu, Y. (2022). The growing water crisis in Central Asia and the driving forces behind it. Journal of Cleaner Production, 378, 134574. https://doi.org/10.1016/j.jclepro.2022.134574
33. Zin, E. N., Inoue, N., & Uenishi, Y. (2025). The Food Water Energy Nexus in Agriculture: Understanding Regional Challenges and Practices to Sustainability. Sustainability, 17(10), 4428. https://doi.org/10.3390/su17104428
34. Zou, S., Abuduwaili, J., Duan, W., Maeyer, P. D., & Voorde, T. V. de. (2019). Human and Natural Impacts on the Water Resources in the Syr Darya River Basin, Central Asia. Sustainability, 11(11), 3084. https://doi.org/10.3390/su11113084