

Significant reduction of river discharge in the mountainous basins of Uzbekistan over the last decades

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Abstract:

Snow is the main hydrological component, and its contribution plays a key role in runoff formation in Uzbekistan, Central Asia. However, climate change has altered snow accumulation dynamics over the past two decades. This study investigated the impacts of seasonal changes in snow on river runoff in the Pskem and Uradarya Basins over the past 22 hydrological years (2001–2023), considering air temperature and precipitation variations. In-situ data from meteorological and hydrological stations in the study areas were used to examine the trend dynamics during the study period. Pearson's correlation analysis was applied to examine the statistical relationship between the winter snow accumulation and summer discharge. The statistical significance of the trend dynamics was tested using the Mann-Kendall test. The results revealed a significant reduction in snow accumulation over the study period and the number of overall snowfall days, with a marked decline observed in recent years. Consequently, the contribution of seasonal snow to river runoff has markedly decreased, leading to a reduction in the discharge volume during the vegetation period. A reduction in discharge volume in both basins over the past 22-year period (2001–2023) was statistically confirmed based on in-situ data.

KEYWORDS snow cover; discharge; mountain basin; climate change; runoff

INTRODUCTION

In Central Asia, seasonal snowmelt from mountain regions is a major contributor to river runoff and a critical water source for downstream communities and agriculture (Kraaijenbrink *et al.*, 2021). In Uzbekistan, the timing and volume of snowmelt-driven discharge determine the availability of water for irrigation, hydropower, and ecosystem services (Gerlitz *et al.*, 2020). However, climate change is increasingly altering snow accumulation, melting patterns, and runoff dynamics across the region. Winter snow accu-

mulation and its dynamics have been strongly affected by climate change (Chen *et al.*, 2023), shortening the duration of snow cover across Central Asian mountain regions (Normatov and Normatov, 2020). Variations in the seasonal distribution of snow cover patterns have also been observed (Kalashnikova and Gafurov, 2017). Vydra *et al.* (2024) documented that during the spring season snow cover duration decreased over the past 22-year period (2000–2022). According to Apel *et al.* (2018), different elevation zones exhibit varying responses to rising air temperature. Huang *et al.* (2022) and Kholmatjanov *et al.* (2020) reported that warming trends accelerated the early seasonal snowmelt. Consequently, the peak discharge period shifted from June–July to April–May (Haag *et al.*, 2019). Likewise, Xiaole (2015) reported a 21% reduction in river flow due to a 20% decline in snow from 1996 to 2005. These changes raise critical questions about the stability of snow-fed river systems in the region.

Most studies have relied on remote sensing or modelling approaches to provide valuable large-scale assessment of snow cover in analysed variations in the upstream catchments of the Syr Darya and Amu Darya Rivers (Dietz *et al.*, 2014; Liu *et al.*, 2017; Ouyang *et al.*, 2023; Sadyrov *et al.*, 2024; Gafurov *et al.*, 2016). These approaches are often limited by scale-related uncertainties and lack of sufficient ground-based validation. In particular, there has been no long-term analysis of the impacts of snow dynamics on discharge validated at the basin scale in the mountainous rivers in Uzbekistan. This study addresses this gap by analysing meteorological and hydrological data from the Pskem and Uradarya River Basins, two of Uzbekistan's highest and most mountainous regions. These basins are strategically important for the country's water security and serve as key sources of runoff for downstream areas. Yet, their snow-runoff dynamics have not been specifically quantified. Here the effects and dynamics of seasonal snow variations and accumulation were examined with the seasonal and annual variability of the observed climatic parameters over the past 22 hydrological years (2001–2023).

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The specific objectives of this study are to: (1) Quantify the trends in seasonal snow depth, air temperature, and precipitation; (2) Analyse the resulting changes in river discharge volume and timing; and (3) Evaluate the statistical relationship between the decline in winter snowpack and the reduction in summer river flow. The trend dynamics of climatic parameters were also evaluated using percentile analyses, considering their impact on the river discharge volume, to better understand recent decrease in the river discharge of the mountain rivers in Uzbekistan.

By focusing on these high-mountain basins, this study provides critical insight into how climate-driven changes in snow accumulation impact river regimes in higher mountains of Central Asia. Although the study focuses on two mountain catchments, these basins are hydrologically significant for downstream regions and regional water supply. Understanding these dynamics is essential for analysis of snow-runoff relationships and improving water resource management, especially under future warming scenarios that threaten the stability of regional snow-fed river systems.

MATERIALS AND METHODS

Study area

The Pskem and Uradarya River Basins are the study areas of this research. The Pskem Basin is located in north-eastern Uzbekistan, whereas the Uradarya Basin is situated in the southern region (Figure 1). The climatic conditions of the basins vary according to their geographical locations, which lie within different mountain ranges. Snow is more dominant in the Pskem Basin, whereas it occurs less frequently in the Uradarya Basin (Figure S1). The observed mean daily air temperature, snow depth, and precipitation data were obtained from the Oygaing (Pskem Basin) and Minchukur (Uradarya Basin) meteorological stations. Mean daily discharge data were collected from the Muallala (Pskem Basin) and Pachkamar (Uradarya Basin) stations operated by the National Hydrometeorological Agency (Uzhydromet, 2025) of Uzbekistan. Daily data are available at the Archive Department of the Uzbekistan Hydrometeorological Center and were used to investigate seasonal variations in climatic parameters in the study areas.

Daily snow depth data (Nov–Apr) were used to explore the seasonal formation of snow accumulation over hydro-

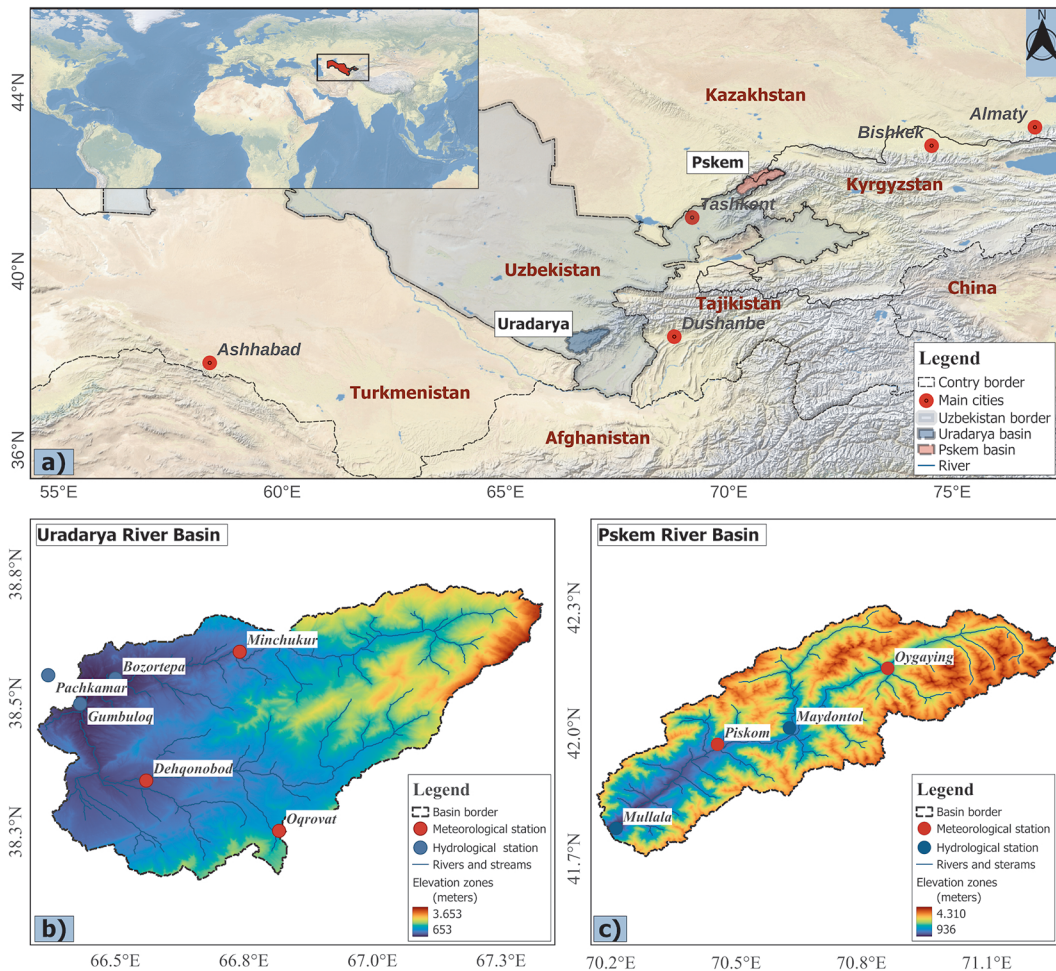


Figure 1. Study area: (a) Geographic overview of Uzbekistan, topography and network of hydrometeorological stations in the (b) Uradarya and (c) Pskem River Basins

logical years from 2001 to 2023. Trends were tested using the Mann-Kendall test. Mean daily air temperature was similarly analysed with percentiles (5th, 50th, 90th) to represent cold, median, and hot conditions. Seasonal averages were also calculated. For peak periods, snow depth (Jan–Mar) and discharge (Jun–Aug) were compared using Pearson correlation. For each statistical analysis presented in the figures, the p -value indicates whether the slope of the regression line differs significantly from zero (i.e. whether a statistically significant trend exists). A p -value below 0.05 was considered statistically significant.

RESULTS AND DISCUSSION

Variations in snow depth accumulation

Seasonal snow accumulation in both basins exhibited considerable interannual variability during 2001–2023 (Figure 2). In the Pskem Basin, the 90th percentile of snow depth frequently exceeded 200 cm in the early 2000s, reaching a maximum of around 230 cm in 2009. After 2011, however, these values declined steadily, with most years registering less than 140 cm. In the Uradarya Basin, snow depth was generally lower, rarely exceeding 120 cm (the 90th percentile), and after 2018 most years remained below 60 cm. The Mann-Kendall test confirmed statistically significant downward trends across all percentiles in both basins (Table SI).

Overall, the results from all percentile analyses highlight that snow depth accumulation fluctuated across seasons in both basins from 2001 to 2023, and steady reductions in

snow depth accumulation have been observed in both basins since 2011. The early 2000s included several high-snow years, but since 2011, shallow-snow seasons have dominated. This shift coincides with regional observations of declining snow cover duration across the Tien Shan and Gissar-Alay (Normatov and Normatov, 2020; Vydra *et al.*, 2024). Annual precipitation showed a downward trend in both basins, suggesting a potential decrease in the precipitation volume from year to year (Figure S2). For the Pskem River, the trend shows decline of 4.64 mm per year, with ($p = 0.48$), the Uradarya Basin exhibits a higher decline of 11.13 mm per year, the trend of which is ($p = 0.06$) close to the threshold of statistical significance.

The increased frequency of low-snow years in the last decade is especially concerning, as it reduces the ability of snowpack to act as a seasonal reservoir. These findings align with reports from other Central Asian basins. In the Chirchik, a tributary of the Syr Darya that includes the Pskem, Kodirov and Gapparov (2020) documented a marked decline in snow days. Gafforov *et al.* (2020) showed similar reductions in the western Tien Shan. In Kyrgyzstan, Gerlitz *et al.* (2020) and Chen *et al.* (2023) also highlighted shorter snow cover duration and earlier melt onset. This confirms that snowpack decline is widespread, affecting both glacierized and non-glacierized basins. It shows that the “natural storage” function of snowpack is weakening. High-snow winters used to guarantee reliable summer runoff, but this buffering capacity is now declining. In the Uradarya Basin, which depends on a relatively thin snowpack, the vulnerability is even greater.

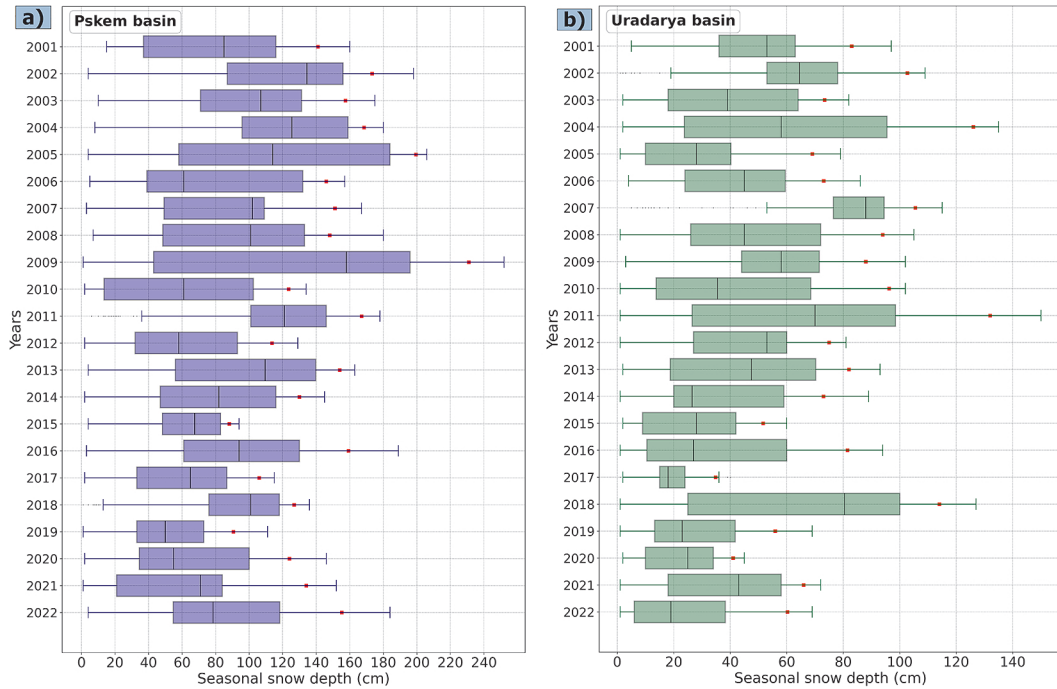


Figure 2. Variations in the seasonal snow depth (Nov–Apr) in the (a) Pskem and (b) Uradarya Basins in 2001–2023 hydrological years. Daily snow depth data from Oygaing and Minchukur meteorological stations were used. Each box represents the seasonal (Nov–Apr) formation of snow depth for each year and represents the 25th, 50th, and 75th percentiles of seasonal snow depth in the study areas. Additionally, the 90th percentile indicates high seasonal snow depth, marked by a red dot line

Variations in air temperature

Air temperature increased in both basins during 2001–2023, with the strongest signal in hot extremes (90th percentile). These rose significantly at $\sim 0.05^\circ\text{C}$ per year ($p = 0.02\text{--}0.03$), amounting to around 1.1°C warming over 22 years (Figure S3). Cold extremes (10th percentile) also increased, though more moderately (0.02°C per year, or $0.4\text{--}0.7^\circ\text{C}$ total). Median values changed little, except for a slight decline in the Uradarya Basin (-0.02°C per year). Seasonal analysis (Figure 3) highlighted significant spring warming, with mean temperatures increasing by 0.09°C per year in Pskem (1.98°C total) and 0.07°C per year in

Uradarya (1.54°C total). Winter warming was weaker and not statistically significant, while autumn exhibited a slight cooling trend in both basins (-0.03 to -0.05°C per year).

Snowmelt typically begins in March, and accelerated warming reduces snow cover duration, advances melt onset, and shifts runoff toward earlier months. Similar spring warming signals have been reported across Central Asia (Feng *et al.*, 2018; Zhang *et al.*, 2019). Kholmatjanov *et al.* (2020) noted that average air temperatures in Uzbekistan increased by $\sim 1^\circ\text{C}$ in both cold and warm periods between 1961 and 2016, with especially strong warming in spring, accelerating glacier retreat (Yu *et al.*, 2021) and reducing snow accumulation. Warmer springs increase the

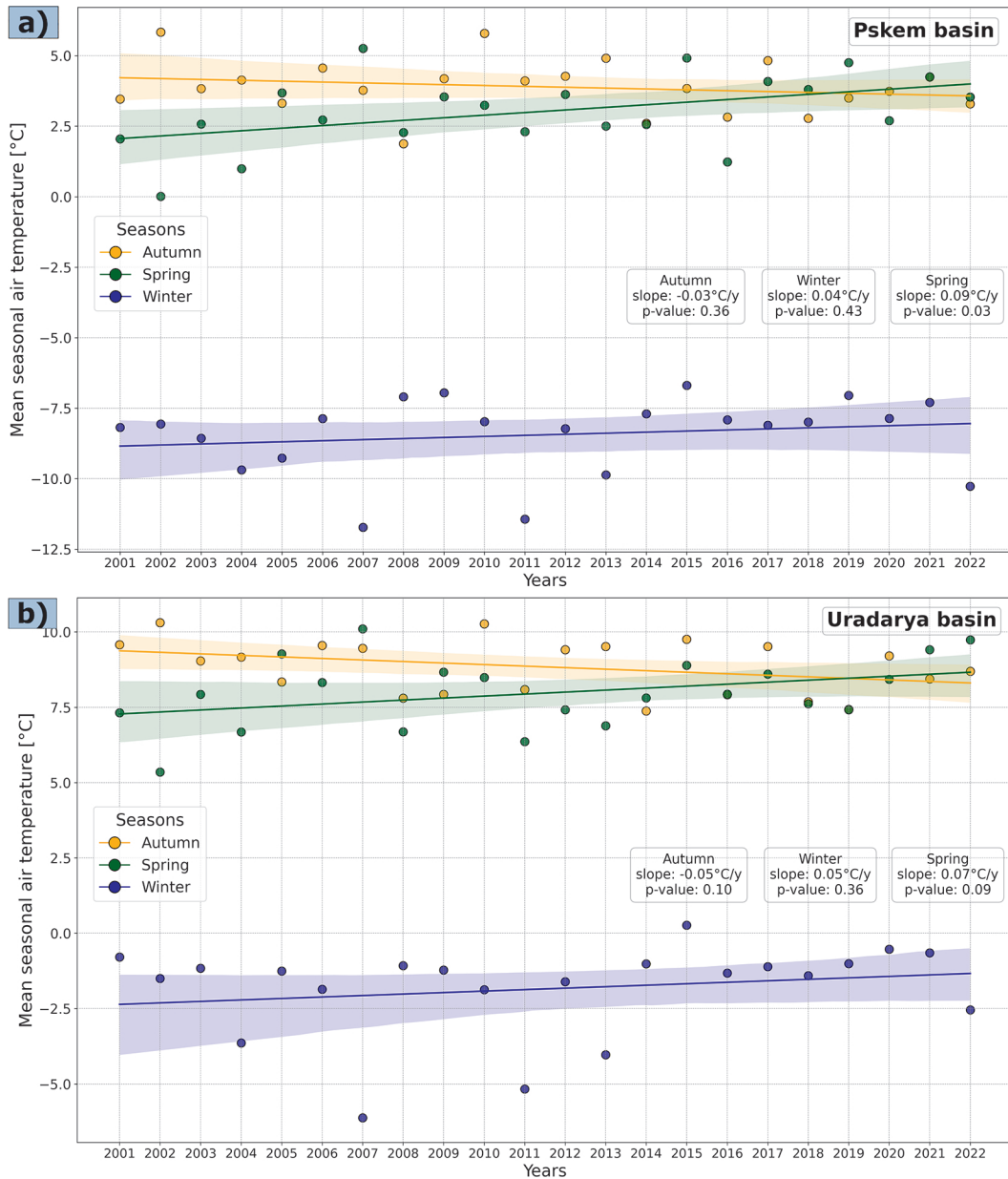


Figure 3. Trends in mean seasonal air temperature in the (a) Pskem and (b) Uradarya Basins from 2001 to 2023. Daily mean air temperature data were averaged at the seasonal scale in each year. The coloured shaded areas (around each regression line for Autumn, Spring, Winter) represent the 95% confidence range of the fitted trend line, showing the uncertainty in the estimated regression line

likelihood of rainfall rather than snowfall, particularly in basins with lower elevations like Uradarya. Our data suggest that this shift is already occurring, as years with low snow depth often coincide with increased spring rainfall. This agrees with Haag *et al.* (2019), who reported a shift from snow to rain during transitional seasons, and Li *et al.* (2020), who linked precipitation phase changes directly to rising temperatures. Such changes reduce snowpack accumulation and further decrease water availability in summer.

Variations in discharge volume

Both basins exhibited significant reductions in discharge over the 22-year period (Figure 3). In Pskem, mean discharge during the vegetation season (Apr–Sep) decreased by $-2.41 \text{ m}^3 \text{ s}^{-1}$ per year ($-53 \text{ m}^3 \text{ s}^{-1}$ total), while in Uradarya the decline was $-0.28 \text{ m}^3 \text{ s}^{-1}$ per year ($-6 \text{ m}^3 \text{ s}^{-1}$ total). In the first decade (2001–2012), discharges above $125 \text{ m}^3 \text{ s}^{-1}$ in Pskem and $10 \text{ m}^3 \text{ s}^{-1}$ in Uradarya were relatively common. After 2012, such flows became rare, and after 2018 low-flow years occurred with increasing frequency. Percentage anomalies (Figure 4) highlight the severity of recent reductions. In Uradarya, discharge was 70–80% below the long-term average in 2021–2022 (Figure S4). In Pskem, discharge was 30% below average in the same years. Both basins indicate a reduction in the discharge volume according to the long-term average. In most years, the mean discharge remained persistently higher than the long-term average until 2006, whereas year-to-year discharge decreased in the Pskem Basin from 2011 and the Uradarya Basin from 2016.

The relationship between winter snowpack and summer discharge was tested using Pearson correlation (Figure 5). Both basins showed significant positive correlations between Jan–Mar snow depth and Jun–Aug discharge ($R = 0.53$ in Pskem; $R = 0.54$ in Uradarya). These moderate but robust values confirm that snowpack decline is a primary driver of reduced summer runoff. However, the correlations are not perfect, which highlights the influence of

additional factors. Seasonal air temperature variability plays a role: warm springs accelerate melt and reduce snowpack storage, while autumn cooling may offset some losses. Precipitation variability is also important, as reduced snowfall and increased rainfall can alter both snow depth and runoff timing. While the statistically significant results highlight that snow is the main factor affecting basin runoff in summer, the moderate correlation coefficients indicated that other factors have contributed significantly (Huang *et al.*, 2022). Other contributing factors could include variability in seasonal air temperature and precipitation patterns (Chevallier *et al.*, 2014). These results fit into a broader regional pattern. Alikhanov *et al.* (2024) found significant decreases in snow and ice cover in the Ugam Basin, another tributary of the Chirchik, leading to reduced discharge. Salokhiddinov *et al.* (2023) reported similar declines in snowpack and runoff in the Kashkadarya Basin, which includes Uradarya. The consistency of findings across multiple basins indicates that snowpack decline is a widespread driver of water shortages in Uzbekistan.

Snowmelt provides critical summer water for irrigation, hydropower, and ecosystems. As snowpack declines and runoff shifts earlier in the year, the mismatch between water supply and demand will intensify. Irrigation systems that depend on reliable summer flows will face greater stress, potentially exacerbating existing problems of salinization and water scarcity in the downstream plains. Hydropower operations, which rely on seasonal flow patterns, will also need to adjust to earlier peak flows. Without adaptation, these changes risk undermining national water security and regional economic stability.

These correlation results emphasize the importance of incorporating seasonal snow depth accumulation into the discharge volume in both basins during the vegetation period. For water management, the reduction in discharge during the vegetation period is particularly concerning. Agriculture in both the Chirchik and Kashkadarya regions depends heavily on summer irrigation. Hydropower genera-

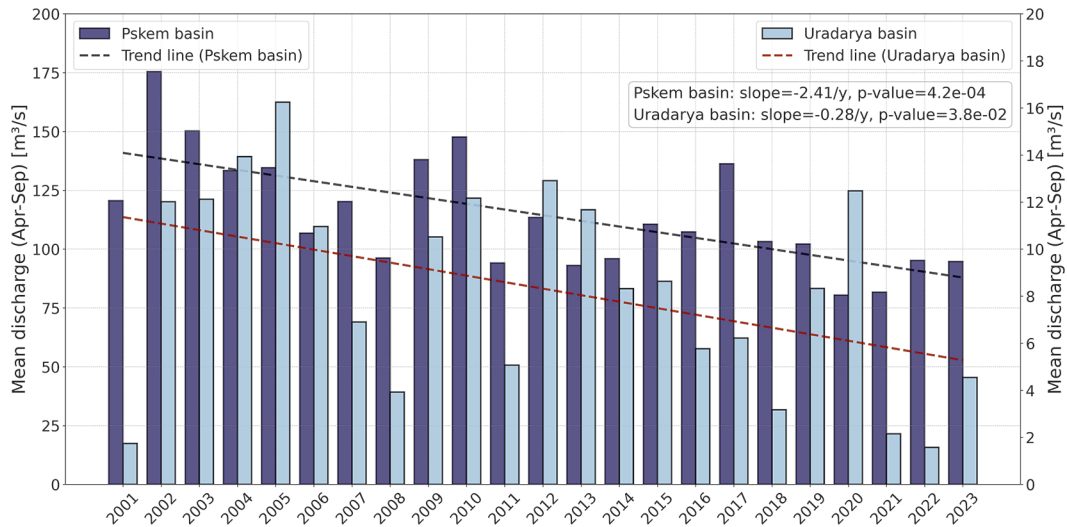


Figure 4. Trends in mean monthly discharge in the Pskem and Uradarya Basins during the vegetation period from 2001 to 2023. Daily discharge in each vegetation period (Apr–Sep) was averaged from 2001 to 2023. The vertical axis is for mean discharge of the Pskem River on the left and for the Uradarya River on the right, please note difference in axes-ticks levels

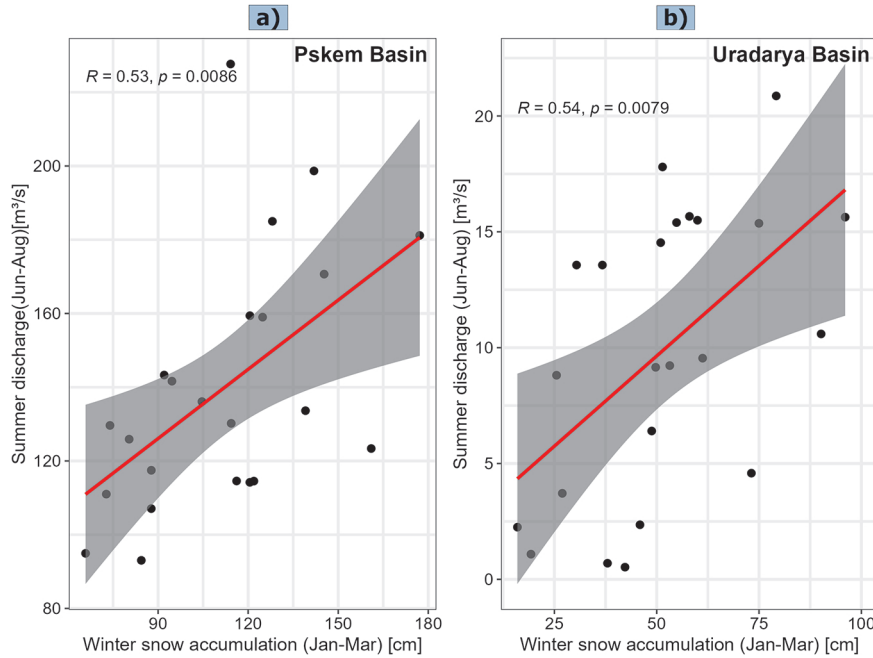


Figure 5. Correlation between mean winter (Jan–Mar) snow accumulation and mean summer (Jun–Aug) discharge for the (a) Pskem and (b) Uradarya Basins. The coloured shaded regions (around each regression line for Autumn, Spring, Winter) represent the 95% confidence range of the fitted trend line, showing the uncertainty in the estimated regression line

tion is also affected, as peak flows now occur earlier in the year (Apr–May), reducing summer water availability. This seasonal shift was reported by Haag *et al.* (2019) and is confirmed by our observations.

CONCLUSION

This research focused on estimating the impacts of seasonal changes in snow on basin discharge volume in the Pskem and Uradarya mountain river basins of Uzbekistan over the past 22 hydrological years from 2001 to 2023, based on in-situ data such as air temperature and precipitation. While winter snow accumulation is the main contributor to discharge during the vegetation period, our findings show that the transition in precipitation patterns and rising air temperature significantly impacted the discharge volume. The moderate correlation between winter snow accumulation and summer discharge suggests that changes in air temperature and precipitation during the snowmelt period are strongly influenced by spring warming. The 22-year observational record reveals clear and consistent signals of climate-driven change in snowpack accumulation, air temperature dynamics, and discharge regimes. Together, these findings highlight the growing vulnerability of snow-fed rivers in Uzbekistan and underscore the urgent need to adapt water resource management to a rapidly changing climate.

The results demonstrate a significant and persistent decline in snow accumulation since around 2011, with the 90th percentile snow depth falling from over 200 cm in the early 2000s to less than 140 cm in Pskem and below 60 cm in Uradarya after 2018. These reductions are statistically significant across all percentiles and align with broader evi-

dence of shrinking snow cover across Central Asia. Air temperature records show that warming is most pronounced in spring, averaging 0.07–0.09 °C per year, which accelerates snowmelt and shortens the duration of snow cover. Winter warming is weaker, while autumn shows slight cooling, but these do not offset the dominant spring signal. Collectively, these changes reduce snowpack storage, advance the timing of melt, and shift precipitation toward rainfall rather than snowfall. In addition, even though 2001–2012 have included several extreme drought events in 2001, 2002, 2008, and 2011 (Food and Agriculture Organization of the United Nations (FAO), 2017) recent observed changes in precipitation and discharge in 2012–2023 show significantly smaller values on average.

In both basins, decreases in annual and seasonal precipitation occurred in 2012 and 2013, with particularly low precipitation. The marked decline was observed in recent years compared with the initial years of the study period in addition to a significant increase in annual air temperatures in both basins. Consequently, the seasonal snow contribution to river runoff has markedly decreased, leading to a reduction in the basin's peak discharge volumes.

The hydrological response is evident in both basins. Discharge during the vegetation period (Apr–Sep) has declined by $\sim 53 \text{ m}^3 \text{ s}^{-1}$ in Pskem and $\sim 6 \text{ m}^3 \text{ s}^{-1}$ in Uradarya over the study period. High flows that were common in the early 2000s have become rare after 2012, and low-flow years have become frequent since 2018. Correlation analysis confirms a strong link between winter snowpack and summer discharge ($R > 0.5$ in both basins), emphasizing the role of snow accumulation in runoff. However, the moderate strength of these correlations also indicates the influence of other factors, including precipitation variability and spring temperature dynamics. These findings are consistent with

studies from other Central Asian basins, reinforcing the conclusion that snowpack decline as a widespread and pressing issue.

However, to better understand the impacts of potential snowpack reduction on discharge volume, further research is needed to apply hydrological models to fully understand the range of basin responses in both basins. The analysis is also based on a limited number of meteorological and hydrological stations, which may not capture full spatial variability. Future work should integrate distributed datasets and all available data from remote sensing and modelling approaches to expand coverage and enhance predictive capability.

In conclusion, the evidence from Pskem and Uradarya shows that climate change is reducing the reliability of snowmelt as a natural reservoir in Uzbekistan's mountains. The resulting declines in summer discharge threaten irrigation, hydropower, and ecosystem services. These findings highlight the urgent need for adaptive water management strategies that account for earlier snowmelt, reduced summer flows, and greater interannual variability. Strengthening observational networks, improving seasonal forecasts, and investing in efficient irrigation technologies will be essential steps. The changes observed in these two basins are not isolated but part of a broader regional pattern, making them directly relevant for water governance across Central Asia. By documenting these transformations through in-situ data, this study contributes critical evidence to guide adaptation in one of the world's most climate-sensitive water systems.

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SUPPLEMENTS

Figure S1. Mean monthly distribution of climatic parameters in the (a) Pskem, and (b) Uradarya Basins. Daily precipitation, snow depth, and mean air temperature data from Oygaing (the Pskem River Basin) and Minchukur (the Uradarya River Basin) meteorological stations from 1990 to 2020. Additionally, the mean daily discharge data (1990–2020) were taken from the Mullala (the Pskem River Basin), and Pachkamar (the Uradarya River Basin) hydrological stations. Daily data were averaged to monthly scales to derive mean monthly climatic parameters (as the hydrological years for the 1990–2020)

Figure S2. Trends in annual amount of precipitation in the Pskem and Uradarya River Basins from 2001 to 2023

Figure S3. Seasonal air temperature fluctuations based on

percentiles in the (a) Pskem and (b) Uradarya Basins from 2001 to 2023. Mean daily air temperature data were used to calculate percentiles. The 5th percentile represents cold air temperatures, the 50th percentile indicates the central tendency, and the 90th percentile illustrates high fluctuations in air temperature over the period from 2001 to 2023.

Figure S4. Trends in mean monthly discharge percentage differences for the (a) Pskem and (b) Uradarya Basins in each vegetation period from 2001 to 2023

Table SI. Trends in the seasonal snow depth (Apr–Sep) in the Pskem and Uradarya Basins in 2001–2023 hydrological years. Daily snow depth data from Oygaing (Pskem Basin) and Minchukur (Uradarya Basin) meteorological stations were used to identify percentiles

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