

Climate Change Reshaping the Water Cycle in Arid Central Asia

Ruoyan Li ^{1,2}, Gonghuan Fang ^{1,2,3,*}, Yaning Chen ^{1,3,*}, Xiaolong Yan ^{1,2}, Junqiang Yao ⁴, Zhi Li ¹, Runze Guo ^{1,2}, Qi Wu ^{1,2}, Azamat Kaldybayev ⁵, Nekruz Gulahmadov ^{1,2,6}, Nomvar Kurbon ⁶ and Farhod Nasrulloev ^{1,6,7}

¹ State Key Laboratory of Ecological Safety and Sustainable Development in Arid Lands, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China

² University of Chinese Academy of Sciences, Beijing 100049, China

³ Ili Station for Watershed Ecosystem Research, Chinese Academy of Sciences, Xinyuan 835800, China

⁴ Institute of Desert Meteorology, China Meteorological Administration, Urumqi 830002, China

⁵ Institute of Geography and Water Security, Al-Farabi Kazakh National University, Almaty 050040, Kazakhstan

⁶ Institute of Water Problems, Hydropower and Ecology of the National Academy of Sciences of Tajikistan, Dushanbe 734042, Tajikistan

⁷ Research Institute for Sustainable Development and Green Economy at the International University of Tourism and Entrepreneurship of Tajikistan, Dushanbe 734055, Tajikistan

* Correspondence: fanggh@ms.xjb.ac.cn (G.F.); chenyn@ms.xjb.ac.cn (Y.C.)

How To Cite: Li, R.; Fang, G.; Chen, Y.; et al. Climate Change Reshaping the Water Cycle in Arid Central Asia. *Hydrology and Water Resources* 2026, 1(3), 13. <https://doi.org/10.53941/hwr.2026.100013>

Received: 30 June 2026

Revised: 14 August 2026

Accepted: 26 August 2026

Published: 17 September 2026

Abstract: Global climate change is reshaping the hydrological regimes in arid Central Asia, where water resources depend heavily on glacier melt, snowmelt, and rainfall. Compared with well-studied high-mountain regions such as the Himalaya and the Alps, hydrological responses in Central Asia remain insufficiently synthesized. This review summarizes recent advances in climate change, moisture transport, glacier and snow dynamics, runoff changes, and related risks under continued warming. During 1960–2024, air temperature rose by ~ 0.33 °C per decade, while precipitation increased modestly by ~ 2.3 mm per decade. Westerly moisture dominates Central Asian precipitation but weakens southward, while recent low-latitude moisture contributions have increased in the southern part, especially the southern Tarim Basin. Persistent warming has driven widespread glacier retreat across Central Asia, with regional mass losses of -0.095 to -0.135 m w.e. a^{-1} during 2000–2016/2018/2019, and even the previously stable Kunlun and Pamir glaciers now showing signs of retreat. Snow-covered area and duration have generally declined, and in the Naryn River Basin, peak snow water equivalent during 2077–2096 is projected to decrease by $\sim 17\%$ relative to 1981–2000 under SSP5-8.5. Runoff has generally increased in the Tianshan (0.50 – 6.12 mm/a) and Kunlun Mountains (0.06 – 0.72 mm/a), whereas the Pamir–Alay region shows spatially heterogeneous changes (-5.02 – 1.78 mm/a), with both increasing and decreasing trends. Future runoff in Central Asia will likely increase in mountainous headwaters during the early to mid-21st century, but become increasingly heterogeneous and seasonally redistributed as glacier storage declines. Future research should strengthen high-mountain observations, cross-border data sharing and multi-source data assimilation to better constrain water availability and support climate change adaptation.

Keywords: moisture source; glacier retreat; runoff change; water security; arid Central Asia



1. Introduction

Rising global temperatures are significantly altering the global water cycle [1–3]. Accelerated glacial retreat [4], shifting precipitation patterns, and intensified evaporation [5] collectively reshape hydrological processes; meanwhile, the frequency and magnitude of extreme events such as heavy precipitation, flooding, and drought are also changing [6,7]. By reshaping the spatiotemporal availability of freshwater resources [8,9], these changes increasingly challenge the development sustainability, ecosystem stability, and societal resilience across arid regions [10–12].

Hydrological processes in arid and semi-arid regions are shaped by distinctive and often competing climate–cryosphere interactions. Glacier melt and snowmelt provide critical runoff to many dryland river systems, while warming can enhance glacier meltwater supply by accelerating glacier melt [13]. Yet this hydrological boosting is offset by intensified evapotranspiration and more frequent compound hot-dry events [14]. Together, these factors making the hydrological processes complex under global warming [15,16].

The arid region of Central Asia, broadly encompassing the five Central Asian countries and Xinjiang, China, is characterized by a dry climate and scarce water resources. Its major river systems are largely sustained by snow- and glacier-fed headwaters in the Tianshan and Pamir Mountains, which serve as the “water tower” of Central Asia and supply essential freshwater resources to downstream populations, particularly for agricultural production in summer and energy production in winter [17]. Glaciers act as critical freshwater reservoirs, storing water in solid form during the accumulation period and releasing meltwater to rivers during the ablation season, thereby regulating seasonal runoff and buffering low flows and droughts [18–20]. This mountain water supply underpins one of the world’s most irrigation-dependent agricultural systems, supporting approximately 110 million people [21], and 44.8 million hectares of irrigated land [22,23], where more than 80% of cultivated land relies on irrigation [20,24]. This dependence is even more pronounced in Xinjiang, China, where agricultural irrigation accounts for more than 90% of total freshwater use, far exceeding the national average [25]. Furthermore, in the upstream mountain states of Central Asia, hydropower accounts for approximately 93% and 91% of total electricity generation in Tajikistan and Kyrgyzstan, respectively [26]. These strong cryosphere–water–food–energy linkages make arid Central Asia particularly sensitive to changes in mountain water supply under climate warming.

Global warming has profoundly affected moisture cycling and hydrological processes in Central Asia. In recent decades, Central Asia has experienced pronounced atmospheric warming [27,28], accompanied by a weak positive precipitation trend [29,30]. Continued warming has led to pronounced glacier retreat and snow-cover decline. In the Tianshan Mountains, glacier area decreased by $18 \pm 6\%$ during 1961–2012 [31], and the rate of glacier retreat has accelerated since 2011 [32]. As glaciers continue to retreat, their capacity to regulate and sustain river runoff during low-flow periods is also changing [33]. Because mountain glaciers generally respond to climatic forcing over decadal timescales, their evolution often lags behind climate change [34–37], further increasing uncertainty in projections of glacier change and runoff variability.

Although regional mean precipitation has shown a weak increasing trend, this increase is unlikely to offset the continued rise in evaporative demand under rapid warming, thereby intensifying atmospheric aridity [38]. Under future high-emission scenarios, approximately 39.01% of the land area and 35.9% of the population are projected to be exposed to severe hydrological drought risk [39], posing substantial threats to agricultural production, food security, and ecosystem stability. Moreover, most river basins in Central Asia are transboundary. Declining water availability and increasing hydrological instability may further intensify competition for water resources across basins and national borders, thereby increasing the potential risk of water-related tensions and conflicts [40–42]. Therefore, a systematic understanding of historical and future changes in hydrological processes and water resources is essential.

Compared with extensively studied mountain water-tower regions, hydrological studies in arid Central Asia remain relatively limited. A Web of Science search using “flood/extreme runoff + snowmelt/glacier melt” identified 164 and 128 relevant studies for the Tibetan Plateau and the Alps, respectively, compared with only 56 for the Tianshan and 13 for the Pamir. Existing reviews of Central Asia have also focused mainly on cryospheric change or climate-change adaptation [18,20], highlighting the need for more integrated assessments linking climate, cryosphere, and basin-scale hydrological responses.

2. Study Area

Here, we define arid Central Asia as the inland Eurasian region that includes Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan and Turkmenistan, as well as Xinjiang, China (Figure 1). Spanning approximately 5.67×10^6 km², the region is defined by a strongly continental climate and pronounced topographic contrasts. This region is characterized by a typical temperate arid to semi-arid climate, with cold winters, hot summers, low precipitation and high evaporative demand. The landscape is exceptionally diverse, with high mountain ranges, plateaus,

enclosed basins and extensive deserts arranged across strong west–east and north–south gradients. The Caspian Sea marks the western boundary, the Tianshan Mountains and Pamir Plateau form the central and eastern highlands, the Karakoram and Kunlun Mountains bound the south, and the Kazakh Uplands connect northward with the West Siberian Plain.

Precipitation in arid Central Asia is generally scarce and exhibits pronounced spatial heterogeneity. Across the five Central Asian countries and Xinjiang, regional mean annual precipitation is approximately 200–207 mm [30], while the station-based mean annual precipitation in Xinjiang was 163 mm during 1961–2018 [43]. Annual precipitation is generally low in plains, basins, and desert areas but can be considerably higher in some mountainous regions. For example, mean annual precipitation is only 11.05 mm in the hinterland of the Taklimakan Desert [44], whereas annual precipitation can reach approximately 2000 mm on the windward slopes of the western Tianshan Mountains [30]. In the Hissar–Alay Mountains, annual precipitation ranges from approximately 350–700 mm in the lowlands to 1500–2500 mm at elevations above 3000 m [45]. Under these climatic conditions, river runoff is generated predominantly in mountain regions and is sustained by a combination of rainfall, snowmelt, and glacier melt. These mountain-derived water resources are essential for downstream oasis agriculture, ecosystems, and domestic water supply [20].

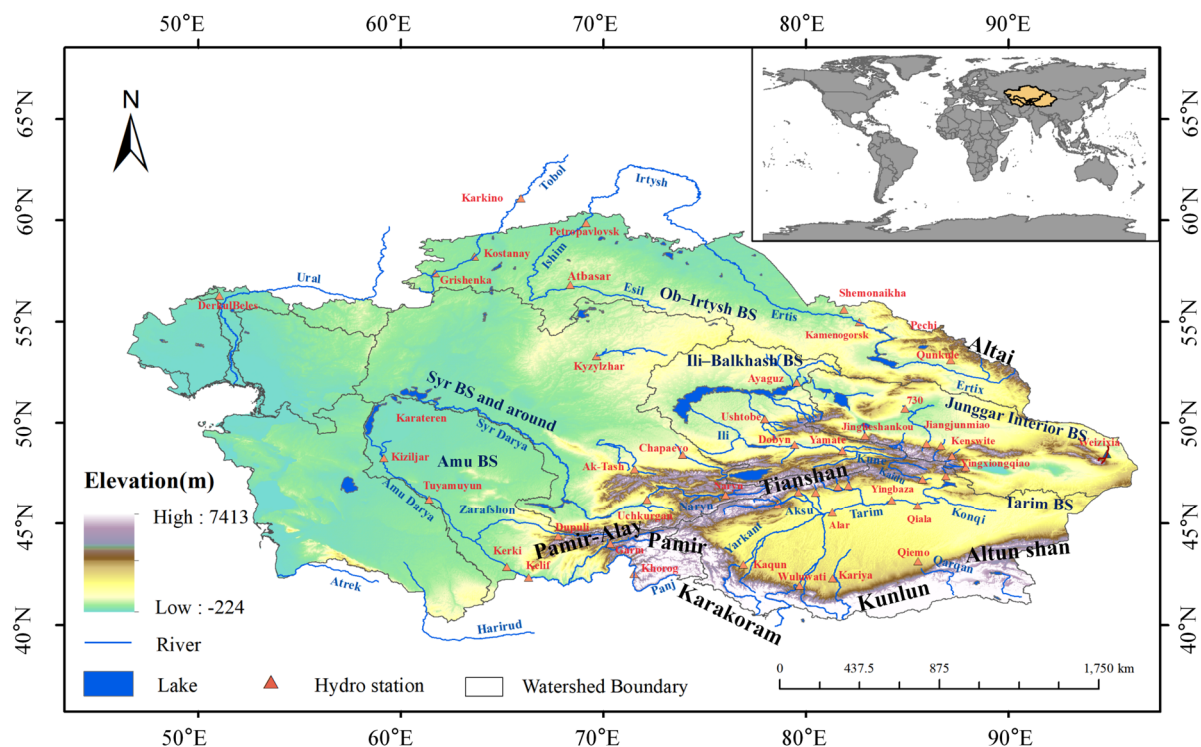


Figure 1. River systems and watershed boundaries in arid Central Asia. The map delineates the Ob–Irtysh, Ili–Balkhash, Junggar Interior, Syr Darya, Amu Darya, and Tarim basin systems and the surrounding high mountain regions, including the Tianshan, Pamir–Alay, Pamir, Kunlun, Karakoram, Altai, and Altun Shan.

Hydrologically, arid Central Asia is dominated by endorheic drainage systems, including the Ili, Syr Darya, Amu Darya, and Tarim river basins, although exorheic drainage is also represented by rivers such as the Irtysh. Regional runoff is generated predominantly in mountain headwaters through the combined contributions of rainfall, snowmelt, and glacier melt. As river water is conveyed from mountain headwaters toward downstream oases and desert plains, discharge is progressively reduced by irrigation withdrawals, evapotranspiration, and infiltration losses.

3. Climate Change

3.1. Rapid Atmospheric Warming Accompanied by Strong Seasonal Shifts

Central Asia has experienced significant and persistent warming over the past century. During 1960–2024, the regional annual mean temperature increased significantly at a rate of $0.33\text{ }^{\circ}\text{C decade}^{-1}$ ($p < 0.001$; Figure 2), exceeding the global mean warming rate and being approximately 30% higher than that observed in Northern Hemisphere regions at similar latitudes [27,28].

At the seasonal scale, warming trends during 1960–2024 were statistically significant in all four seasons, with $p < 0.001$ for spring, summer, and autumn and $p = 0.003$ for winter. The season with the strongest warming has shifted from winter in the earlier period to spring in recent decades. During 1960–1990, winter showed the fastest warming, with a rate of $0.46\text{ }^{\circ}\text{C decade}^{-1}$. By contrast, during 1991–2024, spring warming accelerated markedly, reaching $0.82\text{ }^{\circ}\text{C decade}^{-1}$ and replacing winter as the season with the strongest warming in recent decades [46]. This accelerated spring warming is mainly associated with reduced cloud cover and enhanced surface solar radiation, whereas winter temperature variability is more strongly influenced by large-scale atmospheric circulation, including the intensification of the Siberian High [47].

Spatially, warming is generally stronger in the Aral Sea region and Tianshan region, and the winter warming gradient decreases more prominently from northeast to southwest [27,48–50]. This spatial heterogeneity may reflect the combined effects of large-scale circulation and land–atmosphere hydrothermal processes in arid regions, rather than being controlled solely by elevation differences [51,52] (Figure 2).

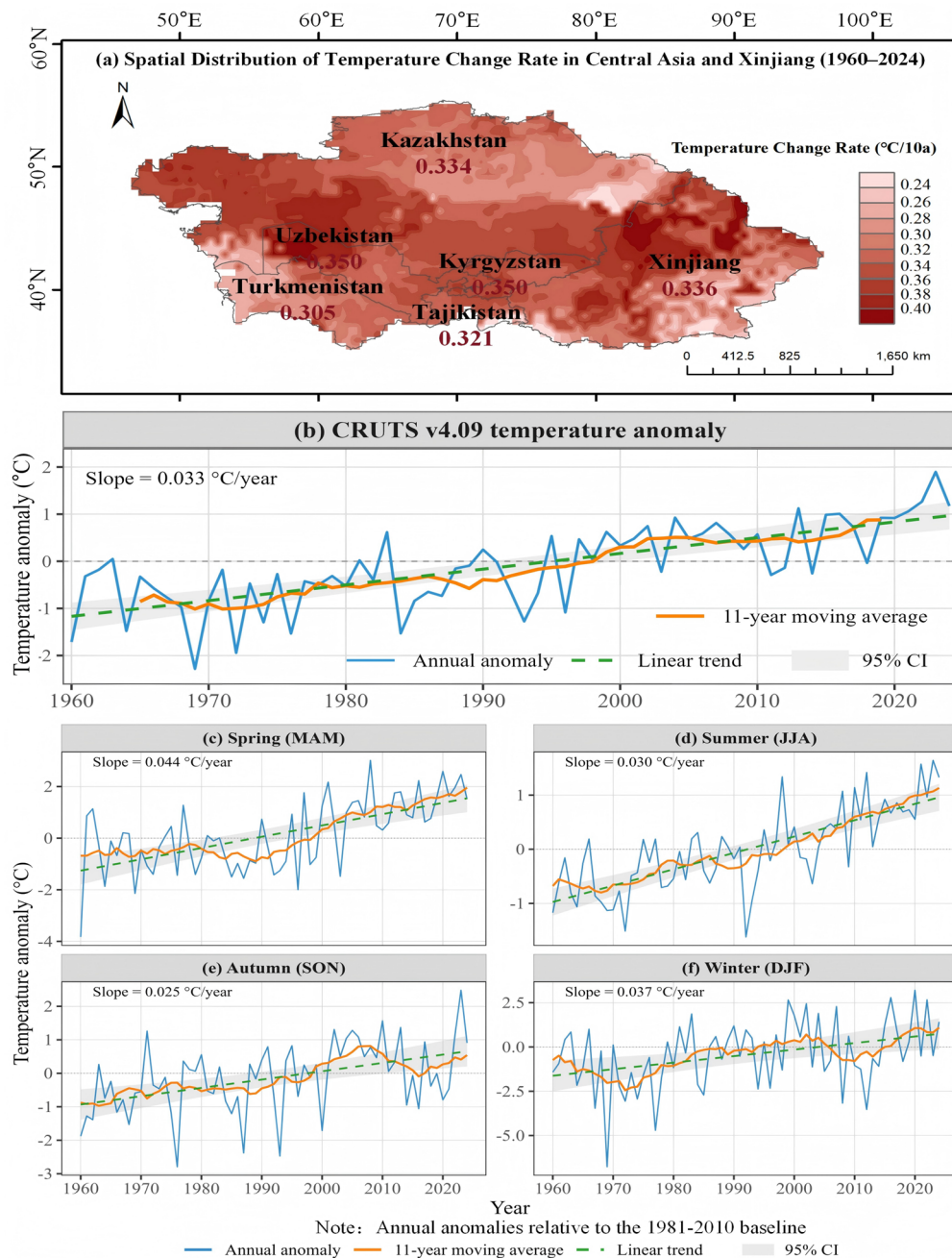


Figure 2. Spatiotemporal patterns of near-surface air temperature changes in Central Asia. (a) the spatial distribution of temperature change rates during 1960–2024 based on CRU TS v4.09, with regional mean warming rates labeled for Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan, Tajikistan, and Xinjiang. (b) the annual temperature anomalies, together with the 11-year moving average and linear trend. (c–f) seasonal temperature anomalies and trends. Temperature anomalies are calculated relative to the 1981–2010 baseline.

3.2. Modest Increases in Precipitation and Potential Evapotranspiration

During 1960–2024, annual precipitation over Central Asia showed a weak positive regional trend of approximately $2.3 \text{ mm decade}^{-1}$, but the trend was not statistically significant ($p = 0.18$). Spatially, however, precipitation trends exhibited pronounced heterogeneity (Figure 3). Relatively strong positive trends were observed in Kyrgyzstan and Tajikistan, with regional mean increases of approximately $8.0 \text{ mm decade}^{-1}$, whereas Turkmenistan showed an overall decreasing trend of about $-2.4 \text{ mm decade}^{-1}$. More moderate increases occurred in Kazakhstan, Uzbekistan, and Xinjiang, with mean trends of approximately 1.8, 2.0, and $3.5 \text{ mm decade}^{-1}$, respectively. At finer spatial scales, areas of increasing and decreasing precipitation occurred simultaneously within several regions, further indicating substantial subregional variability.

Seasonally, winter precipitation increases have been most pronounced in northern Central Asia, particularly Kazakhstan and surrounding regions, whereas summer precipitation increases are more evident in the southeastern part of the study region, especially Xinjiang [29,53–55]. These seasonal changes have been linked to different mechanisms: the increase in winter precipitation has been mainly attributed to greenhouse-gas-induced warming, with additional modulation by internal variability such as the Atlantic Multidecadal Variability, whereas the summer increase has been associated with the influence of Asian anthropogenic aerosols on the westerly jet and moisture transport [56,57]. These findings are generally consistent with estimates derived from multiple observational records and gridded precipitation datasets [58].

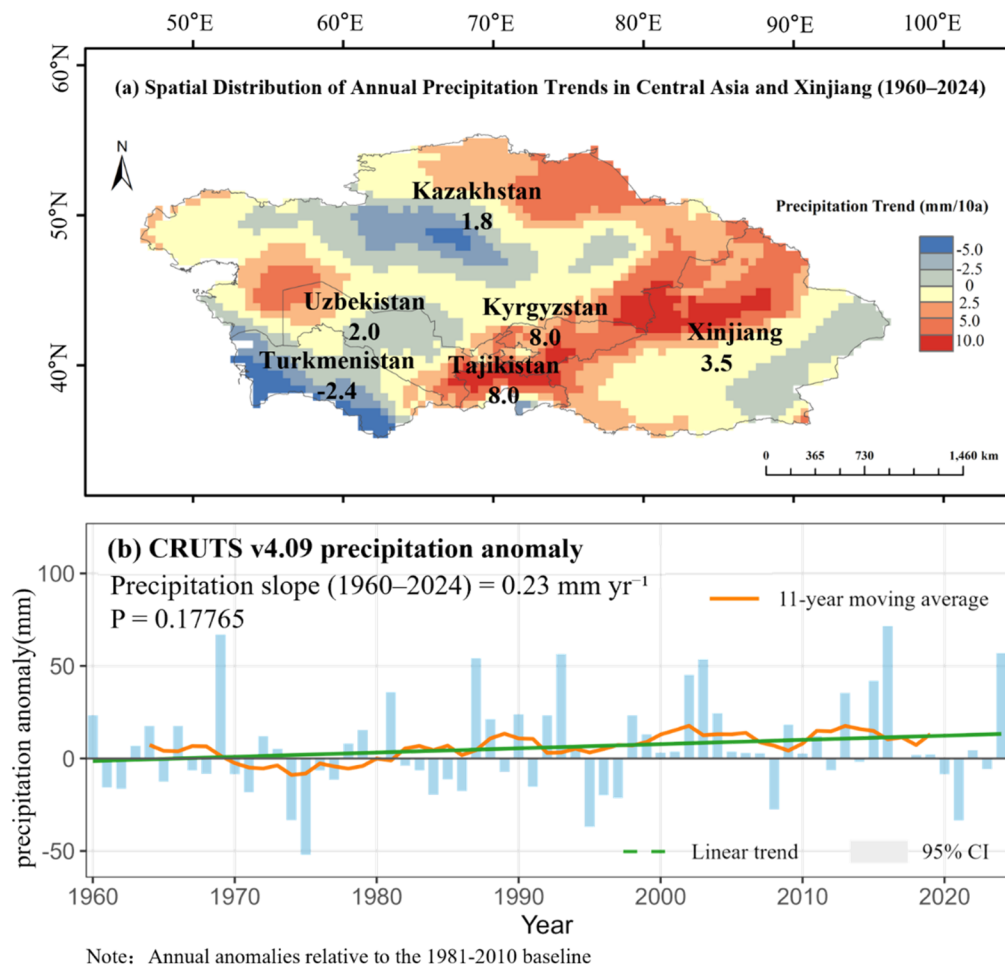


Figure 3. Spatial and temporal patterns of annual precipitation change across Central Asia during 1960–2024. (a) Spatial distribution of linear trends in annual precipitation, expressed in mm decade^{-1} . (b) Regional annual precipitation anomaly time series for Central Asia, together with the linear trend over 1960–2024.

3.3. Intensification of Climate Extremes

Sustained warming has amplified extreme heat and heatwaves across Central Asia. Under the current warming climate, the probability of a $+7 \text{ }^{\circ}\text{C}$ temperature-anomaly event is estimated to be up to seven times as high as that in a counterfactual climate without global warming [59]. Heatwaves have also become more frequent, with the regional mean number of heatwave events increasing at a rate of approximately 0.23 events per decade

during 1967–2016 [60]. Their intensity is further amplified by declining soil moisture, which weakens evaporative cooling and strengthens land–atmosphere feedbacks [61]. This intensification also extends to compound drought–heatwave extremes, with the spring compound index increasing at 0.07 decade^{-1} across Central Asia during 1961–2022 and reaching a record high of 0.88 in 2021; anthropogenic warming contributed approximately 36% to the intensity of the 2021 event [62].

Under global warming, precipitation is becoming more intense, less frequent and more concentrated [8,63]. This shift is also apparent in Central Asia. During 1961–2005, total wet-day precipitation (PRCPTOT) and maximum consecutive 5-day precipitation (Rx5day) showed median increases of 2.19 mm per decade and 0.21 mm per decade, respectively [64]. Regional-scale observations indicate an intensification of precipitation extremes in Xinjiang. During 1961–2014, maximum 1-day precipitation (Rx1day) and Rx5day increased by approximately 0.57 and 0.93 mm per decade, respectively, while consecutive dry days decreased and consecutive wet days increased [65]. In southern Xinjiang, the amount and frequency of summer extreme precipitation and its contribution to seasonal rainfall increased significantly during 1961–2020, with stronger changes after the mid-1980s. During 2011–2020, approximately 30% of stations recorded new historical maxima in daily precipitation since 1961 [66]. Recent events further illustrate the occurrence of intense precipitation in this region. In 2021, Tazhong station recorded 34 mm of precipitation within 12 h, exceeding the local mean annual precipitation and setting a new station record [67]. In the same summer, several stations in southern Xinjiang experienced Rx1day and Rx5day events with estimated return periods exceeding 40 years [68]. These extreme precipitation events have generally been associated with enhanced low-level moisture convergence, strong upward motion and intensified moisture transport across the southern boundary of the region.

3.4. Future Climate Projections

Future temperatures in Central Asia will continue to rise. Relative to 1995–2014, annual mean temperature is projected to increase by approximately $3.1 \text{ }^{\circ}\text{C}$ by the end of the twenty-first century under SSP2-4.5 and by up to $6.1 \text{ }^{\circ}\text{C}$ under SSP5-8.5. In the southwestern part of Central Asia, the ratio of the projected change in the local 90th-percentile temperature to the projected change in local mean air temperature reaches approximately 1.2 under SSP2-4.5 and 1.3 under SSP5-8.5, indicating that the local 90th-percentile temperature may increase by approximately 20–30% more than the mean temperature [69]. Heatwave risk will also continue to increase. By the end of the 21st century, heatwave duration and intensity are projected to rise substantially across Central Asia, with croplands in northern Kazakhstan facing the highest exposure; under SSP5-8.5, exposure to heatwave duration may increase by more than a factor of 10 relative to the historical period [70].

Future precipitation is projected to increase in annual total, but with substantial seasonal redistribution. By the end of the century, wetting is projected over more than 96% of Central Asia [71], with annual mean precipitation increasing by 4.23%, 10.52%, 14.51% and 14.41% under SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively. This wetting is concentrated in spring, whereas summers are projected to become drier [72]. This precipitation increase is linked to enhanced atmospheric moisture availability and stronger southwesterly moisture transport from lower latitudes [73].

Extreme precipitation is projected to intensify more rapidly than mean precipitation [74]. Relative to 1985–2014, the simple daily intensity index (SDII) increases by more than 15% in the mid-future and by more than 25% under SSP5-8.5 by the far future, while the number of days with precipitation exceeding 10 mm (PD10MM) rises from 15–35% in the near future to more than 45% in the far future under SSP3-7.0 and SSP5-8.5. Rx1day increases by up to 10% in the near future and by more than 30% by the end of the century [75]. The largest changes occur in central-southern Central Asia and high-elevation mountain regions. In the Tianshan Mountains, variability in extreme precipitation indices may increase by a factor of 2–6 across multiple timescales [76]. In the southern arid areas, rainfall is likely to remain scarce but become more concentrated and abrupt, increasing flash-flood, landslide and debris-flow risks.

4. Changes in Moisture Sources and Transport Pathways

Moisture sources for precipitation in Central Asia exhibit pronounced multi-source characteristics and seasonality. The westerly circulation represents the dominant external moisture transport pathway, with the North Atlantic, Europe, and the Mediterranean–Black Sea–Caspian Sea region serving as major source regions for regional precipitation. Evidence from moisture source tagging studies further indicates a clear north–south contrast: moisture originating from Europe and the North Atlantic contributes more substantially to precipitation in northern Central Asia, accounting for approximately 56.2% in total, whereas the corresponding contribution in southern Central Asia is about 43.4% [77]. Lagrangian moisture tracking further suggests that westerly-related

moisture transport explains approximately 42% of precipitation over Central Asia and exerts dominant control over western and southwestern Central Asia, where precipitation is mainly concentrated in the cold season [78]. In northern Xinjiang, China, western Eurasian moisture sources also make a substantial contribution to snowfall, accounting for nearly half of the total contribution on average (48.1%) [79] (Figure 4).

Beyond long-range moisture transport, local evaporation recycling provides an important supplementary source of moisture for precipitation over Central Asia. Regional-scale evidence indicates that its contribution to precipitation reaches $19.4 \pm 2.2\%$ in northern Central Asia and $14.7 \pm 1.9\%$ in southern Central Asia [77]. At the more localized oasis scale, stable isotope studies further show that recycled moisture derived from oasis evapotranspiration can substantially contribute to summer precipitation formation, with larger oases generally exhibiting higher moisture recycling contributions than smaller oases [80]. Seasonally, the contribution of local moisture to precipitation in northern Central Asia is less than 10% in winter, but can exceed 30% in summer [77]. At the oasis scale, stable-isotope observations further show summer moisture-recycling ratios of 17.0–63.9% in the Kaxgar–Yarkant Oasis [81]. At the decadal scale, both local evapotranspiration and precipitation recycling have exhibited upward trends in Xinjiang. During 1982–2018, evapotranspiration increased significantly at a rate of approximately $14 \text{ mm decade}^{-1}$. During the wet season from 1982 to 2020, the precipitation-recycling ratio increased significantly at a reported rate of approximately $2.3\% \text{ decade}^{-1}$, and increased recycled precipitation contributed approximately 56% to the wet-season wetting trend in Xinjiang [82]. Meanwhile, the observed increase in precipitation over Central Asia from 1982 to 2019 was closely linked to enhanced local evapotranspiration and an increasing recycling ratio [83].

Low-latitude and monsoon-related moisture makes a relatively limited contribution to annual mean precipitation in Central Asia, but exhibits pronounced regional characteristics. Moisture from low-latitude sources, such as South Asia, the Indian Ocean, and the Arabian Sea, generally does not dominate the annual mean moisture source pattern over Central Asia as a whole. However, its influence is substantially enhanced for summer precipitation in southern Central Asia, southeastern Central Asia, and the Tarim Basin.

Changes in moisture sources and transport pathways further modulate precipitation variability in Central Asia. The strength and trajectory of the westerlies are key controls on regional moisture supply. Stronger westerlies, generally reflected by higher westerly index and NAO index values, facilitate the transport of moisture from the North Atlantic and Europe into the arid regions of Central Asia, thereby enhancing winter precipitation. In contrast, weakened westerlies tend to suppress external moisture input [84,85]. Meanwhile, moisture transport into Central Asia is controlled not only by the intensity of the westerlies but also by the position of the westerly jet. A southward displacement of the westerly jet may facilitate moisture transport into the region [86]. Furthermore, transitions between ENSO phases can modulate winter precipitation over Central Asia by altering the southern branch of the westerlies and low-latitude moisture transport [87–89]. By contrast, South Asian monsoon anomalies primarily regulate warm-season moisture supply to southeastern Central Asia and southern Xinjiang.

In recent decades, summer moisture transport in Central Asia, particularly in southern Central Asia, has shown a trend of increasing influence of low-latitude and easterly moisture [66,87]. This change is reshaping the seasonal distribution and spatial heterogeneity of regional precipitation, as well as the mechanisms underlying extreme precipitation formation [66,77]. Previous studies have suggested that moisture in this region is primarily transported by the mid-latitude westerlies from source areas such as the North Atlantic, the Mediterranean Sea, the Black Sea, and the Caspian Sea [90]. However, studies focusing on the Tarim Basin indicate that, although the climatological mean moisture supply remains dominated by westerly sources, the interannual variability of summer precipitation is more strongly controlled by anomalous moisture transport from the south and east. These anomalous moisture pathways include moisture from the Arabian Sea and the Indian Ocean, as well as low-level moisture transported westward along the eastern and northern margins of the Tibetan Plateau [91]. The contribution of monsoon-related moisture transport has increased, with monsoon moisture transport events explaining 81% of the variance in summer precipitation variability. In the past decade, monsoon-related easterly moisture has become an important moisture source for the lower troposphere over arid Central Asia [92]. In southern Xinjiang, the regional moisture budget increased by $1.33 \times 10^7 \text{ kg s}^{-1}$ during 1986–2020 relative to 1961–1985, with the southern boundary contributing an increase of $1.12 \times 10^7 \text{ kg s}^{-1}$, much larger than the western boundary contribution of $0.11 \times 10^7 \text{ kg s}^{-1}$ [66]. However, this enhanced contribution has not caused monsoon moisture to exceed westerly-related moisture or regional terrestrial moisture. For extreme precipitation events in southern Xinjiang, the combined contribution from the Arabian Sea, the Arabian Peninsula, and the Indian Peninsula is less than 10%, which is substantially lower than the contributions from local evaporation, Northwest Asia, and Central Asia, at 30.2%, 22.1%, and 19.1%, respectively [93].

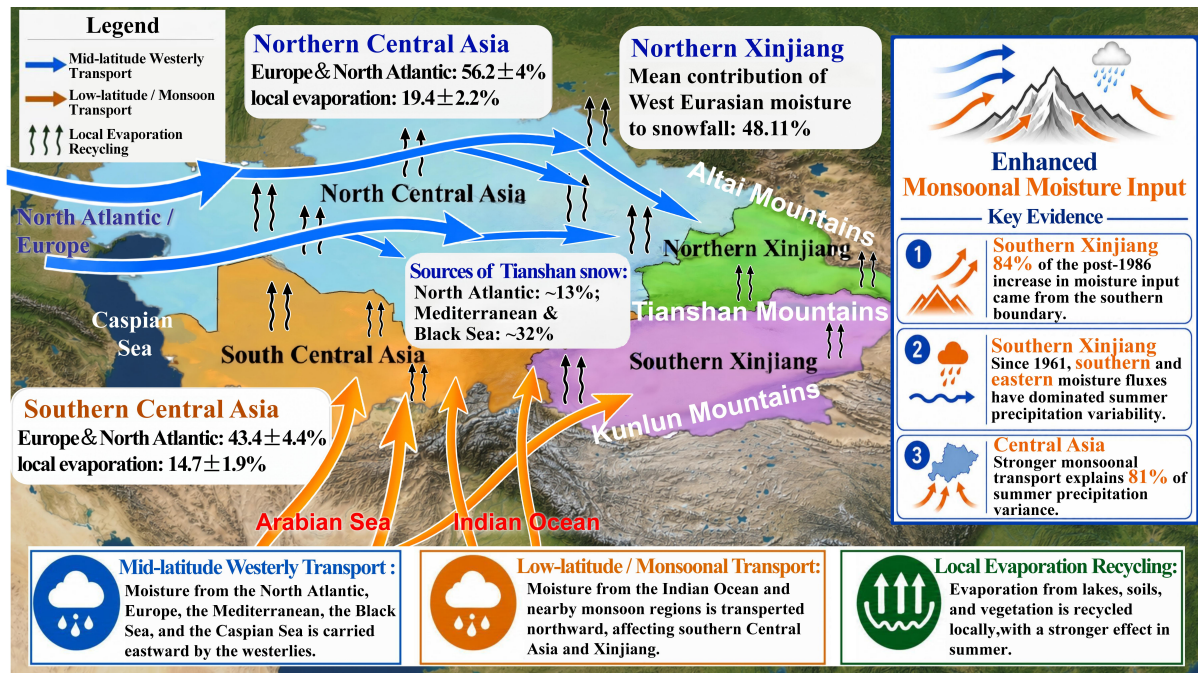


Figure 4. Moisture transport pathways and their recent evolution in Central Asia. Quantitative contributions from the North Atlantic–European sources and local evaporation recycling are based primarily on [77,78], the contribution of western Eurasian moisture to snowfall in northern Xinjiang is from [79], and evidence for enhanced southern and monsoon-related moisture transport is synthesized from [66,82,83,91–93].

5. Glacier and Snow Dynamics in the Alpine Central Asia

5.1. Glacier Distribution in Central Asia

Central Asia hosts one of the most extensive glacier systems in the world's mid-latitude drylands. Based on the Randolph Glacier Inventory (RGI) 7.0 (approx. 2000) [94], the study region contains 69,356 glaciers with a total glacierized area of 57,136.33 km². Glaciers are highly unevenly distributed across the major mountain systems of Central Asia, with the Tianshan (~20,900 glaciers; ~12,400 km²; ~861 km³), Pamir–Alay (~22,000 glaciers; ~13,000 km²; ~1018 km³), Kunlun (~12,400 glaciers; ~11,700 km²; ~1143 km³), and Karakoram (~14,000 glaciers; ~20,000 km²; ~2872 km³) collectively dominating regional glacier storage. These glaciers are mainly distributed along high-elevation belts between 3000 and 6000 m a.s.l., where they provide important meltwater inputs to major inland river basins, including the Amu Darya, Syr Darya, Tarim and Ili basins.

5.2. Recent Glacier Changes

Glaciers across Central Asia are generally thinning, retreating, and losing mass, although near-equilibrium or slightly positive mass budgets have been observed in parts of the Karakoram and Kunlun Mountains (Supplementary Tables S1–S3). Consistent estimates from three geodetic datasets for 2000–2016/2018/2019 yield similar regional means of -0.135 , -0.095 and -0.096 m w.e. a⁻¹, respectively [95–97]. Spatially, mass loss is most pronounced in the Tianshan Mountains, more moderate in the Pamir, and weakest in the Kunlun Mountains, where near-neutral or slightly positive balances have been reported.

The Tianshan Mountains represent one of the most rapidly losing glacier regions. Over the past half-century, they have experienced sustained mass loss, with an apparent acceleration in recent decades. Between 1961 and 2012, glacier area declined by $18 \pm 6\%$ and mass decreased by $27 \pm 15\%$ [31], corresponding to a mean mass balance of -0.36 m w.e. a⁻¹ for 1961–2021 [98]. Mass loss exhibits a clear west–east and elevation-dependent pattern, with stronger depletion at lower elevations [99]. In northern Tianshan, glacier area decreased by 30–40% between 1950 and 1999 [100], with a mean mass balance reaching -0.40 ± 0.07 m w.e. a⁻¹ over 1964–2020, and retreat has further accelerated since 2000 [101]. Several small glaciers have shown fragmentation or complete disappearance [102].

For the Pamir and Pamir–Alay, glacier retreat is comparatively moderate, although the region has transitioned from near-stable or weakly negative conditions to sustained mass loss in the 21st century [97]. The regional mean mass balance was -0.07 ± 0.12 m w.e. a⁻¹ for 2000–2021 [103]. Strong spatial heterogeneity is evident: during 1975–1999, some central Pamir glaciers remained close to equilibrium or even slightly positive (-0.12 to $+0.63$ m w.e. a⁻¹),

whereas both eastern and western Pamir showed negative balances in 1999/2000–2017/18 (-0.12 ± 0.37 and -0.25 ± 0.37 m w.e. a^{-1} , respectively), with stronger losses in the western sector [104].

Glaciers in the Karakoram and parts of the Kunlun Mountains exhibit near-zero or slightly positive mass balances in recent decades, a phenomenon often referred to as the “Karakoram anomaly” [105]. In the Kunlun Mountains, the mean mass balance was $+0.14 \pm 0.08$ m w.e. a^{-1} during 2000–2016 [97], with a pronounced east–west contrast. For 2000–2021, eastern Kunlun showed slight mass loss (-0.09 ± 0.07 m w.e. a^{-1}), whereas western Kunlun exhibited mass gain ($+0.23 \pm 0.13$ m w.e. a^{-1}) [103]. Consistent patterns emerge across varying datasets, with western Kunlun generally showing slight positive balances ($+0.044$ to $+0.156$ m w.e. a^{-1}) and eastern Kunlun weak negative balances (-0.035 to -0.086 m w.e. a^{-1}) (Figure 5) [95–97]. Recent glacier inventories show spatially heterogeneous shrinkage, with more evident area loss in the eastern Karakoram, eastern Kunlun, and small or low-elevation glaciers, while western Kunlun and central–western Karakoram remain comparatively stable.

Further basin-scale analysis of the glacier mass-change dataset of Hugonnet et al. (2021) [96] reveals pronounced spatial heterogeneity in glacier mass balance across the major river basins of Central Asia during 2000–2019. All five major basins experienced net glacier mass loss, although the rates varied substantially among regions. The strongest losses occurred in the Junggar Interior and Ili–Balkhash basins, with mean mass balances of -0.41 and -0.38 m w.e. a^{-1} , respectively, consistent with the widespread and sustained glacier mass loss observed across the Tianshan Mountains. The Syr Darya Basin exhibited an intermediate rate of mass loss (-0.23 m w.e. a^{-1}), whereas the Amu Darya Basin showed a weaker negative mass balance (-0.10 m w.e. a^{-1}), broadly reflecting the more moderate and spatially heterogeneous glacier changes in the Pamir and Pamir–Alay regions. By contrast, the Tarim Basin had a near-balanced glacier mass budget, with a mean mass balance of -0.03 m w.e. a^{-1} . This muted basin-wide signal likely reflects contrasting glacier responses across its extensive headwaters, including the southern Tianshan, Pamir–Karakoram, and Kunlun Mountains, where pronounced mass loss in the southern Tianshan is partly offset by comparatively stable or locally positive mass balances in parts of the Karakoram and Kunlun ranges.

The relative stability of glaciers in the Karakoram–Kunlun region has been attributed to a combination of enhanced accumulation and reduced melt. In the Shimshal Basin, 92% of annual precipitation falls as snow, with $\sim 80\%$ of snowfall occurring above 5000 m and 71% concentrated between December and May, promoting persistent snow accumulation at high elevations. Mean annual air temperature is low (~ -8.8 °C), and available melt energy is $\sim 41\%$ lower than in the central Himalaya (Langtang) [106]. Over 2000–2021, summer temperatures in the Karakoram exhibit a slight cooling trend (-0.06 °C per decade), accompanied by weakly increasing precipitation (~ 2 mm per decade), declining net shortwave radiation (-3.5 and -3.4 W m^{-2} per decade for annual and summer means), and increasing cloud cover (~ 0.02 per decade), collectively suppressing surface melt [107]. Similar conditions prevail over the Gulya Ice Cap in western Kunlun, where lower ablation-season temperatures (~ -6.1 °C), together with increases in precipitation ($+50$ mm) and snowfall ($+64$ mm w.e. relative to 1970–1999), further sustain a low-ablation, high solid-accumulation regime [108].

Glaciers in lower-elevation mountain systems, such as the Altai and Junggar Alatau, have experienced pronounced mass loss, although available observations remain limited.

In addition to regional geodetic and remote-sensing studies, annual in situ surface mass-balance observations are available for 16 glaciers across Central Asia, including sites in China, Kazakhstan, Kyrgyzstan, Uzbekistan, and Tajikistan (Table S4). Van Tricht et al. (2026) compiled observations from these glaciers through 2025 and found that nine of the 16 glaciers experienced their most negative annual mass balance on record in 2025 [109], highlighting the exceptional and spatially coherent glacier mass loss across the Tien Shan–Pamir region.

Surge-type glaciers are also widespread in Central Asia and can complicate the interpretation of glacier-change trends. A recent inventory identified 507 surge-type glaciers in the Tajik Pamirs, of which 96 were actively surging during 2000–2024 [110], while 171 pulsating glaciers were identified in the Hissar–Alay region [45]. Because surges redistribute ice within individual glaciers, local advances or thickening may reflect glacier dynamics rather than contemporaneous climatic forcing.

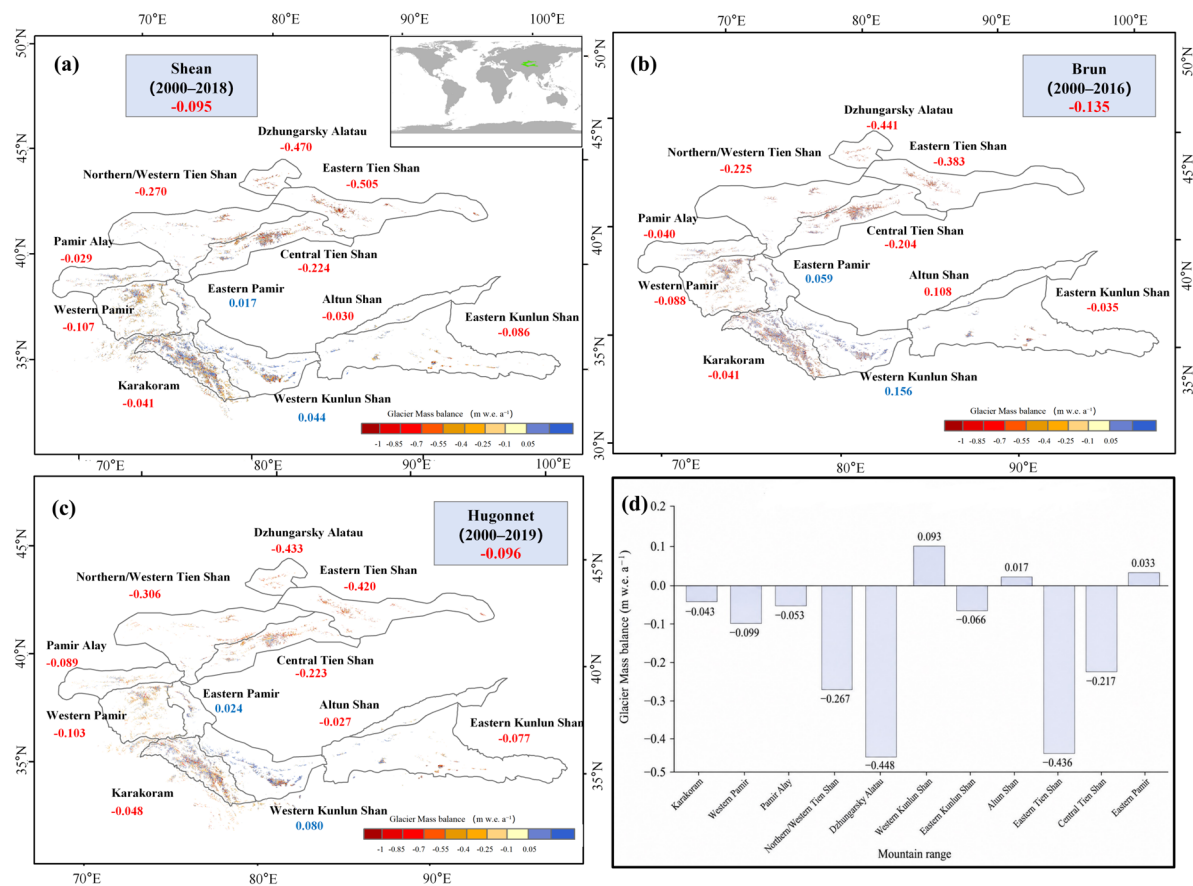


Figure 5. Spatial distribution of glacier mass balance across the glacierized mountain regions of arid Central Asia based on three geodetic datasets: (a) Shean et al. [95] (2000–2018), (b) Brun et al. [97]. (2000–2016), and (c) Hugonnet et al. [96]. (2000–2019). Regional mean glacier mass balance values are indicated for each mountain region, with red representing mass loss and blue representing mass gain. (d) Comparison of the mean glacier mass balance for each mountain region averaged across the three datasets. The mountain-region divisions follow the regional subdivision used by Bolch et al. (2019) [111]. The inset in panel (a) shows the global location of the study area.

5.3. Changes in Glacier Runoff

Glacier runoff is a key component of river discharge in Central Asian inland basins [112–114]. Its contribution to annual runoff in major rivers generally ranges from 10% to 40%, increasing to 60–70% in high-elevation, snow- and ice-dominated catchments [115]. In the upper Amu Darya basin, including the headwater catchments of the Panj and Vakhsh Rivers, snowmelt and glacier melt contribute approximately 67% and 15% of total runoff, respectively, with combined cryospheric contributions reaching ~82% [116]. In six typical catchments of the northern and central Tianshan, glacier melt accounts for 12–59% of July–August discharge, increasing with glacierized area fraction [117]. In the upper Syr Darya (Naryn River), glacier-melt runoff accounted for approximately 23% of total runoff in 1992 and 28% in 2016, while its volume increased by more than 50% during 1993–2017 relative to 1964–1992 [118,119].

Changes in glacier runoff are fundamentally controlled by the evolving balance between increased melt under warming and declining glacier storage. Under continued glacier retreat, enhanced ablation initially increases meltwater supply, but this effect is ultimately constrained by the reduction in glacier volume available for melt. In the Tianshan Mountains, glacier runoff is projected to increase by 15–24% relative to 2000–2020, reaching a peak before approximately 2050, followed by a decline of 14–20% by 2100 under continued mass loss, accompanied by a 69–93% reduction in glacier volume [120]. In contrast, in the Kunlun Mountains, the timing of peak glacier runoff is projected to occur later (after ~2055), while under high-emission scenarios a clear peak may not emerge within the 21st century, with sustained increases in glacier runoff instead [121]. Seasonally, glacier runoff is projected to shift earlier, with pronounced reductions in late-summer discharge. For example, August glacier runoff in the Syr Darya and Chu basins may decrease by 74–79% under SSP5-8.5, and by up to 87% in the Talas basin, substantially increasing late-summer water scarcity risks [120]. Across a global warming range of 2–6 °C,

glacier retreat in Central Asia is expected to continue, although projections of glacier runoff remain highly uncertain due to differences in model structure and assumptions [122–125].

5.4. Changes in Snow Cover and Snowmelt Runoff

Snow water equivalent (SWE) exhibits strong elevation and regional contrasts. Peak SWE exceeds 1 m in the Pamir and Karakoram, whereas it typically remains below 1 m in the Tianshan. Mean SWE reaches up to approximately 0.5 m in the Tianshan and Pamir during winter and increases further in spring across the western HMA mountains, reaching up to approximately 1 m. In summer, persistent snowpack with SWE values up to approximately 0.3 m remains in parts of the Pamir and Karakoram [126].

Over recent decades, snow in Central Asian high mountains has shown an overall pattern of declining low- to mid-elevation snow cover, earlier melt onset, and reduced summer snow extent [127,128]. In the Tianshan Mountains, summer and winter snow cover area decreased by 12.2% and 2.9% during 2001–2015, while autumn snow-covered area increased by approximately 16.0% [129]. Snow cover duration shortened across the central and eastern Tianshan (−11.88% and −8.03%), but increased in the northern and western sectors (+9.36% and +7.47%), reflecting spatial differences in the responses of snow cover to temperature and precipitation variability [129]. Satellite-based analyses further confirm pronounced interannual variability in snow conditions across major basins, with deviations in snow cover indices reaching ~20% [130]. In the upper Amu Darya and Syr Darya basins, snowmelt timing has advanced by up to ~11 days over 1986–2014, accompanied by a significant reduction in snow-covered days, particularly between 2100 and 3500 m a.s.l. [131].

Snowmelt constitutes a dominant component of runoff generation in Central Asian basins, together with glacier melt contributing ~69–79% of annual discharge, with snowmelt generally exceeding glacier contributions [132]. In the Manas River basin (northern Tianshan), snowmelt accounts for ~48% of runoff, compared to ~27% from glacier melt, with snowmelt peaking 2–3 months earlier and thus dominating spring hydrographs, while glacier melt sustains summer discharge, forming a temporal compensation mechanism [133].

Under continued warming, snow related hydrological regimes are projected to shift substantially. In the Tianshan region, peak snow accumulation is projected to advance by ~26 days relative to 1981–2000, accompanied by a ~17% reduction in peak snow water equivalent [134]. These changes lead to earlier snowmelt and a corresponding shift in spring runoff timing [135], while summer (July–August) snowmelt runoff declines markedly. Under SSP5-8.5, total runoff in the Naryn basin is projected to decrease by ~16%, which is partly linked to reduced snow accumulation, and a weakening of snowmelt-derived summer water supply [134].

6. Changes in Runoff Regimes

6.1. Runoff Generation and Source Contributions

As shown in Figure 6, among the 31 catchments with available published data, eight have glacier melt and snowmelt contributions exceeding 50% of total runoff.

In several basins on the southern slope of the Tianshan Mountains and the northern slope of the Kunlun Mountains, including the Aksu, Yarkand, Hotan, Keriya, Baiyang, Kaidu, and Kumalak basins, glacier melt and snowmelt make substantial contributions to runoff, although the magnitude varies markedly among basins. The Keriya Basin has the highest contribution, at approximately 71%. The Yarkand and Hotan basins also have glacier melt and snowmelt contributions of 53.0% and 52.5%, respectively, while the Baiyang Basin reaches 49.4%. In contrast, the Kaidu basin has lower contributions.

In basins on the northern slope of the Tianshan Mountains, such as the Manasi, Jinghe, Urumqi, Hutubi, and Alagou basins, precipitation runoff generally plays a more prominent role. In some basins, the contribution of precipitation approaches or exceeds 35%, and in individual cases reaches around 40%. Meanwhile, groundwater runoff and glacier melt and snowmelt runoff still account for notable proportions of total runoff.

For the Pamir Plateau and adjacent high mountain regions, glacier melt and snowmelt contributions are generally high. The Vakhsh Basin has the highest glacier melt and snowmelt contribution, exceeding 80%, followed by the Pyanj and Zeravshan basins. At the same time, precipitation and groundwater also contribute to runoff.

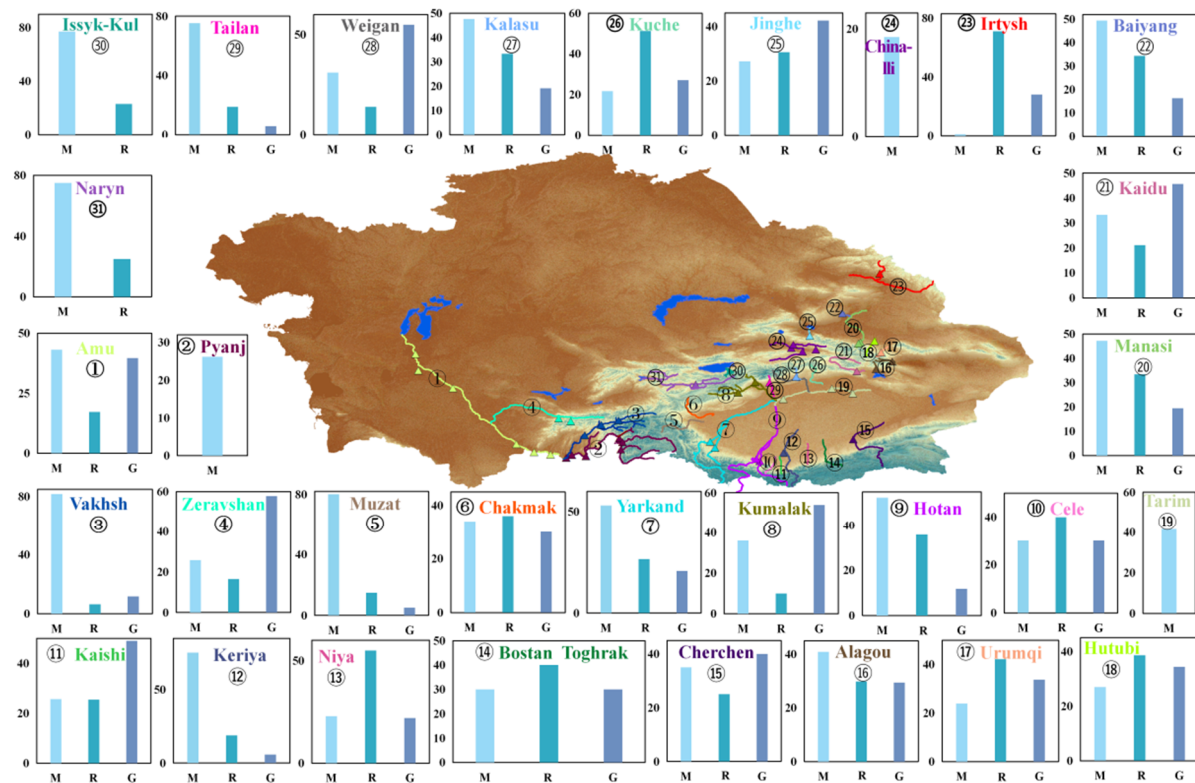


Figure 6. Spatial distribution of runoff components across Central Asian river basins. The x-axis represents runoff components, and the y-axis shows the relative contribution of each water source to runoff (%). M denotes glacier–snow meltwater, R rainfall, and G groundwater. River runoff components were compiled from the following studies: 1–3, [136]; 4, [137]; 5, 11, 17–22, 25–27, and 29, [117]; 6, 10, 13–14, 16, and 28, [138]; 8, [139]; 7, 9 and 23, [140]; 12, [141]; 15, [142]; 24, [143]; 30, [144]; and 31, [134].

6.2. Spatial Distribution of Runoff Change Rates

Since the 1950s, runoff trends in Central Asian rivers have shown pronounced spatial heterogeneity. Stations in upstream mountainous headwaters have generally shown increasing trends, whereas those in plains and arid basin reaches have more often exhibited weak changes or persistent declines (Figure 7). The increase in upstream runoff mainly reflects enhanced glacier and snow melt, together with changes in precipitation under climate warming. In contrast, runoff declines in plains and arid basin reaches are closely associated with human activities, including irrigation withdrawals, reservoir regulation, channel losses, and ecological water management.

At the scale of river systems, the direction and magnitude of runoff trends differ substantially among the major river systems in Central Asia. The Tarim River system and its headwater regions in the southern Tianshan and Kunlun Mountains represent one of the most prominent areas of runoff increase. Runoff trends at upstream control stations are generally positive. In the southern Tianshan headwaters, most stations show increasing rates of 0.44–2.67 mm/a. Along the northern slope of the Kunlun Mountains, runoff also shows an increasing trend, with the largest increase observed at the Yuzimenleke station, reaching 0.72 mm/a. In contrast, most stations along the middle and lower main stream of the Tarim River show declining trends, with overall negative rates of approximately −0.52 to −0.76 mm/a. From 1957 to 2006, runoff from the four headstreams at the mountain outlets increased from $216.0 \times 10^8 \text{ m}^3/\text{a}$ to $260.3 \times 10^8 \text{ m}^3/\text{a}$, whereas runoff in the main stream decreased by $15.4 \times 10^8 \text{ m}^3/\text{a}$ over the past five decades. This indicates that the increase in upstream inflow was not fully transmitted to the downstream plain reaches, but was strongly modified by human activities in the middle and lower reaches. During 2010–2022, with increasing inflow from the headstreams and the implementation of ecological water conveyance in the Tarim River Basin, runoff in the main stream increased substantially. Runoff at the Alar, Yingbaza, and Qiala stations recovered to levels comparable to those in the 1960s and exceeded the 1990–2009 average by 51%.

The Syr Darya River system and its surrounding areas also show clear differences between upstream and downstream reaches. Runoff trends at upstream stations are mainly positive, with relatively strong increases at Naryn town and Andijan. Other stations, such as Uchkurghan, also show positive trends, whereas changes at Ak-Tash are relatively weak. By contrast, runoff trends at stations in the middle and lower reaches tend to weaken or become negative. Karateren, Kyzylzhar, and Chapaevo generally show weak declining trends, with Chapaevo decreasing at approximately −0.16 mm/a. Previous studies have shown that, among 11 hydrological stations in the

Syr Darya Basin during 1930–2015, runoff decreased significantly at eight stations, and human activities contributed 82.6–98.7% of the runoff reduction, mainly through irrigation withdrawals [145]; This is consistent with the pattern of runoff decline in the middle and lower reaches shown in Figure 7.

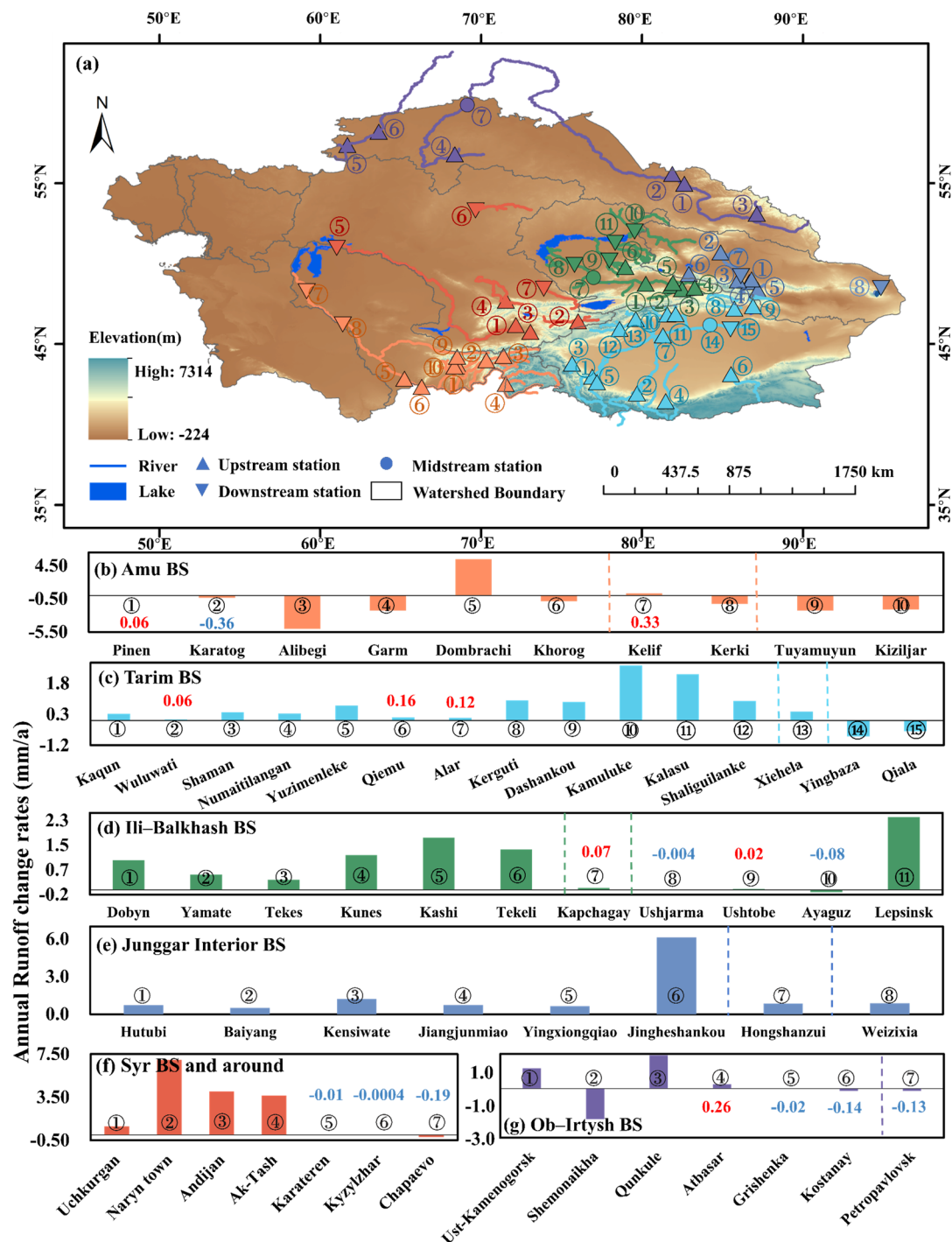


Figure 7. Spatial distribution of runoff change rates in major Central Asian rivers. **(a)** Locations of hydrological stations. **(b–g)** Annual runoff change rates for station-controlled river reaches across different basins. Runoff change rates were compiled from published studies listed in Table S6. Numerical labels in red indicate positive runoff change rates (increasing trends), whereas those in blue indicate negative runoff change rates (declining trends).

The Amu Darya River system exhibits pronounced spatial variability. Runoff trends in the upstream areas are mixed, with both increases and decreases, whereas stations in the middle and lower reaches generally show weak increases or declining trends. In the upper tributaries of the Vakhsh River, Garm and Dombrachi show significant increases, with rates of 6.18 mm/a and 5.51 mm/a, respectively. Historical observations also indicate that runoff in the Kyzyl-Suu River increased by 7% during 2000–2020 [146]. In contrast, Karatog and Alibegi

show negative trends, with Alibegi exhibiting an annual runoff change rate of -5.02 mm/a, representing one of the strongest negative trends in the study region. Along the middle-lower Amu Darya mainstream, discharge shows a slight increase at Kelif but declines at Kerki, Tuyamuyun, and Kiziljar.

The Ili–Balkhash River system is generally characterized by increasing runoff, although clear differences exist among the upstream, middle, and lower reaches. Most upstream stations show positive trends, ranging from approximately -0.08 to 1.69 mm/a, with relatively large increases at Kashi and Kunes. Tekeli also shows a marked increase. In the middle reaches, trends at Kapchagay and Ushjarma are weak and close to zero, suggesting that the upstream runoff increase is attenuated during downstream transmission. In the lower reaches, changes are relatively small. Ushtobe and Lepsy show weak increases, whereas Ayaguz shows a slight decline of approximately -0.08 mm/a.

Runoff in the Junggar inland river system generally shows an increasing trend. Upstream stations, including Hutubi, Baiyang, Kensiye, Jiangjunmiao, Yingxiongqiao, and Jingshankou, all show positive trends, with rates of approximately 0.50 – 1.83 mm/a. The largest increase occurs at Jingshankou. The midstream Hongshanzui station and downstream Weizixia station also show positive trends, although the magnitude of increase is lower. For example, runoff in the Manas River increases at a rate of 1.21 mm/a at the upstream Kensiye station, while the increase at the downstream Hongshanzui station is 0.83 mm/a.

As the only major exorheic river system in the study region, the Ob–Irtys River system shows runoff changes that are generally small in magnitude and inconsistent in direction. Trends at upstream and midstream stations range from -1.86 to 2.03 mm/a. Qunkule and Ust-Kamenogorsk show increasing trends, with the largest increase at Qunkule, approximately 2.03 mm/a. In contrast, Shemonaikha shows a marked decline of approximately -1.86 mm/a. Atbasar shows a weak increase, whereas Grishenka and Kostanay show near-zero or slightly negative trends. The downstream Petropavlovsk station shows a weak declining trend.

6.3. Future Runoff Changes and Water Resource Security

6.3.1. Future Runoff Changes

Under continued global warming, future runoff changes in Central Asia are unlikely to follow a simple monotonic increase or decrease. Instead, they are expected to exhibit pronounced stage-dependent patterns and spatial heterogeneity. During the first half of the 21st century, increased precipitation and accelerated glacier melt may enhance runoff in some mountain catchments. For example, runoff across 221 high-mountain basins in Central Asia is projected to increase by 3.8% during 2011–2040 and by 5.0% during 2041–2070 [147]. By the late 21st century, however, continued depletion of glacier storage, reduced snowmelt contribution, and increased evaporative demand are likely to weaken summer runoff supply in some basins [120,122,148,149].

In the Ili River basin, future runoff is generally projected to increase under a warmer and wetter climate, with snow and ice melt and mountain precipitation playing increasingly important roles (Supplementary Table S5). At the headwater scale, runoff in the Kunes River is sensitive to changes in snow cover and air temperature, and warming may reduce runoff while advancing the timing of runoff generation. Basin-wide projections indicate that annual runoff in the Ili River may increase by 12.8 – 14.3% ; however, land-use change and reservoir construction may partly offset this natural increase. Meanwhile, the increasing share of surface runoff and the declining contribution of subsurface runoff suggest a shift toward faster runoff-generation pathways.

In the Syr Darya basin, projected runoff changes are characterized by relatively limited changes in total annual runoff but marked seasonal redistribution (Supplementary Table S7). Existing studies indicate that basin-wide runoff changes under different 21st-century scenarios remain moderate, ranging from -6% to 6% . In contrast, upstream runoff is highly sensitive to precipitation changes, increasing under wetter scenarios but decreasing substantially under drier scenarios. At the tributary scale, the Naryn River is projected to experience higher peak flows and lower low flows, implying a simultaneous intensification of flood and low-flow risks. Although runoff from glacierized areas of the Tianshan may increase temporarily during the early to mid-21st century, continued glacier volume loss will reduce long-term summer water-supply capacity and further intensify irrigation-season water stress in the Syr Darya basin.

Future runoff changes in the Amu Darya basin also show clear stage-dependent and spatially heterogeneous characteristics (Supplementary Table S5). For the basin as a whole and for its upper reaches, annual runoff is projected to increase under most 21st-century scenarios, although the sign and magnitude of change differ among climate combinations. At the tributary scale, runoff in the Vakhsh River is projected to show a substantial overall increase under high-emission scenarios in the far future, with projected changes ranging from -6.4% to 52.3% , whereas the Vanj River and other western Pamir tributaries may experience simultaneous declines in annual runoff

and glacier-melt contribution. Meanwhile, the Zeravshan, Kafirnigan, and Tupalang tributaries generally show increased spring runoff, reduced summer–autumn runoff, and an earlier runoff peak.

Across the headwaters of the Tarim River, runoff is projected to increase or remain at high levels during the early to mid-21st century, whereas the direction and magnitude of change are expected to diverge substantially among tributaries by the late 21st century (Supplementary Table S5). Existing studies suggest that near-future runoff in headwaters such as the Kaidu, Aksu, Yarkant, and Hotan rivers will generally increase or remain high. By the late 21st century, however, some basins, such as the Kaidu River and Huangshuigou, may show slight declining trends, whereas projections remain highly uncertain for the strongly glacierized source regions on the northern slope of the Kunlun Mountains. Some studies suggest that runoff in the Yarkant, Karakash, and Yurungkash rivers may fall substantially below baseline levels as glacier reserves are depleted. Other studies, however, indicate that runoff in these rivers may remain relatively high even after reaching peak glacier melt around 2050–2070, subsequently declining toward the end of the century relative to peak-melt conditions while still exceeding historical levels (Supplementary Table S5).

In the Irtysh River basin, future runoff changes are projected to show pronounced contrasts between relatively less-regulated upper and tributary catchments and the more strongly regulated middle and lower reaches (Supplementary Table S5). In the relatively less-regulated upper and tributary catchments, including the Oba, Ulbi, Zhabay, and Bukhtarma catchments, runoff is generally projected to increase under continued warming, particularly where precipitation also increases, with projected changes ranging from 5% to 32%. Alongside the increase in annual runoff, marked seasonal redistribution is expected, including an advance of the spring runoff peak by up to one month, a shortened snow-accumulation period, and reduced summer discharge in several tributaries. In contrast, the middle and lower reaches are strongly affected by reservoir regulation and water withdrawals. Operation of the upper Irtysh reservoir cascade has already reduced summer flow by approximately 38% and increased winter flow by approximately 70% relative to pre-regulation conditions, and may further alter the seasonal distribution of downstream runoff while weakening the natural climate-driven increase in water availability.

6.3.2. Extreme Hydrological Events

Flooding represents one of the most direct future risks among extreme hydrological events in the snow- and glacier-fed basins of Central Asia. Global warming has already increased the frequency and intensity of extreme precipitation events in the region. In mountainous areas of Tajikistan, Kyrgyzstan, and western China, intense precipitation events that were formerly expected once every 50 years may now recur in less than 20 years under the current climate, providing stronger triggering conditions for mountain floods [59].

Future flood risk is expected to be expressed mainly through enhanced flood peaks, earlier high-flow periods, and increased risk of sudden-onset mountain floods. In the upper Syr Darya basin, peak flood discharge is projected to increase by more than 60% by the end of the 21st century [150]. Research on the Naryn River, one of its major headwaters, further indicates that shifts in precipitation phase from snow to rain will substantially intensify peak-runoff extremes at lower elevations, causing runoff events that historically occurred once every 10 years to occur every 3–4 years in the future [134]. In addition to stronger flood peaks, warming-driven advances in snowmelt and glacier melt will alter the seasonal distribution of flooding. For example, the runoff peak of the Vakhsh River, a tributary of the Amu Darya, may shift from July to June, while the runoff peak of the Yarkant River, a tributary of the Tarim River, may shift from August to July. These changes suggest that high-flow risk may increasingly shift toward early summer [151,152]. Glacial lake outburst floods (GLOFs) are also an important type of sudden-onset flood hazard in the high-mountain basins of Central Asia. Continued glacier retreat across the Third Pole is expected to promote glacial lake expansion and substantially increase GLOF risk, with the overall risk potentially approaching three times the present level [153].

Hydrological drought is another major form of future extreme hydrological events in the snow- and glacier-fed basins of Central Asia, manifested primarily as low river flows, reduced summer water availability, and increased risk of water scarcity. Regional-scale studies indicate that future hydrological drought risk in Central Asia will show strong spatial heterogeneity, with drought duration and severity increasing in the Amu Darya basin under high-emission scenarios. Under SSP5-8.5, approximately 39.01% of Central Asia's land area and 35.9% of its population may be exposed to severe drought risk [39]. In the upper Syr Darya basin, summer runoff may decrease by 16–30% by the end of the 21st century, drought duration may increase by more than one month, and drought intensity may increase by a factor of approximately 4.6 [150]. In the Naryn River, low flows may decline by 36.8% by the 2080s, and each additional hectare of cultivated land is estimated to increase water-resource deficits by an average of approximately $10.9 \times 10^3 \text{ m}^3$ [154]. The headwaters of the Tarim River may also face increasing flash-drought risk. Based on ten CMIP6 models and the VIC model, Yu et al. projected overall increases

in the frequency, duration, and intensity of flash droughts during 2021–2100, with higher frequency and intensity in mountainous areas than in plains [155]. Studies of the Ili River have focused more on water-resource vulnerability and ecological-flow reliability. de Boer et al. identified approximately 11 billion m³ as the critical inflow threshold required to maintain the ecological functions of wetlands in the Ili Delta and Lake Balkhash. Under scenarios of high water demand, about 70% of years may fall below this threshold, and 20% may even fall below 7 billion m³, indicating that increased upstream water use could substantially raise the frequency and intensity of downstream environmental water shortages [156].

6.3.3. Debris Flows and Landslides

In the characteristic mountain–basin setting of arid Central Asia, hydrogeomorphic hazards, particularly debris flows and landslides, pose substantial threats to mountain water security and the sustainability of downstream oasis systems. Despite generally low regional precipitation, high mountain regions remain highly susceptible to such hazards because of their steep topographic gradients and abundant unconsolidated material. This susceptibility is further amplified by extreme precipitation, rapid snowmelt, glacier retreat, and glacial lake outburst floods (GLOFs), which collectively increase exposure to climatic extremes. According to the Northern Tianshan disaster database, 458 debris-flow events were recorded between 1887 and 2020, including 55 triggered by GLOFs; all subsequently evolved into debris flows. These findings underscore the critical role of cryospheric change and sudden-onset hydrological processes in driving debris-flow activity across the mountains of Central Asia [157].

Over recent decades, debris-flow activity in the mountains of Central Asia has progressively shifted toward higher elevations. In the Ile Alatau of the central Northern Tianshan Mountains, initiation zones of rainfall-induced and mixed-type debris flows are concentrated between 1200 and 3600 m. Within the 2500–3600 m elevation band, the number of recorded debris-flow events increased from 20 during 1931–1960 to 47 during 1991–2020, suggesting a gradual increase in debris-flow activity at higher elevations [157]. In addition, glacier retreat and permafrost degradation can increase the availability of loose debris and reduce slope stability in high-mountain environments, thereby enhancing the potential for mass movements and debris-flow hazards [158]. Landslide activity may also be influenced by the combined effects of permafrost degradation, intensified rainfall, and glacier retreat under a warming climate, although long-term trends in landslide occurrence are generally less evident in observational records than those of debris flows. Rising temperatures and permafrost degradation can weaken the mechanical support provided by ground ice within ice-cemented slopes and ice-filled rock fractures, whereas intense rainfall increases slope saturation and pore-water pressure, thereby enhancing the likelihood of shallow landslides, rockfalls, and debris flows [159,160]. In deglaciating mountain environments, glacier retreat may further destabilize valley slopes and promote the failure of moraine dams and unconsolidated moraine deposits, creating cascading hazard sequences that connect landslides, GLOFs, and debris flows [158].

6.3.4. Future Water Resource Risks and Adaptation

Future water security in Central Asia will be challenged not only by the increasing occurrence of hydrological extremes, but also by growing uncertainty in water availability, rising water demand, and mounting pressures on transboundary water governance. In addition, the mismatch between upstream water supply from mountain regions and downstream water demand is expected to become more pronounced. Glacier retreat, declining snow storage, and shifts in runoff seasonality are likely to reduce the reliability of summer water supplies, leaving some basins vulnerable to increased spring runoff but diminished water availability during the irrigation season [120]. These changes may increase uncertainty in both agricultural irrigation and hydropower generation [161]. At the same time, agriculture in Central Asia remains highly dependent on irrigation, while population growth, irrigation expansion, and enhanced evapotranspiration are projected to further increase agricultural water demand [162].

On the management side, this tension between water supply and demand is especially pronounced in transboundary river basins, manifesting primarily as a seasonal mismatch between hydropower generation and irrigation water use, high water consumption in irrigation districts, and insufficient provision for ecological water demand. The Amu Darya and Syr Darya exhibit a longstanding conflict between winter hydropower generation in the upstream reaches and summer agricultural irrigation in the downstream reaches, while climate-change-induced earlier snowmelt and declining summer runoff further intensify water stress in downstream agricultural areas [114,163]. At the same time, total water withdrawal in Central Asia in 2020 reached 127.3 km³, of which irrigation accounted for 100.4 km³ (approximately 80%). Moreover, nearly 40% of irrigation water was lost during canal conveyance, highlighting the coexistence of rigid demand and inefficient water use across the region [162].

Against this background, and in support of the United Nations Water Action Decade (2018–2028) and the Sustainable Development Goals (SDGs), future adaptation efforts in Central Asia should focus on addressing changing runoff regimes, intensifying hydrological extremes, and growing transboundary water challenges through the following priorities. First, integrated monitoring of meteorological, hydrological, glacier, snow, and permafrost conditions in high-mountain regions should be strengthened, alongside greater sharing of transboundary monitoring data. These efforts would help reduce uncertainties in climate forcing, snow and ice process parameterization, and hydrological model simulations and assessments [96,164–166]. Second, research should shift from the study of individual hazards toward understanding cascading multi-hazard processes and strengthening integrated transboundary risk management. Particular emphasis should be placed on the triggering and propagation of hazard cascades involving extreme precipitation, rapid snowmelt, GLOFs, debris flows, landslides, and fluvial flooding, while enhancing risk assessment, monitoring and early-warning systems, and emergency response capacity [167,168]. Third, enhancing flood regulation and storage capacity while maximizing the beneficial use of floodwater should be prioritized. This can be achieved through the coordinated operation of reservoirs, flood storage and detention areas, canal networks, and interregional water transfer systems. In addition, greater emphasis should be placed on strengthening connectivity between mainstem and tributary river systems, improving coordinated water allocation across regions and among multiple water sources, and promoting floodwater utilization through groundwater recharge, ecological flow restoration, wetland rehabilitation, and river–lake connectivity [169–174]. Fourth, improving agricultural water use efficiency and strengthening integrated water–food–energy–ecosystem management should be prioritized. This can be achieved through the adoption of water-saving irrigation technologies, adjustments in cropping patterns, modernization of irrigation systems, and the conjunctive management of surface water and groundwater. At the same time, the broader implications of water-saving measures for energy consumption, food security, ecological water requirements, and carbon emissions should be comprehensively evaluated [162,175]. Fifth, research on the efficient utilization of water resources during runoff surplus periods should be further strengthened. Given the transient nature of runoff increases in some mountain river basins, this short-lived hydrological opportunity should be effectively leveraged to optimize the storage, allocation, and ecological utilization of excess runoff. These processes are critical for enhancing the resilience of downstream oases and riparian ecosystems, and for supporting regional water security, ecological conservation, and the Sustainable Development Goals (SDGs) [176].

7. Conclusions

This study systematically reviews the changes in moisture transport, glacier dynamics, and runoff processes in Central Asia under climate change. The region is undergoing a climate–hydrological system adjustment characterized by significant warming, weak precipitation increases, spatially heterogeneous glacier mass balance and shifted runoff regimes.

- (1) In terms of climate change, the mean annual air temperature in Central Asia increased at a rate of approximately 0.33 °C per decade during 1960–2024, which is substantially higher than the global mean warming rate over the same period. In contrast, annual precipitation increased only slightly, at about 2.3 mm per decade. Precipitation increased significantly in the eastern and northern part (e.g., Tianshan region, Kunlun Mountains), but weak changes or even decreasing trends in some inland lowlands of Central Asia. In terms of moisture sources, westerly transport remains the dominant external moisture source for precipitation in Central Asia, contributing more to the northern and western regions; local moisture recycling is an important supplement to summer precipitation. The overall contribution of low-latitude moisture is limited, but in recent years its contribution to southern Central Asia, especially the southern Tarim River Basin, has increased, with enhanced southwesterly moisture transport.
- (2) Warming has driven widespread glacier retreat with mean glacier mass balances ranging from -0.095 to -0.135 m w.e. a^{-1} during 2000–2016/2018/2019. Glacier retreat is most pronounced in the Tianshan Mountains, moderate in the Pamir, and relatively weak in parts of the Karakoram and Kunlun Mountains. For regions such as the Kunlun Mountains and Pamir, where glacier stability or even advances have attracted attention, glaciers have also begun to show signs of retreat since the 21st century.
- (3) Runoff has generally increased in the Tianshan, northern Kunlun, and northern Pamir, with rates of about 0.50–6.12 mm $year^{-1}$ in most Tianshan rivers and 0.06 to 0.72 mm $year^{-1}$ in the Kunlun Mountains, while the Pamir–Alay and some upper Amu Darya tributaries show mixed trends. In contrast, runoff changes in the middle and lower reaches and plain areas show a decreasing trend; however, with human intervention, this decreasing trend has been reversed into an increasing trend in the Tarim River and Ili River, and has also stabilized in the Amu Darya and Syr Darya, where runoff no longer declines.

- (4) Looking ahead, water-resource management in arid Central Asia will need to address increasing temporal variability and spatial heterogeneity in runoff. In basins such as the Tarim and, under most scenarios, the Amu Darya, annual runoff may increase or remain relatively high, but greater variability will require improved reservoir regulation, storage, conveyance, and coordinated allocation. In glacier-dependent regions such as the Syr Darya and parts of the Tianshan Mountains, continued glacier retreat may eventually reduce late-summer mountain runoff, requiring gradual adjustment of water-use structures and reduced dependence on glacier-fed flows. More broadly, accelerating glacier retreat is likely to amplify spatial differences in water availability, highlighting the need for stronger hydrological connectivity and coordinated water management across upstream and downstream regions.

Supplementary Materials

The additional data and information can be downloaded at: <https://media.scilit.com/articles/others/2609171419071150/HWR-26060281-SI.pdf>. Refs. [177–238] are cited in the supplementary materials.

Author Contributions

R.L.: Conceptualization, Data curation, Formal analysis; Writing—Original Draft; G.F.: Conceptualization, Methodology, Supervision, Writing—Review & Editing; Y.C.: Conceptualization, Supervision, Writing—Review & Editing; X.Y.: Data curation, Writing—Review & Editing; J.Y.: Resources, Writing—Review & Editing; Z.L.: Resources, Writing—Review & Editing; R.G.: Data curation; Q.W.: Data curation; A.K.: Resources, Validation; N.G.: Resources, Validation; N.K.: Resources, Validation; F.N.: Resources, Validation, Writing—Review & Editing. All authors have read and agreed to the published version of the manuscript.

Funding

This research was supported by and the National Natural Science Foundation of China (W2412135), Xinjiang Major Science and Technology Project (2024A03006-2) and the Youth Innovation Promotion Association of the Chinese Academy of Sciences.

Data Availability Statement

All data used in this review were obtained from publicly available literature, databases, and published sources cited in the manuscript and Supplementary Materials. No new primary datasets were generated in this study.

Conflicts of Interest

Gonghuan Fang is an Editorial Board Member of *Hydrology and Water Resources*. Given his role as an Editorial Board Member, Gonghuan Fang had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal. The other authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used ChatGPT to assist in creating the schematic illustration in Figure 4, which depicts moisture transport pathways and their recent evolution in Central Asia. The AI tool was used solely for visual presentation and graphic design. All scientific content, quantitative information, labels, and interpretations presented in the figure were derived from the cited literature and were determined and verified by the authors. The authors subsequently reviewed and edited the figure as necessary and accept full responsibility for the content of the published article.

References

1. Ravinandrasana, V.P.; Franzke, C.L.E. The first emergence of unprecedented global water scarcity in the Anthropocene. *Nat. Commun.* **2025**, *16*, 8281. <https://doi.org/10.1038/s41467-025-63784-6>.
2. Zhang, W.; Furtado, K.; Wu, P.; et al. Increasing precipitation variability on daily-to-multiyear time scales in a warmer world. *Sci. Adv.* **2021**, *7*, eabf8021. <https://doi.org/10.1126/sciadv.abf8021>.
3. IPCC. *Climate Change 2023: Synthesis Report*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2023; pp. 35–115. <https://doi.org/10.59327/ipcc/ar6-9789291691647>.

4. Zemp, M.; Jakob, L.; Dussaillant, I.; et al. Community estimate of global glacier mass changes from 2000 to 2023. *Nature* **2025**, *639*, 382–388. <https://doi.org/10.1038/s41586-024-08545-z>.
5. Konapala, G.; Mishra, A.K.; Wada, Y.; et al. Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation. *Nat. Commun.* **2020**, *11*, 3044. <https://doi.org/10.1038/s41467-020-16757-w>.
6. Ficklin, D.L.; Null, S.E.; Abatzoglou, J.T.; et al. Hydrological Intensification Will Increase the Complexity of Water Resource Management. *Earth's Future* **2022**, *10*, e2021EF002487. <https://doi.org/10.1029/2021ef002487>.
7. Thackeray, C.W.; Hall, A.; Norris, J.; et al. Constraining the increased frequency of global precipitation extremes under warming. *Nat. Clim. Chang.* **2022**, *12*, 441–448. <https://doi.org/10.1038/s41558-022-01329-1>.
8. Lesk, C.S.; Mankin, J.S. More concentrated precipitation decreases terrestrial water storage. *Nature* **2026**, *653*, 425–432. <https://doi.org/10.1038/s41586-026-10487-7>.
9. Zhang, Y.; Li, C.; Chiew, F.H.S.; et al. Southern Hemisphere dominates recent decline in global water availability. *Science* **2023**, *382*, 579–584. <https://doi.org/10.1126/science.adh0716>.
10. Stringer, L.C.; Mirzabaev, A.; Benjaminsen, T.A.; et al. Climate change impacts on water security in global drylands. *One Earth* **2021**, *4*, 851–864. <https://doi.org/10.1016/j.oneear.2021.05.010>.
11. Wang, X.; Chen, Y.; Fang, G.; et al. The growing water crisis in Central Asia and the driving forces behind it. *J. Clean. Prod.* **2022**, *378*, 134574. <https://doi.org/10.1016/j.jclepro.2022.134574>.
12. Whateley, S.; Steinschneider, S.; Brown, C. A climate change range-based method for estimating robustness for water resources supply. *Water Resour. Res.* **2014**, *50*, 8944–8961. <https://doi.org/10.1002/2014wr015956>.
13. Yang, Z.; Bai, P.; Tian, Y.; et al. Glacier Coverage Dominates the Response of Runoff and Its Components to Climate Change in the Tianshan Mountains. *Water Resour. Res.* **2025**, *61*, e2024WR037947. <https://doi.org/10.1029/2024WR037947>.
14. Chen, Y.; Fang, G.; Li, Z.; et al. The Crisis in Oases: Research on Ecological Security and Sustainable Development in Arid Regions. *Annu. Rev. Environ. Resour.* **2024**, *49*, 1–20. <https://doi.org/10.1146/annurev-environ-111522-105932>.
15. Li, C.; Fu, B.; Wang, S.; et al. Drivers and impacts of changes in China's drylands. *Nat. Rev. Earth Environ.* **2021**, *2*, 858–873. <https://doi.org/10.1038/s43017-021-00226-z>.
16. Lian, X.; Piao, S.; Chen, A.; et al. Multifaceted characteristics of dryland aridity changes in a warming world. *Nat. Rev. Earth Environ.* **2021**, *2*, 232–250. <https://doi.org/10.1038/s43017-021-00144-0>.
17. Gafurov, A.; Selyuzhenok, V.; Latinovic, M.; et al. GRACE observes the natural and irrigation-induced regional redistribution of water storage in Central Asia. *J. Hydrol. Reg. Stud.* **2024**, *56*, 101994. <https://doi.org/10.1016/j.ejrh.2024.101994>.
18. Barandun, M.; Fiddes, J.; Scherler, M.; et al. The state and future of the cryosphere in Central Asia. *Water Secur.* **2020**, *11*, 100072. <https://doi.org/10.1016/j.wasec.2020.100072>.
19. Pohl, E.; Gloaguen, R.; Andermann, C.; et al. Glacier melt buffers river runoff in the Pamir Mountains. *Water Resour. Res.* **2017**, *53*, 2467–2489. <https://doi.org/10.1002/2016wr019431>.
20. Saidaliyeva, Z.; Muccione, V.; Shahgedanova, M.; et al. Adaptation to climate change in the mountain regions of Central Asia: A systematic literature review. *WIREs Clim. Chang.* **2024**, *15*, e891. <https://doi.org/10.1002/wcc.891>.
21. Central Asia Population. Available online: <https://www.worldometers.info/world-population/central-asia-population/> (accessed on 2 September 2026).
22. Ministry of Natural Resources of the People's Republic of China. *Bulletin of the Third National Land Survey*; Ministry of Natural Resources of the People's Republic of China: Beijing, China, 2021.
23. Food and Agriculture Organization. *FAOSTAT Database: Arable Land*; Food and Agriculture Organization: Rome, Italy, 2021.
24. Peng, J.; Liu, T.; Chen, J.; et al. The conflicts of agricultural water supply and demand under climate change in a typical arid land watershed of Central Asia. *J. Hydrol. Reg. Stud.* **2023**, *47*, 101384. <https://doi.org/10.1016/j.ejrh.2023.101384>.
25. Li, Y.; Deng, M. Spatiotemporal variations of agricultural water footprint and its economic benefits in Xinjiang, northwestern China. *Sci. Rep.* **2021**, *11*, 23864. <https://doi.org/10.1038/s41598-021-03240-9>.
26. United Nations Industrial Development Organization; International Center on Small Hydro Power. *World Small Hydropower Development Report 2022: Central Asia*; United Nations Industrial Development Organization: Vienna, Austria; International Center on Small Hydro Power: Hangzhou, China, 2022.
27. Hu, Z.; Zhang, C.; Hu, Q.; et al. Temperature Changes in Central Asia from 1979 to 2011 Based on Multiple Datasets. *J. Clim.* **2014**, *27*, 1143–1167. <https://doi.org/10.1175/jcli-d-13-00064.1>.
28. Zhang, M.; Chen, Y.; Shen, Y.; et al. Tracking climate change in Central Asia through temperature and precipitation extremes. *J. Geogr. Sci.* **2019**, *29*, 3–28. <https://doi.org/10.1007/s11442-019-1581-6>.
29. Chen, F.; Huang, W.; Jin, L.; et al. Spatiotemporal precipitation variations in the arid Central Asia in the context of global warming. *Sci. China Earth Sci.* **2011**, *54*, 1812–1821. <https://doi.org/10.1007/s11430-011-4333-8>.
30. Hu, Z.; Zhou, Q.; Chen, X.; et al. Variations and changes of annual precipitation in Central Asia over the last century. *Int. J. Climatol.* **2017**, *37*, 157–170. <https://doi.org/10.1002/joc.4988>.

31. Farinotti, D.; Longuevergne, L.; Moholdt, G.; et al. Substantial glacier mass loss in the Tien Shan over the past 50 years. *Nat. Geosci.* **2015**, *8*, 716–722. <https://doi.org/10.1038/ngeo2513>.
32. Zhuang, L.; Ke, C.; Cai, Y.; et al. Measuring glacier changes in the Tianshan Mountains over the past 20 years using Google Earth Engine and machine learning. *J. Geogr. Sci.* **2023**, *33*, 1939–1964. <https://doi.org/10.1007/s11442-023-2160-4>.
33. Viviroli, D.; Archer, D.R.; Buytaert, W.; et al. Climate change and mountain water resources: overview and recommendations for research, management and policy. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 471–504. <https://doi.org/10.5194/hess-15-471-2011>.
34. Christian, J.E.; Whorton, E.; Carnahan, E.; et al. Differences in the transient responses of individual glaciers: a case study of the Cascade Mountains of Washington State, USA. *J. Glaciol.* **2022**, *68*, 751–763. <https://doi.org/10.1017/jog.2021.133>.
35. Hodge, S.M.; Trabant, D.C.; Krimmel, R.M.; et al. Climate Variations and Changes in Mass of Three Glaciers in Western North America. *J. Clim.* **1998**, *11*, 2161–2179. [https://doi.org/10.1175/1520-0442\(1998\)011<2161:cvacim>2.0.co;2](https://doi.org/10.1175/1520-0442(1998)011<2161:cvacim>2.0.co;2).
36. Bliss, A.; Hock, R.; Radić, V. Global response of glacier runoff to twenty-first century climate change. *J. Geophys. Res. Earth Surf.* **2014**, *119*, 717–730. <https://doi.org/10.1002/2013jf002931>.
37. Zheng, Z.; Hong, S.; Deng, H.; et al. Impact of Elevation-Dependent Warming on Runoff Changes in the Headwater Region of Urumqi River Basin. *Remote Sens.* **2022**, *14*, 1780. <https://doi.org/10.3390/rs14081780>.
38. Li, M.; Yao, J.; Zheng, J. Spatio-temporal changes in atmospheric aridity over the arid region of Central Asia during 1979–2019. *Ecol. Indic.* **2024**, *169*, 112814. <https://doi.org/10.1016/j.ecolind.2024.112814>.
39. Wu, X.; Tang, W.; Chen, F.; et al. Attribution and Risk Projections of Hydrological Drought Over Water-Scarce Central Asia. *Earth's Future* **2025**, *13*, e2024EF005243. <https://doi.org/10.1029/2024ef005243>.
40. Bernauer, T.; Siegfried, T. Climate change and international water conflict in Central Asia. *J. Peace Res.* **2012**, *49*, 227–239. <https://doi.org/10.1177/0022343311425843>.
41. Wegerich, K. Hydro-hegemony in the Amu Darya Basin. *Water Policy* **2008**, *10*, 71–88. <https://doi.org/10.2166/wp.2008.208>.
42. World Bank. *Central Asia Water & Energy Program*; World Bank: Washington, DC, USA, 2026.
43. Hu, W.; Yao, J.; He, Q.; et al. Changes in precipitation amounts and extremes across Xinjiang (Northwest China) and their connection to climate indices. *PeerJ* **2021**, *9*, e10792. <https://doi.org/10.7717/peerj.10792>.
44. Li, S.; Lei, J.; Xu, X. Genetic Conditions of Sandstorms in the Hinterland of Taklimakan Desert. *J. Appl. Meteorol. Sci.* **2007**, *18*, 490–496.
45. Mattea, E.; Bhattacharya, A.; Ghuffar, S.; et al. Multi-Sensor Analysis of Predicted and Observed Glacier Instabilities in the Hissar–Alay of Central Asia. *Remote Sens.* **2026**, *18*, 699. <https://doi.org/10.3390/rs18050699>.
46. Sun, F.; Li, Y.; Chen, Y.; et al. The dominant warming season shifted from winter to spring in the arid region of Northwest China. *npj Clim. Atmos. Sci.* **2024**, *7*, 178. <https://doi.org/10.1038/s41612-024-00724-z>.
47. Wang, G.; Yuan, X.; Jing, C.; et al. The Decreased Cloud Cover Dominated the Rapid Spring Temperature Rise in Arid Central Asia Over the Period 1980–2014. *Geophys. Res. Lett.* **2024**, *51*, e2023GL107523. <https://doi.org/10.1029/2023gl107523>.
48. Li, B.; Chen, Y.; Shi, X. Does elevation dependent warming exist in high mountain Asia? *Environ. Res. Lett.* **2020**, *15*, 024012. <https://doi.org/10.1088/1748-9326/ab6d7f>.
49. Zhang, Y.; An, C.B.; Liu, L.Y.; et al. High-elevation landforms are experiencing more remarkable wetting trends in arid Central Asia. *Adv. Clim. Chang. Res.* **2022**, *13*, 489–495. <https://doi.org/10.1016/j.accre.2022.04.007>.
50. Haag, I.; Jones, P.D.; Samimi, C. Central Asia's Changing Climate: How Temperature and Precipitation Have Changed across Time, Space, and Altitude. *Climate* **2019**, *7*, 123. <https://doi.org/10.3390/cli7100123>.
51. Wu, L.; Zheng, H. Regional Climate Effects of Irrigation under Central Asia Warming by 2.0 °C. *Remote Sens.* **2023**, *15*, 3672. <https://doi.org/10.3390/rs15143672>.
52. Li, Y.; Duan, W.; Zeng, Z.; et al. Asynchronous abrupt warming across Eurasia since the 1980s. *npj Clim. Atmos. Sci.* **2025**, *8*, 327. <https://doi.org/10.1038/s41612-025-01209-3>.
53. Song, S.; Bai, J. Increasing Winter Precipitation over Arid Central Asia under Global Warming. *Atmosphere* **2016**, *7*, 139. <https://doi.org/10.3390/atmos7100139>.
54. Ma, Q.; Zhang, J.; Game, A.T.; et al. Spatiotemporal variability of summer precipitation and precipitation extremes and associated large-scale mechanisms in Central Asia during 1979–2018. *J. Hydrol. X* **2020**, *8*, 100061. <https://doi.org/10.1016/j.hydroa.2020.100061>.
55. Peng, D.; Zhou, T.; Zhang, L.; et al. Human Contribution to the Increasing Summer Precipitation in Central Asia from 1961 to 2013. *J. Clim.* **2018**, *31*, 8005–8021. <https://doi.org/10.1175/jcli-d-17-0843.1>.
56. Guo, J.; Xie, X.; Myhre, G.; et al. Distinct drivers of recent seasonal precipitation increase over Central Asia: roles of anthropogenic aerosols and greenhouse gases. *Atmos. Chem. Phys.* **2026**, *26*, 5169–5184. <https://doi.org/10.5194/acp-26-5169-2026>.
57. Yao, M.; Tang, H.; Huang, G. Roles of External Forcing and Internal Variability in Winter Precipitation Changes over Central Asia. *Earth's Future* **2025**, *13*, e2025EF006064. <https://doi.org/10.1029/2025ef006064>.

58. Zhou, G.; Chen, Y.; Yao, J. Variations in precipitation and temperature in Xinjiang (Northwest China) and their connection to atmospheric circulation. *Front. Environ. Sci.* **2023**, *10*, 1082713. <https://doi.org/10.3389/fenvs.2022.1082713>.
59. Fallah, B.; Rostami, M. Exploring the impact of the recent global warming on extreme weather events in Central Asia using the counterfactual climate data ATTRICI v1.1. *Clim. Chang.* **2024**, *177*, 80. <https://doi.org/10.1007/s10584-024-03743-0>.
60. Yu, S.; Yan, Z.; Freychet, N.; et al. Trends in summer heatwaves in central Asia from 1917 to 2016: Association with large-scale atmospheric circulation patterns. *Int. J. Climatol.* **2020**, *40*, 115–127. <https://doi.org/10.1002/joc.6197>.
61. Wang, X.; Li, Y.; Chen, Y.; et al. Intensification of heatwaves in Central Asia from 1981 to 2020—Role of soil moisture reduction. *J. Hydrol.* **2023**, *627*, 130395. <https://doi.org/10.1016/j.jhydrol.2023.130395>.
62. Li, L.; Yang, Y.; Zhang, X.; et al. Attribution of the 2021 record-breaking compound drought-heatwave extreme in Central Asia to anthropogenic warming, atmospheric circulation, and NAO. *J. Hydrol.* **2026**, *679*, 136282. <https://doi.org/10.1016/j.jhydrol.2026.136282>.
63. Feldman, A.F.; Feng, X.; Felton, A.J.; et al. Widespread Co-Location of Less Frequent and More Intense Daily Precipitation Over Land. *Geophys. Res. Lett.* **2026**, *53*, e2025GL120745. <https://doi.org/10.1029/2025gl120745>.
64. Zou, S.; Abuduwaili, J.; Duan, W.; et al. Attribution of changes in the trend and temporal non-uniformity of extreme precipitation events in Central Asia. *Sci. Rep.* **2021**, *11*, 15032. <https://doi.org/10.1038/s41598-021-94486-w>.
65. Guan, J.; Yao, J.; Li, M.; et al. Historical changes and projected trends of extreme climate events in Xinjiang, China. *Clim. Dyn.* **2022**, *59*, 1753–1774. <https://doi.org/10.1007/s00382-021-06067-2>.
66. Jin, C.; He, Q.; Huang, Q. Extreme Summer Precipitation Characteristics and Associated Water Vapor Transport in Southern Xinjiang. *Water* **2023**, *15*, 2361. <https://doi.org/10.3390/w15132361>.
67. Li, M.; Yao, J. Precipitation extremes observed over and around the Taklimakan Desert, China. *PeerJ* **2023**, *11*, e15256. <https://doi.org/10.7717/peerj.15256>.
68. Aihaiti, A.; Wang, Y.; Ali, M.; et al. Probability distribution characteristics of summer extreme precipitation in Xinjiang, China during 1970–2021. *Theor. Appl. Climatol.* **2023**, *151*, 753–766. <https://doi.org/10.1007/s00704-022-04272-5>.
69. Hua, L.; Zhao, T.; Zhong, L. Future changes in drought over Central Asia under CMIP6 forcing scenarios. *J. Hydrol. Reg. Stud.* **2022**, *43*, 101191. <https://doi.org/10.1016/j.ejrh.2022.101191>.
70. Li, T.; Song, F.; Bao, J.; et al. Historical and Projected Cropland Impacts of Heatwaves in Central Asia under Climate Change. *Earth's Future* **2025**, *13*, e2024EF005595. <https://doi.org/10.1029/2024ef005595>.
71. Xie, B.; Guo, H.; Meng, F.; et al. Historical Evolution and Future Trends of Precipitation Based on Integrated Datasets and Model Simulations of Arid Central Asia. *Remote Sens.* **2023**, *15*, 5460. <https://doi.org/10.3390/rs15235460>.
72. Jiang, J.; Zhou, T.; Chen, X.; et al. Future changes in precipitation over Central Asia based on CMIP6 projections. *Environ. Res. Lett.* **2020**, *15*, 054009. <https://doi.org/10.1088/1748-9326/ab7d03>.
73. Huang, A.; Zhou, Y.; Zhang, Y.; et al. Changes of the Annual Precipitation over Central Asia in the Twenty-First Century Projected by Multimodels of CMIP5. *J. Clim.* **2014**, *27*, 6627–6646. <https://doi.org/10.1175/jcli-d-14-00070.1>.
74. Gutiérrez, J.M.; Jones, R.G.; Narisma, G.T.; et al. Atlas. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2023; pp. 1927–2058. <https://doi.org/10.1017/9781009157896.021>.
75. Gummadi, S.; Samineni, S.; Lopez-Lavalle, L.A.B. Assessing high-resolution precipitation extremes in Central Asia: evaluation and future projections. *Clim. Chang.* **2025**, *178*, 29. <https://doi.org/10.1007/s10584-025-03872-0>.
76. Zhang, X.; Chen, Y.; Fang, G.; et al. Increasing multiscale variability in extreme precipitation under global warming in the Tianshan Mountains, Central Asia. *J. Hydrol.* **2023**, *626*, 130158. <https://doi.org/10.1016/j.jhydrol.2023.130158>.
77. Jiang, J.; Zhou, T.; Wang, H.; et al. Tracking moisture sources of precipitation over central Asia: A study based on the water-source-tagging method. *J. Clim.* **2020**, *33*, 10339–10355. <https://doi.org/10.1175/jcli-d-20-0169.1>.
78. Zhong, L.; Hua, L.; Gong, Z.; et al. Quantifying the Spatial Characteristics of the Moisture Transport Affecting Precipitation Seasonality and Recycling Variability in Central Asia. *Adv. Atmos. Sci.* **2022**, *39*, 967–984. <https://doi.org/10.1007/s00376-021-1383-5>.
79. Wang, W.; Li, H.; Wang, J.; et al. Water vapor from western Eurasia promotes precipitation during the snow season in northern Xinjiang, a typical arid region in central Asia. *Water* **2020**, *12*, 141. <https://doi.org/10.3390/w12010141>.
80. Wang, S.; Zhang, M.; Che, Y.; et al. Contribution of recycled moisture to precipitation in oases of arid central Asia: A stable isotope approach. *Water Resour. Res.* **2016**, *52*, 3246–3257. <https://doi.org/10.1002/2015wr018135>.
81. Wang, S.; Wang, L.; Zhang, M.; et al. Quantifying moisture recycling of a leeward oasis in arid central Asia using a Bayesian isotopic mixing model. *J. Hydrol.* **2022**, *613*, 128459. <https://doi.org/10.1016/j.jhydrol.2022.128459>.
82. Zhang, J.; Wang, S.; He, Y.; et al. Contribution of the precipitation-recycling process to the wetting trend in Xinjiang, China. *J. Geophys. Res. Atmos.* **2022**, *127*, e2021JD036407. <https://doi.org/10.1029/2021jd036407>.
83. Ren, Y.; Yu, H.; Liu, C.; et al. Attribution of Dry and Wet Climatic Changes over Central Asia. *J. Clim.* **2022**, *35*, 1399–1421. <https://doi.org/10.1175/jcli-d-21-0329.1>.

84. Syed, F.S.; Giorgi, F.; Pal, J.S.; et al. Effect of remote forcings on the winter precipitation of central southwest Asia part 1: Observations. *Theor. Appl. Climatol.* **2006**, *86*, 147–160. <https://doi.org/10.1007/s00704-005-0217-1>.
85. Yin, Z.Y.; Wang, H.; Liu, X. A Comparative Study on Precipitation Climatology and Interannual Variability in the Lower Midlatitude East Asia and Central Asia. *J. Clim.* **2014**, *27*, 7830–7848. <https://doi.org/10.1175/jcli-d-14-00052.1>.
86. Yan, D.; Xu, H.; Lan, J.; et al. Solar activity and the westerlies dominate decadal hydroclimatic changes over arid Central Asia. *Glob. Planet. Chang.* **2019**, *173*, 53–60. <https://doi.org/10.1016/j.gloplacha.2018.12.006>.
87. Chen, Y.; Li, Z.; Fang, G.; et al. Large hydrological processes changes in the transboundary rivers of Central Asia. *J. Geophys. Res. Atmos.* **2018**, *123*, 5059–5069. <https://doi.org/10.1029/2017jd028184>.
88. Mariotti, A. How ENSO impacts precipitation in southwest central Asia. *Geophys. Res. Lett.* **2007**, *34*, L16706. <https://doi.org/10.1029/2007gl030078>.
89. Rana, S.; McGregor, J.; Renwick, J. Dominant modes of winter precipitation variability over Central Southwest Asia and inter-decadal change in the ENSO teleconnection. *Clim. Dyn.* **2019**, *53*, 5689–5707. <https://doi.org/10.1007/s00382-019-04889-9>.
90. Yang, H.; Xu, G.; Mao, H.; et al. Spatiotemporal Variation in Precipitation and Water Vapor Transport Over Central Asia in Winter and Summer under Global Warming. *Front. Earth Sci.* **2020**, *8*, 297. <https://doi.org/10.3389/feart.2020.00297>.
91. Huang, W.; Feng, S.; Chen, J.; et al. Physical mechanisms of summer precipitation variations in the Tarim Basin in northwestern China. *J. Clim.* **2015**, *28*, 3579–3591. <https://doi.org/10.1175/jcli-d-14-00395.1>.
92. Chen, C.; Zhang, X.; Lu, H.; et al. Increasing summer precipitation in arid Central Asia linked to the weakening of the East Asian summer monsoon in the recent decades. *Int. J. Climatol.* **2021**, *41*, 1024–1038. <https://doi.org/10.1002/joc.6727>.
93. Hu, Q.; Zhao, Y.; Huang, A.; et al. Moisture Transport and Sources of the Extreme Precipitation Over Northern and Southern Xinjiang in the Summer Half-Year During 1979–2018. *Front. Earth Sci.* **2021**, *9*, 770877. <https://doi.org/10.3389/feart.2021.770877>.
94. Randolph Glacier Inventory Consortium. *Randolph Glacier Inventory—A Dataset of Global Glacier Outlines*; Version 7; National Snow and Ice Data Center: Boulder, CO, USA, 2023. <https://doi.org/10.5067/f6jmovy5navz>.
95. Shean, D.E.; Bhushan, S.; Montesano, P.; et al. A Systematic, Regional Assessment of High Mountain Asia Glacier Mass Balance. *Front. Earth Sci.* **2020**, *7*, 363. <https://doi.org/10.3389/feart.2019.00363>.
96. Hugonnet, R.; McNabb, R.; Berthier, E.; et al. Accelerated global glacier mass loss in the early twenty-first century. *Nature* **2021**, *592*, 726–731. <https://doi.org/10.1038/s41586-021-03436-z>.
97. Brun, F.; Berthier, E.; Wagnon, P.; et al. A spatially resolved estimate of High Mountain Asia glacier mass balances from 2000 to 2016. *Nat. Geosci.* **2017**, *10*, 668–673. <https://doi.org/10.1038/ngeo2999>; Corrected in *Nat. Geosci.* **2018**, *11*, 543.
98. Li, H.; Wang, P.; Li, Z.; et al. Historical reconstruction and future projection of glacier mass balance and their meltwater runoff in Bogda region, Eastern Tianshan Mountains. *CATENA* **2026**, *263*, 109711. <https://doi.org/10.1016/j.catena.2025.109711>.
99. Liu, X.; Li, L. Progress of research on climate change impact on water resources in Central Asia. *Prog. Geogr.* **2025**, *44*, 2008–2020. <https://doi.org/10.18306/dlkxjz.2025.10.002>.
100. Kriegel, D.; Mayer, C.; Hagg, W.; et al. Changes in glacierisation, climate and runoff in the second half of the 20th century in the Naryn basin, Central Asia. *Glob. Planet. Chang.* **2013**, *110*, 51–61. <https://doi.org/10.1016/j.gloplacha.2013.05.014>.
101. Bhattacharya, A.; Bolch, T.; Mukherjee, K.; et al. High Mountain Asian glacier response to climate revealed by multi-temporal satellite observations since the 1960s. *Nat. Commun.* **2021**, *12*, 4133. <https://doi.org/10.1038/s41467-021-24180-y>.
102. Li, Y.; Li, Y. Topographic and geometric controls on glacier changes in the central Tien Shan, China, since the Little Ice Age. *Ann. Glaciol.* **2014**, *55*, 177–186. <https://doi.org/10.3189/2014aog66a031>.
103. Fan, Y.; Ke, C.Q.; Zhou, X.; et al. Glacier mass-balance estimates over High Mountain Asia from 2000 to 2021 based on ICESat-2 and NASADEM. *J. Glaciol.* **2023**, *69*, 500–512. <https://doi.org/10.1017/jog.2022.78>.
104. Barandun, M.; Pohl, E.; Naegeli, K.; et al. Hot Spots of Glacier Mass Balance Variability in Central Asia. *Geophys. Res. Lett.* **2021**, *48*, e2020GL092084. <https://doi.org/10.1029/2020gl092084>.
105. Farinotti, D.; Immerzeel, W.W.; de Kok, R.J.; et al. Manifestations and mechanisms of the Karakoram glacier Anomaly. *Nat. Geosci.* **2020**, *13*, 8–16. <https://doi.org/10.1038/s41561-019-0513-5>.
106. Bonekamp, P.N.J.; de Kok, R.J.; Collier, E.; et al. Contrasting Meteorological Drivers of the Glacier Mass Balance Between the Karakoram and Central Himalaya. *Front. Earth Sci.* **2019**, *7*, 107. <https://doi.org/10.3389/feart.2019.00107>.
107. Lhakpa, D.; Fan, Y.; Cai, Y. Continuous Karakoram Glacier Anomaly and Its Response to Climate Change during 2000–2021. *Remote Sens.* **2022**, *14*, 6281. <https://doi.org/10.3390/rs14246281>.
108. Zhu, M.; Yao, T.; Yang, W.; et al. Possible Causes of Anomalous Glacier Mass Balance in the Western Kunlun Mountains. *J. Geophys. Res. Atmos.* **2022**, *127*, e2021JD035705. <https://doi.org/10.1029/2021jd035705>.
109. Van Tricht, L.; Kneib, M.; Huss, M.; et al. Record-breaking glacier mass loss in Central Asia in 2025. *Environ. Res. Lett.* **2026**, *21*, 104021. <https://doi.org/10.1088/1748-9326/ae6712>.
110. Safarov, M.; Li, J.; Gulayozov, M.; et al. Surge-type glacier activity in the Tajik Pamirs from 2000 to 2024. *Glob. Planet. Chang.* **2026**, *263*, 105543. <https://doi.org/10.1016/j.gloplacha.2026.105543>.

111. Bolch, T.; Shea, J.M.; Liu, S.; et al. Status and Change of the Cryosphere in the Extended Hindu Kush Himalaya Region. In *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People*; Springer International Publishing: Cham, Switzerland, 2019; pp. 209–255. https://doi.org/10.1007/978-3-319-92288-1_7.
112. Aizen, V.B.; Aizen, E.M.; Melack, J.M. Precipitation, melt and runoff in the northern Tien Shan. *J. Hydrol.* **1996**, *186*, 229–251. [https://doi.org/10.1016/s0022-1694\(96\)03022-3](https://doi.org/10.1016/s0022-1694(96)03022-3).
113. Armstrong, R.L.; Rittger, K.; Brodzik, M.J.; et al. Runoff from glacier ice and seasonal snow in High Asia: separating melt water sources in river flow. *Reg. Environ. Chang.* **2019**, *19*, 1249–1261. <https://doi.org/10.1007/s10113-018-1429-0>.
114. Pohl, B.; Kramer, A.; Hull, W.; et al. *Rethinking Water in Central Asia: The Costs of Inaction and Benefits of Water Cooperation*; Swiss Agency for Development and Cooperation: Bern/Zollikofen, Switzerland; adelphi: Berlin, Germany; CAREC: Tashkent, Uzbekistan, 2017.
115. Chen, Y.; Li, W.; Fang, G.; et al. Review article: Hydrological modeling in glacierized catchments of central Asia—Status and challenges. *Hydrol. Earth Syst. Sci.* **2017**, *21*, 669–684. <https://doi.org/10.5194/hess-21-669-2017>.
116. Wang, X.; Sun, L.; Zhang, Y.; et al. Runoff generation in the headwater of Amu Darya, Central Asia. *Prog. Geogr.* **2015**, *34*, 364–372. <https://doi.org/10.11820/dlkxjz.2015.03.011>.
117. Chen, H.; Chen, Y.; Li, W.; et al. Quantifying the contributions of snow/glacier meltwater to river runoff in the Tianshan Mountains, Central Asia. *Glob. Planet. Chang.* **2019**, *174*, 47–57. <https://doi.org/10.1016/j.gloplacha.2019.01.002>.
118. Kalashnikova, O.Y.; Usualiev, R.A.; Alamanov, S.K. Changing the Volume of Components Flow on the Naryn River for Many Years Period (1964–2017 Years). *Izvestiya VUZov Kyrgyzstana* **2020**, 8–13. <https://doi.org/10.26104/IVK.2019.45.557>.
119. Shannon, S.; Payne, A.; Freer, J.; et al. A snow and glacier hydrological model for large catchments—Case study for the Naryn River, central Asia. *Hydrol. Earth Syst. Sci.* **2023**, *27*, 453–480. <https://doi.org/10.5194/hess-27-453-2023>.
120. Van Tricht, L.; Zekollari, H.; Huss, M.; et al. Reduced Future Summer Water Availability in the Tien Shan Due to Glacier Wastage. *Water Resour. Res.* **2026**, *62*, e2025WR040877. <https://doi.org/10.1029/2025wr040877>.
121. Lyu, H.; Fang, G.; Chen, Y.; et al. Hydrological response to glacier peak water in the largest inland river basin of China. *J. Hydrol.* **2026**, *676*, 135695. <https://doi.org/10.1016/j.jhydrol.2026.135695>.
122. Huss, M.; Hock, R. Global-scale hydrological response to future glacier mass loss. *Nat. Clim. Chang.* **2018**, *8*, 135–140. <https://doi.org/10.1038/s41558-017-0049-x>.
123. Marzeion, B.; Hock, R.; Anderson, B.; et al. Partitioning the Uncertainty of Ensemble Projections of Global Glacier Mass Change. *Earth's Future* **2020**, *8*, e2019EF001470. <https://doi.org/10.1029/2019ef001470>.
124. Rounce, D.R.; Hock, R.; Maussion, F.; et al. Global glacier change in the 21st century: Every increase in temperature matters. *Science* **2023**, *379*, 78–83. <https://doi.org/10.1126/science.abo1324>.
125. Wimberly, F.; Ultee, L.; Schuster, L.; et al. Inter-model differences in 21st century glacier runoff for the world's major river basins. *Cryosphere* **2025**, *19*, 1491–1511. <https://doi.org/10.5194/tc-19-1491-2025>.
126. Liu, Y.; Fang, Y.; Margulis, S.A. Spatiotemporal distribution of seasonal snow water equivalent in High Mountain Asia from an 18-year Landsat–MODIS era snow reanalysis dataset. *Cryosphere* **2021**, *15*, 5261–5280. <https://doi.org/10.5194/tc-15-5261-2021>.
127. Meredith, M.; Sommerkorn, M. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC)*; IPCC: Geneva, Switzerland, 2019.
128. Smith, T.; Bookhagen, B. Changes in seasonal snow water equivalent distribution in High Mountain Asia (1987 to 2009). *Sci. Adv.* **2018**, *4*, e1701550. <https://doi.org/10.1126/sciadv.1701550>.
129. Tang, Z.; Wang, X.; Wang, J.; et al. Spatiotemporal Variation of Snow Cover in Tianshan Mountains, Central Asia, Based on Cloud-Free MODIS Fractional Snow Cover Product, 2001–2015. *Remote Sens.* **2017**, *9*, 1045. <https://doi.org/10.3390/rs9101045>.
130. Dietz, A.J.; Kuenzer, C.; Conrad, C. Snow-cover variability in central Asia between 2000 and 2011 derived from improved MODIS daily snow-cover products. *Int. J. Remote Sens.* **2013**, *34*, 3879–3902. <https://doi.org/10.1080/01431161.2013.767480>.
131. Dietz, A.J.; Conrad, C.; Kuenzer, C.; et al. Identifying Changing Snow Cover Characteristics in Central Asia between 1986 and 2014 from Remote Sensing Data. *Remote Sens.* **2014**, *6*, 12752–12775. <https://doi.org/10.3390/rs61212752>.
132. Savoskul, O.S.; Smakhtin, V. *Glacier Systems and Seasonal Snow Cover in Six Major Asian River Basins: Hydrological Role under Changing Climate*; International Water Management Institute (IWMI): Colombo, Sri Lanka, 2013. <https://doi.org/10.5337/2013.204>.
133. Wang, X.; Yang, T.; Xu, C.-Y.; et al. Understanding the discharge regime of a glacierized alpine catchment in the Tianshan Mountains using an improved HBV-D hydrological model. *Glob. Planet. Chang.* **2019**, *172*, 211–222. <https://doi.org/10.1016/j.gloplacha.2018.09.017>.
134. Sadyrov, S.; Isaev, E.; Tanaka, K.; et al. High-resolution assessment of climate change impacts on the surface energy and water balance in the glaciated Naryn River basin, Central Asia. *J. Environ. Manag.* **2025**, *374*, 124021. <https://doi.org/10.1016/j.jenvman.2024.124021>.

135. Barnett, T.P.; Adam, J.C.; Lettenmaier, D.P. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* **2005**, *438*, 303–309. <https://doi.org/10.1038/nature04141>.
136. Hou, M.; Cuo, L.; Murodov, A.; et al. Streamflow Composition and the Contradicting Impacts of Anthropogenic Activities and Climatic Change on Streamflow in the Amu Darya Basin, Central Asia. *J. Hydrometeorol.* **2023**, *24*, 185–201. <https://doi.org/10.1175/jhm-d-22-0040.1>.
137. Konovalov, V.G. Past and prospective changes in the state of Central Asian glaciers. *Ice Snow* **2011**, *3*, 60–68.
138. Zuo, H.; Li, B.; Wang, Y. Characteristics of Streamflow Components in the Tarim River Basin Based on Hydrogen and Oxygen Isotopes. *Acta Sci. Nat. Univ. Pekin.* **2025**, *61*, 358–368. <https://doi.org/10.13209/j.0479-8023.2024.104>.
139. Sun, C.; Chen, Y.; Li, X.; et al. Analysis on the streamflow components of the typical inland river, Northwest China. *Hydrol. Sci. J.* **2016**, *61*, 970–981. <https://doi.org/10.1080/02626667.2014.1000914>.
140. Wang, H.; Chen, Z.; Chen, Y.; et al. Identification of the Space-Time Variability of Hydrological Drought in the Arid Region of Northwestern China. *Water* **2019**, *11*, 1051. <https://doi.org/10.3390/w11051051>.
141. Wang, J.; Zhang, F.; Luo, G.; et al. Influence of natural and anthropogenic controls on runoff in the Keriya River, central Tarim Basin, China. *PLoS ONE* **2022**, *17*, e0269132. <https://doi.org/10.1371/journal.pone.0269132>.
142. Gao, X.; Ye, B.; Zhang, S.; et al. Glacier runoff variation and its influence on river runoff during 1961–2006 in the Tarim River Basin, China. *Sci. China Earth Sci.* **2010**, *53*, 880–891. <https://doi.org/10.1007/s11430-010-0073-4>.
143. Kogutenko, L.; Severskiy, I.; Shahgedanova, M.; et al. Change in the Extent of Glaciers and Glacier Runoff in the Chinese Sector of the Ile River Basin between 1962 and 2012. *Water* **2019**, *11*, 1668. <https://doi.org/10.3390/w11081668>.
144. Sadyrov, S.; Tanaka, K.; Satylkanov, R.; et al. Modelling runoff components and hydrological processes in glaciated catchments of the inner Tien-Shan, Kyrgyzstan. *Front. Earth Sci.* **2024**, *11*, 1306476. <https://doi.org/10.3389/feart.2023.1306476>.
145. Bissenbayeva, S.; Abuduwaili, J.; Saparova, A.; et al. Long-term variations in runoff of the Syr Darya River Basin under climate change and human activities. *J. Arid Land* **2021**, *13*, 56–70. <https://doi.org/10.1007/s40333-021-0050-0>.
146. Kalashnikova, O.Y.; Niyazov, J.; Nurbatsina, A.; et al. Kyrgyz transboundary rivers' runoff assessment (Syr-darya and Amu-darya river basins) in climate change scenarios. *Cent. Asian J. Water Res.* **2023**, *9*, 59–88. <https://doi.org/10.29258/cajwr/2023-r1.v9-1/59-88.eng>.
147. Siegfried, T.; Mujahid, A.U.H.; Marti, B.; et al. Unveiling the future water pulse of central asia: a comprehensive 21st century hydrological forecast from stochastic water balance modeling. *Clim. Chang.* **2024**, *177*, 141. <https://doi.org/10.1007/s10584-024-03799-y>.
148. Khanal, S.; Lutz, A.F.; Kraaijenbrink, P.D.A.; et al. Variable 21st Century Climate Change Response for Rivers in High Mountain Asia at Seasonal to Decadal Time Scales. *Water Resour. Res.* **2021**, *57*, e2020WR029266. <https://doi.org/10.1029/2020wr029266>.
149. Reyer, C.P.O.; Otto, I.M.; Adams, S.; et al. Climate change impacts in Central Asia and their implications for development. *Reg. Environ. Chang.* **2017**, *17*, 1639–1650. <https://doi.org/10.1007/s10113-015-0893-z>.
150. Su, F.; Pritchard, H.D.; Yao, T.; et al. Contrasting Fate of Western Third Pole's Water Resources under 21st Century Climate Change. *Earth's Future* **2022**, *10*, e2022EF002776. <https://doi.org/10.1029/2022ef002776>.
151. Gulakhmadov, A.; Chen, X.; Gulahmadov, N.; et al. Simulation of the Potential Impacts of Projected Climate Change on Streamflow in the Vakhsh River Basin in Central Asia under CMIP5 RCP Scenarios. *Water* **2020**, *12*, 1426. <https://doi.org/10.3390/w12051426>.
152. Xiang, Y.; Wang, Y.; Chen, Y.; et al. Impact of Climate Change on the Hydrological Regime of the Yarkant River Basin, China: An Assessment Using Three SSP Scenarios of CMIP6 GCMs. *Remote Sens.* **2022**, *14*, 115. <https://doi.org/10.3390/rs14010115>.
153. Zheng, G.; Allen, S.K.; Bao, A.; et al. Increasing risk of glacial lake outburst floods from future Third Pole deglaciation. *Nat. Clim. Chang.* **2021**, *11*, 411–417. <https://doi.org/10.1038/s41558-021-01028-3>.
154. Wu, J.S.; Li, Y.P.; Sun, J.; et al. Identifying the runoff variation in the Naryn River Basin under multiple climate and land-use change scenarios. *J. Water Clim. Chang.* **2022**, *13*, 574–592. <https://doi.org/10.2166/wcc.2021.422>.
155. Yu, X.; Zeng, X.; Gui, D.; et al. Projection of Flash Droughts in the Headstream Area of Tarim River Basin Under Climate Change Through Bayesian Uncertainty Analysis. *J. Geophys. Res. Atmos.* **2023**, *128*, e2022JD037634. <https://doi.org/10.1029/2022jd037634>.
156. de Boer, T.; Paltan, H.; Sternberg, T.; et al. Evaluating Vulnerability of Central Asian Water Resources under Uncertain Climate and Development Conditions: The Case of the Ili-Balkhash Basin. *Water* **2021**, *13*, 615. <https://doi.org/10.3390/w13050615>.
157. Shahgedanova, M.; Saidaliyeva, Z.; Mussina, A.; et al. Debris flows in the northern Tien Shan, Central Asia: regional database, meteorological triggers, and trends. *npj Nat. Hazards* **2024**, *1*, 49. <https://doi.org/10.1038/s44304-024-00050-7>.
158. Stoffel, M.; Huggel, C. Effects of climate change on mass movements in mountain environments. *Prog. Phys. Geogr. Earth Environ.* **2012**, *36*, 421–439. <https://doi.org/10.1177/0309133312441010>.
159. Huggel, C.; Clague, J.J.; Korup, O. Is climate change responsible for changing landslide activity in high mountains? *Earth Surf. Process. Landf.* **2012**, *37*, 77–91. <https://doi.org/10.1002/esp.2223>.

160. Haeberli, W.; Schaub, Y.; Huggel, C. Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges. *Geomorphology* **2017**, *293*, 405–417. <https://doi.org/10.1016/j.geomorph.2016.02.009>.
161. World Bank. *Turn Down the Heat: Confronting the New Climate Normal*; World Bank: Washington, DC, USA, 2014. <https://doi.org/10.1596/978-1-4648-0437-3>.
162. Ahunbaev, A.; Chuyev, S.; Adakhayev, A.; et al. *Efficient Irrigation and Water Conservation in Central Asia*; Eurasian Development Bank: Almaty, Kazakhstan, 2023.
163. Siegfried, T.; Bernauer, T.; Guennet, R.; et al. Will climate change exacerbate water stress in Central Asia? *Clim. Chang.* **2012**, *112*, 881–899. <https://doi.org/10.1007/s10584-011-0253-z>.
164. Su, J.; Miao, C.; Zwiers, F.; et al. Precipitation observing network gaps limit climate change impact assessment. *Nature* **2026**, *652*, 119–125. <https://doi.org/10.1038/s41586-026-10300-5>.
165. Sun, Q.; Miao, C.; Duan, Q.; et al. A Review of Global Precipitation Data Sets: Data Sources, Estimation, and Intercomparisons. *Rev. Geophys.* **2018**, *56*, 79–107. <https://doi.org/10.1002/2017rg000574>.
166. Wortmann, M.; Duethmann, D.; Menz, C.; et al. Projected climate change and its impacts on glaciers and water resources in the headwaters of the Tarim River, NW China/Kyrgyzstan. *Clim. Chang.* **2022**, *171*, 30. <https://doi.org/10.1007/s10584-022-03343-w>.
167. Emmer, A.; Allen, S.K.; Carey, M.; et al. Progress and challenges in glacial lake outburst flood research (2017–2021): A research community perspective. *Nat. Hazards Earth Syst. Sci.* **2022**, *22*, 3041–3061. <https://doi.org/10.5194/nhess-22-3041-2022>.
168. Prniyazova, A.; Turaeva, S.; Turgunov, D.; et al. Sustainable Transboundary Water Governance in Central Asia: Challenges, Conflicts, and Regional Cooperation. *Sustainability* **2025**, *17*, 4968. <https://doi.org/10.3390/su17114968>.
169. Kato, T. Strengthening the water-energy nexus for a climate resilient Central Asia. *OECD Green Growth Pap.* **2025**. <https://doi.org/10.1787/632162c2-en>.
170. Ziganshina, D. Water infrastructure in Central Asia: Legal and institutional frameworks. *Front. Clim.* **2023**, *5*, 1284400. <https://doi.org/10.3389/fclim.2023.1284400>.
171. Chen, Y.; Chen, Y.; Zhu, C.; et al. Ecohydrological effects of water conveyance in a disconnected river in an arid inland river basin. *Sci. Rep.* **2022**, *12*, 9982. <https://doi.org/10.1038/s41598-022-14524-z>.
172. Jiao, A.; Wang, W.; Ling, H.; et al. Effect evaluation of ecological water conveyance in Tarim River Basin, China. *Front. Environ. Sci.* **2022**, *10*, 1019695. <https://doi.org/10.3389/fenvs.2022.1019695>.
173. Fu, A.; Li, W.; Chen, Y.; et al. The effects of ecological rehabilitation projects on the resilience of an extremely drought-prone desert riparian forest ecosystem in the Tarim River Basin, Xinjiang, China. *Sci. Rep.* **2021**, *11*, 18485. <https://doi.org/10.1038/s41598-021-96742-5>.
174. UNECE. *Reconciling Resource Uses in Transboundary Basins: Assessment of the Water-Food-Energy-Ecosystems Nexus in the Syr Darya River Basin*; United Nations Economic Commission for Europe: Geneva, Switzerland, 2017.
175. Hu, Y.; Duan, W.; Zou, S.; et al. Coupling coordination analysis of the water-food-energy-carbon nexus for crop production in Central Asia. *Appl. Energy* **2024**, *369*, 123584. <https://doi.org/10.1016/j.apenergy.2024.123584>.
176. Chen, Y.; Fang, G.; Hao, H.; et al. Water use efficiency data from 2000 to 2019 in measuring progress towards SDGs in Central Asia. *Big Earth Data* **2022**, *6*, 90–102. <https://doi.org/10.1080/20964471.2020.1851891>.
177. Kapitsa, V.; Shahgedanova, M.; Severskiy, I.; et al. Assessment of Changes in Mass Balance of the Tuyuksu Group of Glaciers, Northern Tien Shan, Between 1958 and 2016 Using Ground-Based Observations and Pléiades Satellite Imagery. *Front. Earth Sci.* **2020**, *8*, 259. <https://doi.org/10.3389/feart.2020.00259>.
178. Zhao, G.; Zhang, Z.; Liu, L.; et al. Changes of glacier mass balance in Manas river basin based on multi-source remote sensing data. *Acta Geogr. Sin.* **2020**, *75*, 98–112. <https://doi.org/10.11821/dlxb202001008>.
179. Che, Y.; Zhang, M.; Li, Z.; et al. Understanding the Mass Balance Characteristics of Qingbingtan Glacier No. 72 during the Period of 2008–2014. *J. Glaciol. Geocryol.* **2020**, *42*, 318–331. <https://doi.org/10.7522/j.issn.1000-0240.2019.0035>.
180. Azisov, E.; Hoelzle, M.; Vorogushyn, S.; et al. Reconstructed Centennial Mass Balance Change for Golubin Glacier, Northern Tien Shan. *Atmosphere* **2022**, *13*, 954. <https://doi.org/10.3390/atmos13060954>.
181. Pieczonka, T.; Bolch, T. Region-wide glacier mass budgets and area changes for the Central Tien Shan between ~1975 and 1999 using Hexagon KH-9 imagery. *Glob. Planet. Chang.* **2015**, *128*, 1–13. <https://doi.org/10.1016/j.gloplacha.2014.11.014>.
182. Van Tricht, L.; Paice, C.M.; Rybak, O.; et al. Reconstruction of the Historical (1750–2020) Mass Balance of Bordu, Karabatkak and Sary-Tor Glaciers in the Inner Tien Shan, Kyrgyzstan. *Front. Earth Sci.* **2021**, *9*, 734802. <https://doi.org/10.3389/feart.2021.734802>.
183. Wang, P.; Xu, M.; Han, H.; et al. Response of glacier mass balance and meltwater runoff to climate change in the Akesu River Basin, southern Tianshan. *Earth Sci. Front.* **2024**, *31*, 435–446. <https://doi.org/10.13745/j.esf.sf.2023.2.50>.
184. Shangguan, D.H.; Bolch, T.; Ding, Y.J.; et al. Mass changes of Southern and Northern Inylchek Glacier, Central Tian Shan, Kyrgyzstan, during ~1975 and 2007 derived from remote sensing data. *Cryosphere* **2015**, *9*, 703–717. <https://doi.org/10.5194/tc-9-703-2015>.

185. Zhang, Y.; Liu, S.Y.; Ding, Y.J.; et al. Preliminary Study of Mass Balance on the Keqicar Baxi Glacier on the South Slopes of Tianshan Mountains. *J. Glaciol. Geocryol.* **2006**, *28*, 477–484. <https://doi.org/10.7522/j.issn.1000-0240.2006.0069>.
186. Kenzhebaev, R.; Barandun, M.; Kronenberg, M.; et al. Mass balance observations and reconstruction for Batysh Sook Glacier, Tien Shan, from 2004 to 2016. *Cold Reg. Sci. Technol.* **2017**, *135*, 76–89. <https://doi.org/10.1016/j.coldregions.2016.12.007>.
187. Fujita, K.; Takeuchi, N.; Nikitin, S.A.; et al. Favorable climatic regime for maintaining the present-day geometry of the Gregoriev Glacier, Inner Tien Shan. *Cryosphere* **2011**, *5*, 539–549. <https://doi.org/10.5194/tc-5-539-2011>.
188. Kronenberg, M.; Barandun, M.; Hoelzle, M.; et al. Mass-balance reconstruction for Glacier No. 354, Tien Shan, from 2003 to 2014. *Ann. Glaciol.* **2016**, *57*, 92–102. <https://doi.org/10.3189/2016aog71a032>.
189. Hoelzle, M.; Azisov, E.; Barandun, M.; et al. Re-establishing glacier monitoring in Kyrgyzstan and Uzbekistan, Central Asia. *Geosci. Instrum. Methods Data Syst.* **2017**, *6*, 397–418. <https://doi.org/10.5194/gi-6-397-2017>.
190. Yang, X.; Zhao, J.; Han, H. Study on glacier mass balance in the Karlik Range, East Tianshan Mountains during 1972–2016. *J. Glaciol. Geocryol.* **2019**, *41*, 1–11. <https://doi.org/10.7522/j.issn.1000-0240.2019.0004>.
191. Xu, C.; Li, Z.; Wang, F.; et al. Geodetic Mass Balance of Haxilegen Glacier No. 51, Eastern Tien Shan, from 1964 to 2018. *Remote Sens.* **2022**, *14*, 272. <https://doi.org/10.3390/rs14020272>.
192. Fan, R.; Sun, M.; Wang, R.; et al. Modeling on glacier mass balance and glacier runoff in the Tianshan region of China from 1961 to 2020. *J. Glaciol. Geocryol.* **2025**, *47*, 239–254. <https://doi.org/10.7522/j.issn.1000-0240.2025.0019>.
193. Zhou, Y.; Li, Z.; Li, J.; et al. Geodetic glacier mass balance (1975–1999) in the central Pamir using the SRTM DEM and KH-9 imagery. *J. Glaciol.* **2019**, *65*, 309–320. <https://doi.org/10.1017/jog.2019.8>.
194. Lambrecht, A.; Mayer, C.; Wendt, A.; et al. Elevation change of Fedchenko Glacier, Pamir Mountains, from GNSS field measurements and TanDEM-X elevation models, with a focus on the upper glacier. *J. Glaciol.* **2018**, *64*, 637–648. <https://doi.org/10.1017/jog.2018.52>.
195. Zhu, M.; Yao, T.; Yang, W.; et al. Reconstruction of the mass balance of Muztag Ata No. 15 glacier, eastern Pamir, and its climatic drivers. *J. Glaciol.* **2018**, *64*, 259–274. <https://doi.org/10.1017/jog.2018.16>.
196. Lv, M.; Quincey, D.J.; Guo, H.; et al. Examining geodetic glacier mass balance in the eastern Pamir transition zone. *J. Glaciol.* **2020**, *66*, 927–937. <https://doi.org/10.1017/jog.2020.54>.
197. Barandun, M.; Huss, M.; Sold, L.; et al. Re-analysis of seasonal mass balance at Abramov glacier 1968–2014. *J. Glaciol.* **2015**, *61*, 1103–1117. <https://doi.org/10.3189/2015jog14j239>.
198. Zhou, Y.; Li, Z.; Li, J. Slight glacier mass loss in the Karakoram region during the 1970s to 2000 revealed by KH-9 images and SRTM DEM. *J. Glaciol.* **2017**, *63*, 331–342. <https://doi.org/10.1017/jog.2016.142>.
199. Bhattacharjee, S.; Pandey, A.C.; Garg, R.D. Mapping spatial patterns of glacier elevation changes and mass balance between 2000–2023 across the Karakoram-Himalayan Range. *Environ. Earth Sci.* **2025**, *84*, 309. <https://doi.org/10.1007/s12665-025-12307-z>.
200. Bhattacharjee, S.; Chandra Pandey, A. Contrasting behaviour of temporal glacier changes and long term estimation of glacier mass balance across Himalayan–Karakoram range. *Geocarto Int.* **2022**, *37*, 5807–5831. <https://doi.org/10.1080/10106049.2021.1923832>.
201. Agarwal, V.; Bolch, T.; Syed, T.H.; et al. Area and mass changes of Siachen Glacier (East Karakoram). *J. Glaciol.* **2017**, *63*, 148–163. <https://doi.org/10.1017/jog.2016.127>.
202. Wei, J.F.; Liu, S.Y.; Xu, J.L.; et al. Mass loss from glaciers in the Chinese Altai Mountains between 1959 and 2008 revealed based on historical maps, SRTM, and ASTER images. *J. Mt. Sci.* **2015**, *12*, 330–343. <https://doi.org/10.1007/s11629-014-3175-1>.
203. Bai, C.; Wang, F.; Bi, Y.; et al. Increased Mass Loss of Glaciers in the Sawir Mountains of Central Asia between 1959 and 2021. *Remote Sens.* **2022**, *14*, 5406. <https://doi.org/10.3390/rs14215406>.
204. World Meteorological Organization. *State of the Climate in Asia 2024*; 978-92-63-11374-0; World Meteorological Organization: Geneva, Switzerland, 2025.
205. Zhao, X.E.; Li, L.; Zhang, H.; et al. Response of the Ishim River Streamflow in Northern Kazakhstan to Climate Change and Human Activities. *Desert Oasis Meteorol.* **2022**, *16*, 102–109.
206. Didovets, I.; Krysanova, V.; Nurbatsina, A.; et al. Attribution of current trends in streamflow to climate change for 12 Central Asian catchments. *Clim. Chang.* **2024**, *177*, 16. <https://doi.org/10.1007/s10584-023-03673-3>.
207. Kozykeyeva, A.; Mustafayev, Z.; Tastemirova, B. ВЛИЯНИЕ КЛИМАТИЧЕСКИХ ФАКТОРОВ НА ГИДРОЛОГИЧЕСКИЙ РЕЖИМ ВОДОСБОРА БАССЕЙНА РЕКИ ТОБОЛ. *REPORTS* **2021**, 32–38. <https://doi.org/10.32014/2021.2518-1483.45>.
208. Bai, X.; Zhao, W. Impacts of climate change and anthropogenic stressors on runoff variations in major river basins in China since 1950. *Sci. Total Environ.* **2023**, *898*, 165349. <https://doi.org/10.1016/j.scitotenv.2023.165349>.
209. Qin, J.; Liu, Y.; Chang, Y.; et al. Regional runoff variation and its response to climate change and human activities in Northwest China. *Environ. Earth Sci.* **2016**, *75*, 1366. <https://doi.org/10.1007/s12665-016-6187-z>.

210. Pu, Z.C.; Zhang, S.Q.; Li, J.L.; et al. Effect of Climate Change to Annual Runoff in Hutubi River Basin. *Desert Oasis Meteorol.* **2007**, *1*, 44–47.
211. Ran, L.; Zhu, H.J.; Ziyabieke, A. Impact of Climate Change on Hydrological Regime in the Baiyanghe River Basin in Tacheng, Xinjiang during 1962–2007. *J. Glaciol. Geocryol.* **2010**, *32*, 921–926.
212. Jiang, L. Analysis on the Trend of Climate and Runoff Changes of Manas River Basin Upstream. *Environ. Prot. Xinjiang* **2016**, *38*, 44–48.
213. Tang, X.L.; Li, J.F.; Lv, X.; et al. Analysis of the Characteristics of Runoff in Manasi River Basin in the Past 50 Years. *Procedia Environ. Sci.* **2012**, *13*, 1354–1362. <https://doi.org/10.1016/j.proenv.2012.01.128>.
214. Zhang, H.; Li, Z.; Mu, J.; et al. Impact of the Glacier Change on Water Resources in the Kuytun River Basin, Tianshan Mountains During Recent 50 Years. *Sci. Geogr. Sin.* **2017**, *37*, 1771–1777. <https://doi.org/10.13249/j.cnki.sgs.2017.11.020>.
215. Li, Y.; Han, T.; Shen, Y.; et al. Characteristics of runoff variation and its response to climate change of Qingshuihe River and Alagou River watersheds in southern slopes of the Tianshan Mountains. *J. Glaciol. Geocryol.* **2018**, *40*, 127–135. <https://doi.org/10.7522/j.issn.1000-0240.2017.0317>.
216. Bai, L. Climate Change and its Impacts on Runoff Process for Typical River Basin in the Southern Slopes of Tianshan Mountains—Cases in the Kaidu River and Aksu River Basins. Ph.D. Thesis, East China Normal University, Shanghai, China, 2016.
217. Zhang, Q.; Chen, Y.; Li, Z.; et al. Recent Changes in Water Discharge in Snow and Glacier Melt-Dominated Rivers in the Tianshan Mountains, Central Asia. *Remote Sens.* **2020**, *12*, 2704. <https://doi.org/10.3390/rs12172704>.
218. Mtalip, T.; Xu, H.L.; Liu, X.H. Trend analysis and forecast of the runoff change in Tarim River basin. *J. Water Resour. Water Eng.* **2012**, *23*, 77–82.
219. Liu, J. Analysis on the evolution principle and trend of runoff in Kushan River Basin under the influence of climate for many years. *Environ. Sustain. Dev.* **2021**, *46*, 81–88. <https://doi.org/10.19758/j.cnki.issn1673-288x.202105081>.
220. Aini, G. The Study of Climate Change in the Tiznap River Basin, Xinjiang, and Its Effects on Runoff. Master's Thesis, Xinjiang Normal University, Urumqi, China, 2014.
221. Hong, L.; Wang, L.; Sun, J.; et al. Analysis of Runoff Time Series Characteristics of the Qarqan River in Xinjiang from 1957 to 2021. *Water Resour. Plan. Des.* **2025**, 62–66. <https://doi.org/10.3969/j.issn.1672-2469.2025.05.011>.
222. Duan, J.J.; Wang, Y.G.; Wang, X.F.; et al. Impact of Climate Change and Human Activities on the Water Resources and Ecological Environments in the Tarim River Basin in 1957–2006. *J. Glaciol. Geocryol.* **2009**, *31*, 781–791. <https://doi.org/10.7522/j.issn.1000-0240.2009.0108>.
223. Gan, G.; Wu, J.; Yang, R.; et al. Modeling Decadal Snow/Ice Dynamics and Their Hydrological Impacts with Remote Sensing Data Constraints in the Balkhash Lake Basin, Central Asia. *SSRN* **2025**, 5238759. <https://doi.org/10.2139/ssrn.5238759>.
224. Wang, X.; Luo, Y.; Sun, L.; et al. Attribution of Runoff Decline in the Amu Darya River in Central Asia during 1951–2007. *J. Hydrometeorol.* **2016**, *17*, 1543–1560. <https://doi.org/10.1175/jhm-d-15-0114.1>.
225. Reyisha, J. Study on the Impacts of Climate Change and Human Activities on Runoff in the Amu Darya River, Central Asia. Ph.D. Thesis, Xinjiang Normal University, Urumqi, China, 2019.
226. Normatov, I.; Normatov, P. Monitoring of Meteorological, Hydrological Conditions and Water Quality of the Main Tributaries of the Transboundary Amu Darya River. In *Achievements and Challenges of Integrated River Basin Management*; Komatina, D., Ed.; IntechOpen: London, UK, 2018.
227. Wang, X.; Cui, B.; Chen, Y.; et al. Dynamic changes in water resources and comprehensive assessment of water resource utilization efficiency in the Aral Sea basin, Central Asia. *J. Environ. Manag.* **2024**, *353*, 120198. <https://doi.org/10.1016/j.jenvman.2024.120198>.
228. Myktybekovna, S.N.; Chen, Y.N.; Salamat, A. Climate change and its impact on the hydrological processes of the Talas river in central Asia. *Fresenius Environ. Bull.* **2014**, *23*, 1423–1432.
229. Liu, S.; Long, A.; Yan, D.; et al. Predicting Ili River streamflow change and identifying the major drivers with a novel hybrid model. *J. Hydrol. Reg. Stud.* **2024**, *53*, 101807. <https://doi.org/10.1016/j.ejrh.2024.101807>.
230. Gan, R.; Luo, Y.; Zuo, Q.; et al. Effects of projected climate change on the glacier and runoff generation in the Naryn River Basin, Central Asia. *J. Hydrol.* **2015**, *523*, 240–251. <https://doi.org/10.1016/j.jhydrol.2015.01.057>.
231. Hou, M.; Cuo, L.; Xu, H. Hydrological response to twenty-first century climate change in the Amu Darya Basin, Central Asia. *J. Hydrol. Reg. Stud.* **2025**, *61*, 102606. <https://doi.org/10.1016/j.ejrh.2025.102606>.
232. Murodov, M.; Li, L.; Weili, D.; et al. Impacts of future climate change on runoff and its components for the Vanj river basin in the western Pamir. *J. Hydrol. Reg. Stud.* **2025**, *62*, 102916. <https://doi.org/10.1016/j.ejrh.2025.102916>.
233. Didovets, I.; Lobanova, A.; Krysanova, V.; et al. Central Asian rivers under climate change: Impacts assessment in eight representative catchments. *J. Hydrol. Reg. Stud.* **2021**, *34*, 100779. <https://doi.org/10.1016/j.ejrh.2021.100779>.
234. Fang, G.; Li, Z.; Chen, Y.; et al. Projecting the Impact of Climate Change on Runoff in the Tarim River Simulated by the Soil and Water Assessment Tool Glacier Model. *Remote Sens.* **2023**, *15*, 3922. <https://doi.org/10.3390/rs15163922>.

235. Gao, X.; Fang, G.; Chen, Y.; et al. Analysis of runoff variations in an arid catchment based on multi-model ensemble- a case study in the Tarim River Basin in Central Asia. *Front. Earth Sci.* **2023**, *11*, 1249107. <https://doi.org/10.3389/feart.2023.1249107>.
236. Liu, L.; Zhang, L.; Zhang, Q.; et al. A warming-induced glacier reduction causes lower streamflow in the upper Tarim River Basin. *J. Hydrol. Reg. Stud.* **2024**, *53*, 101802. <https://doi.org/10.1016/j.ejrh.2024.101802>.
237. Cheng, Y.; Fang, G.; Zhou, H. Characteristics of Runoff in Huangshuigou River Basin and Its Future Change Trend. *J. Water Resour. Res.* **2022**, *11*, 42–49. <https://doi.org/10.12677/jwrr.2022.111004>.
238. Semakova, E.; Floricioiu, D.; Bühler, Y.; et al. Satellite data synergy for analysis of the glacier daily lowering rate in the Pskem River basin, Uzbekistan. In Proceedings of the International Mountain Conference, Innsbruck, Austria, 14–18 September 2025.