Review

Sustainable Irrigation in Central Asia: A Review of Historical Development, Water Governance, Climate Change, and Digital Transformation

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ABSTRACT

Irrigated agriculture dominates water use in Central Asia, underpinning regional food security but facing challenges from ageing Soviet-era infrastructure, environmental degradation, and complex transboundary governance. Here we review historical irrigation development, water governance reforms, climate change impacts, and digital transformation by integrating policy analysis with Earth Observation datasets assessing vegetation dynamics, evapotranspiration, and water availability. Our findings reveal sustained high irrigation demand and intensified consumptive water use despite modernization efforts, compounded by climate-driven reductions in snow and glacier-derived water resources. Emerging technologies such as remote sensing and digital water management offer opportunities to improve irrigation efficiency and transparency. However, sustainable irrigation in Central Asia will require coupling technological innovation with stronger institutional reforms, basin-scale water accounting, and enhanced regional cooperation to address increasing water scarcity and climate variability. This integrated approach provides a pathway to support adaptive, evidence-based irrigation management and long-term water security in the region.

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INTRODUCTION

Central Asia is one of the most irrigation-dependent regions in the world, where agricultural production relies heavily on large-scale irrigation systems supplied primarily by two major river systems, the Amu Darya and Syr Darya rivers [1]. Irrigated agriculture plays a central role in regional food security, rural livelihoods, and national economies, accounting for the majority of water withdrawals across the region [2,3]—also see Table 1. Much of the current irrigation infrastructure and agricultural production systems were developed during the Soviet period, when extensive canal networks, reservoirs, and pumping systems were constructed to expand irrigated cotton production across arid and semi-arid landscapes. These large hydraulic developments enabled rapid agricultural expansion but also produced significant environmental consequences, most notably the dramatic desiccation of the Aral Sea and widespread soil salinisation and land degradation across irrigated areas [4–6].

Following the dissolution of the Soviet Union in 1991, the newly independent Central Asian states inherited extensive irrigation infrastructure and highly interconnected transboundary water systems. However, they lacked the centralized political framework that had previously coordinated water allocation across the region. At the regional level, efforts to maintain cooperation were supported through the Almaty Agreement in 1992, which preserved many of the existing water-sharing arrangements, and later through agreements such as the Syr Darya Framework Agreement in 1998. Some basin-scale management institutions established during the Soviet era, including the Basin Water Organizations (BWOs) of the Amu Darya and Syr Darya, continued to operate and provided an institutional foundation for post-Soviet transboundary water management. Subsequently, new regional organizations, including the Interstate Commission for Water Coordination (ICWC) and the International Fund for Saving the Aral Sea (IFAS), were established to facilitate cooperation and coordination among the riparian states.

Following the dissolution of the Soviet Union in 1991, the newly independent Central Asian states inherited extensive irrigation infrastructure and highly interconnected transboundary water systems, but without the centralized political framework that had previously coordinated water allocation across the region [7]. At the regional level, efforts to maintain cooperation were supported through the Almaty Agreement in 1992, which preserved many of the existing water-sharing arrangements, and later through agreements such as the Syr Darya Framework Agreement in 1998. Importantly, some basin-scale management institutions established during the Soviet era, including the Basin Water Organizations (BWOs) of the Amu Darya and Syr Darya, continued to operate and provided an institutional foundation for post-Soviet transboundary water management. New regional organizations, including the Interstate Commission for Water Coordination (ICWC) and the International Fund for Saving the Aral Sea (IFAS), were subsequently established to facilitate cooperation and coordination among the riparian states.

At the national and local levels, countries implemented a range of institutional and policy reforms to improve irrigation governance, strengthen water management institutions, and modernize agricultural production systems [8–10]. These reforms included updating national water legislation, adopting Integrated Water Resources Management (IWRM) principles—which promote coordinated development and management of water, land, and related resources—and establishing Water User Associations (WUAs) to enhance local participation in irrigation management. However, despite these efforts, irrigation systems across the region still face challenges such as ageing infrastructure, inefficient water distribution networks, and limited adoption of modern technologies like drip and sprinkler irrigation [10–12]. Furthermore, limited institutional capacity, financial constraints, and uneven implementation of reforms continue to hinder progress toward more sustainable and efficient irrigation management.

At the same time, the hydroclimatic conditions supporting irrigated agriculture in Central Asia are undergoing significant change. The region is highly vulnerable to climate change due to its predominantly arid and semi-arid climate, uneven distribution of water resources, and strong dependence on meltwater from mountain snowpacks and glaciers [13,14]. Observed and projected warming trends across Central Asia exceed the global average, with temperature increases of approximately 2–6 °C projected by the end of the twenty-first century [15,16]. Climate change is already altering regional hydrology through earlier snowmelt, glacier retreat, and increasing variability in precipitation patterns, which together influence the timing and reliability of water supply for irrigation [17,18]. These changes are expected to increase irrigation water demand while simultaneously reducing the stability of river flows that sustain agricultural production in downstream areas [19,20].

While numerous studies have examined individual aspects of irrigated agriculture in Central Asia—including water governance, climate change, irrigation modernization, and transboundary water management—few have integrated these themes within a single framework. In addition, recent advances in Earth Observation (EO), GIS, Artificial Intelligence (AI), and digital irrigation technologies have created new opportunities to monitor basin-scale water balance, land use, evapotranspiration, and agricultural water use [21], yet their role in supporting sustainable irrigation and water governance has not been comprehensively reviewed.

This review brings together historical irrigation development, climate change impacts, basin-scale water balance, land-use dynamics, Earth Observation (EO), digital technologies, and transboundary water governance to provide an integrated perspective on irrigation sustainability in Central Asia. By combining evidence from scientific literature and satellite observations, the review illustrates how EO, basin-scale water accounting, and digital technologies can support more adaptive, transparent, and evidence-based irrigation management in the face of increasing climate variability and water scarcity.

Table 1. Key Indicators of Irrigation, Water Use, and Food Security in Central Asia.

Aspect	Data/Observation	Source(s)
Irrigated area (2008)	10.5 million ha	[3,4]
Water withdrawal for irrigation	75.6% (Kazakhstan), >90% (other countries)	[2,3]
Main crops	Wheat (61%), Barley (12%), Cotton (10%), Rice, Maize	[2]
Irrigation efficiency	<40% utilisation; 46% of water used at field level	[22,23]
Aral Sea shrinkage	74% area, 90% volume lost since 1960	[4,5]
Water productivity (wheat)	0.881 kg/m^3	[24]
Food insecurity	Nearly 1 million people severely food insecure	[22]
Water use in GDP	>15% (except Kazakhstan: 9.9%)	[25]

HISTORICAL EVOLUTION OF IRRIGATION IN CENTRAL ASIA

Pre-Soviet and Early Irrigation Systems

Irrigation has played a central role in agricultural production across Central Asia for millennia, enabling cultivation in the region's predominantly arid and semi-arid environments. Early irrigation systems developed along major river valleys and oasis settlements where communities relied on seasonal river flows and groundwater sources to sustain crop production. These systems supported oasis agriculture across river deltas and alluvial plains, where crops such as wheat, fruits, and vegetables were cultivated using gravity-fed canals and small diversion structures. Traditional irrigation management was typically organised at local community levels, where water allocation and canal maintenance were coordinated through customary governance arrangements and collective labour. These early irrigation systems were generally adapted to local hydrological conditions and relied on relatively small-scale water diversions compared with modern irrigation schemes. Agricultural production was closely linked to seasonal water availability, and irrigation networks were limited in spatial extent due to technological constraints and the need to maintain ecological balance within riverine environments. Although historical irrigation supported regional trade and settlement development, the scale of irrigated agriculture remained modest compared with the extensive irrigation expansion that occurred during the twentieth century. As a result, natural river flows continued to sustain downstream ecosystems, including the Aral Sea basin, which historically received substantial inflows from the Amu Darya and Syr Darya rivers.

Soviet Irrigation Expansion (1960–1991)

Large-scale irrigation development in Central Asia accelerated during the Soviet period, when agricultural policies prioritised expanding irrigated land to increase production of strategic crops, particularly cotton and wheat. From the 1960s onwards, extensive canal networks, reservoirs, and pumping systems diverted water from the Amu Darya and Syr Darya rivers, enabling irrigation across vast desert and steppe landscapes in Uzbekistan, Turkmenistan, and southern Kazakhstan. As a result, irrigated arable land increased by approximately 60% between 1962 and 2002, reflecting a strong emphasis on agricultural expansion rather than water-use efficiency [13,26]. Large state farms, centralised water management, and extensive infrastructure such as the Karakum Canal and irrigation networks in the Fergana Valley transformed agricultural production but substantially altered the natural hydrology of the region.

These developments also generated significant environmental impacts. Diversion of river flows for irrigation contributed to the rapid shrinkage of the Aral Sea, which has lost approximately 74% of its surface area and around 90% of its volume since 1960 [4,5]. Intensive irrigation further accelerated soil salinisation, waterlogging, and land degradation, particularly in downstream areas with inefficient irrigation and drainage systems [6,27]. Although the Soviet-era infrastructure remains the backbone of agricultural production today, it faces growing challenges associated with ageing infrastructure, fragmented post-Soviet water governance, and increasing hydroclimatic variability.

POST-SOVIET INSTITUTIONAL AND POLICY TRANSFORMATION

Irrigation Governance after Independence

The dissolution of the Soviet Union in 1991 marked a major transition in irrigation governance across Central Asia. Under the Soviet system, water allocation, energy production, and agricultural planning were managed through a highly centralized framework (Table 2). Following independence, the newly established states inherited extensive irrigation infrastructure but lacked the unified institutions responsible for coordinating water allocation and maintaining irrigation networks. Although Basin Water Organizations (BWOs) for the Amu Darya and Syr Darya continued to operate and Soviet-era allocation arrangements remained influential, regional water management evolved from internal administrative coordination to complex transboundary governance among independent nations.

In response, countries established national water management institutions and introduced reforms to decentralize irrigation management through Water User Associations (WUAs). These organisations were intended to improve irrigation efficiency, strengthen farmer participation, and assume responsibility for tertiary and on-farm irrigation systems. However, their effectiveness has been constrained by limited financial resources, weak institutional capacity, ageing infrastructure, and insufficient technical support [28,29]. Despite these reforms, irrigation governance remains fragmented. Ageing Soviet-era infrastructure, overlapping institutional responsibilities, limited investment, and declining technical capacity continue to reduce irrigation efficiency and hinder modernization efforts. These challenges have constrained the region's ability to adapt irrigation management to increasing climatic variability and growing water demand [2,30].

Table 2. Key Characteristics of Post-Soviet Irrigation Governance and Water Management in Central Asia.

Aspect	Key Characteristics After Independence	Sources
Regional Water Governance	Establishment of ICWC and IFAS; continuation of transboundary cooperation mechanisms and Soviet-era Basin Water Organizations (BWOs)	[8,10]
Legal and Policy Reforms	Adoption of national water codes, IWRM principles, and sector reforms aimed at decentralization and improved water management	[8,9]
Water User Associations (WUAs)	Introduction of WUAs to promote participatory irrigation management and strengthen local-level governance	[8,31]
Institutional Challenges	Limited financial resources, ageing infrastructure, weak institutional capacity, and uneven implementation of reforms	[2,10]
Irrigation System Legacy	Continued reliance on Soviet-era canals, reservoirs, and water allocation practices	[2,30]
Transboundary Water Management	Ongoing challenges in balancing upstream hydropower production and downstream irrigation demands	[8,32]
Modernization Priorities	Irrigation efficiency improvements, infrastructure rehabilitation, digital water management, and climate adaptation	[11,12,33]
Emerging Challenges	Climate change, population growth, increasing water demand, and evolving regional water-sharing arrangements	[27,34]

Regional Water Governance and Transboundary Agreements

The transboundary nature of the Amu Darya and Syr Darya rivers adds significant complexity to irrigation governance in Central Asia, making regional cooperation essential for sustainable water management. Following independence, the five Central Asian republics established several regional institutions to coordinate shared water resources. The Interstate Commission for Water Coordination (ICWC), established in 1992, oversees water allocation through the Basin Water Organizations (BWOs) of the Amu Darya and Syr Darya and plays a key role in coordinating seasonal water releases and irrigation allocations across the region [7]. To address the environmental degradation associated with intensive irrigation and the shrinking Aral Sea, the International Fund for Saving the Aral Sea (IFAS) was created to coordinate regional restoration efforts, water management initiatives, and international cooperation. In addition, the 1998 Syr Darya Agreement sought to balance upstream hydropower generation in Kyrgyzstan and Tajikistan with downstream irrigation demands in Kazakhstan, Uzbekistan, and Turkmenistan, highlighting the close interdependence between water and energy systems [9,10]. Although these institutions and agreements have strengthened regional cooperation and helped reduce major conflicts, their effectiveness continues to be constrained by competing national priorities, limited enforcement mechanisms, insufficient data sharing, and increasing pressures from water scarcity and climate variability.

National Irrigation Reforms

Since independence, Central Asian countries have introduced reforms to modernize irrigation infrastructure, improve water-use efficiency, and strengthen water governance, although progress has varied according to institutional capacity, economic conditions, and water availability. Uzbekistan, home to the region's largest irrigated areas, has promoted water-saving technologies, infrastructure modernization, and crop diversification beyond cotton. Nevertheless, irrigation remains dominated by surface systems and extensive canal networks, with substantial water losses due to ageing infrastructure and inefficient distribution [13,33]. Kazakhstan has incorporated Integrated Water Resources Management (IWRM) principles into national water policy to improve water accounting, basin planning, and stakeholder participation, but its downstream location leaves the country vulnerable to upstream water management and climate variability [10]. In Kyrgyzstan and Tajikistan, irrigation governance is closely linked to hydropower reservoir operations. Winter water releases for electricity generation often conflict with downstream irrigation demands during the summer growing season, creating persistent water–energy trade-offs within the Amu Darya and Syr Darya basins [9]. While Tajikistan has invested in irrigation rehabilitation, modernization remains constrained by financial and technical limitations. Turkmenistan continues to rely heavily on large-scale irrigation systems supporting water-intensive crops, particularly cotton. Despite substantial policy reforms, much of Central Asia's irrigation infrastructure and governance still reflect Soviet-era systems. Improving long-term irrigation efficiency will require continued technological modernization alongside stronger institutions, more effective water governance, and enhanced regional cooperation.

CHANGES IN CLIMATE AND WATER AVAILABILITY

Climate Trends

Central Asia is highly vulnerable to climate change because of its predominantly arid and semi-arid climate and its strong dependence on irrigated agriculture [13,14]. Observations and climate projections indicate significant regional warming, with temperatures expected to increase by approximately 2–6 °C by the end of the century [15,16]. Higher temperatures are projected to increase evapotranspiration, intensify drought conditions, and raise irrigation water demand. Precipitation trends are more variable, with some mountainous areas projected to receive increased winter precipitation, while western regions, including Turkmenistan, Uzbekistan, and parts of Kazakhstan, may experience declining summer rainfall [14,18]. This variability increases uncertainty in water availability and drought risk. Given that irrigated agriculture accounts for 80–90% of regional water withdrawals, even modest climatic changes can substantially affect irrigation water supplies [20]. Climate impacts also differ between the two major river basins. The Amu Darya is particularly vulnerable to long-term glacier retreat due to its dependence on runoff from the Pamir and Hindu Kush mountains, whereas the Syr Darya, originating in the Tien Shan, is more affected by shifts in snowmelt timing and increasing competition between upstream hydropower generation and downstream irrigation. In both basins, earlier snowmelt and altered runoff seasonality are expected to exacerbate water shortages during peak irrigation periods (Table 3).

Table 3. Comparison of climate change impacts on the Amu Darya and Syr Darya basins.

Characteristic	Amu Darya	Syr Darya
Main source regions	Pamir & Hindu Kush	Tien Shan
Glacier contribution	Higher	Moderate
Snow contribution	High	High
Dependence on meltwater	Very high	High
Projected glacier retreat	Significant	Significant
Seasonal runoff shift	Earlier peak flows	Earlier peak flows
Irrigation dependency	Very high	Very high
Key vulnerability	Reduced summer flows	Water allocation conflicts
Major downstream users	Turkmenistan, Uzbekistan	Uzbekistan, Kazakhstan

Cryosphere Changes

In addition to changing temperature and precipitation patterns, climate change is significantly altering cryospheric processes across Central Asia's mountain regions. Snowpack and glacier systems in the Tian Shan and Pamir mountains serve as natural water storage reservoirs, releasing meltwater during spring and summer and sustaining river flows during the peak irrigation season. However, rising temperatures are accelerating glacier retreat and reducing seasonal snow storage across much of the region [17,34]. Satellite observations and hydrological studies indicate that snow cover duration has declined in many mountainous areas, and the timing of snowmelt has shifted toward earlier in the spring season [18]. Declining snow water equivalent and reduced persistence of seasonal snow cover limit the amount of water stored in mountain catchments during winter months. As a result, water that historically contributed to sustained summer flows is increasingly released earlier in the year. Glacier retreat further compounds these changes. In the short term, increased glacier melt may temporarily augment river flows, but continued glacier mass loss is expected to reduce the long-term buffering capacity of mountain water resources. This decline in cryosphere-derived water storage (related to Glaciers and snow) is particularly significant for irrigation systems that depend on meltwater to maintain stable river flows during the summer growing season.

Implications for River Runoff

Climate change and cryospheric processes are significantly altering river runoff in the Amu Darya and Syr Darya basins (Table 4). Earlier snowmelt, glacier retreat, and declining snow storage are shifting river discharge towards spring, reducing water availability during the late spring and summer irrigation season when agricultural demand is highest [14,17]. These changes pose particular challenges for downstream irrigated agriculture in Uzbekistan, Turkmenistan, and southern Kazakhstan, where irrigation relies heavily on regulated reservoir releases and snowmelt-driven flows, increasing competition among agricultural, hydropower, and environmental water users [19,20]. Although the Amu Darya is especially vulnerable because of its dependence on glacier melt from the Pamir Mountains, and the Syr Darya benefits from greater flow regulation through upstream reservoirs and hydropower infrastructure, both basins are experiencing increasing pressure from rising temperatures, changing hydrological regimes, and growing irrigation demands. These hydroclimatic changes are expected to intensify seasonal mismatches between water supply and irrigation demand, highlighting the need for more adaptive irrigation management and stronger transboundary water governance across Central Asia.

Table 4. Summary of key climate change drivers, projected impacts on water resources, agriculture, and food security in Central Asia, and associated adaptation responses reported in the literature.

Impact Area/Driver	**Observed or Projected Change**	**Implications/Key Findings**	**Adaptation or Response**	**Sources**
Temperature	Warming projected at +2–6 °C by 2100, especially in summer and autumn	Increased heat stress, higher evapotranspiration, and greater drought risk	Adjust cropping calendars; adopt heat- and drought-tolerant crops	[14–16,18]
Precipitation	Spatial variability with declining summer precipitation and possible winter increases in some areas	Greater seasonal imbalance in water availability and increased drought frequency	Improve irrigation efficiency and water storage management	[14,17,18]
River Runoff & Hydrology	Earlier spring discharge peaks and reduced summer runoff due to glacier retreat	Reduced water availability during peak irrigation periods	Improve reservoir operations and integrated basin management	[15,17,35]
Irrigation Water Demand	Increasing irrigation requirements for cotton and wheat (up to ~50% in some regions)	Higher pressure on limited water resources	Adoption of efficient irrigation systems and crop selection strategies	[19,36–38]
Crop Yields	Declines reported in several regions (−20–50%) with some spatial variability	Higher vulnerability of agricultural production and rural livelihoods	Climate-smart agriculture, crop diversification, improved agronomic practices	[37,39–41]
Water Scarcity	High irrigation demand combined with ageing infrastructure and inefficient water use	Growing water stress and potential transboundary tensions	Modernisation of irrigation infrastructure and improved governance	[13,15,20]
Food Security	Increasing reliance on food imports and potential supply instability	Exposure to global food price volatility and inequality	Regional cooperation, agricultural trade integration, policy reform	[15,41,42]
Adaptation Strategies	Need for improved resilience in agricultural systems	Integration of agronomic, technological, and institutional solutions	Early sowing, crop diversification, improved water management	[13,38,40]

Consumptive Water Use and Evapotranspiration

Actual evapotranspiration (ETa) provides a direct measure of consumptive water use and is a key indicator of irrigation demand across the Amu Darya and Syr Darya basins. Satellite-derived ETa products enable continuous basin-scale monitoring of water consumption associated with crop growth and irrigation practices (Figure 1). Both basins exhibit pronounced seasonal cycles, with low evapotranspiration during winter and peak values during the growing season, closely corresponding to periods of maximum vegetation activity and irrigation demand. Although the Syr Darya Basin displays relatively stable seasonal dynamics, the Amu Darya Basin shows greater interannual variability, reflecting differences in snow and glacier contributions and water availability. Despite increasing investment in irrigation modernization and water-saving technologies, satellite observations indicate that basin-scale consumptive water use has remained largely unchanged, and in some areas has increased slightly due to intensified agricultural production and expanded cropping. This suggests that gains in irrigation efficiency have often been offset by increased water consumption, highlighting the well-known rebound effect. Under increasing climate variability and declining cryosphere-derived water resources, sustained high evapotranspiration will continue to place pressure on regional water supplies and intensify competition among agricultural, hydropower, and environmental water users. These findings demonstrate the value of integrating satellite-based evapotranspiration monitoring into irrigation management and water allocation strategies to support more sustainable use of Central Asia's transboundary water resources.

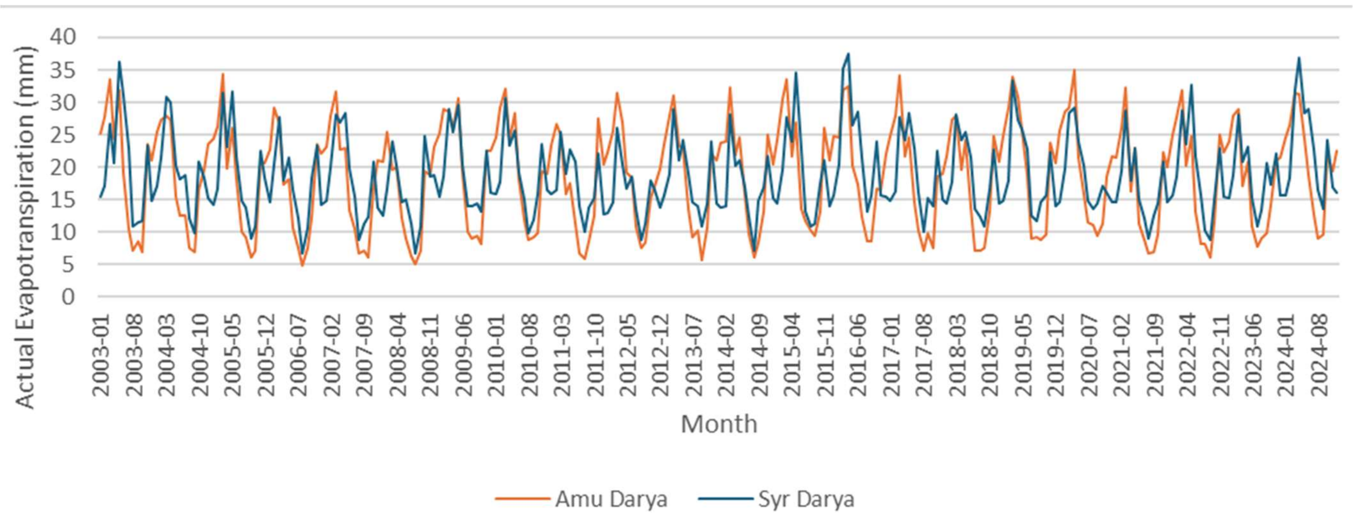
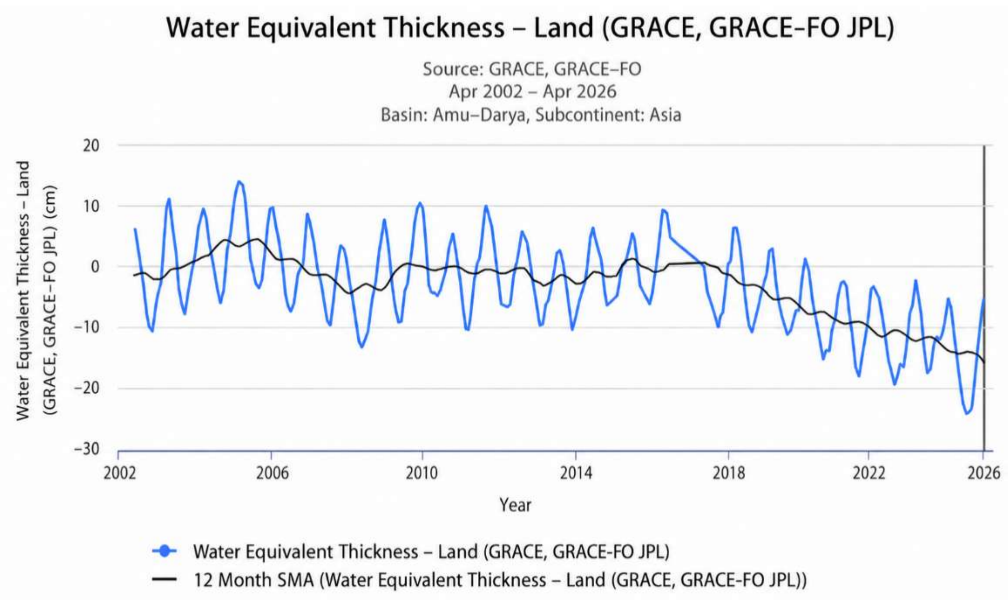


Figure 1. Monthly actual evapotranspiration (AET) in the Syr Darya and Amu Darya catchments from 2003 to 2024 derived from Earth Observation datasets. The time series shows pronounced seasonal cycles with summer maxima linked to peak vegetation activity and irrigation demand, as well as interannual variability associated with snow and glacier melt contributions, highlighting the influence of cryosphere-driven hydrology on catchment-scale water availability.

Catchment Water Balance and Water Storage Dynamics

Understanding catchment-scale water balance is fundamental for assessing long-term water availability in Central Asia. The total water stored within a river basin reflects the balance between water inputs, including precipitation and snow and glacier melt, and water losses through evapotranspiration, river discharge, and human water withdrawals, particularly for irrigation. Changes in terrestrial water storage therefore provide an integrated measure of the combined effects of climate variability, hydrological processes, and water resource management across the basin. To evaluate long-term changes in basin water availability, GRACE and GRACE Follow-On (GRACE-FO) satellite observations were used to analyse terrestrial water storage (TWS) anomalies in the Amu Darya and Syr Darya basins from April 2002 to April 2026 (Figure 2). Both basins exhibit pronounced seasonal fluctuations associated with precipitation, snow accumulation and melt, glacier contributions, evapotranspiration, river discharge, and irrigation withdrawals. Superimposed on these seasonal cycles is a persistent long-term decline in terrestrial water storage, particularly after 2018, indicating that water losses have increasingly exceeded water inputs at the basin scale. The decline is more pronounced in the Amu Darya Basin, which shows a greater reduction in water equivalent thickness than the Syr Darya Basin, suggesting more severe depletion of catchment water storage. This pattern is consistent with the potential impacts of intensive irrigation, prolonged drought, glacier mass loss, and increasing evaporative demand under a warming climate. The GRACE observations therefore provide independent satellite-based evidence that the long-term water balance of Central Asia's two major transboundary basins has become increasingly negative, highlighting growing pressure on regional water resources.



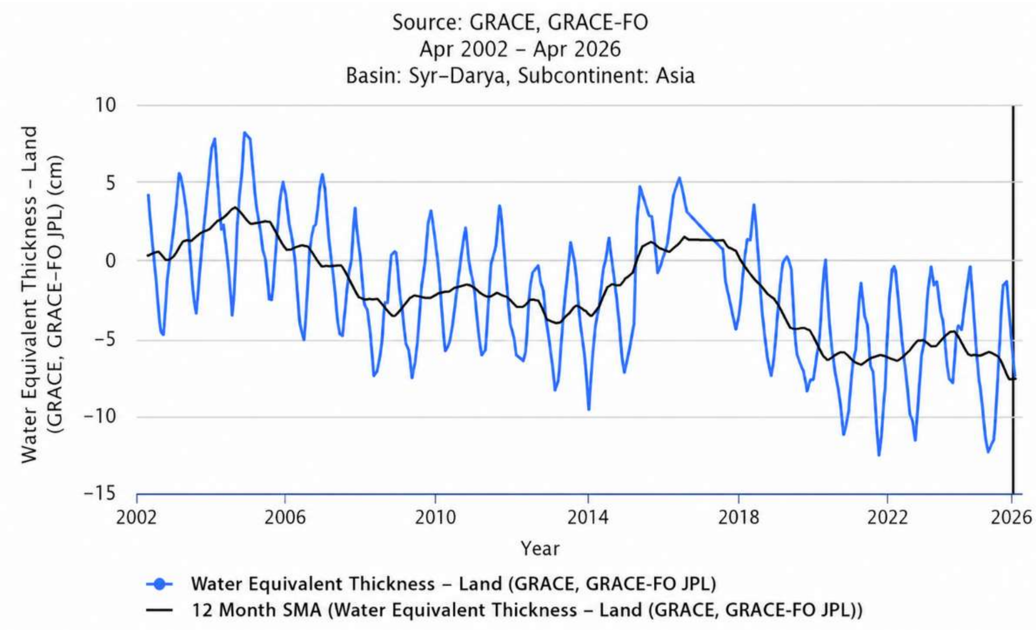


Figure 2. Time series of terrestrial water storage anomalies expressed as water equivalent thickness derived from GRACE and GRACE-FO (JPL mascon solution) for the (**top**) Amu Darya Basin and (**bottom**) Syr Darya Basin during April 2002–April 2026. The blue line represents monthly terrestrial water storage anomalies, while the black line shows the 12-month simple moving average (SMA), highlighting long-term trends. Both basins exhibit strong seasonal variability associated with the annual hydrological cycle, together with a persistent long-term decline in terrestrial water storage, indicating progressive depletion of regional water resources over the past two decades.

Land Use and Land Cover Dynamics

Earth Observation (EO) provides an effective means of monitoring long-term land use and land cover (LULC) changes across Central Asia, enabling continuous assessment of irrigated agriculture, crop dynamics, vegetation productivity [43,44], and agricultural intensification over large transboundary river basins where ground observations are limited (Figure 3). Multi-decadal satellite analyses indicate that irrigated agriculture has remained the dominant land use across the Amu Darya and Syr Darya basins since the post-Soviet transition, with extensive irrigated areas concentrated in the Fergana Valley, the Amu Darya delta, and the agricultural plains of Uzbekistan, Turkmenistan, and southern Kazakhstan. Rather than experiencing substantial contraction, irrigated land has generally remained stable, with localized expansion and increasing agricultural intensification observed in several regions. Satellite-derived vegetation indices, particularly NDVI, reveal longer growing seasons, increased cropping intensity, and in some areas a transition from single- to double-cropping systems, reflecting greater pressure on irrigation systems to sustain agricultural productivity. Although cotton and wheat continue to dominate irrigated agriculture, supported by extensive canal networks developed during the Soviet era, crop diversification, including wheat, maize, and rice, has occurred in response to changing food security priorities, with rice remaining one of the region's most water-intensive crops [2]. Comparative analyses further show that the Syr Darya Basin generally exhibits higher vegetation productivity than the Amu Darya Basin, while both basins display considerable interannual variability associated with fluctuations in snowmelt, water availability, and climate conditions. In particular, reduced vegetation greenness during drought years demonstrates the increasing sensitivity of irrigated agriculture to hydroclimatic variability, especially within the Amu Darya Basin. Overall, satellite observations demonstrate that agricultural production in Central Asia has become increasingly intensive rather than spatially expansive, reinforcing the importance of continuous EO monitoring to support sustainable land management, irrigation planning, and regional food security.

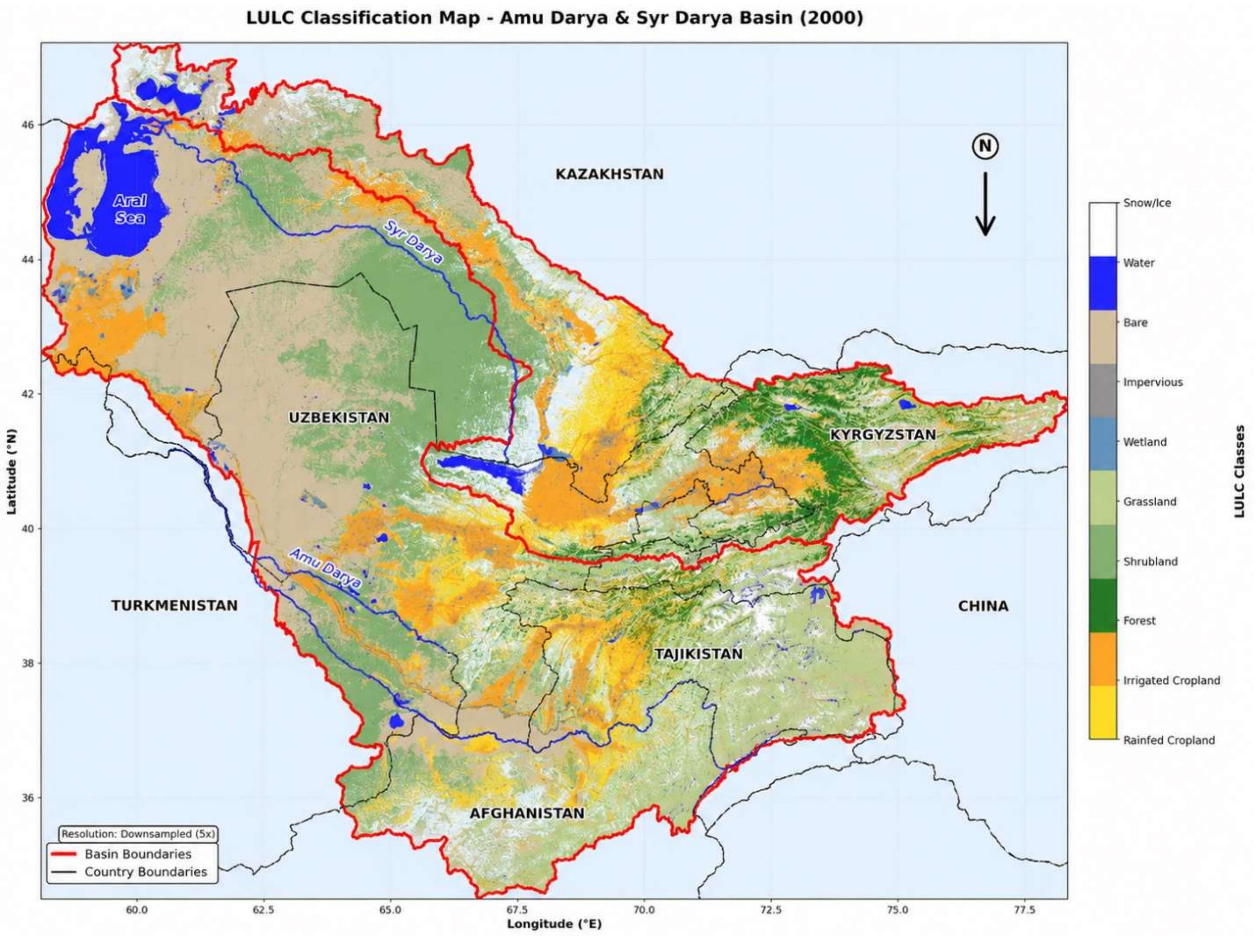


Figure 3. Land use and land cover (LULC) classification of the Amu Darya and Syr Darya basin derived from satellite observations for the year 2000. The map illustrates the spatial distribution of major land cover classes, including irrigated cropland, rainfed cropland, forest, shrubland, grassland, wetlands, bare land, water bodies, and snow/ice across the basin. Irrigated agriculture is concentrated along the major river corridors and delta regions, highlighting the strong dependence of agricultural production on surface water resources within the Aral Sea Basin.

IRRIGATION INFRASTRUCTURE AND EFFICIENCY CHALLENGES

Irrigation efficiency in Central Asia should be considered across multiple spatial scales, including conveyance efficiency, field application efficiency, and basin-scale water productivity, as improvements at one scale do not necessarily reduce overall consumptive water use. Although the region possesses one of the world's largest irrigation networks, much of its infrastructure was constructed during the Soviet era and now suffers from ageing canals, pumping stations, and drainage systems following decades of limited investment and maintenance after independence. Consequently, irrigation efficiency remains relatively low compared with global standards [13,33]. Water losses during conveyance are particularly significant, with unlined and poorly maintained canals experiencing substantial seepage and evaporation. It is estimated that only about 46% of diverted irrigation water reaches agricultural fields, while overall water-use efficiency in many irrigation schemes remains below 40% [22,23]. Inefficient irrigation and inadequate drainage have also resulted in widespread waterlogging, shallow groundwater rise, and soil salinisation, particularly across the downstream floodplains of Uzbekistan, Turkmenistan, and Kazakhstan, where decades of intensive irrigation have reduced agricultural productivity and accelerated land degradation [2,6,29]. Groundwater provides an important supplementary water source in some areas, but canal seepage and excessive irrigation frequently cause artificial groundwater recharge, further exacerbating salinity and drainage problems [23,45]. Addressing these interconnected challenges (Table 5) will require modernization of irrigation infrastructure, including canal rehabilitation, improved drainage systems, efficient irrigation technologies, and integrated management of surface water and groundwater resources to enhance long-term agricultural productivity and water security across the Amu Darya and Syr Darya basins.

Table 5. Summary of irrigation challenges and responses in Central Asia.

Challenge	Description	Response/Transformation	Source(s)
Water scarcity	High irrigation water use, low efficiency, climate change impacts	Modernization, efficiency improvements	[3,13,29,33]
Environmental degradation	Salinization, waterlogging, Aral Sea shrinkage	Crop structure adjustment, tech adoption	[2,46,47]
Outdated infrastructure	Inefficient, high losses at conveyance and field levels	Investment in new technologies	[13,29]
Governance and institutional gaps	Top-down reforms, lack of local input, poor coordination	Participatory governance, regional cooperation	[17,28]
Climate change	Increased temperature, variable precipitation, glacier melt	Integrated water management, adaptation	[3,17,19,37]

TECHNOLOGICAL TRANSFORMATION IN IRRIGATION MANAGEMENT

Technological innovation is increasingly recognized as a critical pathway for improving irrigation efficiency, water governance, and agricultural sustainability in Central Asia. Advances in Earth observation (EO), geospatial analysis, digital irrigation management, and artificial intelligence are transforming the way irrigation systems can be monitored and managed across large river basins. These technologies provide new opportunities to assess irrigation performance, quantify agricultural water use, and support more informed decision-making in complex transboundary water systems. In regions such as Central Asia—where irrigation networks are extensive, data availability is often limited, and water management challenges are significant—these tools offer important capabilities for improving water allocation transparency and supporting adaptive management strategies.

Remote Sensing for Irrigation Monitoring

Recent advances in Earth Observation (EO) have transformed the monitoring and management of irrigated agriculture across Central Asia by providing continuous, basin-scale information on land use, crop phenology, surface water dynamics, and evapotranspiration (ET), enabling more effective assessment of agricultural water use and environmental change [22,48,49]. Multi-sensor satellite datasets, including Landsat, MODIS, RapidEye, and newer high-resolution missions, combined with machine learning and object-based image analysis, have demonstrated strong capability for mapping irrigated croplands, identifying major crops such as cotton and winter wheat, monitoring cropping intensity, and estimating regional irrigation demand through crop water requirement and ET models [22,48]. Satellite-derived ET products further provide direct estimates of consumptive water use, allowing evaluation of irrigation performance, seasonal water demand, and water-use efficiency across large irrigation schemes [49]. Increasingly, these EO products are being integrated with telemetry networks, automated canal control systems, hydrological models, and digital decision-support platforms to improve irrigation planning and water allocation. However, despite their demonstrated potential, operational adoption across Central Asia remains limited due to financial constraints, ageing infrastructure, fragmented institutional responsibilities, limited technical capacity, and restricted access to high-quality data [29,33]. Bridging this “last-mile” gap between scientific innovation and operational water management will require sustained investment in monitoring infrastructure, capacity building, institutional coordination, and the integration of EO products into routine irrigation management and policy decisions.

Digital Irrigation and Automation

Digital technologies are increasingly recognised as a key pathway for improving irrigation efficiency, climate resilience, and water security across Central Asia. Advances in Internet of Things (IoT) sensors, telemetry networks, automated canal control, smart flow meters, remote sensing, artificial intelligence (AI), and decision-support systems enable near real-time monitoring of soil moisture, crop water requirements, canal flows, and irrigation performance, supporting more efficient water allocation from basin to farm scales [50]. These technologies complement satellite-based Earth Observation by integrating field observations with weather forecasts, hydrological models, and automated irrigation scheduling, allowing irrigation systems to respond dynamically to changing environmental conditions.

Despite their considerable potential, adoption of digital irrigation technologies across Central Asia remains limited. Financial constraints, ageing irrigation infrastructure, fragmented institutional responsibilities, limited technical capacity, and regulatory barriers continue to restrict large-scale implementation [50]. Irrigated agriculture still accounts for more than 90% of total water withdrawals across most Central Asian countries and approximately 75% in Kazakhstan, while irrigation efficiency often remains below 50% because of conveyance losses, inefficient surface irrigation practices, and deteriorating canal networks [2,10,13,33]. These inefficiencies contribute to waterlogging, soil salinisation, declining water quality, and continued environmental degradation across the Aral Sea Basin [29].

Digital irrigation should therefore be viewed as more than simply introducing new technologies. Sustainable modernisation requires integrating Earth Observation, IoT monitoring, automated infrastructure, AI-based irrigation scheduling, and digital decision-support systems with improved governance and institutional coordination. Such integrated approaches can improve transparency, optimise water allocation, reduce operational losses, and strengthen climate adaptation under increasing water scarcity and hydroclimatic variability. However, improvements in conveyance and field-scale irrigation efficiency do not necessarily reduce basin-scale consumptive water use. Consistent with the irrigation efficiency paradox (rebound effect), increased irrigation efficiency may facilitate expansion of irrigated land, higher cropping intensity, or shifts towards more water-intensive crops, resulting in little or no reduction in overall evapotranspiration and water demand. Following post-Soviet agricultural reforms, changes in cropping patterns—including expansion of rice cultivation in parts of Kazakhstan and Uzbekistan—and increasing cropping intensity have contributed to sustained irrigation demand despite technological improvements [2,13,26,51]. Earth Observation analyses of land-use change and evapotranspiration further demonstrate that reductions in conveyance losses have not always translated into proportional reductions in basin-scale consumptive water use, reinforcing the need to evaluate irrigation performance at both field and catchment scales.

GIS, AI, and Decision Support Systems

The integration of Geographic Information Systems (GIS), Earth Observation (EO), Artificial Intelligence (AI), and decision-support systems is transforming irrigation planning and water management across Central Asia (Table 6). Multi-source satellite observations combined with GIS enable continuous monitoring of irrigated areas, reservoir storage, crop water use, and irrigation withdrawals, providing the spatial information needed for basin-scale water accounting and irrigation planning [49]. Machine learning and object-based image analysis applied to satellite datasets such as RapidEye, Landsat, and MODIS have demonstrated strong capability for mapping irrigated crops, including cotton and winter wheat, estimating irrigation demand, and identifying cropping patterns across large agricultural landscapes [22,48]. GIS-based multi-criteria analyses integrating topography, soils, geology, land cover, and hydrological information have also proven effective for identifying groundwater recharge zones and supporting conjunctive management of surface water and groundwater resources, particularly in Uzbekistan [45]. Groundwater remains an important buffer during droughts in irrigation regions such as the Fergana Valley and Khorezm, where recharge is strongly influenced by canal seepage and irrigation return flows [23]. Increasingly, these EO and GIS datasets are being integrated with AI algorithms and hydrological models to automate crop classification, estimate irrigation demand at pixel scale, optimise water allocation, and support real-time irrigation decision making. Although these technologies provide powerful tools for improving irrigation efficiency, operational implementation remains constrained by limited water availability, ageing infrastructure, and continuing environmental degradation, including soil salinisation and the decline of the Aral Sea [33,52]. Future irrigation management will therefore rely on integrated digital decision-support systems that combine EO, GIS, AI, and hydrological modelling to support adaptive, evidence-based water governance and sustainable management of Central Asia's transboundary river basins

Table 6. Summary of technologies and applications in Central Asian irrigation and water management.

Technology/Method	Application Area	Purpose/Outcome	Reference(s)
Remote sensing & satellite altimetry	Uzbekistan irrigation oases	Quantify water use, monitor reservoirs, inform management	[49]
Object-based classification + AI	Fergana Valley, Uzbekistan	Crop mapping, irrigation water requirement estimation	[22,48]
GIS-based MCDA	Bostanlik district, Uzbekistan	Groundwater potential zoning	[45]
Water balance modeling	Fergana Valley, Khorezm	Quantify groundwater recharge/discharge	[23]
Hydrological modeling (MIKE-SHE)	Nukus irrigation area	Groundwater regulation planning	[53]

TRANSBOUNDARY WATER GOVERNANCE AND REGIONAL COOPERATION

Central Asia is one of the world's most interconnected transboundary water regions, where the Amu Darya and Syr Darya rivers sustain agriculture, hydropower generation, and ecosystem health across multiple countries. The Aral Sea Basin, shared by Afghanistan, Tajikistan, Uzbekistan, Turkmenistan, and Kazakhstan, receives approximately 77 km^3 of annual river inflow, of which nearly 96% is allocated to agriculture [54]. Together with other shared rivers, including the Chu, Talas, Tarim, and Irtysh, these basins illustrate the region's strong hydrological interdependence [55]—also see Figure 4. However, water availability is highly uneven. Kyrgyzstan generates most of its renewable water resources internally, whereas Uzbekistan and Turkmenistan depend on upstream inflows for more than 90% of their renewable water supplies, and Kazakhstan remains highly dependent on transboundary water despite considerable regional disparities [56]. These asymmetries are further intensified by the contrasting needs of upstream countries, which prioritise winter reservoir releases for hydropower generation, and downstream countries, which require summer flows to sustain irrigation-intensive agriculture. Climate change, glacier retreat, changing runoff seasonality, and increasing drought frequency are expected to exacerbate these water–energy trade-offs, placing additional pressure on already stressed river systems. Although regional agreements—including the 1992 Almaty Agreement, the Interstate Commission for Water Coordination (ICWC), the Nukus Declaration, and the 1998 Syr Darya Basin Agreement—have established important frameworks for cooperation, their effectiveness continues to be constrained by competing national priorities, limited data sharing, and weak enforcement mechanisms. Strengthening transboundary cooperation will therefore require integrated water–energy–food governance, improved information sharing, joint monitoring using Earth Observation and digital technologies, coordinated reservoir operations, and adaptive management strategies capable of responding to increasing hydroclimatic uncertainty while supporting long-term regional water security.

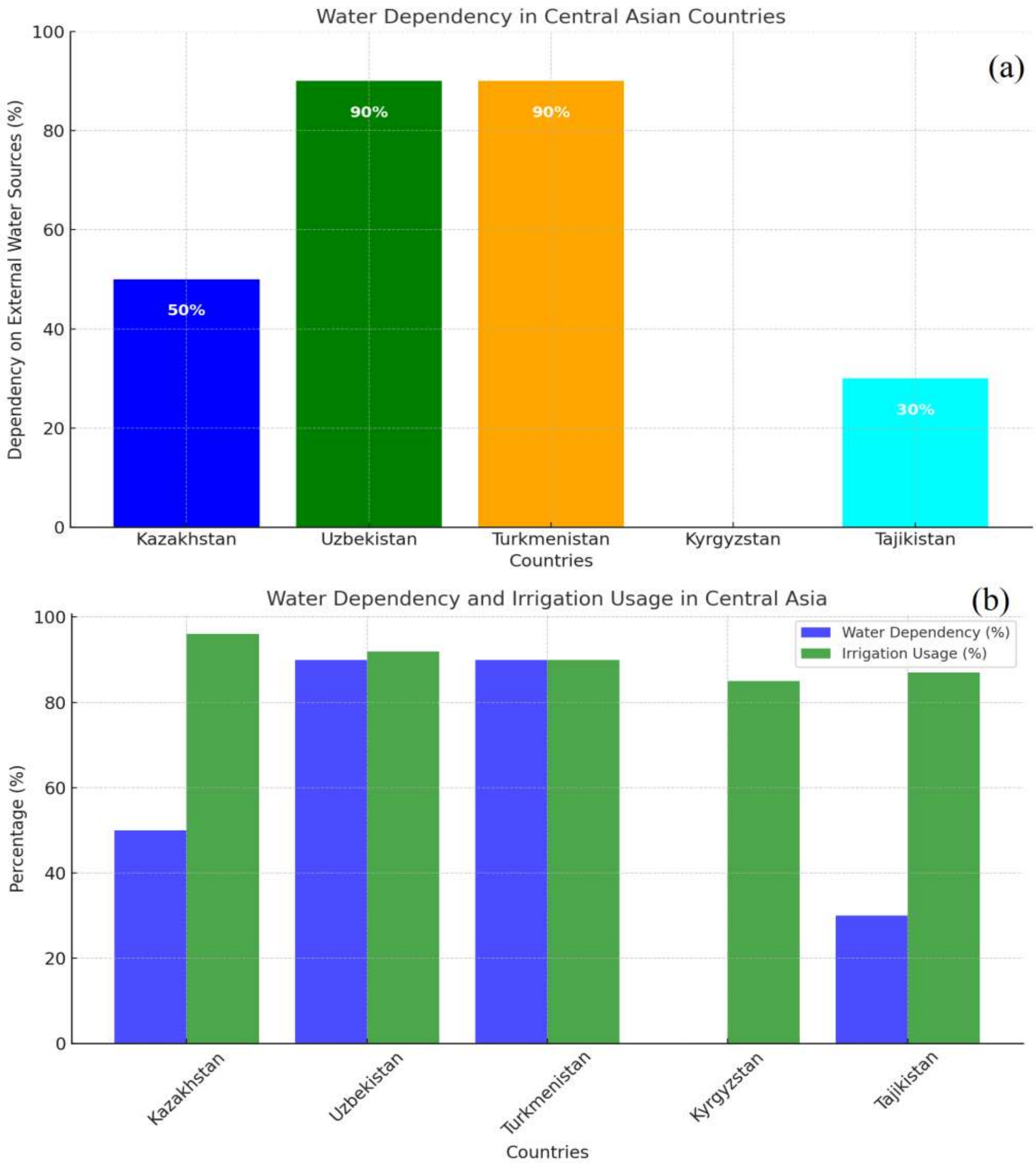


Figure 4. (**a**) Dependence of Central Asian countries on external water resources. Graph (**b**) shows the dependence and irrigation needs of Central Asian countries on transboundary water resources in percentage terms: The blue columns indicate the level of dependence on transboundary water resources; The green columns show the proportion of water used for irrigation.

FUTURE OUTLOOK FOR IRRIGATED AGRICULTURE

The future sustainability of irrigated agriculture in Central Asia will depend on the region's ability to adapt to increasing climatic, hydrological, and socio-economic pressures while improving water governance and irrigation efficiency. Rising temperatures of approximately 2–6 °C by the end of the century are expected to increase evapotranspiration and crop water requirements, particularly for water-intensive crops such as cotton and rice [15,16]. At the same time, declining snow storage, accelerating glacier retreat in the Tien Shan and Pamir mountains, and earlier snowmelt will progressively reduce the natural regulation of river flows, increasing seasonal water shortages during the summer irrigation period [17,34]. Climate-induced reductions in river discharge of 5–30% during drought years have already been projected for parts of the Amu Darya and Syr Darya basins, posing significant risks to agricultural productivity, food security, and regional water availability [19,20].

Future water demand will also be shaped by population growth, economic development, agricultural intensification, and expanding irrigation infrastructure. Satellite observations indicate that recent agricultural development has been driven primarily by increasing cropping intensity rather than expansion of irrigated land, maintaining high irrigation demand despite improvements in irrigation technologies. Emerging developments, including construction of the Qosh Tepa Canal in Afghanistan, have the potential to further alter regional water allocation within the Amu Darya Basin, increasing competition for limited water resources and adding new uncertainty to transboundary water management [7].

Meeting these challenges will require a transition from traditional irrigation management towards integrated, data-driven water governance. Priority actions include modernising irrigation infrastructure, improving canal and drainage systems, expanding water-saving technologies such as drip and sprinkler irrigation, diversifying towards less water-intensive crops, and strengthening conjunctive management of surface water and groundwater. Equally important will be the integration of Earth Observation, IoT sensor networks, artificial intelligence, hydrological modelling, and digital decision-support systems to provide real-time monitoring of water availability, irrigation demand, and crop water use. Such technologies can support adaptive reservoir operations, transparent basin-scale water accounting, and more efficient transboundary water allocation. However, technological innovation alone will not be sufficient. Long-term water security will also depend on stronger regional cooperation, improved institutional coordination, enhanced data sharing, and integrated water–energy–food nexus governance. Together, these approaches offer the greatest opportunity to improve irrigation resilience, sustain agricultural productivity, and ensure the long-term sustainability of Central Asia’s shared water resources under a changing climate.

TOWARDS INTEGRATED AND DATA-DRIVEN WATER GOVERNANCE IN CENTRAL ASIA

The findings of this review demonstrate that improving irrigation sustainability in Central Asia requires a transition from traditional infrastructure-based management towards integrated, data-driven water governance. Despite recent investments in irrigation modernization, the region continues to experience high consumptive water use, ageing infrastructure, and increasing vulnerability to climate change. A key priority is the implementation of basin-scale water accounting, which focuses on actual consumptive water use rather than water diversion volumes. Satellite-derived evapotranspiration and terrestrial water storage observations now provide robust tools for quantifying basin water balances and supporting transparent water allocation across the Amu Darya and Syr Darya basins [49,57].

Earth Observation has become an important tool for monitoring irrigated agriculture through satellite-derived land use, vegetation dynamics, evapotranspiration, reservoir storage, and surface water extent. When integrated with GIS, hydrological models, Internet of Things (IoT) sensors, Artificial Intelligence (AI), and digital decision-support systems, these technologies enable near real-time monitoring of water availability and irrigation demand, improving drought monitoring, irrigation planning, and adaptive water allocation. However, operational implementation remains constrained by limited investment, fragmented institutions, restricted data sharing, and insufficient technical capacity. Overcoming these barriers will require sustained investment in digital infrastructure, capacity building, and stronger stakeholder engagement.

Technological innovation alone will not achieve sustainable irrigation. Long-term resilience depends equally on effective governance, institutional reform, and regional cooperation. Water allocation should increasingly reflect basin-scale water availability, while strengthening Water User Associations, improving coordination among water, agriculture, and energy agencies, and adopting an integrated water–energy–food–environment nexus approach will support more adaptive water management [28,29]. Strengthening regional institutions such as the Interstate Commission for Water Coordination (ICWC) and the International Fund for Saving the Aral Sea (IFAS), together with improved data sharing, joint monitoring, and coordinated reservoir operations, will be essential for addressing growing hydroclimatic uncertainty and balancing competing water demands. Unlike previous reviews that have examined irrigation infrastructure, governance, or climate change separately, this review integrates historical development, hydroclimatic change, Earth Observation, digital technologies, and transboundary governance within a single framework for irrigation sustainability. The synthesis suggests that combining Earth Observation, AI, digital monitoring, and basin-scale water accounting with stronger governance and regional cooperation may offer a practical pathway towards improving irrigation efficiency, enhancing climate resilience, and ensuring the long-term sustainability of Central Asia's shared water resources [21].

CONCLUSIONS

Irrigated agriculture will remain fundamental to the economies, food security, and livelihoods of Central Asia, yet its long-term sustainability is increasingly threatened by climate change, ageing infrastructure, inefficient irrigation systems, and the complex governance of transboundary water resources. While substantial policy reforms have been implemented since the dissolution of the Soviet Union, irrigation across the region continues to be characterised by high consumptive water use, significant conveyance losses, and increasing pressure on the shared waters of the Amu Darya and Syr Darya basins. At the same time, rising temperatures, increasing evapotranspiration, glacier retreat, and changing runoff seasonality are reducing water availability during critical irrigation periods, intensifying competition among agricultural, hydropower, environmental, and domestic water users.

This review suggests that the future of irrigation management in Central Asia may benefit from integrating Earth Observation (EO), basin-scale water accounting, digital irrigation technologies, Artificial Intelligence (AI), GIS, and hydrological modelling within adaptive water governance frameworks. Satellite observations of land use, evapotranspiration, terrestrial water storage, and surface water dynamics now provide unprecedented opportunities to monitor irrigation performance, quantify consumptive water use, and support evidence-based decision making across large transboundary basins. However, technological advances alone will not ensure sustainable water management. Their successful implementation will require stronger institutions, improved data sharing, greater technical capacity, and enhanced regional cooperation among riparian countries.

A key contribution of this review is the integration of historical irrigation development, hydroclimatic change, governance, and emerging digital technologies into a single framework for understanding irrigation sustainability in Central Asia. Rather than treating these issues independently, the review highlights how their interactions shape regional water security and identifies Earth Observation as an important bridge between scientific understanding and operational water management. Future research should focus on improving basin-scale water accounting, evaluating the operational adoption of digital irrigation technologies, quantifying the effects of climate change on water availability and consumptive water use, and strengthening integrated water–energy–food–environment nexus approaches for transboundary river basins. Ultimately, achieving sustainable irrigation in Central Asia will require coordinated policy reform, technological innovation, institutional strengthening, and regional collaboration to balance agricultural production, water security, energy generation, and ecosystem protection under an increasingly uncertain climate.

DATA AVAILABILITY

The dataset of the study is available from the authors upon reasonable request.

AUTHOR CONTRIBUTIONS

Conceptualization, ZT, BP and BJ; methodology, ZT, KZ and BJ; formal analysis, ZT, KZ and BJ; investigation, ZT, BP, AB, AP, S.K. and BJ; resources, S.K., AB, AP and S.K.; data curation, ZT, KZ and BJ; writing—original draft preparation, ZT and BJ; writing—review and editing, ZT, BP, AB, AP, KZ, SK and BJ; visualization, ZT, KZ and BJ; supervision, BP and BJ; project administration, ZT, BP and BJ; funding acquisition, ZT, AP and SK. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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