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Sustainability of Irrigated Agriculture in Central Asia: Historical Development, Policy Transitions, and Future Challenges Under Climate Change

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Abstract

Irrigated agriculture is the dominant water user in Central Asia and is critical for regional food security and livelihoods. Much of the irrigation infrastructure, developed during the Soviet era, enabled large-scale agricultural expansion but contributed to environmental degradation, including the desiccation of the Aral Sea. Since 1991, countries have implemented reforms to improve water governance and efficiency. This review integrates historical policy analysis with Earth observation–based assessments of land use, vegetation dynamics, evapotranspiration, and hydroclimatic trends. Satellite evidence indicates that irrigation demand remains high and has intensified in some regions despite modernization efforts. Meanwhile, climate change—through rising temperatures, reduced snow storage, and increased variability—further pressures water resources. Although emerging technologies such as remote sensing and digital water management offer opportunities for improvement, achieving sustainable irrigation will require stronger institutional reforms, improved basin-scale water accounting, and enhanced transboundary cooperation.

Keywords: Central Asia; irrigated agriculture; water resources management; earth observation; climate change

1. 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 the Amu Darya and Syr Darya rivers. 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 [1,2]. 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 and wheat production across arid and semi-arid landscapes. These large hydraulic developments enabled rapid agricultural expansion but also produced

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significant environmental consequences, most notably the dramatic desiccation of the Aral Sea and widespread soil salinisation and land degradation across irrigated areas [3–5].

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 management framework that had previously coordinated water allocation across the basin. In response, regional institutions such as the Interstate Commission for Water Coordination (ICWC) and the International Fund for Saving the Aral Sea (IFAS) were established to facilitate cooperation in managing shared water resources. At the national level, countries have introduced a range of institutional and policy reforms aimed at improving irrigation governance, strengthening water management institutions, and modernising agricultural production systems [6–8]. These reforms have included the introduction of water user associations, adoption of Integrated Water Resources Management (IWRM) principles, revisions to national water legislation, and increasing emphasis on irrigation efficiency and climate adaptation. However, irrigation systems across the region remain characterized by ageing infrastructure, inefficient water distribution networks, and limited adoption of modern irrigation technologies such as drip or sprinkler systems [8–10].

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 [11,12]. 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 [13,14]. 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 [15,16]. These changes are expected to increase irrigation water demand while simultaneously reducing the stability of river flows that sustain agricultural production in downstream areas [17,18].

Recent advances in Earth observation (EO) technologies provide new opportunities to monitor irrigated landscapes and water use dynamics across large transboundary basins. Satellite observations enable detailed mapping of irrigated land use, crop phenology, surface water dynamics, and evapotranspiration, offering valuable insights into agricultural water consumption and environmental change across Central Asia [19–21]. EO-based approaches are increasingly complemented by digital irrigation management tools, including telemetry systems, automated canal control, and decision-support platforms that integrate remote sensing and hydrological modelling to improve water allocation and irrigation planning. Despite these technological advances, irrigation systems across Central Asia continue to face significant sustainability challenges related to inefficient water use, environmental degradation, and complex transboundary governance arrangements [22,23].

Given these challenges, understanding the interactions between historical irrigation development, evolving policy frameworks, hydroclimatic change, and emerging technological solutions is critical for identifying sustainable pathways for agricultural water management in Central Asia. This article provides a comprehensive review of irrigated agriculture in Central Asia since the dissolution of the Soviet Union. Specifically, the study examines (i) the historical development of irrigation systems and agricultural landscapes, (ii) post-Soviet policy and institutional transformations in water governance, (iii) changes in hydroclimatic conditions and water availability, (iv) land use and irrigation dynamics revealed through Earth observation datasets, and (v) the role of emerging technologies and regional cooperation in improving irrigation sustainability. By synthesizing evidence from policy analysis, satellite observations, and recent scientific literature, the study aims to provide an integrated perspective on the future sustainability of irrigated agriculture in Central Asia under conditions of climate change and increasing water scarcity.

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2. Historical Evolution of Irrigation in Central Asia

2.1. 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.

2.2. Soviet Irrigation Expansion (1960–1991)

Large-scale transformation of irrigation systems in Central Asia occurred during the Soviet period, when agricultural policies prioritised rapid expansion of irrigated land to increase production of strategic crops, particularly cotton and wheat. Beginning in the 1960s, major hydraulic engineering projects were implemented to divert water from the Amu Darya and Syr Darya rivers through extensive canal networks, reservoirs, and pumping systems. These developments enabled the expansion of irrigated agriculture across vast desert and steppe landscapes, particularly in Uzbekistan, Turkmenistan, and southern Kazakhstan. Between 1962 and 2002, irrigated arable land in Central Asia increased by approximately 60%, reflecting the strong emphasis placed on expanding agricultural production rather than improving water productivity [11,24].

The Soviet agricultural system was characterised by large-scale state farms and highly centralised water management institutions that coordinated irrigation supply across the region. Cotton monoculture became a dominant feature of agricultural production in many areas, particularly in Uzbekistan and Turkmenistan, where irrigation water was heavily allocated to support cotton exports within the Soviet economic system. Extensive canal systems such as the Karakum Canal in Turkmenistan and the irrigation networks of the Fergana Valley facilitated large water diversions from major rivers to agricultural lands. These developments enabled rapid agricultural growth but significantly altered the natural hydrology of the Amu Darya and Syr Darya basins.

The expansion of irrigation infrastructure and intensive water withdrawals produced profound environmental consequences across the region (Table 1). One of the most visible impacts was the dramatic decline of the Aral Sea, which began to shrink rapidly as river inflows were diverted to irrigated agriculture. Since 1960, the Aral Sea has lost approximately 74% of its surface area and around 90% of its volume, transforming what was once the world's fourth-largest inland lake into a fragmented and highly degraded ecosystem [3,4]. Intensive irrigation practices also contributed to widespread soil salinisation, waterlogging, and degradation of agricultural lands, particularly in downstream areas where inefficient irrigation systems and drainage networks allowed salts to accumulate in soils [5,25].

Despite these environmental costs, the irrigation systems constructed during the Soviet period established the foundation for modern agricultural production across Central Asia. Much of the region's existing irrigation infrastructure—including major canals, reservoirs, and pumping stations—remains in use today. However, these systems were designed under conditions of centrally planned management and abundant water allocation, and they now face increasing pressure from ageing infrastructure, institutional fragmentation following the dissolution of the Soviet Union, and growing hydroclimatic variability across the region.

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	[2,3]
Water withdrawal for irrigation	75.6% (Kazakhstan), >90% (other countries)	[1,2]
Main crops	Wheat (61%), Barley (12%), Cotton (10%), Rice, Maize	[1]
Irrigation efficiency	<40% utilisation; 46% of water used at field level	[19,26]
Aral Sea shrinkage	74% area, 90% volume lost since 1960	[3,4]
Water productivity (wheat)	0.881 kg/m³	[27]
Food insecurity	Nearly 1 million people severely food insecure	[3]

3. Post-Soviet Institutional and Policy Transformation

3.1. Irrigation Governance After Independence

The dissolution of the Soviet Union in 1991 marked a major institutional transition for irrigation governance in Central Asia. Under the Soviet system, water allocation and irrigation management were coordinated through a highly centralized planning framework that integrated water, energy, and agricultural production across the region (Table 2). Following independence, the newly established Central Asian states inherited extensive irrigation infrastructure but lacked the unified management structure that had previously coordinated water allocation and maintenance of irrigation networks. As a result, irrigation governance shifted from centralized planning toward nationally managed water systems, creating new institutional and operational challenges for managing shared water resources.

In response to these changes, each country introduced national water management institutions and began reforming irrigation governance frameworks. A key component of these reforms was the decentralization of irrigation management through the establishment of Water User Associations (WUAs), which were intended to transfer responsibility for local irrigation management and canal maintenance to groups of farmers. These institutions aimed to improve water distribution efficiency, enhance local participation in irrigation management, and reduce the administrative burden on national water authorities. However, the effectiveness of WUAs has varied considerably across the region due to limited financial resources, weak institutional capacity, and insufficient technical support for farmers managing complex irrigation infrastructure [22,29].

Despite these reforms, irrigation governance in Central Asia remains characterized by institutional fragmentation and persistent operational challenges. Many irrigation systems continue to rely on ageing infrastructure designed under Soviet-era conditions, while responsibilities for water allocation, infrastructure maintenance, and agricultural planning are often divided among multiple agencies with overlapping mandates. In addition, limited financial resources and declining technical capacity following the transition period have contributed to reduced maintenance of irrigation infrastructure and continued inefficiencies in water distribution networks [1,30]. These institutional constraints have made it difficult for countries to fully modernize irrigation systems and adapt water management practices to emerging climatic and socio-economic pressures.

Table 2. Key Features of Irrigation Policy in Central Asia.

Aspect	Key Points	Sources
Main Water Sources	Amu Darya, Syr Darya (transboundary rivers)	[7,8,31]
Dominant Irrigation Methods	Flood and furrow irrigation; limited adoption of drip/sprinkler	[8–10]
Irrigation Efficiency	Generally low (<50%); high water withdrawals	[8,22,23]
Environmental Impact	Aral Sea desiccation, ecological degradation	[1,30,32]
Policy Focus	Efficiency, modernization, integrated management, regional cooperation	[6,9,23,32]
Institutional Challenges	Aging infrastructure, reduced management capacity post-independence	[1,30]
Climate Change Consideration	Increased risk of scarcity, need for adaptive strategies	[10,25,33]

3.2. Regional Water Governance and Transboundary Agreements

The transboundary nature of Central Asia's major river systems adds an additional layer of complexity to irrigation governance. The Amu Darya and Syr Darya rivers flow through several Central Asian countries and form the primary water sources for irrigated agriculture across the region. As a result, irrigation sustainability depends heavily on regional cooperation and coordinated water management among upstream and downstream states.

To facilitate such cooperation, the five Central Asian republics established several regional institutions and agreements in the early years following independence. One of the most important of these institutions is the Interstate Commission for Water Coordination (ICWC), which was created in 1992 to coordinate water allocation and management among Central Asian countries. The ICWC operates through basin water organizations responsible for managing water distribution within the Amu Darya and Syr Darya river basins and plays a central role in coordinating seasonal water releases and irrigation allocations across the region.

In parallel, the International Fund for Saving the Aral Sea (IFAS) was established to address the severe environmental degradation associated with irrigation expansion and declining river inflows to the Aral Sea. IFAS serves as a regional platform for coordinating environmental restoration programs, water management initiatives, and international development assistance related to the Aral Sea basin.

Another key milestone in regional water governance was the 1998 Syr Darya Agreement, which sought to coordinate water releases for irrigation in downstream countries with hydropower generation in upstream states. This agreement reflects the complex interdependence between water and energy systems in Central Asia, where upstream countries such as Kyrgyzstan and Tajikistan rely on reservoirs for hydropower production while downstream countries depend on summer water releases for irrigation [7,8]. Although these regional agreements have helped prevent major conflicts over water allocation, their implementation has often been constrained by competing national priorities, limited enforcement mechanisms, and insufficient data sharing among countries. Consequently, transboundary water governance in Central Asia remains an ongoing challenge, particularly under conditions of increasing water scarcity and climatic variability.

3.3. National Irrigation Reforms

Since independence, Central Asian countries have implemented various national reforms aimed at modernizing irrigation infrastructure, improving water-use efficiency, and strengthening water governance. However, the scope and effectiveness of these reforms vary significantly across countries due to differences in institutional capacity, economic conditions, and water resource availability.

Uzbekistan, which hosts some of the largest irrigated agricultural areas in the region, has introduced several policies aimed at improving irrigation efficiency and modernizing agricultural

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production systems. Recent reforms have emphasized the adoption of water-saving technologies, modernization of irrigation infrastructure, and the gradual diversification of cropping systems away from heavy reliance on cotton monoculture. Despite these efforts, irrigation in Uzbekistan continues to depend heavily on surface irrigation systems and large canal networks, and significant water losses still occur due to outdated infrastructure and inefficient water distribution systems [11,23].

Kazakhstan has pursued irrigation reforms within a broader framework of water resource management modernization. Revisions to national water legislation and the introduction of Integrated Water Resources Management (IWRM) principles have aimed to improve water accounting, strengthen basin-level planning, and increase stakeholder participation in water governance. However, Kazakhstan's irrigation sector remains sensitive to upstream water management decisions and climatic variability due to its downstream position within the Syr Darya basin [8].

In Kyrgyzstan and Tajikistan, irrigation governance is closely linked to the management of hydropower reservoirs that regulate water flows within the Amu Darya and Syr Darya systems. These upstream countries rely heavily on hydropower generation for electricity production, which often requires water releases during winter months. This seasonal pattern differs from downstream irrigation demands, which peak during the summer growing season, creating a persistent water–energy management challenge within the region's transboundary river basins [7].

Tajikistan has implemented various programs aimed at rehabilitating irrigation infrastructure and improving water management institutions, although financial constraints and technical limitations continue to restrict the pace of modernization. Meanwhile, Turkmenistan remains heavily dependent on large-scale irrigation systems supporting water-intensive crops, particularly cotton, and irrigation expansion continues to play an important role in national agricultural policy.

Overall, while significant policy reforms have been introduced across Central Asia since independence, many irrigation systems continue to operate under institutional and infrastructural conditions inherited from the Soviet period. As a result, improving irrigation sustainability requires not only continued technological modernization but also stronger institutional coordination, improved water governance frameworks, and enhanced regional cooperation to manage shared water resources effectively.

4. Changes in Water Availability and Hydroclimate

Water availability in Central Asia is strongly influenced by hydroclimatic processes occurring across the mountainous headwaters of the Amu Darya and Syr Darya river basins. These rivers originate in the high mountain regions of the Tian Shan and Pamir ranges, where snow accumulation and glacier melt play a critical role in sustaining downstream water supply for irrigated agriculture. Changes in regional climate conditions therefore have significant implications for the timing and reliability of water resources across the region. In recent decades, Central Asia has experienced substantial climatic shifts that are altering precipitation patterns, temperature regimes, and cryospheric processes, thereby affecting river flows and irrigation water availability.

4.1. Climate Trends

Central Asia is considered highly vulnerable to climate change due to its predominantly arid and semi-arid climate and strong dependence on irrigated agriculture for economic stability and rural livelihoods [11,12]. Observational records and climate model projections indicate that the region has experienced significant warming over recent decades, with projected temperature increases ranging from approximately 2 °C to 6 °C by the end of the twenty-first century [13,14]. Rising temperatures are expected to increase evapotranspiration rates, intensify drought conditions, and increase water demand for agricultural production.

Precipitation trends across Central Asia are more spatially heterogeneous. Some areas may experience modest increases in winter precipitation, particularly in mountainous regions, while other areas—especially the western parts of the region including Turkmenistan, Uzbekistan, and parts of

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Kazakhstan—may experience declining precipitation during the summer months [12,16]. This spatial variability contributes to growing uncertainty in water availability and increases the frequency of drought events affecting agricultural production. Given that irrigated agriculture accounts for up to 80–90% of water withdrawals in many parts of Central Asia, even relatively small changes in precipitation and temperature can significantly affect water availability for irrigation [18].

4.2. 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 [15,33].

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 [16]. 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 is particularly significant for irrigation systems that depend on meltwater to maintain stable river flows during the summer growing season.

4.3. Implications for River Runoff

Changes in regional climate and cryospheric processes have direct implications for river runoff patterns in the Amu Darya and Syr Darya basins (Table 3). Earlier snowmelt and declining glacier storage are altering the seasonal timing of river discharge, with increasing proportions of runoff occurring during spring rather than summer months [12,15]. This shift affects the alignment between water supply and agricultural water demand, as peak irrigation requirements typically occur during late spring and summer.

Reduced summer runoff poses particular challenges for downstream irrigated agriculture in Uzbekistan, Turkmenistan, and southern Kazakhstan, where irrigation systems depend heavily on regulated releases from upstream reservoirs and snowmelt-driven river flows. Several studies suggest that climate-induced changes in runoff could reduce water availability during critical irrigation periods, potentially affecting crop yields and increasing competition for water among agricultural, energy, and environmental sectors [17,18].

The implications of these changes differ between the region's two major river basins. The Amu Darya basin, which receives substantial contributions from glacier melt in the Pamir mountains, is particularly sensitive to long-term glacier retreat and changes in snow storage. In contrast, the Syr Darya basin, which is more strongly regulated by reservoirs and hydropower infrastructure in upstream countries, exhibits somewhat greater buffering capacity against short-term hydroclimatic variability. Nevertheless, both basins face increasing pressure from rising temperatures, growing irrigation demand, and changing hydrological regimes.

Together, these hydroclimatic trends highlight the growing vulnerability of Central Asian irrigation systems to climate change. Declining snow storage, glacier retreat, and shifting runoff patterns are likely to intensify seasonal mismatches between water supply and irrigation demand, increasing pressure on existing water management systems and reinforcing the need for more adaptive and coordinated approaches to water governance across the region.

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5. Land Use and Irrigated Agriculture Dynamics

Earth observation (EO) datasets provide valuable insights into the spatial and temporal dynamics of irrigated agriculture across Central Asia (Figure 1). Satellite observations allow long-term monitoring of land use changes, crop dynamics, vegetation productivity, and consumptive water use across large river basins where ground observations are limited. By integrating multi-decadal satellite imagery with hydroclimatic indicators, it is possible to identify trends in irrigated land expansion, cropping intensity, vegetation productivity, and agricultural water demand across the Amu Darya and Syr Darya basins. These analyses reveal that irrigated agriculture has remained highly persistent across the region and, in many areas, has intensified rather than declined since the post-Soviet transition.

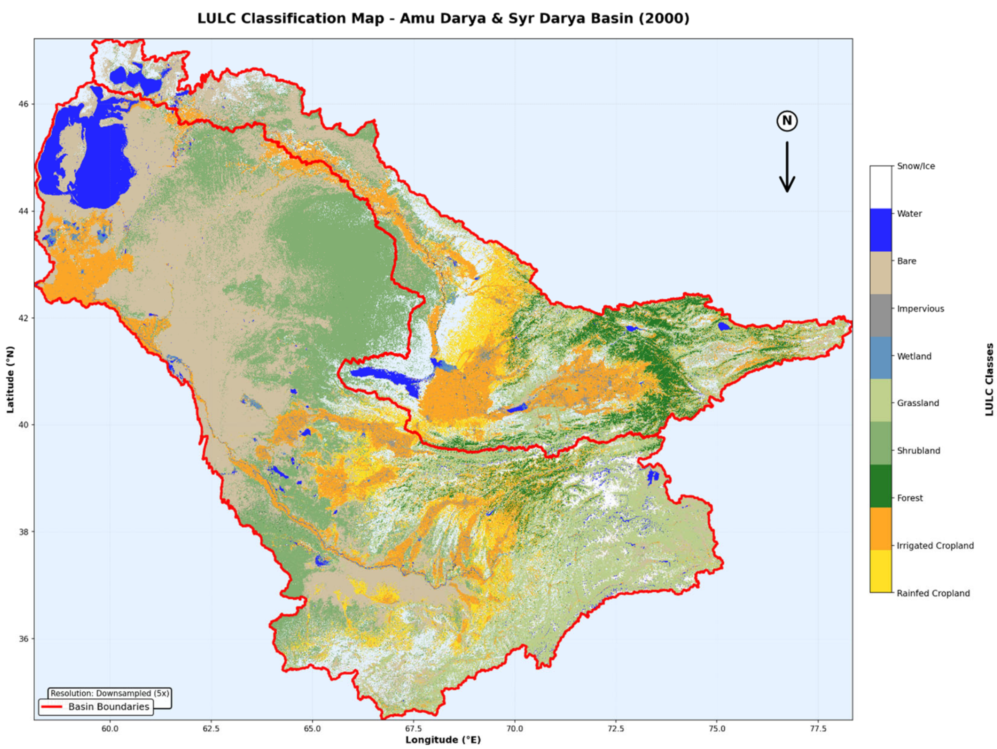

Figure 1. Land use and land cover (LULC) classification of the Amu Darya and Syr Darya basin derived from satellite observations for the year 2000. The map illustrates the spatial distribution of major land cover classes, including irrigated cropland, rainfed cropland, forest, shrubland, grassland, wetlands, 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.

5.1. Changes in Irrigated Area

Satellite-based land use and land cover analyses indicate that irrigated agriculture continues to dominate agricultural landscapes across Central Asia, particularly in the downstream plains of the Amu Darya and Syr Darya river basins. Irrigated croplands remain concentrated in major agricultural regions such as the Fergana Valley, the Amu Darya delta, and irrigated oases across Uzbekistan, Turkmenistan, and southern Kazakhstan. These areas rely heavily on extensive canal systems that divert water from major rivers to support agricultural production.

Time-series analysis of satellite imagery suggests that irrigated agriculture has not undergone large-scale contraction since the collapse of the Soviet Union. Instead, irrigated land has generally remained stable in spatial extent, with some localized expansion occurring in certain regions. More importantly, many areas show evidence of agricultural intensification rather than spatial expansion alone. Satellite-derived vegetation indicators reveal increasing cropping intensity in several irrigation zones, reflected by extended periods of vegetation activity and multiple seasonal peaks in vegetation indices. These patterns indicate a transition toward more intensive irrigation practices and increased agricultural productivity within existing irrigated areas.

5.2. Crop Structure and Agricultural Intensification

The structure of irrigated agriculture in Central Asia remains strongly influenced by historical cropping patterns established during the Soviet period. Cotton and wheat continue to dominate irrigated agriculture across much of the region, particularly in Uzbekistan and Turkmenistan, where cotton production has historically played a central role in national agricultural economies. According to regional agricultural statistics, wheat, barley, and cotton together account for a large proportion of harvested agricultural land across Central Asia [1].

In addition to cotton and wheat, rice and maize are also cultivated in irrigated areas, particularly in regions with more abundant water resources. Rice cultivation is especially significant because it is one of the most water-intensive crops grown in the region, placing additional pressure on irrigation systems in downstream river basins. Changes in crop structure have occurred in some countries as part of agricultural reforms aimed at diversifying production and improving food security. For example, several countries have promoted the expansion of wheat cultivation to reduce reliance on imported grain.

Satellite-based analysis of crop phenology also indicates increasing cropping intensity in certain regions, including transitions from single cropping to double cropping systems. These changes are reflected in the timing and magnitude of vegetation index peaks throughout the growing season and suggest increasing pressure on irrigation systems to sustain higher levels of agricultural productivity.

5.3. Vegetation Dynamics and Productivity

Vegetation dynamics across irrigated landscapes can be effectively monitored using satellite-derived vegetation indices such as the Normalized Difference Vegetation Index (NDVI). NDVI time-series analysis reveals strong seasonal patterns in vegetation growth across both the Amu Darya and Syr Darya basins, with rapid green-up occurring during spring, peak vegetation activity during late spring and early summer, and declining vegetation activity toward the autumn harvest period.

Comparative analysis between the two basins shows that the Syr Darya basin generally exhibits higher NDVI values and larger seasonal amplitudes than the Amu Darya basin, suggesting higher overall vegetation productivity in many parts of this catchment. However, NDVI time series also reveal significant interannual variability in vegetation productivity across both basins. Years characterized by reduced snow persistence or lower water availability often exhibit lower NDVI peak values, indicating reduced vegetation growth and agricultural productivity.

In recent years, vegetation dynamics appear to have become increasingly sensitive to hydroclimatic variability, particularly in the Amu Darya basin. Declines in vegetation greenness during dry years suggest that agricultural production in some regions is becoming more vulnerable to fluctuations in water availability, highlighting the growing importance of reliable irrigation supply.

5.4. Consumptive Water Use and Evapotranspiration

Actual evapotranspiration (ETa) provides an important indicator of consumptive water use in irrigated agricultural systems. Satellite-based ETa products allow basin-scale assessment of water consumption associated with crop growth and irrigation practices (Figure 2). These approaches have been widely applied in Central Asia to quantify agricultural water use and evaluate irrigation performance at regional scales [19,21]. Analysis of ETa patterns across the Amu Darya and Syr Darya basins shows pronounced seasonal cycles, with minimal evapotranspiration during winter months and peak values occurring during the main growing season when crop water demand is highest.

The timing of peak evapotranspiration closely corresponds with periods of maximum vegetation activity, reflecting the combined influence of crop growth and irrigation supply. While both basins exhibit similar seasonal patterns, the Syr Darya basin generally shows slightly more stable evapotranspiration dynamics, whereas the Amu Darya basin exhibits greater interannual variability. These differences are partly related to variations in snow storage and water availability between the two basins.

Despite increasing emphasis on irrigation efficiency and modernization policies in recent decades, satellite-derived ETa trends suggest that basin-scale consumptive water use has not declined substantially. In some areas, evapotranspiration has remained stable or increased slightly, reflecting intensified cropping activity and sustained irrigation demand. This finding indicates that improvements in irrigation efficiency may have been partially offset by agricultural intensification and expansion of crop production, a pattern also observed in regional water-use assessments [21,23].

The persistence of high consumptive water use has important implications for irrigation sustainability in Central Asia. Under conditions of increasing climate variability and declining cryosphere-derived water supply, continued high irrigation demand may intensify pressure on water resources and increase competition among agricultural, energy, and environmental water uses. These trends highlight the importance of integrating satellite-based water monitoring with irrigation management policies to support more sustainable and adaptive water allocation across the region's major river basins.

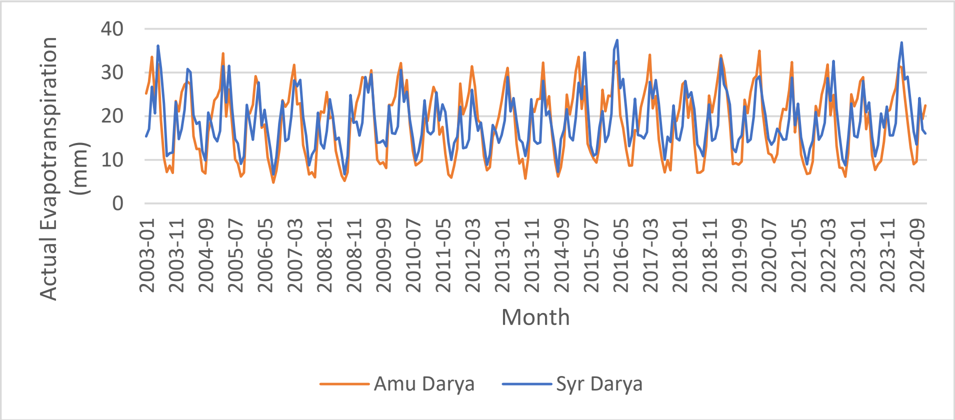

Figure 2. Monthly actual evapotranspiration (AET) in the Syr Darya and Amu Darya catchments from 2003 to 2024 derived from Earth Observation datasets. The time series shows pronounced seasonal cycles with summer maxima linked to peak vegetation activity and irrigation demand, as well as interannual variability associated with snow and glacier melt contributions, highlighting the influence of cryosphere-driven hydrology on catchment-scale water availability.

Table 3. 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	**Sources**
Temperature	Warming projected at +2–6 °C by 2100, especially in summer and autumn	Increased heat stress, higher evapotranspiration, and greater drought risk	[12–14,16]

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Precipitation	Spatial variability with declining summer precipitation and possible winter increases in some areas	Greater seasonal imbalance in water availability and increased drought frequency	[12,15,16]
River Runoff & Hydrology	Earlier spring discharge peaks and reduced summer runoff due to glacier retreat	Reduced water availability during peak irrigation periods	[13,15,34]
Irrigation Water Demand	Increasing irrigation requirements for cotton and wheat (up to ~50% in some regions)	Higher pressure on limited water resources	[17,35–37]
Crop Yields	Declines reported in several regions (−20–50%) with some spatial variability	Higher vulnerability of agricultural production and rural livelihoods	[36,38–40]
Water Scarcity	High irrigation demand combined with ageing infrastructure and inefficient water use	Growing water stress and potential transboundary tensions	[11,13,18]

6. Irrigation Infrastructure and Efficiency Challenges

Despite the extensive irrigation infrastructure developed across Central Asia during the twentieth century, irrigation systems across the region continue to face significant operational and environmental challenges. Much of the infrastructure currently in use was constructed during the Soviet period and was designed under conditions of centralized management, abundant water allocation, and extensive state support for maintenance and operation. Following the dissolution of the Soviet Union, many irrigation systems experienced declining investment in infrastructure maintenance, leading to deterioration of canals, pumping stations, and drainage systems. As a result, irrigation efficiency across much of Central Asia remains relatively low compared with global standards [11,23].

One of the most significant sources of inefficiency in Central Asian irrigation systems is water loss during conveyance through large canal networks. Many irrigation canals remain unlined or poorly maintained, allowing substantial seepage losses as water is transported from river diversion points to agricultural fields. Studies indicate that only about 46% of diverted irrigation water ultimately reaches crops, while the remainder is lost through conveyance inefficiencies, evaporation, and leakage within irrigation infrastructure [19,26]. As a result, overall water utilisation efficiency across the region often remains below 40%, placing considerable pressure on river systems that supply irrigation water.

In addition to conveyance losses, drainage and waterlogging problems remain widespread in many irrigated areas. Inefficient irrigation practices and inadequate drainage infrastructure can lead to rising groundwater levels and waterlogging of agricultural soils, particularly in downstream delta regions of the Amu Darya and Syr Darya rivers. Excess irrigation water that infiltrates into soils or irrigation canals can accumulate in shallow groundwater systems, altering local hydrological balances and contributing to long-term land degradation. These processes are particularly common in low-lying irrigated landscapes where natural drainage is limited and irrigation return flows accumulate within the soil profile [22,26].

Soil salinisation represents one of the most serious environmental consequences associated with long-term irrigation in Central Asia. In arid environments, evaporation of irrigation water can leave behind dissolved salts that gradually accumulate within agricultural soils. Without adequate drainage systems to remove saline water from the root zone, salt concentrations can reach levels that significantly reduce crop productivity and degrade soil quality. Widespread soil salinisation has been reported across large irrigated areas of Uzbekistan, Turkmenistan, and Kazakhstan, where decades of intensive irrigation combined with inefficient drainage have led to declining agricultural productivity and increasing land degradation [1,5].

Groundwater dynamics also play an important role in irrigation system performance across Central Asia. In some regions, groundwater provides a supplementary source of irrigation water, particularly during periods of drought. However, groundwater resources remain relatively underutilized in many parts of the region compared with surface water irrigation systems. At the same time, excessive irrigation and canal seepage often contribute to artificial groundwater recharge, raising water tables and exacerbating problems of soil salinity and waterlogging in irrigated landscapes [26,42]. Managing the interaction between surface irrigation systems and groundwater resources therefore represents an important challenge for improving irrigation efficiency and long-term land productivity.

Together, these infrastructural and environmental challenges highlight the need for substantial modernization of irrigation systems across Central Asia. Improving canal lining, upgrading pumping systems, rehabilitating drainage infrastructure, and implementing more efficient irrigation technologies are widely recognised as key priorities for improving water-use efficiency and reducing environmental degradation. Addressing these issues is essential not only for maintaining agricultural productivity but also for ensuring the long-term sustainability of water resources within the Amu Darya and Syr Darya river basins.

7. 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.

7.1. Remote Sensing for Irrigation Monitoring

Satellite-based Earth observation has become an essential tool for monitoring irrigated agriculture across Central Asia. Multi-sensor satellite datasets provide continuous observations of land surface conditions, enabling large-scale mapping of irrigated areas, crop dynamics, and water consumption patterns. Optical satellite imagery combined with time-series vegetation indices allows accurate identification of irrigated cropland based on characteristic phenological signatures associated with irrigated crop growth.

Remote sensing techniques have been widely applied to map crop distribution and irrigation patterns across Central Asian agricultural regions. Object-based image analysis and machine learning classification methods using satellite datasets such as Landsat, RapidEye, and MODIS have demonstrated strong capability in identifying major crops including cotton and winter wheat and mapping irrigated agricultural landscapes [19,20]. These approaches allow detailed monitoring of cropping patterns and seasonal irrigation practices and can be integrated with crop water requirement models to estimate irrigation demand at regional scales.

In addition to land use mapping, satellite observations can also provide valuable information on agricultural water consumption. Remote sensing–derived evapotranspiration products enable basin-scale estimation of consumptive water use associated with crop growth and irrigation practices.

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These datasets allow researchers and water managers to quantify crop-specific water use, evaluate irrigation performance, and assess seasonal water demand across large irrigation systems. Satellite-based monitoring therefore provides a powerful tool for evaluating irrigation efficiency and identifying areas where water management improvements may be needed [21].

7.2. Digital Irrigation and Automation

Digital technologies are increasingly recognised as key drivers of agricultural transformation, offering new opportunities to improve productivity, strengthen climate resilience, and enhance market integration. In Central Asia, however, the adoption of digital innovations in agriculture remains limited and uneven. Structural constraints within the region's digital ecosystem, combined with regulatory and institutional barriers, continue to shape the pace of technological uptake. Digital tools—including climate and weather services, early warning systems, agricultural finance platforms, remote sensing–based monitoring, and digital extension services—have significant potential to support more efficient and climate-resilient farming systems. Yet, most initiatives remain at pilot stages and have not scaled widely across national agricultural sectors [43]. As climate variability intensifies and water resources become increasingly constrained, digital technologies are increasingly viewed as essential for improving resource efficiency, optimising input use, and strengthening agricultural supply chains.

The transformation of agricultural systems in Central Asia has also been shaped by broader institutional changes following the dissolution of the Soviet Union in 1991. The transition from centrally planned irrigation management to more decentralised and market-oriented governance systems altered land tenure, water rights, and agricultural management structures. Institutions such as water user associations were introduced to decentralise irrigation management, although many farmers faced challenges adapting to these new frameworks. At the same time, the region inherited a legacy of extensive irrigation expansion from the Soviet era, when irrigated arable land increased by roughly 60% between 1962 and 2002 as agricultural policies prioritised expansion of cultivated area rather than improvements in water productivity [11,24]. Combined with large-scale cotton monoculture, these practices contributed to severe environmental impacts, including soil salinisation, desertification, and the dramatic shrinkage of the Aral Sea [1,44].

Today, irrigated agriculture remains the dominant water user in Central Asia, accounting for more than 90% of water withdrawals in most countries and around 75% in Kazakhstan [1,8]. Surface water from the Amu Darya and Syr Darya rivers supplies the majority of irrigation demand, while groundwater remains a relatively minor source. However, ageing infrastructure, fragmented irrigation networks, and limited coordination between farm-level and inter-farm water systems have resulted in low irrigation efficiency—often below 50%—and significant conveyance losses in canals and fields [11,23]. These inefficiencies contribute to environmental degradation, including waterlogging, soil salinity, declining water quality, and broader ecosystem stress across irrigated landscapes. The cumulative effects are particularly evident in the Aral Sea Basin, where the expansion of irrigated agriculture has been closely linked to large-scale reductions in inflow and water storage, leaving rural communities highly vulnerable to water shortages and governance challenges [22].

In response, technological modernisation and digitalisation of irrigation systems are increasingly viewed as key pathways for improving water security and environmental sustainability. While traditional irrigation practices such as flood and furrow irrigation still dominate, emerging strategies emphasise the adoption of more efficient technologies—including drip and sprinkler irrigation—as well as modern monitoring and management systems. Innovations such as canal rehabilitation, flow measurement technologies, telemetry networks, automated control structures, and remote sensing–based decision-support systems can enable real-time water monitoring, improve allocation transparency, and reduce conveyance losses. At the same time, climate change is expected to intensify pressure on irrigation systems through rising temperatures, glacier retreat, and increasing variability in precipitation. Addressing these challenges will require integrated approaches that combine technological innovation with institutional reform, improved water governance, and stronger regional cooperation to ensure sustainable management of land and water resources across Central Asia.

Table 4. Summary of irrigation challenges and responses in Central Asia.

Challenge	Description	Response / Transformation	**Sources**
Water scarcity	High irrigation water use, low efficiency, climate change impacts	Modernization, efficiency improvements	[2,11,22,23]
Environmental degradation	Salinization, waterlogging, Aral Sea shrinkage	Crop structure adjustment, technology adoption	[1,45,46]
Outdated infrastructure	Inefficient systems, high losses at conveyance and field levels	Investment in new technologies	[11,22]
Governance and institutional gaps	Top-down reforms, lack of local input, poor coordination	Participatory governance, regional cooperation	[15,47]
Climate change	Increased temperature, variable precipitation, glacier melt	Integrated water management and adaptation strategies	[2,15,17,36]

7.3. GIS, AI, and Decision Support Systems

Across Central Asia's major irrigation oases and river deltas, Earth observation (EO) technologies have become increasingly important for monitoring water use, diagnosing inefficiencies, and supporting irrigation management (Table 5). Satellite observations from optical sensors, combined with complementary datasets such as satellite laser altimetry, now enable detailed tracking of reservoir storage, irrigation withdrawals, and crop water consumption at regional scales. These approaches allow crop-specific water accounting and provide insights into seasonal irrigation practices, including water use during soil preparation and non-growing periods [21]. In addition, remote sensing methods using object-based image analysis and machine-learning classifiers have demonstrated strong capability in mapping irrigated crops such as cotton and winter wheat. By integrating datasets from sensors such as RapidEye, Landsat, and MODIS with crop water models, these methods can estimate irrigation requirements, identify cropping patterns, and support more informed water allocation and irrigation planning across large agricultural landscapes [19,20].

EO-based analyses are increasingly complemented by GIS-based decision-support frameworks that help identify groundwater potential and guide conjunctive water management strategies. Multi-criteria spatial analysis integrating soil characteristics, geology, topography, land cover, and hydrological proximity has shown promising results in identifying groundwater recharge zones and potential irrigation sources in parts of Uzbekistan [42]. Groundwater also plays an important buffering role during drought periods in irrigation regions such as the Fergana Valley and Khorezm, where recharge often occurs through canal seepage and excessive irrigation return flows [26]. More recently, EO and GIS workflows have been combined with artificial intelligence and machine-learning techniques to automate crop classification and estimate irrigation demand at pixel scales, improving the precision of seasonal planning and resource allocation in large irrigation networks [19,20].

Despite these technological advances, irrigation systems across Central Asia continue to face significant challenges, including limited water availability, inefficient irrigation practices, and growing environmental pressures. Average irrigation efficiency in many systems remains below 50%, while excessive withdrawals from the Amu Darya and Syr Darya rivers have contributed to widespread ecological degradation, including soil salinisation and the dramatic shrinkage of the Aral Sea [23,48]. Although EO and GIS technologies now provide powerful tools to monitor irrigation dynamics and evaluate management interventions at basin scales, important knowledge gaps

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remain, particularly regarding groundwater dynamics and the ecological thresholds of irrigation-driven hydrological changes. Continued integration of EO, GIS, and advanced modelling frameworks will therefore be critical for supporting evidence-based water governance, improving irrigation efficiency, and ensuring the long-term sustainability of irrigated agriculture across Central Asia and the Aral Sea basin.

Table 5. 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	[21]
Object-based classification + AI	Fergana Valley, Uzbekistan	Crop mapping, irrigation water requirement estimation	[19,20]
GIS-based MCDA	Bostanlik district, Uzbekistan	Groundwater potential zoning	[42]
Water balance modeling	Fergana Valley, Khorezm	Quantify groundwater recharge/discharge	[26]
Hydrological modeling (MIKE-SHE)	Nukus irrigation area	Groundwater regulation planning	[49]

8. Transboundary Water Governance and Regional Cooperation

Transboundary water systems are a defining feature of global hydropolitics, with more than 300 international river basins spanning over 150 countries and supporting more than 40% of the world's population [50]. Central Asia exemplifies the complexity of managing shared water resources, where major rivers such as the Amu Darya and Syr Darya traverse multiple national borders and underpin agricultural production, energy generation, and ecosystem health. The Aral Sea Basin, shared by Afghanistan, Tajikistan, Uzbekistan, Turkmenistan, and Kazakhstan, receives approximately 77 km^3 of water annually, of which nearly 96% is used for agriculture [51]. Additional transboundary rivers—including the Chu, Talas, Tarim, and Irtysh—further reinforce the region's hydrological interconnectedness. However, upstream and downstream states have fundamentally different priorities: Kyrgyzstan and Tajikistan rely heavily on hydropower generation and reservoir storage for winter electricity production, while downstream countries such as Uzbekistan, Turkmenistan, and Kazakhstan depend on reliable summer flows to sustain irrigation-intensive agriculture. This seasonal mismatch between water storage and irrigation demand has been a persistent source of regional tension and has contributed to large-scale environmental consequences, most notably the collapse of the Aral Sea ecosystem.

Central Asia also exhibits strong asymmetries in water availability and dependence on transboundary flows (Figure 3). Kyrgyzstan is the only country whose renewable water resources originate almost entirely within its own territory, while other countries rely heavily on upstream inflows. Uzbekistan and Turkmenistan are particularly vulnerable, with more than 90% of their renewable water resources originating outside their national borders. Kazakhstan faces somewhat lower external dependence (around 50%), but internal disparities in water distribution remain significant, with abundant resources in eastern regions and chronic scarcity in western and southern areas [52]. These structural imbalances, combined with the region's heavy reliance on irrigation—which accounts for over 90% of water use in several countries—intensify competition for water and heighten sensitivity to upstream management decisions and climate variability.

Recognising these challenges, Central Asian states have established several cooperative frameworks aimed at managing shared water resources. Key initiatives include the 1992 Almaty Agreement on equitable water distribution, the establishment of the Interstate Commission for Water Coordination (ICWC), the Nukus Declaration on sustainable development in the Aral Sea Basin, and

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the 1998 Syr Darya Basin Agreement for coordinated water–energy management. These agreements represent important steps toward regional water diplomacy and basin-level cooperation. Nevertheless, implementation remains uneven due to competing national priorities, limited data sharing, and weak enforcement mechanisms. As a result, transboundary water governance in Central Asia continues to be shaped not only by hydrological realities but also by broader geopolitical, economic, and energy-security considerations. Strengthening regional cooperation, improving information exchange, and developing integrated water–energy–food governance frameworks will therefore be critical for ensuring sustainable water management and reducing future conflicts in the region.

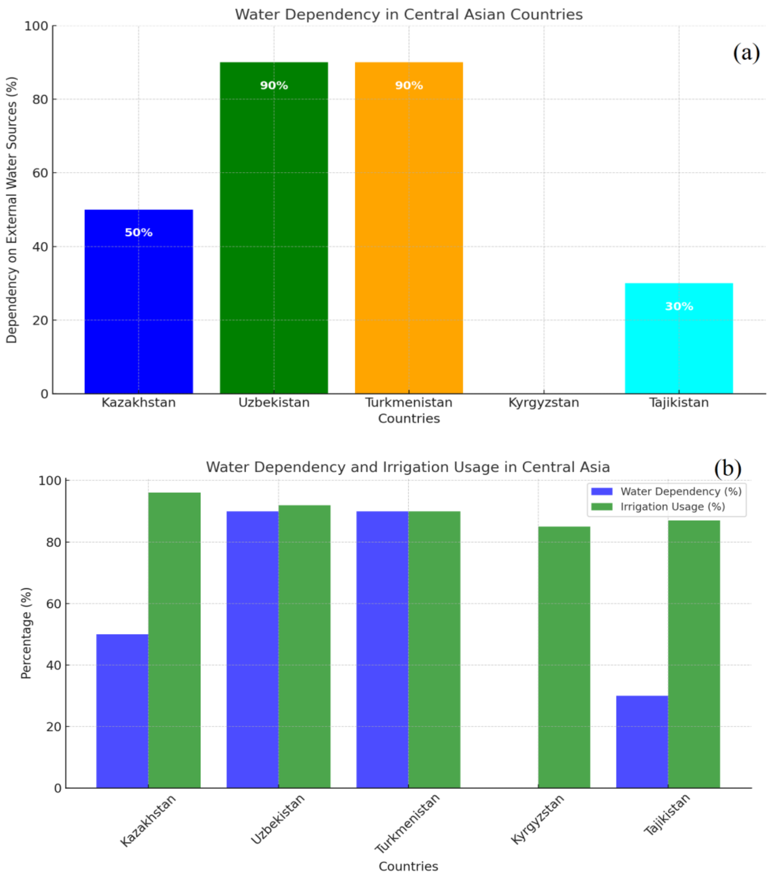

Figure 3. (a) Dependence of Central Asian countries on external water resources. Graph (b) shows the dependence and irrigation needs of Central Asian countries on transboundary water resources in percentage terms: The blue columns indicate the level of dependence on transboundary water resources. The green columns show the proportion of water used for irrigation.

9. Future Outlook for Irrigated Agriculture

The sustainability of irrigated agriculture in Central Asia will increasingly depend on how irrigation systems respond to future climatic, hydrological, and socio-economic pressures. The region's strong reliance on irrigated agriculture, combined with growing climate variability and transboundary water dependencies, creates a complex set of challenges for agricultural water management. Projections of rising temperatures, changing precipitation patterns, and declining cryosphere-derived water supply suggest that irrigation systems across the Amu Darya and Syr Darya basins will face increasing stress in coming decades. Addressing these challenges will require both technological and institutional adaptations to ensure that agricultural production can be sustained under changing environmental conditions.

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9.1. Climate Change Impacts on Irrigation

Climate change is expected to significantly affect irrigation systems across Central Asia through rising temperatures, increased evapotranspiration, and changing hydrological regimes. Temperature projections for the region indicate increases of approximately 2–6 °C by the end of the twenty-first century, which will increase evaporative demand and raise crop water requirements [13,14]. Higher evapotranspiration rates will increase irrigation demand for major crops such as cotton and wheat and intensify pressure on already limited water resources.

At the same time, declining snow storage and accelerating glacier retreat in the Tian Shan and Pamir mountains are expected to reduce the natural buffering capacity that historically maintained stable summer river flows [15,33]. Earlier snowmelt and reduced glacier mass may initially increase spring runoff but are likely to reduce water availability during the summer growing season when irrigation demand is highest. As glacier mass continues to decline, the long-term contribution of meltwater to river flows may decrease, potentially leading to reduced water supply for downstream agricultural regions.

These changes are likely to increase the frequency and severity of drought events affecting irrigated agriculture. Climate-driven reductions in river flows in the Amu Darya and Syr Darya basins have been estimated at between 5% and 30% during drought periods in some studies, which could significantly affect agricultural productivity and water security across the region [17,18]. As a result, irrigation systems that depend heavily on cryosphere-derived water resources will become increasingly vulnerable to climate variability.

9.2. Future Irrigation Demand

Future irrigation demand in Central Asia will be shaped by both climatic and socio-economic factors. Rising temperatures and increasing evapotranspiration are expected to increase crop water requirements, particularly for water-intensive crops such as cotton and rice. At the same time, population growth and economic development may increase pressure to expand agricultural production and maintain food security within the region.

In many countries, irrigated agriculture remains a major contributor to national economies and rural employment. As a result, there may be continued pressure to maintain or expand irrigated cropping areas despite increasing water scarcity. Satellite-based analyses indicate that agricultural intensification rather than spatial expansion has been a dominant trend in recent decades, with increased cropping intensity and extended growing seasons contributing to sustained irrigation demand across many regions.

However, the persistence of high irrigation demand under conditions of declining water availability may lead to increasing competition for water among agricultural, energy, and environmental sectors. Downstream regions that depend heavily on transboundary water flows may be particularly vulnerable to reductions in water supply. Without improvements in irrigation efficiency and water governance, rising irrigation demand could exacerbate existing water stress and increase the risk of conflicts over water allocation.

9.3. Adaptation Strategies

Ensuring the long-term sustainability of irrigated agriculture in Central Asia will require the adoption of adaptation strategies that improve water-use efficiency and reduce vulnerability to climate variability. One important strategy involves diversification of cropping systems toward crops that require less water or are more resilient to drought conditions. Reducing reliance on water-intensive crops such as cotton and rice in certain regions could help lower irrigation demand and improve the resilience of agricultural systems.

Improving irrigation efficiency is another critical priority. Modern irrigation technologies, including drip and sprinkler irrigation systems, can significantly reduce water losses compared with traditional flood irrigation methods. Rehabilitation of irrigation infrastructure, improved canal lining, and better drainage systems can also reduce conveyance losses and improve water delivery efficiency across irrigation networks.

Equally important is the improvement of water allocation mechanisms and governance frameworks. Basin-scale water accounting, supported by Earth observation technologies and digital monitoring systems, can provide more accurate assessments of water use and availability. Integrating satellite-based monitoring with water management policies could help improve transparency in water allocation and support more adaptive irrigation management under changing climatic conditions.

Ultimately, sustainable irrigation in Central Asia will require coordinated action across multiple levels of governance, including national policy reforms, technological innovation, and strengthened regional cooperation among countries sharing transboundary river systems. By aligning agricultural production strategies with available water resources and improving the efficiency of irrigation systems, Central Asian countries can better adapt their agricultural systems to the challenges posed by climate change and increasing water scarcity.

10. Policy Implications and Pathways Forward

The findings presented in this review highlight the complex interactions between irrigation development, hydroclimatic change, and governance structures that shape the sustainability of irrigated agriculture in Central Asia. Despite substantial policy reforms and technological advances in recent decades, irrigation systems across the region continue to experience high consumptive water use, ageing infrastructure, and increasing vulnerability to climate variability. Addressing these challenges requires coordinated policy responses that integrate improved water accounting, technological innovation, institutional reforms, and strengthened regional cooperation across the transboundary river basins of Central Asia.

10.1. Basin-Scale Water Accounting

One of the most important priorities for improving irrigation sustainability in Central Asia is the development of basin-scale water accounting systems capable of accurately monitoring water withdrawals, consumptive use, and hydrological balances across the Amu Darya and Syr Darya basins. Traditional water management approaches in the region have often focused on water diversion volumes rather than actual consumptive use, which can obscure the true impact of irrigation on basin water resources.

Satellite-derived evapotranspiration and water storage observations now provide powerful tools for estimating basin-scale water consumption and identifying discrepancies between water allocation policies and actual water use [21,53]. Integrating these data into water management frameworks can help improve transparency in water allocation and support more effective planning of irrigation withdrawals. Basin-scale water accounting is particularly important in transboundary river basins where upstream water management decisions can significantly affect downstream agricultural production.

10.2. Earth Observation–Based Monitoring

Earth observation technologies offer a transformative opportunity to improve water governance and irrigation management in Central Asia. Satellite observations enable continuous monitoring of irrigated land use, crop dynamics, surface water storage, and evapotranspiration across large river basins, providing objective and spatially consistent information that is often unavailable through conventional monitoring systems.

Integrating EO-based monitoring into water management institutions could improve early detection of drought conditions, enhance assessment of irrigation performance, and support adaptive water allocation decisions. Satellite-based monitoring can also facilitate cross-border data sharing among countries, helping to build trust and transparency in transboundary water governance. As remote sensing technologies continue to improve in spatial resolution and temporal coverage, their role in supporting water management decisions is likely to become increasingly important.

10.3. Policy and Institutional Reforms

While technological innovations can provide valuable tools for improving irrigation management, sustainable water use ultimately depends on effective policy and institutional frameworks. Many irrigation systems in Central Asia continue to operate under institutional arrangements inherited from the Soviet period, where water allocation was primarily driven by production targets rather than long-term water sustainability.

Policy reforms should therefore focus on aligning water allocation mechanisms with basin-scale water availability and environmental sustainability objectives. This may involve introducing regulatory frameworks that limit consumptive water use, strengthening enforcement of water allocation agreements, and improving coordination among agencies responsible for water management, agriculture, and energy production. Strengthening the capacity of Water User Associations and other local water management institutions may also help improve irrigation governance and encourage more efficient water use at the farm level [22,29].

10.4. Integrated Water–Energy–Food Governance

The sustainability of irrigation systems in Central Asia is closely linked to the broader water–energy–food nexus that shapes resource management across the region. Upstream countries rely heavily on hydropower generation, while downstream countries depend on reliable water flows for irrigated agriculture. Balancing these competing demands requires coordinated planning that considers the interdependencies among water, energy, and food systems.

Integrated governance frameworks that explicitly address these linkages could help reduce tensions between upstream and downstream countries while improving the efficiency of water resource use. For example, coordinated reservoir operation strategies and water–energy exchange agreements could help align hydropower production schedules with irrigation water requirements. Such approaches may also support climate adaptation by improving flexibility in water allocation under changing hydrological conditions.

10.5. Strengthening Regional Cooperation

Finally, strengthening regional cooperation is essential for ensuring the long-term sustainability of water resources in Central Asia. Institutions such as the Interstate Commission for Water Coordination (ICWC) and the International Fund for Saving the Aral Sea (IFAS) already provide important platforms for dialogue and coordination among countries sharing transboundary water resources. However, further efforts are needed to enhance the effectiveness of these institutions and improve cooperation among riparian states.

Improved data sharing, joint hydrological monitoring programs, and coordinated infrastructure planning could help strengthen trust and collaboration among countries in the region. The integration of satellite-based monitoring systems into regional water management frameworks may also help reduce uncertainty and support more transparent decision-making. As climate change continues to alter hydrological conditions across the region, cooperative approaches to water governance will become increasingly important for balancing agricultural production, energy generation, and ecosystem protection within the shared river basins of Central Asia.

Together, these policy pathways highlight the importance of combining technological innovation with institutional reforms and regional cooperation to ensure the sustainable management of irrigation systems in Central Asia. By aligning irrigation development with available water resources and integrating modern monitoring technologies into governance frameworks, Central Asian countries can improve resilience to climate change while safeguarding the long-term productivity of their agricultural systems.

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11. Conclusions

Irrigated agriculture remains central to the economies and food systems of Central Asia, yet its sustainability is increasingly challenged by structural, environmental, and institutional pressures. Much of the region's irrigation infrastructure and management practices continue to rely on systems established during the Soviet period, which were designed to maximise agricultural production—particularly cotton cultivation—rather than optimise water efficiency. Although significant policy reforms and institutional restructuring have occurred since independence, including the creation of national water authorities and regional governance mechanisms, overall consumptive water use in irrigation remains high. Ageing infrastructure, inefficient irrigation methods, and persistent conveyance losses continue to place considerable pressure on regional water resources.

At the same time, climate change is altering the hydrological foundations that support irrigated agriculture in the region. Rising temperatures, increasing evapotranspiration, and declining glacier and snow storage in the Tian Shan and Pamir mountains are reducing the natural cryospheric buffering that historically sustained river flows during the irrigation season [13,15,33]. These changes increase the vulnerability of downstream agricultural systems and intensify competition for water among agricultural, energy, and environmental sectors. Under these conditions, improving water-use efficiency and strengthening adaptive water management will be essential to maintaining agricultural productivity.

Emerging technological solutions offer new opportunities to address these challenges. Earth observation technologies now provide consistent and transparent basin-scale monitoring of irrigated land use, crop dynamics, evapotranspiration, and water availability across the Amu Darya and Syr Darya basins. When integrated with digital irrigation management systems and improved hydrological modelling, these tools can support more accurate water accounting, enhance decision-making, and improve transparency in transboundary water management.

Ultimately, ensuring the long-term sustainability of irrigated agriculture in Central Asia will require a combination of policy reform, technological innovation, and strengthened regional cooperation. Basin-scale water governance, improved irrigation efficiency, and coordinated management of shared river systems will be critical to balancing agricultural production with environmental sustainability and water security under a changing climate.

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References

1. Han, S.; Xin, P.; Li, H.; Yang, Y. Evolution of agricultural development and land–water–food nexus in Central Asia. *Agric. Water Manag.* **2022**, *273*. https://doi.org/10.1016/j.agwat.2022.107874

 doi:10.20944/preprints202604.1442.v1

2. Li, Z.; Fang, G.; Chen, Y.; Duan, W.; Mukanov, Y. Agricultural water demands in Central Asia under 1.5 °C and 2.0 °C global warming. *Agric. Water Manag.* **2020**, *231*. https://doi.org/10.1016/j.agwat.2020.106020
3. Ma, Y.; Li, Y.; Huang, G. A bi-level chance-constrained programming method for quantifying the effectiveness of water-trading to water-food-ecology nexus in Amu Darya River basin of Central Asia. *Environ. Res.* **2020**, *183*. https://doi.org/10.1016/j.envres.2020.109229
4. Tang, X.; Huang, Y.; Pan, X.; Liu, T.; Ling, Y.; Peng, J. Managing the water–agriculture–environment–energy nexus: Trade-offs and synergies in an arid area of Northwest China. *Agric. Water Manag.* **2024**, *295*. https://doi.org/10.1016/j.agwat.2024.108776
5. Liu, Y.; Wang, P.; Gojenko, B.; Yu, J.; Wei, L.; Luo, D.; Xiao, T. A review of water pollution arising from agriculture and mining activities in Central Asia: Facts, causes and effects. *Environ. Pollut.* **2021**, *291*. https://doi.org/10.1016/j.envpol.2021.118209
6. Orazaliev, K.; Mukasheva, A.; Ybyray, N.; Nurekeshov, T. Current regulation of water relations in Central Asia. *Reg. Sci. Policy Pract.* **2024**, *16*. https://doi.org/10.1016/j.rspp.2024.100038
7. Baranwal, P.; Nayak, S.; Jindal, M. River policy: Navigating Asia's water needs in a changing climate. In *River Basin Ecohydrology in the Indian Sub-Continent*; **2024**. https://doi.org/10.1016/B978-0-323-91545-8.00017-6
8. Wang, X.; Chen, Y.; Li, Z.; Fang, G.; Wang, Y. Development and utilization of water resources and assessment of water security in Central Asia. *Agric. Water Manag.* **2020**, *240*. https://doi.org/10.1016/j.agwat.2020.106297
9. Gao, P.; Li, Y.; Huang, G.; Su, Y. An integrated Bayesian LS-SVM factorial-analysis method for inferring inflow from the Amu Darya to the Aral Sea. *J. Hydrol.* **2021**, *594*. https://doi.org/10.1016/j.jhydrol.2020.125909
10. Thevs, N.; Aliev, K.; Lleshi, R. Water productivity of tree windbreak agroforestry systems in irrigated agriculture: An example from Ferghana Valley, Kyrgyzstan. *Trees For. People* **2021**, *4*. https://doi.org/10.1016/j.tfp.2021.100085
11. Lioubimtseva, E. Food security factors and trends in Central Asia. In *Encyclopedia of Food Security and Sustainability*; **2018**. https://doi.org/10.1016/B978-0-08-100596-5.21983-5
12. Didovets, I.; Lobanova, A.; Krysanova, V.; Menz, C.; Babagalieva, Z.; Nurbatsina, A.; Gavrilenko, N.; Khamidov, V.; Umirbekov, A.; Qodirov, S.; et al. Central Asian rivers under climate change: Impacts assessment in eight representative catchments. *J. Hydrol. Reg. Stud.* **2021**, *34*. https://doi.org/10.1016/j.ejrh.2021.100779
13. Mannig, B.; Pollinger, F. Impacts of climate change in Central Asia. In *Encyclopedia of the Anthropocene*; **2018**. https://doi.org/10.1016/B978-0-12-809665-9.09751-2
14. Lioubimtseva, E.; Henebry, G. Climate and environmental change in arid Central Asia: Impacts, vulnerability, and adaptations. *J. Arid Environ.* **2009**, *73*. https://doi.org/10.1016/j.jaridenv.2009.04.022
15. Sorg, A.; Mosello, B.; Shalpykova, G.; Allan, A.; Hill Clarvis, M.; Stoffel, M. Coping with changing water resources: The case of the Syr Darya river basin in Central Asia. *Environ. Sci. Policy* **2014**, *43*. https://doi.org/10.1016/j.envsci.2013.11.003
16. Lobanova, A.; Didovets, I.; Menz, C.; Umirbekov, A.; Babagalieva, Z.; Hattermann, F.; Krysanova, V. Rapid assessment of climate risks for irrigated agriculture in the Aral Sea Basin. *Agric. Water Manag.* **2021**, *243*. https://doi.org/10.1016/j.agwat.2020.106381
17. Tian, J.; Zhang, Y. Detecting changes in irrigation water requirement in Central Asia under CO_2 fertilization and land use changes. *J. Hydrol.* **2020**, *583*. https://doi.org/10.1016/j.jhydrol.2019.124315
18. Duan, W.; Chen, Y.; Zou, S.; Nover, D. Managing the water–climate–food nexus for sustainable development in Turkmenistan. *J. Clean. Prod.* **2019**, *220*. https://doi.org/10.1016/j.jclepro.2019.02.040
19. Conrad, C.; Dech, S.; Hafeez, M.; Lamers, J.; Tischbein, B. Remote sensing and hydrological measurement-based irrigation performance assessments in the upper Amu Darya Delta. *Phys. Chem. Earth* **2013**, *61*. https://doi.org/10.1016/j.pce.2013.05.002
20. Conrad, C.; Lamers, J.; Ibragimov, N.; Löw, F.; Martius, C. Analysing irrigated crop rotation patterns in arid Uzbekistan using remote sensing. *J. Arid Environ.* **2016**, *124*. https://doi.org/10.1016/j.jaridenv.2015.08.008

21. Ragettli, S.; Kreiner, A.; Yakovlev, A.; Anarbekov, O.; Al-Zu'bi, M.; Urazkeldiyev, A.; Siegfried, T. Unraveling agricultural water use in Central Asian irrigation oases using remote sensing. *J. Hydrol. Reg. Stud.* **2025**, *59*. https://doi.org/10.1016/j.ejrh.2025.102414
22. Bekchanov, M.; Ringler, C.; Bhaduri, A.; Jeuland, M. Optimizing irrigation efficiency improvements in the Aral Sea Basin. *Water Resour. Econ.* **2016**, *13*. https://doi.org/10.1016/j.wre.2015.08.003
23. Qin, J.; Duan, W.; Chen, Y.; Dukhovny, V.; Sorokin, D.; Li, Y.; Wang, X. Comprehensive evaluation and sustainable development of water–energy–food–ecology systems in Central Asia. *Renew. Sustain. Energy Rev.* **2022**, *157*. https://doi.org/10.1016/j.rser.2021.112061
24. Lioubimtseva, E.; Cole, R.; Adams, J.M.; Kapustin, G. Impacts of climate and land-cover changes in arid lands of Central Asia. *J. Arid Environ.* 2005, *62*, 285–308. https://doi.org/10.1016/j.jaridenv.2004.11.005
25. Zhou, Y.; Li, X.; Chen, Y.; Zhang, Q.; Wang, H. Soil salinization and agricultural land degradation under irrigation in Central Asia: Processes, impacts, and mitigation strategies. *Agric. Water Manag.* 2026, *285*, 108345. https://doi.org/10.1016/j.agwat.2025.108345
26. Ibrakhimov, M.; Khamzina, A.; Forkutsa, I.; Paluasheva, G.; Lamers, J.P.A.; Tischbein, B.; Vlek, P.L.G.; Martius, C. Groundwater table and salinity: Spatial and temporal distribution and influence on soil salinization in Khorezm region (Uzbekistan, Aral Sea Basin). *Irrig. Drain.* **2018**, *67*, 147–159.
27. Zhang, Y.; et al. Water productivity of irrigated wheat in Central Asia under changing climate conditions. *Agric. Water Manag.* **2019**, *216*, 186–195.
28. Lee, K.; Jung, H. Water use efficiency and economic productivity in Central Asia: A sectoral analysis. *Water Policy* **2018**, *20*, 123–139.
29. Hamidov, A.; Helming, K.; Balla, D. Impact of agricultural land use in Central Asia: A review. *Agron. Sustain. Dev.* **2015**, *35*, 123–138.
30. Cai, X.; McKinney, D.C.; Lasdon, L.S. Integrated hydrologic-agronomic-economic model for river basin management. *J. Water Resour. Plan. Manag.* **2003**, *129*, 4–17.
31. Zhou, Y.; Chen, Y.; Li, W.; Zhang, Q. Water resources and their distribution in Central Asia: Implications for transboundary management. *Water* **2019**, *11*, 1234.
32. Fang, G.; Chen, Y.; Li, Z.; Han, S. Environmental consequences of irrigation expansion and water diversion in Central Asia. *Sci. Total Environ.* **2018**, *635*, 120–131.
33. Barandun, M.; Huss, M.; Usubaliev, R.; Azisov, E.; Berthier, E.; Kääb, A.; Hoelzle, M. Multi-decadal mass balance series of three Kyrgyz glaciers derived from in situ measurements. *Cryosphere* **2020**, *14*, 4035–4050.
34. Hou, J.; Cuo, L.; Xu, C.-Y. Climate change impacts on hydrology in Central Asia: A basin-scale assessment. *J. Hydrol.* **2025**, *630*, 130456.
35. Ochege, F.U.; Yuan, Y.; Luo, Y. Irrigation water demand under climate change scenarios in Central Asia. *Agric. Water Manag.* **2025**, *290*, 108556.
36. Babakholov, T.; et al. Climate impacts on irrigated agriculture productivity in Central Asia. *Sustainability* **2022**, *14*, 12345.
37. Kobuliev, D.; et al. Agricultural water management and irrigation efficiency improvements in Central Asia. *Water* **2021**, *13*, 987.
38. Schierhorn, F.; Müller, D.; Beringer, T.; Prishchepov, A.V.; Kuemmerle, T.; Balmann, A. Post-Soviet cropland abandonment and climate impacts on yields in Central Asia. *Glob. Environ. Chang.* **2020**, *60*, 101987.
39. Sommer, R.; Glazirina, M.; Yuldashev, T.; Otarov, A.; Ibragimov, N.; Martius, C. Impact of climate change on wheat yields in Central Asia. *Agric. Ecosyst. Environ.* **2013**, *178*, 78–88.
40. Bobojonov, I.; Aw-Hassan, A. Impacts of climate change on farm income and food security in Central Asia. *Agric. Syst.* **2014**, *123*, 58–70.
41. Akter, S.; Nasher, R. Food security and trade dynamics in Central Asia under climate change. *Food Policy* **2025**, *130*, 102345.
42. Alikhanov, B.; et al. Groundwater dynamics and irrigation interactions in Central Asia: Implications for sustainable water management. *Water* **2021**, *13*, 2456.
43. Tabe-Ojong, M.P.; et al. Digital agriculture and climate resilience in Central Asia: Opportunities and barriers. *Agric. Syst.* **2024**, *214*, 103820.

 doi:10.20944/preprints202604.1442.v1

44. Saiko, T.A.; Zonn, I.S. Irrigation expansion and environmental change in the Aral Sea Basin. *J. Arid Environ.* **2000**, *44*, 345–362.
45. Meybeck, M. Global analysis of river systems: From Earth system controls to Anthropocene syndromes. *Philos. Trans. R. Soc. B* **2009**, *364*, 437–447.
46. Wichelns, D.; Qadir, M. Achieving sustainable irrigation requires effective management of salts, soil salinity, and shallow groundwater. *Agric. Water Manag.* **2015**, *157*, 31–38.
47. Hamidov, A.; Thiel, A.; Zikos, D. Institutional design in transformation: A comparative study of local irrigation governance in Uzbekistan. *Water* **2015**, *7*, 3996–4017.
48. Zakeri, F.; et al. Water use, irrigation efficiency, and environmental sustainability in Central Asia: A systems perspective. *Water* **2022**, *14*, 3567.
49. **Guo, H.; et al. Application of MIKE-SHE model for groundwater and irrigation water management in arid regions: A case study from Central Asia. *J. Hydrol.* 2024, *628*, 129345.**
50. Sarsembekov, T.; Kozhakov, R. International water law and transboundary water management in Central Asia. *Water Int.* **2002**, *27*, 123–135.
51. Kukushkina, N.; Sodikov, J. Water resources management and agricultural water use in the Aral Sea Basin. *Water Policy* **2018**, *20*, 456–472.
52. Pulatov, A.; et al. Water availability and transboundary dependency in Central Asia: Implications for sustainable development. *Sustainability* **2021**, *13*, 9876.
53. Gafurov, A.; et al. Satellite-based water storage and evapotranspiration monitoring for basin-scale water accounting in Central Asia. *Remote Sens.* **2024**, *16*, 1123.

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