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Sustainable Transboundary Water Governance in Central Asia: Challenges, Conflicts, and Regional Cooperation

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Abstract: Sustainable transboundary water governance in Central Asia faces significant challenges, including political tensions, ecological issues, such as the drying Aral Sea, and seasonal hydropower disruptions impacting downstream countries. This study aims to address these problems by examining the complexities of water resource governance in the region, emphasizing the interplay between national interests and regional cooperation. We analyze how social, economic, environmental, and political factors influence water diplomacy among Central Asian states. Key challenges include water scarcity, climate change impacts and the growing tensions over transboundary river basins, particularly in the Aral Sea basin (i.e., the development of the Kushtepa Canal in Afghanistan). The intricate linkages between water, energy, and agriculture further complicate decision-making processes among riparian nations. While recent diplomatic efforts signal a shift towards enhanced regional cooperation, existing agreements remain fragmented, and a sustainable, long-term governance framework is still lacking. Our findings highlight the importance of an integrated, basin-wide approach to transboundary water management. We argue that a cohesive regional water strategy—grounded in international legal frameworks and supported by collaborative governance mechanisms—can mitigate conflicts and promote water security in Central Asia. The significance of this study lies in its potential to inform policy decisions and promote sustainable practices in transboundary water governance, ultimately contributing to the broader goals of sustainable development and regional cooperation.

Keywords: transboundary water management; water security; regional cooperation; hydro–politics; Central Asia; climate change; Aral Sea basin

Academic Editor: Tim Gray

Received: 23 March 2025
Revised: 17 May 2025
Accepted: 26 May 2025
Published: 28 May 2025

Citation: Prniyazova, A.; Turaeva, S.; Turgunov, D.; Jarihani, B. Sustainable Transboundary Water Governance in Central Asia: Challenges, Conflicts, and Regional Cooperation. *Sustainability* **2025**, *17*, 4968. https://doi.org/10.3390/su17114968

1. Introduction

Water resource management is a critical issue in Central Asia, influencing regional economic development, political stability, and environmental sustainability. The United Nations (UN) projects indicate that global freshwater scarcity will become one of the major challenges of the 21st century, potentially surpassing concerns about fossil fuel shortages [1]. In Central Asia, where water resources are abundant yet unevenly distributed,

the management of transboundary water bodies—particularly the Amu Darya and Syr Darya rivers—has been a source of geopolitical tensions [2–6]. Central Asia's major river systems are shared across multiple nations, with 86% of water resources originating in upstream countries, such as Kyrgyzstan and Tajikistan, while downstream nations (Uzbekistan, Turkmenistan, and Kazakhstan) depend heavily on these water sources for irrigation, agriculture, and industry [5,7,8]. The transition from Soviet-era water governance—which relied on a centralized system of hydropower dams and irrigation networks—to independent national policies has led to political disputes over water access, hydroelectric energy, and irrigation [1,9,10].

Climate change is further exacerbating water-related challenges in the region [11,12]. Rising temperatures are accelerating glacier melt, altering river flow regimes, and increasing the frequency of droughts [13–16]. Some reports suggest that over 30% of Central Asia's glaciers could disappear by 2050, severely impacting water availability in downstream areas [12,17–19]. Additionally, water pollution, ecosystem degradation, and biodiversity loss pose serious threats to environmental sustainability, yet regional cooperation on these issues remains limited [20–24]. The climate in Central Asia is warming at a rate significantly faster than the global average, with temperatures rising by 1.5–2 °C over the past 70 years and projections suggesting further increases of 1.5–2.8 °C by 2060 and up to 5.1–5.8 °C by 2100 [25,26]. This warming has already led to a 30% reduction in glacier area over the past 50–60 years, with predictions indicating glacier volume could decline by 50% with a 2 °C rise and by 78% with a 4 °C increase. These changes threaten water availability, with expected reductions of up to 5% in the Syr Darya basin and 15% in the Amu Darya basin by 2050. In Uzbekistan, water deficits could rise from 3 billion m^3 before 2015 to 7 billion m^3 by 2030 and 15 billion m^3 by 2050 [25,26]. Climate change is also causing more frequent and extreme weather events, such as floods, droughts, and heatwaves, highlighting the urgent need for improved early warning systems, enhanced risk management, and new adaptation strategies. As water demand grows due to population and economic development, particularly in agriculture, where over 90% of the land depends on irrigation, the region's water deficit worsens. The volume of water available per person has dropped from 8400 m^3 to 2500 m^3 annually over the past 40 years and could fall below 1700 m^3 by 2030. To meet basic needs, an additional 500–700 million m^3 of water may be required each year. Central Asia also ranks among the least efficient regions globally in water use, consuming 2.5 m^3 per dollar of GDP [25,26]. Even under scenarios with stable or increased runoff in the Amu Darya and Syr Darya rivers, future deficits could range from 8% to as high as 33%. With the population expected to reach 90–100 million by 2050, the region could face a water shortage of 25–30%, and agricultural water demand may grow by 30% by 2030. Moreover, recent studies also emphasize the importance of urban water resilience in addressing water scarcity and reducing pressure on shared water resources. Innovative strategies, such as stormwater reuse and decentralized water systems, not only enhance local water security but also contribute to mitigating transboundary tensions by reducing dependency on upstream flows [27]. Addressing these challenges requires regional cooperation and more rational water use, which the UN estimates could provide an economic benefit of around 5% of GDP—or approximately $20 billion [25,26].

The geopolitical landscape of Central Asia has been shaped by historical disputes over water allocation. With the collapse of the Soviet Union and the shift to market economies, the previously integrated water–energy exchange system broke down, leading to hydro–political deadlocks [2,28,29]. Upstream nations (Kyrgyzstan and Tajikistan) prioritize hydropower generation, while downstream countries (Uzbekistan, Turkmenistan, and Kazakhstan) require a stable and predictable water supply for irrigation [30–32]. This tension escalated in the 1990s, when Kyrgyzstan and Tajikistan resumed construction

of major hydroelectric projects, raising security concerns in Uzbekistan, which relies on seasonal water releases for its agricultural sector [33,34]. Despite these challenges, regional dialogue on water cooperation has been revived in recent years. Between 2018 and 2024, multiple high-level meetings among Central Asian leaders focused on water governance, infrastructure, and transboundary river management [35–38]. This growing engagement signals a renewed opportunity to develop collaborative water-sharing agreements, improve water governance frameworks, and strengthen regional water security [7,8,39].

Given the complexity of water-related conflicts in Central Asia, this study aims to examine the decision-making processes surrounding water security from national and regional perspectives. Specifically, the research focuses on the tensions between national sovereignty and regional cooperation in transboundary river governance, with an emphasis on policy solutions, sustainable water management strategies, and climate adaptation measures [2,40]. This manuscript aims to analyse these challenges and explore pathways toward cooperative transboundary water management in Central Asia. The research applies the Regional Security Complex Theory (RSCT) to examine how environmental, political, and economic dimensions shape water diplomacy in the region. A core contribution of this study lies in its integration of legal, institutional, and climate-related analyses to provide a holistic view of water governance. The research objectives are threefold:

- to provide a historical and policy-oriented overview of water management practices in the region;
- to assess current legal frameworks and geopolitical tensions through case studies, such as the Aral Sea basin and Qush Tepa Canal;
- to present recommendations for developing sustainable, equitable, and technologically advanced solutions, including greater use of digital water monitoring tools and improved regional coordination.

By highlighting both historical legacies and emerging dynamics, the study offers critical insights for policymakers, scholars, and stakeholders working to ensure water security and cooperation in Central Asia.

2. Research Methods

This study is based on a comprehensive analysis of official documents from Central Asian countries and international organizations, including the Food and Agriculture Organization of the United Nations (FAO), the World Bank, the Asian Development Bank (ADB), USAID, and the International Water Management Institute (IWMI). These sources provide insights into national water policies, regional cooperation frameworks, and international best practices in water governance and digitalization.

The methodological foundation of this research (Figure 1) is built upon a combination of qualitative approaches. The study employs data collection, generalization, systematization, and analysis techniques to evaluate the methods, algorithms, procedures, and digitalization trends within the water sector. Special emphasis is placed on understanding the current state of digital transformation in water management, assessing its development trajectory, and reviewing expert evaluations of digital integration across the region. This study adopts a qualitative, policy-oriented research approach, focused on the review and analysis of official policy documents, legal frameworks, and international reports related to transboundary water governance in Central Asia. Rather than an experimental design typical of natural sciences, this research applies a comparative and interpretive methodology to examine governance structures, institutional arrangements, and regional cooperation mechanisms. The evaluation is based on document analysis, a synthesis of secondary data from international organizations (e.g., FAO, World Bank, IWMI), and a comparative review

of national strategies and legislation. This approach is appropriate given the policy-driven and institutional focus of the research.

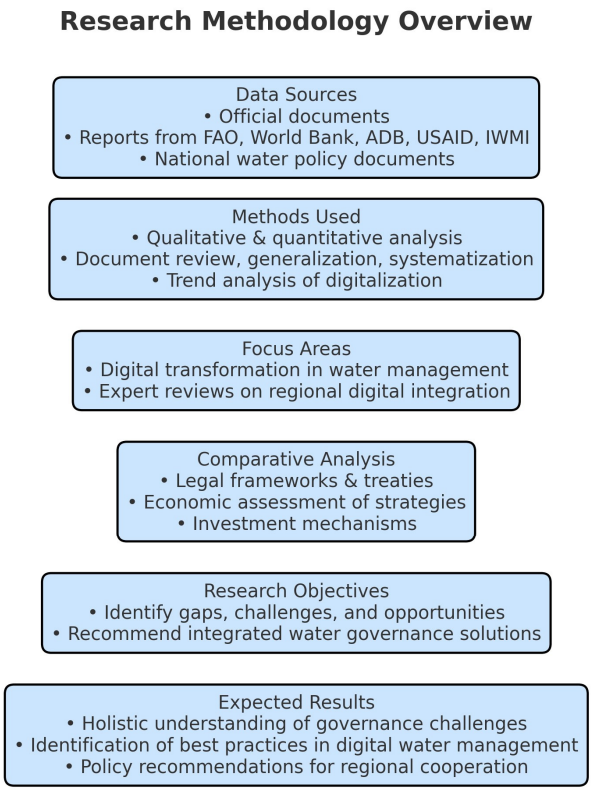

Figure 1. Overview of the research methodology used in the study. The infographic summarizes the key components of the methodology, including data sources, analytical techniques, focus areas, and comparative approaches. It concludes with the expected outcomes, which aim to provide a comprehensive understanding of water governance challenges in Central Asia and offer policy-relevant recommendations for digital transformation and regional cooperation.

A comparative analysis approach is applied to assess transboundary water governance in Central Asia. This includes a comparative legal examination of water policies, treaties, and regulatory frameworks, as well as an economic assessment of water management strategies and investment mechanisms. By integrating policy analysis with technical assessments of water resource management, this research aims to identify gaps, opportunities, and challenges in the region's water governance landscape.

3. Results

3.1. Water Resource Management in Central Asia: Historical Context and Contemporary Challenges

The efficient management of water resources has become increasingly critical for Central Asian countries due to global climate change and anthropogenic pressures [41,42]. Historically, water distribution in the region was regulated by the Scientific and Technical Council of the USSR's Ministry of Water Management, with agreements still influencing contemporary water governance. Key documents outlining transboundary water-sharing mechanisms include Protocol No. 413 (7 February 1984) for the Syr Darya River basin and Protocol No. 566 (12 March 1987) for the Amu Darya. These agreements allocated 46% of the Syr Darya's flow to Uzbekistan (22.7 billion cubic meters), 44% to Kazakhstan, 8% to Tajikistan, and 2% to Kyrgyzstan. Similarly, in the Amu Darya basin, 48.2% of water is allocated to Uzbekistan, 35.8% to Turkmenistan, 15.4% to Tajikistan, and 0.6% to Kyrgyzstan, excluding Afghanistan.

Following the collapse of the Soviet Union, the Almaty Agreement of 1992 was signed, establishing regional cooperation on water governance. Under this agreement, key water management infrastructure of regional significance was transferred to the following Basin Organizations (BOs) for collective operation while maintaining national ownership:

- BO Amu Darya oversees 84 hydropower stations, including 36 head river water intakes, 169 hydro posts, and 386 km of interstate canals in Tajikistan, Turkmenistan, and Uzbekistan.
- BO Syr Darya manages 198 hydraulic structures, with 21 located on major tributaries, such as the Naryn, Syr Darya, Karadarya, and Chirchik rivers.

Despite agreements ensuring joint financing for infrastructure maintenance, funding remains inconsistent, affecting regional cooperation. Furthermore, Afghanistan remains outside of these agreements, yet its increasing water consumption is significantly impacting regional hydropolitics. As illustrated in Figures 2 and 3, agriculture is the largest water-consuming sector in the region, accounting for 87.2% of total water withdrawal. Uzbekistan alone consumes 56 km^3 of water annually, which represents nearly 45% of the region's total water volume of 124 km^3. This consumption is notably high, being twice that of Turkmenistan, the country with the second-largest consumption. In Uzbekistan, 90% of water is used for agriculture, while industrial use is minimal, at just 2.7%. In contrast, the combined water consumption of the upstream countries, Kyrgyzstan and Tajikistan, is only 15.6% of the region's total, which is roughly one-third of Uzbekistan's consumption.

One of the most contentious recent developments is Afghanistan's Qush Tepa Canal, which, upon completion, is expected to divert 13 km^3 of water annually from the Amu Darya River [43,44]. The canal spans 281 km in length, 100 m in width, and 8 m in depth, with a projected intake of 650 cubic meters per second from the Afghanistan–Tajikistan border. This project will irrigate between 550,000 and 585,000 hectares in Balkh, Jowzjan, and Faryab provinces [45,46]. This canal, a revived component of Afghanistan's 1955–1961 Economic and Social Seven-Year Plan, has now reached one-third of its planned length and is anticipated to be completed within five years. However, its construction raises concerns among Uzbekistan, Turkmenistan, and Tajikistan, which depend on Amu Darya flows for agricultural and hydropower purposes. Experts, such as Jahan Taganova, a New York-based water security analyst, warn that the project will exacerbate regional water scarcity, intensify interstate disputes, and potentially trigger hydro–political conflicts [47].

Meanwhile, Tajikistan has prioritized the development of the Rogun hydroelectric power plant on the Vakhsh River, a project that has been at the core of the country's energy and economic strategy. However, this project has raised significant geopolitical and economic concerns in the region. Ajdar Kurtov, Editor-in-Chief of National Strategy Issues at the Russian Institute for Strategic Studies, has argued that a single hydroelectric power plant will not resolve all of Tajikistan's energy challenges. Instead, the Rogun Dam project has been framed as a symbol of national progress, despite its economic and logistical complexities [48]. The post-construction phase of the Rogun project presents considerable challenges, particularly regarding the procurement and distribution of electricity. The high cost of construction and limited market demand for its electricity pose financial risks. Kazakhstan, a key regional player, has no significant need for additional energy from the project, and alternative markets are fraught with economic and logistical constraints. The CASA-1000 project, which aims to export electricity to Pakistan, India, and Afghanistan, faces hurdles due to Afghanistan's increasing domestic energy ambitions and its growing focus on self-sufficiency. Additionally, Pakistan's energy sector has been strengthening ties with China, potentially limiting its reliance on Tajikistan's energy exports.

Figure 2. Water resource use in Central Asia. Source: Zoï Environment Network, 2018.

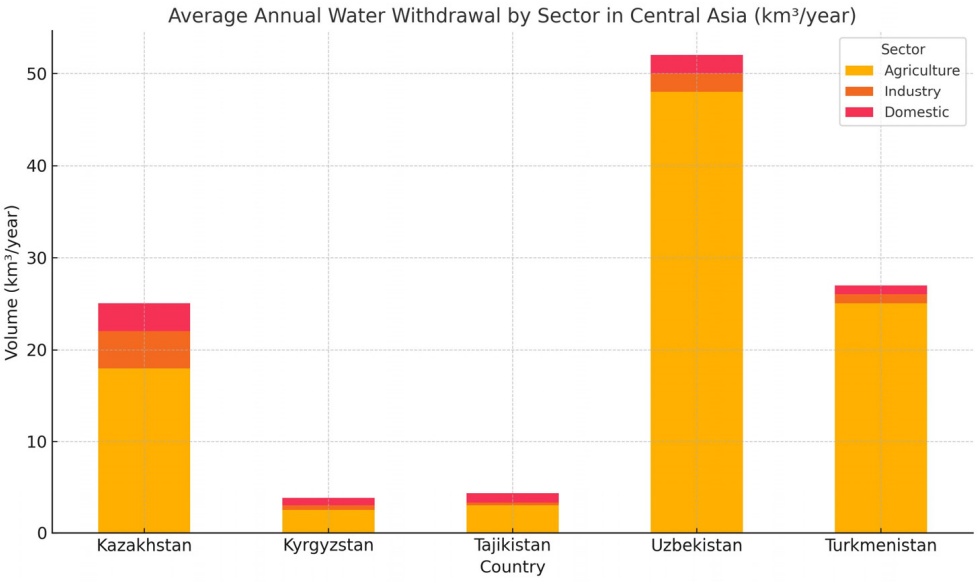

Figure 3. Average annual water withdrawal by sector in Central Asian countries (in km^3/year). Data are approximate and synthesized from publicly available sources, including FAO AQUASTAT (Water Withdrawal by Sector Dataset, FAO 2021 https://data.apps.fao.org/catalog/dataset/water-withdrawal-by-sector-national-year/resource/12011a9d-1b43-4819-a60e-4b015aeebd26, accessed on 11 April 2025) and the World Bank (Annual Freshwater Withdrawals https://data.worldbank.org/indicator/ER.H2O.FWTL.K3, accessed on 11 April 2025).

These developments highlight the complex interplay between water management, energy security, and regional geopolitics in Central Asia. While hydropower projects offer economic potential, they also present challenges related to transboundary water governance, international energy markets, and political cooperation among the region's nations.

In recent years, the modernization and development of national legislative frameworks in Central Asia have advanced toward a more structured and collaborative approach. A significant step in this direction is the operationalization of the Interstate Coordination Commission on Water Management of the Central Asian States, which serves as a platform for regional water governance and cooperative decision making among riparian nations.

The economies of Central Asian states are characterized by high energy and capital intensity, particularly in the agricultural and industrial sectors, both of which heavily rely on water resources. Despite these dependencies, water use efficiency in the region remains significantly lower than global standards (Table 1). This inefficiency highlights the urgent need for policy reforms, improved water management strategies, and stronger regional cooperation to ensure sustainable resource utilization and long-term economic stability in the face of growing water scarcity and climate variability.

Table 1. Status of water use efficiency indicators in Central Asia, 2021, USD/m^3.

Indicators	Turkmenistan	Kazakhstan	Kyrgyzstan	Uzbekistan	Tajikistan
Irrigated land	0.146	0.035	0.102	0.458	0.227
Industry	28,916	11,556	5504	12,026	1643
Services	19,228	31,380	17,298	14,026	5472
General indicators	1525	7201	0.842	1431	0.882

Note: Compiled by the author based on [49].

In 2021, water use efficiency in Central Asian countries varied significantly, ranging from \$0.842/m^3 in Kyrgyzstan to \$7.2/m^3 in Kazakhstan. Across the region, the average water use efficiency is projected to be between \$2 and \$2.5 per cubic meter, which remains substantially lower than the global weighted average of \$19.01 per cubic meter. In contrast, two-thirds of countries worldwide exhibit water use efficiency rates between \$5 and \$100 per cubic meter. Notably, four out of the five Central Asian nations—excluding Kazakhstan—rank among the top 10 global outliers in this metric, based on an analysis of 168 countries. The regional economy is predominantly agrarian, with service-oriented sectors playing a relatively minor role in natural resource consumption. This economic structure contributes to one of the lowest water use efficiency rates globally, averaging \$2.50 per cubic meter, while industrialized nations achieve rates as high as \$1096 per cubic meter due to greater efficiency in resource utilization.

The effectiveness and fairness of water resource distribution in Central Asia largely depend on the availability, accuracy, and analysis of hydrological data [50]. Kazhydromet, Kazakhstan's national hydrometeorological service, plays a crucial role in monitoring environmental, meteorological, and hydrological conditions. As of 2022, Kazhydromet operated 377 hydrological stations, providing essential data for water management and climate adaptation planning. A key area of focus in improving water governance is the digital transformation of the water sector, particularly in Kazakhstan and Uzbekistan [51]. Both countries have taken legislative steps to integrate digital technologies into water resource regulation. Kazakhstan's Aerospace Committee, under the Ministry of Digitalization, is actively testing flood monitoring devices, reflecting a broader commitment to leveraging digital tools for real-time water management, pollution control, and disaster preparedness. Regarding the water resources of the Aral Sea, it is essential to define and quantify the water basin extents for each Central Asian nation, ensuring alignment with the specific requirements and allocation frameworks established for regional water management (Table 2).

The data presented in the table highlight notable discrepancies and exclusions in the regulation of legal standards among Central Asian nations, particularly regarding the establishment of equitable water management frameworks. One key example is Afghanistan, which remains outside many regional agreements, raising concerns about its role in the broader transboundary water governance structure.

Table 2. Surface water resources of the Aral Sea basin (average annual runoff, km^3/year).

State	River Basin		Aral Sea Basin	
	Syr Darya	Amu Darya I	km^3	%
Kazakhstan	2516	-	2516	2.2
Kyrgyzstan	27,542	1654	29,196	25.2
Tajikistan	1005	58,732	59,737	51.5
Turkmenistan	-	1405	1405	1.2
Uzbekistan	5562	6791	12,353	10.6
Afghanistan and Iran	-	10,814	10,814	9.3
Aral Sea Basin Summary	36,625	79,396	116,021	100

Note: Compiled by the author based on [52].

3.2. Legal and Institutional Framework for Water Governance in Central Asia

The legal framework governing water resource management in Central Asia varies significantly between nations. We will analyze the regulatory and legal frameworks governing water resource management in Central Asian countries, as summarized in Table 3.

Table 3. Regulatory and legal frameworks for water resource management in Central Asian states.

State	Key Regulatory and Legal Acts on Water Resources	National Water Strategy
Republic of Kazakhstan	- Constitution of Kazakhstan (1995) Water Code (2003) Environmental Code (2007) National Plan for Collaborative Water Resource Management and Efficiency Improvement (2009–2025) Concept of the Green Economy (2013) State Water Resources Management Program (2014)	- Strategy 2050: Comprehensive analysis of national water management strategies and conservation efforts Adoption of advanced technologies for groundwater extraction and efficient usage Implementation of moisture-conserving technologies Addressing nationwide water supply issues by 2050 Resolving irrigation water challenges by 2040
Republic of Kyrgyzstan	- Constitution of Kyrgyzstan (2010) Water Code (2005) Environmental Protection Act (1999) Law on Associations of Water Users (2002)	- Sustainable Development Strategy 2040: Implementation of water conservation and recycling technologies Establishment of a national water recycling and replenishment system Ensuring universal access to potable water Transitioning towards a market-based water management system Strengthening oversight of mining operations to prevent water contamination
Republic of Uzbekistan	- Constitution of Uzbekistan (1992) Law on Water and Water Use (1993) Nature Conservation Act (1992) Environmental Control Act (2013)	- Strategy for Further Development: Expansion of water-conserving technologies to rehabilitate degraded lands Expansion of potable water networks in rural areas Construction of 415 km of new water supply infrastructure
Republic of Tajikistan	- Constitution of Tajikistan (1994) Water Code (2000) Law on Water Users Associations (2006) Environmental Protection Act (2011) Drinking Water and Sanitation Act (2010)	- National Development Strategy 2030: Development and expansion of hydropower infrastructure Modernization of existing hydro and thermal power plants Implementation of Integrated Water Resources Management (IWRM) Strengthening water sector institutions Optimization of irrigation and reclamation practices Strengthening policies to prevent water pollution Rehabilitation of irrigation and drainage systems to increase water availability Support for the development of Water Users Associations (WUA)

Table 3. *Cont.*

State	Key Regulatory and Legal Acts on Water Resources	National Water Strategy
Republic of Turkmenistan	- Constitution of Turkmenistan (1992) Water Code (2004, revised in 2016) Law on Nature Protection (2014) Law on Drinking Water (2010)	- Water Management Development Framework 2030: Ensuring environmental protection and sustainable resource use Strengthening the legal framework governing water resources Encouraging public and inter-industry participation in water infrastructure development Establishing community-based water management councils (Mirabs) Expanding e-government initiatives for water sector transparency Increasing the reuse of treated wastewater

Note: Compiled by the author based on literature review [53–61].

The analysis of national water legislation across the five Central Asian states reveals a broadly comparable hierarchy of normative legal acts. However, key differences exist, particularly in Kyrgyzstan, where the constitution does not explicitly establish the supremacy of ratified international treaties. Moreover, a major shortcoming across the region is the inconsistent incorporation of international legal principles into national water governance frameworks.

A fundamental challenge in the region is the absence of a cohesive and comprehensive conceptual framework for water resource utilization and conservation. This gap has led to fragmented and often conflicting approaches to water governance among Central Asian countries [13,62,63]. A striking example is Turkmenistan's Water Code, where Article 3 defines the state water fund to include rivers, reservoirs, lakes, inter-farm canals, drainage collectors, other surface water bodies, groundwater resources, and even the Caspian Sea along Turkmenistan's state border. However, Article 82 of the same code only addresses the procedural aspects of transboundary water utilization without providing a clear legal definition of transboundary waters. Consequently, apart from this provision, Turkmenistan lacks a well-defined legal framework governing shared water resources. Within its legal hierarchy, the Water Code is subordinate to both international treaties and the constitution, which means it lacks the authority to establish binding transboundary water management protocols.

Similarly, Uzbekistan's Law on Water and Water Use shares conceptual similarities with Kazakhstan's Water Code. Article 3 of Uzbekistan's law declares water resources as state property, emphasizing rational utilization and state-led protection. While this aligns with Kazakhstan's approach, a lack of explicit mechanisms for transboundary water cooperation creates challenges in regional water governance [64]. To effectively assess the robustness of water laws, it is essential to consider their position within the National Legal Act (NLA) hierarchy. Across all five states, foundational legislation related to water—whether codified or not—forms the backbone of national water governance. However, despite the presence of national water laws, their implementation remains inconsistent, with significant variations in enforcement and interpretation. Ultimately, the legal frameworks governing water resources in Central Asia require significant harmonization to address regional water challenges [65]. Establishing a unified, integrated water management framework that aligns national legislation with international legal standards would be a crucial step toward ensuring sustainable and equitable water resource utilization across the region.

A comparative analysis of Kazakhstan's national water legislations and policies reveals the following key disparities:

1. International Treaties and Agreements—All international water-related treaties ratified by the Republic of Kazakhstan, which establish frameworks for transboundary water cooperation and management.
2. Constitutional Provisions—Article 6 of the Constitution of the Republic of Kazakhstan, which defines the legal status and ownership of natural resources, including water.
3. National Water and Environmental Legislation—Key legislative acts governing water resource management, including:
    - Water Code of the Republic of Kazakhstan (9 July 2003, No. 481-II);
    - Code on Administrative Offenses (9 January 2007, No. 212-III);
    - Environmental Code (2007);
    - Land Code (20 June 2003, No. 442-II).
4. National Water Resource Management Strategy—Presidential Decree approving the National Plan for Integrated Water Resource Management and Water Use Efficiency Improvement (2009–2025), aimed at ensuring sustainable water use and addressing water security challenges.
5. Government Regulations and Policy Frameworks—Resolutions and legislative acts that influence public administration and regulatory mechanisms for water resource management, such as the Resolution of the Government of Kazakhstan (28 January 2009, No. 67).
6. Regulatory Framework for Water Governance—National laws and regulations that govern water use, conservation, and distribution, ensuring compliance with environmental and sustainability standards.
7. Subordinate Legislative Acts—Sector-specific regulations and executive orders that support the implementation of national water policies and ensure alignment with broader environmental objectives.
8. Customary Practices in Water Management—Traditional and regionally accepted practices influencing business and community-level water use, particularly in rural and agricultural sectors.
9. Economic and Trade-Related Water Regulations—Legislative frameworks governing water-related business activities, including commercial water use, hydropower development, and irrigation for agricultural enterprises.
10. Public–Private Partnership and Stakeholder Engagement Mechanisms—Policies and initiatives facilitating collaboration between the government, private sector, and civil society in water resource management, ensuring inclusive and sustainable governance.

The primary objective of Kazakhstan's water legislation is to establish and maintain an ecologically sustainable and economically efficient system for water utilization, conservation, and management. This framework aims to ensure the equitable distribution of water resources while enhancing water supply and sanitation services. Additionally, it seeks to protect water bodies from overuse and contamination, thereby preserving both human well-being and the ecological balance of the country's water systems.

The responsibilities outlined in the Water Code encompass several key areas. It mandates the implementation of state policies for the rational use and conservation of water resources, ensuring their long-term sustainability. Furthermore, it provides a regulatory framework governing water supply, wastewater treatment, and sanitation infrastructure to promote efficiency and equitable access. Sustainable water utilization is a priority, necessitating conservation measures and protective strategies to mitigate environmental degradation. To strengthen water governance, the legislation establishes a comprehensive legal framework that guides resource allocation, technological advancements, and institutional management. It also ensures law and order in all aspects of water utilization, protection, supply, and sanitation, reinforcing accountability and compliance. Addition-

ally, it defines fundamental principles for water governance, including sanitation policies and regulatory mechanisms, to foster a cohesive and efficient water management system. Research and exploration play a crucial role in advancing water security. The Water Code mandates the oversight of scientific research and integrated management strategies for hydromelioration systems, water infrastructure, and resource sustainability. It also outlines strategies for land reclamation, ensuring the protection of human populations and economic assets from hydrological risks, such as floods and droughts.

A distinctive feature of Kazakhstan's Water Code is its direct provisions for transboundary water management (Chapter 31). This legal framework sets clear guidelines for international cooperation on shared water resources, making it one of the most structured and comprehensive regulatory mechanisms in Central Asia. From a legal and theoretical perspective, it serves as a robust foundation for developing a broader regional approach to water governance, promoting collaboration and sustainable resource management across national borders. The Water Code of 2003 established a comprehensive framework for the management of water basins in Kazakhstan, emphasizing the formation of basin organizations that incorporate all relevant stakeholders. These organizations are tasked with overseeing water distribution, conservation efforts, and the implementation of sustainable management practices. To promote equitable and efficient water utilization, the code introduced the concept of environmental revenues, which aims to balance water supply and consumption while ensuring long-term resource sustainability. In 2009, the National Strategy for Integrated Basin Management was introduced, followed by the implementation of a State Water Resources Management Program, aligning Kazakhstan's water governance policies with international best practices.

Despite Kazakhstan's efforts to enhance water governance, regional hydropolitics continue to present significant challenges, according to McKinney [63]. In 2017, relations between Kyrgyzstan and Kazakhstan became particularly strained due to disputes over transboundary water resources. As an upstream nation, Kyrgyzstan holds a strategic position in controlling water flow to downstream countries, including Kazakhstan. This geopolitical dynamic led to tensions, culminating in a public statement by former Kyrgyz President Almazbek Atambayev, who threatened to restrict water access to Kazakhstan during a press conference, exacerbating diplomatic friction between the two nations.

However, following the election of President Sooronbay Jeenbekov, bilateral relations began to improve. During Jeenbekov's official visit to Kazakhstan, diplomatic negotiations prioritized water and energy cooperation, aiming to establish a more sustainable and collaborative approach to transboundary water management. One key aspect of these discussions was the reactivation of the International Fund for Saving the Aral Sea (IFAS), a crucial regional initiative that had previously seen Bishkek suspend its participation in 2018. As a result of these efforts, both Astana and Bishkek reaffirmed their commitment to viewing transboundary water resources as a shared regional asset, emphasizing the need for cooperative governance to ensure water security for all nations involved. This diplomatic shift marked an important step toward fostering trust, collaboration, and long-term sustainability in Central Asia's water sector.

Uzbekistan initially opposed the construction of the Kambar-Ata-1 and Kambar-Ata-2 hydroelectric power plants in Kyrgyzstan, citing concerns over potential disruptions to the downstream water supply. However, through diplomatic negotiations, a shift toward cooperation in the water and energy sector emerged. By 2017, Uzbekistan and Kyrgyzstan reached an agreement, signaling their willingness to collaborate on hydropower projects. This commitment was formalized through the signing of a memorandum of understanding between the National Energy Holding Company of Kyrgyzstan and Uzbekhydroenergo, outlining a cooperative framework for the Kambar-Ata-1 hydropower plant project.

Meanwhile, Kazakhstan has intensified its efforts in water cooperation, expanding its focus to include non-governmental organizations (NGOs), environmental movements, and political entities that contribute to regional environmental initiatives. These efforts have enhanced the role of water user associations, basin organizations, and other civic institutions in decision-making processes. NGOs play an active role by organizing seminars, conferences, and public discussions, as well as implementing practical initiatives, such as tree planting and the restoration of water protection zones. Additionally, Kazakhstani NGO representatives are actively engaged in the Global Water Partnership for Central Asia and the Caucasus, where they contribute to public participation in integrated water resource management efforts across the region. Kazakhstan's active participation in global water resource events and its endorsement of key international conventions on water management underscore its commitment to aligning national policies with International Water Law. These efforts highlight the recognition of NGOs as equal stakeholders in water governance, ensuring their involvement in decision making, policy implementation, and project execution. This inclusive approach is further reinforced within Kazakhstan's updated water legislation, which formally codifies the role of NGOs in the sustainable management and protection of water resources.

Clause 3 of Article 63 of the Water Code of the Republic of Kazakhstan grants public associations the authority to conduct public oversight on the utilization and conservation of water resources. The execution of this oversight is determined by these associations in accordance with their charters and in collaboration with state entities responsible for regulatory enforcement. This provision ensures greater transparency and civic participation in water governance, reinforcing the role of non-governmental stakeholders in sustainable water management. Currently, Kazakhstan has established a comprehensive legislative framework that supports the development of a broader conceptual approach to water governance across Central Asia. The country has also laid the foundation for greater public participation in decision-making processes regarding water use and conservation. Other regional nations are making efforts to enhance public engagement in addressing water-related challenges, but discrepancies in national legislation and governance structures continue to present obstacles. These inconsistencies, coupled with the increasingly complex demands of water resource management, are expected to remain significant challenges for an extended period [2,3,5,8,37,38,46,48,62,65,66].

To facilitate regional cooperation, the Interstate Coordination Commission for Water Management of Central Asia (ICWC) was established under the 1992 agreement on transboundary water management. Initially, the commission consisted of three core executive bodies: the Secretariat, the Syr Darya Basin Organization, and the Amu Darya Basin Organization. Over time, the Scientific and Information Center of the ICWC and the Coordination and Metrological Center were also established, further strengthening regional collaboration on water governance, data exchange, and policy coordination. However, despite these institutional mechanisms, political and economic differences among Central Asian states continue to hinder the development of a truly integrated water management strategy.

3.3. Transboundary Basin Organizations and Their Challenges

Transboundary basin organizations can generally be categorized into three distinct groups, as illustrated in Figure 4. Among them, the Interstate Coordination Commission for Water Management of Central Asia (ICWC) falls into the second type of organization. According to the 1992 agreement, the ICWC is responsible for establishing and approving water consumption limits for each member republic, as well as for the entire region (Article 8). Additionally, the commission is tasked with ensuring strict compliance with permit and limit regulations (Article 10).

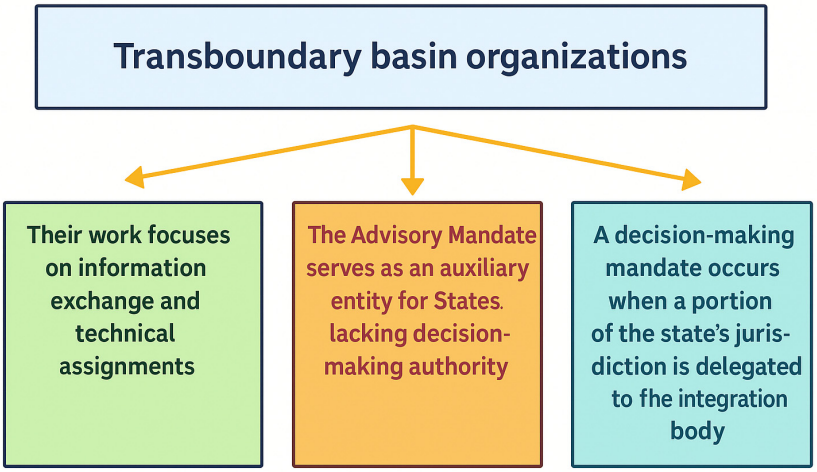

Figure 4. Transboundary basin organizations.

Despite their mandates, the Amu Darya Basin Organization and the Syr Darya Basin Organization have never achieved the status of interdepartmental regulatory entities with authoritative oversight. During periods of low water availability, challenges in enforcing agreed-upon water flow and consumption limits become even more pronounced, as the ICWC and its associated Basin Organizations struggle to maintain allocations and commitments. Notably, the World Trade Organization's (WTO) authority does not extend across the entire river basin, and its decisions remain advisory rather than legally binding. Experts widely acknowledge that the 1992 agreement has not been fully implemented. One of the most critical gaps is the lack of an accountability framework for violations of water-sharing agreements and resource limitations. While a mechanism for enforcing compliance should have been integrated into the agreement, no formal sanctions or punitive measures have been developed to date. Additionally, funding for basin organizations remains unevenly distributed. The Amu Darya Basin Organization is primarily financed by Uzbekistan and Turkmenistan, whereas the Syr Darya Basin Organization relies on contributions from Kazakhstan and Uzbekistan. However, these financial contributions do not follow the principle of proportional parity and shared participation as outlined in Article 9 of the agreement.

3.4. Institutional Stability and International Best Practices

One of the key characteristics of effective basin organizations is their ability to maintain long-term institutional stability, even amid political and economic disparities among riparian states. This stability is critical for ensuring predictable water management and reducing geopolitical tensions over shared resources [36]. An exemplary model of an international water governance structure is the International Joint Commission (IJC) between the United States and Canada. This organization was established under the 1909 Boundary Waters Treaty and operates with equal representation from both nations. The IJC has a supranational jurisdiction that ensures autonomous decision making beyond the direct influence of either government. Additionally, the commission maintains offices in both countries, reinforcing its role as an independent arbitrator in transboundary water disputes. By examining successful international water governance frameworks, it becomes evident that Central Asian basin organizations require stronger institutional structures, enhanced regulatory authority, and improved financial mechanisms to ensure sustainable and equitable water management across the region.

3.5. Technical Recommendations for Advancing Water Resource Management Through Digital Innovation

To improve transboundary water governance and resource management in Central Asia, the adoption of advanced digital technologies is essential. Countries in the region should prioritize the integration of remote sensing and Earth observation satellites (e.g., Sentinel, Landsat, SWOT) to monitor surface water extent, snowpack, evapotranspiration, and land use changes in near real time. These tools enable transparent, data-driven decision making and facilitate cross-border information sharing. Complementing satellite data, the deployment of Internet of Things (IoT) technologies, such as smart sensors and telemetry systems, can enhance in situ monitoring of river discharge, groundwater levels, water quality, and reservoir storage. Combined with hydrological and climate modelling platforms (e.g., SWAT, WEAP, or regional climate models), these technologies support predictive water management, scenario planning, and early warning systems for droughts and floods. Furthermore, the concept of digital or virtual twins—real-time digital replicas of river basins and infrastructure—can help stakeholders simulate and optimize water operations, evaluate management scenarios, and visualize trade-offs among users. To support the sustainable implementation of these innovations, higher education institutions in Central Asia should integrate modules on geospatial science, environmental modelling, data analytics, and digital water governance into engineering and environmental science curricula. Strengthening university–government–industry partnerships will also be critical to building regional expertise and ensuring that digital water management tools are not only adopted but effectively utilized across all levels of decision making.

3.6. Role of International Organizations in Central Asia's Water Sector

International organizations have played a critical role in addressing Central Asia's complex water governance challenges. Since the breakup of the Soviet Union, the region has relied on international support to manage transboundary water resources, modernize infrastructure, and build institutional capacity. The World Bank has led regional initiatives, such as the Central Asia Water and Energy Program (CAWEP) and supported major infrastructure and reform projects, including irrigation modernization in the Ferghana Valley. The Swiss Agency for Development and Cooperation (SDC), through the Blue Peace Central Asia initiative, has strengthened regional dialogue, water diplomacy, and local governance structures, such as river basin councils. The European Union has promoted integrated water resources management (IWRM) through its WECOOP platform and environmental cooperation programs, supporting policy harmonization and stakeholder engagement. The Asian Development Bank (ADB) has invested in climate-resilient water infrastructure and transboundary cooperation under the CAREC Water Pillar. The Aga Khan Development Network (AKDN), particularly through its Mountain Societies Development Support Programme (MSDSP), has focused on community-based water management and rural resilience in mountainous areas of Tajikistan and Kyrgyzstan. Collectively, these organizations have contributed to digital innovation, capacity building, and regional cooperation, helping Central Asia move toward a more sustainable and collaborative water governance model.

4. Discussion

This study provides a comprehensive assessment of transboundary water governance challenges in Central Asia, offering a multidimensional analysis that integrates political, institutional, socio-economic, and environmental perspectives. While earlier research has predominantly focused on basin-level allocation disputes or technical cooperation among states [7,65,67–69], this work expands the discussion by framing water governance within

a broader regional agenda of climate resilience, sustainable development, and cooperative diplomacy. By examining both historical legacies and emerging initiatives, we emphasize the importance of multi-level collaboration, including the role of civil society, regional platforms, such as CAREC, and initiatives, such as Green Central Asia. This approach moves beyond traditional state-centric or hydro–political analyses and sets the stage for deeper reflection on three critical dimensions: the fragmented yet evolving legal and institutional frameworks, the region's ongoing water management challenges, and the growing potential of digital and technological innovation to transform water governance in the face of escalating climate pressures and geopolitical uncertainty. In the following sections, we discuss these three dimensions in detail to evaluate opportunities and gaps in advancing transboundary water cooperation in Central Asia.

4.1. Water Resources Management in Central Asia

Water resource management in Central Asia is shaped by a complex interplay of historical legacies, geopolitical tensions, and structural inefficiencies. The Soviet-era water-sharing agreements, while foundational, no longer reflect current political realities or demographic and climate pressures. Although frameworks such as the Almaty Agreement and the establishment of Basin Organizations (BOs) were intended to maintain regional coordination, their effectiveness has been undermined by inconsistent funding, limited legal enforcement, and the absence of comprehensive participation from all riparian states—most notably Afghanistan.

The region remains heavily dependent on agriculture, with irrigation accounting for over 85% of total water use. This has contributed to extreme disparities in water withdrawal, with Uzbekistan alone consuming nearly half of the region's water. Meanwhile, upstream countries, such as Kyrgyzstan and Tajikistan, with lower consumption, pursue hydropower development, adding another layer of tension to water–energy trade-offs. Projects, such as Afghanistan's Qush Tepa Canal and Tajikistan's Rogun Dam, have heightened concerns over future availability, reflecting how infrastructure development, if pursued unilaterally, can intensify hydro–political conflict. Despite attempts at cooperation, the region suffers from one of the lowest global water use efficiency rates, averaging below $2.50 per cubic meter. This inefficiency is largely due to outdated irrigation systems, weak economic incentives, and the dominance of low-value-added agricultural production. Countries like Kazakhstan have made progress through digital transformation and the integration of hydrological data systems (e.g., Kazhydromet); however, such initiatives remain uneven across the region.

The future of water governance in Central Asia depends on advancing legal harmonization, modernizing infrastructure, and embracing digital water management. It also requires active diplomatic engagement to incorporate non-signatory states, such as Afghanistan, into regional agreements. Without addressing the institutional asymmetries and geopolitical dynamics that underpin water sharing, regional cooperation will remain fragile. Sustainable water governance in Central Asia must be grounded in basin-wide planning, transparent data sharing, and integrated strategies that account for both ecological constraints and socio-economic development goals.

4.2. Legal and Institutional Frameworks for Transboundary Water Governance in Central Asia

The analysis of Central Asia's legal and institutional frameworks reveals both progress and persistent fragmentation in regional water governance. While all five countries have developed national legislation addressing water management, significant inconsistencies remain in terms of legal definitions, the integration of international water law principles, and the implementation of regulatory frameworks. Countries such as Kazakhstan and

Uzbekistan have comparatively advanced water codes and strategic planning instruments, including explicit reference to integrated water resources management (IWRM) and transboundary cooperation. Kazakhstan's Water Code stands out for its detailed provisions on transboundary water issues and institutional mechanisms for basin-level management. However, even in Kazakhstan, the application of these provisions remains subject to political will and regional cooperation dynamics.

Challenges are particularly evident in countries like Turkmenistan, where contradictions within the national legal hierarchy, such as vague definitions of transboundary waters, limit the enforceability of international water obligations. Similarly, while Kyrgyzstan and Tajikistan have made notable efforts to establish user associations and decentralized frameworks, weak institutional capacity and limited enforcement mechanisms hamper the effectiveness of these laws. One of the central issues is the lack of a harmonized regional framework that aligns national legislation with basin-level governance and cross-border water management protocols. Opportunities exist, however, in the growing political recognition of water as a shared strategic asset. Diplomatic developments, such as renewed cooperation between Uzbekistan and Kyrgyzstan on hydropower infrastructure and Kazakhstan's support for public participation and NGO involvement, reflect a regional shift toward more inclusive and cooperative governance. The formal integration of civil society into water policy processes—especially in Kazakhstan—demonstrates evolving institutional maturity and could serve as a model for broader regional reforms. To advance effective transboundary governance, Central Asia will require not only stronger legal harmonization but also the operationalization of legal frameworks through capacity building, transparent enforcement, and regional platforms for cooperation. Establishing an integrated legal and institutional architecture that bridges national priorities with basin-wide objectives remains essential for achieving long-term water security and regional stability.

4.3. Technological Innovation and Its Role in Water Governance in Central Asia

While Central Asia faces persistent challenges in transboundary water governance, technological advancement offers a critical pathway to reforming outdated systems and building resilient, adaptive water management frameworks. This study highlights the importance of leveraging digital tools, remote sensing, climate modelling, and integrated data systems as essential components for strengthening governance mechanisms across the region. Unlike traditional assessments that rely heavily on hydrological infrastructure or state-centric negotiations, this analysis underscores a transformative approach rooted in data transparency, climate-informed planning, and institutional capacity building.

Integrated Water Resources Management (IWRM) provides a conceptual and practical foundation for this transformation. Built on principles of equity, efficiency, sustainability, and stakeholder participation, IWRM promotes basin-scale planning that transcends national borders and sectoral silos. Its successful implementation depends on the availability of real-time hydrological data, forecasting tools, and geospatial technologies, many of which are increasingly accessible thanks to Earth observation satellites, Internet of Things (IoT) sensors, and open-source platforms. In this context, digital transformation is not only a technical upgrade but a governance enabler, facilitating cooperative decision making, dispute resolution, and equitable water allocation among Central Asian states. Kazakhstan and Uzbekistan have made initial strides in integrating technology into their national water policies. For example, Kazakhstan's digitalization initiatives include the use of satellite-based flood monitoring systems and hydroinformatics platforms for early warning and planning. Similarly, Uzbekistan is investing in smart irrigation networks and telemetry systems to optimize water use in agriculture. However, these efforts remain fragmented and largely limited to national scopes, with few cross-border applications. A more regionalized

approach is needed—one that builds interoperable systems and harmonizes data standards to support shared hydrological monitoring and basin-wide forecasting.

The experience of international river basin organizations offers valuable lessons for improving transboundary water governance in Central Asia. For example, the International Commission for the Protection of the Rhine (ICPR) and the International Joint Commission (IJC) between the United States and Canada exemplify how sustained investment in joint monitoring systems, transparent data sharing, and participatory governance can lead to effective, science-based water management. These institutions benefit from strong legal mandates, clearly defined responsibilities, and long-standing political commitment, enabling them to implement coordinated flood control, pollution management, and ecosystem restoration programs.

In contrast, Central Asia's transboundary water governance remains fragmented, with weak enforcement mechanisms, inconsistent legal frameworks, and limited public participation. While some progress has been made through bilateral and regional agreements, the lack of a unified basin-wide authority and the absence of Afghanistan from most cooperative frameworks limit the effectiveness of current governance structures.

The Mekong River Commission (MRC) in Southeast Asia provides another valuable point of comparison. Despite political tensions among its member countries, the MRC has developed a well-established platform for data sharing, climate adaptation, and stakeholder engagement. Its emphasis on adaptive management and inclusive decision making has allowed the region to better address the impacts of hydropower development and climate variability. Similarly, the Danube River Basin has seen successful cooperation among more than a dozen European countries, enabled by EU water directives, integrated modelling tools, and environmental standards that guide transboundary collaboration.

These models demonstrate the benefits of institutional clarity, technological integration, and stakeholder inclusivity—elements that are urgently needed in Central Asia. In the face of growing climate stress, demographic shifts, and geopolitical sensitivities, the region must transition from reactive, fragmented management to adaptive, integrated governance.

This study advocates for the regional application of Integrated Water Resources Management (IWRM) principles, supported by digital technologies, such as Earth observation systems, hydrological modelling, and open-access data platforms. Institutional reforms that align national water laws with international norms, coupled with investments in regional climate modelling and decision-support systems, will not only enhance climate resilience but also promote long-term cooperation, trust building, and sustainable development across Central Asia. Drawing on global best practices while tailoring strategies to the region's unique hydropolitical context can offer a practical roadmap for water security and regional stability.

5. Conclusions

This study provides a comprehensive analysis of the current state and challenges of transboundary water governance in Central Asia. By examining legal frameworks, institutional arrangements, and emerging technological opportunities, the research highlights critical gaps and pathways for improving cooperation and sustainability in the region. The findings underscore the urgent need for integrated, adaptive governance models to address the escalating pressures of climate change, water scarcity, and geopolitical complexity.

Effective transboundary water governance in Central Asia demands a holistic and adaptive approach that integrates the political, legal, environmental, and technological dimensions of shared water resource management. This study has highlighted the complex interplay between hydro–political dynamics, national development priorities, and climate change vulnerabilities, offering a multidimensional assessment that moves be-

yond traditional state-centric or technical analyses. This research underscores how power asymmetries and national security concerns shape water policy and interstate relations across the region. A central challenge lies in the institutional and legal fragmentation that characterizes water governance in Central Asia. While foundational national water codes exist, they vary significantly in scope, enforcement, and alignment with international law. The absence of Afghanistan from formal agreements further complicates regional cooperation, despite its increasing role in upstream water use—most notably through projects such as the Qush Tepa Canal. Updating and harmonizing legal frameworks, including the integration of Afghanistan and the alignment with global water law principles, will be critical for inclusive and sustainable governance.

At the same time, technological innovation presents a powerful opportunity to enhance cooperation and improve water management outcomes. Digital tools—such as Earth observation satellites, IoT-based monitoring systems, and predictive climate-hydrological models—can support real-time decision making, increase data transparency, and foster shared understanding among riparian states. However, these tools must be embedded in strong institutional arrangements and supported by political will to have a meaningful impact. Drawing on international best practices, such as the Rhine and Great Lakes governance models, this study emphasizes the need for adaptive and participatory governance mechanisms. Incentive-based cooperation models, such as the Shu-Talas River profit-sharing framework between Kazakhstan and Kyrgyzstan, offer promising pathways for resolving upstream-downstream tensions and achieving equitable water distribution.

In conclusion, the future of water security in Central Asia will depend on the region's ability to transition from fragmented, reactive approaches to integrated, forward-looking strategies that promote joint investment, cross-sectoral collaboration, and environmental sustainability. This requires not only legal and institutional reforms but also deeper regional trust, political commitment, and capacity building. Future research should prioritize the development of actionable strategies that embed digital technologies and inclusive governance models into regional water policy, particularly in the context of climate change and shifting geopolitical dynamics. Only through such comprehensive cooperation can Central Asia ensure long-term, equitable, and resilient management of its most vital resource.

Author Contributions: Writing—original draft preparation, A.P.; writing—review and editing, B.J. and D.T.; supervision, S.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: Authors acknowledge support given by Academy of Public Administration under the President of the Republic of Kazakhstan, Astana, Kazakhstan.

Conflicts of Interest: The authors declare no conflicts of interest.

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