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FROM DATA GAPS TO DECISION SUPPORT: THE ROLE OF HYDROLOGICAL MONITORING AND EARTH OBSERVATION IN CENTRAL ASIA

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ABSTRACT. *Water resource management in Central Asia is increasingly challenged by climate change, glacier retreat, population growth, and rising socio-economic demands. While regional discourse has largely focused on transboundary governance and institutional coordination, a critical underlying constraint remains the limited availability, consistency, and integration of hydrological data. The decline of hydrological monitoring networks and fragmentation of data systems have significantly reduced the reliability of observations, constraining forecasting accuracy and water allocation processes. This commentary argues that interoperable hydrological monitoring and data-sharing systems are not only technical requirements but foundational preconditions for credible water allocation, forecasting, climate adaptation, and trust-building in transboundary basins. Persistent data gaps, particularly in high-altitude, groundwater, and precipitation monitoring, continue to limit effective planning and decision-making (Liu & Li, 2025).*

This policy commentary argues that strengthening hydrological monitoring systems – through the restoration of in-situ observation networks and their integration with Earth Observation (EO), machine learning, and digital technologies – represents a foundational requirement for effective water governance in Central Asia. The paper highlights how interoperable monitoring and data-sharing systems can improve transparency, reduce uncertainty in water availability assessments, support more credible forecasting and allocation decisions, and ultimately strengthen cooperation across transboundary river basins. Advances in satellite-based observations, data analytics, and modelling tools provide new opportunities to enhance monitoring capacity, improve transparency, and support evidence-based water management. Bridging the gap between data collection and policy implementation is essential for reducing uncertainty, strengthening transboundary water governance, and advancing climate resilience. An

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integrated approach will be critical for enabling sustainable and cooperative water management across Central Asia.

KEYWORDS: *Central Asia, transboundary water governance, hydromet networks, earth observation, data sharing, decision support systems, climate resilience, cryosphere monitoring.*

INTRODUCTION

Central Asia is widely recognized as one of the most climate-vulnerable regions globally, characterized by arid and semi-arid climates, high dependence on transboundary water resources, and increasing climate variability. Major river systems such as the Amu Darya and Syr Darya are critical for sustaining agriculture, hydropower generation, and broader socio-economic development across multiple countries. However, these systems are under growing pressure due to glacier retreat, shifting precipitation patterns, and rising water demand, all of which are intensifying competition over limited water resources.

The region's hydrological regime is particularly sensitive to climatic variability, largely due to its reliance on glacier-fed rivers and snowmelt processes originating in high mountain catchments. Recent studies have highlighted substantial changes in the Central Asian water cycle, driven by both climate change and anthropogenic influences (Unger-Shayesteh et al., 2013). At the same time, water scarcity is further exacerbated by the transboundary nature of key river basins and the continued reliance on aging infrastructure inherited from the Soviet period (Karthe et al., 2015).

Despite the existence of regional cooperation frameworks and institutions, water management in Central Asia continues to face persistent structural challenges. While much of the regional discourse has focused on governance, allocation mechanisms, and institutional coordination, a critical but often underemphasized constraint is the declining capacity of hydrological monitoring systems. The reduction of observation networks, combined with outdated technologies and fragmented data management practices, has significantly limited the availability of reliable, consistent, and comparable hydrological data.

While climate change, population growth, and competing water demands are widely recognized challenges across Central Asia, the ability to respond effectively to these pressures is increasingly constrained by a less visible but equally important bottleneck: fragmented hydrological information systems and limited data interoperability. In many parts of the region, monitoring networks have deteriorated, data-sharing arrangements remain inconsistent, and institutional responsibilities are distributed across multiple agencies and jurisdictions. As a result, uncertainty surrounding water availability, seasonal forecasting, and resource allocation continues to undermine evidence-based decision-making and transboundary cooperation.

Although previous studies have extensively examined climate change impacts, glacier retreat, water scarcity, and regional water governance, comparatively less attention has been given to the role of hydrological monitoring systems and data governance as enabling foundations for effective water management. This paper argues that strengthening monitoring networks, improving data interoperability, and integrating emerging Earth Observation technologies into operational decision-making frameworks represent critical prerequisites for enhancing water security, climate resilience, and regional cooperation in Central Asia.

Inadequate data sharing and weak integration of monitoring systems further undermine regional forecasting, planning, and decision-making processes (Abdullaev & Rakhmatullaev, 2014). This disconnect between data generation and its effective use in policy and operational contexts represents a fundamental barrier to sustainable water governance. Addressing this gap is essential for improving water allocation, enhancing transparency, and strengthening cooperation in transboundary river basins. Drawing upon recent scientific literature, institutional reports, and regional experiences, this commentary examines the role of hydrological monitoring and interoperable data systems in strengthening water governance, climate resilience, and transboundary cooperation in Central Asia.

METHODOLOGICAL APPROACH

This paper is presented as a policy commentary informed by a structured review of scientific literature, regional policy documents, institutional reports, and recent developments in hydrological monitoring and Earth Observation applications relevant to Central Asia. The objective is not to conduct a systematic review or meta-analysis, but rather to synthesize current knowledge and identify practical pathways for strengthening hydrological information systems to support climate resilience and transboundary water governance.

The evidence base was compiled from peer-reviewed journal articles, reports published by international organizations and development partners (including the World Bank, Asian Development Bank, FAO, UNESCO, WMO, and regional water institutions), and publicly available documentation related to hydrological monitoring, climate change impacts, water governance, and digital technologies in Central Asia. Particular attention was given to publications produced during the last decade, while selected foundational studies were included where necessary to provide historical and institutional context.

The review focused on four thematic areas: (1) hydrological monitoring networks and data availability; (2) transboundary water governance and regional cooperation mechanisms; (3) Earth Observation, digital technologies, and decision-support systems; and (4) policy and institutional pathways for improving water management under increasing climate variability and change. Rather than evaluating individual technologies or governance frameworks in isolation, the paper adopts an integrated perspective that examines how improved monitoring systems, interoperable data infrastructures, and institutional cooperation can collectively support more informed decision-making, forecasting, water allocation, and climate adaptation across the major transboundary river basins of Central Asia.

KEY CHALLENGES

Central Asia's water management challenges are shaped by a combination of data limitations, climate-driven hydrological change, and institutional constraints. These interrelated factors create a complex environment in which uncertainty remains high and decision-making capacity is constrained. Addressing these challenges requires a clear understanding of the underlying structural weaknesses in monitoring systems, environmental change, and governance frameworks.

Hydrological Data Gaps

Significant deficiencies in hydrological monitoring persist across Central Asia, particularly in critical observation domains that are essential for understanding and managing water resources (Table 1). These gaps are most pronounced in high-altitude regions, groundwater systems, and precipitation monitoring, all of which play a fundamental role in the regional hydrological cycle. Limited monitoring in mountainous areas constrains the understanding of snow accumulation, glacier mass balance, and meltwater dynamics, which are key drivers of river flow in the region (Schöne et al., 2013). Given that a substantial portion of Central Asia's water resources originates in these high-elevation zones, the lack of consistent and high-quality observations introduces significant uncertainty into hydrological assessments and forecasts. Groundwater systems, which are increasingly important for water supply and drought resilience, remain fragmented and poorly monitored, particularly in countries such as Uzbekistan and Kazakhstan (Schmidt et al., 2024). This limits the ability to assess groundwater availability, recharge processes, and long-term sustainability under changing climatic and anthropogenic pressures.

In addition, precipitation data—one of the most critical inputs for hydrological modelling—remains highly uncertain. Studies indicate that precipitation uncertainty can account for up to 50% of model variability, significantly affecting the reliability of hydrological simulations and forecasts (Malsy et al., 2015). This uncertainty is further exacerbated by sparse observation networks and complex terrain, which challenge accurate measurement and spatial interpolation. Land cover changes, including agricultural expansion, deforestation, and land degradation, further influence runoff generation, evapotranspiration, and water quality, adding another layer of complexity to hydrological processes (Wade et al., 2024). However, the integration of land surface dynamics into monitoring and modelling frameworks remains limited. Collectively, these data gaps reduce the reliability of hydrological models, constrain forecasting accuracy, and limit the effectiveness of water allocation and management strategies across the region.

Table 1. Changes in the number of hydrological gauging stations in Central Asia (1980s–present), showing a decline after the Soviet period and only partial recovery

Country	1980s (Soviet period)	Late 1990s	Current (latest)	Change vs 1980s
Kazakhstan	506	354	410	↓ ~19%
Kyrgyzstan	147	111	78	↓ ~47%
Tajikistan	139	85	96	↓ ~31%
Turkmenistan	38	23	33	↓ ~13%
Uzbekistan	155	119	133	↓ ~14%

Source: SIC ICWC Policy Brief No. 10 (2026).

Note: *Station numbers were compiled from national hydrometeorological services, regional reports, and published literature available at the time of writing (2024–2025). "Current/Latest" refers to the most recent publicly available information identified for each country. Direct comparison between countries should be interpreted with caution, as monitoring networks differ in spatial coverage, station type, operational status, reporting practices, and data accessibility.*

While the number of monitoring stations provides a useful indicator of network capacity, station counts alone do not fully reflect the quality or operational value of hydrological information systems. In many cases, monitoring challenges relate not only to the density of stations but also to issues of station functionality, maintenance, calibration, metadata quality, data continuity, and accessibility. Some stations may be inactive, operate intermittently, or lack standardized procedures for data management and sharing. As a result, assessments of monitoring capacity should consider both quantitative indicators (e.g., station numbers) and qualitative aspects related to data reliability, interoperability, and long-term operational sustainability.

Climate Change and Cryosphere Decline

Climate change is intensifying existing vulnerabilities in Central Asia's water systems, particularly through its impacts on the cryosphere. Glacier retreat is accelerating across Central Asia, with some studies projecting glacier volume losses exceeding 50–80% by the end of the 21st century under high-emission scenarios, particularly in parts of the Tien Shan and Pamir Mountain systems (Liu & Li, 2025). This has profound implications for river systems that depend on glacier and snowmelt contributions, especially during dry seasons. Declining snowfall further exacerbates these challenges by reducing the natural storage and gradual release of water from snowpack systems (Jouberton et al., 2025). As a result, the timing and magnitude of river flows are becoming increasingly variable and less predictable. These changes are expected to significantly alter:

- Seasonal flow regimes, with earlier peak flows and reduced late-season water availability;
- Overall water availability, particularly during critical agricultural periods;
- Long-term water security, as natural buffering systems decline.

The combination of cryosphere degradation and climatic variability increases uncertainty in water supply, placing additional pressure on already limited monitoring and management capacities.

Institutional and Transboundary Constraints

Hydrological challenges in Central Asia are closely intertwined with governance and institutional limitations. Effective water management in the region requires coordination across multiple countries, yet institutional fragmentation and weak collaboration mechanisms continue to hinder data exchange and integration (Cassara et al., 2019). Upstream–downstream dynamics further complicate cooperation, as countries often have competing priorities related to water use for hydropower, irrigation, and domestic supply (Ugli et al., 2025). These competing interests can limit the willingness to share data and adopt coordinated management approaches.

In addition, legal and regulatory frameworks governing water resources remain fragmented and inconsistently applied, reducing their effectiveness in supporting integrated basin management (Janusz-Pawletta, 2015). Institutional arrangements often lack the flexibility and capacity required to respond to rapidly changing environmental conditions. As a result, even where hydrological data exists, it is frequently underutilized or not fully integrated into policy and operational decision-making processes. This gap between data availability and its practical application represents a critical barrier to improving water governance and achieving sustainable, cooperative management of transboundary water resources.

Regional Water Governance and Monitoring Architecture

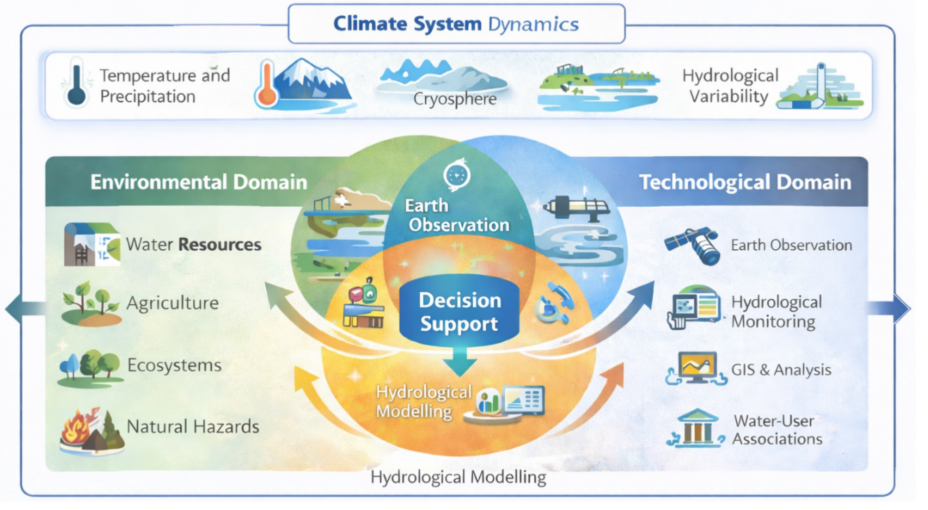
Effective hydrological monitoring and water governance in Central Asia depend on a complex institutional architecture comprising national hydrometeorological agencies, basin organizations, regional coordination bodies, and international development partners. National Hydromet agencies remain the primary providers of hydrological and meteorological observations, while regional coordination mechanisms such as the Interstate Commission for Water Coordination (ICWC), its Scientific Information Centre (SIC ICWC), and the Basin Water Organizations (BWO) of the Amu Darya and Syr Darya support basin-scale planning, water allocation, and information exchange. At the regional level, the International Fund for Saving the Aral Sea (IFAS) provides an important platform for cooperation and environmental initiatives. Despite these institutional arrangements, data sharing remains uneven, monitoring standards vary among countries, and interoperability challenges continue to constrain the effective use of hydrological information for decision-making.

TECHNOLOGICAL OPPORTUNITIES

While Central Asia faces significant challenges related to hydrological data gaps and institutional constraints, recent advances in Earth Observation (EO), machine learning, and digital technologies offer substantial opportunities to transform water monitoring and management systems. These technologies provide new pathways to enhance data availability, improve forecasting accuracy, and support evidence-based decision-making. Importantly, their greatest value lies not in replacing traditional monitoring systems, but in enabling, multi-source data frameworks that combine in-situ observations with advanced analytical tools.

Figure 1 summarizes the conceptual framework underpinning this paper. The framework illustrates how climate change, population growth, and increasing water demand place growing pressure on water resources across Central Asia. In response, integrated monitoring systems that combine conventional hydrological observations with Earth Observation, machine learning, IoT networks, and digital twin technologies can strengthen data availability and interoperability. These enhanced information systems support decision-support tools for forecasting, water allocation, drought management, and flood risk assessment, ultimately contributing to improved climate resilience, evidence-based water governance, and transboundary cooperation.

Figure 1. Conceptual framework illustrating how integrated hydrological monitoring systems, combining in-situ observations, Earth Observation, and emerging digital technologies, can support data-driven decision-making, climate resilience, and transboundary water governance in Central Asia.



Source: Developed by the authors

Earth Observation and Hydrological Monitoring

Advances in Earth Observation have significantly expanded the capacity to monitor hydrological processes across large and often inaccessible regions of Central Asia. Satellite-based systems provide consistent spatial coverage, enabling observation of remote mountainous areas where traditional monitoring networks are sparse or absent. In addition, EO technologies offer near real-time monitoring of water dynamics, as well as long-term datasets that are essential for climate and hydrological trend analysis. A range of satellite missions now support hydrological applications at multiple scales. For example, satellite altimetry missions such as ICESat-2 enable high-precision monitoring of water surface elevation, contributing to improved understanding of river, lake, and reservoir dynamics (Khorrami et al., 2021). Similarly, gravimetric missions such as GRACE and GRACE-FO provide valuable insights into regional-scale groundwater storage changes, capturing both natural variability and anthropogenic impacts (Gafurov et al., 2024).

In addition, optical and radar remote sensing techniques are widely used for surface water mapping, irrigation monitoring, and land-use assessment, providing critical information for water resource management and agricultural planning (Krutikov et al., 2004). These technologies are particularly valuable in transboundary contexts, where consistent and comparable data across national boundaries is essential. Despite these advantages, EO data alone is not sufficient. Its effective application depends on integration with ground-based observations, which provide calibration, validation, and local context. This highlights the importance of developing hybrid monitoring systems that leverage both in-situ and satellite-based data.

While Earth Observation provides unprecedented opportunities for large-scale and near-real-time monitoring, it should be viewed as complementary to, rather than a replacement for, in-situ monitoring networks. Ground-based observations remain essential for calibration, validation, uncertainty assessment, and long-term continuity of hydrological records. The operational use of EO-derived products also depends on national ownership, institutional capacity, standardized data protocols, and integration into existing decision-making processes. Challenges related to data interoperability, technical skills, maintenance of monitoring systems, and the translation of scientific products into operational services must be addressed to ensure sustained uptake by water agencies and basin organizations. Strengthening the link between satellite observations, national hydrometeorological services, and regional data-sharing platforms will therefore be critical for maximizing the value of Earth Observation in Central Asia.

Machine Learning and Data Integration

Machine learning (ML) techniques are increasingly being applied to address the complexity and uncertainty inherent in hydrological systems. By enabling the analysis of large and heterogeneous datasets, ML approaches can improve both data interpretation and predictive modelling. Recent studies demonstrate the potential of ML for high-resolution hydrological applications. For example, machine learning-based downscaling techniques have been used to generate fine-scale groundwater storage anomaly maps, significantly improving spatial resolution compared to traditional approaches (Yuan et al., 2025). Similarly, ML methods have enhanced the estimation of snow water equivalent (SWE) by integrating meteorological and remote sensing data, reducing uncertainty in snowpack assessments (Goodarzi et al., 2025). These approaches are particularly valuable in data-scarce environments such as Central Asia, where traditional monitoring networks are limited. By combining multiple data sources—such as EO, climate data, and in-situ measurements—ML techniques enable the development of data-driven hydrological models that can support forecasting, scenario analysis, and decision-making. However, the effective application of these tools requires not only technical capacity but also institutional readiness and access to high-quality input data, reinforcing the need for integrated monitoring systems.

Integrated Monitoring and Smart Irrigation Systems

The convergence of digital technologies, including the Internet of Things (IoT), automated monitoring systems, and digital twin modelling, is creating new opportunities for real-time, adaptive water management. These technologies facilitate the transition from static monitoring approaches to dynamic systems capable of responding to changing environmental and operational conditions. Automated hydrological monitoring stations, including multi-parameter observation networks in high mountain regions, are expanding the availability and continuity of critical hydrological data (Schöne et al., 2013). These systems enable more frequent and reliable measurements, supporting improved forecasting and early warning capabilities. In the agricultural sector, smart irrigation technologies are demonstrating significant potential to enhance water use efficiency. Pilot studies of automated and IoT-enabled irrigation systems in Central Asia have reported water-use efficiency improvements ranging from approximately 25% to 59%, depending on crop type, irrigation infrastructure, and local operating conditions

(Batykova et al., 2025). This is particularly important in Central Asia, where agriculture remains the dominant water user.

Digital twin approaches further extend these capabilities by enabling the simulation and optimization of water systems under different scenarios. For example, digital twin-based irrigation models allow for adaptive management of water resources, integrating real-time data with predictive modelling to support decision-making at farm and basin scales (Arifjanov et al., 2025). Together, these technologies provide a foundation for transitioning toward integrated, water management systems. However, their successful implementation depends on overcoming existing institutional and technical barriers, including data sharing limitations, capacity constraints, and the need for coordinated regional frameworks.

Operational Challenges and Limitations

Despite the considerable potential of Earth Observation, machine learning, IoT networks, and digital twin technologies, their successful implementation in Central Asia faces several practical and institutional challenges. Many advanced monitoring systems require sustained investment in infrastructure, technical expertise, maintenance, and long-term operational support. In some regions, limitations in data availability, monitoring network density, and historical records constrain the development and validation of predictive models. Earth Observation products often require calibration and validation using ground-based measurements, while machine learning approaches depend on the availability of reliable training datasets. Similarly, IoT-based monitoring systems may face challenges related to equipment maintenance, communication infrastructure, power supply, and long-term sustainability, particularly in remote environments. Digital twins, although promising, require substantial data integration, computational resources, and institutional coordination to support operational decision-making.

Additional challenges include data interoperability, inconsistent metadata standards, fragmented data governance arrangements, and varying levels of technical capacity among institutions. Addressing these constraints will be essential to ensure that emerging technologies can be effectively integrated into national monitoring systems and regional water management frameworks. Consequently, technological innovation should be accompanied by investments in institutional capacity, governance mechanisms, data standards, and long-term operational support.

POLICY IMPLICATIONS

Addressing hydrological data gaps and leveraging emerging technologies has direct and far-reaching implications for water governance in Central Asia. Improved monitoring systems not only enhance scientific understanding but also strengthen decision-making processes, operational management, and regional cooperation mechanisms. By transforming how data is collected, shared, and applied, Central Asian countries can move toward more proactive, transparent, and adaptive water management frameworks.

Improved hydrological monitoring systems have direct implications for a range of operational and strategic water management decisions across Central Asia. Reliable observations of streamflow, reservoir storage, precipitation, snowpack, glacier conditions, and groundwater levels support seasonal water allocation planning between upstream and downstream users, optimize reservoir operations, and strengthen drought early warning systems. Enhanced monitoring can also improve flood forecasting, irrigation scheduling, groundwater management, and climate adaptation planning. By reducing uncertainty in water availability assessments and providing a shared evidence base for decision-making, monitoring systems can support more transparent and informed management of transboundary water resources.

Better Data for Better Decisions

Reliable and integrated hydrological data is fundamental to effective decision-making across multiple scales, from local water management to national planning and regional coordination. Improved monitoring systems—particularly those combining in-situ observations with Earth Observation and digital tools—enable more accurate and timely assessments of water availability and variability. Enhanced data availability directly supports seasonal forecasting, which plays a critical role in planning agricultural production, hydropower operations, and water allocation strategies. Climate-informed forecasting approaches have demonstrated the ability to improve anticipatory decision-making, reducing uncertainty and increasing system resilience (Gerlitz et al., 2020).

In the agricultural sector, where water demand is highest, improved data and monitoring systems can significantly enhance efficiency and productivity. Studies conducted in irrigated agricultural systems in Central Asia have reported crop yield improvements of approximately 15–30% where improved water management and irrigation practices were implemented, although outcomes vary according to crop type, climate conditions, and management approaches (Amirbekuly et al., 2024). This is particularly important in Central Asia, where irrigation accounts for the majority of water use. Improved monitoring also strengthens flood forecasting and hazard response systems, enabling earlier detection of extreme events and more effective risk mitigation. Remote sensing and advanced monitoring technologies have been successfully applied to enhance flood detection and response capabilities, reducing the impacts of hydrological hazards (Arkhipkin & Sagatdinova, 2017). Overall, improved hydrological data systems support a transition from reactive to proactive water management, enabling decision-makers to anticipate risks, optimize resource allocation, and respond more effectively to changing conditions.

Transboundary Governance Benefits

In a region where water resources are inherently transboundary, the availability of reliable, shared, and transparent data is essential for effective cooperation. Hydrological data is not only a technical resource but also a strategic asset for building trust and facilitating dialogue among countries. Strengthened data-sharing mechanisms can enhance the effectiveness of regional institutions such as the International Fund for Saving the Aral Sea (IFAS), which rely on coordinated data inputs to support basin-scale planning and decision-making (Prniyazova et al., 2025). By improving the quality and accessibility of hydrological information, countries can develop a shared understanding of water availability and variability, reducing uncertainty in negotiations and planning processes.

Harmonized monitoring systems and standardized data protocols further contribute to transparency and comparability, which are critical for building confidence among stakeholders. Previous research highlights that improved data management and sharing practices can significantly enhance integrated water resources management across the region (Abdullaev & Rakhmatullaev, 2014). In this context, hydrological monitoring systems play a dual role: as a technical foundation for water management, and as a mechanism for strengthening regional cooperation and water diplomacy. By enabling more transparent and evidence-based decision-making, improved data systems can help mitigate conflicts, align national interests, and support more sustainable and cooperative management of shared water resources.

POLICY RECOMMENDATIONS

Addressing the complex and interconnected challenges of water management in Central Asia requires a coordinated set of policy actions that integrate technological innovation, institutional reform, and regional cooperation. The following recommendations outline priority areas for strengthening hydrological monitoring systems and enhancing decision-making across the region.

Expand Hybrid Monitoring Systems

A critical priority is the development of integrated or hybrid monitoring systems that combine multiple data sources, including ground-based hydrological stations, Earth Observation (EO), unmanned aerial vehicles (UAVs), and machine learning-based analytical tools. Such systems can significantly enhance spatial and temporal data coverage, particularly in remote and data-scarce regions. By integrating these technologies, countries can improve the accuracy and reliability of hydrological assessments, enabling more robust modelling and forecasting capabilities. Hybrid approaches also facilitate cross-validation between data sources, reducing uncertainty and strengthening confidence in decision-making processes (Ouyang et al., 2023).

Establish Regional Data-Sharing Protocols and Standards

Effective transboundary water management depends on the availability of shared, standardized, and transparent data systems. Establishing regional data-sharing protocols is essential to ensure consistency in data collection, processing, and dissemination across countries. This includes the adoption of harmonized monitoring standards aligned with international best practices, as well as the development of digital platforms for real-time data exchange. Strengthening legal and institutional frameworks for data sharing can further support cooperation and improve the effectiveness of water resources management at the basin scale (Ziganshina, 2022).

Mainstream Cryosphere-Informed Planning

Given the central role of glaciers and snowmelt in the region's hydrology, it is essential to incorporate cryosphere dynamics into national and regional water management strategies. This includes integrating glacier retreat projections, snowpack variability, and long-term climate trends into planning and policy development. Mainstreaming cryosphere-informed approaches can improve the resilience of water systems by enabling more accurate projections of future water availability and supporting the design of adaptive management strategies. Such approaches are particularly important for addressing long-term water security under changing climatic conditions (Liu & Li, 2025).

Strengthen Technical and Institutional Capacity

The successful implementation of advanced monitoring systems and data-driven approaches requires sustained investment in technical capacity and institutional development. This includes training professionals in hydrology, geospatial analysis, data science, and digital technologies, as well as strengthening institutional frameworks for data management and coordination. Capacity-building initiatives should also focus on enhancing the ability of institutions to integrate scientific data into policy and operational decision-making, ensuring that monitoring systems translate into practical outcomes. Investment in education, training programs, and digital skills development will be critical for supporting long-term sustainability (Amanzholova et al., 2024).

Scale Smart Irrigation and Digital Water Management Technologies

Agriculture remains the largest consumer of water in Central Asia, making it a key sector for improving water use efficiency. Scaling up the adoption of smart irrigation technologies, including systems based on remote sensing, digital modelling, and real-time monitoring, can significantly reduce water losses and improve productivity. Digital and EO-based irrigation management systems enable more precise water allocation, optimizing usage based on crop needs, soil conditions, and climatic factors. These approaches not only enhance water efficiency but also contribute to increased agricultural productivity and sustainability (Droogers & Bastiaanssen, 2002).

A Phased Implementation Pathway for Central Asia

While the recommendations outlined above are interconnected, their implementation requires a phased and coordinated approach involving national agencies, regional organizations, and development partners. Table 2 presents a proposed implementation pathway that prioritizes actions across short-, medium-, and long-term time horizons to strengthen hydrological monitoring, data sharing, and decision-support systems in Central Asia.

Table 2. Suggested Implementation Roadmap

Timeframe	Priority Action	Lead Institutions	Initial Steps	Expected Outcome
Short-term (1–3 years)	Inventory and rehabilitate hydrometeorological stations; assess data gaps and station functionality	National Hydromets, Ministries of Water Resources, WMO partners	Audit network functionality	Improved availability and reliability of monitoring data
Short-term (1–3 years)	Develop common metadata standards and data-sharing protocols	ICWC, SIC ICWC, Hydromets	Develop protocols	Improved interoperability and data exchange
Medium-term (3–5 years)	Establish shared regional hydrological databases and EO platforms	IFAS, ICWC, Basin Organizations, Development Partners	Pilot projects	Enhanced access to harmonized regional information
Medium-term (3–5 years)	Expand capacity building and operational EO integration within agencies	National agencies, Universities, Development Partners	Pilot projects	Increased technical capability and operational adoption

Long-term (5–10 years)	Develop regional decision-support systems for water allocation, drought monitoring, and flood forecasting	ICWC, BWOs, IFAS, National Water Authorities	Operational forecasting	Improved evidence-based decision-making
Long-term (5–10 years)	Institutionalize integrated forecasting and climate adaptation frameworks	Regional governments and basin organizations	Mainstream monitoring	Enhanced climate resilience and transboundary cooperation

Source: Developed by the authors

CONCLUSION

Water challenges in Central Asia are shaped by the convergence of climate change impacts, persistent hydrological data gaps, and institutional fragmentation, all of which collectively constrain effective water management and regional cooperation. While considerable attention has been given to governance reforms and transboundary agreements, this study highlights that a critical underlying bottleneck lies in the declining capacity and limited integration of hydrological monitoring systems. The reduction and fragmentation of observation networks, particularly in high-altitude and data-scarce regions, have significantly weakened the reliability of hydrological data, thereby limiting forecasting accuracy and evidence-based decision-making. At the same time, rapid environmental changes especially glacier retreat and declining snowpack are increasing uncertainty in water availability and intensifying pressure on already constrained systems.

The central argument of this paper is that strengthening hydrological monitoring and data-sharing systems is not merely a technical challenge but a governance priority for Central Asia. Reliable and interoperable monitoring networks provide the foundation for more credible forecasting, water allocation, climate adaptation, and transboundary cooperation. While Earth Observation, machine learning, IoT networks, and digital twin technologies offer significant opportunities to strengthen hydrological information systems, their effectiveness ultimately depends on how they are integrated into existing institutional and operational frameworks.

The long-term value of hydrological data systems lies not simply in generating information, but in ensuring that information is routinely used to support decisions. This requires sustained investment in monitoring infrastructure, clear institutional mandates, common data standards, adequate technical capacity, and well-defined decision-support processes. Strengthening these governance foundations will be essential for translating technological advances into improved water security, climate resilience, and regional cooperation across Central Asia.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

BJ: conceptualization, methodology, investigation, data analysis, visualization, writing – original draft preparation, writing – review and editing, supervision, and project administration; BP: conceptualization, technical review, validation – review and editing, and contribution to interpretation of results; VS: literature review, data compilation, analysis support, writing – review and editing, and manuscript revision; MK: scientific review, supervision, writing – review and editing, and overall project guidance.

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