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Development of a Gauging Station Network as a Key Element of Hydrological Monitoring of Transboundary Rivers in the Aral Sea Basin

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ABSTRACT

This policy brief examines the issues related to installation and maintenance of gauging stations along transboundary rivers of the Aral Sea Basin in the context of hydrological monitoring and water forecasting. Given the increasing water scarcity, climate change, and, at the same time, the high socio-economic role of transboundary water, rehabilitation and expansion of the hydrological observation network have become matters of growing strategic importance. The brief demonstrates that hydrological monitoring is a comprehensive system encompassing observations, forecasting, and control; however, its primary element is an

operational network of gauging stations. It also reviews the roles of the Interstate Commission for Water Coordination (ICWC) and the International Fund for Saving the Aral Sea (IFAS) in river flow monitoring and forecasting, provides definitions of gauging stations and transboundary gauging stations, and analyzes the existing legal-regulatory, and methodological framework, as well as practical experience gained through relevant projects. The policy brief identifies the key challenges and future prospects for the development of the gauging network as a cornerstone of sustainable water management in the region.

Relevance of hydrological monitoring and gauging stations

Hydrological monitoring is the cornerstone of water management. It encompasses the systematic observation of water bodies, the analysis and forecasting of river flows, and the provision of data for water allocation. Consequently, the efficacy of any monitoring system hinges directly on the availability and operational state of its primary observation network.

In recent decades, hydrological monitoring networks worldwide have faced a severe decline. Operational gauging stations have decreased in number, equip-

ment has become obsolete, and the continuity of long-term observation records has been disrupted¹.

This vulnerability is particularly acute in developing and arid regions, where financial and institutional constraints frequently hinder the maintenance of dense, modern networks.

In the Aral Sea Basin, this challenge is particularly critical. The region's shared water resources are vital for irrigation, hydropower, and public water supply.

In the context of climate change, accelerating glacier retreat, and escalating water demand, the need for objective, standardized, and transparent water accounting has become paramount.

Under these conditions, the establishment and robust operation of gauging stations represent the most fundamental requirement of hydrological monitoring. Without a fully functioning network, neither reliable flow forecasts nor the coordinated management of transboundary water is possible.

Hydrological monitoring as a basis of water management

Hydrological monitoring is the systematic process of observing, analyzing, and assessing the condition and regime of water bodies. It establishes the essential information base required for informed decision-making, strategic water planning, and proactive adaptation to hydrological extremes.

The primary source of information within a hydrological monitoring system is the data on water levels and flow discharge collected at gauging stations. These data form the baseline for water balance calculations, river flow assessments, and the development of both seasonal and operational forecasts. In transboundary river basins, the significance of these observations is magnified as the reliability and comparability of hydrological data are essential for the equitable allocation of shared water resources among riparian states.

Consequently, the establishment and maintenance of a gauging station network is a fundamental prerequisite for any effective hydrological monitoring system. Without a stable, operational network, it is

impossible to ensure the continuity of historical records or provide the insights required for sound water management.

Against the backdrop of escalating water scarcity, climate change, and growing demand, priority must be given not only to preserving existing stations but also to rehabilitating discontinued sites, expanding networks, and integrating them into national and basin-wide systems. To this end, the modernization and automation of gauging stations are critical tools for improving the timeliness, transparency, and reliability of data.

Ultimately, *hydrological monitoring* operates as a multi-level framework encompassing observation, forecasting, modeling, and control. At its foundation lies the gauging network. The quality of forecasts, the efficacy of transboundary water management, and the long-term sustainability of regional water relations are entirely dependent upon the health and development of this network.

Definition of a gauging station and its role in the monitoring system

A gauging station is a specially equipped site on a river, lake, or reservoir used to conduct systematic hydrological observations. Operating under established monitoring programs and standardized procedures, these stations primarily track water levels and discharge rates. Depending on their specific purpose, they may also monitor additional hydrological parameters, such as water temperature, turbidity, and sediment transport.

To illustrate **what a gauging station is, how it operates, and the types of hydrological observations conducted there**, this policy brief examines the gauging station on the Ugam River in the Republic of Uzbekistan (Figure 1). This specific site was selected because the Ugam River is a vital component of

Central Asia's transboundary water system. Originating in the mountainous regions of the Western Tien Shan, the river exhibits the distinct snow-rain and snow-glacier-fed hydrological regimes characteristic of the region.

The river's hydrological regime features pronounced seasonal variations in streamflow, a characteristic typical of Central Asian mountain rivers. This specific gauging station in Uzbekistan was also chosen because of its long-term, comprehensive observation

¹ Chapter 2.3.4 of WMO Guide to Hydrological Practices (No. 168, 6th ed., 2011), Volume I – Hydrology – From Measurement to Hydrological Information



Figure 1
A gauging station on the Ugam – Khojikent village

records. These historical datasets provide an ideal basis for demonstrating the core aspects of hydrological monitoring, including water level and discharge measurements, seasonal flow fluctuations, and standard observation practices. Consequently, the Ugam River gauging station serves as a representative example to illustrate the fundamental principles of hydrological monitoring in Central Asia.

The gauging station is located on the outskirts of Khojikent village, approximately 400-500 m downstream of a pedestrian bridge. Situated within a mountainous terrain, the river valley exhibits a distinct V-shaped cross-section. The left side of the valley is steep, with slopes reaching up to 45°, whereas the right side is gentler and transitions into a terrace that accommodates the village. Shrub vegetation and scattered trees cover the valley slopes.

Transboundary gauging station: characteristics and importance

A transboundary gauging station is located on a watercourse that either crosses an international border or delineates one. Unlike purely national facilities, transboundary stations carry immense political and institutional weight alongside their technical functions. The Khojikent station fits this description precisely, as it monitors a transboundary system. The Ugam River is a mountain stream shared by Kazakhstan and Uzbekistan, serving as a major right-bank tributary of the Chirchik River.

In the vicinity of the station, the river channel follows a straight alignment, although the overall river course is sinuous. The channel bed consists of coarse alluvial material dominated by boulders. The right bank is gently sloping, while the left bank features a well-defined floodplain that merges into the valley slope and becomes inundated during flood periods. Both banks are composed of gravel and boulder deposits with admixtures of sand and clay. Notably, an active landslide zone is located upstream of the gauging section on the left bank, and bank ice typically forms along the channel margins during winter.

The gauge is positioned on the right bank and is equipped with a Valdai-type automatic water-level recorder. The elevations of the station benchmarks and monitoring facilities were established via Class IV leveling in 1981. An auxiliary slope gauge is situated on the left bank at a distance of 40 m. The gauge zero elevation is set at 744.00 m above mean sea level in the Baltic System.

The hydrometric cross-section is located 5.2 m downstream of the water gauge and features a two-cable suspended measuring platform. Complex hydrodynamic conditions, including occasional reverse and oblique flows, are observed within this measurement section.

Data collected at such gauging stations form the base for constructing hydrological time series, analyzing hydrological regimes, and developing water forecasts. Ultimately, the reliability and representativeness of these datasets depend on the precise selection of the station site, strict adherence to observation methodologies, and maintenance of the monitoring equipment.

Because the data collected at such stations are utilized by multiple nations, all parties shall recognize the observations as objective and authoritative. Achieving this requires the harmonization of monitoring methodologies, consistency in technical approaches, and transparent information exchange. Consequently, transboundary gauging stations play a vital role in reducing regional tensions and building mutual trust, serving as practical instruments of modern water diplomacy.

Condition and dynamics of hydrological network in the Central Asian countries

According to data of national hydrometeorological services and archives, the hydrological monitoring network in Central Asia was considerably more extensive in the late 1980s, offering much denser spatial coverage than it does today. Operating within

the unified hydrometeorological observation system, this network ensured comprehensive monitoring of river runoff, covering major, medium, and small watercourses, as well as a substantial portion of transboundary rivers within the Aral Sea basin.

In the 1980s, the regional hydrological network comprised gauging stations distributed as follows: 506 in Kazakhstan, 147 in Kyrgyzstan, 139 in Tajikistan, 38 in Turkmenistan, and 155 in Uzbekistan. These figures aligned with the water management and river flow forecasting requirements of the centralized monitoring system (Table 1).

By the late 1990s, all countries in the region experienced a sharp decline in the number of operational gauging stations. By 1998, the network had contracted to 354 stations in Kazakhstan, 111 in Kyrgyzstan, 85 in Tajikistan, 23 in Turkmenistan 119, and in Uzbekistan. This degradation stemmed from post-Soviet institutional reforms, funding cuts, deteriorating monitoring infrastructure, and the disintegration of the formerly unified observation system.

Currently, the number of operational gauging stations remains significantly below 1980s levels. The latest available data indicate that the network now comprises 410 stations in Kazakhstan, 78 in Kyrgyzstan, 96 in Tajikistan, 33 in Turkmenistan, and 133 in Uzbekistan.

In most countries of the region, the network has shrunk by 30% to 50% compared to the late Soviet period, with some nations losing more than half of their original monitoring capacity.

This thinning of the hydrological monitoring network has reduced spatial observation coverage, caused interruptions in long-term hydrological time series, and diminished the representativeness of hydrological data, particularly for small and transboundary watercourses. Consequently, this severely constrains river runoff monitoring and forecasting capabilities, complicating evidence-based water allocation among the Aral Sea basin states.

Given these circumstances, rehabilitating and expanding the gauging network – specifically by aligning it with river basin boundaries and integrating it into existing national and regional monitoring frameworks – is a critical priority for advancing hydrological observation and a prerequisite for improving transboundary water management.

Table 1

Gauging stations in Central Asia

Country	Number of gauging stations*		Currently operational gauging stations**
	80-s	Late 90-s	
Kazakhstan	506***	354	410
Kyrgyzstan	147	111	78
Tajikistan	139	85	96
Turkmenistan	38	23	33****
Uzbekistan	155	119	133

Note: The information in this Table shows the gauging stations that are on the balance sheets of national hydrometeorological services

Data sources: (*) – https://unece.org/fileadmin/DAM/env/water/cwc/Info-pp/ppt/myagkov_ru.pdf;

(**) – GFDRR (Global Fund for Disaster Risk Reduction) and the World Bank;

(***) – <https://unece.org/sites/default/files/2023-02/S1-1%20Ravza%20Ashanova.pdf>;

(****) – <https://wecoop.eu/wp-content/uploads/2021/11/4-1.4-Turkmenhydromet-Agalhanowa.pdf>

Assessment of spatial coverage of hydrological monitoring

To assess the adequacy and spatial representativeness of the gauging station network, hydrologists widely use the river network density index.

Defined as the ratio of the total length of all surface watercourses to the total land area, this indicator is expressed in kilometers of watercourses per square kilometer (km/km²). It reflects the development of the

hydrographic network and is used to analyze the complexity of river systems, as well as to justify monitoring requirements.

Applying this approach to Central Asia provides a more objective basis for evaluating the condition and adequacy of the existing gauging network. The region is characterized by pronounced natural hete-

rogeneity. The mountainous areas of Kyrgyzstan and Tajikistan exhibit high river network density, complex topography, and strong seasonal runoff variability, necessitating a denser observation network, particularly on small and medium-sized streams within runoff-generating zones. In contrast, the arid lowlands of Kazakhstan, Uzbekistan, and Turkmenistan feature extensive catchment areas and sparse river networks, where monitoring needs are driven by the considerable length of transit river reaches and intensive water-resource utilization.

A comparison of river network density with the current number of active gauging stations indicates that the existing network does not provide sufficient spatial coverage in many countries across the region. Despite substantial differences in physical geography, the reduction in the number of gauging stations since the late 1980s and early 1990s has resulted in the loss of observations on small and medium-sized watercourses and a decline in monitoring resolution, including along transboundary river reaches in the Aral Sea basin.

To further assess the spatial coverage of hydrological monitoring, the indicator of land area per operational gauging station was employed. This metric is widely used internationally as an integrated measure of network density².

Calculations based on the current number of operational stations (Kazakhstan – 410, Kyrgyzstan – 78, Tajikistan – 96, Turkmenistan – 33, and Uzbeki-

stan – 133) reveal significant disparities in the coverage of hydrological observations across the region.

The most critical situation is observed in Turkmenistan, where more than 14,000 km² of territory is served by a single gauging station, indicating an extremely sparse network. In Kazakhstan, the corresponding figure is approximately 6,600 km² per station, which, given the country's vast territory and diverse environmental conditions, also limits spatial monitoring resolution. In Uzbekistan, the load per station remains high at approximately 3,400 km² – a particularly pressing concern for transboundary rivers and intensively utilized watercourses.

Even in countries with relatively denser observation networks, such as Kyrgyzstan and Tajikistan, the spatial distribution of stations does not always align with the boundaries of river systems or runoff-generation zones. This reduces the representativeness of observations and complicates river flow forecasting, particularly in a transboundary context.

These findings underscore the need for a targeted expansion of the gauging station network, better alignment of stations with river basin boundaries, integration into national and regional monitoring systems, and the adoption of standardized, automated observation methods. Such measures would enhance the spatial representativeness of hydrological data, improve data comparability between countries, and strengthen the basis for joint forecasting and water allocation in the Aral Sea basin.

Role of ICWC and IFAS in flow monitoring and forecasting

Transboundary water management in the Aral Sea basin is inextricably linked to the framework of regional agreements and international legal instruments. The basin encompasses all five Central Asian states and is fed by its two principal rivers – the Amu Darya and the Syr Darya (Figure 2).

The foundation of regional water cooperation in Central Asia is the Agreement on Cooperation in the Field on Management, Use, and Protection of Water Resources in Interstate Sources, signed in Almaty in 1992³. Under this Agreement, the region's states committed to the coordinated management of water resources, including regular information exchange, hydrological monitoring, and the development of river flow forecasts.

Although the Agreement does not explicitly specify the technical aspects of hydrological monitoring, its effective implementation relies on a functioning network of gauging stations capable of providing reliable data on transboundary flow regimes.

The Interstate Commission for Water Coordination (ICWC) plays a central role in coordinating water use and allocating river flows among the member states. To fulfill these responsibilities, the Commission relies on hydrological observation data, which form the basis for seasonal flow forecasts and support decision-making regarding water allocation during both growing and non-growing seasons.

The International Fund for Saving the Aral Sea (IFAS) serves as an important institutional platform for implementing projects aimed at environmental improvement in the basin and monitoring strengthening. Within the framework of IFAS programs, numerous initiatives have been undertaken – and remain

² Calculation is made using the indicator of Density of hydrological networks (United Nations Division for Sustainable Development)

³ Agreement between the Republic of Kazakhstan, the Kyrgyz Republic, the Republic of Tajikistan, Turkmenistan and the Republic of Uzbekistan on Cooperation in the Field of Management, Use and Protection of Water Resources in Interstate Sources



Figure 2
Map of the Aral Sea Basin with major transboundary rivers⁴

ongoing – to modernize gauging stations and automate monitoring systems.

Gauging stations of the Basin Water Organizations Syr Darya and Amu Darya (BWOs). A network of gauging stations operates in the Syr Darya and Amu Darya river basins to support day-to-day water

management. However, this network is characterized by uneven spatial distribution, limited density, and varying levels of equipment and operational capacity. Several stations require modernization, while along some transboundary river sections, observations are either absent or insufficient to ensure the consistency and comparability of hydrological data.

Regulatory framework and harmonization of monitoring methodologies

The establishment and operation of gauging stations are governed by the applicable Guidelines for Hydrometeorological Operations (Issues 2, 6, and 7), as well as regulatory document RD 52.04.107-86: Guidelines for Hydrometeorological Stations and Posts. These documents set forth standard requirements for site selection, measurement methodologies, and the organization of hydrological observations.

Hydrological monitoring is carried out in line with Issue 6 of the Guidelines (Hydrological Observations at River Stations and Posts), which consists of two parts: Part I: *Hydrological Observations on Large and Medium Rivers* (Gidrometeoizdat, Leningrad, 1978,

3rd ed.) and Part II: *Hydrological Observations on Small Rivers* (Gidrometeoizdat, Leningrad, 1972).

The Guidelines for Hydrometeorological Stations and Posts comprise a series of regulatory documents governing the organization and methodology of hydrometeorological observations. These guidelines are divided into several issues, each addressing a specific type of observation or operational aspect of stations and posts.

⁴ FAO Aquastat, "Transboundary River Basin Overview – Aral Sea" (FAO, 2012)

For hydrological observations, the most relevant document is Issue 2, Part II: *Hydrological Observations at Gauging Stations* (Gidrometeoizdat, Leningrad, 1975, 3rd ed.)⁵.

This regulatory document establishes the procedures for observations at river gauging stations/posts, outlining methodologies to measure water levels, water discharge, water temperature, turbidity, suspended sediment load, and bottom sediments.

The third edition of this issue describes all types of observations included in the standard program for Category I gauging stations operating on medium and large rivers. Observations on small rivers, as well as on lakes and reservoirs, are conducted in line with other sections of the Guidelines, namely Issue 6, Part II (1972)⁶ and Issue 7, Part I (1973)⁷.

The second part of the first section notes that an observation network comprising several thousand

gauging stations has been established across the CIS territory, where observations of hydrological regime elements are routinely carried out.

Globally, the key reference document is the WMO Guide to Hydrological Practices (WMO-No.168),⁸ which emphasizes the importance of harmonizing monitoring methodologies, automating observations, and ensuring data comparability.

This framework is complemented by the UNECE recommendations on transboundary water monitoring,⁹ as well as by international conventions that oblige states to exchange hydrological information.¹⁰

Harmonizing monitoring methodologies is a prerequisite for the mutual recognition of data collected at transboundary gauging stations by all riparian countries and for its effective use in joint water management.

Requirements for the establishment of gauging stations under the Guidelines for Hydrometeorological Stations and Posts

According to the Guidelines, gauging stations must comply with a comprehensive set of organizational and technical requirements.

Gauging stations are required to meet established accuracy standards for measuring water levels, flow velocity, sediments, and water temperature. The use of standardized hydrometric instruments is essential to ensure the reliability and accuracy of observations.

Regular calibration and verification of equipment are mandatory, as is the employment of qualified personnel trained in hydrometeorological observation methods.

Equally important is the uninterrupted transmission of data to national and international hydrological monitoring centers.

In addition, the Guidelines establish several specific requirements:

- *Site selection:* A gauging station should be located on a representative section of a watercourse where flow conditions are relatively uniform and where the influence of local disturbances – such as bridges, backwaters, or wastewater discharges – is minimized.

- *Safety and protection:* Monitoring equipment must be protected against floods, ice drift, wind loads, and vandalism. This requires the installation of protective structures and the use of robust, reliable mounting systems.

- *Methodological standardization:* Measurements of water levels, discharge, turbidity, and water temperature must be carried out in strict accordance with approved methodological documents, including the Guidelines, the WMO Guide to Hydrological Practices (WMO-No.168), and other applicable standards. This ensures data comparability across different gauging stations and countries.

- *Quality assurance and control:* Observation logs must be maintained systematically, critical measurements must undergo independent verification, and historical data archives must be preserved to support subsequent analysis and validation.

⁵ "Наставление гидрометеорологическим станциям и постам. Выпуск 2. Часть II. Гидрологические наблюдения на постах" (утв. ГУГМС СССР 01.11.1973 г.)

⁶ "Наставление гидрометеорологическим станциям и постам. Выпуск 6. Часть II. Гидрологические наблюдения и работы на малых реках"

⁷ "Наставление гидрометеорологическим станциям и постам. Выпуск 7. Часть I. Гидрометеорологические наблюдения на озерах и водохранилищах" (3-е изд-е, переработ. и дополнен.)

⁸ https://mgmtmo.ru/edumat/wmo/168_1.pdf

⁹ https://unece.org/fileadmin/DAM/env/water/publications/WAT_Guide_to_Implementing_Convention/ECE_Water_Guide_Rus_WEB.pdf

¹⁰ Convention on the Law of the Non-navigational Uses of International Watercourses

Establishment and automation of gauging stations: lessons and challenges

In recent years, Central Asian countries have implemented numerous projects aimed at strengthening hydrological monitoring systems, establishing new gauging stations, and modernizing existing observation networks. Significant contributions to these efforts have been made through initiatives supported by the World Bank, the Asian Development Bank, the Global Environment Facility (GEF), the Global Facility for Disaster Reduction and Recovery (GFDRR), the United Nations Economic Commission for Europe (UNECE), and other international organizations. These projects have facilitated the deployment of automated water-level sensors, telemetry-based data transmission systems, modern hydrometric equipment, and the integration of monitoring data with geographic information systems (GIS) and digital platforms.

Overall, these projects have had a positive impact on the development of hydrological observation networks and have partially addressed deficiencies in data availability, particularly along priority and transboundary river reaches. However, in practice the establishment and subsequent automation of gauging stations require more comprehensive feasibility studies and a systematic planning approach.

In several cases, new gauging stations have been established by individual projects without sufficient integration into existing national networks. Such stations are often not incorporated into basin-wide monitoring systems, aligned with existing water management zoning schemes, or integrated into the operational information flows of basin organizations. Consequently, their practical value for river flow forecasting and water management is significantly reduced.

CONCLUSIONS AND RECOMMENDATIONS

The analysis demonstrates that establishing, rehabilitative, and further modernizing gauging stations on transboundary rivers of the Aral Sea basin constitute an indispensable prerequisite for effective hydrological monitoring, river flow forecasting, and sustainable regional water management. Gauging stations serve as the primary source of objective data, without which neither reliable forecasts nor coordinated interstate water allocation can be achieved.

An assessment of hydrological observation networks in Central Asia reveals a substantial decline in the number of gauging stations compared with the 1980s. Although partial restoration has occurred in recent years, the current number of operational

A further challenge is the insufficient attention paid to the vertical geodetic referencing of newly established gauging stations to the national leveling network. Without a reliable geodetic framework, the comparability of water-level data becomes problematic, the continuity of long-term observation records is compromised, and the usefulness of the data for long-term analysis and hydrological modeling is diminished.

In addition, several systemic constraints remain. These include the limited integration of project-based gauging stations into national and regional databases, differences in measurement methodologies, shortages of qualified personnel capable of operating and maintaining automated equipment, and the lack of sustainable funding mechanisms following the completion of externally funded projects. Collectively, these factors prevent technically advanced stations from becoming fully functional components of a unified hydrological observation network.

The experience gained from project implementation clearly demonstrates that the development of gauging networks in the region should not be limited to equipment installation and automation. A comprehensive approach is required, encompassing the alignment of gauging stations with river basin management structures, their integration into national and regional networks, the implementation of geodetic and methodological standards, and the provision of adequate institutional and human-capacity support. Only under these conditions can project-based gauging stations effectively fulfill their role within systems for hydrological monitoring and forecasting of transboundary water resources.

stations across the region remains below historical levels. This has reduced spatial coverage, caused the loss of valuable long-term hydrological records, and degraded data representativeness, particularly on small rivers and transboundary watercourses.

Evaluating spatial adequacy through indicators such as river network density and the area served per operational station confirms significant disparities both among countries and within individual river basins. Given the region's pronounced environmental heterogeneity – characterized by mountainous runoff-generating areas and extensive lowland transit zones – the existing gauging network often fails to align with the hydrographic structure of river sys-

tems and associated water management load. This substantially constrains capacities for routine monitoring, long-term assessment, and streamflow forecasting.

An examination of the roles of ICWC and IFAS indicates that their ability to coordinate water allocation and forecast resources depends directly on the availability of reliable, comparable observation data. In this context, developing transboundary gauging stations, harmonizing measurement methodologies, and establishing transparent data-sharing mechanisms transcend technical utility; they hold profound institutional significance as instruments for strengthening trust and water diplomacy in the region.

Lessons gained from international projects on establishment and automation of gauging stations demonstrate their positive contribution while simultaneously highlighting several systemic challenges. These include insufficient integration of newly established stations into national and basin-wide networks, a lack of comprehensive vertical geodetic referencing to

national leveling systems, limited integration into national and regional information platforms, and post-project shortages of financial and human resources. Consequently, technically advanced gauging stations do not always evolve into sustainable, fully functional components of a unified monitoring system.

Overall, the findings confirm that the development of gauging networks in the Aral Sea basin must be approached as a comprehensive and integrated task. This should include the restoration of discontinued observations, the strategic expansion of the monitoring network based on river basin characteristics, the harmonization of monitoring methodologies, geodetic and institutional integration, and the gradual implementation of automation. The adoption of such an approach would enhance the spatial and temporal representativeness of hydrological data, strengthen the scientific basis for river flow forecasting, and create conditions necessary for more effective and sustainable management of transboundary water in the face of growing climatic and socio-economic challenges.