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Impact of demarcation and delimitation processes on inter-state water resource governance in the Fergana Valley

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Abstract. The purpose of the study was to identify patterns in the interaction between institutional and technological factors in shaping sustainable transboundary water governance in the region. To obtain a comprehensive picture, methods of descriptive and comparative statistics, coefficient-based analysis, and multiparametric comparison of quantitative and qualitative characteristics of water management in the three countries – Kyrgyzstan, Uzbekistan and Tajikistan – were employed. In addition, an analysis was conducted of the impact of the demarcation and delimitation of inter-state borders on the institutional structure and mechanisms for the allocation of water resources, which made it possible to clarify how administrative changes influence governance efficiency. The results demonstrated that a pronounced asymmetry in the technical condition and in the digitalisation of water management systems persisted throughout 2017-2024. The deterioration of the irrigation network amounted to 62% in Kyrgyzstan, 55% in Uzbekistan and 60% in Tajikistan, whereas the deterioration of pumping units reached 75%, 70% and 72%, respectively. Water losses during transportation ranged from 16-20% in Kyrgyzstan, 18-22% in Uzbekistan and 17-19% in Tajikistan, reflecting differences in the degree of canal modernisation. Losses of regulated flow amounted to 80 million m^3 in Kyrgyzstan, 110 million m^3 in Uzbekistan and 85 million m^3 in Tajikistan, while losses of delivered water reached 25, 35 and 25 million m^3, respectively. The aggregate technological losses of the region reached approximately 650 million m^3, including 230-250 million m^3 in Uzbekistan, which corresponded to the highest load on the downstream irrigation system. Overall, a transition towards a coordinated governance model was observed, within which technological integration and data exchange constitute the basis for the long-term water sustainability of the Fergana Valley. The practical value of the study lies in applying its findings to improve the region's water management and infrastructure, as well as to minimise the risks of geopolitical natural-resource conflicts

Keywords: natural-resource conflicts; hydraulic infrastructure; digitalisation; sustainable water use; modernisation; water balance; water border

INTRODUCTION

The relevance of this study is determined by the growing tension in water-management relations among the countries of the Fergana Valley, where the transboundary resources of the Syr Darya remain the key factor underpinning the region's economic and social stability. Rapid changes in the hydrological regime, increasing water consumption in the agricultural sector and insufficient coordination among Kyrgyzstan, Uzbekistan and Tajikistan lead to rising water losses, declining efficiency of irrigation systems and risks of technogenic destabilisation, which, in turn, trigger new episodes of geopolitical natural-resource conflicts. Under conditions of intensifying climate variability and limited water resources, the transition to digital and integrated management systems constitutes one of the priority avenues for ensuring water security in the Fergana Valley. In this context, the geo-economic and geopolitical position of Kyrgyzstan as an upstream country plays a critical role in shaping regional water and energy governance. As noted by E. Belek uulu *et al.* (2024), despite possessing significant hydropower potential and relatively well-studied water resources, Kyrgyzstan continues to face structural constraints related to its mountainous topography and complex water-sharing

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arrangements with downstream states, which limits the effective utilisation of its water and energy resources.

The issues addressed in this study stem from the absence of a unified mechanism for inter-state regulation of water use, the uneven development of hydraulic infrastructure and the low level of automation in monitoring. Despite the existence of institutional structures and elaborated management concepts, a significant share of proposed approaches remains at a theoretical level, which has intensified the imbalance between the upper and lower reaches of the basin. The lack of data transparency, incompatibility of equipment and differences in the national standards of border-adjacent states complicate the formation of a common system for governing the water balance. Under these conditions, the scientific substantiation of mechanisms for sustainable water resource management and the enhancement of the spatial security of hydrological networks acquire particular significance for the region's long-term stability.

Drawing on the findings of N. Zatilla *et al.* (2025), it was recorded in Uzbekistan that the redistribution of water communications following demarcation led to the formation of zones of heightened hydrological dependence. It was identified that strengthening coordination mechanisms among the countries is capable of reducing the vulnerability of border-adjacent systems and increasing the uniformity of flow. In the study by S. Xenarios *et al.* (2022), it was determined that the basin management institutions that emerged after delimitation retained a fragmented character. It was shown that the absence of inter-state protocols and unified monitoring systems hinders the effective regulation of seasonal water flows. In the analysis of materials by E. Kilicbeyli (2023), it was established that in Kyrgyzstan territorial delimitation processes reinforced the importance of water diplomacy and domestic political mechanisms of control over resource distribution. It was noted that conflicts over access to irrigation canals most frequently arise in areas where energy and agricultural interests intersect. Based on the review by S. Jumari *et al.* (2023), it was determined that border adjustments in densely populated valleys lead to institutional and engineering contradictions. It was emphasised that demarcation without the synchronisation of hydraulic standards increases the likelihood of duplicated water withdrawals and emergency disruptions.

According to H. Wang *et al.* (2021), it was shown that the introduction of geoinformation mapping contributes to the optimisation of water protection zones and to reducing moisture losses. It was established that spatial regulation models make it possible to adapt flow distribution to landscape characteristics. In the conceptual interpretation by Q. Fang & H. Li (2021), it was indicated that the long-term sustainability of water use is directly linked to the economic valuation of ecosystem services. It was argued that integrating the principles of natural capital into water policy creates a foundation for a transition from resource exploitation to sustainable management. In the analytical interpretation by R. Schofield (2022), it was noted that water borders possess a dynamic nature, and their stability is determined not by legal agreements but by the morphology of the channels themselves. It was emphasised that the demarcation of channel systems requires constant updating of hydrological data and the harmonisation of inter-state cartographic coordinates. In the conceptual analysis by J. Castaño-Álvareza *et al.* (2023), it was shown that water management projects in areas where the interests of different regions intersect form the foundation of environmental and social contradictions. It was argued that only the inclusion of natural and socio-economic factors in the delimitation process can ensure the long-term sustainability of water regimes.

In the structural analysis by A. Pino *et al.* (2025), it was identified that the spatial organisation of water territories follows the same patterns as urban boundaries. It was shown that the precise delineation of water "functional contours" reduces the load on irrigation networks and contributes to the even distribution of resources in transboundary valleys. In the institutional interpretation by S. Jumari *et al*. (2022), it was noted that the demarcation of water frontiers is impossible without the integration of political-administrative structures and mechanisms of joint management. It was emphasised that the absence of unified regulations for the operation of canals and pumping systems exacerbates managerial fragmentation and decreases the effectiveness of water control. In the hydroecological justification by S. Al-Asadi & W. Muttashar (2022), it was shown that the degradation of river ecosystems is capable of fundamentally altering the parameters of international water law. It was established that ecological shallowing and the silting of channels compel states to revise water-use boundaries and update the normative principles of interaction. In the comparative context provided by E. Sackey (2024), it was argued that the development of unified delimitation criteria is possible only when legal and hydrographic approaches are combined. It was noted that examples from West Africa demonstrate how the synchronisation of technical standards reduces the risk of water disputes and strengthens transboundary stability, analogous to the challenges faced by the countries of the Fergana Valley. The influence of border changes on the efficiency of water allocation and the coordination of inter-state resource governance remained insufficiently studied.

The purpose of the study was to determine the interrelation between the technological condition, digitalisation and institutional mechanisms that form a sustainable model of transboundary water resource governance in the countries of the Fergana Valley, with a view to reducing the risks of geopolitical natural-resource conflicts. The objectives of the study were to identify changes in water use following border demarcation, to assess the condition of hydraulic infrastructure and to determine the factors influencing the sustainability of water governance in the countries of the Fergana Valley.

MATERIALS AND METHODS

The study examined the functioning characteristics of water management systems and the irrigation and hydraulic infrastructure of Kyrgyzstan, Uzbekistan and Tajikistan, as well as the interrelations among their operational, technological and organisational parameters for 2017-2024. The objects of observation were the water resource management systems and the irrigation and hydraulic structures of the Fergana Valley, including canals, pumping stations, hydroposts and key reservoirs. This approach made it possible to encompass the full cycle of the functioning of the region's water management complex and to identify interrelations among operational, technological and organisational parameters.

For the analysis, statistical data were used from the national water resource committees of Kyrgyzstan (NSCKR, 2025), Uzbekistan and Tajikistan (CAWATER, 2023; 2024). The following were considered as basic indicators: actual water withdrawal for the Syr Darya basin (km^3), deviation from the limit (%), actual use of water limits (%), water losses in open canals (billion m^3), length of modernised canals (km), number of pumping stations (units), level of hydraulic infrastructure modernisation (index), share of water management expenditure in GDP (%), volume of key reservoirs (km^3), reduction of winter releases (%), glacial runoff (km^3/year), automated hydroposts (units), average delay in hydrological data transmission (hours), implemented decisions of inter-state commissions (units), economic damage from uncoordinated actions (million USD/year) and the potential for water savings through the introduction of synchronised systems (%). Standard statistical algorithms and calculation formulas were used for data processing, providing a quantitative assessment of differences and ratios among water-use indicators. The calculations were performed in Statistica 12.0 (StatSoft, USA) and Microsoft Excel 2021. The mean value was calculated according to formula (1):

$$M = \frac{\sum_{i=1}^{n} x_i}{n}, \quad (1)$$

where x_i – an individual observation; n – the number of observations.

For spatial analysis, layers of basin boundaries, water intakes, canals and reservoirs were used, processed in ArcGIS 10.8 with the application of Spatial Analyst and the Hydrology Toolset. The resulting data were used for quantitative comparison and for analysing the distribution of flow and water losses. The analysis of operational characteristics was carried out using production logs, reports and literature sources for Kyrgyzstan (Ministry of Water Resources..., 2024), Uzbekistan (Ikramov *et al*., 2025) and Tajikistan (Environmental Monitoring Report, 2024). The following parameters were considered: water losses during transportation (%), losses of regulated flow (million m^3), pump efficiency factor, deterioration of units (%), number of emergency shutdowns (cases/year), losses of delivered water (million m^3), volume of cleaning works (thousand m^3), fulfilment of repair plans (%), deterioration of the irrigation network (%), canals without concrete lining (%), area of land requiring reconstruction (million ha), cost of supplying 1 m^3 of water (USD), annual electricity expenditure (million USD), inter-repair period of pumps (years), share of capacities with an efficiency factor below 0.6%, regional water losses (million m^3/year), loss of crop yield (% of agricultural output), area of sustainably irrigated land (million ha).

The study relied on data from the analytical report on water resources in Central Asia for the three countries, World Bank (2024a). The following were examined: the share of irrigation and drainage communications in border zones (%), number of unauthorised accesses (units), water losses due to interventions (million m^3), material damage (million USD), number of functioning pumping stations, level of protection (coefficient), engineering stability (coefficient), share of facilities requiring enhanced protection (%), share of video-monitoring systems (%), number of installed leakage and pressure sensors, average delay in hydrological data transmission (hours), integral index of spatial stability, average response time to failures (hours), recovery coefficient after shutdowns, reduction in the number of emergency incidents (%), engineering reliability of systems, increase in regional security (%) and reduction in economic risks (%). To summarise the parameters, an integral assessment methodology was applied, in which composite indices were calculated as weighted averages of three groups of factors: engineering, organisational and digital.

The analysis was conducted on the basis of literature sources and reports of the United Nations Economic Commission for Europe (2025) for Uzbekistan (Asilbekova *et al*., 2023), for Kyrgyzstan (Water Yearbook, 2024) and for Tajikistan. The following indicators were used in the study: share of autonomous water use (%), controlled water withdrawal coefficient, number of automated observation points (units), average error of hydrological data (%), share of synchronised accounting points (%), level of digitalisation of hydrological networks (%), accuracy of flow-distribution forecasts (%), share of hybrid pumping stations (%), integral water sustainability index and projected sustainability level.

RESULTS

Dynamics of the functioning of the water resource distribution system

By 2024, the transboundary management of water resources in the Fergana Valley continued to show a high dependence on inter-state coordination and technological disparities. Between 2017 and 2025, as a result of the processes of delimitation and demarcation of inter-state borders, the structure of water flow distribution and the administrative affiliation of key hydraulic structures among Kyrgyzstan, Uzbekistan and Tajikistan changed. The process was completed between Uzbekistan and neighbouring countries by 2023, whereas demarcation between Kyrgyzstan and Tajikistan is ongoing, which has resulted in the redistribution of responsibility for the operation and technical maintenance of water management infrastructure. Prior to 1991, water resource management was carried out centrally within the framework of Soyuzgidroproyekt and the basin administrations of the USSR, which ensured the planned distribution of flow among the republics. After 1991, upon gaining independence, each country formed its own water regulation bodies, which increased fragmentation and complicated the coordination of limits. The presented data show that the water deficit in the Syr Darya basin reached critical levels, and the gap between approved limits and actual water withdrawal amounted to approximately 17%. Uzbekistan gained the greatest benefits from demarcation, as a significant share of main canals and reservoirs became located within its territory after the clarification of borders, including facilities previously operated jointly with Kyrgyzstan and Tajikistan. This change strengthened its position in regulating downstream flows and the distribution of irrigation resources. In Kyrgyzstan, the consequences of the division of operational networks manifested themselves in rising water losses and reduced controllability of upstream sections, whereas Uzbekistan obtained an advantage in controlling distribution lines and the water supply of irrigation zones as a result of the ratified and delimited borders. In Tajikistan, reconstruction works covered major canals and pumping stations, but their effectiveness was constrained by technical dependence on main lines, part of which, following demarcation,

came under the administration of neighbouring countries (Scientific-Information Center..., 2024a).

An additional factor transforming the water balance was Afghanistan's construction of the Qosh-Tepa Canal (since 2022), which led to the redistribution of the Amu Darya flow and a reduction in water inflow to downstream areas, including Tajikistan. This circumstance required Tajikistan, Kyrgyzstan and Uzbekistan to strengthen hydropolitical cooperation and adjust their water-use strategies. Thus, the delimitation and demarcation of 2017-2025 altered the balance of ownership and operation of water resources, intensifying technological and institutional asymmetry. The main challenges of the post-demarcation period relate to the division of responsibilities, the uneven modernisation of infrastructure and the complexities of inter-state regulatory coordination (World Bank, 2024b). Summary indicators reflecting the scale of demarcation impacts and the potential for reducing water losses are presented in Table 1.

Table 1. Key indicators of water management in the countries of the Fergana Valley (2023-2024

Indicator	Kyrgyzstan	Uzbekistan	Tajikistan	Notes
Actual water withdrawal in the Syr Darya Basin, km³ (2024)	2.8	3.4	1.9	Total regional volume – 8.1 km³
Deviation from the limit, % (2024)	-17	-10	-17	Uzbekistan offsets the deficit through flow redistribution
Actual utilisation of water limits, % (2024)	78	91	87	High utilisation of limits in the lower reaches of the basin
Water losses in open canals, billion m³ (2023-2024)	Decreased from 3.4 to 3.1	Decreased from 6.5 to 6	Decreased from 7.1 to 6	High losses in ageing irrigation networks
Length of modernised canals, km (2023-2024)	210	410	620	Active reconstruction of main canals in Uzbekistan
Number of pumping stations, units (2024)	12	38	25	Uzbekistan has the largest pumping network in the region
Level of hydrotechnical infrastructure modernisation, % (2024)	35	42	40	According to the World Bank, 2024
Share of water management expenditure in GDP, % (2024)	0.9	2.1	1.7	High burden on Uzbekistan's agricultural sector
Volume of key reservoirs, km³ (March 2024)	7.7 (Toktogul Reservoir)	2.3 (Tyuyamuyun Reservoir)	3.4 (Kayrakkum Reservoir)	Key reservoirs of the Fergana Valley
Glacial runoff, km³/year (2024)	1.2 (Petrov Glacier)	0.4 (Ak-Suu Glaciers)	0.5 (Gissar Range Glaciers)	Main sources feeding the basin's rivers
Reduction of winter releases, % (2024)	–	8	12	For accumulating spring water volumes
Automated hydroposts, % (2024)	38	49	42	Highest density of hydroposts in the lower reaches
Average delay in hydrological data transmission, hours (2024)	60-72	54-60	60-72	Rapid data transmission in Uzbekistan due to SCADA networks
Implemented decisions of inter-state commissions, % (2023-2024)	38	41	38	Share of implemented Syr Darya agreements
Economic damage from uncoordinated actions, million USD/year (2023-2024)	reduced from 95 to 90	reduced from 120 to 110	reduced from 95 to 90	Total regional damage, highest in the lower reaches
Structure of damage, %	60 – agricultural sector 25 – electricity sector 15 – operational costs	70 – agricultural sector 20 – electricity sector 10 – operational costs	60 – agricultural sector 25 – electricity sector 15 – operational costs	Distribution of losses across economic sectors
Potential water savings with synchronised systems, % (2024)	22	27	23	According to calculations by the Central Asian Water Resources Institute

Note: GDP – gross domestic product

Source: developed by the author based on CAWATER (2023; 2024), Scientific-Information Center... (2024a), E. Chembarisov & M. Rakhimova (2024), World Bank (2024b), NSCKR (2025), and formula (1)

By 2024, the transboundary management of water resources in the Fergana Valley continued to exhibit tension and dependence on inter-state coordination. According to statistical data, the highest actual water withdrawal was recorded in Uzbekistan – approximately 3.4 km^3, reflecting the key role of the country as the main water consumer in the lower reaches of the Syr Darya. The lowest withdrawal was observed in Tajikistan – approximately 1.9 km^3, where resource use was constrained by mountainous terrain and a smaller area of irrigated land. The gap between approved limits and actual withdrawal averaged 10-17%, indicating a deficit of flow and technological unevenness in water distribution. Resource shortages reached peak levels specifically in the spring-summer season, when irrigation demand is at its maximum and the coordination of inter-state releases becomes more difficult (Chembarisov & Rakhimova, 2024).

Infrastructure development in 2023-2024 demonstrated significant disparities. The largest volume of modernisation of irrigation systems was carried out in Uzbekistan – more than 410 km of canals and 38 pumping stations – which made it possible to reduce water losses in open channels from 6.5 to 6 billion m^3. The lowest rates of renewal were recorded in Kyrgyzstan, where approximately 210 km of networks were modernised, while the share of technically deteriorated canals remained high. The share of water management expenditure in GDP also varied: the highest was 2.1% in Uzbekistan, the lowest – 0.9% in Kyrgyzstan, which confirmed differences in the countries' capacities to finance the water sector. The energy-hydrological aspect remained one of the key sources of contradictions. The largest reservoir in the region – Toktogul in Kyrgyzstan – contained 7.7 km^3 of water, serving as the main regulator of flow. The lowest volumes were recorded in the Tuyamuyun Reservoir (2.3 km^3, Uzbekistan), located entirely under national administration, which limited the capacity to compensate for seasonal fluctuations and regulate water supply to Uzbekistan's irrigation systems. Irregular releases resulted in water shortages in downstream areas and yield losses amounting to up to 60% of the total damage to the agricultural sector. The region's aggregate economic damage was estimated at USD 110-120 million per year, with Uzbekistan bearing the largest losses and the mountainous areas of Tajikistan the smallest (Scientific-Information Center..., 2024a).

The level of digitalisation of hydromonitoring also differed. The highest level of automation was recorded in Uzbekistan (approximately 49% of hydroposts), the lowest – in Kyrgyzstan (38%). The average delay in data transmission amounted to 54-72 hours, which limited the effectiveness of response during inter-agency coordination. The potential for water savings under the transition to synchronised systems reached up to 27% in Uzbekistan, whereas the smallest effect – approximately 22% – was projected for Kyrgyzstan. These differences show that, after the completion of demarcation and delimitation processes, the sustainability of water governance in the Fergana Valley is determined not by the physical availability of water, but by the level of technological modernisation, digital exchange and inter-state coordination (World Bank, 2024b). Regions with the highest water withdrawals and the highest level of automation (Uzbekistan) gain an advantage in the stability of flow distribution, whereas territories with minimal modernisation (Kyrgyzstan) remain vulnerable to seasonal shortages and losses.

Dynamics of the modernisation and reconstruction of irrigation networks

The technological structure of the irrigation infrastructure of the Fergana Valley in 2023-2024 demonstrated the consequences of the administrative division of water systems among Kyrgyzstan, Uzbekistan and Tajikistan. The analysis of water transfer indicators and the operation of pumping stations indicated a pronounced heterogeneity in technical condition and differences in management efficiency. Uzbekistan gained relative advantages after the completion of demarcation and delimitation processes, as key sections of main canals and part of the pumping stations, which ensure stable water inflow to the lower parts of the valley, came under its control. At the same time, Kyrgyzstan and Tajikistan faced increased dependence on border-adjacent flows and the need to coordinate water-release regimes through inter-state commissions. The impact of demarcation and delimitation of state borders exerted substantial influence on the contemporary configuration of water management. The division of what was previously a unified irrigation network led to the redistribution of ownership zones and responsibilities for the operation of hydraulic structures, including pumping stations, distribution nodes and flow-regulation systems. Part of the infrastructure previously under joint use came under the jurisdiction of Uzbekistan, which increased its level of control over water supply to downstream basin areas. Meanwhile, Kyrgyzstan lost part of its regulating capacities, particularly in territories where borders passed along old riverbeds and canals. This resulted in a mismatch between administrative and technical boundaries, complicating coordination and the planning of water supply. The delimitation processes intensified management fragmentation, especially in the border areas of the Fergana Valley, where the need emerged for precise synchronisation of water-use schedules and the coordination of seasonal releases. This, in turn, required new mechanisms of inter-agency exchange and digital monitoring, without which it is impossible to implement coordinated water-use regimes within transboundary basins (Cohen *et al*., 2025).

Comparative analysis of operational reliability showed that the highest concentration of controllable capacities was observed in Uzbekistan, where the level of technical modernisation was above the regional average. The systems of Kyrgyzstan remained the least resilient to operational failures, which was associated with high equipment deterioration and limited reserve capacities. Collectively, this reflected the increasing institutional and technological asymmetry between the countries, manifested in differences in energy efficiency, digitalisation and the responsiveness of flow regulation. Thus, the processes of demarcation and delimitation altered not only the geography of water use but also the distribution of advantages in the management of water structures, heightening the need for inter-state coordination and the alignment of technical standards (Central Asia Water & Energy Program, 2023). Summary indicators characterising these differences are presented in Table 2.

Table 2. Key technological indicators of the irrigation infrastructure of the Fergana Valley

Indicator	Kyrgyzstan	Uzbekistan	Tajikistan	Regional average
Water losses during transport, %	16-20	18-22	17-19	19
Losses of managed flow, million m³/year	80	110	85	92
Efficiency coefficient of pumping stations	0.64-0.68	0.66	0.65	0.65
Wear of pumping units, %	75	70	72	72
Number of emergency shutdowns, cases/year	7	6	6	6
Losses of supplied water, million m³/year	25	35	25	28
Annual volume of cleaning works, km	180	320	240	247
Fulfilment of repair plans, %	32	48	38	39
Wear of the irrigation network, %	62	55	60	59
Canals without concrete lining, %	40	33	40	38
Area of land requiring reconstruction, thousand ha	70	90	100	87
Cost of supplying 1 m³ of water, USD	0.025	0.021	0.022	0.023
Annual electricity expenditure, million USD	10	20	10	13
Average inter-repair period of pumps, years	5	6	5	5.3
Share of capacities with efficiency below 0.6%	25	22	25	24
Water losses across the region, million m³/year	200	230	200	210
Yield losses, % of gross agricultural output	8	6	8	7
Area of sustainably irrigated land, million ha	0.3	1.4	0.5	1.07

Source: developed by the author based on Central Asia Water & Energy Program (2023), Ministry of Water Resources... (2024), Environmental Monitoring Report (2024), N. Ikramov *et al*. (2025), A. Cohen *et al.* (2025)

The technological parameters of the operation of the irrigation infrastructure of the Fergana Valley in 2023-2024 demonstrated significant differences among the countries of the region, reflecting both the technical condition of the systems and the consequences of the demarcation of water borders. Uzbekistan was characterised by the most stable indicators of water use, where water losses during transportation amounted to 18-22%, which was lower than in Kyrgyzstan (up to 20%) and comparable to Tajikistan (17-19%). The lowest pump efficiency factor was recorded in Tajikistan (approximately 0.65), whereas in Uzbekistan it reached 0.66, reflecting the comparatively better technical condition of equipment and partial automation of water delivery.

The highest deterioration of pumping units was observed in Kyrgyzstan – up to 75%, with the regional average around 72%, indicating chronic underfunding of repair programmes. The lowest deterioration was recorded in Uzbekistan (approximately 70%), where more regular maintenance and canal cleaning works were carried out. The frequency of emergency shutdowns also differed: the highest number (7 cases per year) was recorded in Kyrgyzstan, and the lowest (6 cases) in Uzbekistan. These differences demonstrated the heterogeneity of electricity supply and the level of technical resilience of pumping systems. Following the demarcation and delimitation of state borders carried out in 2017-2024, what had previously been a unified irrigation network became divided among the countries, leading to a shift in water flows and in the distribution of responsibilities for the operation of facilities. As a result, the largest losses of regulated flow were recorded in Uzbekistan – approximately 110 million m^3 per year – and the smallest in Kyrgyzstan (80 million m^3). This difference reflected the countries' positions within the hydrological structure of the basin: the upper reaches in Kyrgyzstan form the flow, whereas the downstream sections in Uzbekistan experience losses during transport and distribution (Cohen *et al*., 2025).

The volume of annual cleaning and restoration works in Uzbekistan reached approximately 320 km, the highest value in the region, whereas in Kyrgyzstan their length did not exceed 180 km. The fulfilment of repair plans also varied: the maximum (48%) was recorded in Uzbekistan, and the minimum (32%) in Kyrgyzstan, which directly influenced the operational reliability of systems. At the same time, the largest share of canals without concrete lining (40%) persisted in Kyrgyzstan and Tajikistan, whereas in Uzbekistan it did not exceed 33%, which reduced filtration losses. Energy indicators likewise demonstrated substantial differences: annual electricity expenditure in Uzbekistan amounted to approximately USD 20 million, the highest among the countries of the region, whereas the lowest costs (USD 10 million) were recorded in Kyrgyzstan and Tajikistan. The cost of supplying water ranged from USD 0.021 per m^3 in Uzbekistan (the lowest) to USD 0.025 in Kyrgyzstan (the highest), confirming the relationship between energy efficiency and the modernisa-

tion of equipment. The area of land requiring reconstruction was lowest in Kyrgyzstan (70 thousand ha) and highest in Uzbekistan (90 thousand ha), reflecting differences in the scale of irrigation networks and the level of technogenic load. Overall, the data for 2023-2024 show that Uzbekistan obtained the greatest advantages from demarcation and delimitation, strengthening its control over the lower links of the irrigation network and centralising water distribution management. Kyrgyzstan, by contrast, faced increasing operational risks due to the fragmentation of hydrosystems (Central Asia Water & Energy Program, 2023). Thus, the analysis of the highest and lowest indicators demonstrates that the territorial boundary-setting processes of 2017-2025 led to technological and institutional asymmetry, whereby Uzbekistan consolidated its position in managing water facilities, while Kyrgyzstan and Tajikistan remained more vulnerable.

Comprehensive analysis
of the spatial reliability of the region's hydrosystems

Following the completion of the demarcation and delimitation of inter-state borders carried out between 2017 and 2025, a significant share of the irrigation and drainage communications of the Fergana Valley became divided among Uzbekistan, Kyrgyzstan and Tajikistan. Demarcation altered the configuration of ownership of water management facilities, while delimitation clarified the legal boundaries of responsibility for the operation of canals, reservoirs and pumping stations. As a result, what had previously been a unified water-use system fragmented into separate segments, the management of which now required constant inter-agency coordination. The alignment of engineering communications with political-administrative boundary lines created new risk zones and laid the foundation for a geopolitical natural-resource conflict. In border-adjacent areas where irrigation networks pass through several countries, the need emerged for daily coordination of water releases and technical maintenance. This increased the dependence of the functioning of hydrosystems on political stability and the level of inter-state cooperation. After delimitation, Uzbekistan gained control over several strategically significant hydraulic facilities in the lower reaches of the Fergana Valley, including distribution nodes and pumping stations that ensure the water supply of densely populated agricultural districts. Kyrgyzstan, by contrast, retained predominantly the upper reaches of rivers where the main flow is formed, but found itself constrained in its ability to regulate that flow due to the loss of part of its infrastructure. Tajikistan occupied an intermediate position, retaining part of the main canals and reservoirs, while simultaneously increasing its dependence on coordination with neighbouring states regarding seasonal release regimes (World Bank, 2024a).

Demarcation and delimitation not only consolidated new borders but also altered the mechanisms of ownership and water allocation. Whereas in the Soviet period (until 1991) the regulation of water resources was conducted centrally under the unified administration of Sredazgiprovodkhoz, after independence and the completion of territorial boundary-setting each country created its own departmental structures and water-use standards. This resulted in the emergence of duplicating functions, the misalignment of water delivery schedules and an increase in operational pressure on regional services. The most sensitive consequence of boundary-setting was the loss of the integrity of irrigation systems and the need to restructure water-release balances. Thus, water delivery that previously moved along unified main canals now crosses multiple jurisdictions, each of which regulates its own section. This led to an increase in technological losses and complicated the maintenance of stable irrigation regimes. The policy of Afghanistan became an additional destabilising factor. The construction of the Qosh-Tepa Canal in the northern provinces of Afghanistan, which began in 2022, reduced the inflow of Amu Darya waters, adversely affecting the water supply of the southern regions of Tajikistan. This circumstance further strengthened the significance of the Fergana Valley as a key node of geopolitical control over water resources (Wang *et al*., 2022).

In response to these challenges, Tajikistan began developing a strategy of geopolitical partnership with Uzbekistan and Kyrgyzstan aimed at the joint regulation of seasonal releases and the monitoring of flow. The establishment of unified inter-state observation stations and real-time hydrological data exchange is being considered. Such measures are viewed as part of a geopolitical mechanism for preventing natural-resource conflicts and strengthening regional resilience. Uzbekistan, for its part, strengthened its role in the management of water facilities and dispatch control in the lower reaches, which gave it a relative advantage after demarcation. Kyrgyzstan and Tajikistan remain more vulnerable but retain strategic significance as sources of flow formation. Parallel initiatives developed for the creation of unified indicators of engineering reliability, energy efficiency and digitalisation, allowing comparisons of the condition of water management systems. By the end of 2024, the region demonstrated signs of a transition to a more coordinated governance model, in which technical modernisation was accompanied by political negotiations and attempts to develop unified safety standards (Golunov & Bitabar, 2025). Thus, demarcation and delimitation not only altered administrative boundaries but also reshaped the water management system, transforming it into an instrument of geopolitical interaction. These processes determined the balance of interests among Uzbekistan, Kyrgyzstan and Tajikistan, where control over water facilities became a factor of not only economic but also political weight. Summary indicators of engineering protection, digitalisation and operational resilience by country are presented in Table 3.

Table 3. Spatial security and resilience of the hydraulic infrastructure of the Fergana Valley (2023-2024)

Indicator	Kyrgyzstan	Uzbekistan	Tajikistan	Notes
Share of irrigation and drainage communications in border zones, %	38	42	41	After border demarcation, zones of operational risk for system maintenance
Number of recorded unauthorised accesses (2023-2024)	11	9	10	Interventions in the operation of gates and canals

Table 3. Continued

Indicator	Kyrgyzstan	Uzbekistan	Tajikistan	Notes
Total water losses due to interventions, million m³	25	28	32	Average annual regional loss volume: 75 million m³
Direct material damage, million USD	3.2	2.9	2.6	Total regional damage: USD 7.6 million
Number of functioning pumping stations, units	6	9	8	Greatest density in the lower reaches of the valley
Level of protection of pumping stations (coefficient)	0.72	0.75	0.69	Reflects the presence of control and security systems
Engineering stability of water supply networks (coefficient)	0.68	0.77	0.74	Characterises the technical condition of infrastructure
Share of facilities requiring enhanced engineering protection, %	31	26	36	Facilities with low stability and high wear
Video-monitoring systems, % of total number of canals	43	54	46	Level of digital monitoring of the hydraulic network
Installed leakage and pressure sensors, units	12	38	18	Increased the rapid detection of leakages
Average delay in hydrological data transmission, hours	70	58	65	Regional average indicator: 64 hours
Integral index of spatial sustainability	0.73	0.79	0.71	Aggregate assessment of engineering, digital and organisational protection
Average response time to emergency failures, hours	5	4	6	Reduced following the introduction of a three-level control system
Restoration coefficient after emergency shutdowns	0.83	0.86	0.82	Reflects the effectiveness of maintenance services
Reduction in the number of emergency incidents, % compared with 2023	12	16	17	Dynamics of improvement after digitalisation
Engineering reliability of systems (national average)	0.74	0.76	0.74	Regional average level
Increase in regional security level, %	11	12	11	As a result of digitalisation and the coordination of engineering standards
Reduction of economic risks, %	15	16	15	Compared with 2023

Source: developed by the author based on World Bank (2024a), Scientific-Information Center... (2024b)

In 2023-2024, aggregate water losses resulting from technical failures and interventions remained substantial and were distributed unevenly across the countries of the region. The highest leakages were recorded in Tajikistan – approximately 32 million m^3 – which was associated with the high level of infrastructure deterioration and insufficient automation of processes. The lowest values were observed in Uzbekistan, where losses did not exceed 28 million m^3 owing to the introduction of remote monitoring and the systematic servicing of pumping stations. Kyrgyzstan occupied an intermediate position, demonstrating a gradual reduction in losses against the background of equipment modernisation programmes (Argali, 2025).

According to the Central Asian Water Resources Institute, the level of protection of pumping stations ranged from 0.69 in Tajikistan to 0.75 in Uzbekistan, which reflected differences in technical policy and operational organisation. Uzbekistan employed a comprehensive approach that included video monitoring, perimeter security, pressure sensors and automatic diagnostics, which made it possible to minimise the risk of accidents and unauthorised interventions. In Kyrgyzstan and Tajikistan such mechanisms were still in a formative stage, increasing the likelihood of technological failures. Indicators of engineering resilience of water supply networks demonstrated the same pattern: the highest level was recorded in Uzbekistan (approximately 0.77), and the lowest – in Kyrgyzstan (around 0.68). These differences were explained by the degree of equipment renewal, the intensity of repair works and the level of energy efficiency. Uzbekistan maintained an optimal ratio between the volume of supplied water and electricity consumption, whereas the other countries of the region faced rising operational costs (Scientific-Information Center..., 2024b).

Uzbekistan also remained the leader in terms of digitalisation, providing automated control for more than half of its pumping stations (approximately 54%). In Tajikistan and Kyrgyzstan this indicator remained lower, which had a direct effect on the speed of response to emergency situations. The average time required to eliminate malfunctions amounted to around 4 hours in Uzbekistan and up to 6 hours in Tajikistan. Demarcation and delimitation of inter-state borders significantly influenced the organisation of water management and the distribution of powers. After the boundary-setting process, what had previously been a unified irrigation network became divided into several national segments with differing operational standards and levels of responsibility. Ownership and operation of a number of pumping stations passed to Uzbekistan, which strengthened its position in managing the lower reaches and ensuring stable water supply. At the same time, the mismatch between technical and administrative boundaries complicated flow management, especially in areas where engineering systems intersected state boundary lines. This resulted in risks of duplicating functions, delays in coordinating water releases and episodic monitoring failures (Argali, 2025).

These processes exacerbated the geopolitical natural-resource conflict, as the regulation of water flows became a factor of political influence and economic stability. Uzbekistan

reinforced its importance as the country controlling key water distribution nodes, whereas Kyrgyzstan and Tajikistan depended on inter-state agreements and seasonal release schedules. The integral index of spatial resilience, reflecting the combined condition of engineering, organisational and digital protection, reached 0.79 in Uzbekistan and 0.71 in Tajikistan. The regional average amounted to approximately 0.74, which indicated a gradual alignment of technical capabilities and the strengthening of security systems. Uzbekistan maintained leadership in infrastructure resilience and response speed, Kyrgyzstan demonstrated positive dynamics owing to network reconstruction, and Tajikistan concentrated its efforts on the development of automation and engineering protection (Golunov & Bitabar, 2025). Thus, after demarcation and delimitation, Uzbekistan obtained the greatest institutional and technological advantages, ensuring a higher level of control, security and digitalisation within the region's water-use system, whereas Tajikistan faced the greatest losses and vulnerability.

Transformation of approaches to water resource management in the region

In 2023-2024, the water sustainability of the Fergana Valley shifted from a short-term regulation regime towards the formation of the foundations of long-term management. The redistribution of irrigation systems among Kyrgyzstan, Uzbekistan and Tajikistan was accompanied by a gradual change in the structure of water use, the emergence of elements of autonomous control and a reduction in dependence on external supplies. These processes reflected the adaptation of national systems to the new conditions of transboundary interaction following the administrative boundary-setting of water management territories. Demarcation and delimitation of inter-state borders exerted a comprehensive influence on the organisation of water resource management, shaping the current state of coordination and the distribution of responsibilities among the countries of the region. The division of what had previously been a unified infrastructure required the clarification of operational zones, the legal status of canals and the mechanisms of inter-agency control. In practice, this resulted in the necessity to coordinate new water-release regulations, to unify approaches to flow accounting and to develop joint standards for the maintenance of hydraulic structures. These processes were accompanied by the emergence of a geopolitical natural-resource conflict associated with control over key water distribution nodes, some of which came under the administration of Uzbekistan. Simultaneously, the legal and technical foundations were being formed for the digital exchange of data, making it possible to integrate national monitoring systems into a unified transboundary network (Prniyazova *et al.*, 2025).

The development of mechanisms for joint monitoring of water flows contributed to increasing transparency in the distribution of resources and reducing discrepancies in data among the countries. During this period, synchronisation in the recording of indicators at border sections improved, and inter-agency groups began to carry out regular automated comparison of information. Uzbekistan simultaneously strengthened its role as a coordinating centre, controlling key pumping stations and distribution nodes in the lower reaches of the valley. This made it possible to achieve greater accuracy in assessing the water balance and greater responsiveness to seasonal fluctuations in inflow. Alongside institutional changes, the technological capacity for management was strengthened. The expansion of the observation network, the introduction of digital platforms and the integration of national databases ensured a higher level of coordination of water-delivery and release schedules. The joint use of telemetric systems and unified reporting formats facilitated progress towards establishing an integrated information environment covering the main basin nodes of the Fergana Valley (Prniyazova *et al.,* 2025). Particular attention was paid to digitalisation and the improvement of energy efficiency in hydraulic systems. The expansion of automated accounting stations, hybrid pumping units and software-based forecasting tools enabled the transition from manual control to algorithmic flow regulation. For Uzbekistan, this became an instrument for strengthening technological influence and stabilising water supply under conditions of geopolitical natural-resource conflict with neighbouring countries. At the same time, Kyrgyzstan and Tajikistan sought to reduce their dependence on decisions made by Uzbekistan by developing their own systems of local regulation.

Taken together, these tendencies indicated a gradual transition from an administratively divided model of water regulation to a coordinated management system based on digital exchange, the unification of technical norms and joint oversight of infrastructure operation. Uzbekistan, possessing the most developed system of monitoring and regulation, consolidated its advantage in managing water flows in the lower reaches, whereas Kyrgyzstan and Tajikistan maintained limited autonomy and dependence on inter-state mechanisms. This process became the key outcome of regional interaction during the period under consideration, forming the basis for the further integration of water management systems (Abdullaev & Akhmedov, 2023). Summary data on digitalisation, the level of autonomous water use and system sustainability indices are presented in Table 4.

Table 4. Water sustainability and long-term resource management in 2023-2024

Indicator	Kyrgyzstan	Uzbekistan	Tajikistan	Notes
Share of autonomous water use, %	65	74	67	Reflects the degree of independent water supply after delimitation
Coefficient of managed water withdrawal	0.78	0.86	0.75	Ratio of supplied to effectively utilised water volume
Automated observation points, units	20	32	18	Joint accounting of flow at transboundary sections
Average hydrological data error, %	8	6	9	Error margin in inter-state data exchange
Share of synchronised accounting points, %	46	58	44	Percentage of facilities integrated into the unified monitoring system

Table 4. Continued

Indicator	Kyrgyzstan	Uzbekistan	Tajikistan	Notes
Level of digitalisation of hydraulic networks, %	49	62	47	Includes telemetric sensors and digital gateways
Accuracy of flow-distribution forecasts, %	87	92	85	Increase in accuracy following the introduction of digital systems
Share of hybrid pumping stations (solar installations), %	11	21	9	Use of renewable energy sources
Integral index of water sustainability (2024)	0.78	0.83	0.76	Comprehensive assessment of technical and institutional sustainability

Source: developed by the author based on I. Abdullaev & Sh. Akhmedov (2023), K. Asilbekova *et al.* (2023), Water Yearbook (2024), United Nations Economic Commission for Europe (2025), A. Prniyazova *et al.* (2025)

According to the United Nations Economic Commission for Europe (2025) on the transformation of water use in Central Asia after border demarcation, in 2023-2024 the water sustainability of the Fergana Valley was shifting from a crisis-management regime towards a more balanced system of long-term governance. The redistribution of irrigation networks among Kyrgyzstan, Uzbekistan and Tajikistan was accompanied by a rise in autonomous water use: the highest share (74%) was recorded in Uzbekistan, where modular pumping stations and automated distribution nodes were being introduced, and the lowest (65%) in Kyrgyzstan, where part of the networks remained dependent on transboundary supplies. These differences demonstrated the influence of administrative boundary-setting, which required the development of new mechanisms of coordination and the delineation of responsibilities among the countries (Asilbekova *et al*., 2023). The coefficient of controlled water withdrawal ranged from 0.86 in Uzbekistan (the highest value) to 0.75 in Tajikistan (the lowest), reflecting differences in the level of automation and the technical condition of pumping systems. Uzbekistan demonstrated the greatest resilience due to digital management of water delivery and release, whereas Tajikistan retained a high share of manual regulation. Kyrgyzstan occupied an intermediate position (0.78), gradually introducing elements of remote regulation. These values indicated a trend towards the alignment of water load and a reduction in dependence on transboundary flows, forming a basis for the transition to joint water resource utilisation (Prniyazova *et al.*, 2025).

The development of monitoring systems became a key instrument for reducing conflict potential and improving flow controllability. In 2023-2024, the highest number of automated observation points was introduced in Uzbekistan (32 units), and the lowest in Tajikistan (18 units). This made it possible to increase the density of the observation network and reduce discrepancies in data among the countries. The average error in hydrological data exchange reached 6% in Uzbekistan (the lowest) and 9% in Tajikistan (the highest), which reflected a rise in measurement accuracy and transparency of regulation. The time lag between the recording of indicators and their transmission decreased from 72 to 48 hours, which is especially important for adaptive management of irrigation regimes (Water Yearbook, 2024). The consequences of demarcation and delimitation were most evident in the area of inter-agency data exchange. The division of water management systems along borders required the integration of national databases and the harmonisation of accounting formats. According to the Water Yearbook, the highest coverage of transboundary accounting points – 58% – was ensured in Uzbekistan, and the lowest – 44% in Tajikistan. This reflected the level of administrative and technical readiness of the countries to operate within a unified information space. Technological integration was enhanced through the introduction of the shared electronic platform "CA-HydroLink", which covered 14 basin nodes. According to literature sources, its use increased the efficiency of inter-state regulation by 9% and reduced the volume of uncoordinated water operations by approximately 10-12%. These improvements made it possible to reduce transportation losses to 6% in Uzbekistan, the lowest value in recent years (Water Yearbook, 2024).

An important direction of modernisation was the use of hybrid pumping units operating partly on solar energy. Their greatest diffusion was observed in Uzbekistan (21% of stations), and the lowest in Tajikistan (9%), reflecting differences in access to financing and technological resources. This transition made it possible to reduce energy costs and strengthen the independence of water supply systems from fluctuations in electricity regimes. The integral water sustainability index of the region in 2024 ranged from 0.83 in Uzbekistan (the highest value) to 0.76 in Tajikistan (the lowest), indicating a trend towards the gradual convergence of technical and organisational characteristics. At the same time, it was precisely in the period following delimitation that the geopolitical natural-resource conflict intensified, associated with the redistribution of ownership and control over water nodes. Uzbekistan obtained key positions in flow management and the maintenance of downstream supply, which increased its strategic influence in the region (Abdullaev & Akhmedov, 2023). These indicators demonstrated that after demarcation and delimitation the countries of the region managed to transition from fragmented water use to a more coordinated and digitally integrated management system, in which technological compatibility and data transparency became the basis of sustainability.

DISCUSSION

The obtained results indicated that by 2024 water management in the Fergana Valley retained features of institutional fragmentation and technological inequality among the countries. The analysis showed that existing differences in actual water withdrawal and the level of modernisation reflected not only disparities in resources but also the quality of inter-agency coordination. The uneven utilisation of water limits and the dependence on weather and energy conditions pointed to the absence of a unified strategic model for managing transboundary flows. The comparison of data for Kyrgyzstan, Uzbekistan and Tajikistan revealed that meas-

ures aimed at modernising infrastructure had a limited effect due to equipment deterioration and incompatibility of regulation systems. The low level of automation and delays in hydrological data transmission increased the risk of errors in calculating the water balance. At the same time, contradictions persisted between energy and irrigation priorities, causing instability in water supply during seasonal cycles. The institutional weakness of inter-state commissions was manifested in the low implementation of agreed protocols and in rising economic losses. These results confirmed that technological integration and the unification of digital monitoring are necessary conditions for the region's transition from crisis regulation to sustainable water use and for reducing conflict potential.

In the context of the general theoretical works of A. Ghaffar *et al*. (2023) and S. Yusof & M. Saman (2023), the issue of the delimitation of water systems was examined from the standpoint of legal doctrine and geopolitical interpretation. A. Ghaffar *et al*. analysed the scientific evolution of approaches to delimitation over five decades, identifying changes in the conceptual framework. S. Yusof & M. Saman focused on the legal procedures of maritime boundary delimitation between Malaysia and Indonesia, where the normative aspect, rather than the functional parameters of systems, was regarded as central. Both studies were theoretical in nature, confined to interpretative models. The present study on the Fergana Valley also relied on theoretical analysis; however, it was distinguished by the inclusion of structural comparison of the technological, institutional and energy indicators of the three countries, forming an interdisciplinary basis for understanding regional sustainability.

From the analytical perspective of the works of M. Salameh *et al*. (2021) and B. Jabbar (2024), water systems were considered as part of the political-economic structures that shape resource-centred dependencies. M. Salameh *et al*. examined the water crisis in Middle Eastern countries, linking it to macroeconomic imbalances, whereas B. Jabbar described the interconnection of water and energy interests in the Mediterranean in the context of a theoretical model of interdependence. These studies remained conceptual and did not engage with cross-sectoral interrelations. In contrast, the theoretical study on the Fergana Valley relied on the comparison of water-energy and organisational factors, which made it possible to identify the internal logic of regional vulnerability and systemic imbalance, a level of understanding unattainable in narrower models. In the epistemological context of the studies by J. Choi (2024) and M. Hossain *et al*. (2021), attention was focused on the institutional dimension of transboundary governance. J. Choi examined interaction mechanisms on the Korean Peninsula as a model of trust-building within a peace process, while M. Hossain *et al*. considered the judicial delimitation of the Bay of Bengal as a theoretical example of the legal codification of conflicts. Both studies remained within the confines of normative-institutional analysis and did not incorporate cross-sectoral comparisons. In contrast, the conducted study of the Fergana Valley retained a theoretical character but relied on a multilayered methodology, integrating institutional, infrastructural and technological parameters into a unified conceptual model of the regional water balance. This made it possible to substantiate the integrative potential of a theoretical system for managing transboundary resources that extends beyond individual legal cases.

Within the analytical syntheses of M. Aryal & M. Jung (2023) and T. Aklilu *et al*. (2024), attention was directed towards developing theoretical models for the interaction of natural and institutional factors in delineating water-use zones. M. Aryal & M. Jung examined the settlement of India-Nepal border disputes through a politico-legal prism, describing delimitation as a form of diplomatic compromise. The study was conceptual in nature, without recourse to statistical or operational data. T. Aklilu *et al*., by contrast, focused on the theoretical vulnerability of water sources in the Upper Awash Basin and the idea of protective zoning, yet without inter-state comparisons or infrastructure analysis. Both works represented typical normative-analytical approaches, in which spatial parameters were examined through models and assumptions rather than empirical observations. The theoretical study of the Fergana Valley developed this approach further by offering a comprehensive interpretation of the delimitation of water systems as a process affecting technological, institutional and environmental sustainability. Such an interdisciplinary synthesis made it possible to move beyond geopolitical models and to formulate a structured concept of the region's water balance.

In the context of the spatial-ecological interpretations of M. de Andrés & J. Barragán Muñoz (2022) and W. Ribeiro *et al*. (2022), attention was focused on the relationship between theoretical principles of water ecosystem management and the socio-economic parameters of land use. M. de Andrés & J. Barragán Muñoz examined the delimitation of coastal zones in Andalusia as an element of socio-ecological planning aimed at the sustainable use of natural resources, yet without extending the analysis to interregional interconnections. W. Ribeiro *et al*. analysed water consumption in irrigated zones of Brazil, describing mechanisms for the distribution of water flows within the theoretical context of sustainable agriculture. In both studies, there was no practical assessment of the technical condition of infrastructure, and water management was considered as a theoretical model of rationalisation. In contrast, the study of the Fergana Valley, while theoretical, was nonetheless systemic: it combined the spatial logic of ecosystem analysis with institutional and technological approaches, encompassing not only issues of balance but also the structural asymmetry of water distribution among the countries of the region.

From a methodological perspective, F. Pinillos *et al*. (2023) and B. Farhat *et al*. (2023) developed theoretical approaches to the spatial differentiation of water systems using geoinformation and multicriteria methods. F. Pinillos *et al*. proposed a concept of integrated management of Chilean coastal zones based on cartographic models and systems for the theoretical delineation of natural territories. B. Farhat *et al*. presented an analytical methodology for assessing groundwater potential using GIS and hierarchical analysis, viewing water resources as an object of conceptual stratification according to utilisation priorities. Both studies were distinguished by a strong methodological component; however, they were confined to demonstrating tools without practical interpretation for inter-state systems. The theoretical study of the Fergana Valley, by contrast, employed similar methodologies to construct a comprehensive

scheme of regional water sustainability. Geoinformation and index-based analyses were applied not as abstract models but as elements of a systemic reconstruction of water management, enabling a theoretical description of transboundary flow coordination and the dependence of infrastructural indicators on the level of digitalisation.

Within the framework of the theoretical developments of N. López-Calatayud *et al*. (2022) and N. Thanh Minh *et al*. (2023), attention was focused on the modelling and allocation of water resources in various geopolitical and natural contexts. N. López-Calatayud *et al*. examined the management of wetlands under the Ramsar Convention, where modelling processes were conducted in a normative-ecological dimension and did not include inter-state parameters of water use. The study was conceptual in nature, aimed at formulating general principles of sustainable management of natural areas. N. Thanh Minh *et al*., in turn, analysed the process of allocating water and maritime spaces between Vietnam and neighbouring states, focusing on the politico-legal aspects of maritime delimitation. The authors' study constituted a theoretical reconstruction of an interaction model, without incorporating quantitative indicators or hydrological data. Both works were significant for the development of the theoretical foundation of water policy, yet remained confined to normative and conceptual levels. In this context, the theoretical study of the Fergana Valley possessed greater systemic depth: it integrated spatial, institutional and technological aspects, elucidating not only the concept of delimitation but also its functional implications for the sustainability of water systems under conditions of transboundary interdependence. The obtained results confirmed that the key factors of regional sustainability are the coherence of hydraulic infrastructure, the digitalisation of water monitoring and the institutional compatibility of management systems. In contrast to existing theoretical concepts, the present study proposed a holistic model linking water, energy and spatial sustainability. This made it possible to determine the dependence of the water balance on the level of technological modernisation and to demonstrate that the long-term stability of transboundary systems requires not only legal regulation but also the integration of technical and organisational mechanisms.

CONCLUSIONS

The conducted study showed that in 2017-2024 water management in the Fergana Valley was in a transitional state between a fragmented and a coordinated regulatory system. The actual water withdrawal in the Syr Darya Basin amounted to 8.1 km^3, which was 10-17% below the approved limits. The highest level of limit utilisation was observed in Uzbekistan (91%), where the largest pumping network in the region operated, and the lowest in Kyrgyzstan (78%), reflecting differences in the degree of automation and institutional coherence. The overall water deficit reached 2 km^3, indicating the persistence of uneven flow distribution between the upper and lower reaches of the basin. Water losses during transport ranged from 16-20% in the upper reaches to 18-22% in the lower reaches, associated with canal deterioration and the uneven density of distribution networks. Uzbekistan implemented the most extensive restoration works: the length of annual cleaning operations reached 320 km, and the fulfilment of repair plans amounted to 48%. The wear of pumping units across the region remained high, averaging 70-75%, with an efficiency coefficient not exceeding 0.66. The integral index of spatial sustainability stood at 0.79 in Uzbekistan and 0.71 in Tajikistan, reflecting differences in engineering and digital protection. The average delay in hydrological data transmission decreased to 54-60 hours in Uzbekistan compared with 70 hours in Kyrgyzstan.

The level of digitalisation of hydraulic networks reached 62%, ensuring more rapid responses to emergency disruptions. Despite the completion of territorial boundary-setting, the Fergana Valley continued to experience a geopolitical natural-resource conflict driven by uneven distribution of headwaters, the concentration of hydraulic structures in the upper reaches, institutional differences and population growth in the lower reaches. Demarcation and delimitation did not eliminate these contradictions but merely altered their form, shifting them into a geopolitical dimension. Water resources continued to constitute a key element of regional stability, with the balance of interests among Uzbekistan, Kyrgyzstan and Tajikistan determining the prospects for sustainable development. Future research should focus on the empirical assessment of the effectiveness of digital monitoring systems and on modelling scenarios of sustainable water use under conditions of transboundary interaction.

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Фергана өрөөнүндөгү мамлекеттер аралык суу ресурстарын башкарууга демаркация жана делимитация процесстеринин таасири

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Аннотация. Изилдөөнүн максаты аймакта туруктуу трансчек аралык суу ресурстарын башкарууну өнүктүрүүдө институционалдык жана технологиялык факторлордун өз ара аракеттенүү үлгүлөрүн аныктоо болгон. Комплекстүү көрүнүштү алуу үчүн сүрөттөмө жана салыштырмалуу статистикалык ыкмалар, коэффициенттик анализ жана үч өлкөдө – Кыргызстан, Өзбекстан жана Тажикстанда – суу ресурстарын башкаруунун сандык жана сапаттык мүнөздөмөлөрүн көп өзгөрмөлүү салыштыруу колдонулган. Мамлекеттер аралык чек араларды демаркациялоонун жана делимитациялоонун институционалдык түзүмгө жана суу ресурстарын бөлүштүрүү механизмдерине тийгизген таасирин кошумча талдоо административдик өзгөрүүлөрдүн башкаруунун натыйжалуулугуна тийгизген таасирин тактоого мүмкүндүк берди. Жыйынтыктар көрсөткөндөй, суу ресурстарын башкаруу системаларынын техникалык абалында жана санариптештирүүсүндө айкын асимметрия 2017-жылдан 2024-жылга чейин сакталып калган. Сугат тармагынын эскириши Кыргызстандагы 62 %, Өзбекстандагы 55 % жана Тажикстандагы 60 % түздү, ал эми насостук агрегаттардын эскириши тиешелүүлүгүнө жараша 75 %, 70 % жана 72 %га жеткен. Ташуу учурундагы суунун жоготуулары Кыргызстандагы 16-20 %, Өзбекстандагы 18-22 % жана Тажикстандагы 17-19 % чегинде өзгөрүп турган, бул каналдарды модернизациялоо даражасындагы айырмачылыктарды чагылдырат. Башкарылуучу агым жоготуулары Кыргызстандагы 80 миллион м^3, Өзбекстандагы 110 миллион м^3 жана Тажикстандагы 85 миллион м^3 түздү, ал эми берилген суунун жоготуулары тиешелүүлүгүнө жараша 25, 35 жана 25 миллион м^{3}ге жетти. Региондогу жалпы технологиялык жоготуулар болжол менен 650 миллион м^{3}ге жетти, анын ичинде Өзбекстандагы 230-250 миллион м^3, бул төмөнкү агымды сугаруу системасына эң жогорку жүктөмгө туура келди. Жалпысынан алганда, Фергана өрөөнүндөгү узак мөөнөттүү суу туруктуулугунун негизин технологиялык интеграция жана маалымат алмашуу түзгөн координацияланган башкаруу моделине өтүү белгиленди. Изилдөөнүн практикалык баалуулугу анын жыйынтыктарын аймактагы сууну башкарууну жана инфраструктураны жакшыртууга, ошондой эле жаратылыш ресурстары боюнча геосаясий чыр-чатактардын тобокелдиктерин минималдаштырууга колдонууда жатат

Негизги сөздөр: жаратылыш ресурстарынын чыр-чатактары; гидротехникалык инфраструктура; санариптештирүү; сууну туруктуу пайдалануу; модернизациялоо; суу балансы; суу чек арасы

Воздействие процессов демаркации и делимитации на межгосударственное управление водными ресурсами стран Ферганской долины

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Аннотация. Целью исследования являлось выявление закономерностей взаимодействия институциональных и технологических факторов в формировании устойчивого трансграничного водного управления региона. Для получения комплексной картины использовались методы описательной и сравнительной статистики, коэффициентный анализ, а также многопараметрическое сопоставление количественных и качественных характеристик водного менеджмента трех стран – Кыргызстана, Узбекистана и Таджикистана. Дополнительно проведен анализ воздействия демаркации и делимитации межгосударственных границ на институциональную структуру и механизмы распределения водных ресурсов, что позволило уточнить влияние административных изменений на эффективность управления. Результаты показали, что в 2017-2024 годах сохранялась выраженная асимметрия в техническом состоянии и цифровизации систем водного хозяйства. Износ ирригационной сети составлял 62 % в Кыргызстане, 55 % в Узбекистане и 60 % в Таджикистане, тогда как износ насосных агрегатов достигал 75 %, 70 % и 72 % соответственно. Потери воды при транспортировке варьировали в пределах 16-20 % в Кыргызстане, 18-22 % в Узбекистане и 17-19 % в Таджикистане, что отражало различия в степени модернизации каналов. Потери управляемого стока составляли 80 млн м^3 в Кыргызстане, 110 млн м^3 в Узбекистане и 85 млн м^3 в Таджикистане, а потери подаваемой воды достигали 25, 35 и 25 млн м^3 соответственно. Совокупные технологические потери региона достигали около 650 млн м^3, включая 230-250 млн м^3 в Узбекистане, что соответствовало самой высокой нагрузке на оросительную систему низовьев. В целом отмечен переход к координированной модели управления, где технологическая интеграция и обмен данными формируют основу долгосрочной водной устойчивости Ферганской долины. Практическая ценность исследования состоит в применении его результатов для совершенствования водного управления и инфраструктуры региона, а также в целях минимизации рисков геополитических природно-ресурсных конфликтов

Ключевые слова: природно-ресурсные конфликты; гидротехническая инфраструктура; цифровизация; устойчивое водопользование; модернизация; водный баланс; водная граница