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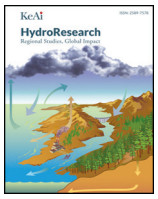

Environmental-economic accounting for sustainable water planning: A case study of water supply systems in Kazakhstan

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ABSTRACT

Kazakhstan faces growing water-security challenges driven by climate variability, urbanisation, ageing infrastructure, and limited integration of environmental considerations into water planning. This study presents the first application of the System of Environmental-Economic Accounting–Ecosystem Accounting (SEEA-EA) framework to a water resource system in Kazakhstan. Applied to the Astana Reservoir, the primary water source for the country's capital, the framework combined spatial analysis, hydrological modelling, economic valuation, and stakeholder engagement. Four ecosystem services (ES)—water supply, water purification, erosion control, and recreation—were assessed. In 2019, the reservoir supplied 90.3 million m^3 of water, meeting approximately 88% of Astana's demand. Natural purification processes provided an equivalent treatment service of 6.1 million m^3/year, while catchment ecosystems retained 13,313 t of soil annually. The total annual value of assessed ES was estimated at US$59.7–80.9 million. The study demonstrates how SEEA-EA can support water planning, policy development, and sustainable water governance in Kazakhstan and Central Asia.

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1. Introduction

Kazakhstan, the largest landlocked country in Central Asia, is facing mounting water resource challenges driven by climate variability, regional water dependency, and unsustainable management practices. More than 45% of the country's renewable freshwater originates from transboundary sources, making Kazakhstan highly vulnerable to upstream water use and to international water-sharing agreements (UNECE, 2019). Southern Kazakhstan already experiences significant water deficits during the irrigation season, with available supplies in some basins falling almost one-third short of required volumes (Aben and Zholdaskyzy, 2026) Meanwhile, the central and eastern basins are increasingly suffering from declining water quality, desertification, and ecosystem degradation. The northern parts of Kazakhstan experience high levels of precipitation, mainly winter snowfall, and frequently face spring flooding in the northern regions bordering Russia due to snowmelt linked to rising temperatures, which severely affects water supply systems. Water availability in the region is increasingly constrained by recurring drought events and competing water demands (Xenarios et al., 2022). These challenges are intensified by ageing infrastructure, fragmented governance, and underfunded regulatory frameworks.

While these national-scale pressures affect water security across Kazakhstan, they are particularly evident in Astana, the country's rapidly growing capital. Over the past two decades, Astana's population has increased by approximately 271% (Bureau of National Statistics, 2023), substantially raising demand for reliable water supplies.

Despite this rapid urban expansion, the city remains heavily dependent on a single source: The Astana Reservoir. This dependence has transformed the reservoir into a critical bottleneck where climatic variability, increasing water demand, infrastructure limitations, and governance challenges intersect. As water consumption has grown, pressure on the reservoir has intensified. In 2019, total urban water intake reached 122 MCM as per the Benchmarking Network for Water and Sanitation Utilities (IBNET, 2025) — substantially surpassing the

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reservoir's sustainable design capacity of 89 million m³ per year, which covers about 88% of the overall demand in the city (Kazvodkhoz, 2023).[1] Also, over the past decade, biophysical and chemical indicators have shown clear signs of water quality deterioration, with most exceeding the national thresholds (Astana Su Arnasy, 2023; Kazhydromet, 2023; Kazvodkhoz, 2023).[2]

The root causes of these challenges lie not only in environmental and demographic pressures but also in institutional and historical legacies. Kazakhstan's water sector has inherited a centralised, top-down governance structure from the Soviet era (Baitursunov, 2020; Zhupankhan et al., 2018). There have been noteworthy initiatives for improvement, like the adoption of Integrated Water Resources Management (IWRM) principles since 2000 (Xenarios et al., 2021), and the establishment of the Ministry of Water Resources and Irrigation in 2023 (President of the Republic of Kazakhstan, 2023).

Despite ongoing reforms, significant governance challenges continue to limit the effectiveness of water planning in Kazakhstan. In particular, planning processes remain largely infrastructure-oriented, with limited incorporation of environmental and ecological considerations. Additional constraints include inadequate interagency coordination, insufficient integration of ecosystem services (ES) into water resource management and water supply planning, and weak stakeholder engagement mechanisms (Utepov et al., 2021). These shortcomings reduce the capacity of existing institutions to respond effectively to increasing climatic, environmental, and urban-development pressures.

The limited integration of ES into planning is particularly notable given the growing attention the concept has received within Kazakhstan's environmental research community. Over the last decade, a number of studies have applied ES approaches across diverse environmental settings, yet implementation remains fragmented and largely confined to specific sectors and local case studies. For example, ecosystem-based assessments have been used to estimate the value of non-market forest products and carbon sequestration in northern protected areas (Kitaibekova et al., 2023).

In dryland rangelands, researchers have applied the Common International Classification of Ecosystem Services (CICES) framework to support biodiversity-offset planning in mining landscapes (Barnes et al., 2023). In urban contexts, research in Astana has demonstrated that conserving natural wetlands can provide greater long-term economic benefits than constructing equivalent green infrastructure alternatives (Utepov et al., 2021). These studies illustrate an increasing recognition of ecosystem contributions to economic development and environmental management in Kazakhstan. However, their influence on policy and planning remains limited.

Although the Environmental Code of 2021 and broader public-sector digitalisation initiatives have strengthened environmental information systems and governance transparency, important institutional and regulatory barriers persist. Existing legislation provides only limited operational mechanisms and indicators for incorporating ecosystem values into resource-management decisions, resulting in a disconnect between national sustainability objectives and their practical implementation (Oshakbaev et al., 2021). This gap is particularly apparent in the water sector. Consequently, there is limited evidence on how ES can be systematically identified, quantified, and integrated into water planning and decision-making processes. This shortcoming is especially important for water-supply systems, where ecosystem functions such as water purification, erosion control, and recreation directly influence the long-term sustainability and resilience of water resources.

ES provide a useful framework for linking ecological processes with water planning and management by recognising the benefits that ecosystems generate for society, including water purification, flood regulation, soil retention, and recreation (Costanza et al., 1997; Pahl-Wostl et al., 2013). By accounting for these contributions, ES approaches encourage decision-makers to move beyond infrastructure-centred planning towards more integrated and sustainable water management. However, despite growing international uptake, ES concepts remain only marginally incorporated into water governance and planning in Kazakhstan, as illustrated by the urban planning case of the Maly Taldykol lake group in the capital (Utepov et al., 2021).

To address this gap, this study adopts the System of Environmental-Economic Accounting–Ecosystem Accounting (SEEA-EA) framework. Developed by the United Nations Statistical Commission, SEEA-EA provides a standardised approach for quantifying ecosystem extent, condition, service flows, and their economic value within a single accounting framework. The framework has been widely applied to support environmental decision-making and resource management in countries such as Australia, Mexico, and South Africa (Vardon et al., 2019). For example, ecosystem accounts have informed water-allocation decisions in the Central Highlands of Victoria, Australia (Vardon et al., 2019), while in Central Asia, recent applications have supported ecosystem service accounting for natural resource management in the Kyrgyz Republic (Sylla et al., 2021).

The application of SEEA-EA is particularly relevant for reservoirs, which function as hybrid socio-ecological systems that simultaneously provide water supply, regulating, and cultural services while generating environmental trade-offs. By linking biophysical conditions, ES flows, and monetary values within a common accounting structure, SEEA-EA offers a practical mechanism for integrating ecological information into water-planning decisions and improving transparency, consistency, and evidence-based resource management.

This study advances the integration of ES into water planning and policy by applying the SEEA-EA framework to the Astana Reservoir, the primary water source for Kazakhstan's capital. As the first application of SEEA-EA to a major reservoir system in Kazakhstan, the study quantifies four key ES—water supply, water purification, erosion control, and recreation. Multi-temporal satellite data were used to develop an Ecosystem Extent Account for the reservoir and its catchment, providing the biophysical basis for ES assessment and economic valuation through market-price, avoided-cost, and travel-cost approaches. The resulting accounts were subsequently evaluated through interviews with policymakers, utility managers, and water users. By integrating ecological, economic, and stakeholder perspectives, the study underscores the importance of ES in supporting evidence-based water management. Additionally, for Kazakhstan, it highlights the institutional and governance obstacles that impede their incorporation into policymaking processes (Chen and Vardon, 2024; Moore et al., 2014).

2. Methodology

2.1. Study area and problem definition

The study focuses on the Astana Reservoir to examine trends in ES provision under the pressures of rapid urbanisation and to demonstrate how ES assessment can support water governance and planning. The Astana Reservoir is located 65 km southwest of the city. It was built in 1969 during the Soviet era, as part of the broader hydraulic regulation and streamflow control of the Yesil-Ishim River, which flows through Kazakhstan and Russia, with a length of 2450 km (Fig. 1).

According to the original engineering design, the reservoir's maximum annual water supply capacity is 89 million m^3 (244,000 m^3/day), with a total storage volume of 458.45 million m^3, and a surface area of 47.3 km^2. The catchment area feeding the reservoir covers approximately 5210 km^2 (Akiyanova et al., 2020; Kazvodkhoz, 2023).

[1] Kazvodkhoz is the national state-owned operator responsible for reservoir and major water infrastructure management.

[2] Astana Su Arnasy is the public utility responsible for urban water supply and wastewater services in Astana;
Kazhydromet is the national agency responsible for hydrometeorological and water-quality monitoring in Kazakhstan.

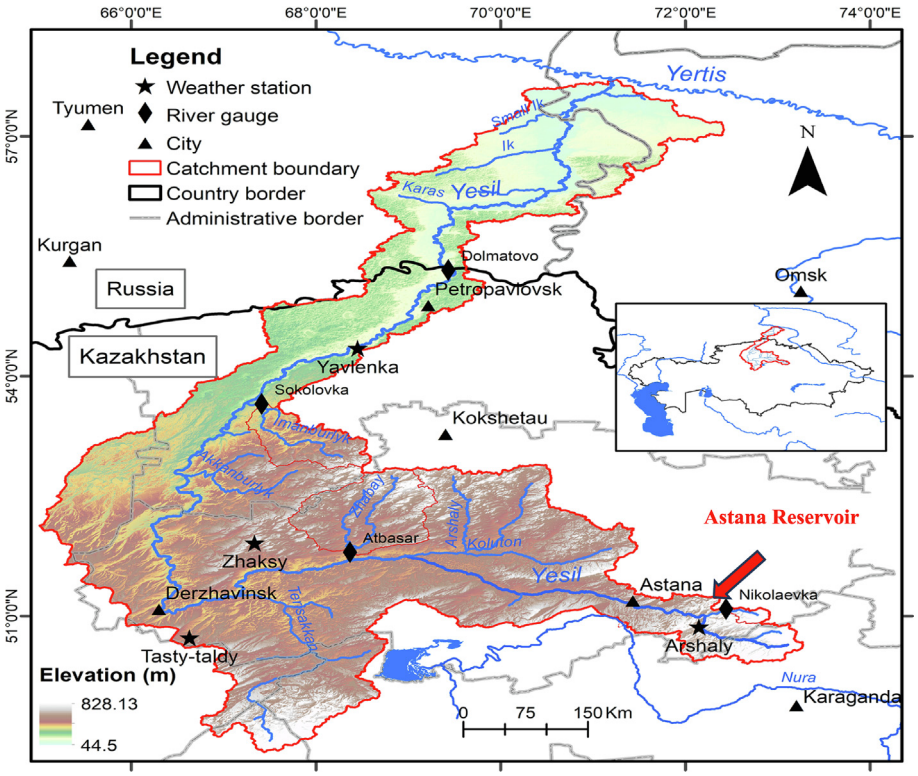

Fig. 1. Location of the Astana reservoir in the catchment boundary of the Yesil-Ishim river, Source: Adapted from (Ongdas et al., 2025).

The reservoir was initially designed to supply a population equivalent of 250,000–300,000, quite above the 180,000 inhabitants of former Tselinograd (now Astana) in the 1970s and to support irrigation in nearby villages and regional industries (JICA, 2001). The reservoir was also planned to cover the irrigation needs of adjacent areas and the industrial demand from enterprises in the region (more information on the Astana reservoir is presented in Appendix A).

However, since Astana became Kazakhstan's capital in 1997, the population surged from 0.34 million in 1999 to 1.3 million in 2022 (Bureau of National Statistics, 2023). The reservoir's available capacity has not been expanded to meet the rapid population growth and the accompanying industrial and irrigation demands. The reservoir has not been retrofitted with modern equipment, and sediment accumulation has reduced its available capacity. Meteorological data indicate that over the past two decades, annual precipitation in the Astana Reservoir basin has declined by about ~8–12%, while mean summer air temperatures have increased by approximately 1.5 °C, leading to higher evaporation losses and a progressive reduction in available storage. Both values were computed in this study from the monthly precipitation and air-temperature series for the reservoir basin used in this study (2000–2022).Water quality indicators assessed in 2022 by the water and wastewater utility (Astana Su Arnasy) exceeded national thresholds for total suspended solids (TSS), ammonia nitrogen, and total phosphorus. Riparian vegetation around the reservoir has decreased by 25–30% since 2000 due to land conversion and sedimentation, which is associated with reduced self-purification capacity and increasing eutrophication risk.

In response, local authorities have relied mainly on hydraulic-engineering interventions to strengthen Astana's water security. A key measure has been the inter-basin water transfer through the Nura–Ishim Canal, which diverts water from the Nura River Basin to the Yesil-Ishim basin to supplement inflows to the Astana Reservoir. The canal was initially constructed during the Soviet era and was reconstructed in 2011, thereby securing Astana's water supply and supporting regional industry and agriculture. Large-scale inter-basin transfers can alter natural flow regimes and affect ecosystem functions, including water filtration, erosion control, and flood regulation (Wang et al., 2025). While acknowledging the interdependence between the transfer system and the reservoir, the valuation focuses on ES generated within the Astana Reservoir and its catchment. The Nura–Ishim Canal is treated as an external driver influencing the environmental conditions of the Astana Reservoir.

2.2. Analytical framework: SEEA-EA for ecosystem service assessment

We use the SEEA-EA as the overarching framework to assess selected ES in the study area (United Nations et al., 2021). SEEA-EA provides an integrated statistical approach that connects biophysical ecosystem information with ES flows and economic valuation. A key feature of the framework—shown conceptually in Fig. 2—is its distinction between ecosystem stocks (ecosystem extent and ecosystem condition) and ecosystem flows (annual ES supplied and used).

In SEEA-EA, ecosystem asset (stock) accounts describe the state and functional capacity of ecosystems, while ES (flow) accounts represent the annual contributions that ecosystems make to society. SEEA-EA integrates spatial analysis, hydrological and environmental monitoring, and economic assessment into a standardised accounting framework highly relevant to policy. The framework has been widely applied at both national and regional levels worldwide, with established and validated processes used by international agencies, research organisations, and policy-making bodies.

The methodological design of SEEA-EA allows flexibility to reflect local context and features of each case. In this study, the methodological design combined spatial analysis, hydrological monitoring, valuation techniques, and stakeholder engagement to capture the ES flows and economic values contributing to the Astana Reservoir. The research

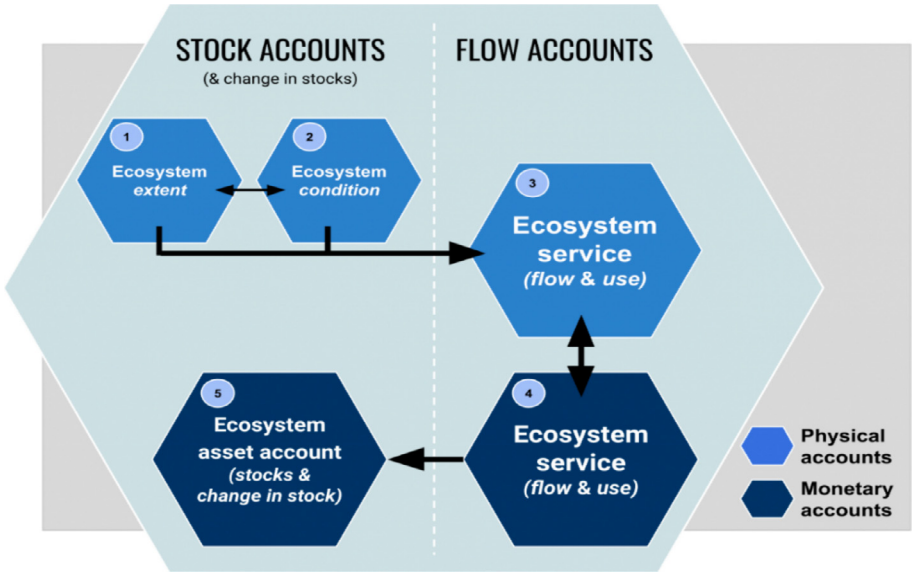

Fig. 2. Ecosystem accounts and relationships between stock-flows and physical-monetary assessment of services (United Nations et al., 2021).

framework was introduced in five sequential phases, as shown in Fig. 3. Colour differentiation was used to distinguish the phases of the research design.

2.3. Phase 1: background analysis

The first phase examined Kazakhstan's water planning and management context and reviewed the application of the SEEA-EA framework in similar studies. This was done through a literature review using the ROSES (Reporting Standards for Systematic Evidence Syntheses) framework. ROSES is widely used for literature reviews because it provides a clear, structured synthesis of evidence across four stages: Identification, Screening, Eligibility, and Quality Appraisal (Haddaway et al., 2018). The review documented the broader research and practical efforts to integrate ES into water planning. It helped clarify how institutional arrangements and policy implementation influence the management of the Astana Reservoir. Relevant keywords such as 'water resource management in Kazakhstan', 'water planning in Kazakhstan / Astana', 'water regulations' and 'water resource planning' were used across multiple academic databases (e.g. CNKI, Google Scholar, Web of Science, Scopus) and official reports from relevant agencies in Kazakhstan (e.g., Kazvodkhoz, Kazhydromet). We focused on peer-reviewed publications and reports from governmental and international organisations for the last twenty years. The results were summarized to identify common management issues, gaps in policy, and challenges in implementing SEEA-EA while incorporating ES, particularly in Kazakhstan.

2.4. Phase 2: ecosystem functioning assessment

Phase 2 focused on compiling biophysical evidence regarding the structure, characteristics, and ecological processes of the reservoir, which together represent the ecosystem asset (stock) components recognised within the SEEA-EA framework (Turner et al., 2000), as described below:

(1) **Structure:** The structural composition of the Astana Reservoir and its surrounding catchment was characterised within the SEEA-EA ecosystem extent (stock) accounting framework using long-term land-cover data and ecosystem-type classification. Land-cover information for the period 1993–2020 was obtained for all five contributing watersheds surrounding the reservoir. The information was collected through the European Space Agency Climate Change Initiative Land Cover (ESA CCI-LC) dataset (300 m spatial resolution, derived from ENVISAT MERIS), accessed via the Earth Map platform and the ESA/CCI Land Cover Viewer (Harper et al., 2023).

These land-cover classes were then reclassified into ecosystem types using the IUCN Global Ecosystem Typology 2.0 and became the input for the Ecosystem Extent Account. The Ecosystem Extent Account reports the area (km^2) of the main ecosystem types in the reservoir landscape (aquatic ecosystems, boreal temperate montane forest and woodland, cool temperate heathland, cropland, rocky pavement/lava flow scree, and urban–industrial ecosystems), as well as their net changes over time. This procedure captured land-cover dynamics (e.g., the expansion of rainfed cropland and the reduction in sparse vegetation) during 1993–2020. It expressed them as ecosystem-extent information that provides the structural basis for the subsequent hydrological, biophysical, and ES analyses in Phases 2 and 3.

To ensure temporal consistency, long-term hydrological data (1971–2022) were used to calibrate the Water Balance Model, while the SEEA-EA accounts were restricted to the period shared by both the hydrological and land-cover datasets (1993–2020). Ecosystem extent maps and ES flow estimates were subsequently aligned for the benchmark years 2000 and 2019, providing a consistent basis for the spatial, biophysical, and economic analyses.

(2) **Characteristics:** Reservoir characteristics describe the hydrological and chemical attributes that determine the system's natural storage dynamics and water quality.

Hydrological characteristics—including inflow (Qi), outflow (Qo), precipitation (P), evaporation (E), and abstraction (Qabs) were monitored monthly over the 1971–2022 period using the Water Balance Model (Zhu et al., 2022):

$$(Qi + P) - (Qo + Qabs + E) = \Delta S \quad (1)$$

Where: Qi is the monthly surface water inflow to the reservoir (m3/month); P is the monthly volume of precipitation falling directly onto the reservoir surface (m3/month); Qo is the monthly surface water outflow released from the reservoir (m3/month); Qabs is the monthly anthropocentric water abstraction for urban, industrial, and agricultural use (m3/month); E is the monthly open-water evaporation volume from the

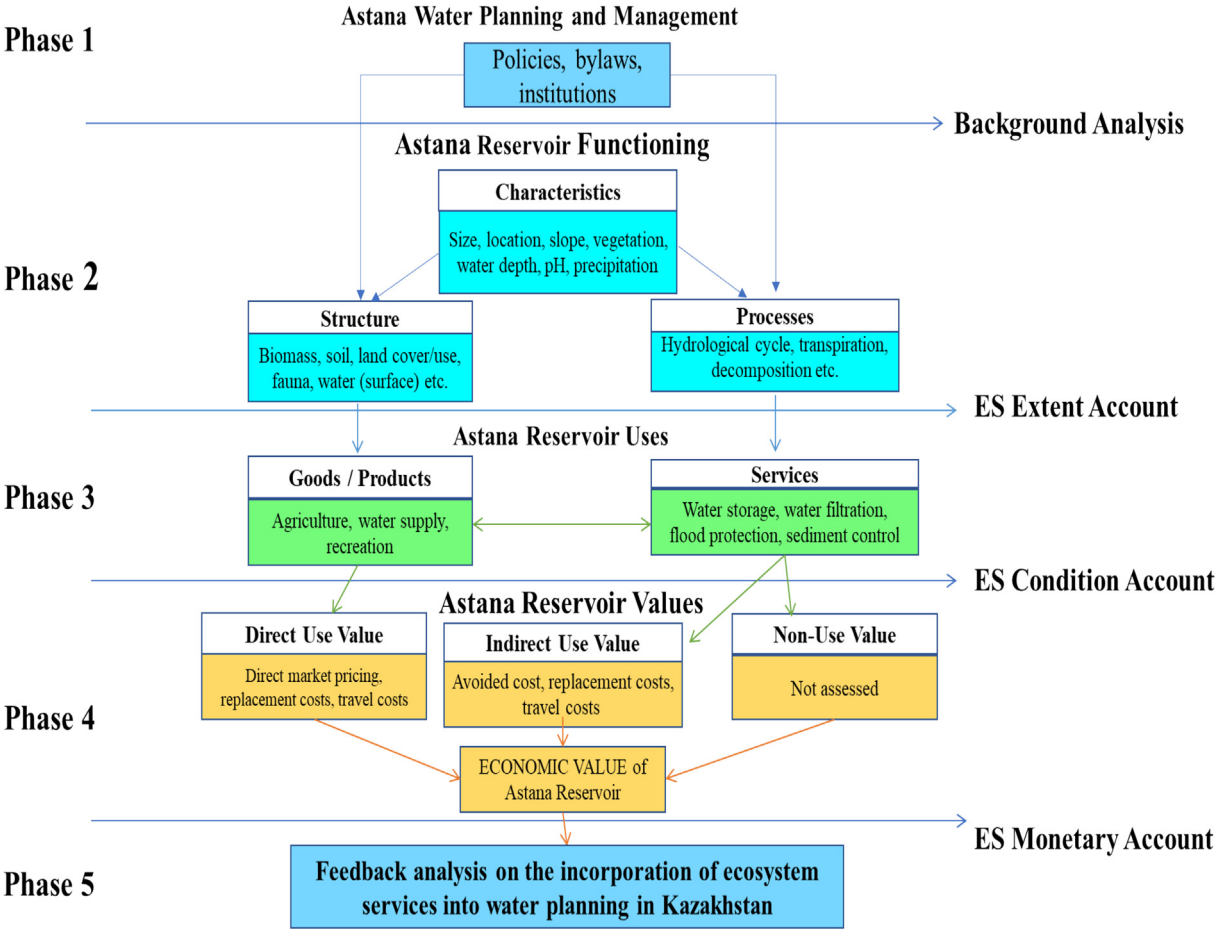

Fig. 3. Research design based on the SEEA-EA Framework for the assessment of selected ES in Astana Reservoir.

reservoir (m3/month); DS represents the net change in the active reservoir water storage volume (m3/month).

Monthly inflow and outflow data were obtained from hydrological gauging stations operated by the Kazvodkhoz, while precipitation and evaporation records were sourced from Kazhydromet. Modelled storage changes (ΔS) were validated against historical water level–storage records from Kazvodkhoz (2004, 2023). Because direct groundwater monitoring data are currently unavailable for the Astana Reservoir, groundwater seepage and other minor losses could not be quantified explicitly. Instead, these processes were incorporated through empirical loss coefficients. This approach was adopted because direct groundwater observations remain limited in many parts of the Aral Sea Basin and Kazakhstan, constraining explicit representation of groundwater-surface water interactions (Gafurov et al., 2019).

Chemical characteristics—including pH, nutrient concentrations (NH_3-N, TP), BOD, COD, dissolved oxygen, and TSS—were assessed from the national hydrometeorological agency (Kazhydromet) monthly for the period 2000–2022. These indicators were evaluated alongside hydrological outputs to determine how changes in water quality are linked to storage deficits, retention time, and climatic variability. At this stage, hydrological and chemical indicators are treated as strictly natural-system attributes.

(3) **Biophysical Processes:** The biophysical component analyzed the processes of material and energy transfer within the ecosystem, with a focus on two key components: (i) sediment regulation and (ii) soil conservation. For the case of the Astana Reservoir, these processes were analyzed to understand their role in determining the reservoir's long-term storage capacity and ecological stability. Sediment regulation and soil conservation were assessed for the period 2000–2019, aligning with the evaluation of ecosystem extent. The Sediment Regulation Model, based on the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991), was applied to assess erosion dynamics:

$$A = R \times K \times LS \times C \times P \quad (2)$$

Where: A is the computed average annual soil loss (t/ha/yr); R is the rainfall-runoff erosivity factor (MJ·mm/ha/h/yr); K is the soil erodibility factor (t·ha·h/ha/MJ/mm);LS is the dimensionless topographic factor combining slope length (L) and slope steepness (S); C is the dimensionless vegetation cover and management factor; P is the dimensionless support/conservation practice factor.

The RUSLE model was implemented in the ARIES platform to assess sediment regulation and soil conservation within the reservoir catchment. Two scenarios were simulated—current vegetation cover and bare soil—to estimate the ecosystem's capacity to retain soil and reduce sediment delivery to the reservoir. Soil retention was calculated as the difference in erosion rates between the two scenarios.

Model inputs were derived from regional datasets. Rainfall erosivity (R) was estimated using long-term precipitation records from Kazhydromet; soil erodibility (K) was parameterised based on regional soil maps; and topographic factors (LS) were derived from the HydroSHEDS digital elevation model. Simulated erosion and soil-retention estimates were validated against historical sedimentation records, bathymetric surveys, and storage-capacity assessments from Kazvodkhoz (2023) and Akiyanova et al. (2020), which document an

8.2% decline in effective reservoir storage due to sediment accumulation.

Combined with the Water Balance Model, the sediment-regulation analysis provided an integrated assessment of hydrological dynamics, erosion processes, and sedimentation pressures within the Astana Reservoir system. These results from the biophysical basis for the ES assessments presented in Phase 3.

2.5. Phase 3: ecosystem services flow assessment

Phase 3 links the biophysical functions identified in Phase 2 to the ES that society benefits from, thereby establishing a clear link between ecological processes and their economic valuation. The ecological processes and functions in the Astana Reservoir provide the biophysical foundation, while the supply of ES accounts for the physical "flows" of these services. The biophysical variables introduced in Phase 2 were also used together with additional variables in Phase 3 to calculate the physical flows of ES into goods and products supplied to households, industry, and agriculture. Physical variables such as water quantity, water level, together with model-derived soil erosion estimates, were combined with chemical parameters, including pH, biochemical oxygen demand (BOD), chemical oxygen demand (COD), nutrient concentrations, and total suspended solids (TSS).

These variables describe the ecological status and conditions of the reservoir. Soil erosion data, derived from the sediment regulation models in Phase 2, provide insight into land degradation and the impacts of sediment inflow on water quality. These condition variables are additional inputs to the SEEA-EA Condition Account, which assesses whether the reservoir is improving, stable, or degrading, thereby influencing its capacity to supply ES. We analyzed the temporal changes in the physical flows of these services from 2000 to 2019.

To classify ES as per a structure typology, we used the Common International Classification of Ecosystem Services (CICES V4.3) (Haines-Young and Potschin, 2013), which has been widely applied in similar SEEA-EA assessments. We selected key ES for the Astana Reservoir that align with the system's profile, focusing on provisioning (water supply), regulating (purification and erosion control), and cultural (recreation) services that support human well-being and regional environmental stability. A similar emphasis on these services in relation to water supply systems has been documented in other case studies worldwide (Chen and Vardon, 2024; Vardon et al., 2019).

2.6. Phase 4: economic valuation of the selected ecosystem services

This phase translated the ES selected for the Astana Reservoir into measurable economic values using established valuation approaches. Provisioning services, represented by the water supply function, were assessed using the market price approach by estimating the economic value of water based on actual transactions for domestic, agricultural, industrial, and environmental uses (Zhao and Wang, 2021). The calculation was estimated as:

$$V_1 = \Sigma(Q_{1i} \times P_{1i}) \quad (3)$$

Where: V_1 is the total economic value of the water provisioning service (US$/year); Q_{1i} denotes the annual water volume supplied for a specific economic sector or use i (m3/year); P_{1i} represents the established market price or water tariff for sector i (US$/m3).

The regulating services—water purification and erosion control — were valued using the avoided cost method (Freeman III et al., 2014; Wang et al., 2015). The water-purification service was assessed using two complementary cost-based components. The first component estimates the costs avoided by the municipal utility through the reservoir's natural purification functions, using conventional treatment costs as a proxy for the additional engineering measures required in the absence of these ecosystem processes. The second component captures household defensive expenditures on bottled water and other alternative drinking-water sources, reflecting consumers' willingness to incur additional costs to secure drinking water perceived as safe (Karaca et al., 2019; Statista, 2023).

These two components represent different economic consequences of water-quality degradation along the water-supply chain. Treatment costs are incurred regardless of consumer behaviour, as water must be treated to meet regulatory standards before distribution. It is noted that the physical flow of the water-purification service was quantified using an equivalent treatment-volume approach based on a multi-parameter water-quality indicator framework. This approach reflects the fact that the pollutants are regulated simultaneously by the reservoir's natural purification processes and would likewise be treated through integrated operational processes within a municipal water-treatment system. Estimating separate treatment volumes for each pollutant would risk double-counting the physical service flow. Consistent with SEEA-EA ES accounting principles (United Nations et al., 2021; Edens et al., 2022), the resulting indicator represents the annual volume of water benefiting from the reservoir's combined water-quality regulation functions and provides the physical basis for the subsequent avoided-cost valuation.

Household expenditures occur after treatment and distribution and reflect consumer responses to perceived or actual concerns about drinking-water quality. Consequently, the two components are considered complementary rather than alternative measures, capturing costs borne by different actors at different stages of the water-supply system. Together, they reflect both the contribution of natural purification to reducing treatment requirements and the broader economic implications of water-quality risks for end users.

The value of the water purification service was calculated as:

$$V_2 = \Sigma(Q_{2i} \times P_{2i} + C_2) \quad (4)$$

Where: V_2 is the total economic value of the water purification ecosystem service (US$/year); Q_{2i} denotes the physical volume or capacity of pollutant i removed or treated by the reservoir ecosystem (t/year); P_{2i} represents the associated engineering unit cost for replacing that specific chemical purification capacity via *industrial infrastructure (US$/t); C_2 represents the opportunity costs or defensive expenditures spent on commercial bottled water purchased by Astana's inhabitants (US$/year)*. The share of residents who rely on bottled water for drinking rather than tap water (65%) is taken from the household survey reported for the city by Karaca et al. (2019), and the per-capita bottled-water cost is taken from Statista (2023). The valuation is expressed on the same 2019 basis as the other monetary accounts.

The erosion control service was assessed as:

$$V_3 = Q_3 \times P_3 \quad (5)$$

Where V_3 is the total economic value of the soil erosion-control service (US$/year), Q_3 is the annual amount of soil retained by vegetation relative to a bare-soil scenario (t/year), and P_3 is the economic cost of land degradation or sediment removal (US$/t).

This approach captures the economic savings generated by the ecosystem's capacity to reduce erosion, limit sediment delivery to the reservoir, and avoid future remediation and maintenance costs. The unit cost parameter (P_3) was derived by dividing the national annual cost of land degradation in Kazakhstan for 2009, estimated at US$ 3.06 billion (Mirzabaev et al., 2016), by the country's total land area of 2.7 million km^2 (World Bank, 2024), yielding an approximate unit cost of US$ 1122.94 km^{-2} year^{-1}, assuming spatial homogeneity of land degradation across the country. Because the physical soil-retention account produced by the ARIES-RUSLE model is expressed in tonnes, the area-based cost was converted to US$/t using soil-density values representative of the dominant land-cover types in the catchment. Local watershed heterogeneities, including soil erodibility (K factor), slope length and steepness (LS factor), and vegetation and land-use effects

(C factor), were explicitly captured during the ARIES-RUSLE simulation stage.

Soil densities ranged from 400 to 1506 kg m^{-3} across forest, heathland, and cropland ecosystems. For example, the corresponding unit cost for cropland was estimated at US$ 406.05/t. This procedure links the biophysical outputs of the ARIES-RUSLE model directly to their economic implications while accounting for differences in soil characteristics and land-cover composition across the catchment.

Cultural services, primarily recreation, were assessed through the Zonal Travel Cost Method (Ward and Beal, 2000). The relationship between visitation and total trip cost was expressed as:

$$V_4 = A_4 - B_4 \times C_4 \quad (6)$$

Where V_4 is the estimated recreational value flow (US$/year); C_4 represents the total travel cost per individual trip (US$/trip); A_4 and B_4 are parameters estimated through statistical regression, where A_4 represents the potential maximum visitation at zero travel cost and B_4 represents the marginal decrease in visitation as travel costs increase.

The consumer surplus, defined as the area under the demand curve, represented the economic value of recreation. To ensure the reliability of the valuation, all travel-cost inputs were obtained from verified multi-source data—including semi-structured telephone inquiries and key informant consultations with local travel agencies and service operators, GIS-based distance estimates, official population statistics, and publicly accessible price information—and cross-verified for internal consistency in accordance with best-practice methodologies (Freeman III et al., 2014). All monetary values were converted to US$ using the average exchange rate for the national currency (KZT) in 2019, when the most recent data were collected.

2.7. Phase 5: stakeholders' feedback on SEEA-EA into water planning

Various stakeholder groups reviewed the economic validation findings to enhance the reliability and consistency of the outcomes, consistent with other studies. Purposive and snowball sampling methods were employed to identify and engage 25 key stakeholders, from four main categories:

(1) central government authorities, such as the Ministry of Water and Irrigation and the Ministry of Ecology and Natural Resources;
(2) basin, aquifer, and city-level organisations, including the supervising state authority for irrigation and drinking water supply (Kazvodkhoz), river basin inspectorates, and the Astana drinking water company (Astana Su Arnasy);
(3) the scientific and technological community, represented by universities and research institutes (e.g., Nazarbayev University and the Eurasian National University);
(4) water users, including industrial suppliers and national and foreign oil companies.

Other stakeholder groups like agricultural water users and environmental non-governmental organisations (NGOs) were represented indirectly through basin-management institutions and expert stakeholders, while downstream community perspectives were captured through consultations with local residents and water users.

Interviews, conducted either in person or online, lasted 30–45 min and were recorded with participants' consent. All respondents were assigned anonymous codes to ensure confidentiality. The interview protocol covered three overarching thematic areas: (i) current challenges in Kazakhstan's water resource management; (ii) stakeholder perceptions of the Astana Reservoir ES valuation results; and (iii) views on the feasibility, institutional requirements, and challenges of integrating ES into national water planning processes. All interview procedures were reviewed and approved by the Nazarbayev University Institutional Research Ethics Committee.

The stakeholders' findings were analyzed using relational content analysis to identify key themes and examine linkages between ecosystem services, policy instruments, and institutional responses (Molino et al., 2020). The NVivo software was used for systematic coding, data organisation, and traceable documentation of analytical decisions. These procedures underpinned the internal consistency, transparency, and reliability of the qualitative analysis. The findings from this phase provide critical insights into policy gaps, institutional capacities, and governance readiness for integrating ecosystem service valuation into Kazakhstan's future water resource planning and management frameworks.

2.8. Data collection

In line with Vardon's framework (United Nations et al., 2021) on SEEA-EA development and data requirements, multiple data sources were used—surveys, administrative records, hydrological and meteorological data, land-cover information, and research outputs—to ensure comprehensive coverage. Hydrological and water-quality series for 1970–2023 were obtained from the Kazvodkhoz, Kazhydromet and Astana Su Arnasy.

The above agencies provided information on inflows, withdrawals, storage levels, and water quality indicators, such as TSS, NH_3-N, and TP, enabling us to capture seasonal fluctuations and anthropogenic pressures on the reservoir.

GIS and remote-sensing data, including NDVI, land cover maps (CCI), hydroBASINS platform, and climate variables such as precipitation and evapotranspiration, were used to map spatial changes in ecosystem conditions and catchment dynamics (Abatzoglou et al., 2018; Harper et al., 2023; Lehner and Grill, 2013; Yapiyev et al., 2019). These datasets were processed in ArcGIS to delineate the study area and integrate soil, hydrological, and climatic information.

Administrative and institutional reports provided essential contextual and technical data. Reports and operational documents from utilities and basin agencies included water consumption records, pumping volumes, tariff information, and system technical characteristics (Astana Su Arnasy, 2023; Kazvodkhoz, 2023). Additionally, secondary sources, such as the International Benchmarking Network for Water and Sanitation Services (IBNET) platform on water supply and wastewater systems, provided longitudinal data on water use and service efficiency (IBNET, 2025). Policy and legal documents—including Kazakhstan's Water Law, national water resource strategies, and Astana city water management plans—were used to link ES outcomes to governance mechanisms.

Finally, the input for the questionnaire design and the interviews conducted between September and December 2023 was informed by the valuation findings and followed a similar approach, reviewing SEEA-EA applications through stakeholder engagement. The combination of quantitative, spatial, and qualitative data provided a triangulated, policy-relevant, and methodologically robust foundation for assessing the ES of the Astana Reservoir. Table 1 presents the data clusters, indicators, time coverage, and sources used for the analysis.

3. Results

3.1. Reviewing water planning and management in Kazakhstan (Phase 1)

The initial phase of this study examined how water planning and management in Kazakhstan have been discussed in the existing literature and how similar approaches to the SEEA-EA framework have been utilised in water planning. As outlined in the methodology, the ROSES framework was employed to structure the review. In the Identification phase, 2603 records were retrieved from Scopus, Web of Science, Google Scholar, and Kazakhstan's legal documentation platform (Adilet). During Screening, records were filtered by language (English), document type, and publication year (2010–2024 for academic literature; 2000–2024 for laws and policies), leaving 1985 entries.

Table 1
Data resources used for the implementation of SEEA-EA framework in Astana reservoir.

Category	Variables / Indicators	Time coverage	Sources / Organisations
Hydrological & Water Quality Data	Reservoir inflows/outflows, water balance, storage levels; water quality indicators (TSS, NH_3-N, TP); water levels & volumes from monitoring stations	1970–2023 (monthly & yearly series)	Kazvodkhoz; Kazhydromet; Astana Su Arnasy
GIS & Remote Sensing Data	Land cover (NDVI, CCI maps); catchment boundaries (hydroBASINS); precipitation & evapotranspiration; soil and erosion datasets	1992–2023 (yearly & real-time updates)	UCL-Geomatics; WWF-US; University of Idaho (TerraClimate); ISRIC Soil Hub; Kazakhstan Soil Microbiome
Reports & Administrative Documents	Water intake and consumption reports; pumping station volumes; tariffs and user breakdown; general technical reports	2000–2022 (annual & monthly)	Astana Su Arnasy; Kazvodkhoz; IBNET
Stakeholder Interviews	Semi-structured interviews with officials, engineers, hydrologists, NGOs, farmers, and residents	Sep–Dec 2023	Ministry of Ecology; Astana Su Arnasy; Kazvodkhoz; Kazhydromet; local communities & academia

After assessing the relevance of these sources to the Astana Reservoir case and ensuring full-text availability at the Eligibility phase, 166 publications remained. In the Quality Appraisal, the research design, data validity, and robustness were evaluated, and 75 publications met all criteria, as shown in Fig. 4.

The 75 sources included peer-reviewed journal articles, national legal and policy documents, and grey literature such as government and international organisation reports (e.g., UNDP, OECD, World Bank), as summarized in Table 2.

The 75 selected studies covered topics including water quantity and quality, sustainable use, transboundary management, and data governance. Despite their diverse focus areas, they converge on one conclusion: Kazakhstan's water planning remains fragmented, reactive, and poorly aligned with ecosystem requirements. The review identified three structural challenges in Kazakhstan's water governance:

- High dependence on transboundary resources — about half (44%) of the country's surface water originates from upstream states, creating strong geopolitical dependency (Assubayeva, 2021; Zhupankhan et al., 2018).
- A gap between strategy and implementation — national strategies such as Kazakhstan-2030, Kazakhstan-2050, and the Concept for Transition to a Green Economy (IEA, 2022) acknowledge these vulnerabilities, but progress on implementation remains weak (World Bank, 2022).
- Minimal integration of ES into planning and weak participatory mechanisms — implementation is constrained by a lack of technical and institutional initiatives, insufficient financing, and weak coordination among agencies.
- Programs such as Drinking Water (2001—2010) and Ak Bulak (2011—2020) improved access to drinking water services, but largely overlooked the ES contributions. Also, Participatory mechanisms such as River Basin Councils remain underfunded and have limited influence (Xenarios et al., 2022). The Astana Reservoir illustrates how these structural weaknesses manifest at the local level, influence water supply resilience of the capital, and offers insights for regions facing similar challenges.

3.2. Structure and biophysical processes of the Astana Reservoir (Phase 2)

The results of Phase 2 describe the 'natural functioning' of the Astana Reservoir ecosystem—its hydrological behaviour, sediment dynamics, water quality, land-cover structure, and vegetation conditions. These biophysical outcomes reflect 'how the ecosystem operates as a natural

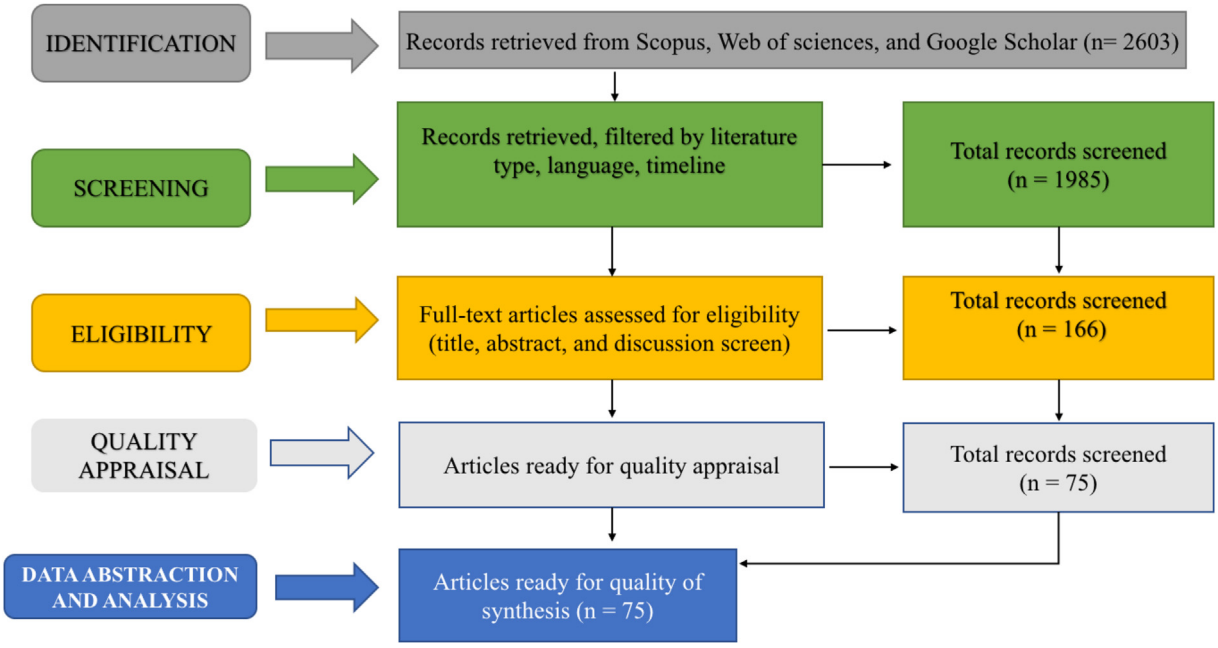

Fig. 4. Findings of ROSES literature review, Source: Author (2024).

Table 2
Sources collected and filtered through ROSES technique.

Sources		Identification	Screening	Eligibility	Quality appraisal
Research Literature	Scopus	430	154	19	10
	Web of Science	681	384	38	18
	Google Scholar	1160	1130	54	27
Grey Literature	Adilet	307	297	40	15
	Int. Organ.	25	20	12	5
Total		2603	1985	166	75

Note: Adilet = Online library of the legal documentation of Kazakhstan (Adilet); Int. Organ. = Reports collected directly online from international organisations.

system', independent of human use, and form the biophysical basis for the ES flows analyzed in Phase 3.

(a) Structures of the Reservoir

The structural composition of the Astana Reservoir and its catchment was assessed through changes in land cover and ecosystem extent between 2000 and 2019. Based on the ESA Climate Change Initiative Land Cover dataset (Harper et al., 2023) and the IUCN Global Ecosystem Typology 2.0 classification, the Ecosystem Extent Account covered a total area of 594.34 km^2 and identified six major ecosystem types: aquatic ecosystems, boreal temperate montane forest and woodland, cool temperate heathland, cropland, rocky pavement/lava flow scree, and urban–industrial ecosystems. Relative to the 2000 baseline, aquatic ecosystems increased by 13.13% (from 45.48 to 51.45 km^2), boreal temperate montane forest and woodland increased by 9.55%, and cropland expanded by 0.96%. In contrast, cool temperate heathland declined by 8.76% and rocky pavement/lava flow screen decreased by 94.27%. The most pronounced change was the expansion of urban–industrial land, which increased by 181.70% over the study period (Table 3).

It is noted that the aquatic ecosystem category includes not only the permanent reservoir water surface but also associated riparian areas, marshes, and seasonally inundated zones, consistent with the IUCN ecosystem classification framework. Consequently, variations in aquatic ecosystem extent reflect broader changes in the reservoir landscape rather than changes in the engineered reservoir surface alone. Overall, these trends indicate increasing urbanisation and gradual shifts in catchment land-cover composition, providing the structural context for the hydrological processes and ES flows assessed in the subsequent sections.

(b) Characteristics of the Reservoir

The characteristics of the Astana Reservoir reflect its hydrological behaviour and chemical conditions, both of which shape the system's natural storage dynamics and ecological state.

Hydrological Characteristics: Long-term hydrological observations show a substantial increase in water abstraction from 22.5 MCM in 1971 to 89.6 MCM in 2022. As shown in Fig. 5, annual withdrawals exceeded the reservoir's design capacity of 89 MCM/year during several years between 2015 and 2022, as recorded by the urban water supply and wastewater services in Astana, Astana Su Arnasy. The highest withdrawal occurred in 2017, at approximately 97 MCM, exceeding the design capacity by about 9%. It is noted that the excess withdrawal amounts between 2015 and 2022 appear lower than the 122MCM mentioned by IBNET in the Introduction. However, the water utility measures only metered consumption, whereas IBNET estimates unmetered consumption based on reservoir intake, transfers from a river tributary (Nura Ishmim), and population equivalence (Astana Su Arnasy, 2023).

This rise in withdrawals coincides with a gradual decline in storage capacity, primarily due to sedimentation. Over the period 1990–2022, the reservoir's average storage capacity was about 8.2% lower than in the preceding two decades (Kazvodkhoz, 2025). Sedimentation has also reduced the effective storage volume at Normal Water Level from 403 MCM to 367.2 MCM, a cumulative loss of 35.8 MCM (about 8.9%). Also, annual changes in reservoir storage (ΔS), driven by variability in inflows, precipitation, evaporation, and municipal withdrawals, typically ranged from 0 to 70 MCM during 1971–2020. These fluctuations illustrate the reservoir's sensitivity to climatic variability and to increasing anthropogenic pressure.

Chemical Characteristics: Water-quality data spanning the 2000–2022 period indicate that while long-term mean concentrations for several parameters remain within regulatory safety margins, seasonal and episodic exceedances of national maximum permissible concentrations (NMPC) occur, particularly near urban inflows. As quantified in Table 4, the overall mean concentration of total suspended solids (TSS) stands at 6.2 mg/L, which is compliant with the NMPC threshold of 10 mg/L.

However, the reservoir experiences distinct seasonal peaks during spring runoff, where maximum monthly concentrations reach up to 15.4 mg/L, exceeding the national threshold by 54%. Concurrently, a rising trend in total nitrogen over the past decade has led to intermittent exceedances of the NMPC standard, primarily driven by illegal wastewater discharges near urban entry points. In contrast, a lower but stable long-term trend is observed for total phosphorus.

BOD levels have declined substantially in recent years, indicating improved organic matter decomposition, and have remained below the national maximum permissible concentration throughout the study period. Additionally, there is a concerning trend in which heavy metals, such as copper and zinc, exceed national limits.

Table 3
The Ecosystem Extent Account of Astana Reservoir (in km^2).

Year/Change	Aquatic	B.T.M.F.W.	Cool T.H	Cropland	R.P.L.F. Scree	U.N.Ecos.
Jan. 2000	45.48	1.57	78.26	458.60	8.20	2.24
Dec. 2019	51.45	1.72	71.40	463.00	0.47	6.31
Net change	+13.13%	+9.55%	−8.76%	+0.96%	−94.27%	+181.70%

Note: Jan. = January; Dec. = December; B.T.M.F.W. = Boreal Temperate Montane Forest Woodland; Cool T.H=Cool Temperate Heathland; R.P.L.F.Scree = Rocky Pavement, Lava Flow, Scree; U.N.Ecos. = Urban and Industrial Ecosystem.

(c) Biophysical Processes of the Astana Reservoir

The biophysical processes of the Astana Reservoir explain how material and energy move through the system, with a focus on sediment regulation and soil conservation. These processes influence the reservoir's long-term storage capacity, ecological stability, and overall system performance, and they underpin the ES analyzed in Phase 3.

Sediment Regulation and Soil Conservation: Sediment-regulation dynamics were assessed using the RUSLE-based Sediment Regulation Model implemented in ARIES, in order to quantify the reservoir's capacity to reduce sediment inflow and maintain storage volume over the assessed period (2000–2019). The results show that total soil-retention capacity declined from 15,098.37 tons in 2000 to 13,313.04 tons in 2019, a net loss of 1785.33 tons.

Integration of Sediment Dynamics with Hydrological Functioning: Sediment accumulation has contributed to the documented reduction in effective storage volume, which had fallen to 367.2 MCM at Normal Water Level by 2019.This loss of storage capacity affects how the reservoir responds to inflow variability, seasonal runoff, and municipal water demand. Annual fluctuations in storage, typically ranging between 0 and 70 MCM, therefore reflect not only climatic variability but also the long-term consequences of reduced sediment regulation. These biophysical linkages illustrate how erosion processes, land-cover change, and hydrological behaviour interact to shape the reservoir's natural functioning. Overall, the combined outputs of the Water Balance and

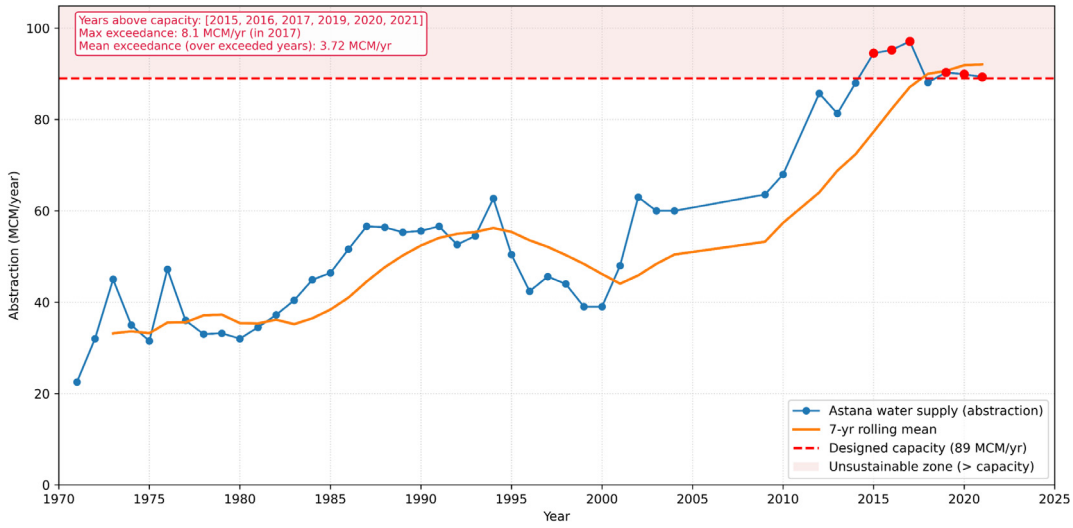

Fig. 5. Annual water withdrawals from the Astana Reservoir, 1971–2022, compared with the engineering design capacity of 89 MCM/year, Source: Kazvodkhoz (2023).

Sediment Regulation models describe the underlying ecological processes of the Astana Reservoir and provide the scientific basis for identifying water-supply, water-purification, and soil-retention services in Phase 3.

3.3. Ecosystem condition and ecosystem service flows (Phase 3)

Phase 3 translates the biophysical functioning of the Astana Reservoir (Phase 2) into ecosystem condition accounts and ES flow accounts following the SEEA-EA guidelines (United Nations et al., 2021). While Phase 2 described 'how the ecosystem operates as a natural system', Phase 3 evaluated 'how society benefits from these natural functions'. The assessment focuses on key provisioning, regulating, and cultural services that are most relevant to the reservoir system. This focus reflects the close interlinkages between ecosystem services, human well-being, and regional water security highlighted in recent systems-based water security research (Alamanos et al., 2025).

3.3.1. Ecosystem condition account (2000–2019)

The ecosystem condition account reorganises Phase 2 indicators into SEEA-EA condition classes to assess whether the reservoir's ecological state is improving, stable, or degrading, as shown in Table 5. These indicators explain the reservoir's capacity to sustain ES supply over time.

The physical condition of the reservoir shows a gradual decline in storage volume and soil retention capacity, whereas chemical indicators suggest only partial improvement in organic pollution (BOD reduction). The substantial rise in annual discharge reflects growing water demand rather than any natural hydrological improvement. Overall, these trends indicate a system under increasing pressure, with implications for the long-term service sustainability of ES flows.

3.3.2. Ecosystem service flow account

The Ecosystem Service Flow Account (Table 6) quantifies the annual physical supply of services delivered by the reservoir. Services were classified according to CICES V4.3 and selected based on data availability and the reservoir's functional relevance.

(a) *Provisioning Service — Water Supply:* The Astana Reservoir supplies the majority of the capital's municipal water. In 2019, it supplied 90.3 MCM, accounting for approximately 88–90% of total demand in Astana. This provisioning service supports household consumption, industrial production, and essential public services, making the reservoir a core component of the city's water security system. In SEEA-EA physical flow, this volume represents the 'annual supply of freshwater' delivered to economic and household sectors.

(b) *Regulating Service — Water Purification:* The Astana Reservoir contributes to water purification through natural processes such as sedimentation, nutrient uptake by aquatic vegetation, and microbial decomposition. Water-quality data indicate that mean concentrations of NH_3-N and TP remained below Kazakhstan's national maximum permissible concentrations (NMPC) throughout the study period; however, both parameters

Table 4
Water quality indicators in the Astana Reservoir and national maximum permissible concentrations (NMPC) for the period 2000–2022.

Parameter	Unit	Observed Values (2000—2022)	NMPC (Kazakhstan)	Comparison to National Thresholds (Quantified)	Main Trends (2000–2022)
Total Suspended Solids (TSS)	mg/L	Mean 6.2 Max 15.4	10	Mean = 38% below MPC; Max = 54% above MPC (seasonal)	Seasonal spring peaks; no long-term increasing trend
Total Nitrogen (NH_3-N)	mg/L	Mean 0.31 Max 0.74	0.5	Mean = 38% below MPC; Max = 48% above MPC	Increased by ~30–40% after 2010, wastewater inputs
Total Phosphorus (TP)	mg/L	Mean 0.05 Max 0.12	0.1	Mean = 50% below MPC; Max = 20% above MPC	Episodic peaks in 2015 and 2020; little long-term upward trend
Biochemical Oxygen Demand (BOD_5)	mg/L	Mean 0.9 Max 2.4	3	Mean = 70% below MPC; all values below MPC	Declined by ~61% compared with the early 2000s
Copper (Cu)	mg/L	Mean 0.021 Max 0.048	0.03	Mean = 30% below MPC; Max = 60% above MPC	Frequent exceedance throughout the study period
Zinc (Zn)	mg/L	Mean 0.15 Max 0.32	0.1	Mean = 50% above MPC; Max = 220% above MPC	Chronic long-term exceedance

Source: (Astana Su Arnasy, 2023; Kazhydromet, 2023).

Table 5
SEEA-EA Ecosystem Condition Account for the Astana Reservoir (2000–2019).

SEEA Ecosystem Condition Typology Class	Variables	Ecosystem type			
	Description	Measurement unit	Opening value (2000)	Closing value (2019)	Change, %
Physical state	Volume at NWL (403.0 m) = DWL + FL	m	389.8	367.2	−5.8
	Volume at DWL	m	30.9	23.29	−24.8
	Sound volume, FL (NWL-DWL)	m	358.8	343.9	−4.2
	Soil erosion control	ton	15,098	13,313	−11.8
	Total annual discharge of the reservoir	Million m3	39	89.2	128.7
Chemical state	pH level (water quality)	–	8.5	8.1	−4.7
	BOD (water quality)	–	2.1	0.86	−61.7

exhibited episodic exceedances, while copper and zinc frequently exceeded regulatory thresholds, indicating ongoing pressures on water quality (Astana Su Arnasy, 2023; Kazhydromet, 2023). Despite these pressures, the reservoir continues to provide an important regulating service by reducing nutrient and suspended-solid loads before water reaches the abstraction and treatment infrastructure.

Following ecosystem accounting guidelines (Edens et al., 2022; United Nations et al., 2021), the physical flow of this service was estimated as an equivalent treatment volume of approximately 6.1 MCM/year. This indicator represents the annual volume of water benefiting from the reservoir's combined natural purification processes and provides a standardised measure of its contribution to water-quality regulation.

Our findings—quantified by this 6.1 MCM/year natural treatment capacity—demonstrate that the reservoir maintains a substantial physical flow to support water quality and reduce downstream treatment requirements. However, as documented in official water-quality monitoring reports (Astana Su Arnasy, 2023; Kazhydromet, 2023), observed seasonal nutrient peaks and persistent heavy-metal exceedances indicate that the long-term sustainability of this regulating service may be compromised if current environmental pressures continue.

(c) *Regulating Service — Erosion Control:* The erosion-control service reflects the reservoir catchment's capacity to retain soil and prevent sediment from entering the reservoir. ARIES-RUSLE modelling indicates that the catchment has retained 13,300–15,100 tons/year over the last 20 years (2000–2019) by providing a major erosion-control function. However, this retention has considerably declined from 15,098 tons of soil in 2000 to 13,313 tons in 2019, indicating a weakening of the natural protection against sedimentation. As a result, more sediment enters the reservoir, reducing its storage capacity and increasing the likelihood and cost of dredging.

(d) *Cultural Service — Recreation:* The findings indicated that the reservoir provides significant recreational values due to its proximity to Astana. Based on preliminary estimations derived from key informant interviews with local travel agencies conducted in this study (2023), the reservoir receives approximately 34,000 recreational visits per year. These activities primarily include picnicking, fishing, leisure walking, and shoreline recreation. Although formal visitor monitoring and recreational facilities remain limited, this estimated level of visitation highlights the reservoir's local importance for cultural well-being and outdoor recreation. The findings on ES flows are presented in Table 6.

While Table 6 presents ES flows for the 2019 baseline, these services evolved differently over the 2000–2019 period. Provisioning and cultural services generally increased in response to Astana's rapid population growth and expanding water demand. In contrast, regulating services showed signs of decline.

As indicated by the ecosystem condition account, sediment accumulation, reduced soil retention, and deteriorating water-quality indicators placed increasing pressure on the reservoir's natural purification and erosion-control functions. These trends suggest a gradual reduction in the reservoir's capacity to provide key regulatory services, with implications for long-term water security and management.

3.4. Monetary valuation of the selected ecosystem service accounts (Phase 4)

Phase 4 converts the physical ES flows of the Astana Reservoir into monetary terms, following the SEEA-EA Monetary Ecosystem Asset Account.

(a) *Provisioning service – water supply*: The water-supply service was valued using a direct market-price approach based on 2019 water tariffs and consumption across five user groups (households, heat-energy enterprises, budgetary organisations, legal entities, and technical water users. Tariffs ranged from 0.08 to 0.51 US$/m^3, with a weighted average of 0.19 US$/m^3. Applying the share of withdrawals from the Astana Reservoir (88.44% of total urban supply in 2019) and a 10% contingency to account for non-payment and billing uncertainties, the annual value of the water-supply service was estimated at US$ 14.1–16.7 million.

(b) *Regulating service – water purification:* The annual value of the water-purification service was estimated at US$ 35.5–45.1 million. This estimate captures the economic costs associated with maintaining drinking-water quality, including municipal treatment expenditures and household spending on alternative drinking-water sources. The results highlight the substantial financial implications of water-quality degradation for both utilities and consumers within Astana's urban water-supply system.

(c) *Regulating service – soil erosion control:* The catchment retained an estimated 13,313 t/year of soil in 2019, preventing sediment from entering the reservoir and reducing losses of storage

Table 6
Ecosystem Service Flow Account for the Astana Reservoir (CICES V4.3).

Service type	Indicator / Flow	2019 Value	Method / Data source
Provisioning (Water supply)	Municipal withdrawals	90.3 MCM (88.4% of total city demand)	Utility records, Astana Su Arnasy (2023)
Regulating (Purification)	Reduction in N and P loads (partial self-purification)	Equivalent to treatment of ~6.1 MCM/year	Inflow–outflow comparison, Kazhydromet data
Regulating (Erosion control)	Soil retention	13,313 t/year (↓ 1785 t since 2000)	ARIES–RUSLE, Yapiyev et al. (2019)
Cultural (Recreation)	Visitors (estimated)	~34,000 visits/year	Travel cost survey, 5 recreation sites

capacity. Applying land-degradation cost estimates for Kazakhstan (Mirzabaev et al., 2016) yielded an annual economic value of US$ 9.8–18.8 million. This range reflects variations in soil density and land-cover characteristics across the catchment, which influence the estimated costs of erosion and sediment removal. The results demonstrate that natural erosion control generates substantial economic benefits by reducing sedimentation and associated maintenance costs. However, the service declined by approximately 12% between 2000 and 2019, when annual soil retention decreased from 15,098 t to 13,313 t, indicating increasing pressure on this regulating function.

(d) *Cultural service – recreation:* Recreational services were valued using a zonal travel-cost method combined with consumer-surplus estimation. Travel costs (fuel, time, and on-site expenditures) were calculated for five main recreation centers in the Arshaly district surrounding the Astana Reservoir, using key informant consultation data from local travel agencies and secondary information on distances, travel times, and on-site spending by using online geospatial platforms (e.g. Google Maps, Budget Your Trip). Based on the demand curve derived from the relationship between total travel cost and visitation rates, the annual consumer surplus for visits to the recreation centers surrounding the Astana reservoir was estimated at US$ 0.34 million. Table 7 presents the monetary values of the selected ES and their relative contributions to the total annual estimate. The total value of the four assessed ES ranges from US$ 59.7 million to US$ 80.9 million per year.

3.5. Stakeholder perspectives on integrating ES into water planning (Phase 5)

Stakeholder interviews revealed distinct but complementary viewpoints on the role of ES valuation in water planning. Although perspectives varied by institutional background, a consistent message emerged: ES valuation provides the missing information needed to align water supply security, ecological health, and economic decision-making in Kazakhstan.

Government officials focused primarily on infrastructure stress and supply reliability, noting that withdrawals from the Astana Reservoir have already reached or surpassed engineering design limits. For them, ES strengthens existing planning tools by quantifying the economic importance of a reliable water supply and the risks associated with further depletion. Experts from academia and research organisations placed greater emphasis on ecosystem conditions—highlighting nutrient enrichment, declining water quality, and reduced soil retention capacity. They stressed that unless these ecological pressures are addressed, regulating services such as purification and erosion control will continue to deteriorate, undermining long-term water security. Water users—including industrial consumers and residents —expressed concern about tap water quality, reliance on bottled water, and rising treatment costs, underscoring the high monetary value of the purification service. Their experiences illustrate how the degradation of ecosystem condition is already translating into higher private expenditures and reduced trust in the municipal water supply.

Recreational visitors and residents pointed to insufficient facilities, shoreline pollution, and accessibility issues. Although the current monetary value of recreation services is relatively low, interviewees emphasised strong latent demand that could be realised if water quality and infrastructure improve—indicating a potential economic upside that SEEA-EA can help make visible.

Overall, stakeholder insights align closely with the SEEA-EA results: the reservoir provides significant economic value, but its capacity is declining as hydrological, chemical, and ecological conditions deteriorate. Across all groups, there was broad agreement that integrating ES valuation into water planning could improve transparency, justify ecological investments, and support the long-term sustainability of the Astana water supply system.

Table 7
Monetary valuation of ecosystem services provided annually by the Astana Reservoir (baseline year 2019).

Service type	Value (million US$)	Share of total (%)
Provisioning (Water supply)	14.1–16.7	21.9
Regulating (Purification)	35.5–45.1	57.3
Regulating (Erosion control)	9.8–18.8	20.3
Cultural (Recreation)	0.34	0.5
Total	**59.7–80.9**	100

Note: All values correspond to the baseline year 2019, ensuring comparability across all ecosystem service accounts.

4. Discussion

4.1. Significance of the ecosystem services

Kazakhstan's water resource management has undergone significant transitions since independence in 1991, shifting from a narrow technical focus to one that grapples with complex socio-political and ecological challenges. Despite national strategies such as Kazakhstan 2030 (Strategy for Development of the Republic of Kazakhstan until 2030, 1997) and Kazakhstan-2050 (Strategy "Kazakhstan-2050", 2012), legal frameworks remain fragmented and implementation weak, while ageing infrastructure and mounting environmental pressures continue to deteriorate water supply performance.

The Astana Reservoir, as the capital's primary water source, exemplifies these dynamics. In Astana, water demand has surged by nearly 400% since 1971 and until 2021. Water quality problems, such as heavy metal contamination, pose risks to public health and ecological integrity. Current responses, including expansion of supply via inter-basin transfers, provide short-term relief but do not address underlying sustainability concerns.

The Astana reservoir, part of the Soviet-era centralised infrastructure planning, was a single-source supply designed to meet Astana's water demand. The lack of diversification in water sources reflects a legacy of monofunctional design that has not kept pace with the city's rapid demographic and industrial growth. The economic valuation of water supply services $14.1–16.7 million annually, underscores the reservoir's irreplaceable role, yet this figure also highlights the vulnerability of relying on a single source. Declining dead water levels and sedimentation trends indicate a system under stress, in which supply augmentation strategies (e.g., inter-basin transfers) risk exacerbating ecological fragility rather than resolving structural inefficiencies.

These findings suggest that future water-supply planning in Astana should consider not only water availability but also the ecological functions that sustain it. As Kazakhstan revises its Water Code (Water Code, 2003), ES accounts could be incorporated into Basin Water Allocation Plans, enabling the consideration of sedimentation and water-quality degradation risks alongside conventional infrastructure investments.

The water-purification service, valued at US$ 35.5–45.1 million annually, underscores the substantial economic costs of maintaining drinking-water quality in Astana. This value reflects both the costs incurred by the municipal utility to treat raw water for supply and the additional expenditures borne by households for bottled water and other alternative drinking water sources. Together, these costs demonstrate the economic importance of preserving water quality within the Astana Reservoir system.

Although municipal treatment enables compliance with most regulatory standards, recurring exceedances of nutrients, suspended solids, and, in particular, heavy metals indicate growing pressure on both the reservoir ecosystem and the treatment infrastructure. Human activities, including urban runoff and untreated industrial discharges, are

increasingly straining the system's capacity to maintain acceptable water quality.

The continued reliance of many households on bottled water, despite access to municipally treated supply, suggests a persistent gap between regulatory compliance and consumer perceptions of drinking-water quality. Whether these concerns originate from source-water conditions, treatment processes, or the distribution network, they translate into tangible costs for consumers. Consequently, water-quality degradation imposes costs at multiple points along the water-supply chain, affecting both utilities and end users. The Astana case is consistent with findings from ecosystem accounting studies in Australia, where water-quality regulation generates benefits that often exceed the direct value of water abstraction itself (Vardon et al., 2019). Similarly, consumer reliance on bottled water in other post-Soviet and transition economies has been linked to concerns about municipal water quality. These results underline the importance of maintaining ecosystem condition not only to safeguard ecological integrity but also to minimise the economic burdens associated with drinking-water provision.

The erosion control function, valued between $9.8 and $18.8 million annually, is shaped by land use transitions in the reservoir's catchment. The expansion of rain-fed agriculture and reduction in sparse vegetation since the 1990s have increased sediment loads, diminishing the reservoir's retention capacity. These trends are driven by policy incentives favouring agricultural intensification without adequate safeguards for soil conservation. The economic valuation highlights the cost of inaction: sedimentation not only reduces storage capacity but also accelerates the need for capital-intensive dredging.

The erosion control service thus reflects the interplay between land governance, ecological integrity, and long-term infrastructure sustainability. The findings indicate that declining soil retention accelerates reservoir siltation and inflates dredging costs.

Recreational services, valued at US$340,000 annually, represent an untapped opportunity constrained by infrastructure and environmental challenges. The relatively low visitation rates are not due to a lack of demand, but rather to inadequate access, poor water quality, and limited amenities. Existing facilities are basic, lacking rest areas, signage, and sanitation. Access is further hindered by the absence of public transportation and poor road conditions, which discourage higher visitation to the area.

The travel cost analysis indicates that while recreational demand is sensitive to costs, improving infrastructure and accessibility could significantly unlock underutilized visitation potential without compromising the area's ecological status. By promoting multifunctional landscape planning that integrates ecological restoration with community engagement, the reservoir can support both ecological resilience and public benefit, transforming it from a monofunctional utility into a multifunctional landscape. Improved recreational infrastructure can potentially increase the attractiveness of reservoir areas and enhance their recreational and cultural value.

While the assessed services generate a substantial annual value of US$ 59.7–80.9 million, this estimate should be regarded as a conservative representation of the Astana Reservoir's overall socio-ecological value. Several important ES, including flood regulation, aquatic biodiversity conservation, and microclimate regulation, were not included due to data and monitoring limitations. Their omission is particularly relevant to Astana's water security. For example, beyond supplying water, the reservoir helps attenuate floods during spring snowmelt, thereby reducing potential risks to downstream settlements and infrastructure.

Similarly, the exclusion of biodiversity and other non-market ecosystem benefits means that the valuation does not fully capture the ecological significance of the reservoir and its catchment. Consequently, the estimated value of US$ 59.7–80.9 million per year is likely to underestimate the reservoir's total natural capital contribution. Future research could address these gaps by improving environmental monitoring and collecting primary social preference data, including willingness-to-pay surveys and choice experiments, to better quantify non-market ecosystem benefits and other currently unaccounted ES.

4.2. Methodological and technical challenges of SEEA-EA implementation

Implementing the SEEA-EA framework in the Astana Reservoir revealed several methodological and technical challenges, particularly in quantifying and integrating ES. Classifying ES using frameworks such as the Millennium Ecosystem Assessment (MA), The Economics of Ecosystems and Biodiversity (TEEB), and the Common International Classification of Ecosystem Services (CICES) proved difficult. These frameworks differ in their conceptual foundations, terminologies, and categorisations—MA and TEEB include 'supporting' or 'habitat' services, while CICES excludes them to avoid double-counting by focusing solely on "final" services directly consumed by humans.

Nevertheless, overlaps continue to pose significant challenges. For instance, water purification can be classified as a provisioning, regulating, or supporting service depending on the framework, leading to ambiguous service boundaries and inflated valuations. The lack of standardised indicators and the difficulty of distinguishing between intermediate and final services—especially in multifunctional systems such as reservoirs —further complicate classification. In Kazakhstan, these issues were exacerbated by limited data availability, institutional fragmentation, and the absence of regulatory mandates for ES assessment. To mitigate these risks, the study adopted the CICES V4.3 frameworks, which provides a hierarchical structure and emphasizes final services, while carefully disaggregating overlapping functions and documenting classification assumptions to ensure transparency and avoid aggregation errors. Nonetheless, the experience underscores the need for harmonized, context-sensitive ES typologies and for capacity-building among practitioners to ensure robust, policy-relevant ecosystem accounting.

The assessment focused on four ES and excluded others, including flood regulation, aquatic biodiversity, and groundwater-related services, due to data limitations. Similarly, the Nura–Ishim inter-basin transfer was treated as an external driver, and its potential effects on the reservoir's hydrology, water quality, and ES provision were not explicitly quantified due to insufficient monitoring data.

The omission of groundwater–surface water interactions represents a further limitation. Although groundwater exchanges can influence long-term reservoir storage and water balances in semi-arid environments (Gafurov et al., 2019; Yapiyev et al., 2019), continuous groundwater monitoring data are currently unavailable for the Astana Reservoir. Future ecosystem accounting efforts would benefit from dedicated groundwater monitoring to better represent these hydrological processes under changing climatic conditions.

Even for the services assessed, valuation relied on indirect approaches, including avoided-cost methods for water purification and erosion control, and travel-cost methods for recreation. While these approaches are widely applied in ES assessments, they remain sensitive to assumptions, proxy values, and benefit-transfer estimates, particularly in data-constrained settings. Consequently, the monetary values presented should be interpreted as indicative rather than precise estimates. Future research should strengthen the evidence base by improving environmental monitoring and conducting primary socioeconomic surveys to support more comprehensive and robust ecosystem accounting in Kazakhstan.

Data integration presented an additional challenge, as information was sourced from multiple institutions using different formats, temporal frequencies, and spatial resolutions. Harmonising hydrological, environmental, spatial, and economic datasets required extensive preprocessing and introduced uncertainty associated with data compatibility and scaling. These challenges were compounded by gaps and inconsistencies in some of the long-term records used to support the Water Balance and ARIES-RUSLE models.

To improve the reliability of the assessment, model outputs and ES accounts were reviewed through stakeholder consultations with policy-makers, utility managers, researchers, and water users. While the stakeholder sample was designed to capture perspectives from key organisations involved in water governance and water use, representation was not uniform across all stakeholder groups. Agricultural water users and environmental non-governmental organisations (NGOs) were represented indirectly through basin-management institutions and expert stakeholders, while downstream community perspectives were captured through consultations with local residents and water users. Given the study's focus on urban water-supply planning and the institutional implementation of SEEA-EA, greater emphasis was placed on stakeholders directly involved in water management, regulation, and major water consumption. Consequently, the limited direct participation by agricultural users, environmental NGOs, and downstream communities should be taken into account when interpreting the stakeholder findings.

We finally reaffirm that uncertainty propagates throughout the ecosystem-accounting process, from data compilation and biophysical modelling to economic valuation. At the biophysical stage, uncertainties arise from integrating hydrological, water-quality, remote-sensing, and land-cover datasets obtained from multiple institutions with different monitoring protocols, temporal frequencies, and spatial resolutions.

Additional uncertainty arises from the assumptions and input parameters used in the Water Balance and ARIES-RUSLE models, particularly where long-term environmental records are incomplete or inconsistent. These uncertainties subsequently influence the economic valuation stage. Consequently, the reported ES values should be interpreted as indicative rather than precise estimates. To improve transparency, key ES values were reported as ranges rather than single-point estimates, thereby reflecting uncertainty associated with both the underlying biophysical assessments and the valuation assumptions.

4.3. Policy and planning implications

The ecosystem accounts developed in this study provide a broader evidence base for water policy and planning by integrating ecological information with the hydrological, engineering, and economic data that traditionally support reservoir management. Water planning requires reliable information on water availability, storage capacity, infrastructure performance, abstraction, and treatment requirements.

The SEEA-EA framework complements these planning components by systematically accounting for ecosystem extent, ecosystem condition, and ecosystem-service flows, thereby making visible the ecological assets and processes that contribute to the long-term performance of the water-supply system. By organising these different sources of information within a common accounting structure, ecosystem accounting supports a more comprehensive understanding of the interactions between catchment condition, reservoir function, and water-resource management.

The results further demonstrate that ecosystem accounting provides information that extends beyond the monetary valuation of ecosystem services. The physical accounts developed for the Astana Reservoir identify changes in ecosystem conditions and ecosystem service provision that are directly relevant to planning and management. When combined with monetary information, these accounts provide complementary perspectives for evaluating management alternatives, identifying environmental pressures, monitoring ecosystem assets, and assessing the long-term sustainability of reservoir operations. This integrated perspective strengthens the analytical basis for planning by connecting ecological processes with the environmental and economic outcomes that they influence.

The stakeholder consultations highlight the value of incorporating multiple perspectives into ecosystem accounting and water planning. Although all stakeholder groups recognised the relevance of the ecosystem services assessed in this study, differences emerged in the priorities assigned to the information generated by the accounts.

Stakeholders responsible for water-supply operations emphasised supply reliability and infrastructure performance, whereas other participants placed greater emphasis on ecosystem condition and water quality. These complementary perspectives illustrate the diverse objectives that water planning must accommodate and demonstrate the importance of ensuring that ecosystem accounts are developed and interpreted through inclusive planning processes. Similar experience has been reported in ecosystem accounting and ecosystem-service assessments, where stakeholder participation has strengthened the relevance, transparency, and legitimacy of environmental information for policy and decision-making (Vardon et al., 2019).

The findings demonstrate how ecosystem accounting can strengthen water resource planning in Kazakhstan by integrating ecosystem and economic information into a common decision-making framework. The Astana Reservoir case shows that SEEA-EA can support monitoring, evaluation, and management by linking ecosystem condition, water quality, sediment dynamics, and water supply, thereby improving the evidence base for sustainable and adaptive water planning.

5. Conclusion

This study represents the first application of the SEEA-EA framework to a water resource system in Kazakhstan. Earlier studies have examined the ecological-economic value and governance of water resources in the country (e.g., Utepov et al., 2021; Zhupankhan et al., 2018), providing important knowledge on sectoral challenges and management priorities. Rather than replacing these approaches, the SEEA-EA framework complements them by integrating biophysical, spatial, and economic information within a common accounting structure. This enables ecosystem conditions, ES provision, and economic benefits to be assessed consistently and incorporated into water planning and policy processes.

The literature review and empirical evidence indicate that Kazakhstan has faced several technical and institutional challenges in integrating ES into water resource planning. These include a fragmented legal and institutional landscape, limited technical capacity, and a disconnect between ES and the development of water supply systems. The legacy of centralised, infrastructure-focused governance has also led to weak interagency coordination and limited stakeholder engagement.

To address these constraints, we adopted a phased, mixed-methods approach that integrated geospatial analysis, hydrological modelling, and stakeholder engagement, applied to the central water supply system of Astana. This design enabled the development of a locally grounded ES account tailored to the reservoir's specific ecological and governance context. The use of spatial datasets, long-term hydrological records, and remote sensing supported the quantification of key services, including water supply, purification, erosion control, and recreation. Semi-structured interviews with stakeholders, including government engineers, utility managers, and community representatives, provided critical insights into service prioritisation, trade-offs, and the perceived legitimacy of the valuation results. This iterative process of technical assessment and stakeholder validation helped ensure that the ES accounts reflected both empirical realities and local planning needs.

While the SEEA-EA assessment was constrained by data gaps and the exclusion of important services such as flood regulation and aquatic biodiversity, it nevertheless demonstrates the feasibility and value of ecosystem accounting in Kazakhstan's water sector. Future studies could build on this foundation by expanding environmental monitoring and incorporating additional ES to provide a more complete assessment of natural capital. The Astana Reservoir case can offer a practical model for embedding ES considerations into water planning and policy, supporting more sustainable, resilient, and transparent management

of urban water-supply systems in Kazakhstan and the wider Central Asian region.

CRediT authorship contribution statement

Ardak Nassir: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation. **Stefanos Xenarios:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Data curation, Conceptualization. **Murodbek Laljebaev:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Conceptualization. **Cecilia Tortajada:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Peiyue Li:** Writing – review & editing, Writing – original draft, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Technical characteristics of the Astana Reservoir

Parameter	Value / Description	Source
Official name	Astana Reservoir (formerly Vyacheslav Reservoir)	Kazvodkhoz, 2004
River	Yesil/Ishim River, Irtysh–Aral Basin	Kazvodkhoz, 2004
Year of construction	1969 (Soviet period)	Kazvodkhoz, 2004
Location	5 km southeast of the Arnasay village and 65 km of Astana	Author's estimations
Primary purposes	Urban drinking water supply; irrigation; industrial water	JICA, 2001; Kazvodkhoz, 2004
Designed maximum supply capacity	89 million m^3 per year	Kazvodkhoz, 2004
Daily designed water supply	244,000 m^3 per day	JICA, 2001
Total storage volume	458.45 million m^3	Kazvodkhoz, 2004
Effective storage	≈367 million m^3,reduced by sedimentation	Kazvodkhoz, 2023; Akiyanova et al., 2020
Surface area	47.3 km^2	Kazvodkhoz, 2004
Average and maximum depth	6.3 m and 25 m	Kazvodkhoz, 2004
Catchment area	5210 km^2	Kazvodkhoz, 2004
Dam type	Earth-fill embankment dam + concrete spillway	JICA, 2001
Dam Height	32 m	Kazvodkhoz, 2023
Water users	Astana Su Arnasy (municipal utility), irrigation users, industries	Kazvodkhoz, 2023
Irrigated Area	6100 acres	Kazvodkhoz, 2023
Designed population served	250,000–300,000 people	Author's estimation based on the design rate

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.hydres.2026.09.003.

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