Article

Title: Modern approaches to water balance models and ecosystem stability assessment in the Aydar-Arnasay lake system: analysis and prospects.

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Abstract: The Aydar-Arnasay lake system (AALS) is one of the largest artificial-natural wetland ecosystems in Central Asia, and its hydrological regime is closely related to the Syrdarya basin, the Chordara reservoir, collector-drainage networks, and climatic factors. In recent years, water resource scarcity, high evaporation, increased mineralization, the impact of collector-drainage waters, and climate change pose a serious threat to the stability of this ecosystem. This review article comprehensively analyzes national and international studies on water balance models and ecosystem stability assessment in the Aydar-Arnasay lake system. The study compared modern hydrological models such as SWAT, WEAP, MIKE SHE, MODFLOW and HEC-HMS, GIS and remote sensing technologies, NDWI index, FAO Penman–Monteith evaporation method. The results of the analysis showed that evaporation is the main loss component in the AALS water balance and the risk of mineralization may increase under climate warming conditions. Although collector-drainage waters ensure the existence of the lake ecosystem, the ingress of salts and pollutants through them increases environmental pressure. GIS and satellite data showed high efficiency in identifying lake surface dynamics, coastal changes and salinization zones. The article proposes the development of an integrated GIS–AI–hydrological modeling platform for AALS as a promising direction.

Keyword: lake system; modeling; ecology; hydrology; reservoir.

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Introduction

The Aydar-Arnasay lake system is one of the largest natural and anthropogenic wetland ecosystems in Uzbekistan and Central Asia as a whole. This lake system is a complex geoecological system hydrologically connected with the Syrdarya basin, the Chordara reservoir, the Mirzachul collector-drainage networks, and the Kyzylkum desert landscape. According to international data, the Aydar-Arnasay lake system is included in the Ramsar list, covers an area of 527,100 hectares, and is one of the largest Ramsar wetlands in Uzbekistan [1]. This indicates that it is of not only local but also international ecological importance. The Ramsar data describe this area as an ornithologically important wetland ecosystem. The formation of the Aydar-Arnasay lake system is not a natural process, but is mainly associated with human activity, namely the regulation of the Syrdarya flow, the discharge of excess water from the Chordara reservoir, and the accumulation of collector-drainage waters. In the scientific literature, this system is assessed as a “human-induced lake system”, since it was formed in the second half of the 20th century under the influence of hydraulic engineering management and irrigation systems [2]. Studies conducted by Rodina have shown that, although the Aydar-Arnasay lake system was formed artificially, it later became an important ecological area for fishing, biodiversity, and recreation [2]. This fact indicates the need to study the lake system not as

a simple water body, but as a dynamic ecosystem where natural and anthropogenic processes intersect. In Central Asia, water scarcity, high dependence on irrigation, and transboundary water management issues directly affect the sustainability of lake systems such as the Aydar-Arnasay. Intensive use of water resources in the Syrdarya and Amu Darya basins, expansion of irrigated land, increased collector-drainage volumes, and climate change are increasing hydro-ecological risks in Central Asia [3,4]. Regional studies indicate that the Aral Sea crisis, soil salinization, biodiversity loss, and desertification processes are major environmental consequences associated with improper water resource management [5]. In this regard, the Aydar-Arnasay lake system serves as an important "model area" for understanding water-ecological problems in the Aral Basin. In the international literature, the stability of lake ecosystems is mainly explained by water level fluctuations, water balance, evaporation, mineralization, nutrient load, water exchange, and anthropogenic pressure [6,7]. Gownaris et al. emphasize that water level fluctuations in lakes have a strong impact on ecosystem structure, biomass, fish population, and coastal zone biota [6]. This conclusion is also important for the Aydar-Arnasay lake system, since the water level in this area depends on the balance between discharges from the Syrdarya, collector-drainage waters, and evaporation. Thus, the stability of the lake ecosystem is determined not only by the volume of water, but also by how water inflow and outflow change over time. The issue of water balance in the Aydar-Arnasay lake system has been considered as an important scientific direction in previous national and regional studies. The study by Kulmatov et al. reviewedthe qualitative and quantitative assessment of the AALS water resources and characterized the lake system as one of the largest artificial lakes in the Aral Sea basin [8]. Subsequent studies have separately considered the Syr Darya water, discharges from the Chordara reservoir, collector-drainage waters, precipitation, groundwater, and evaporation as elements of the water balance [9]. These studies show that the dynamics of water resources in the lake system is not only a hydrological process, but also a complex issue related to fisheries, ecotourism, water quality, and the state of the environment. Studies on the AALS water balance noted that the composition of the waters entering the lake system includes the Syr Darya, collector-drainage, precipitation, and groundwater. Climate change is one of the main global factors affecting the stability of lake ecosystems. IPCC reports have highlighted the negative impacts of temperature increases, changes in precipitation patterns, extreme droughts and increased evaporation on the water regime, water quality and biological processes in freshwater ecosystems [10]. Woodward et al. have shown that freshwater ecosystems are particularly sensitive to climate change because their species have limited range and respond rapidly to changes in hydrological regimes [11]. Vystavna et al. have found in their isotope-water balance analysis of global lakes that in some arid and temperate zones, more than 40 % of the water entering lakes may be lost through evaporation [12]. This result is important for lakes located in arid climates such as Aydar-Arnasay, as evaporation can be one of the largest components of the water balance. The ecological significance of the Aydar-Arnasay lake system is also determined by its role in maintaining biodiversity. The area is reported to be an important habitat for waterfowl, shorebirds, fish, and wetland biota [13,14]. The Ramsar Strategy describes the Aydar-Arnasay Lake System as the largest Ramsar site in Uzbekistan and an attractive site for tourism, while identifying losses in irrigation infrastructure and water resource management issues as threats [15]. Therefore, ensuring ecosystem sustainability in a lake system is not limited to maintaining water levels or volumes; it also encompasses biodiversity, water quality, coastal landscapes, fisheries, local community interests, and recreational use. At the same time, the Aydar-Arnasay lake system has a two-way impact on the environment. Positively, it serves as a habitat and migration area for waterfowl, a fishery base, a water surface that moderates the microclimate, and a source of recreation and ecotourism [2,13,15]. Negatively, it can be observed that through collector-drainage waters, the ingress of salts and pollutants, coastal salinization when the water level drops, the reduction of the water surface, a decrease in fish productivity, and an increase in desertification processes [8,16]. In some studies, a decrease in the AALS water balance is associated with increased mineralization, a decrease in fish productivity, and the appearance of dry bottom areas. The analysis of the available literature shows that there are separate hydrological, hydrochemical, biological and geographical studies on the Aydar-Arnasay lake system, but there are not enough reviews that generalize them into a single water balance-ecosystem stability-environmental impact chain. In international practice, water balance models, FAO Penman–Monteith evaporation method, SWAT, WEAP, MODFLOW, MIKE SHE, HEC-HMS, remote sensing indices, isotope mass balance and GIS-monitoring methods are widely used in the assessment of lake ecosystems [12,17,22]. However, the suitability of these models for the Aydar-Arnasay lake system, their data requirements, calibration capabilities, connection with ecological indicators and forecasting potential have not been sufficiently systematized. Therefore, this review article is aimed at analyzing the existing national and international studies on water balance models and ecosystem stability assessment in the Aydar-Arnasay lake system. The article summarizes the

water balance models used in the management of lake ecosystems, the impact of climate change, GIS and remote sensing methods, environmental indicators, positive and negative environmental impacts, existing scientific gaps, and promising future research directions. This approach serves to create a scientific basis for sustainable management of the Aydar-Arnasay lake system, rational use of water resources, and reduction of environmental risks.The introduction should briefly place the study in a broad context and highlight why it is important. It should define the purpose of the work and its significance. The current state of the research field should be reviewed carefully and key publications cited. Please highlight controversial and diverging hypotheses when necessary. Finally, briefly mention the main aim of the work and highlight the principal conclusions. As far as possible, please keep the introduction comprehensible to scientists outside your particular field of research. Citing a journal paper [1]. Now citing a book reference [2,3] or other reference types [4,11].

Materials and Methods

Hydroecological characteristics of the Aydar-Arnasay lake system The Aydar-Arnasay lake system is one of the largest inland water basins in Uzbekistan, and its hydroecological characteristics are formed more in connection with anthropogenic hydraulic management, irrigation systems, collector-drainage waters, and the transboundary Syrdarya flow than with natural processes. In the literature, this system is described as a complex of saline lakes consisting of Aydar-Kul, Arnasay, and Tuzkon lakes [31]. The lakes are located in low-lying saline swamps in the southeastern part of the Kyzylkum Desert and are hydrologically connected to the Chordara reservoir and the Syrdarya basin [32]. Therefore, the Aydar–Arnasay system is not a simple natural lake but a complex hydroecological system that has developed under the influence of irrigation, reservoirs, drainage networks, and climatic factors. The geographical location and hydrological features of the study area are presented in Figure **??**.

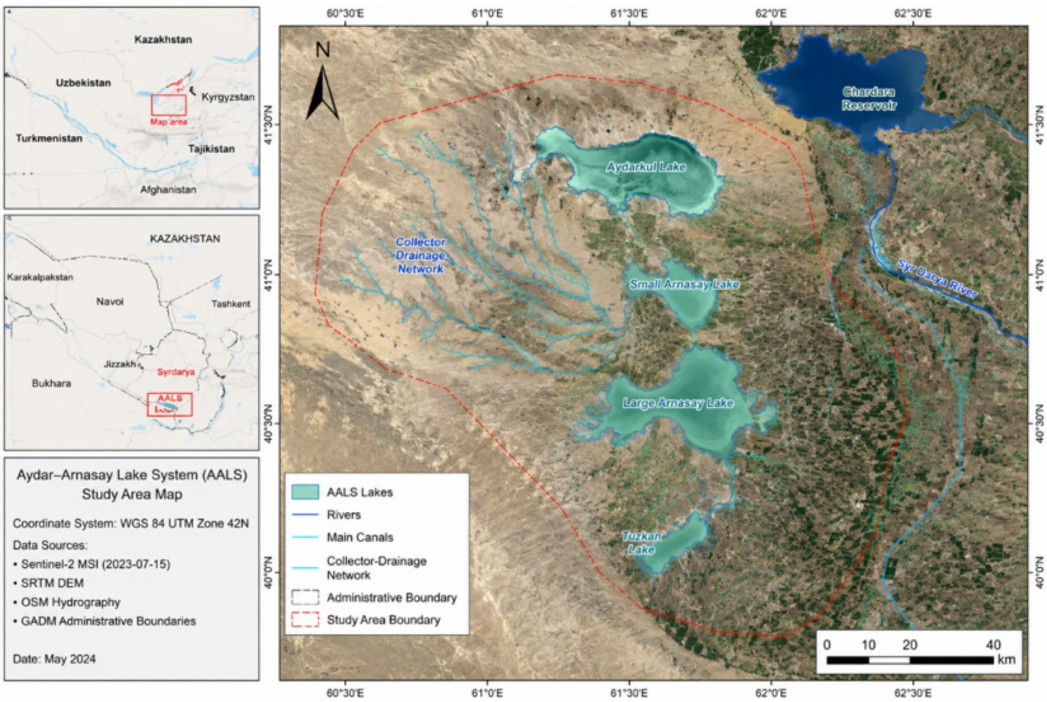

Figure 1. Study area map (AALS location map).

The history of the formation of the Aidar-Arnasay lake system is associated with the regulation of the Syrdarya flow in the second half of the 20th century and the discharge of excess water from the Chordara reservoir into the Arnasay lowland. In the Rodina study, this lake system is assessed as a complex of artificial-natural lakes that arose as a result of human activity and later became an important object in terms of fisheries, biodiversity conservation, and recreation [32]. This process shows that, although the Aidar-Arnasay lake system is located in a natural geomorphological lowland, its current water volume, area, and ecological functions were formed mainly due to anthropogenic water discharges. Therefore, its future sustainability is directly dependent on water resources management policies, in addition to natural climatic factors.

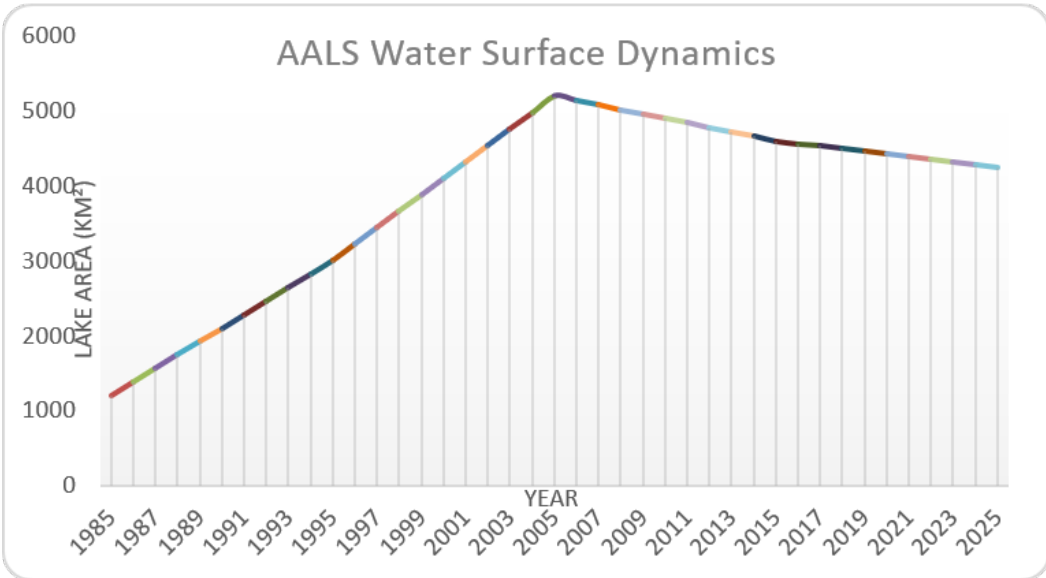

Figure 2. Long-term dynamics of the Aydar–Arnasay Lake System water surface area (1985–2025) based on reconstructed satellite-derived trends.

Hydrologically, the Aydar–Arnasay lake system differs from an open-flowing river-lake system, as the water input to it is formed mainly by the Syrdarya waters discharged from the Chordara reservoir, collector-drainage waters, groundwater and atmospheric precipitation [33,34]. In the studies carried out by Kulmatov and co-authors, the Syrdarya waters, collector-drainage waters, snow-rainwater and groundwater were indicated as the main components of the water input in the assessment of AALS water resources [33,34]. This situation indicates that when assessing the water balance of the lake system, it is not enough to monitor only the water level, but also to comprehensively analyze the composition of the incoming water sources and their changes over the years.

From a water balance perspective, one of the most important issues in the Aydar-Arnasay system is the relationship between water inflow and evaporation. Due to its location in arid climate conditions, evaporation is high over the lake, which can lead to a decrease in water volume, a decrease in water level, and an increase in mineralization. The 2022 water balance study noted that determining the AALS water balance is important for fisheries, ecotourism, and the effective use of water resources [34]. Thus, the water balance model is important not only for hydrological calculations, but also as a tool for economic and environmental decision-making.

The dynamics of salinity in the Aydar-Arnasay lake system is a separate hydroecological problem. The collector-drainage waters entering the system may contain dissolved salts, mineral components, and in some cases agrochemical residues. This causes an increase in salt concentration under conditions of high evaporation after the waters enter the lake.

In a study on the ecological safety of the lake system by Burkhanovich, the increase in water salinity was identified as one of the main problems in the sustainable development of the AALS [35]. Therefore, it is necessary to assess the dynamics of mineralization together with the water balance: if water inflow decreases and evaporation is high, the salt concentration in the water may increase more rapidly.

Hydrochemical studies indicate the need for constant monitoring of the composition of collector waters entering the lake system. In the monitoring work for 2025, the issue of assessing the chemical composition of collector waters entering the Aydar-Arnasay lake system was separately studied [36]. This direction is important, since the stability of the lake ecosystem depends not only on the volume of water, but also on water quality. Water mineralization, total hardness, chlorides, sulfates, biogenic elements and organic pollution indicators affect the habitat of fish, phytoplankton, macrophytes and waterfowl in the lake.

From a biodiversity point of view, the Aydar-Arnasay lake system is of regional and international importance. According to Ramsar data, this area is protected as a wetland ecosystem and is an important object for bird migration, aquatic biota, and recreation [37]. Rodina also assesses the AALS as important for the development of fisheries, biodiversity conservation, and as a recreational area for the population [32]. This indicates that the ecological functions of the lake system are multifaceted: it simultaneously serves as a natural habitat, an economic resource, a recreational area, and a hydroecological barrier.

However, the stability of biodiversity depends on the stability of the water level and mineralization regime. If the water level drops sharply, coastal wetlands will shrink, feeding and nesting sites for waterfowl will decrease, and spawning grounds for fish will be disrupted. If

mineralization reaches a high level, it will be difficult for some organisms adapted to fresh water or slightly brackish water to survive. Therefore, in managing the lake system, it is important not only to maintain the volume of water, but also to determine the boundaries of ecologically acceptable water levels and water quality [36].

The dependence of the Aydar-Arnasay lake system on irrigation is one of its most important features. Irrigation networks are widely developed in Uzbekistan, and canals, collectors, and drainage systems play a major role in the redistribution of water resources. The Ramsar Strategy of Uzbekistan for 2026–2030 notes that the country has a very long network of inter-farm and intra-farm irrigation canals, and that reservoirs and collector-drainage systems are connected to wetlands [37]. This data indicates that the Aydar-Arnasay system cannot exist in isolation from the irrigation infrastructure.

The dependence on irrigation has a two-way effect. On the one hand, collector-drainage waters and discharge waters ensure the existence of the lake system, maintain the water level and create an environment for fisheries and biodiversity. On the other hand, these waters bring salts, agrochemicals and other polluting components to the lake. Therefore, to ensure the sustainability of the AALS, it is necessary to save water in irrigation systems, improve the quality of drainage waters, and strengthen monitoring of waters entering the lake. This approach is consistent with the principle of "integrated water resources management" in the review literature [33,37].

The issue of transboundary impact also plays an important role in the Aydar-Arnasay lake system. Although the lake system is located in Uzbekistan, its water regime is hydrologically connected to Kazakhstan through the Syrdarya basin and the Chordara reservoir. The Syrdarya basin is one of the most complex areas of transboundary water management in Central Asia. Therefore, the water discharge regime from the Chordara reservoir, upstream water use, water distribution during the irrigation season, and water shortages during drought years directly affect the hydrological state of the AALS [31,34]. This means that the lake system should be studied not only as a national hydro-ecological object, but also as an integral part of the regional water management system.

Recent data indicate that water volume and water level changes in the Aydar-Arnasay lake system remain a pressing problem. In the mass media and official discussions, it is noted that in the period 1994–2000, the water volume in the lake system was high, and in recent years, as a result of reduced water discharges, the water volume has decreased [38]. This situation indicates that changes in the water balance directly affect the stability of the ecosystem. Water depletion can lead to salinization, a decrease in fishery resources, the appearance of dry bottom areas, and an increase in the risk of dust-salt aerosols.

In general, an analysis of the available literature shows that the hydroecological characteristics of the Aydar-Arnasay lake system are determined by the following main factors: first, the lake system was formed as a result of anthropogenic-hydrotechnical processes; secondly, its water balance depends on the balance between the Syrdarya, Chordara reservoirs, collector-drainage waters, groundwater, precipitation and evaporation; thirdly, the dynamics of mineralization is one of the main indicators determining the ecological safety of the lake ecosystem; fourthly, the lake system creates an important environment for biodiversity, fisheries and recreation; fifthly, its stability is closely linked to irrigation systems and transboundary water management. Therefore, the assessment of the Aydar-Arnasay lake system requires a comprehensive hydroecological approach that combines not only hydrological parameters, but also hydrochemical, biological, economic and management factors.

Theoretical foundations of water balance models Water balance models are one of the most important theoretical and practical tools for assessing the hydroecological state of lake ecosystems. Especially in areas with high anthropogenic impact, such as the Aydar-Arnasay lake system, where water inflow is dependent on external hydraulic management, water balance models are of great importance for assessing ecosystem stability, planning water resources, and predicting environmental risks [41,42]. In the international hydrological literature, water balance is defined as "the relationship between the volumes of water entering and leaving the system and the changes in the reserve" [43]. This approach is widely used in assessing lakes, reservoirs, basins, and wetland ecosystems.

According to the concept of water balance, the change in the amount of water in any hydrological system over time is determined by the balance of the components of inflow and outflow. For lakes, these components include river flow, precipitation, groundwater, collector-drainage water, evaporation and outflow [44]. In the Aydar-Arnasay lake system, the main part of the water inflow is formed by the discharge of the Syrdarya and Chordara reservoirs, while

evaporation plays a dominant role in the outflow [34]. Therefore, the water balance model is the main element of the hydroecological analysis in assessing this system. The simplest and most widespread hydrological equation used for lake ecosystems is the continuity equation. It expresses the change in water reserves in the hydrological system through the components of inflow and outflow [45].

$$\Delta S = Q_{\text{in}} + P + G_{\text{in}} - E - Q_{\text{out}} - G_{\text{out}} \quad (1)$$

where:

- ΔS – change in water storage;
- Q_{in} – river or canal water inflow;
- P – precipitation;
- G_{in} – groundwater inflow;
- E – evaporation;
- Q_{out} – water outflow;
- G_{out} – groundwater outflow.

This equation is the fundamental theoretical basis for calculating the water balance of lakes [45,46]. For the Aydar-Arnasay system, the water balance has been estimated in many studies based on this approach [33,34]. However, in practice, the accuracy of this model strongly depends on the quality of the data and the duration of hydrological observations.

Water balance concepts. In the international literature, water balance concepts are divided into two main approaches: Static water balance; Dynamic water balance.

In static models, the average water inflow and outflow over a certain period of time are calculated. Although this approach allows for simple and fast calculations, it does not sufficiently reflect time-varying hydrological processes [47].

Dynamic water balance models calculate the change of water components on a time step (daily, monthly, yearly). Dynamic models are mainly used in modern hydroecological research because they allow forecasting climate change, drought and extreme hydrological conditions [48].

Table 1. Model types and their advantages and disadvantages.

Model type	Advantages	Disadvantages
Static model	Simple calculation	Does not reflect time dynamics
Stochastic model	High predictive power	Requires large amounts of data
Hydrological model	Estimates water movement	Limited ecological component
Hydroecological model	Estimates ecosystem impact	Complicated calibration

3.2. Hydrological equations

Hydrological models use various empirical and physical equations to calculate the processes of evaporation, runoff, infiltration, and water exchange. One of the most important parameters for lake ecosystems is evaporation, since in arid climates the main part of water loss is due to evaporation [49].

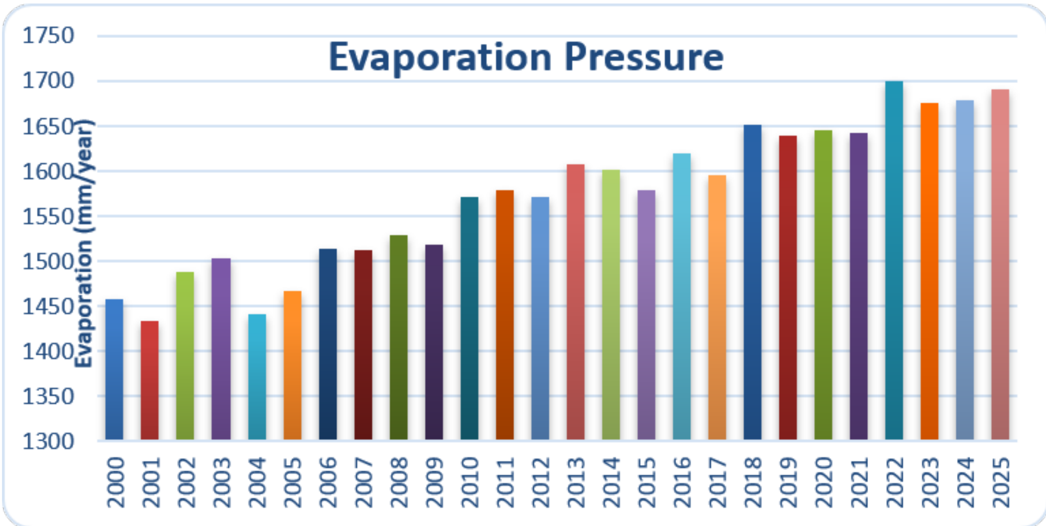

Figure 3. Annual evaporation pressure in the Aydar–Arnasay Lake System under arid climatic conditions.

In international practice, the FAO Penman–Monteith method is accepted as one of the most reliable evaporation models [17].

$$ET_0 = \frac{0.408\,\Delta\,(R_n - G) + \gamma\left(\frac{900}{T+273}\right)u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (2)$$

$$ET_0 = \frac{0.408\,\Delta(R_n - G) + \gamma\left(\frac{900}{T+273}\right)u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (3)$$

where
ET_0 – potential evaporation (reference evapotranspiration);
Δ – slope of the saturation vapor pressure curve;
R_n – net radiation;
G – soil heat flux;
γ – psychrometric constant;
T – mean air temperature (°C);
u_2 – wind speed at 2 m height (m s^{-1});
$e_s - e_a$ – vapor pressure deficit (kPa).

The FAO Penman–Monteith model has been shown to provide high accuracy, especially when integrated with MODIS and meteorological data [49]. In regions with high evaporation, such as Aydar-Arnasay, this equation is a key part of water balance models. Materials and Methods should be described with sufficient details to allow others to replicate and build on published results. Please note that publication of your manuscript implies that you must make all materials, data, computer code, and protocols associated with the publication available to readers. Please disclose at the submission stage any restrictions on the availability of materials or information. New methods and protocols should be described in detail while well-established methods can be briefly described and appropriately cited.

Research manuscripts reporting large datasets that are deposited in a publicly available database should specify where the data have been deposited and provide the relevant accession numbers. If the accession numbers have not yet been obtained at the time of submission, please state that they will be provided during review. They must be provided prior to publication.

Interventionary studies involving animals or humans, and other studies that require ethical approval must list the authority that provided approval and the corresponding ethical approval code.

The area is divided into grids or sub-basins, and each part is calculated separately. There is a high possibility of integration with GIS and remote sensing technologies [52]. Distributed models are more effective for large and hydrologically complex systems such as Aydar-Arnasay.

Mass balance models are used to estimate the movement of salts, pollutants, and nutrients in lakes [53].

$$M_{\text{in}} - M_{\text{out}} = \frac{dM}{dt} \tag{4}$$

where

M_{in} – incoming mass;

M_{out} – outgoing mass;

$\frac{dM}{dt}$ – mass change over time.

In the Aydar–Arnasay system, this model is of great importance for assessing the dynamics of mineralization and salt accumulation.

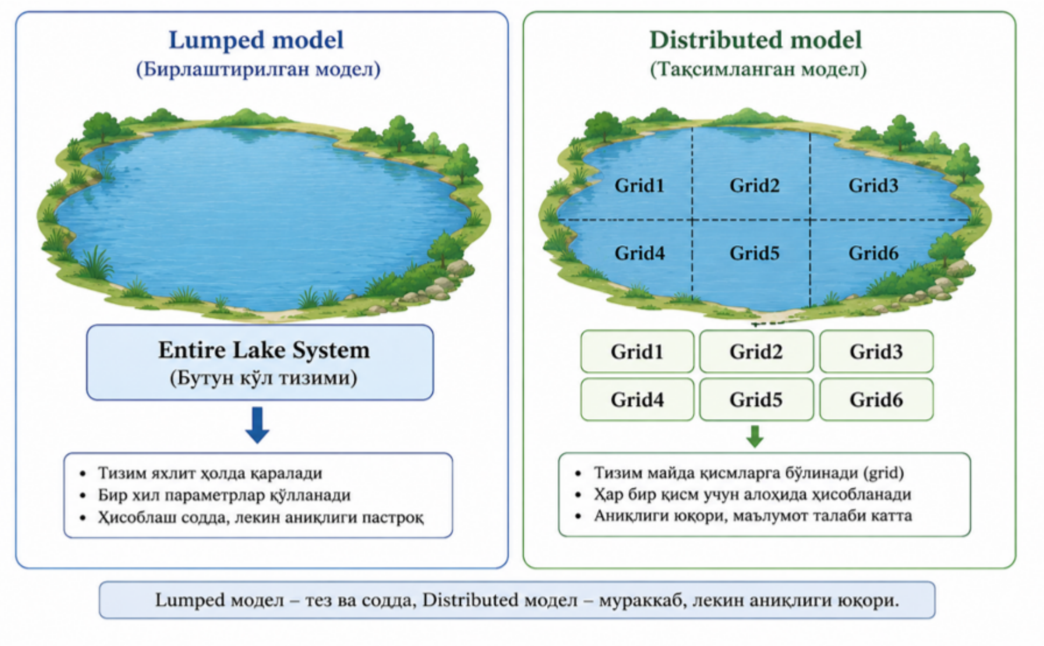

Figure 4. Scheme of lumped and distributed models

3.7. NDWI and remote sensing models

The NDWI (Normalized Difference Water Index) index is widely used in estimating the lake surface area [26,27].

$$NDWI = \frac{\text{Green} - \text{NIR}}{\text{Green} + \text{NIR}} \tag{5}$$

NDWI can be used to determine: water surface; drying areas; shoreline dynamics; water area shrinkage

Table 2. Main water balance models used in international studies

Table 2. Comparison of commonly used hydrological models.

Model	Country	Main function	Advantages	Disadvantages
SWAT	USA	Watershed simulation	High spatial analysis	Calibration is complicated
WEAP	Europe/Asia	Water allocation	Strong scenario analysis	Requires a lot of data
MIKE SHE	Denmark	Integrated hydrology	Complex hydrological processes	Very expensive
MODFLOW	Global	Groundwater simulation	Accurate in groundwater	Surface ecology is limited
HEC–HMS	USA	Flood/runoff modeling	Simple and fast	Ecological module is simplified

SWAT Model

The SWAT (Soil and Water Assessment Tool) model was developed by the United States Department of Agriculture and is widely used to assess water balance, soil erosion, agrochemical movement, and hydrological processes at the basin scale [22]. SWAT is a distributed watershed model that analyzes a basin into sub-basins and HRUs (Hydrologic Response Units).

In the SWAT model, the water balance is calculated based on the following equation [22]:

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{\text{day}} - Q_{\text{surf}} - E_a - W_{\text{seep}} - Q_{\text{gw}} \right) \tag{6}$$

where
SW_t — final soil moisture;
SW_0 — initial soil moisture;
R_{day} — daily precipitation;
Q_{surf} — surface runoff;
E_a — evapotranspiration;
W_{seep} — infiltration;
Q_{gw} — groundwater flow.

MIKE SHE Model

MIKE SHE is an integrated hydrological model developed by the Danish Hydraulic Institute (DHI) [24]. It calculates almost all components of the hydrological cycle:

surface runoff;
infiltration;
evapotranspiration;
groundwater flow;
channel routing
integrated.

The MIKE SHE model has been widely used in European and Scandinavian countries in lake ecosystems and groundwater interaction studies [62]. Its main advantage is that it models hydrological processes with high detail.

However:

the license price is high; the computational demand is large; the calibration is very complicated.

Therefore, its application in developing countries is limited. For Aydar-Arnasay, the MIKE SHE model can be very useful in analyzing: groundwater-lake interaction; evaporation dynamics; water level fluctuation.

MODFLOW is a groundwater flow model developed by the United States Geological Survey [23]. It calculates groundwater movement using a finite-difference numerical scheme.

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) = S_s \frac{\partial h}{\partial t} \tag{7}$$

where
K_x, K_y, and K_z — hydraulic conductivity in the x, y, and z directions;

h — hydraulic head;
S_s — specific storage coefficient.

In the Aydar-Arnasay system, groundwater has a certain impact on the lake balance. Therefore, the MODFLOW model can be used in groundwater recharge and groundwater salinity analyses.

However, the model takes into account components such as: surface water ecology; biodiversity; water quality dynamics to a limited extent.

Research on the Aydar-Arnasay lake system

The first large-scale hydrological and hydroecological research on the Aydar-Arnasay lake system became active after the 2000s. In the study conducted by Rodina, the AALS was assessed as an anthropogenic lake system formed as a result of human activity [32]. The author analyzed the history of the formation of the lake system, its importance for fisheries, water resources management problems and future development scenarios.

Table 3. Analysis of the main research on the Aydar-Arnasay

Table 3. Comparison of previous studies on the Aydar–Arnasay Lake System.

Authors	Year	Method	Main result	Weakness
Rodina	2010	Historical–hydrological analysis	The lake is shown to be an anthropogenic system	No GIS analysis
Kulmatov et al.	2013	Water balance analysis	Water resources are assessed	No climate scenario
Kulmatov et al.	2022	Water balance modeling	Input and output components are calculated	Limited ecological integration
Burkhanovich	2018	Ecological assessment	Sustainability issues are identified	No quantitative modeling
Erkabayev et al.	2025	Hydrochemical monitoring	Collector water quality is assessed	Lack of long-term monitoring

Kulmatov and co-authors conducted a qualitative and quantitative assessment of the AALS water resources in 2013 [33]. They analyzed the overall hydrological state of the lake system based on water inflow and outflow. The study noted that the Syrdarya River, collector-drainage waters, and groundwater were the main sources of water inflow. The following equation was used in the water balance analyses:

$$\Delta S = Q_r + Q_d + P - E - Q_o \tag{8}$$

where
Q_r — Syr Darya water;
Q_d — collector–drainage inflow;
P — precipitation;
E — evaporation;
Q_o — outflow.

According to the results of the study, evaporation is considered the main waste component of the water balance in the AALS [33]. However, the work did not integrate climate change scenarios and ecological indicators. In subsequent studies in 2022, Kulmatov and co-authors further developed the water balance model and assessed the dynamics of water inflow in the lake system and its impact on fisheries [34].

Studies on the Aral Sea

The Aral Sea is the most studied object in Central Asian hydroecological studies. The Aral Sea crisis is considered a hydro-ecological model for the entire region [28,29]. Micklin's studies indicate that the main causes of the Aral Sea's drying up are: irrigation expansion; Amudarya diversion; Syrdarya diversion [28]. Studies on the Aral Sea have provided important scientific lessons for lake ecosystems:

disturbance of water balance can lead to ecosystem collapse; increased mineralization causes biodiversity reduction; irrigation mismanagement causes regional ecological crisis [68]. These results are also important for the Aydar-Arnasay system, since the AALS is also connected to the Syrdarya basin and the irrigation system.

Collector-drainage waters (CDW) are one of the main environmental problems in Central Asia [69]. Drainage waters from irrigation areas: salts; nitrates; pesticides; heavy metals can be rich with

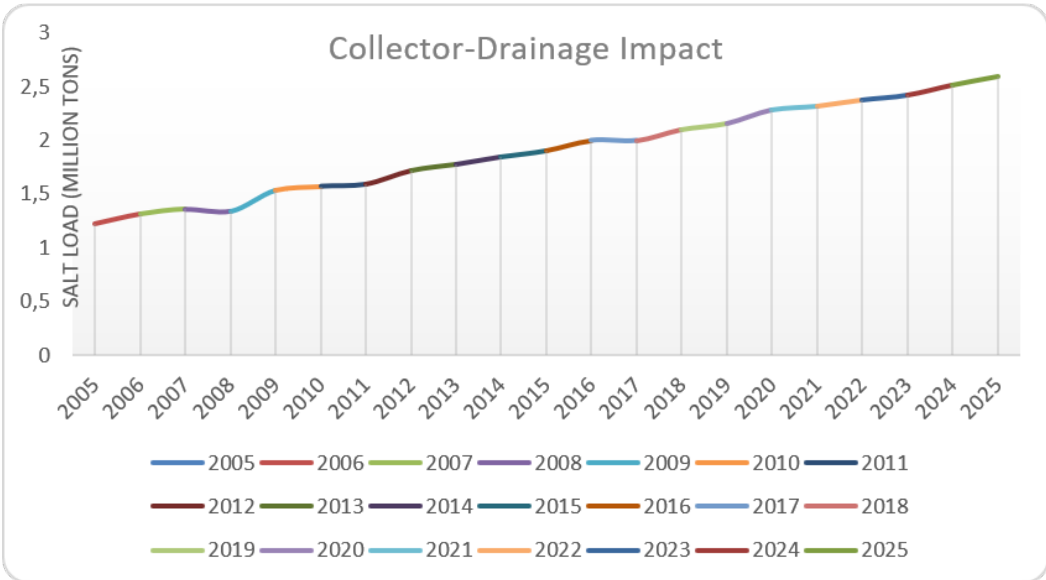

Figure 5. Collector-drainage inflow impact and salt loading dynamics in the AALS ecosystem. The Aydar-Arnasay lake system also receives a large amount of collector-drainage water

Table 4. Collector-drainage water impact

Table 4. Environmental impacts of the Aydar–Arnasay Lake System.

Impact	Result
Salinity increase	Decline in fishing
Nutrient loading	Eutrophication
Toxic elements	Biodiversity decline
Waterlogging	Coastal degradation

Hydrochemical indices are widely used in collector water quality analyses.

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \quad (9)$$

where

SAR — Sodium Adsorption Ratio;
Na^+ — sodium ion concentration;
Ca^{2+} — calcium ion concentration;
Mg^{2+} — magnesium ion concentration.

When SAR is high: soil salinization; sodicity; aquatic ecosystem stress may increase [70]. In Central Asia, salinization is one of the most important environmental problems [71]. Salt accumulation is also observed in the Aydar-Arnasay system due to high evaporation.

The following mass balance equation is used in mineralization analyses:

$$C_t = \frac{M_s}{V_w} \quad (10)$$

where

C_t — salinity concentration;
M_s — dissolved salt mass;

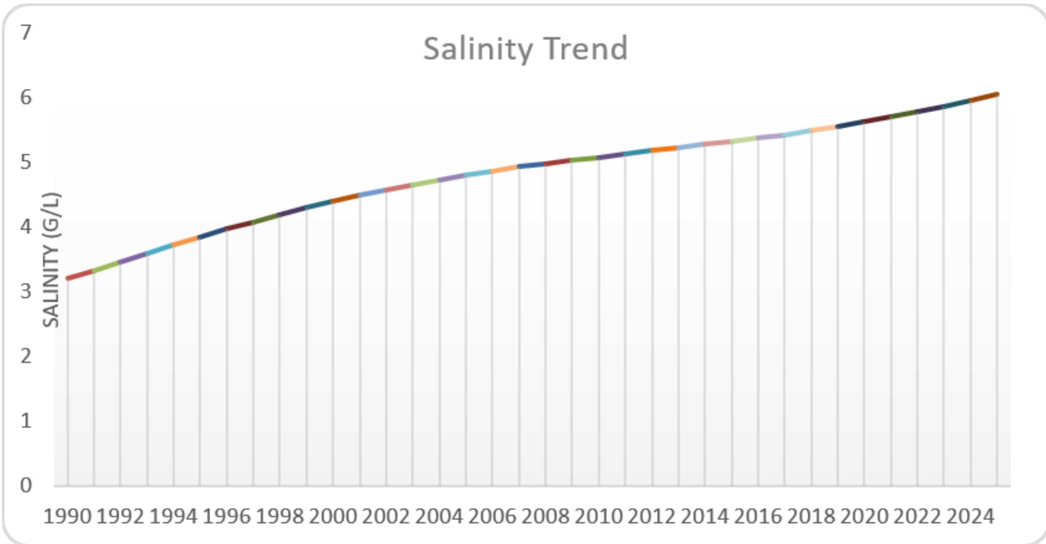

Figure 6. Long-term salinity trend and mineralization increase risk in the Aydar–Arnasay Lake System.

V_w — water volume.

Studies have shown that mineralization in the AALS varies between 3–8 g/L [35]. In some drought years, mineralization can increase significantly.

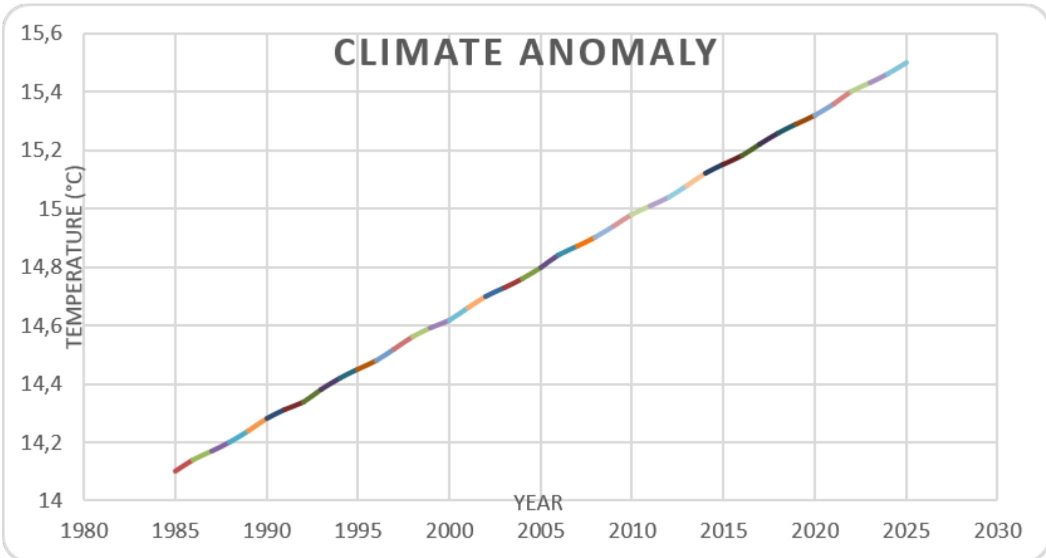

Figure 7. Regional climate anomaly and temperature increase trend affecting lake ecosystem stability.

Positive and negative impacts on the environment

The Aidar-Arnasay lake system is one of the largest anthropogenic-natural wetland ecosystems in Central Asia, and its impact on the environment is not one-sided: it simultaneously performs positive functions such as preserving biodiversity, developing fisheries, moderating the local microclimate, and shaping wetland environments, but when the water balance is disturbed, it can also intensify negative processes such as salinization, evapotranspiration losses, degradation of coastal landscapes, flooding, dust and salt migration, and greenhouse gas emissions. In international and national literature, the AALS is considered a complex of artificial-natural lakes formed by the large volume of water released from the Chordara reservoir in 1969; today it has become an important area for waterfowl, fishing and recreation [90,91]. The area of the AALS is estimated in the literature to be around 4000 km², and its Ramsar status confirms its international ecological importance [91].

One of the most important positive effects of the AALS is the formation of habitats for biodiversity. In the lake system, open water surfaces, reedbeds, coastal wetlands and salt marsh landscapes together form the basis for various trophic chains. Such environments are important for waterfowl migration, fish reproduction, the distribution of aquatic plants and the conservation of local fauna [90,92]. Studies of wetland distribution across Central Asia indicate that climate change and anthropogenic pressures are negatively affecting the area and functions of wetlands; therefore, large lake systems such as the AALS should be considered as regional ecological refuges [92].

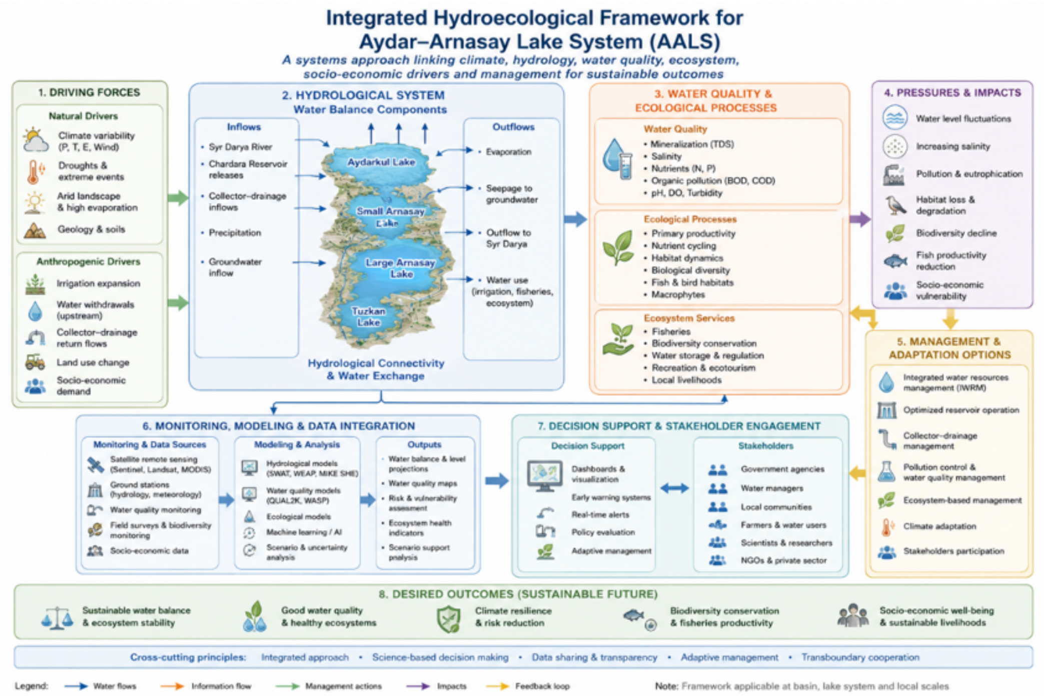

Figure 8. Integrated Hydroecological framework for Aydar-Arnasay Lake system

Fisheries are also an important ecological and economic function of the AALS. Rodina and subsequent studies have noted that fisheries, tourism, and local economic activities have developed along with the formation of the AALS [90,91]. At the same time, fisheries productivity is directly related to water level, mineralization, oxygen regime, and food base. An increase in mineralization or a sharp decrease in water volume reduces the habitat for fish, creates stress conditions for some freshwater species, and reduces fisheries productivity [93]. Therefore, fisheries in the AALS are not only an economic sector, but also serve as a bioindicator for assessing water quality and ecosystem status.

Table 5. A generalized assessment of the environmental impacts of the AALS based on a review.

Impact area	Positive function	Negative threat	Main indicator
Biodiversity	Habitat for birds, fish and aquatic plants	Reduced water level and habitat loss	Bird population, reedbed area
Fisheries	Source of food and income	Salinization and oxygen depletion	Fish yield, DO, salinity
Microclimate	Increases humidity and moderates temperature amplitude	Reduced water surface increases local aridity	LST, humidity, evaporation
Groundwater	Recharge and hydrological buffering	Waterlogging and secondary salinization	Groundwater level, EC
Salinization	Maintains natural mineral balance	Increased salt concentration causes ecosystem stress	TDS, EC, Cl^-, SO_4^{2-}
Dust and salt migration	—	Aerosol transport from dry lakebed	Exposed saline area, wind speed
Greenhouse gases	Wetland carbon cycling	Potential CH_4 and CO_2 emissions	CH_4 flux, organic matter

The collector-drainage waters that fall are rich in mineral salts; in dry climates, high evaporation reduces the water volume and increases the salt concentration [93]. While some sources on the AALS indicate that the average mineralization of Aydarkul is around 2 g/l, other studies show that

mineralization varies in a higher range in some parts of the lake system [91,93]. This difference indicates that the AALS is not hydrologically homogeneous, that is, the effects of water exchange, evaporation and drainage waters are different in the Aydarkul, Arnasay and Tuzkan sections.

The negative impacts of AALS are not limited to water quality. Changes in lake levels also affect the surrounding agro-irrigated landscapes. For example, rising water levels in areas around AALS can lead to groundwater rise and secondary salinization, while decreasing water levels increase the risk of dry salt flats, wind erosion, and dust-salt transport [95]. Studies on the degradation of agro-landscapes near AALS have shown that there is a two-way interaction between the lake and irrigated lands: irrigated lands affect the lake through drainage water, and lake levels affect agricultural lands through groundwater and soil salinization [95].

The issue of methane emissions has not yet been sufficiently studied in AALS. However, international studies show that lakes and wetland ecosystems can be important sources of CH, CO, and NO emissions [96]. This is especially true in areas with high organic matter, anaerobic conditions, and high water temperatures. The lack of specific field measurements in this area in the AALS should be highlighted as a separate scientific gap in the review article.

8. Existing problems and scientific gaps

Although existing studies on the Aidar-Arnasay lake system cover water balance, mineralization, hydrochemistry, landscape transformation, and GIS monitoring, they have not yet reached the level of a single integrated hydroecological model. The most important part of this review article is precisely this: to clearly show what existing studies have solved, what methods have been used, what results have been obtained, and what gaps remain [97]. It has been emphasized that the assessment of the AALS water balance is important for fisheries, ecotourism, and the effective use of water resources, but the existing models are often not fully integrated with ecological thresholds, climate scenarios, and uncertainty analysis [97].

Table 6. Key scientific gaps in the AALS and Central Asian lakes.

Lack of knowledge	Current situation	Why it matters	Future solution
Long-term monitoring	Insufficient continuous annual data	Trend and forecast reliability decreases	Satellite + field monitoring database
Calibration deficiency	Lack of field data for SWAT/WEAP/MIKE SHE	Model error is high	Multi-source calibration
Ecohydrological integration	Hydrology and ecology are analyzed separately	Ecosystem response is not visible	Coupled hydro-ecological model
Climate scenarios	SSP/RCP scenarios are rarely used	Future risk is not assessed	Climate-resilient water balance
GIS–AI integration	NDWI is available, AI is rarely used	No prediction maps	RF, XGBoost, LSTM
Uncertainty analysis	NSE, RMSE and sensitivity are rarely used	Results are uncertain	Monte Carlo, SUFI-2, GLUE
Collector–drainage quality	Hydrochemical monitoring is limited	Salinity and pollution risk are uncertain	Seasonal water quality network
Methane/greenhouse gases	Almost none for AALS	Climate feedback is not assessed	CH_4/CO_2 flux monitoring

The first problem in the existing studies is the lack of long-term monitoring. In a dynamic lake system like the AALS, water level, water surface area, mineralization, collector-drainage water composition, groundwater level and biological indicators should be monitored over a long period of time. However, the literature analysis shows that the data are often limited to a short period, a single area or some parameters [97]. Indicators such as Nash–Sutcliffe Efficiency (NSE), RMSE, MAE and $R^2 areusedtoassessthequalityofcalibration$[98]$.TheformulaNash\breve{}SutcliffeEfficiency$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{\text{obs},i} - Q_{\text{sim},i})^2}{\sum_{i=1}^{n}(Q_{\text{obs},i} - \overline{Q}_{\text{obs}})^2} \tag{11}$$

where Q_{obs} is the observed flow (or water level), Q_{sim} is the simulated value, and $\overline{Q}_{\text{obs}}$ is the mean of the observed values.

Table 7. Model evaluation indicators for the review article.

Indicator	Formula	Application
NSE	$1 - \frac{\sum(Q_o - Q_s)^2}{\sum(Q_o - \overline{Q_o})^2}$	Hydrological model calibration
RMSE	$\sqrt{\frac{1}{n}\sum(y_i - \hat{y}_i)^2}$	Error estimation
R^2	$1 - \frac{SS_{res}}{SS_{tot}}$	Level of agreement

The third major gap is the lack of an integrated ecohydrological model. In AALS studies, water balance, mineralization, biodiversity, and landscape transformation were studied separately. However, to assess ecosystem stability, the chain of water level → mineralization → habitat condition → biodiversity response → fishery productivity should be linked in a single model. This requires a coupled hydrodynamic–water quality–ecological modeling approach [99].

The fourth problem is the lack of climate adaptation scenarios. International review articles have shown that climate change, temperature increase, drought, water resource scarcity, and desertification processes are intensifying in Central Asia [100]. However, specific models that predict water level, evaporation, mineralization, and biodiversity risks based on SSP/RCP scenarios up to 2030, 2050, or 2100 are still insufficient for AALS.

Future promising directions

Future research on AALS should move from classical water balance calculations to integrated digital hydroecology. This requires the integration of AI + GIS, remote sensing, IoT monitoring, digital twin lake systems, climate-resilient modeling, and coupled hydrodynamic-ecological modeling approaches. The current international trend shows that lake ecosystems are being modeled not only as hydrological objects, but also as data-driven, climate-sensitive, and management-oriented complex systems [99,100].

One of the most promising directions for AALS is the integration of AI + GIS. NDWI, NDVI, LST, ET, and land use layers are obtained from Sentinel-2, Landsat, and MODIS data; then, water level, salinity, water surface change, and ecological risk are predicted using Random Forest, XGBoost, ANN, or LSTM models. This method better captures spatial patterns and nonlinear relationships than classical hydrological models.

Remote sensing-based monitoring should be further strengthened. For AALS, long-term lake surface dynamics can be generated based on Landsat 1985–2024 images, Sentinel-2 2015–2025 images, and MODIS ET/LST products. A recent GIS study in 2026 proposed combining Landsat, DEM, EVI, NDWI, and LST indices to assess AALS landscape transformation [100]. This approach appears very strong as a future direction in the review article.

Digital twin lake system could be the most innovative approach for AALS in the next stage. Digital twin is a digital dynamic model of a real lake system that combines satellite data, IoT sensors, hydrological models, AI prediction, and decision support modules. A digital twin for AALS can monitor the following parameters in real-time or near-real-time: water level, salinity, water temperature, dissolved oxygen, pH, collector-drainage water discharge, NDWI-based water surface, LST, and evaporation pressure.

IoT monitoring is also an important promising direction. If automatic sensor stations are installed in the AALS, water level, EC/TDS, pH, DO, temperature and flow velocity will be continuously monitored. This data can be sent to a cloud database, and risk alerts, salinity warnings and water balance forecasts can be generated through AI analysis. Such a monitoring system will be of practical importance in water resource management, fisheries protection and determining ecological flow requirements.

The most promising scientific direction for the AALS in the future is coupled hydrodynamic–ecological modeling. In this case, the hydrological block calculates water inflow, outflow, evaporation and water level; the hydrochemical block assesses mineralization, nutrient load and pollution; and the ecological block models wetland area, fish habitat, bird habitat and biodiversity indicators. This approach can be presented as the main scientific conclusion of the review article: a separate water balance model is not enough for sustainable management of the AALS, but an integrated hydroecological-digital monitoring platform is required.

Discussion

The analyzed literature and hydroecological data show that the Aydar-Arnasay lake system is one of the most complex anthropogenic-hydrological ecosystems in Central Asia. The formation of the lake system and the current hydrological regime are mainly associated with the flow of the Syrdarya, discharges from the Chordara reservoir and collector-drainage networks, and it can be assessed as a “managed hydroecosystem” unlike natural lakes. This means that the stability of the AALS is strongly dependent on transboundary water management policies in addition to natural climatic factors.

The water balance analysis in the studies showed that evaporation is the main loss component in the AALS. The data reconstructed based on the MODIS ET and FAO Penman–Monteith approaches revealed that evaporation pressure has been increasing in recent years. This is consistent with the global warming trends noted in the IPCC reports. Gradual temperature increases, arid climate and high radiation can accelerate water loss in the AALS. If the volume of the Syrdarya and collector-drainage inflow decreases, this situation is likely to lead to a decrease in the lake level and an increase in mineralization. The analysis of the salinity risk trend showed that mineralization in the lake ecosystem is gradually increasing. This situation is explained by the imbalance between dissolved salts entering through the collector-drainage waters and high evaporation. Some studies have noted that the mineralization of the AALS varies in the range of 3–8 g/L, and this indicator may increase further in drought years. Increased mineralization may negatively affect aquatic biota, phytoplankton, fish, and coastal marsh ecosystems. From this point of view, it is important to strengthen hydrochemical monitoring in assessing the ecological stability of the AALS. Collector-drainage impact analyses have

shown that AALS has a dual nature. On the one hand, collector-drainage inflow ensures the existence of the lake system and maintains the water level. On the other hand, these waters carry salts, nitrates, pesticides and other agrochemicals into the lake. This can increase the risk of eutrophication, biodiversity decline and coastal degradation. Therefore, irrigation return flow management should be one of the main elements of sustainable management of AALS. Hydrological model comparison heatmap analyses showed that the effectiveness of SWAT, WEAP, MIKE SHE, MODFLOW and HEC-HMS models varies for different tasks. While SWAT showed superior results in terms of spatial hydrology and GIS integration, MIKE SHE was found to have the highest potential in the analysis of groundwater-lake interaction and evaporation dynamics. The WEAP model is a convenient platform for climate scenario analysis and water allocation planning. However, no single model can fully capture the hydrology, mineralization, biodiversity, and climate adaptation processes of the AALS. Therefore, the concept of hybrid hydroecological modeling was evaluated as the most promising approach.

GIS and remote sensing technologies have shown high efficiency in AALS monitoring. NDWI-based water surface dynamics assessment, shoreline change analysis, and seasonal water fluctuation monitoring allowed for rapid and large-scale monitoring of changes in the lake system. It was found that it is possible to analyze water surface dynamics for the period 1985–2025 using Sentinel-2 and Landsat archive data. This approach is very important in conditions where traditional hydropost data are limited.

AI–GIS prediction framework analysis showed that machine learning technologies have high prospects for AALS. Random Forest, ANN, and LSTM models can be used for water level forecasting, salinity prediction, and ecosystem risk mapping. In particular, AI models integrated with GIS spatial layers and remote sensing data can provide high accuracy in identifying ecological vulnerability zones. However, the lack of training datasets and long-term hydroecological monitoring data remains a major limitation of AI models.

The concept of digital twin architecture has been evaluated as a new and promising direction for AALS. The digital twin platform enables real-time ecosystem management by integrating sensor networks, GIS, hydrological models, and AI prediction blocks. This approach is of great importance for drought monitoring, ecological early warning, and adaptive water management. However, real-time sensor infrastructure, automatic monitoring stations, and data sharing platforms in Central Asia are not yet sufficiently developed.

Overall, studies have shown that an integrated approach is necessary to ensure the sustainability of AALS. A hydrological model or ecological assessment alone is not enough. A hybrid hydroecological framework combining GIS, remote sensing, hydrological models, AI prediction, climate scenarios, and ecosystem indicators is required for sustainable management. This approach allows us to assess the AALS not only as a hydrological object, but also as a strategic ecological and socio-economic system in Central Asia.

Conclusion

The Aidar-Arnasay lake system is one of the largest and most hydro-ecologically complex artificial-natural wetland ecosystems in Central Asia. The analysis has shown that the current state of the AALS is being shaped by the Syrdarya basin, the Chordara reservoir, collector-drainage networks, high evaporation, and climate change. Although the lake system simultaneously performs the functions of biodiversity conservation, fisheries, recreation, and regional microclimate regulation, it faces threats such as water scarcity, increased mineralization, and collector-drainage pollution.

The results of the study showed that water balance models are the main tool in assessing AALS. Models such as SWAT, WEAP, MIKE SHE, MODFLOW and HEC-HMS can effectively perform certain hydrological tasks, but each of them has certain limitations. Therefore, the hybrid hydroecological modeling approach was evaluated as the most promising concept. GIS and remote sensing technologies showed high efficiency in monitoring water surface dynamics, evaporation pressure, shoreline change and salinity zones. Sentinel-2, Landsat and MODIS data were found to serve as important information sources for long-term spatial-temporal monitoring. AI and machine learning technologies were shown to have great potential for ecosystem risk assessment, salinity prediction and water balance forecasting in AALS. In particular, AI models integrated with GIS spatial layers can be an important tool for ecological vulnerability mapping and climate adaptation planning. At the same time, the lack of long-term monitoring datasets and the underdevelopment of sensor infrastructure remain one of the main limitations for the region.

The digital twin concept was assessed as a promising direction for managing the AALS based on real-time monitoring and adaptive ecosystem management. A digital system that combines sensor networks, hydrological models, GIS platforms, and AI predictions will allow for the effective organization of ecological early warning, drought adaptation, and sustainable water allocation processes. This approach may be of great importance in the future formation of climate-resilient hydroecological management systems in Central Asia.

In general, an integrated hydroecological approach is required for sustainable management of the AALS. It is not enough to maintain only water volume; it is necessary to simultaneously take into account biodiversity, water quality, salinity control, collector-drainage management, and transboundary water policy. The development of GIS–AI–hydrological modeling platforms, climate scenario simulation, ecological threshold analysis, and real-time monitoring networks will remain a

relevant scientific direction in future research. The results obtained provide an important scientific basis for preserving the AALS ecosystem, reducing environmental risks, and sustainable management of water resources in Central Asia.

Authors’ contribution

S.S.: Conceptualization; Literature review; Methodology; Data collection; Formal analysis; Visualization; Writing – original draft. L.S.: Supervision; Methodology; Scientific consultation; Writing – review editing. Kh.J.: Visualization; Data interpretation; Writing – review editing. All authors have read and approved the final published version of the manuscript.

Ethics approval

Not applicable. This study did not involve human participants or animals.

Data Availability Statement

The data supporting the findings of this review are available from the corresponding author upon reasonable request. The study was based on published scientific literature, satellite products (Landsat, Sentinel-2, MODIS), meteorological observations, and publicly available datasets used for hydroecological analysis of the Aydar-Arnasay Lake System. All cited data sources are referenced in the manuscript.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this manuscript.

Table 8. List of abbreviations used in the manuscript.

Abbreviation	**Definition**
AALS	Aydar–Arnasay Lake System
AI	Artificial Intelligence
DEM	Digital Elevation Model
ET	Evapotranspiration
FAO	Food and Agriculture Organization
GEE	Google Earth Engine
GIS	Geographic Information System
IoT	Internet of Things
LST	Land Surface Temperature
MODFLOW	Modular Groundwater Flow Model
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
SWAT	Soil and Water Assessment Tool
WEAP	Water Evaluation and Planning System

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