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Ecological Water Demand and Near-Natural Water-Replenishment Schemes for Wetlands in Semi-Arid Regions

Mingze Xiao [1,2,3], Fangli Su [1,2,3], Di Wang [1,2,3], Zining Wang [1,2,3], Pengxing Su [1,2,3], Hao Xu [4], Fei Song [1,2,3], Chao Wei [1,2,3], Haifu Li [1,2,3] and Shuang Song [1,2,3,*]

[1] College of Water Conservancy, Shenyang Agricultural University, Shenyang 110866, China; 2025220066@stu.syau.edu.cn (M.X.); sufangli@syau.edu.cn (F.S.); wangdi@syau.edu.cn (D.W.); wangzining@stu.syau.edu.cn (Z.W.); 2025220063@stu.syau.edu.cn (P.S.); songfei@syau.edu.cn (F.S.); weichao@syau.edu.cn (C.W.); syaulhf@syau.edu.cn (H.L.)
[2] Liaoning Panjin Wetland Ecosystem National Observation and Research Station, Shenyang 110866, China
[3] Liaoning Shuangtai Estuary Wetland Ecosystem Research Station, Panjin 124112, China
[4] College of Engineering, Ocean University of China, Qingdao 266404, China; xuhaohao@stu.ouc.edu.cn
* Correspondence: songshuang5@syau.edu.cn

Abstract

Semi-arid wetlands are highly sensitive to changes in hydrological regimes, as strong evaporation often exceeds limited natural recharge. Ecological water replenishment is widely used to restore these systems, but schemes designed only to meet water-volume targets may cause excessive hydrodynamic disturbance, promote sediment resuspension, and increase the release of internal pollutants. In this study, we developed an ecological water-replenishment assessment framework for Chahannaoer Wetland that incorporates ecological water-demand thresholds, suspended-solids disturbance, and an AHP–entropy weight–TOPSIS decision model. Using hydrological and meteorological data from 2014 to 2024, six replenishment scenarios were evaluated in terms of water-balance recovery, disturbance control, and habitat suitability. The results show that Chahannaoer Wetland experienced a persistent evaporation-dominated water deficit. The mean annual natural recharge was 0.225×10^8 m^3, with a mean annual ecological water shortage of 1.03×10^8 m^3 and an evapotranspiration-to-recharge ratio of 3.42–4.56. Based on the previous comprehensive water-quality assessment using DO, COD, NH_3-N, TN, and TP, the minimum water volume required to maintain Class IV water quality was 0.86×10^8 m^3, whereas the suitable ecological water demand ranged from 1.27×10^8 to 1.56×10^8 m^3. With the total replenishment volume held constant, centralized replenishment met the required water volume but substantially increased near-bed disturbance and sediment resuspension risk. By contrast, decentralized uniform replenishment performed best, with the highest relative closeness coefficient of 0.9105, a disturbance index of approximately 0.32, and water depths maintained within the suitable habitat range of 30–50 cm. These findings suggest that ecological restoration in semi-arid wetlands should move beyond volume-based water supplementation and pay greater attention to the timing, pathway, and hydrodynamic effects of replenishment. The proposed framework provides a quantitative basis for optimizing ecological water replenishment in evaporation-dominated wetlands and other inland lakes in arid and semi-arid regions.

Keywords: Chahannaoer Wetland; near-natural water replenishment; relict gull; ecological threshold; scheme evaluation

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1. Introduction

Inland wetlands regulate regional hydrological processes, sustain biodiversity, and buffer local climatic variability [1]. In semi-arid regions, terminal lakes are increasingly destabilized by climate warming and intensified water withdrawals, which together drive hydrological contraction, salinization, and habitat degradation [2]. These shallow endorheic systems depend largely on episodic runoff recharge but lose substantial water through evaporation, leaving their water balance highly sensitive to climatic variability and external water regulation [3]. As lake levels decline, exposed sediments become sources of salt accumulation and potential internal pollution, while the fragmentation of aquatic and littoral habitats reduces the capacity of wetlands to support waterfowl breeding and regional biodiversity [4,5]. Restoring degraded wetlands in semi-arid regions therefore requires not only sufficient ecological water supplementation, but also effective control of hydrodynamic disturbance induced by the replenishment process.

Ecological water demand defines the minimum hydrological condition required to sustain wetland structure, ecosystem processes, and key habitat functions [6]. Its quantification has commonly relied on water-balance, water-exchange, and ecological-function approaches, each emphasizing different hydrological processes and ecological requirements. Water-balance methods estimate demand from the equilibrium between inflows and losses, but their reliability is often constrained by uncertainties in runoff, seepage, and evaporation dynamics [7,8]. Water-exchange methods capture water-renewal requirements and hydrological connectivity, yet they provide limited representation of intra-annual variation in habitat and vegetation water demand. Ecological-function methods offer a more process-oriented alternative by integrating vegetation evapotranspiration, habitat maintenance, and open-water evaporation. This integrated approach is particularly suitable for degraded semi-arid wetlands, where ecological water demand is shaped not only by volumetric deficits, but also by habitat maintenance, vegetation water use, and ecosystem stability [9,10]. For example, using a wetland restoration project in western Jilin Province, China, as a case study, Xu et al. estimated suitable ecological water demand under different historical restoration scenarios using the ecological-function method and showed that wetland area, precipitation, evapotranspiration, and other environmental factors jointly influenced changes in wetland ecological water demand [11].

Ecohydrological research has moved beyond water-quantity regulation and now places greater emphasis on the interactions among hydrological processes, ecological responses, and human activities in ecosystem restoration [12]. This development has encouraged the use of multi-source monitoring and integrated modelling across different spatial and temporal scales. However, conventional static estimates of ecological water demand often fail to capture the dynamic relationships among water quantity, water level, water quality, and habitat response during wetland restoration. Evidence from large North American basins and inland lakes in Central Asia also shows that maintaining water levels alone is not sufficient to ensure long-term ecosystem stability [13]. Artificial replenishment can further alter local hydrodynamic conditions, resuspend bed sediments, and promote the release of internal pollutants, thereby reducing the expected improvement in water quality [14].

Ecological thresholds are therefore essential for interpreting wetland responses to replenishment. Water depth, water-level fluctuation, and water-renewal rate influence nutrient transport, vegetation succession, and waterfowl habitat suitability, and thus serve as key indicators of wetland functional stability [15]. Existing multi-criteria decision-making methods, however, still depend heavily on subjective weighting and pay insufficient attention to physical processes such as hydrodynamic disturbance and sediment stability. This limitation calls for an assessment approach that links ecological water demand with hydrodynamic thresholds and habitat requirements in wetland replenishment planning [16].

Despite substantial progress in estimating wetland ecological water demand, applying these estimates to practical replenishment planning remains challenging under complex and variable hydrological conditions. Many existing studies rely on short observational records, which limits their ability to account for the effects of long-term climatic variability on ecological water requirements. They also tend to focus on static water-demand estimation, while the adaptive evaluation of alternative replenishment scenarios remains underdeveloped. In addition, conventional multi-criteria evaluation frameworks often emphasize weighting schemes but give limited consideration to hydrodynamic disturbance, sediment stability, and habitat suitability. These limitations indicate the need for a replenishment-assessment framework that integrates long-term hydrological change, ecological water-demand thresholds, and physically based constraints.

Chahannaoer Wetland, located in the transition zone between the Inner Mongolia Plateau and the mountainous region of northern Hebei Province, is a typical precipitation-fed, salinized shallow lake wetland in a semi-arid region [17]. It also provides important breeding habitat for the globally endangered Relict Gull (Larus relictus). Under a prolonged negative water balance, the wetland has experienced sustained surface-area shrinkage and ecological degradation. Restoration efforts are further constrained by uncertainties in ecological water demand, inefficient water-regulation strategies, and the lack of a quantitative basis for optimizing ecological replenishment [18].

Here, we develop a hydrodynamically constrained ecological replenishment framework for Chahannaoer Wetland, a representative semi-arid inland wetland, using multi-source hydrometeorological data from 2014 to 2024. The framework couples ecological water-demand thresholds, water-balance processes, and hydrodynamic constraints to test three research questions:

(1) Chahannaoer Wetland has remained in an evaporation-dominated negative water-balance state, and a substantial quantitative gap exists between natural recharge and ecological water demand;
(2) Ecological water demand is governed by multiple threshold components related to habitat maintenance, vegetation transpiration, lake evaporation–seepage loss, and water-quality dilution;
(3) Replenishment configuration, rather than replenishment volume alone, significantly affects hydrodynamic disturbance, sediment resuspension risk, and habitat suitability.

Accordingly, this study quantifies ecological water-demand thresholds and interannual replenishment deficits, characterizes the long-term evolution of wetland water balance, and identifies an ecological replenishment strategy that integrates hydrological stability, water-quality regulation, and habitat suitability across multiple scenarios.

2. Overview of the Study Area and Data Sources

2.1. Overview of the Study Area

The Chahannaoer Wetland (113°13′03″–114°26′12″ E, 41°05′12″–42°03′24″ N) straddles the border between Shangdu County in the Inner Mongolia Autonomous Region and Shangyi County in Hebei Province, China. Positioned in the transition zone between the Inner Mongolia Plateau and the mountainous region of northern Hebei (Figure 1), the wetland is a typical precipitation-fed, salinized shallow lake wetland in a semi-arid region [19]. The region is characterized by a temperate continental climate, with mean annual precipitation of approximately 321.8 mm, strong seasonal variability in rainfall, and potential evapotranspiration that substantially exceeds precipitation. Wetland hydrology is sustained by precipitation, episodic surface runoff, and groundwater inflow, with direct precipitation serving as the primary recharge source [20]. In recent decades, climatic vari-

ability and intensive human water use have jointly driven a marked contraction of the lake surface area, intensifying lakebed exposure, soil salinization, and ecosystem degradation [2]. The wetland supports distinctive biological assemblages, including emergent macrophyte communities dominated by Phragmites australis and isolated sandbars that provide critical breeding habitat for the globally endangered Relict Gull (Larus relictus) [13,21]. These biotic components are highly sensitive to water-level fluctuation, sediment-resuspension-induced turbidity, and habitat fragmentation. Ecological restoration in Chahannaoer therefore requires more than volume-based water supplementation; it also depends on regulating hydrodynamic disturbance, maintaining water clarity, and sustaining suitable water depths for nesting and foraging habitats.

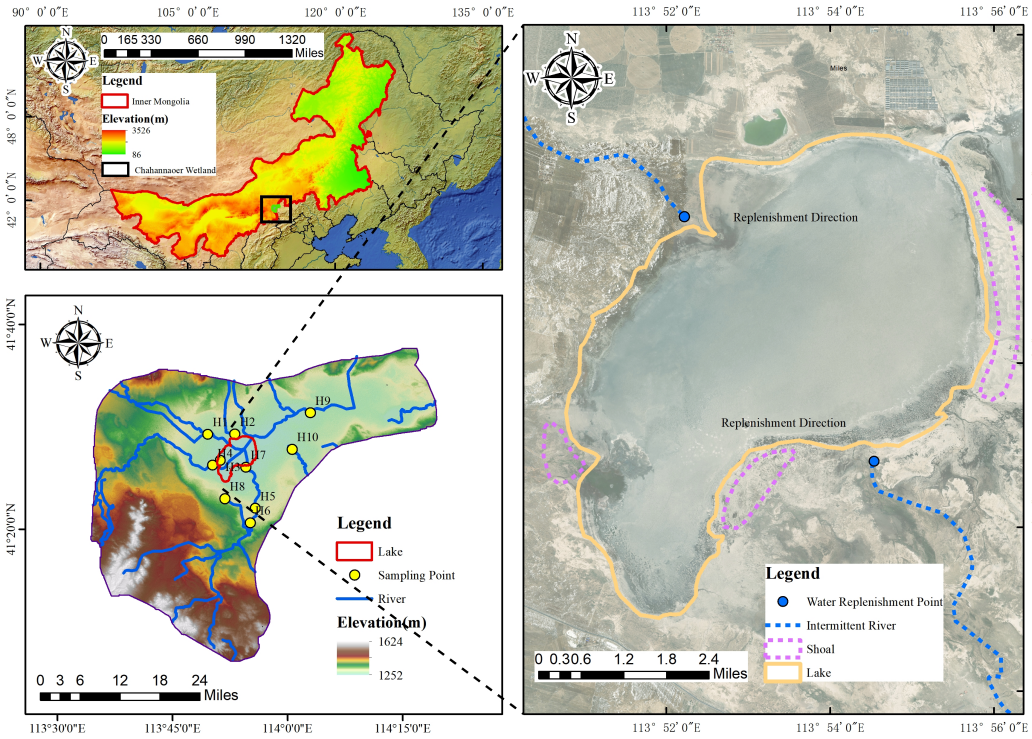


Figure 1. Location of the Chahannaoer Wetland and its surrounding hydrological setting.

2.2. Wetland Water-Balance Model

The hydrological budget of Chahannaoer Wetland was quantified using a wetland water-balance model based on mass conservation [22]. Over a given time interval, the change in wetland water storage was calculated as the difference between total inflows and total outflows. The model is expressed as

$$\Delta V = P_{in} - (E_{water} + T_{veg} + S_{leak}) \quad (1)$$

where ΔV denotes the change in wetland water storage (m^3); P_{in} denotes the long-term mean natural inflow to the lake. Considering that surface runoff is strongly regulated by upstream reservoirs and that stable groundwater recharge has been weakened by regional groundwater-level decline [23], P_{in} in this study mainly refers to rainfall recharge; E_{water} denotes lake-surface evaporation loss (m^3); T_{veg} denotes vegetation transpiration water consumption (m^3), with Phragmites australis used as the representative species; and S_{leak} denotes groundwater leakage loss from the lake area (m^3).

Lake-surface evaporation was calculated from observed evaporation data and water-surface area. Vegetation transpiration was estimated using Phragmites australis as the representative species. Groundwater leakage was calculated using Darcy's law:

$$Q = K \times i \times A \tag{2}$$

where Q is the seepage flux ($m^3\ d^{-1}$); K is the hydraulic conductivity ($m\ d^{-1}$); i is the hydraulic gradient; and A is the cross-sectional area perpendicular to the flow direction (m^2). In this study, K was set to 0.17 $m\ d^{-1}$, mainly based on the silty loam texture of the Chahannaoer lake area and typical hydraulic conductivity values for comparable soils. The hydraulic gradient i was set to 1%, based on regional groundwater-gradient data. The cross-sectional area A was set to 50.8 km^2, primarily according to remote-sensing interpretations of the Chahannaoer lake–marsh area, lake-basin boundary, and potential seepage-control zone from the research team's previous work.

2.3. Ecological Water Demand Accounting Method

2.3.1. Water Requirement of Biological Habitat

Habitat water requirement was defined as the water volume needed to maintain suitable inundated area and water-depth conditions for waterbirds and other wetland organisms [24]. It was calculated as follows:

$$W_q = A \times b \times h \tag{3}$$

where W_q is the habitat water requirement (m^3), A is the total lake area (m^2), b is the proportion of flooded area, and h is the suitable water depth (m). According to wetland habitat-maintenance requirements and relevant studies, inundation over 40–50% of the total wetland area is generally favorable for sustaining biological habitat conditions. Accordingly, the inundated-area proportions were set to 40% and 50% for the minimum and suitable ecological water-demand scenarios, respectively. The corresponding representative water depths were set to 0.5 m and 1.0 m, respectively; these values can satisfy the general shallow-water habitat requirements for reed growth as well as fish growth and reproduction, and they fall within the observed water-depth range of Chahannaoer Wetland.

2.3.2. Vegetation Transpiration Water Requirement

Vegetation transpiration water requirement was estimated using the FAO crop-coefficient method [25]:

$$W_p(t) = \int_0^t \sum_{i=1}^{n} (K_{ci} \times ET_0 \times A_{pi})\, dt \tag{4}$$

where K_{ci} is the crop coefficient of reed at different growth stages, with values of 0.9, 1.2, and 0.7 for the initial, middle, and late stages, respectively; ET_0 is the reference crop evapotranspiration; and A_{pi} is the reed distribution area.

Reference crop evapotranspiration (ET_0) was calculated using the FAO Penman–Monteith equation:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{5}$$

where R_n is net radiation ($MJ\ m^{-2}\ d^{-1}$), G is soil heat flux ($MJ\ m^{-2}\ d^{-1}$), T is average temperature (°C), u_2 is wind speed at 2 m height ($m\ s^{-1}$), $e_s - e_a$ is the saturated water

vapor pressure difference (kPa), Δ is the slope of saturated water vapor pressure curve, and γ is the psychrometric constant.

2.3.3. Evaporation Leakage Water Requirement of Lake

The lake evaporation–seepage water requirement includes surface evaporation loss and groundwater seepage loss. Surface evaporation loss was estimated as follows:

$$W_z = E \times A_t \times \beta \times 10^{-3} \quad (6)$$

where W_z is the net evaporation loss of the water body during the calculation period (m^3), E is the evaporation depth during the calculation period (m), A_t is the mean water surface area during the calculation period (m^2), and β is the evaporation conversion coefficient.

Groundwater seepage was estimated using Darcy's law, as expressed in Equation (2). The total ecological water requirement of the wetland was then obtained by summing habitat water demand, vegetation transpiration demand, and evaporation–seepage demand [26].

2.3.4. Water-Quality Dilution Requirement

This study further introduced the minimum dilution water volume required to maintain Class IV water quality. The water-quality target was determined according to the Environmental Quality Standards for Surface Water (GB3838–2002), with dissolved oxygen (DO), chemical oxygen demand (COD), ammonia nitrogen (NH_3-N), total nitrogen (TN), and total phosphorus (TP) considered comprehensively. Among these indicators, DO reflects oxygen availability and basic habitat conditions; COD and NH_3-N indicate organic pollution and recent pollution inputs; and TN and TP represent nutrient loading and the risk of eutrophication.

The water-quality dilution demand was estimated using a complete-mixing dilution model:

$$W_{dil,j} = V_0 \frac{C_{0,j} - C_{IV,j}}{C_{IV,j} - C_{in,j}} \quad (7)$$

where $W_{dil,j}$ is the dilution water volume required for the j-th pollutant indicator to meet the Class IV water-quality target; W_{dil} is the total water-quality dilution requirement; V_0 is the current water volume; $C_{0,j}$ is the current concentration of the j-th indicator in the water body; $C_{IV,j}$ is the Class IV standard limit for the j-th indicator; and $C_{in,j}$ is the concentration of the j-th indicator in the replenishment water source. When $C_{0,j} < C_{IV,j}$, the indicator does not impose a dilution constraint, and $W_{dil,j}$ is set to 0.

Because the same replenishment volume can simultaneously dilute multiple pollutants, the total water-quality dilution requirement was defined as the maximum dilution water volume required among the pollutant indicators, rather than the sum of the individual dilution volumes. Thus:

$$W_{dil} = \max(W_{dil,j}) \quad (8)$$

2.4. Scenario Design and Evaluation Framework for Ecological Water Replenishment

To evaluate the effects of different replenishment regimes and water-conveyance pathways on hydrodynamic disturbance, water-quality response, and habitat stability in the wetland, six ecological water-replenishment scenarios were developed under the same ecological water-demand constraint. The six scenarios were generated by combining three replenishment regimes with two water-conveyance pathways. Temporally, the regimes included concentrated short-duration replenishment, adaptive replenishment, and uniform replenishment. Spatially, the pathways included replenishment through the main Daqing River channel and replenishment through the Bolihujing River–reclaimed water auxiliary pathway.

Considering both cost-type and benefit-type indicators, this study calculated the suspended-solids disturbance index, vegetation coverage, dissolved oxygen concentration, and total replenishment volume [27]. The AHP–entropy weight–TOPSIS method was then used to comprehensively evaluate the six ecological water-replenishment scenarios.

The suspended-solids disturbance index can be expressed as follows:

$$D_{SS} = \frac{\sigma_{SS}}{\overline{SS}} \tag{9}$$

where D_{SS} denotes the suspended-solids disturbance index, and σ_{SS} and $\overline{SS}$ represent the standard deviation and mean concentration of suspended solids during the replenishment process, respectively.

The AHP–entropy weight–TOPSIS method was used to comprehensively evaluate the six ecological water-replenishment scenarios. First, the analytic hierarchy process (AHP) was applied to determine subjective weights. Pairwise comparisons among indicators were based on their relative importance for wetland restoration objectives, including disturbance control, habitat maintenance, water-quality improvement, and replenishment-scale constraint.

The entropy weight method (EWM) was then introduced to calculate objective weights, reflecting the dispersion degree and information contribution of each indicator across the six scenarios. The AHP weights represent expert judgment on wetland restoration objectives, whereas the entropy weights reflect the differentiation capacity of the data matrix. The two weights were combined through multiplicative normalization:

$$W_j = \frac{w'_j \cdot g_j}{\sum_{j=1}^{n}(w'_j \cdot g_j)} \tag{10}$$

where w'_j denotes the AHP-derived subjective weight, and g_j denotes the entropy-based difference coefficient.

After the combined weights were obtained, the TOPSIS method was then applied to calculate each scheme's distance from the positive and negative ideal solutions, and the schemes were ranked by their relative closeness coefficients to identify the optimal water-replenishment scheme [28].

2.5. Data Source

A multi-source dataset integrating meteorological, hydrological, remote-sensing, and field-monitoring data was compiled for this study (Table 1). Meteorological and hydrological data were mainly obtained from the China Meteorological Data Service Centre and long-term hydrological yearbooks. Daily meteorological variables, basin runoff, and inflow recharge data from 2014 to 2024 were extracted to support water-balance analysis and ecological water-demand estimation. Landsat 8 and Sentinel-2 images were used to delineate the lake water surface area and the spatial distribution of major vegetation communities, including Phragmites australis, providing the spatial basis for estimating habitat water demand and vegetation transpiration demand. To improve the reliability of water-environment parameters, representative sampling sites were established in 2024, where water samples were collected and indicators such as suspended solids (SS), dissolved oxygen (DO), chemical oxygen demand (COD), ammonia nitrogen (NH_3-N), total nitrogen (TN), and total phosphorus (TP) were measured. These data were used to characterize water-quality responses and sediment resuspension risk under different replenishment scenarios. Together, the datasets supported the construction of the water-balance model, the identification of ecological water-demand thresholds, and the AHP–entropy weight–TOPSIS comprehensive evaluation framework.

Table 1. Data sources, variables, and spatiotemporal resolution used in this study.

Data Type	Variables	Unit	Source	Time Range	Temporal Resolution	Spatial Resolution
Meteorological data	Precipitation, air temperature, relative humidity, wind speed, sunshine duration	mm, °C, %, m/s, h	China Meteorological Data Service Centre	2014–2024	Daily	Station-based
Hydrological data	River runoff and lake inflow	m^3/s; converted to m^3	Hydrological Yearbook of the P.R. China	2014–2024	Monthly/Annual	Basin scale
Remote-sensing data	Lake water-surface area, exposed lakebed area, reed distribution, vegetation coverage	km^2, %	Landsat 8 and Sentinel-2 imagery	2014–2024	Seasonal/Annual	10–30 m
Field water-quality data	SS, DO, COD, NH_3-N, TN, TP	mg/L	Field monitoring and laboratory analysis	2024	Sampling period/Seasonal	Sampling sites
Seepage parameters	K, i, A	m/d, %, km^2	Soil texture, regional hydrogeological data, and lake geometry estimation	Parameter estimation	Static parameter	Lake area
Scenario design parameters	Water source, replenishment timing, routing, replenishment volume	m^3 or 10^8 m^3	Ecological water-replenishment scenario design	Scenario period	Scenario scale	Scenario scale

2.6. Multi-Source Data Integration and Model-Coupling Workflow

To improve the comparability of multi-source data and clarify the linkage among ecological water-demand estimation, replenishment-scale determination, and scenario evaluation, a workflow integrating model coupling and temporal-scale harmonization was established (Figure 2). First, meteorological, hydrological, remote-sensing, and field-monitoring data were standardized to consistent temporal scales. Daily meteorological data were aggregated to monthly and annual scales, hydrological runoff data were converted into annual natural recharge, and remote-sensing images were used to obtain lake-surface area and reed-distribution information. Field-monitoring data were used to characterize suspended solids, dissolved oxygen, and other water-quality indicators.

Second, the standardized datasets were coupled with the ecological water-demand accounting model, water-quality dilution model, and scenario-evaluation model. The water-balance model provided the natural recharge and water-deficit baseline; the ecological-function method estimated habitat, vegetation, and evaporation–seepage demands; and the water-quality dilution model provided the Class IV water-quality safety threshold. These outputs jointly constrained the target replenishment scale and were then used as input conditions for the scenario design. Finally, the AHP–entropy weight–TOPSIS model evaluated the six replenishment schemes by combining hydrodynamic disturbance, habitat response, water-quality response, and replenishment-volume constraints.

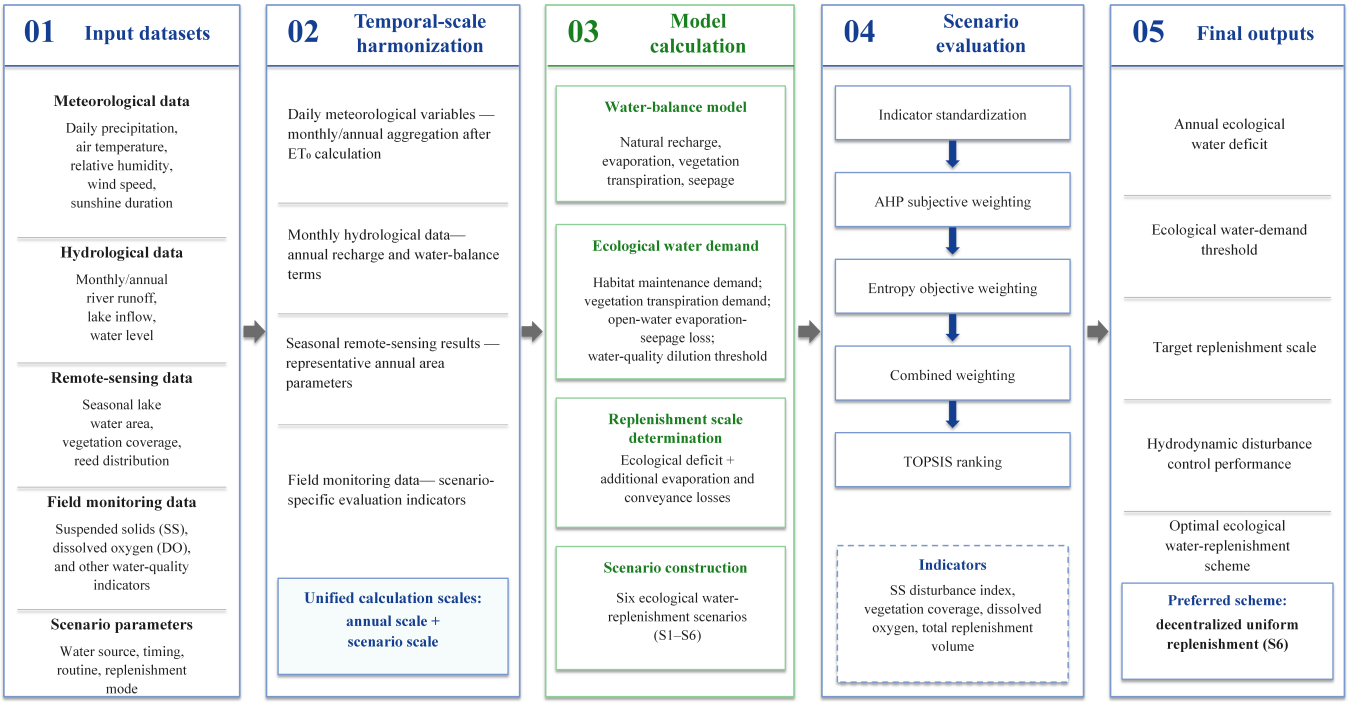


Figure 2. Workflow of multi-source data integration, temporal-scale harmonization, model coupling, and ecological water-replenishment scenario evaluation.

3. Results

3.1. Interannual Dynamics of Water Balance in Chahannaoer Wetland

From 2014 to 2024, the hydrological budget of Chahannaoer Wetland showed marked interannual variability, while the net water balance remained consistently negative (Figure 3). Mean annual natural recharge was 0.225×10^8 m^3, substantially lower than the mean annual water demand required to sustain basic ecological functions, which reached 1.033×10^8 m^3. The evapotranspiration-to-recharge ratio (ET/R) ranged from 3.42 to 4.56, indicating that evaporative losses greatly exceeded recharge inputs. In the representative dry year of 2023,

the deficit intensified further and was accompanied by a pronounced contraction of the lake surface area. Sustained water deficits have promoted progressive lakebed exposure and increased the risk of soil salinization. When natural recharge fell below the minimum dilution threshold required to maintain Class IV water quality, estimated at 0.86 × 10^8 m^3, the water-environment carrying capacity declined substantially. These results indicate that Chahannaoer Wetland is subject to a chronic evaporation-dominated water deficit, and that natural hydrological inputs alone are insufficient to maintain ecosystem stability.

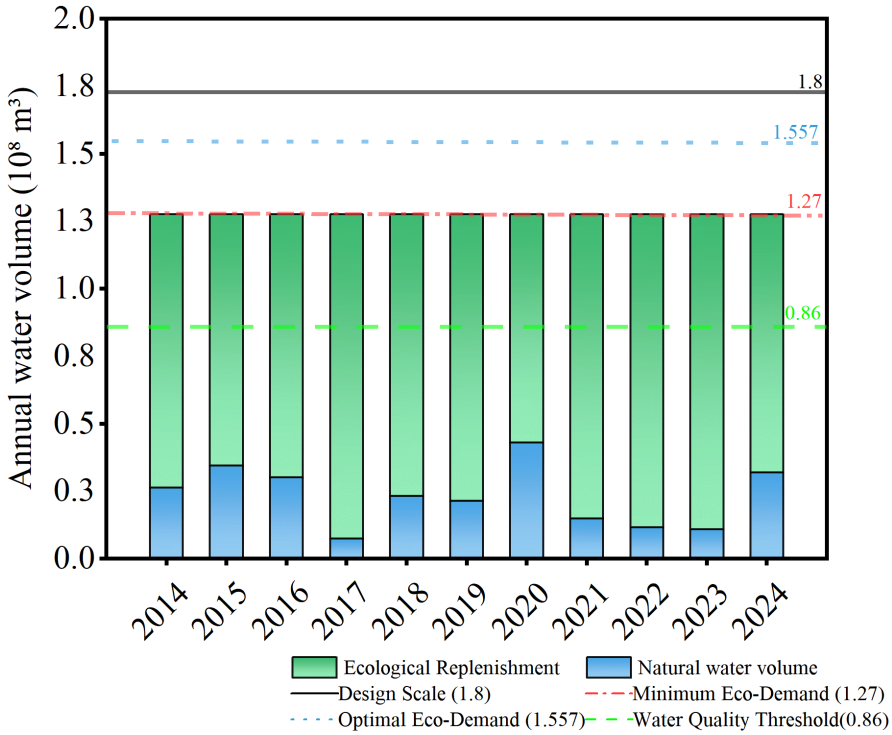


Figure 3. Annual natural water volume and ecological replenishment requirement in Chahannaoer Wetland during 2014–2024. Stacked bars represent annual natural water volume and the corresponding calculated ecological replenishment. Horizontal dashed lines denote the design water level, minimum ecological water demand, optimal ecological water demand, and water-quality dilution threshold.

3.2. Ecological Water Demand Accounting Results

The ecological-function method partitioned the ecological water demand of Chahannaoer Wetland into three components: habitat maintenance, vegetation transpiration, and open-water evaporation–seepage loss (Figure 4). The minimum water demand required to sustain basic wetland functions was estimated at 1.27 × 10^8 m^3, while the optimal demand for maintaining ecosystem stability was 1.56 × 10^8 m^3. Component-level results (Table 2) show that open-water evaporation and seepage were the dominant water-loss terms, with a combined demand of 0.899 × 10^8 m^3. Vegetation transpiration demand was estimated at 0.269 × 10^8 m^3 under the minimum-demand scenario and 0.404 × 10^8 m^3 under the optimal-demand scenario, reflecting the hydrological contribution of the Phragmites australis community. After incorporating water-quality constraints, the minimum dilution threshold required to maintain Class IV water quality was 0.86 × 10^8 m^3. Compared with the mean annual natural recharge of 0.225 × 10^8 m^3, the ecological replenishment deficit was approximately 1.03 × 10^8 m^3. These results indicate that artificial replenishment should be evaluated against both ecological water-demand thresholds and additional losses associated with in-lake evaporation, seepage, and water conveyance.

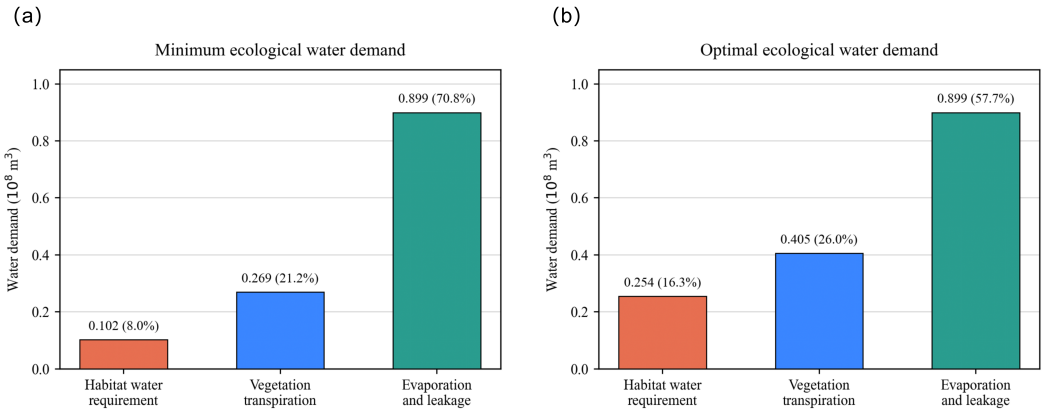


Figure 4. Components of ecological water demand in Chahannaoer Wetland under different ecological water-demand scenarios. (**a**) Minimum ecological water demand; (**b**) optimal ecological water demand. Bars represent the water demand of habitat water requirement, vegetation transpiration, and evaporation and leakage, and labels indicate the corresponding volume and percentage contribution.

Table 2. Components of ecological water demand in Chahannaoer Wetland.

Component	Minimum Demand (10^8 m^3)	Share of Minimum Demand (%)	Optimal Demand (10^8 m^3)	Share of Optimal Demand (%)
Habitat maintenance demand	0.102	8.03	0.254	16.31
Vegetation transpiration demand	0.269	21.18	0.404	25.95
Open-water evaporation–seepage loss	0.899	70.79	0.899	57.74
Total ecological water demand	1.27	100	1.557	100

3.3. Scenario Design for Near-Natural Ecological Water Replenishment

This study incorporated the concept of near-natural regulation into scenario design. By adjusting the timing of replenishment and the water-conveyance pathways, artificial replenishment was designed to approximate natural recharge in terms of hydrodynamic characteristics. Based on the water-balance analysis, ecological water-demand estimation, and water-quality dilution threshold, the target annual replenishment scale was set at approximately 1.8×10^8 m^3, considering the minimum dilution threshold of 0.86×10^8 m^3, the suitable ecological water demand of 1.56×10^8 m^3, and evaporation and conveyance losses. This scale does not represent the static water volume required to raise the lake level to a target elevation at one time. Rather, it represents an integrated annual water-volume constraint for habitat maintenance, water-quality dilution, evaporation–seepage compensation, and low-disturbance water delivery. The optimal water level was treated as an important boundary condition for controlling ecological restoration targets and replenishment intensity.

In terms of spatial configuration, the replenishment sources included the Daqing River, the Bolihujing River, and reclaimed water, forming a coordinated multi-source replenishment system. The main Daqing River channel represented the primary riverine inflow pathway, whereas the Bolihujing River–reclaimed water auxiliary pathway represented a dispersed multi-source conveyance route. These two pathways differed in inflow location, local velocity distribution, and affected area, allowing comparison of their effects on hydrodynamic disturbance and habitat stability.

Temporally, replenishment was mainly arranged in March, September, and November. March replenishment was designed for spring water-level recovery and shallow-water habitat preparation before the breeding period. September replenishment compensated for the water deficit after strong evaporation in late summer and early autumn. November

replenishment maintained wetland water conditions before freeze-up. Under the uniform replenishment mode, additional replenishment nodes were arranged in May and July to alleviate continuous evaporation and vegetation water consumption during the growing season and to reduce the effects of rapid water-level fluctuations on shallow-water habitats (Figure 5).

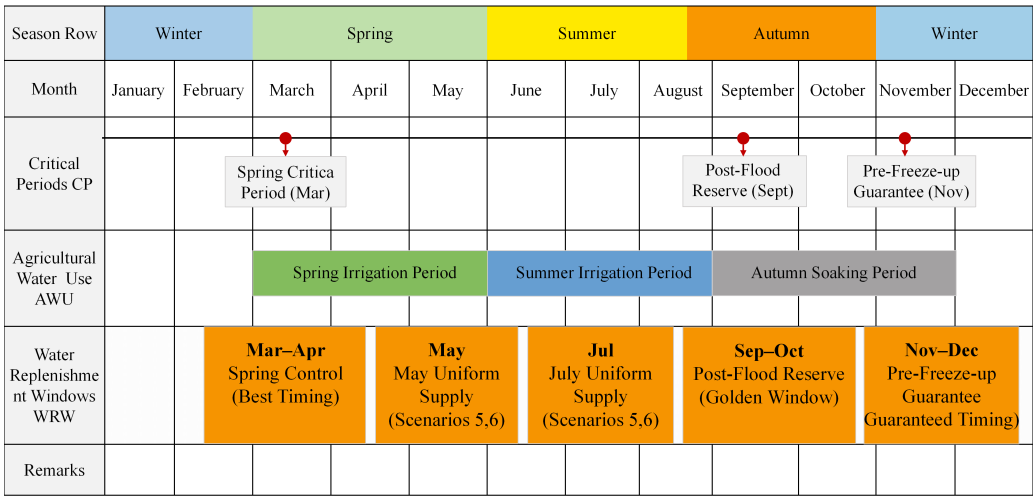


Figure 5. Seasonal scheduling of ecological water replenishment and agricultural water use. The timeline shows the monthly alignment of critical ecological periods (CP), agricultural water use (AWU), and operable water-replenishment windows (WRW). Labeled windows indicate the main replenishment periods, including spring control, uniform supply, post-flood reserve, and pre-freeze-up guarantee periods.

Using replenishment timing and water-conveyance pathway as control variables, three replenishment modes—concentrated, adaptive, and uniform—were constructed and combined with two conveyance pathways to generate six scenarios (S1–S6) (Table 3). S1 and S2 represented concentrated short-duration replenishment, characterized by temporally concentrated water delivery, high instantaneous discharge, and relatively high potential inflow momentum and suspended-solids disturbance risk. S3 and S4 represented adaptive replenishment, in which water delivery was dynamically adjusted according to hydrological conditions and water-quality responses, with a moderate disturbance risk. S5 and S6 represented uniform replenishment, in which the replenishment volume was distributed across multiple key ecological periods, helping to maintain smoother water-level changes and reduce hydrodynamic disturbance risk.

Table 3. Design of ecological water-replenishment scenarios.

Scenario	Replenishment Mode	Primary Water Source	Scenario Description	Expected Disturbance
S1	Concentrated	Daqing River	Large-volume replenishment delivered 2–3 times during March, June, and September through the main river channel.	High
S2	Concentrated	Bolihujing River and reclaimed water	Concentrated replenishment delivered through auxiliary channels during the same periods as S1.	High
S3	Adaptive	Daqing River	Water volume adjusted dynamically according to real-time water-quality monitoring and hydrological conditions.	Moderate

Table 3. *Cont.*

Scenario	Replenishment Mode	Primary Water Source	Scenario Description	Expected Disturbance
S4	Adaptive	Bolihujing River and reclaimed water	Adaptive replenishment delivered through auxiliary channels, with reclaimed water used to stabilize baseline supply.	Moderate
S5	Uniform	Daqing River	Water volume distributed evenly across March, May, July, September, and November to support steady inflow.	Low
S6	Uniform	Bolihujing River and reclaimed water	Uniform replenishment delivered through auxiliary channels to maintain the most stable water-delivery pattern.	Low

3.4. Comprehensive Evaluation and Optimal Decision-Making of Ecological Water-Replenishment Schemes

The six ecological water-replenishment scenarios were evaluated using the AHP–entropy weight–TOPSIS method. The original decision matrix included four indicators: suspended solids disturbance index, vegetation coverage, dissolved oxygen concentration, and total replenishment volume (Table 4). The suspended solids disturbance index and total replenishment volume were defined as cost-type indicators, while vegetation coverage and dissolved oxygen concentration were defined as benefit-type indicators (Table 5).

Table 4. Original decision matrix for the ecological water-replenishment scenarios.

Scenario	Suspended Solids Disturbance Index	Vegetation Coverage (%)	Dissolved Oxygen Concentration (mg/L)	Total Replenishment Volume (10^8 m^3)
S1	0.535	85.47	9.316	0.769
S2	0.5413	86.95	9.102	0.769
S3	0.4686	86.58	9.39	0.769
S4	0.4611	86.2	9.211	0.769
S5	0.347	86.39	8.42	0.769
S6	0.354	86.02	8.541	0.769

Table 5. Presents the subjective, objective, and combined weights of the evaluation indicators.

Evaluation Indicator	Indicator Type	AHP Weight	Information Entropy (ej)	Information Redundancy (dj)	Entropy Weight	Combined Weight
Suspended solids disturbance index	Cost-type	0.3873	0.7477	0.2523	0.4518	0.5904
Vegetation coverage	Benefit-type	0.2215	0.8672	0.1328	0.2378	0.1777
Dissolved oxygen concentration	Benefit-type	0.2215	0.8266	0.1734	0.3104	0.2319
Total replenishment volume	Cost-type	0.1698	1.0000	0.0000	0.0000	0.0000
Total	—	1	—	—	1	1

The TOPSIS results show that S6 ranked first under both ecological water-demand scenarios (Table 6 and Figure 6). In the optimal-demand scenario, S6 had Di^+ = 0.0162, Di^- = 0.1648, and Ci = 0.9105. In the minimum-demand scenario, S6 also ranked first, with Di^+ = 0.0245, Di^- = 0.1436, and Ci = 0.8542. S5 ranked second in both scenarios, followed by the remaining schemes, while S1 and S2 had the lowest comprehensive performance. This suggests that concentrated replenishment can satisfy the prescribed replenishment volume, but produces a weaker overall ecohydrological response.

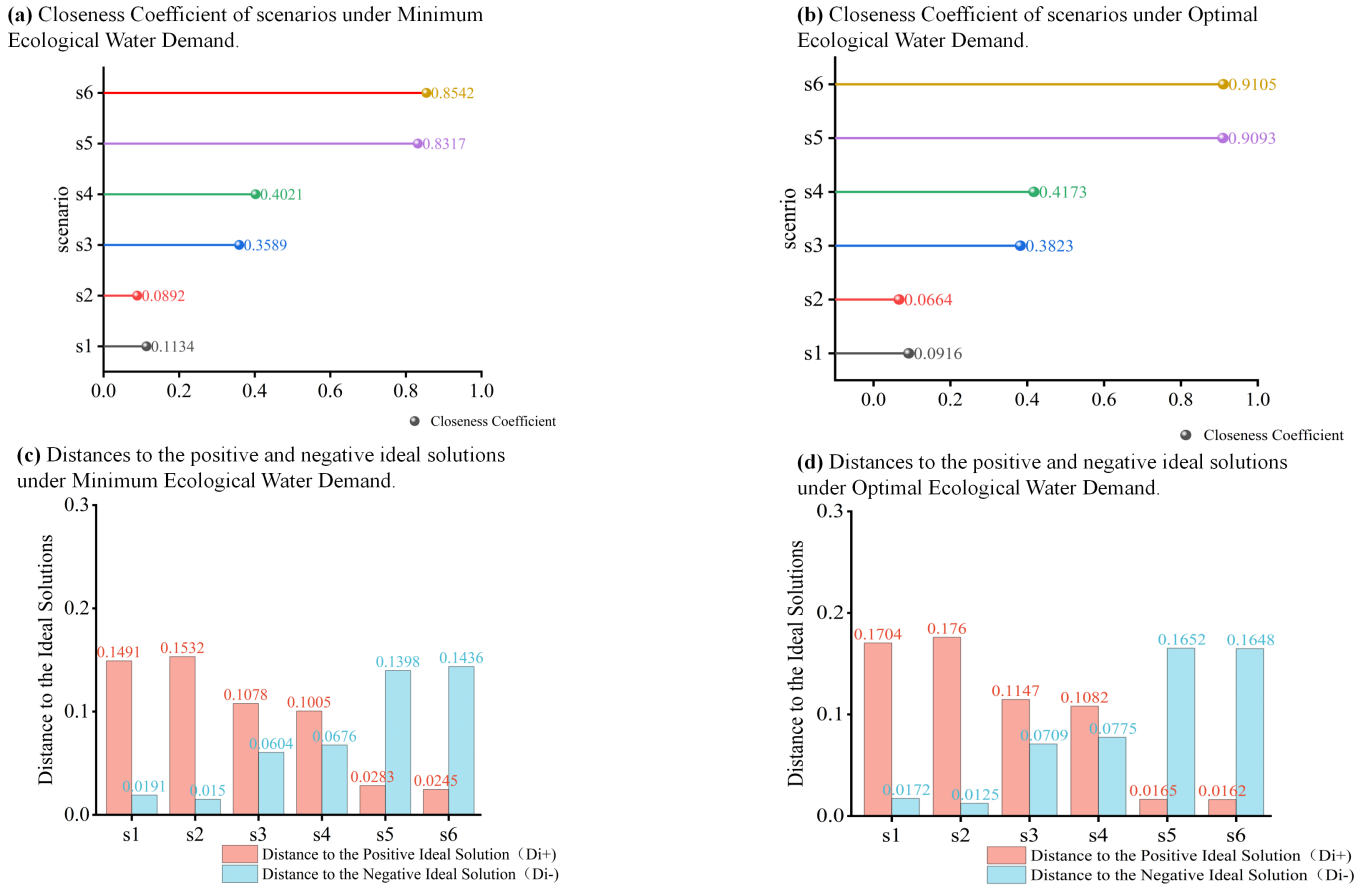


Figure 6. TOPSIS-based evaluation of ecological water-replenishment scenarios under minimum and optimal ecological water-demand conditions. Panels (**a**,**b**) show the relative closeness coefficients of scenarios S1–S6, and panels (**c**,**d**) show the distances to the positive ideal solution (Di^+) and negative ideal solution (Di^-) under the two water-demand conditions.

Table 6. TOPSIS evaluation results of ecological water-replenishment scenarios under different ecological water-demand scenarios.

Scenario	Replenishment Scenario	Optimal Ecological Water Demand				Minimum Ecological Water Demand			
		D_i^+	D_i^-	C_i	Rank	D_i^+	D_i^-	C_i	Rank
S6	Decentralized uniform replenishment	0.0162	0.1648	0.9105	1	0.0245	0.1436	0.8542	1
S5	Decentralized non-uniform replenishment	0.0165	0.1652	0.9093	2	0.0283	0.1398	0.8317	2
S4	Centralized uniform replenishment, January–March	0.1082	0.0775	0.4173	3	0.1005	0.0676	0.4021	3
S3	Centralized uniform replenishment, April–June	0.1147	0.0709	0.3823	4	0.1078	0.0604	0.3589	4
S1	Centralized rapid replenishment, period I	0.1704	0.0172	0.0916	5	0.1491	0.0191	0.1134	5
S2	Centralized rapid replenishment, period II	0.1760	0.0125	0.0664	6	0.1532	0.0150	0.0892	6

S6 performed best because it combined a decentralized delivery pathway with a uniform replenishment rhythm. This arrangement reduced concentrated inflow momentum, weakened hydrodynamic disturbance, and maintained water depth within the suitable habitat range of 30–50 cm. It was therefore selected as the preferred ecological water-replenishment strategy for Chahannaoer Wetland.

4. Discussion

4.1. Water-Balance Mechanism and Drivers of Water Deficit in Chahannaoer Wetland

The mean annual ecological replenishment deficit in Chahannaoer Wetland was approximately 1.03×10^8 m^3, whereas the designed replenishment scale was approximately 1.8×10^8 m^3. This difference indicates that ecological replenishment must not only offset the water-balance deficit, but also meet the requirements of water-quality dilution, water-level recovery, evaporation, seepage, and conveyance losses [29]. The mean evapotranspiration-to-recharge ratio (ET/R) was 3.99, ranging from 3.42 to 4.56 among years. This indicates that the study area has been characterized by a persistent hydrological imbalance, with evaporative losses substantially exceeding natural recharge inputs.

Chahannaoer Wetland is mainly recharged by precipitation, with limited and unstable external inflows. Groundwater contribution is weak, losses during water transfer and infiltration are substantial, and the natural regulation capacity of the system remains low [30]. This hydrological setting is typical of semi-arid inland lakes, where small changes in precipitation or evaporation can cause large shifts in lake water balance. The high ET/R ratio indicates strong sensitivity to climatic variability. Persistent water deficits and lake-area contraction may intensify salinization, alter surface energy exchange, and further increase ecological water demand during extreme dry years. These processes suggest that natural recharge alone is insufficient to maintain wetland ecological functions. Although increasing replenishment volume can alleviate short-term water shortage, it is unlikely to restore system stability unless the timing, pathway, and hydrodynamic effects of replenishment are also regulated. Water-replenishment design should therefore shift toward near-natural regulation that approximates natural hydrological variability while avoiding excessive hydrodynamic disturbance [31].

Compared with other lake and wetland restoration studies in semi-arid regions, Chahannaoer Wetland shows similar mechanisms of water deficit. Studies on the Aral Sea in Central Asia and restored wetlands in western Jilin, China, indicate that ecological water demand in arid and semi-arid wetlands is jointly controlled by runoff recharge, precipitation, evapotranspiration, and wetland area, and that a single static water-demand threshold is insufficient to represent hydrological requirements under different meteorological conditions and restoration targets [11,32]. The results of this study also show that Chahannaoer Wetland has long remained in an evaporation-dominated negative water-balance state, and that its ecological replenishment demand is likewise affected by insufficient natural recharge, evapotranspiration losses, and changes in wetland area. On this basis, water-quality dilution, hydrodynamic disturbance, and key habitat water levels were used as evaluation indicators to compare differences in water-quality maintenance, sediment resuspension risk, and habitat stability under different replenishment timings and water-conveyance pathways [33].

4.2. Effects of Replenishment Configuration on Sediment Resuspension and Hydrodynamic Response

Different replenishment modes alter the temporal allocation and spatial pathways of inflow, thereby affecting suspended-solids responses and potential hydrodynamic disturbance intensity during the replenishment process. Under decentralized uniform replenishment, the suspended solids disturbance index remained at approximately 0.32, indicating a low-disturbance state. Concentrated replenishment, by contrast, produced episodic disturbance peaks and weakened bed stability. This difference was driven mainly by the temporal concentration and spatial superposition of inflow momentum rather than by replenishment volume alone.

Sediment resuspension is primarily controlled by bed shear stress [34]. As velocity gradients and near-bed turbulent kinetic energy increase, bed sediment particles are therefore more likely to be entrained and resuspended, leading to an increase in suspended-solids concentration. Concentrated replenishment delivers high-flow pulses over short periods, leading to rapid momentum release, uneven local velocities, and enhanced turbulence [35]. These conditions may cause short-term exceedance of the critical bed shear stress, triggering sediment resuspension and increasing suspended solids concentrations. Decentralized replenishment reduces the intensity of individual inflows and prolongs water delivery. Momentum input is therefore distributed more gradually, abrupt changes in flow velocity are reduced, and turbulence development is moderated. Under these conditions, bed shear stress is more likely to remain near or below the critical threshold, limiting sediment disturbance to weak or intermittent entrainment [36]. With the total replenishment volume held constant, the timing of water delivery and inflow pathway become key factors controlling the hydrodynamic response.

In many large shallow lakes, sediment disturbance is mainly driven by wind-induced waves and currents [37]. For closed terminal lake wetlands, external inflows during artificial replenishment can further modify the local flow-field structure and bed shear conditions. Suspended-solids indicators can integrate replenishment-induced disturbance, turbidity responses, and potential resuspension risk, and therefore serve as important indicators for comparing replenishment schemes under hydrodynamic constraints. By reducing the concentration of momentum input, decentralized replenishment makes the system response more similar to the gradual inflow of natural runoff into the lake, reflecting the characteristics of near-natural hydrodynamic regulation.

4.3. Effects of Replenishment Rhythm on Relict Gull Breeding Habitat

Relict Gull breeding habitat is highly sensitive to water-level dynamics. Changes in water level affect habitat security by altering the hydrological isolation of breeding islands. Rapid rises may inundate nests [38], whereas sustained declines can reconnect islands with the surrounding land and increase predation risk. Habitat stability during the breeding period is therefore controlled by the magnitude, rate, and duration of water-level fluctuations [39].

During breeding, water levels must remain within a suitable range while avoiding both rapid rises and prolonged recession. Large fluctuations increase the risk of nest inundation or island exposure, and rapid changes reduce the time available for habitat adjustment. Continuous recession weakens island isolation and may increase access for terrestrial predators. The 30–50 cm water-depth range identified in this study helps maintain hydrological isolation around breeding islands while reducing the likelihood of nest inundation, thereby supporting habitat stability.

Replenishment rhythm influences habitat suitability by shaping the trajectory of water-level change. Concentrated replenishment produces step-like rises followed by rapid recession, resulting in larger fluctuation amplitudes and higher rates of change. Decentralized uniform replenishment extends inflow duration, reduces abrupt water-level shifts, and creates a slower, more continuous response. This pattern helps maintain suitable water depths during the breeding period and reduces the frequency of alternating inundation and exposure. Its slow-varying characteristics more closely resemble the water-level response generated by natural precipitation–runoff processes, allowing habitat conditions to remain more stable. These results indicate that replenishment rhythm affects Relict Gull breeding habitat primarily by regulating water-level variability.

4.4. Water-Replenishment Scale and Lake Water-Renewal Processes

The replenishment scale identified in this study reflects not only ecological water demand, but also the water volume required to sustain lake-water renewal. Under an evapotranspiration-to-recharge ratio of 3.42–4.56, replenishment intensity may influence water residence and exchange conditions. When replenishment is insufficient, a large proportion of the added water may be consumed by evaporative losses, leaving little capacity for continuous replacement. The lake then remains in a long-residence-time, weak-exchange state, which favors the accumulation of dissolved substances and pollutants [40]. With increased replenishment, the potential effective exchange volume may expand, residence time may decrease, and renewal frequency may increase. These changes weaken concentration gradients of dissolved substances and support water-quality maintenance.

In closed lakes with limited or no outflow, water renewal depends mainly on internal hydrodynamic forcing and partial water replacement [41]. The timing of inflow determines the structure of momentum input, thereby affecting mixing intensity and transport pathways. Concentrated replenishment delivers high-throughput inflow over short periods, but part of the added water may remain trapped in local circulation and fail to contribute to effective exchange. Decentralized replenishment extends inflow duration, maintains a more stable hydrodynamic field, and allows added water to participate more fully in lake-wide circulation, thereby improving exchange efficiency. Similar observations from Hongjiannao Lake suggest that static or weakly exchanged replenishment conditions can prolong residence time and promote the accumulation of soluble substances [42].

Replenishment scale and temporal configuration jointly regulate residence time, effective exchange ratio, and mixing processes, which together determine water-renewal efficiency. Replenishment scale provides the water-volume basis for renewal, whereas replenishment rhythm controls momentum input and exchange pathways. Their combined effect can shift the lake from an evaporation-dominated retention state toward a more active circulation state, consistent with the principle of near-natural water replenishment [43].

Uncertainties in water-quality targets and replenishment scale may further affect the intensity of lake-water renewal. Stricter water-quality constraints generally require larger dilution and exchange volumes. However, if this volume is supplied through short-duration concentrated inflow, it may intensify local scouring and sediment resuspension; by contrast, if it is delivered in a decentralized and uniform manner, it is more likely to improve the effective exchange ratio while keeping disturbance intensity under control.

5. Conclusions

This study developed a multi-criteria assessment approach for ecological water replenishment in Chahannaoer Wetland by integrating water-balance analysis, ecological water-demand estimation, hydrodynamic constraints, and TOPSIS-based scenario evaluation.

The results show that Chahannaoer Wetland has remained under an evaporation-dominated hydrological regime. From 2014 to 2024, the mean annual ecological replenishment deficit reached 1.03×10^8 m^3, and the evapotranspiration-to-recharge ratio ranged from 3.42 to 4.56. These findings indicate that limited and unstable natural recharge cannot sustain wetland ecological functions, and that simply increasing replenishment volume is unlikely to achieve effective restoration.

The minimum water volume required to maintain Class IV water quality was estimated at 0.86×10^8 m^3, while the suitable ecological water demand ranged from 1.27×10^8 to 1.56×10^8 m^3. These values define the main hydrological thresholds for ecological water regulation. When suspended-solids disturbance was used as a hydrodynamic-response indicator, replenishment configuration had a clear influence on system response. Among the six scenarios, decentralized uniform replenishment performed best, with the highest

relative closeness coefficient of 0.9105, a low disturbance index of approximately 0.32, and water depths maintained within the suitable habitat range of 30–50 cm.

These findings suggest that ecological restoration of semi-arid terminal lakes should not rely solely on volume-based water compensation. Greater attention should be paid to the timing, pathways, and hydrodynamic effects of replenishment. Decentralized uniform replenishment provides a near-natural strategy by distributing inflow more evenly in space and time, reducing hydrodynamic disturbance, and maintaining stable habitat water levels. The assessment approach proposed in this study provides a quantitative basis for optimizing ecological water replenishment and adaptive water-resource management in degraded wetlands of arid and semi-arid regions.

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References

1. Xu, D.; Bisht, G.; Tan, Z.; Sinha, E.; Di Vittorio, A.V.; Zhou, T.; Ivanov, V.Y.; Leung, L.R. Climate change will reduce North American inland wetland areas and disrupt their seasonal regimes. *Nat. Commun.* **2024**, *15*, 2438. [CrossRef]
2. Wang, R.M.; Ding, J.L.; Ge, X.Y.; Wang, J.J.; Qin, S.F.; Tan, J.; Han, L.J.; Zhang, Z. Impacts of climate change on the wetlands in the arid region of Northwestern China over the past 2 decades. *Ecol. Indic.* **2023**, *149*, 110168. [CrossRef]
3. Wang, N.; Yang, J.B.; Zhang, Z.Y.; Xiao, Y.; Wang, H.B.; He, J.J.; Yi, L.Q. Analysis of Detailed Lake Variations and Associated Hydrologic Driving Factors in a Semi-Arid Ungauged Closed Watershed. *Sustainability* **2023**, *15*, 6535. [CrossRef]
4. Zhang, X.; Li, Y.H.; Li, F.D. Spatial distribution characteristics of soil water-salt gradients in the ecological buffer zone of arid zone lakes and their influencing factors. *J. Clean. Prod.* **2024**, *444*, 141299. [CrossRef]
5. Van Tatenhove, A.M.; Neill, J.; Norvell, R.E.; Stuber, E.F.; Rushing, C.S. Scale-dependent population drivers inform avian management in a declining saline lake ecosystem. *Ecol. Appl.* **2024**, *34*, e3021. [CrossRef] [PubMed]
6. Meng, H.X.; Zhong, X.; Wu, Y.F.; Peng, X.J.; Li, Z.J.; Wang, Z.Y. Estimation of Ecological Water Requirement and Water Replenishment Regulation of the Momoge Wetland. *Water* **2025**, *17*, 114. [CrossRef]
7. Liu, C.S.; Liang, L.L.; Wang, L.; Zheng, S. Allocation and Utilization of Coal Mine Water for Ecological Protection of Lakes in Semi-Arid Area of China. *Sustainability* **2022**, *14*, 9042. [CrossRef]
8. Aazami, J.; Motevalli, A.; Savabieasfahani, M. Evaluation of three environmental flow techniques in Shoor wetland of Golpayegan, Iran. *Iran. Int. J. Environ. Sci. Technol.* **2022**, *19*, 7885–7898. [CrossRef]
9. Yu, X.Y.; Zhu, W.B.; Wei, J.X.; Jia, S.F.; Wang, A.D.; Huang, Y.B.; Zhao, Y.J. Estimation of ecological water supplement for typical bird protection in the Yellow River Delta wetland. *Ecol. Indic.* **2021**, *127*, 107783. [CrossRef]
10. Huang, J.; Yang, H.; He, W.; Li, Y. Ecological Service Value Tradeoffs: An Ecological Water Replenishment Model for the Jilin Momoge National Nature Reserve, China. *Int. J. Environ. Res. Public Health* **2022**, *19*, 3263. [CrossRef] [PubMed]
11. Xu, H.; Zhang, D.; Wu, Y.; Qi, P.; Wang, X. Suitable ecological water demand for wetlands restored to different historical periods in a latitude area and their response to changing environments. *Water Resour. Manag.* **2024**, *38*, 5683–5700. [CrossRef]

12. Xia, J.; Zhang, Y.Y.; Mu, X.M.; Zuo, Q.T.; Zhou, Y.J.; Zhao, G.J. A review of the ecohydrology discipline: Progress, challenges, and future directions in China. *J. Geogr. Sci.* **2021**, *31*, 1085–1101. [CrossRef]
13. Zadereev, E.; Lipka, O.; Karimov, B.; Krylenko, M.; Elias, V.; Pinto, I.S.; Alizade, V.; Anker, Y.; Feest, A.; Kuznetsova, D.; et al. Overview of past, current, and future ecosystem and biodiversity trends of inland saline lakes of Europe and Central Asia. *Inland Waters* **2020**, *10*, 438–452. [CrossRef]
14. Zhang, S.Y.; Chen, C.; Tang, H.W.; Jin, G.Q.; Zhou, B.; Ma, R.; Luo, X.Y. Effect of topography and hydrological change on solute transport at the sediment-water interface in seasonal lakes. *J. Hydrol. Reg. Stud.* **2024**, *53*, 101811. [CrossRef]
15. Teng, J.; Zhu, Y.; Duan, H.; Yu, X.; Xia, S.; Wang, R.; Yang, H. Linking hydrological connectivity and waterbirds habitat suitability in floodplain wetlands: Implications for wetland management. *Ecol. Indic.* **2025**, *176*, 113663. [CrossRef]
16. Shi, X.H.; Wang, S.H.; Zhao, S.N.; Sun, B.; Yu, H.F.; Zhang, F.; Zhang, Q.Y. Evaluating the effects of ecological water replenishment on lake water exchange in semi-arid regions: Insights from an 11-year modeling study. *J. Environ. Manag.* **2025**, *391*, 126491. [CrossRef]
17. Li, T.X.; Guo, S.B.; An, D.F.; Nametso, M. Study on water and salt balance of plateau salt marsh wetland based on time-space watershed analysis. *Ecol. Eng.* **2019**, *138*, 160–170. [CrossRef]
18. Cai, Y.J.; Liang, J.S.; Zhang, P.Y.; Wang, Q.Y.; Wu, Y.; Ding, Y.R.; Wang, H.J.; Fu, C.; Sun, J.J. Review on strategies of close-to-natural wetland restoration and a brief case plan for a typical wetland in northern China. *Chemosphere* **2021**, *285*, 131534. [CrossRef] [PubMed]
19. Zhao, L.F.; Ma, R.; Yang, Z.J.; Ning, K.; Chen, P.; Wu, J. Ecosystem health risk assessment of lakes in the Inner Mongolian Plateau based on the coupled AHP-SOM-CGT model. *Ecol. Indic.* **2023**, *156*, 111168. [CrossRef]
20. Huang, N.N.; Ge, R.X.; Ma, C.; Liu, P. Evidence of degradation and disappearance of Ramsar Wetland No. 1148 (Chinese Relict Gull Nature Reserve) due to anthropogenic disturbance and climate change on the ORDOS Plateau for nearly half a century. *Ecol. Indic.* **2024**, *158*, 111418. [CrossRef]
21. Herring, G.; Whipple, A.L.; Aldridge, C.L.; Pulver, B.A.; Eagles-Smith, C.A.; Inman, R.D.; Matchett, E.L.; Monroe, A.P.; Orning, E.K.; Robb, B.S.; et al. Imperiled Great Basin terminal lakes: Synthesizing ecological and hydrological science gaps and research needs for waterbird conservation. *BioScience* **2025**, *75*, 112–126. [PubMed]
22. Wallace, J.; Nicholas, M.; Grice, A.; Waltham, N.J. Application of a water balance model using depth measurements in the Mungalla wetland in north Queensland, Australia. *J. Hydrol.* **2024**, *644*, 132055. [CrossRef]
23. Chen, P. Groundwater-Ecological Interactions in Agro-Pastoral Interlaced Zones in Semi-Arid Areas: A Case Study of Chahannur Basin. Ph.D. Thesis, Chinese Academy of Geological Sciences, Beijing, China, 2023.
24. Zhen, H.B.; Tang, C.H.; Zhang, S.H.; Jia, H.; Xiong, N. Critical habitat factors and their thresholds for conserving and regulating wintering waterbird populations in Poyang Lake Wetland. *J. Environ. Manag.* **2025**, *394*, 127501. [CrossRef]
25. McMahon, T.A.; Peel, M.C.; Lowe, L.; Srikanthan, R.; McVicar, T.R. Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: A pragmatic synthesis. *Hydrol. Earth Syst. Sci.* **2013**, *17*, 1331–1363. [CrossRef]
26. Xu, Z.H.; Yin, X.A.; Yang, Z.F.; Cai, Y.P.; Sun, T. New model to assessing nutrient assimilative capacity in plant-dominated lakes: Considering ecological effects of hydrological changes. *Ecol. Model.* **2016**, *332*, 94–102. [CrossRef]
27. Kirol, A.P.; Morales-Williams, A.M.; Braun, D.C.; Marti, C.L.; Pierson, O.E.; Wagner, K.J.; Schroth, A.W. Linking sediment and water column phosphorus dynamics to oxygen, temperature, and aeration in shallow eutrophic lakes. *Water Resour. Res.* **2024**, *60*, e2023WR034813. [CrossRef]
28. Huang, J.; Zhao, L.; Sun, S.J. Optimization Model of the Ecological Water Replenishment Scheme for Boluo Lake National Nature Reserve Based on Interval Two-Stage Stochastic Programming. *Water* **2021**, *13*, 1007. [CrossRef]
29. Ye, Z.X.; Chen, S.F.; Zhang, Q.F.; Liu, Y.C.; Zhou, H.H. Ecological Water Demand of Taitema Lake in the Lower Reaches of the Tarim River and the Cherchen River. *Remote Sens.* **2022**, *14*, 832. [CrossRef]
30. Yang, Y.; Zhang, R.; Zhang, F.Y.; Li, Y.H. Spatial-Temporal Variation and Health Risk Assessment of Fluoride in Surface Water in the Tibetan Plateau. *Expo. Health* **2023**, *15*, 281–297. [PubMed]
31. Marcoie, N.; Chihaia, Ș.; Barta, A.-I.; Toma, D.; Boboc, V.; Balan, M.G.; Balan, C.D.; Nechita, M.-T. Half a Century of Civil Engineering in the Bahlui River Hydrographic System: The Unexpected Journey from Gray Structures to Hybrid Resilience. *Hydrology* **2026**, *13*, 15.
32. Huang, F.; Ochoa, C.G.; Guo, L. Estimating environmental water requirements for terminal lakes under varying meteorological conditions: A case study of the Big Aral Sea, Central Asia. *J. Hydrol.* **2023**, *621*, 129660. [CrossRef]
33. Bai, T.; Kang, Y.; Liu, D.; Gou, S.J. Study on Watershed Ecological Water Replenishment Coupling Hydrodynamic and Reservoir Operation. *Water Resour. Manag.* **2024**, *38*, 3071–3092. [CrossRef]
34. Luo, W.G.; Lu, J.; Zhu, S.L.; Yue, Y.; Xiao, L.J. Investigation of the impact of hydrodynamic conditions on sediment resuspension in shallow lakes. *Int. J. Digit. Earth* **2022**, *15*, 1676–1691. [CrossRef]
35. Li, C.; Gui, Z.Q.; Sun, S.C.; Shan, Y.Q.; Wu, B.Q.; Liu, C. Sediment deposition in a channel with floating vegetation based on a random displacement model. *J. Hydrodyn.* **2025**, *37*, 569–583. [CrossRef]

36. Liu, D.; Lv, S.; Li, C. Hydrodynamic-Ecological Synergistic Effects of Interleaved Jetties: A CFD Study Based on a 180° Bend. *Hydrology* **2026**, *13*, 17. [CrossRef]
37. Bu, M.S.; Li, Y.P.; Wei, J.; Tang, C.Y. The Influence of Ship Waves on Sediment Resuspension in the Large Shallow Lake Taihu, China. *Int. J. Environ. Res. Public Health* **2020**, *17*, 7055. [CrossRef] [PubMed]
38. Li, X.; Hu, B.S.; Qi, S.H.; Luo, J. The Influence of Short-Term Water Level Fluctuations on the Habitat Response and Ecological Fragility of Siberian Cranes in Poyang Lake, China. *Remote Sens.* **2024**, *16*, 4431. [CrossRef]
39. O'Keeffe, J.; Bukaciński, D.; Bukacińska, M.; Piniewski, M.; Okruszko, T. Future of birds nesting on river islands in the conditions of hydrological variability caused by climate change. *Ecohydrol. Hydrobiol.* **2024**, *24*, 337–353.
40. Xing, Z.Q.; Huang, H.J.; Li, Y.Y.; Liu, S.S.; Wang, D.; Yuan, Y.; Zhao, Z.N.; Bu, L.S. Management of sustainable ecological water levels of endorheic salt lakes in the Inner Mongolian Plateau of China based on eco-hydrological processes. *Hydrol. Processes* **2021**, *35*, e14192. [CrossRef]
41. Chen, J.; Qian, H.; Gao, Y.Y.; Wang, H.K.; Zhang, M.S. Insights into hydrological and hydrochemical processes in response to water replenishment for lakes in arid regions. *J. Hydrol.* **2020**, *581*, 124386. [CrossRef]
42. Sun, M.; Zhang, L.; Yang, R.; Li, X.; Zhao, J.; Liu, Q. Water resource dynamics and protection strategies for inland lakes: A case study of Hongjiannao Lake. *J. Environ. Manag.* **2024**, *355*, 120462. [CrossRef]
43. Teang, L.; Irvine, K.N.; Chua, L.H.C.; Usman, M. Coupling Modeling Approaches for the Assessment of Runoff Quality in an Urbanizing Catchment. *Hydrology* **2026**, *13*, 35. [CrossRef]

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