

## Article

# Quantifying Ecological Water Demand and Spatial Correspondence Under Landscape Pattern Dynamics in Yuehai Lake

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## Abstract

Hydrological processes in dryland urban lakes are jointly shaped by landscape pattern dynamics and water resource scarcity, yet the spatial correspondence between landscape fragmentation and lake ecological water demand remains poorly understood. This study took Yuehai Lake, a typical dryland urban lake in Northwest China, as a case study. Landscape pattern analysis was integrated with a water balance model to quantify ecological water demand and its spatial correspondence with landscape metrics. The model coupled the Penman–Monteith equation, a depth-modified evaporation model, and a Darcy’s Law-based zonal seepage calculation. Results showed that: (1) the landscape structure remained highly stable over 2014–2022, with the Aggregation Index ranging from 95.07% to 95.28% and the Largest Patch Index from 90.20% to 90.70%; (2) the annual ecological water demand for maintaining ecosystem integrity was estimated at  $2036.97 \times 10^4 \text{ m}^3$ , comprising inherent lake water volume of  $1138.02 \times 10^4 \text{ m}^3$  (55.9%), evapotranspiration of  $659.72 \times 10^4 \text{ m}^3$  (32.4%), and lakebed seepage of  $239.23 \times 10^4 \text{ m}^3$  (11.7%); and (3) evapotranspiration was concentrated between May and August, accounting for 80.5% of annual losses, with water surface evaporation dominating the flux at 91.5%. These findings suggest a spatial correspondence between landscape metrics and ecological water demand components, providing quantitative support for differentiated water supplementation strategies in dryland urban lakes.

**Keywords:** dryland urban lake; landscape pattern; ecological water demand; evapotranspiration; groundwater seepage; Yuehai Lake



Academic Editor: Agostina Chiavola

Received: 3 June 2026

Revised: 30 June 2026

Accepted: 9 July 2026

Published: 13 July 2026

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## 1. Introduction

Urban lake wetlands in arid and semi-arid regions are widely recognized as the “kidneys of the city”, playing an irreplaceable role in regulating regional microclimates, maintaining biodiversity, conserving water resources, and providing recreational functions [1]. Under the dual pressures of global climate change and rapid urbanization, dryland lakes are confronted with severe challenges, including area shrinkage, habitat fragmentation, and ecological function degradation [2]. In the inland regions of Northwest China, water resources are extremely scarce, and urban expansion often encroaches upon ecological space, leading to significant changes in the landscape pattern of lake wetlands. These landscape pattern dynamics are manifested as patch fragmentation and declining

connectivity. They undermine ecosystem integrity, disrupt the hydrological cycle, and exacerbate the imbalance between water inflow and outflow in lakes [3]. Therefore, accurately quantifying the ecological water demand (EWD) required to maintain lake ecosystem health and elucidating its spatial correspondence to landscape pattern dynamics have become critical scientific issues for regional water resource allocation and ecological restoration.

The concept of ecological water demand (EWD) originated from river ecological flow research, which emphasizes the minimum water volume threshold necessary for maintaining stable ecosystem structure and function [4]. Advances in ecohydrology have extended this concept to lake and wetland systems [5]. Currently, methods for quantifying EWD primarily include the water balance method, the water quality constraint method, the ecological response curve method, and integrated scenario simulation approaches [6–8]. These methods are based on hydrological processes, habitat requirements, and ecological response mechanisms, providing theoretical and practical foundations for the quantitative analysis of EWD. Among these, the water balance method has been widely applied in dryland lake EWD research owing to its well-defined physical mechanism and high data accessibility [9]. This method integrates the inherent lake water volume, evaporation and evapotranspiration losses, and groundwater exchange into a unified framework, thereby systematically characterizing the EWD structure of lakes [10]. In dryland lake systems, surface-water–groundwater interactions significantly influence lake water balance, with landscape controls often overriding evaporative variability [11]. The Penman–Monteith equation, as updated by Pereira et al. [12], provides a standardized approach for estimating evapotranspiration and has been widely employed in EWD studies. The interaction between lakes and groundwater is also recognized as a critical factor influencing lake water balance. Ying et al. [13] demonstrated that complex surface-water–groundwater interactions exist in drought-sensitive lowland catchments, with implications for lake water budgets, and variations in hydraulic gradients significantly affect lake water balance. Therefore, the integrated consideration of evapotranspiration and groundwater exchange is essential for calculating EWD. In recent years, with the advancement of remote sensing technology and spatial analysis methods, EWD research has gradually shifted from purely hydrological accounting to a coupled analysis of “hydrological process–ecological response–spatial structure”. Gao et al. [14] reviewed that landscape heterogeneity is associated with hydrological processes by modifying energy and water fluxes, thereby establishing a theoretical basis for coupling landscape pattern analysis with ecohydrological research. Stephens et al. [15] synthesized the coupling of landscape pattern and hydrological process, supporting the “pattern-process” paradigm and providing a framework for understanding how spatial patterns correspond to ecological processes. The suite of landscape metrics developed within FRAGSTATS effectively characterizes landscape fragmentation and spatial heterogeneity [16]. Studies have demonstrated that landscape fragmentation significantly affects regional hydrological cycles by modifying surface energy balance and evapotranspiration intensity [17,18]. In lake wetland systems, alterations in water body connectivity and shoreline complexity modify the extent of the land–water interface, thereby influencing water exchange and EWD structure.

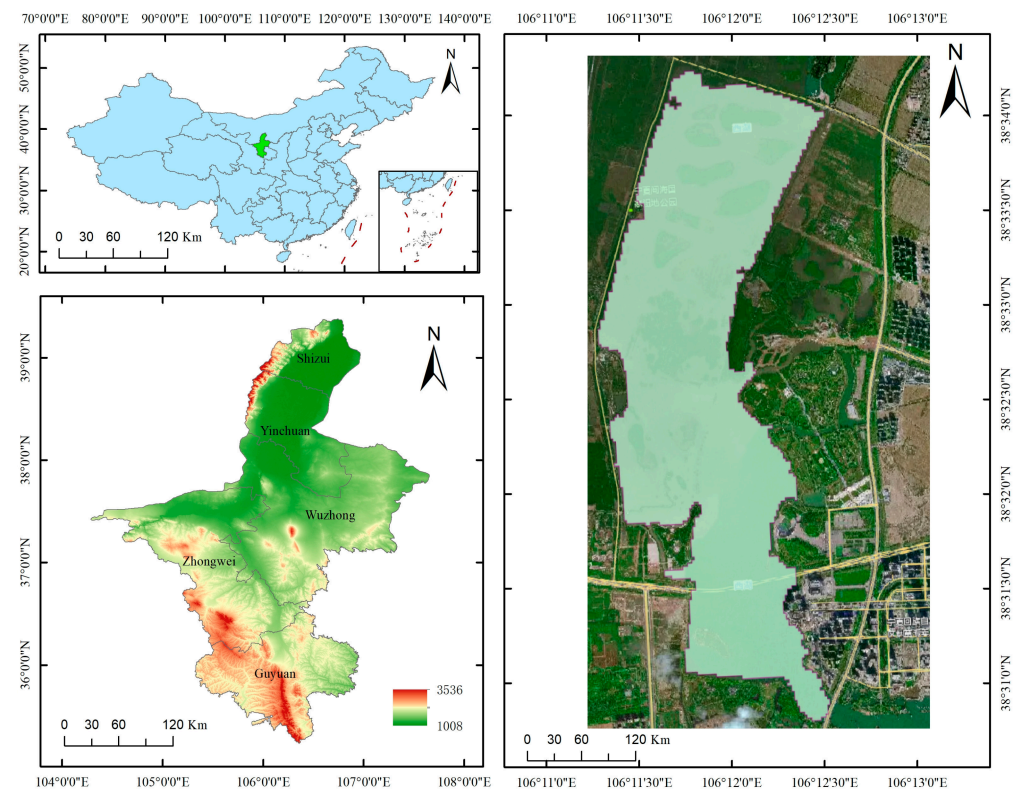
In summary, although current research has made progress in lake ecological water demand (EWD) quantification and landscape pattern analysis, the intrinsic relationship between the two remains poorly understood. Therefore, this study takes Yuehai Lake in Yinchuan, a typical dryland urban lake, as the research object. First, whereas previous studies have largely treated landscape pattern analysis and EWD estimation as separate tasks, this study integrates them within a spatially explicit comparative framework. Landscape metrics and EWD components were quantified independently and then spatially overlaid at a 30 m grid resolution. This approach reveals how landscape heterogeneity, particularly

along the lake edge, regulates evapotranspiration and seepage. Second, a refined water balance model is developed by incorporating a depth-modified evaporation equation, the Penman–Monteith equation, and a zonal Darcy-based seepage calculation. Third, the identified spatial correspondences enable differentiated water supplementation strategies for the lake's core and peripheral zones. By integrating landscape ecology with ecohydrology, this study offers a transferable methodology for science-based water allocation in other dryland urban lakes.

## 2. Materials and Methods

### 2.1. Study Area

Yuehai Lake is situated in the northwest of Jinfeng District, Yinchuan City, at  $106^{\circ}12' \text{ E}$ ,  $38^{\circ}32' \text{ N}$  (Figure 1). It is bordered by West Street to the east, Sanyizhi Ditch to the south, Xihu Ditch to the west, and the Yinchuan Ring Expressway to the north. Located approximately 3 km from the city center, the lake extends 10.0 km from north to south, with an average width of 2.7 km from east to west. The total area is  $7.799 \text{ km}^2$ , of which the lake surface occupies  $7.295 \text{ km}^2$ , and aquatic vegetation accounts for approximately 7% of the total area.



**Figure 1.** Schematic diagram of the study area.

Yinchuan experiences a cold semi-arid climate (Köppen classification: BSk), characterized by a mean annual temperature of approximately  $9.4^{\circ} \text{ C}$  and mean annual precipitation of around 272 mm. Over 65% of the annual precipitation is concentrated in the wet season (June–September), whereas the dry season extends from October to May, with monthly precipitation typically below 20 mm. Strong seasonal fluctuations in temperature and solar radiation drive a pronounced evaporation peak in summer (June–August), when monthly potential evapotranspiration can exceed 150 mm. The mean annual potential evaporation reaches approximately 1450 mm, far surpassing the annual precipitation and underscoring the water-limited nature of this dryland ecosystem.

## 2.2. Data Sources

The foundational data for quantitative landscape fragmentation analysis were obtained from multi-temporal remote sensing images provided by the Geospatial Data Cloud platform (<https://www.gscloud.cn/>). To ensure temporal continuity and inter-period comparability of landscape metrics, image data from five periods—2014, 2016, 2018, 2020, and 2022—were selected, with spatial co-registration and rasterization applied. To support the estimation of long-term land surface evapotranspiration, the China Land Cover Dataset (CLCD) developed by Professor Huang Xin's team at Wuhan University was adopted [19]. This dataset provides annual land cover information for China from 1990 to 2022, with high classification accuracy and spatiotemporal consistency. A high-resolution satellite image from July 2022 was further employed for the refined delineation of vegetation and water surface areas within Yuehai Lake, yielding a total study area of 7.799 km<sup>2</sup>, of which the water area accounted for 7.295 km<sup>2</sup>. Meteorological driving data were acquired from the China Meteorological Data Service Center (China Meteorological Administration, Beijing, China), consisting primarily of monthly meteorological observations from the Yinchuan station for 2022. This dataset includes key parameters—air temperature, air pressure, wind speed, and relative humidity—for calculating monthly average potential water surface evaporation and vegetation evapotranspiration. The mean water depth of 1.56 m was obtained from a bathymetric survey conducted in August 2022. The survey used an unmanned surface vehicle (HW-3, Huace, Shanghai, China) equipped with a single-beam echo sounder (FX160, Nanjing Yuanhou Technology Co., Ltd., Nanjing, China) and Real-Time Kinematic GPS (K50, Huace, Shanghai, China). It covered the entire lake with a grid spacing of approximately 100 m and yielded 140,941 measurement points. Monthly conversion coefficients for potential water surface evaporation were derived from in-situ evaporation experiments at the Ningxia Water and Environment Field Scientific Observation and Research Station (North China University of Water Resources and Electric Power, Zhengzhou, China) over the period 2020–2022, where evaporation pans at six depths ranging from 0.5 to 3.0 m were used to establish the depth–evaporation relationship. Hydraulic conductivity values were obtained from in-situ vertical tube tests using the Hvorslev method, conducted at 62 sampling points across Yuehai Lake, of which 54 were located along the shoreline and 8 within the lake. The hydraulic gradient of 0.097 was calculated from the hydraulic head difference of 0.388 m between the lake water and surrounding groundwater, as recorded by monitoring wells YH01 through YH09, divided by the average lakebed silt layer thickness of 4 m; this thickness was determined from high-density electrical resistivity tomography surveys and confirmed by borehole data from 17 locations. Permeability zone delineation was based on spatial interpolation of hydraulic conductivity values from all 62 test points, combined with lithological data from boreholes.

To assess the representativeness of 2022, we analyzed annual precipitation and mean temperature records from the Yinchuan meteorological station for the period 2014–2022. The long-term mean annual precipitation was 264.7 mm (SD = 38.2 mm), while the 2022 value reached 272 mm, placing it near the 60th percentile and thus characterizing it as a normal-to-slightly-wet year. The mean annual temperature in 2022 (9.6 °C) closely approximated the period mean of 9.4 °C (SD = 0.7 °C). Consequently, 2022 was considered a hydrologically representative year within the 2014–2022 period.

## 2.3. Methods

### 2.3.1. Landscape Metric Calculation Methods

Landscape metrics serve as essential tools for quantifying the spatial structure of landscapes, capturing the degree of habitat fragmentation, shape complexity, and diversity from geometric and physical perspectives [20]. As a typical urban lake wetland in a

dryland region, even subtle changes in the landscape structure of Yuehai Lake can directly trigger shifts in hydrological processes [21]. The four landscape metrics—AI, LPI, LSI, and SHDI—were selected based on their well-documented ecological relevance to hydrological processes and their capacity to provide complementary information. The Aggregation Index (AI) was chosen because it directly measures the physical connectivity of water patches. High AI values indicate well-connected water bodies that contribute to water volume stability. The Largest Patch Index (LPI) was selected as a measure of landscape dominance, reflecting the proportion of the landscape occupied by the largest water patch. This metric is particularly pertinent for lakes where the continuous water body constitutes the dominant landscape element governing base water storage. The Landscape Shape Index (LSI) quantifies patch shape complexity and edge irregularity, and is directly relevant to evapotranspiration because irregular shorelines and complex edges expand the land–water interface area, thereby enhancing aerodynamic roughness and radiation absorption. Shannon’s Diversity Index (SHDI) captures landscape heterogeneity and the evenness of patch type distribution; higher SHDI values indicate greater landscape diversity, which is associated with elevated evapotranspiration in lacustrine systems. To quantitatively characterize the landscape pattern dynamics of Yuehai Lake over the past decade, four metrics with well-defined ecological significance were selected for five periods—2014, 2016, 2018, 2020, and 2022—namely, the Aggregation Index (AI), Largest Patch Index (LPI), Landscape Shape Index (LSI), and Shannon’s Diversity Index (SHDI).

$$AI = \left[ \sum_{i=1}^m \left( \frac{g_{ij}}{\max g_{ij}} \right) p_i \right] \times 100 (0 \leq AI \leq 100) \quad (1)$$

where:  $p_i$  is the area proportion of patch  $i$ ;  $g_{ij}$  is the number of adjacencies between patches  $i$  and  $j$ ;  $\max g_{ij}$  is the maximum possible number of adjacencies between patch types  $i$  and  $j$ .

$$LPI = \frac{\max_{j=1}^n (a_{ij})}{A} \times 100 (0 < LPI \leq 100) \quad (2)$$

where:  $a_{ij}$  is the area of patch  $ij$ ;  $A$  is the total landscape area.

$$LSI = \frac{E_i}{\min E_i} (LSI \geq 1) \quad (3)$$

where:  $E_i$  is the total length of the edge of patch type  $i$ ;  $\min E_i$  is the minimum possible total edge length of patch type  $i$ .

$$SHDI = - \sum_{i=1}^m (P_i \ln p_i) \quad (4)$$

where SHDI is Shannon’s Diversity Index;  $m$  is the number of landscape types in the study area;  $P_i$  is the proportion of the total area occupied by landscape type  $i$ .

### 2.3.2. Ecological Water Demand Quantification Methods

Based on the water balance principle, this study decomposed the total ecological water demand (EWD) of Yuehai Lake into three core components: the inherent lake water volume ( $V_s$ ), lakebed seepage ( $Q$ ), and lake evapotranspiration ( $E$ ). Among these, lake evapotranspiration and lakebed seepage together constitute the dynamic water volume required to compensate for hydrological process losses. The vegetation and water surface areas within the lake were delineated from a July 2022 satellite image, yielding a total study area of 7.799 km<sup>2</sup>, of which the water area was 7.295 km<sup>2</sup> and the vegetation area was 0.504 km<sup>2</sup>, with a mean water depth of 1.56 m under normal conditions.

The inherent lake water volume is primarily required to sustain the basic morphology and depth conditions of the lake, thereby preventing habitat degradation, weakened water body connectivity, and loss of ecological functions that would otherwise result from excessive water level decline [22,23]. It can be estimated from the lake surface area and the mean water depth necessary to maintain a normal ecological state, with the formula:

$$V_s = A_1 \times h_0 \quad (5)$$

where:  $V_s$  is the inherent water volume required by the lake;  $A_1$  is the lake area;  $h_0$  is the mean water depth required to maintain the normal state of the lake.

Although widely applied, traditional methods for calculating lake evaporation neglect the influence of water depth, introducing inaccuracies when applied to dryland lakes. To address this limitation, the present study adopts a depth-modified evaporation model developed from in-situ experiments at the Ningxia Water and Environment Field Scientific Observation and Research Station [24]. This model, parameterized using long-term observations from evaporation ponds of varying depths, yields a water surface evaporation formula tailored to the Yinchuan Plain. It captures the regulatory effect of water depth on the thermal capacity and evaporation dynamics of the water body [25], thereby providing improved accuracy relative to the conventional Penman–Monteith equation. The formula is:

$$E_g = K_i \times \left( 2.05e^{-0.891H} + 0.175T - 0.028P + 3.15 \right) \quad (6)$$

where:  $E_g$  is the potential water surface evaporation in the Yinchuan Plain ( $\text{mm} \cdot \text{d}^{-1}$ );  $K_i$  is the monthly conversion coefficient for potential water surface evaporation;  $H$  is the evaporation depth (m);  $T$  is the temperature ( $^{\circ}\text{C}$ );  $P$  is the air pressure (kPa).

This study employs the Penman–Monteith (P-M) equation to estimate canopy evapotranspiration. Originally proposed by Monteith in 1965, the P-M equation extends the foundational work of Penman and Covey by introducing the concept of canopy resistance [26]. It integrates the atmospheric physical controls on evapotranspiration with the physiological properties of vegetation, offering a physically rigorous basis for resolving the dynamics and governing mechanisms of evapotranspiration [27]. Pereira et al. [12] comprehensively updated the FAO56 Penman–Monteith equation, which remains the reference method for computing reference evapotranspiration. The P-M equation is:

$$E_Z = \frac{\Delta}{\Delta + \gamma} \frac{R_n}{\lambda} + \frac{\gamma}{\Delta + \gamma} \frac{6.43(1 + 0.53u)(e_s - e_a)}{\lambda} \quad (7)$$

$$\Delta = \frac{de_s}{dT} \approx \frac{4098e_s}{(237.3 + T)^2} \quad (8)$$

$$\gamma = 0.00065813P \quad (9)$$

$$e_s = 0.6108e^{\frac{17.27T}{237.3+T}} \quad (10)$$

$$E_a = 0.65e_s \quad (11)$$

where:  $R_n$  is the net radiation at the crop surface ( $\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ );  $\Delta$  is the slope of the saturation vapor pressure curve at 2 m air temperature ( $\text{kPa} \cdot ^{\circ}\text{C}^{-1}$ );  $\gamma$  is the psychrometric constant ( $\text{kPa} \cdot ^{\circ}\text{C}^{-1}$ );  $\lambda$  is the latent heat of vaporization ( $\text{MJ} \cdot \text{kg}^{-1}$ ),  $\lambda = 2.51 - 0.00236T$ ;  $e_s$  is the saturation vapor pressure in the air (kPa);  $e_a$  is the actual vapor pressure at 2 m height (kPa);  $u$  is the wind speed at 2 m height ( $\text{m} \cdot \text{s}^{-1}$ );  $T$  is the mean air temperature ( $^{\circ}\text{C}$ );  $P$  is the mean annual atmospheric pressure, taken as  $P = 89.0196$  kPa.

The formula for calculating net radiation  $R_n$  at the crop surface:

$$R_n = 0.5833(1 - \alpha)R_a - R_{nl} \quad (12)$$

$$R_a = 37.5860d_r(\omega_s \sin \varphi \sin \delta + \cos \varphi \cos \delta \sin \omega_s) \quad (13)$$

$$R_{nl} = 0.7(0.34 - 0.14\sqrt{e_a})(237.3 + T)^4\sigma \quad (14)$$

$$d_r = 1 + 0.033\left(\frac{2\pi}{365}J\right) \quad (15)$$

$$\delta = 0.409\sin\left(\frac{2\pi}{365}J - 1.39\right) \quad (16)$$

$$\omega_s = \cos^{-1}(-\tan \varphi \tan \delta) \quad (17)$$

where:  $R_a$  is the total extraterrestrial radiation received by the Earth's atmosphere ( $\text{MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ );  $R_{nl}$  is the net outgoing longwave radiation ( $\text{MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ );  $\alpha$  is the short-wave radiation albedo, with an empirical value of 0.08 for vegetation;  $d_r$  is the inverse relative Earth–Sun distance;  $\omega_s$  is the sunset hour angle (rad);  $\varphi$  is the latitude at sunset,  $\varphi = 0.6717$  (rad);  $\delta$  is the solar declination at sunset (rad);  $\sigma$  is the Stefan–Boltzmann constant,  $4.903 \times 10^{-9} \text{ MJ}(\text{K}^4\cdot\text{m}^{-2}\cdot\text{d}^{-1})$ ;  $J$  is the day number of the year, e.g., for January 1st,  $J = 1$ .

Lake seepage represents a major component of water loss from Yuehai Lake and a principal source of groundwater recharge [11]. To account for the spatial heterogeneity of lakebed lithology and the seasonal variability of hydrodynamic conditions in the lake [28], a zonal dynamic calculation method based on Darcy's Law was employed to quantify lakebed seepage. The formula is:

$$Q = K \times A \times J \times D \quad (18)$$

where:  $Q$  is the lakebed seepage ( $\text{m}^3\cdot\text{d}^{-1}$ );  $K$  is the mean lakebed hydraulic conductivity ( $\text{m}\cdot\text{d}^{-1}$ );  $A$  is the lakebed area ( $\text{m}^2$ );  $J$  is the hydraulic gradient between the lake water and the lakeshore groundwater;  $D$  is the lakebed seepage duration (d).

Based on the water balance principle and ecohydrological methods, the total ecological water demand (EWD) of Yuehai Lake is defined as the sum of the static base water volume sustaining the existing habitat structure and the dynamic water volume offsetting hydrological process losses. The total EWD for the typical year 2022 was quantified by summing the three core components: the inherent lake water volume ( $V_s$ ), lake evapotranspiration ( $E$ ), and lakebed seepage ( $Q$ ). The total ecological water demand formula is:

$$W = V_s + E + Q \quad (19)$$

where:  $W$  is the total ecological water demand;  $V_s$ ,  $E$ , and  $Q$  are the calculated values of the three components.

### 3. Results

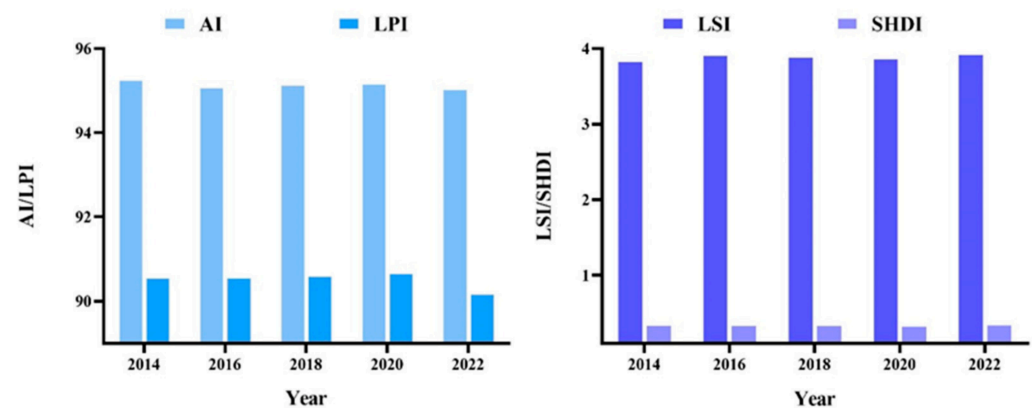
#### 3.1. Landscape Metric Calculation Results

To ensure cross-period comparability, the land use data were first spatially co-registered and rasterized. Landscape metrics for each landscape component were then calculated under unified parameter settings and statistically analyzed to systematically characterize the fragmentation patterns and temporal dynamics within Yuehai Lake. The calculation results of the relevant landscape metrics are summarized in Table 1.

**Table 1.** Statistical values of core landscape metrics for Yuehai Lake, 2014–2022.

| Period | AI      | LPI     | LSI    | SHDI   |
|--------|---------|---------|--------|--------|
| 2014   | 95.2833 | 90.5818 | 3.8514 | 0.3581 |
| 2016   | 95.1039 | 90.5937 | 3.9324 | 0.3560 |
| 2018   | 95.1630 | 90.6291 | 3.9054 | 0.3536 |
| 2020   | 95.1966 | 90.6999 | 3.8892 | 0.3512 |
| 2022   | 95.0708 | 90.2042 | 3.9459 | 0.3616 |

Overall, the landscape structure of Yuehai Lake remained highly stable throughout the study period, with no evidence of significant spatial fragmentation (Figure 2). The Aggregation Index (AI) consistently exceeded 95, reflecting strong spatial aggregation and physical connectivity among landscape patches within the lake. Meanwhile, the Largest Patch Index (LPI) remained stably above 90%, confirming the persistent dominance of the water body patch across all study periods. As the core structural unit of the Yuehai Lake landscape system, this contiguous water patch plays a decisive role in sustaining the region's core ecological functions and maintaining the baseline of hydrological processes.



**Figure 2.** Temporal trends of landscape metrics—Aggregation Index (AI), Largest Patch Index (LPI), Landscape Shape Index (LSI), and Shannon's Diversity Index (SHDI)—for Yuehai Lake from 2014 to 2022. AI and LPI are expressed as percentages; LSI and SHDI are dimensionless.

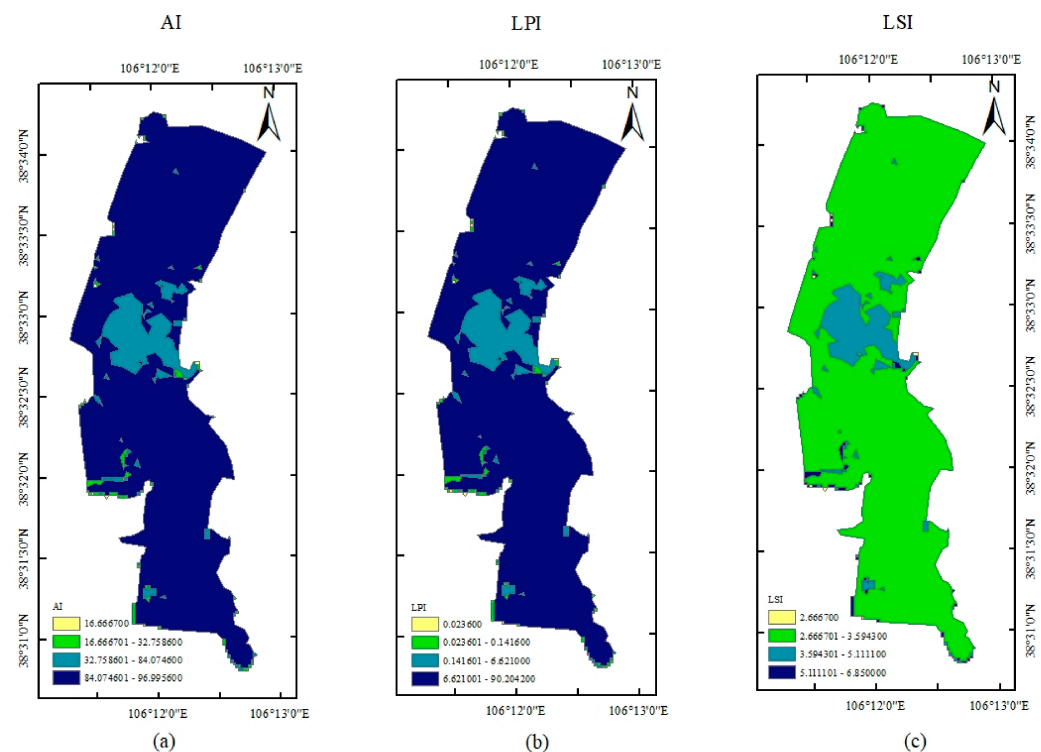
In contrast, the Landscape Shape Index (LSI) and Shannon's Diversity Index (SHDI) exhibited phased fluctuations across the study periods. The fluctuating increase in LSI reflected a trend toward greater lakeshore complexity and more intricate local patch boundaries, closely linked to the seasonal reshaping of edge habitats driven by water level fluctuations typical of dryland lakes. This increasing boundary complexity, in turn, intensified local evapotranspiration by expanding the radiation-receiving area and aerodynamic roughness of the land–water interface. SHDI reached a relatively high level in 2022, signaling enhanced evenness in the distribution of landscape types and elevated landscape heterogeneity. These results indicate that, despite the overall stability of the landscape structure, the spatial configuration of the lake's edge areas and interior habitat patches continued to undergo dynamic adjustment.

From the perspective of ecohydrological mechanisms, different landscape metrics show distinct associations with the ecological water demand (EWD) of the lake. Specifically, AI and LPI primarily capture the overall continuity and structural integrity of the lake water body, thus serving as structural metrics that are associated with the lower limit of EWD. In contrast, LSI and SHDI are more responsive to changes in lakeshore morphology and habitat heterogeneity; they correspond to the spatiotemporal distribution of EWD and

are associated with the extent of the land–water interface, evapotranspiration intensity, and water exchange processes.

### 3.2. Spatial Distribution Characteristics of Landscape Pattern

To further characterize the spatial patterning of landscape heterogeneity, the grid-based distributions of key landscape metrics for Yuehai Lake in 2022 were extracted (Figure 3). High-aggregation and high-dominance areas were predominantly concentrated in the deep-water zone at the lake center, while shape complexity was distributed mainly along the littoral zones and in areas with dense emergent vegetation such as reeds.



**Figure 3.** Spatial distribution of landscape metrics in Yuehai Lake in 2022: (a) Aggregation Index (AI), (b) Largest Patch Index (LPI), (c) Landscape Shape Index (LSI). High AI and LPI values are concentrated in the central deep-water zone, while elevated LSI and SHDI values are distributed along the littoral zones and areas with dense emergent vegetation.

From the perspective of ecohydrological mechanisms, these spatial differentiation patterns show distinct associations with the ecological water demand (EWD) of the lake. The high AI and LPI values in the central water area preserve the overall continuity of the water body, thereby functioning as rigid structural metrics that define the lower limit of the lake's basic EWD. In contrast, the elevated LSI and SHDI along the edge zone coincide spatially with the radiation-receiving area and aerodynamic roughness of the land–water interface, which in turn may influence local water surface evaporation and vegetation evapotranspiration intensity.

### 3.3. Ecological Water Demand Quantification Results

#### 3.3.1. Inherent Lake Water Volume

Water surface area and mean water depth are the two primary parameters governing the inherent lake water volume, which establishes the baseline for sustaining the lake's basic morphology and habitat continuity. The inherent lake water volume was calculated using Equation (5). Based on the 2022 high-resolution imagery, the water area was 7.295 km<sup>2</sup>; combined with a measured mean water depth of 1.56 m derived from lake bathymetry, the

base water volume required to maintain the lake's basic morphology was calculated to be  $1138.02 \times 10^4 \text{ m}^3$ .

### 3.3.2. Lake Evapotranspiration Water Consumption Calculation

Evapotranspiration (ET) represents the dominant component of water loss in dryland lakes. In this study, a depth-modified evaporation model and the Penman–Monteith equation were used to separately quantify physical water surface evaporation and physiological vegetation transpiration. Water surface evaporation was estimated using Equation (6) with the monthly conversion coefficients  $K_i$  listed in Table 2. Vegetation evapotranspiration was calculated using Equations (7)–(17). The evaporation conversion coefficient ( $k$ ) increased nonlinearly with water depth, reflecting the enhanced thermal buffering capacity of deeper water bodies typical of dryland regions. According to the phenological cycle of the Yinchuan Plain, vegetation in Yuehai Lake enters a dormant and wilting phase from late October to late April of the following year, during which vegetation evapotranspiration ( $E_z$ ) was taken as zero. The calculated results are summarized in Table 2 and visualized in Figure 4. In 2022, water surface evaporation totaled  $603.92 \times 10^4 \text{ m}^3$  and vegetation evapotranspiration reached  $55.8 \times 10^4 \text{ m}^3$ , yielding a total ET of  $659.72 \times 10^4 \text{ m}^3$ . Monthly evapotranspiration (ET) peaked in July at  $161.34 \times 10^4 \text{ m}^3$ , accounting for 24.5% of the annual total, and reached its minimum in January at  $6.51 \times 10^4 \text{ m}^3$ , representing just 1.0% of the annual total. The period from May to August alone contributed 80.5% of the annual ET, amounting to  $530.73 \times 10^4 \text{ m}^3$  of the total  $659.72 \times 10^4 \text{ m}^3$ . Water surface evaporation dominated the ET flux, contributing  $603.92 \times 10^4 \text{ m}^3$ , or 91.5% of the total, whereas vegetation evapotranspiration accounted for  $55.80 \times 10^4 \text{ m}^3$ , or 8.5%. This seasonal pattern closely follows the annual cycle of temperature and solar radiation, with vegetation transpiration playing a more prominent role during the peak growing season (June–August), when its contribution rises to 10–12% of total ET. This pronounced seasonal concentration indicates that water resource allocation plans should reserve sufficient replenishment capacity in summer, whereas winter supplementation strategies should prioritize maintaining the dynamic equilibrium between base water storage and groundwater levels.

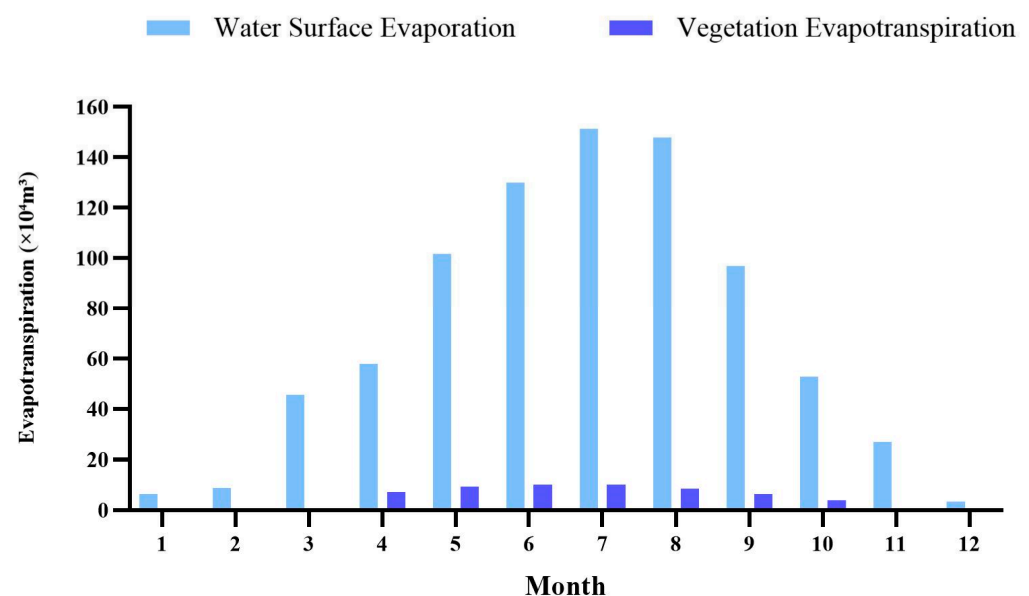


Figure 4. Monthly Lake Evaporation of Yuehai Lake in 2022.

**Table 2.** Monthly evapotranspiration of Yuehai Lake in 2022.

|                                        | Month |      |       |       |        |        |        |        |        |       |       |      |
|----------------------------------------|-------|------|-------|-------|--------|--------|--------|--------|--------|-------|-------|------|
|                                        | 1     | 2    | 3     | 4     | 5      | 6      | 7      | 8      | 9      | 10    | 11    | 12   |
| $K_i$                                  | 0.50  | 0.53 | 0.52  | 0.54  | 0.74   | 0.80   | 0.88   | 0.90   | 0.73   | 0.57  | 0.50  | 0.61 |
| $E_g (\times 10^4 \text{ m}^3)$        | 6.51  | 8.68 | 45.57 | 57.90 | 101.68 | 129.90 | 151.28 | 147.87 | 96.90  | 52.70 | 27.00 | 3.41 |
| $E_z (\times 10^4 \text{ m}^3)$        | 0     | 0    | 0     | 7.32  | 9.45   | 10.12  | 10.06  | 8.59   | 6.31   | 3.97  | 0     | 0    |
| Total ET ( $\times 10^4 \text{ m}^3$ ) | 6.51  | 8.68 | 45.57 | 65.22 | 111.13 | 140.02 | 161.34 | 156.46 | 103.21 | 56.67 | 27.00 | 3.41 |

Table Note:  $K_i$  denotes the monthly conversion coefficient for potential water surface evaporation, derived from long-term evaporation pan observations maintained by the Ningxia Water and Environment Field Scientific Observation and Research Station.  $E_g$  denotes lake water surface evaporation (Equation (6));  $E_z$  denotes aquatic plant evapotranspiration within the lake (Equations (7)–(17)).

### 3.3.3. Lakebed Seepage

Lakebed seepage at Yuehai Lake is predominantly vertical. To account for the heterogeneity of lakebed sedimentary facies, Darcy's Law was applied for zonal quantification. Based on surficial lithological differences, the seepage field was partitioned into three permeability zones: low, moderate, and medium. The hydraulic conductivity of each zone was assigned accordingly, and the area of each zone was measured using ArcGIS 10.5. Results show that the low-permeability zone covers approximately  $4.65 \text{ km}^2$ , the moderate-permeability zone approximately  $1.92 \text{ km}^2$ , and the medium-permeability zone approximately  $1.23 \text{ km}^2$ . Groundwater monitoring data from Yuehai Lake and the adjacent lakeshore area indicate a hydraulic head difference of  $0.388 \text{ m}$  between the lake and the surrounding groundwater. Combined with an average lakebed silt layer thickness of  $4 \text{ m}$  derived from in-situ detection, the hydraulic gradient between the lake and the lakeshore groundwater was determined to be  $0.097$ . Annual seepage volumes for each zone were then calculated using Equation (18), and the corresponding results are presented in Table 3.

**Table 3.** Parameters and results of zonal seepage calculation for Yuehai Lake.

| Permeability Zone     | Area ( $\text{km}^2$ ) | Hydraulic Conductivity ( $\text{m} \cdot \text{d}^{-1}$ ) | Seepage Volume ( $10^4 \text{ m}^3$ ) |
|-----------------------|------------------------|-----------------------------------------------------------|---------------------------------------|
| Low-permeability      | 4.65                   | $4.85 \times 10^{-3}$                                     | 79.84                                 |
| Moderate-permeability | 1.92                   | $1.23 \times 10^{-2}$                                     | 83.61                                 |
| Medium-permeability   | 1.23                   | $1.74 \times 10^{-2}$                                     | 75.77                                 |

### 3.3.4. Total Ecological Water Demand

The total ecological water demand calculated in this study is based on the water balance principle. From the perspective of maintaining the structural stability and functional continuity of the lake ecosystem, the water demand is comprehensively considered at three levels: first, the inherent water volume to maintain the basic water body form of the lake; second, the climatic water consumption compensation for water loss caused by evapotranspiration; and third, the seepage compensation for water exchange between the lake and the groundwater system. The sum of these three components constitutes the total water volume required to maintain the ecological functions of Yuehai Lake under the meteorological conditions of 2022. The total EWD was obtained by summing the three components according to Equation (19). The calculation results are shown in Table 4. The total ecological water demand of Yuehai Lake in 2022 was  $2036.97 \times 10^4 \text{ m}^3$ . Analyzing the water demand structure, the static base water storage accounts for  $55.9\%$ , serving as the core baseline to prevent the lake from degrading into a swamp or saline–alkaline land. Meanwhile, the dynamic loss components—evapotranspiration and seepage—account for  $44.1\%$ , reflecting the pressure of strong atmospheric evaporation potential and lakebed

geological seepage on water resource allocation in dryland regions. This result clarifies the key direction for ecological water supplementation of Yuehai Lake: the base water storage should be rigidly guaranteed through sluice gate regulation during non-flood seasons, while flood season supplementation should prioritize offsetting the evaporation peak and seepage losses from May to August.

**Table 4.** Calculation table for ecological water demand of Yuehai Lake.

| Water Component                             | Inherent Lake Volume (Vs) | Evaporation Loss (E) | Seepage Loss (Q) | Total   |
|---------------------------------------------|---------------------------|----------------------|------------------|---------|
| Annual Volume ( $\times 10^4 \text{ m}^3$ ) | 1138.02                   | 659.72               | 239.23           | 2036.97 |

## 4. Discussion

### 4.1. Stability Characteristics of Landscape Pattern and Their Constraining Effects on Ecological Water Demand

The quantitative analysis of long-term landscape metrics from 2014 to 2022 demonstrates that the landscape structure of Yuehai Lake exhibited pronounced stability. The Aggregation Index (AI) consistently remained above 95, and the Largest Patch Index (LPI) remained stably above 90% (Table 1), with the water body patch maintaining a dominant position in the spatial configuration. This pattern contrasts sharply with the increasing fragmentation of construction land and wetland vegetation reported for the Xinghai Lake wetland during 2005–2016 [29], and with the substantial landscape fragmentation documented for the Ebinur Lake watershed from 1990 to 2021 [30], suggesting that the core water body of Yuehai Lake has not experienced significant development encroachment over the past decade. The strong spatial connectivity reflected by the high AI and LPI values provides a rigid physical boundary that stabilizes the inherent lake water volume, thereby constituting a stable base-flow component within the total ecological water demand (EWD). Although the core water area remained structurally stable, the fluctuating increases in LSI and SHDI in the edge zone (Figure 2) point to enhanced local heterogeneity. Research on the alpine wetland of Bayanbulak Swan Lake has shown that landscape fragmentation and spatial heterogeneity display pronounced seasonal differentiation, with both metrics increasing before August and declining thereafter [31]. Although Yuehai Lake is a dryland urban lake governed by a hydrological regime distinct from that of alpine wetlands, the seasonal fluctuations of LSI and SHDI in its edge zone are similarly modulated by both meteorological forcing and human activities, indicating that water-level fluctuations and edge disturbances can alter lakeshore morphological complexity. From an ecohydrological perspective, the enhanced landscape heterogeneity along the lake margin exerts a nonlinear influence on evapotranspiration water consumption by modifying the area ratio and spatial configuration of the land–water interface zone. As shoreline heterogeneity increases, the water–air interface and emergent vegetation area expand, which in turn enhances evapotranspiration losses. This increased water loss leads to further shoreline exposure and fragmentation during low-water periods, amplifying the spatial correspondence between edge complexity and ET. This feedback mechanism is particularly relevant for actively managed dryland urban lakes, as maintaining higher water levels to minimize shoreline exposure effectively reduces ET losses by decreasing shoreline length and emergent vegetation area. Based on these findings, the following quantitative management recommendations are proposed. First, water replenishment should be concentrated between May and August, when evapotranspiration accounts for 80.5% of annual losses (Table 2). Monthly supplementation volumes of approximately  $15 \times 10^4 \text{ m}^3$  in May and  $98 \times 10^4 \text{ m}^3$  in July are recommended, with intermediate months

adjusted proportionally to the ET curve (Figure 4). Second, a safety margin of 15–20% of the total annual EWD, corresponding to approximately  $300\text{--}400 \times 10^4 \text{ m}^3$ , should be reserved for years with below-average precipitation ( $<230 \text{ mm}$ ). Third, to maintain water levels that prevent excessive shoreline exposure, automatic water level monitoring should be implemented, with supplementation triggered when water levels approach the lower threshold of the normal ecological water level range, thereby ensuring that water depth in the littoral zone does not fall below 1 m. Replenishment should occur at least bimonthly during the summer months to adequately buffer the seasonal ET peak.

The ecological water demand calculation results show that comprehensive evapotranspiration is the primary component of dynamic loss in Yuehai Lake, accounting for 32.4% of the total water demand (Table 4), a proportion consistent with findings from East Juyan Lake. This evaporative dominance is further corroborated by studies on other dryland lakes. For instance, Ovan Lake in Iran, which lies in a semi-arid climate subject to comparable hydrological constraints, experiences its greatest water maintenance challenges during late spring and summer, when precipitation declines and evaporative demand intensifies. For instance, the ecological water requirement of Ovan Lake in Iran, also situated in a semi-arid climate, was estimated at  $241 \times 10^3 \text{ m}^3$  for wet periods and  $207 \times 10^3 \text{ m}^3$  for drought periods, with evaporation consistently identified as the primary loss component [32]. This parallel reinforces that evaporative control is a universal priority for dryland lake management. This study further reveals the spatial correspondence of landscape pattern spatial heterogeneity on this water consumption process. Combining the spatial distribution patterns of landscape metrics (Figure 3), the water surface evaporation process in the central open water area, where high AI and high LPI are clustered, is primarily controlled by meteorological factors and water depth thermal capacity. In contrast, in the lakeshore meandering zones with higher LSI and in vegetation-interface zones with increased SHDI, the increase in aerodynamic roughness and radiation-receiving area drives an elevation in evapotranspiration intensity. Zhao et al. provided quantitative research evidence: in arid and semi-arid regions, vegetation ecological water demand is positively correlated with LPI and negatively correlated with SHDI, meaning that the more fragmented the patches, the lower the ecological water demand [17]. The high LPI in the core area of Yuehai Lake maintains a higher basal water demand, while the increase in SHDI in the edge zone drives increased evapotranspiration water consumption. This echoes the watershed-scale patterns found by Zhao et al. in mechanism but differs in direction, reflecting the essential difference between lake water bodies and watershed vegetation in their pattern-process responses.

#### 4.2. Methodological Limitations and Uncertainty in Ecological Water Demand Estimation

This study employed a Darcy's Law zonal calculation method, dividing the lakebed into low, moderate, and medium permeability zones based on hydraulic conductivity differences, and estimated the annual seepage volume to be  $239.23 \times 10^4 \text{ m}^3$  (Table 3). Compared to the traditional homogeneous assumption, this method characterizes the spatial variability of lakebed geological structure to a certain extent, but limitations still exist. The application of Darcy's Law relies on the assumption of steady-state flow, whereas actual lake–groundwater interactions exhibit non-steady-state characteristics influenced by seasonal water level fluctuations and surrounding extraction activities [11]. Constrained by exploration data, this study simplifies the characterization of the aquifer medium underlying the silt layer, failing to fully reflect the anisotropy of the three-dimensional geological structure. Therefore, while the seepage volume estimated in this study is reasonable in order of magnitude, future research needs to integrate high-density groundwater monitoring well network data with numerical simulation methods to further clarify the spatiotemporal

dynamics of the seepage process and its uncertainty contribution to the total ecological water demand.

It should be emphasized that the EWD estimate of  $2036.97 \times 10^4 \text{ m}^3$  strictly reflects the climatic conditions of 2022. In a drier year (precipitation  $< 230 \text{ mm}$ ), higher atmospheric demand and reduced cloud cover could elevate evapotranspiration losses by 10–15%, while enhanced hydraulic gradients may increase seepage rates by 5–10%. Conversely, in a wetter year (precipitation  $> 300 \text{ mm}$ ), the inherent lake water volume could be slightly larger (by 2–5%), whereas evaporative losses may decrease by 5–10% owing to increased cloud cover and humidity. These interannual climatic variations could cause the total EWD to fluctuate by approximately 10–20% relative to the 2022 estimate. Consequently, water managers should adopt a safety margin of 15–20% (approximately  $300\text{--}400 \times 10^4 \text{ m}^3$ ) during drought periods to safeguard ecological integrity under adverse conditions. The EWD estimates are subject to parameter uncertainties. Based on plausible parameter ranges—mean depth varying within 0.1 m of the baseline, hydraulic conductivity within 20%, Penman–Monteith-derived ET within 8%, and lake area within 2—the propagated uncertainties for each component are as follows: inherent lake water volume, approximately 5.2% (roughly  $59.2 \times 10^4 \text{ m}^3$ ); comprehensive evapotranspiration, approximately 10.1% (roughly  $66.6 \times 10^4 \text{ m}^3$ ); and lakebed seepage, approximately 15.3% (roughly  $36.6 \times 10^4 \text{ m}^3$ ). The total EWD uncertainty consequently falls within roughly 12.8%, yielding an interval of  $1776.6 \times 10^4 \text{ m}^3$  to  $2297.3 \times 10^4 \text{ m}^3$ . A one-at-a-time sensitivity analysis indicated that the total EWD is most sensitive to lake area and mean depth (each approximately 11.2%), followed by evapotranspiration coefficients (approximately 6.5%), whereas seepage-related parameters—hydraulic conductivity and hydraulic gradient, each approximately 2.3—exert relatively minor influences. These uncertainty bounds should be incorporated into water replenishment planning, especially under changing climatic conditions.

The EWD quantification is based solely on the year 2022. Although 2022 was a hydrologically representative year, interannual variability may alter both the absolute magnitude and the relative partitioning of water demand components. The mean lake depth (1.56 m), derived from a single bathymetric survey, does not account for seasonal fluctuations that may vary by approximately 0.1 m, thereby introducing uncertainty into the inherent water volume calculation. The 30 m resolution of the CLCD may inadequately resolve narrow shoreline edges and fragmented vegetation patches, potentially leading to underestimation of LSI and SHDI and overlooking ecologically significant microhabitats. Darcy's Law assumes steady-state flow, whereas lake–groundwater interactions are inherently transient, varying with seasonal water level fluctuations and groundwater extraction activities. Treating the aquifer as homogeneous within each permeability zone neglects anisotropy and three-dimensional geological structures that may govern preferential seepage pathways. The Penman–Monteith equation and the depth-modified evaporation model rely on parameterizations calibrated specifically for the Yinchuan Plain, which may not fully capture interannual variability in meteorological forcing. To address these limitations, future research should integrate high-resolution multispectral UAV imagery to resolve fine-scale landscape heterogeneity, employ stable isotope tracers for source-water fingerprinting, and establish a dense groundwater monitoring network coupled with numerical modeling to refine seepage estimates and validate the spatial correspondence framework across multiple years.

## 5. Conclusions

Based on multi-temporal remote sensing imagery and long-term meteorological and hydrological data, this study analyzed the landscape pattern evolution characteristics of Yuehai Lake from 2014 to 2022, quantified the total ecological water demand and its compo-

ment composition required to maintain the lake ecosystem integrity in 2022, and explored the spatial correspondence between landscape pattern and ecological water demand.

The overall landscape structure of Yuehai Lake has remained highly stable, with extremely strong water body connectivity and no significant fragmentation. Over the past decade, the Aggregation Index (AI) of the core lake landscape patches has consistently stayed above 95, and the Largest Patch Index (LPI) has remained stably above 90%.

In 2022, the annual ecological water demand required to maintain the ecosystem integrity of Yuehai Lake was  $2036.97 \times 10^4 \text{ m}^3$ , including an inherent water volume demand of  $1138.02 \times 10^4 \text{ m}^3$  for maintaining water body morphology, a comprehensive evapotranspiration volume of  $659.72 \times 10^4 \text{ m}^3$ , and a lakebed seepage volume of  $239.23 \times 10^4 \text{ m}^3$ . The static base water storage constitutes the main component of the total ecological water demand, while among the dynamic loss terms, evapotranspiration water consumption occupies the dominant position. However, these quantitative estimates strictly reflect the climatic conditions of 2022 and are subject to variation during extreme dry or wet years.

Several limitations of this study should be acknowledged. The model may be constrained by the spatial resolution of remote sensing imagery and the homogeneous assumption of the lakebed geological structure inherent in Darcy's Law, which limits its ability to characterize the complexity of micro-scale landscape edges and three-dimensional groundwater dynamics. Future research should integrate stable isotope tracing with high-resolution UAV multispectral imagery. This would help investigate the spatiotemporal responses of the lake–groundwater continuum under multiple scenarios and provide more rigorous guidance for spatial management and targeted ecological water supplementation in dryland urban wetlands.

**Author Contributions:** Conceptualization, J.M.; Methodology, J.M. and L.X.; Software, L.X., Y.W., J.R. and L.F.; Validation, L.X.; Formal analysis, L.X.; Data curation, L.X. and J.M.; Writing—original draft, L.X.; Writing—review & editing, J.M.; Supervision, J.M.; Funding acquisition, J.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Natural Science Foundation of China, Zhiping Li (Grant numbers 41901285 and 41972261), and the Training Plan for Young Backbone Teachers in Higher Education Institutions in Henan Province, Junzhen Meng (Grant number 2023GGJS073).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data are available from the corresponding author upon reasonable request.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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