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Determination of the Environmental Water Requirement Based on the Integrating Hydrology and Ecological Response

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ABSTRACT

Lakes, essential for human survival, are highly productive ecosystems that provide services such as water supply and nutrient regulation. However, escalating water scarcity, driven by global population growth and climate change, necessitates a comprehensive, long-term approach. This study employs an integrated framework of hydrology and ecological response components to determine the environmental water requirements for Ovan Lake, Iran. The research examines Ovan Lake's hydrological components, including precipitation, evaporation, and surface and groundwater exchange. Identifying the breeding activities of the great reed warbler in the lake's marginal reed lands as a key ecological relationship, the study highlights its role in reflecting the favorable status of other species and providing conservation benefits. Maintaining a water depth of 50–70 cm near the reeds, with a reed cover width of approximately 20 m in March, the breeding month, is recommended to ensure optimal breeding conditions for great reed warblers. Correlations between hydrological conditions (water depth, area, and volume) and ecological water depth are established, with environmental water requirements estimated at 241,000 m^3 and 207,000 m^3 during drought and wet periods, respectively. The analysis calculates water shortfalls needed to meet environmental water demands under different scenarios and ecological conditions, aligning minimum and optimal water levels to drought and wet periods based on prevailing conditions. Results indicate challenges in maintaining ecological conditions in late spring and summer due to reduced rainfall and increased evaporation, underscoring the need for proactive management strategies to sustain Ovan Lake's environmental health and restoration.

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Introduction

Urbanization and unsustainable water resource exploitation threaten lakes, crucial components of environmental and hydrological networks. These invaluable ecosystems recharge groundwater aquifers, provide food and habitat for diverse species, and play essential roles in water cycles. Recognizing their importance, researchers emphasize the need for holistic management to ensure both ecological health and societal benefits. Studies highlight the complexity of water resource systems and the interconnected social, economic, and environmental factors affecting lakes. Agnihotri et al. (2023) stress the importance of accurately modeling hydrological dynamics, much like accounting for frozen ground effects on snowmelt infiltration, to sustain ecosystems such as lakes that offer essential services like water supply and nutrient regulation. In both cases, a comprehensive, long-term approach is critical for addressing climate change challenges and ensuring accurate prediction of water-related phenomena. Meng et al. (2019) identify the need to balance water usage and wetland protection in the Nenjiang River Basin, revealing a decline in structural efficiency and rising conflicts between water supply and demand. Modabari and Shokoohi (2019) investigated water use in the Amirkalayeh wetland, establishing the environmental water requirement (EWR) at 5.36 million m^3 for minimum conditions and 6.74–7.25 million m^3 for optimal conditions. Sarhadi et al. (2013) compared various hydrological methods for estimating EWRs, finding that hydraulic methods are particularly effective in arid regions and noting limitations in the Tennant and Q95 methods. Hughes et al. (2010) proposed an integrated framework for EWR, examining how altered flow regimes impact ecosystem responses and enabling the design of modified flows to meet ecological objectives, while also addressing implementation challenges with practical examples. Sajedipour et al. (2017) focused on Bakhtegan Lake, recommending EWRs based on socioeconomic, physicochemical, biological, and ecological factors, with a focus on flamingos as keystone species. Gholami et al. (2020) used hydrological, hydraulic, and PHABSIM models to determine EWRs for seasonal rivers feeding the Miankaleh wetland, applying habitat desirability curves for target fish species. Ren et al. (2023) and Zheng et al. (2023) further explored EWR determination and its ecological implications across different contexts. Zhu et al. (2022) and Zhang et al. (2019) examined coordinated development between urban systems and ecosystems, with Zhu et al. (2022) developing a model to analyze the coupling coordination degree between urban development and ecosystems, observing a shift toward lagging ecosystems and recommending proactive policies for restoring balance.

Farmani et al. (2024) highlighted that, just as precise soil hydraulic parameterization in land surface models enhances soil moisture prediction accuracy, understanding and managing the hydrological and ecological dynamics of lakes is essential for sustaining vital ecosystem services amid escalating water scarcity driven by climate change. Zhang et al. (2019) proposed a dynamic evaluation index system to assess water resources and environmental carrying capacity, underscoring its role in guiding the sustainable development and use of water resources. Ahmadi et al. (2024) emphasized the importance of managing lake hydrology and ecology, drawing a parallel to the need for assessing extreme flood impacts on infrastructure like bridges—both crucial for resilience and sustaining ecosystem services in a changing climate.

This study focuses on Ovan Lake, a highland lake in Iran hosting diverse wildlife within its central water zone and two distinct biotopes. Aiming to determine the lake's water demands, a holistic approach is applied, investigating hydrological factors such as precipitation, evaporation, runoff, drainage, and groundwater exchange. Sensitive plant and animal species will be identified as ecological indicators to establish optimal and minimum acceptable conditions for the lake. Based on the lake's morphology and the relationship between index species and hydrological conditions, suitable water volumes will be allocated for both minimum and optimal scenarios. The novelty of this research lies in its integrated framework, which considers multiple aspects of EWR determination, flexible analysis of ecosystem responses, and emphasis on monitoring and data integration. Building on existing studies and adopting a holistic approach, this research contributes to the essential task of preserving and restoring lakes like Ovan Lake, ensuring their ecological viability and safeguarding their invaluable contributions to the environment and local communities.

Methodology

Research design

The study's results have practical applications for various stakeholders, including natural resource managers, rural development officials, agricultural organizations, private sectors involved in medicinal plants, and farmers, making it an applied study in terms of purpose. This research employs a quantitative approach, using a survey for data collection, with a cross-sectional design that examines a specific point in time rather than tracking participants longitudinally. Data was collected via a questionnaire, and a descriptive-correlational method was applied for analysis. Consequently, the study's data analysis methods are both descriptive and relational.

The study area

Ovan Lake, located in Iran's Alborz Mountain range within the Alamut region, is a 9-hectare alpine lake situated at 1800 meters above sea level and spanning around 70,000 square meters. Surrounded by the villages of Ovan, Varbon, Zavar-Dasht, and Zar-Abad, it is mainly fed by the Ovan Stream, rainfall, and springs that provide a year-round supply of clear water. This natural heritage site supports a small yet vital ecosystem, primarily dominated by common reed beds, which serve as a key habitat for breeding and migratory birds, especially during fall. In warmer months, it offers opportunities for recreational activities such as fishing, swimming, and yachting, while winters see the lake's transformation into a space for skiing and ice skating. The lake's bird population, though not fully cataloged, comprises diverse breeding and migratory species, emphasizing Ovan Lake's role as an important seasonal sanctuary.

Ovan Lake serves as a critical breeding ground for various bird species attracted by its reed lands, including the great reed warbler, cuckoo, Cetti's warbler, and moorhen, all nesting among the reeds. Migratory birds also frequent the lake as they navigate the Alborz mountains, making it a valuable birdwatching location. Significant migratory species include plovers, sandpipers, terns, gulls, herons, ducks, as well as both the great crested and little grebes. The lake also supports native fish, notably the introduced common carp and pike, both valued economically. The carp's preference for reed-covered, temperature-tolerant habitats aligns well with Ovan's aquatic environment, although pollution and reed loss are notable threats to its population. The lake, spanning about 7.6 hectares of open water and extending to 9.4 hectares with surrounding reed beds, reaches a depth of 6.5 meters and is enriched by southeast flood-prone sub-basins. Beyond ecological significance, the lake contributes to local tourism and agriculture, sustaining biodiversity while enhancing the landscape's beauty and economic value.

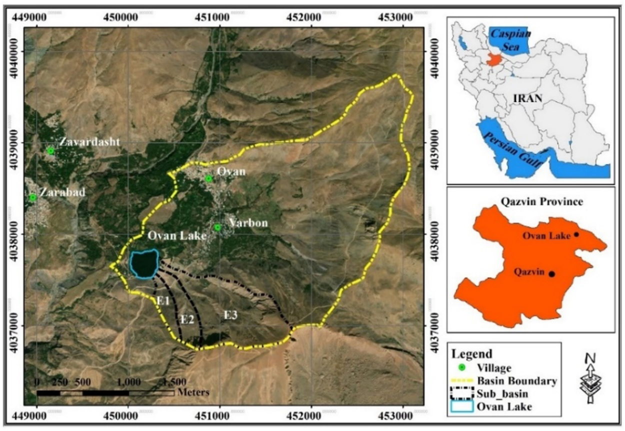

Figure 1. Study Area of the Case Study

Determining the environmental water requirement

The study aimed to assess Ovan Lake's environmental water requirements (EWR) by analyzing key meteorological, hydrological, biological, biodiversity, and ecological parameters. Initial analysis focused on identifying crucial meteorological and hydrological indicators, including precipitation, plant evapotranspiration, precipitation-induced runoff, and both surface and groundwater exchanges. For this stage, meteorological data from Moalem Kalayeh station, sourced from Qazvin regional water corporation, was used to evaluate these factors.

Subsequent stages included examining biological and ecological data to establish direct relationships between protected species—encompassing plant, phytoplankton, and fish species—and the available water levels. Expert surveys helped select index species by evaluating five criteria, as outlined in Table 1. These criteria guided the ranking of plant and animal species based on their relevance as ecological indicators, ultimately calculated using Equation 1 (Shokouhi et al., 2014). This approach allowed for identifying indicator species essential for sustaining lake biodiversity in response to fluctuating water levels.

$$\text{Species rating} = \sum_{1}^{i} Criteria * Coefficient \qquad (1)$$

Where i is the number of criteria, and each coefficient is allocated between 1or 0.

Table 1
Criteria and their coefficients in species index number.

Criteria	Coefficients
International conservation value	9
National conservation value	7
Genetic value	5
Ecological value	5
Economic value	3
Hunting value	1

After selecting index species, the study determined the lake's ecological level needed to sustain habitat suitability for these species. Two ecological conditions were established:

Optimum Ecological Conditions: This level represents the water requirement necessary to maintain the best conditions for the selected species, preventing any population decline. Minimum Ecological Conditions: This threshold is the minimum water level that risks species extinction or loss of habitat suitability, where water volume is significantly reduced compared to natural levels.The water volume corresponding to these conditions was estimated using a volume-surface-height diagram, crucial in assessing the lake’s water requirement at various levels. This diagram, based on the lake's ecological level, guided the calculation of required water volumes to ensure species survival and habitat sustainability.

Investigation of hydrological components

Investigation of Basic and Influential Factors on Hydrological Conditions

The water balance equation considered in this study includes parameters such as rainfall, snow, runoff, evaporation from the water surface, evapotranspiration, and leakage from the lake floor which is shown in Equation 2.

$$\Delta S = P - I - E - T - RO - DD \qquad (2)$$

Where ΔS is the change in root zone soil water storage over the time period of interest, P is precipitation, I is interception loss, E is direct evaporation from the soil surface, T is transpiration by plants, RO is surface runoff or overland flow, and DD is deep drainage out of the root zone. All quantities are expressed in terms of the volume of water per unit land area or equivalent depth of water over the period considered.

To determine the EWR of Ovan Lake using a holistic method, the main water sources of the wetland, including precipitation, the amount of runoff arising from precipitation, and inflow to The study on Ovan Lake utilized the Standardized Precipitation Index (SPI) to classify hydrologic periods into drought, normal, and wet categories. The SPI was calculated using data from the 1966–2020 time series, as shown in Figure 3 and Equation 3. The highest recorded precipitation occurred in the 1991-1992 water year, totaling 569.8 mm, while the lowest precipitation was recorded in the 2011-2012 water year, at 199.4 mm. Figures 2 and 3 illustrate the average monthly values of precipitation and evaporation across different statistical periods. The results indicate a noticeable increasing trend in precipitation over recent years, highlighting changes in the regional hydrological patterns.

$$SPI = P_i - \frac{\overline{P}}{S} \qquad (3)$$

In this regard: Pi is the monthly or annual rainfall of the desired station; $\overline{P}$ and S are average and the standard deviation of the rainfall series, respectively.

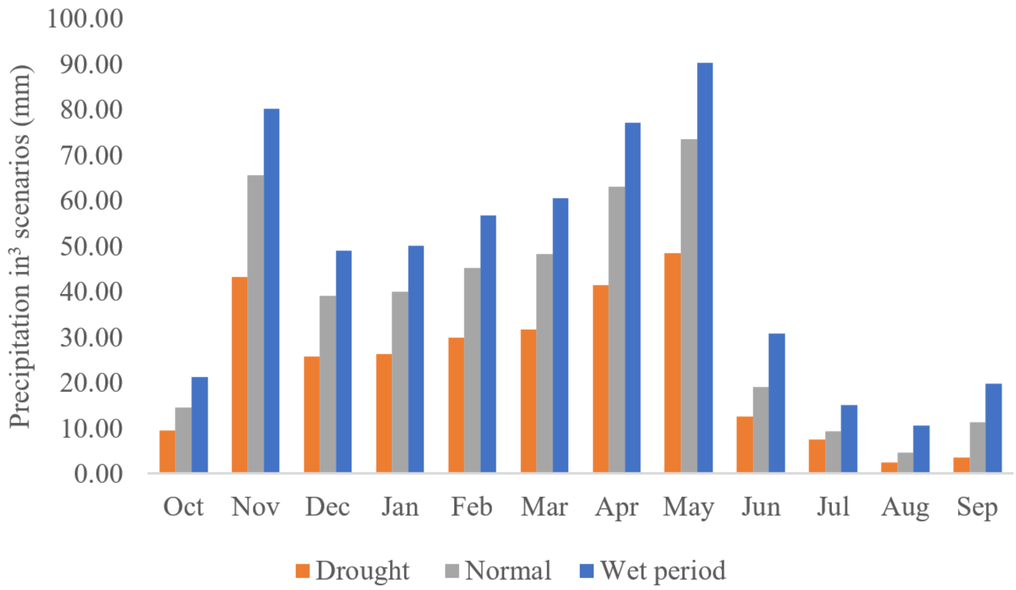

Figure 2. Average Monthly Values of the Precipitation in 3 Statistical Periods at the Moalem Kalaye Station

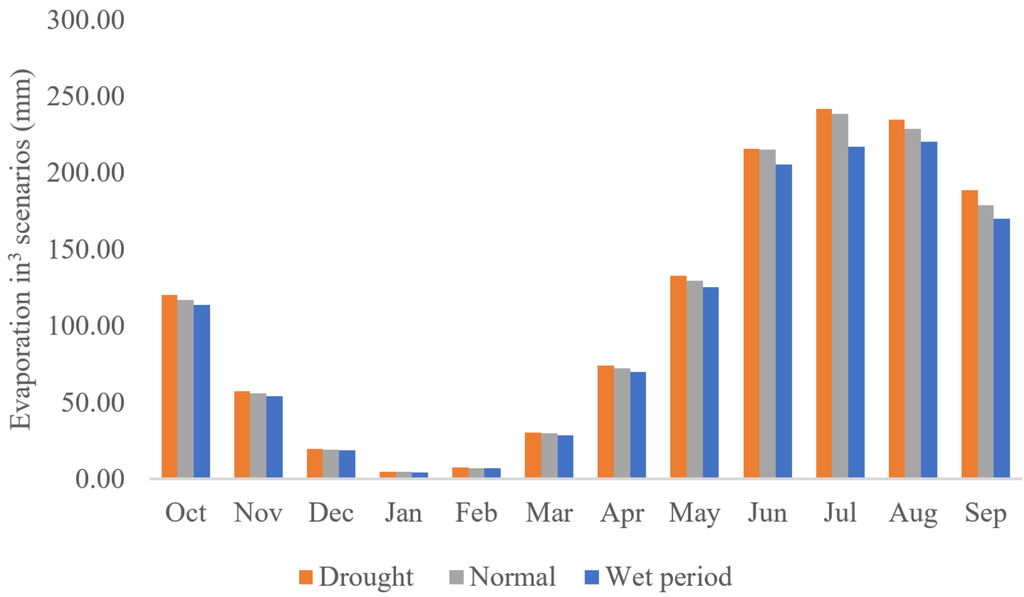

Figure 3. Average Monthly Values of the Evaporation Pan Method in 3 Statistical Periods at the Moalem Kalaye Station

The inflow from local streams in the northern valley of Ovan Lake is a key contributor to the lake's water supply. These streams are integral to the lake’s water balance and serve as indicators of water availability. During agricultural seasons, the streams are primarily used for irrigation, which supports the local economy. In colder months, these streams directly feed the lake, positively influencing its water levels. Water quality tests from these streams, especially at the point where water is divided between agricultural lands and the lake, show that the streams have good water quality. The direct influx of water from these streams during certain periods can significantly impact the lake’s volume and water levels.

Precipitation runoff is another vital component of the lake's water supply. Field studies and available data indicate that rainfall runoff flows primarily in the southeastern part of the hydrological unit, where three sub-basins are prone to flooding due to steep slopes and soil liquefaction during heavy rainfall. These floods transport considerable amounts of sediment, affecting the lake's water quality and overall health. In contrast, runoff from other parts of the hydrological unit does not reach the lake, as these areas have gentler slopes and are used for agriculture.

Evaporation from the lake's surface, along with the evapotranspiration of wetland plants, also plays a significant role in the water balance, further influencing the lake's hydrology and water levels. Table 2 details the characteristics of these sub-basins and their impact on the lake's water system.

Table 2
Characteristics of Subbasins Leading to Ovan Lake.

Units	Area (ha)	Perimeter (km)	Gravelius coefficient	Mainstream length (m)	Mainstream slope (m/m)
Sub-basin E1	7.07	1.48	1.56	820	0.46
Sub-basin E2	17.17	2.11	1.43	990	0.41
Sub-basin E3	75.76	4.15	1.34	1380	0.39

To estimate the evapotranspiration (ET) of wetland plants in Ovan Lake, the FAO56 publication method was used, incorporating the plant coefficient (Kc) for wetland plants during their growth periods, as referenced in Anda et al. (2014 and 2015). The Common reed, the dominant plant species in the lake, was primarily considered for this calculation. The estimated evapotranspiration values for the lake are presented in Table 3, with an annual total of 1117 mm. The highest evapotranspiration occurred in the middle growth stage, reaching 585 mm, while the lowest was recorded during the final stage at 32 mm. Groundwater also plays a critical role in the lake’s water balance. As Ovan Lake is an ephemeral stream, it only flows when its reservoir is full. Overflow water exits the lake to the southwest of the valley, and it is highly likely that water emerges from cracks and seams at the lake’s bottom, contributing to the water supply. This groundwater inflow is an important factor in maintaining the lake's water levels and overall hydrological balance.

Table 3
Evapotranspiration Values of Common reed During its Growth Period (Anda et al., 2014).

Growth stages by period	The initial stage	Intermediate stage	The final stage
Growth period by day	120	180	65
Plant coefficient (Kc)	1	1.37	1.2
Evapotranspiration (mm)	500	585	32
Total evapotranspiration (mm)	1117		

To estimate the maximum flood values for Ovan Lake, the water resources system and flood-prone sub-basins leading to the lake were evaluated. Due to the absence of a hydrometer station, various methods were employed to estimate flood values, including Deacon's experimental methods, Special Flood, Franco-Rodier and Fuller methods, and physical precipitation-runoff methods using nearby stations.

To assess water exchange at the bottom of Ovan Lake, the main outlet was identified by comparing changes in the reservoir volume to evaporation over time. This method, based on the Langbein method (Langbein et al., 1951), involves monitoring the reservoir volume changes while ensuring no surface inflow into the lake. By plotting the changes in volume against evaporation and fitting the data to a trendline, the water exchange can be inferred. If the intercept is positive, it suggests leakage from the lake, indicating groundwater outflow. A negative intercept suggests the lake is being recharged by groundwater, while an intercept of zero indicates the presence of an impermeable floor at the lake's bottom.

Drawing the surface-volume-height curve of the lake

To estimate the water balance of Ovan Lake more accurately, it is essential to determine the relationships between the lake's surface area, volume, and height. Relevant diagrams were created in GIS using bathymetric data of the lake surface and the DEM of the lake and its margins, derived from hydrographic information. Figure 4 shows the surface-volume-height curve, generated using the least squares method. This figure suggests that the geometry of the Ovan Lake reservoir allows the water surface area to reach 9.2 hectares at a level of 1800 m, with a maximum depth of approximately 7.5 m. Between 1799 and 1800 m, the slope intensity near the lakefront decreases slightly, resulting in a more substantial increase in lake volume and area for each meter of water level change.

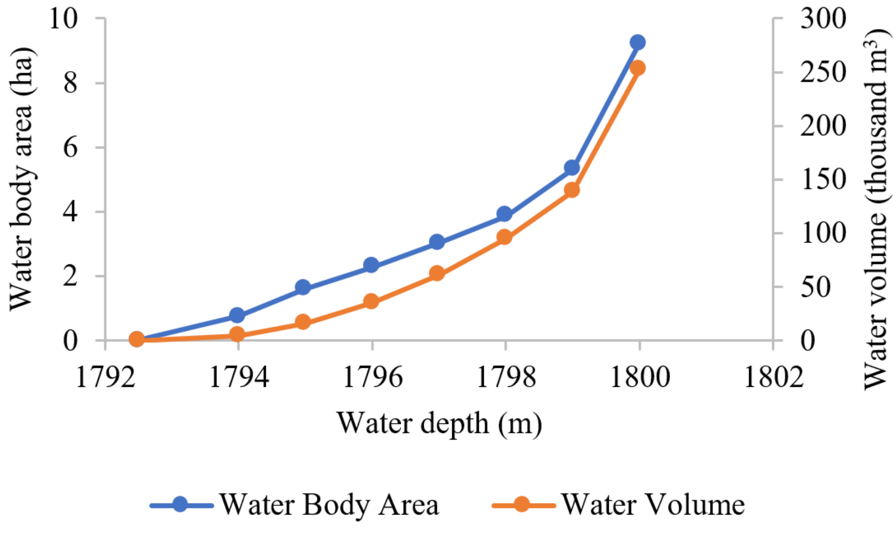

Figure 4. Surface-height and Volume-height Curves of Ovan Lake.

Results and Discussion

Ovan Lake's water balance

Meteorological data from Moalem Kalayeh station for precipitation and evaporation are displayed in Figures 2 and 3, along with the SPI index. Additionally, referencing the lake's tidemarks and watermarks, the Special Flood method was used to provide more reliable values for flood assessments. For groundwater assessments using the Langbein method, the water channel valves entering the lake were closed from early fall 2020 through spring (October to April), a period of seven months. During this time, changes in the lake's water level were recorded (Figure 5), showing the relationship between the lake reservoir volume and evaporation. A comparison of the changes in the lake's reservoir volume and evaporation values revealed a positive intercept, indicating that the lake water exchanges with groundwater, with water both leaking and discharging at the surface.

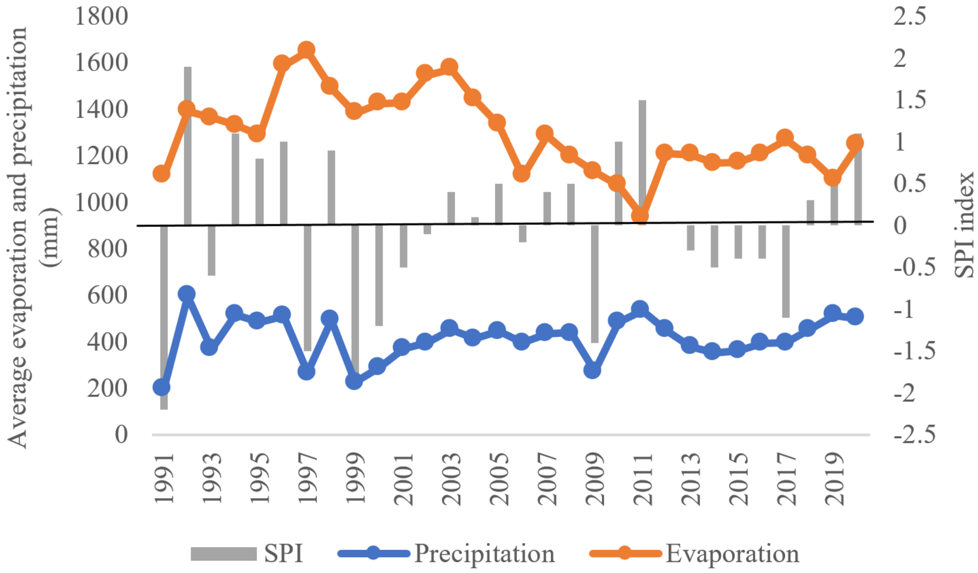

Figure 5. Average Evaporation, Precipitation, and SPI Index at Moalem Kalaye Station.

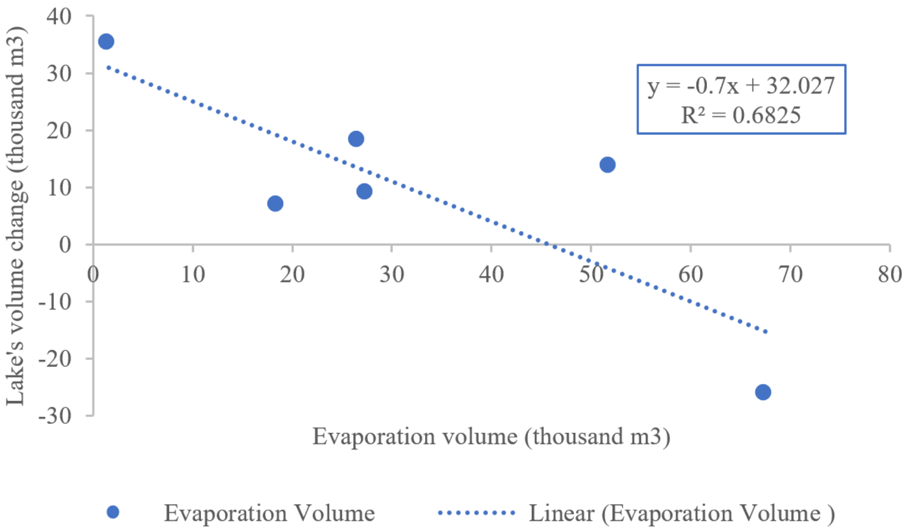

Figure 6. Rate of Changes in Lake's Volume Versus Evaporation Recorded for 7 Months.

During the investigation, the surface water inlet valves to the lake were closed, allowing the estimation of leakage from the lake floor by analyzing other parameters in the water balance equation. Changes in the lake reservoir's water volume were calculated over various time intervals, with input and output parameters analyzed in Table 4. Findings indicate that in all recorded periods, leakage from the lake floor exceeded the combined effects of evaporation and evapotranspiration. Thus, lake floor leakage was identified as the primary form of water output, estimated at an average of 39,400 m^3 discharged through leakage. This leakage estimate may increase when considering subsurface flow and the potential presence of a spring within the lake. Including groundwater discharge offers a more comprehensive estimate of total water exchange with groundwater. In the second half of the water year (April to September), decreased inflow leads to a drop in the lake's volume and water level, reducing the hydraulic load. According to Langbein's field measurements, this reduction in hydraulic load results in decreased leakage from the lake floor (Langbein et al., 1951).

Selection of ecological index

Selection of ecological index to determine the environmental water requirement of Ovan Lake

In this section, ecological indices were selected, and the water balance of Ovan Lake was determined using daily and monthly rainfall and evaporation data from the Moalem Kalayeh station, along with lake water level measurements collected over seven months. This assessment utilized balance Equation 2, applied to drought, normal, and wet period scenarios, to estimate the lake's inflow, discussed further in section 4.4 (Zhang et al., 2002). Additionally, ecological indices were selected by identifying protected plant and animal species and analyzing their direct relationship with the lake's water level and volume. Baseline data in the biodiversity section were analyzed to support this goal, showing that the extent, depth, and volume of aquatic vegetation are crucial in attracting various wildlife, especially waterfowl, to lakes. Ovan Lake, in particular, offers an optimal habitat for sustaining both wildlife and fish species.

Table 4
Components of Ovan Lake Balance Equation in 7 Months Used for Estimating the Exchange Rate of the Lake and Ground-water.

Sampling Date							
Day	**7**	**5**	**8**	**11**	**31**	**24**	**5**
Month	**Oct**	**Nov**	**Dec**	**Jan**	**Jan**	**Feb**	**Mar**
Depth (cm)	80	49	72	56	50	42	30
Volume (thousand m^3)	229	194	220	202	195	186	172
number of days		28	33	34	19	25	49
Volume changes (thousand m^3)		352	-261	182	681	908	136
Precipitation (mm)		10	107	25	20	47	7W0
Snow (cm)		0	9	25	20	0	26
Runoff (mm)		5	58	23	15	24	48
Evaporation pan (mm)		94	39	23	8	13	87
Evaporation from the water surface (mm)		59	23	14	6	9	64
Evapotranspiration (mm)		81	32	19	7	11	64
Direct rainfall (thousand m^3)		1	10	2.4	1.9	4.4	6.6
The volume of direct snow water (thousand m^3)		0	0.8	2.3	1.9	0	2.4
Runoff volume (m3)		5.1	5.8	22.8	15.1	23.8	47.8
Evaporation volume from the water surface (thousand m^3)		4.5	1.7	1	0.4	0.7	4.8
Evapotranspiration volume (thousand m^3)		1.5	0.5	0.3	0.1	0.2	1.1
Calculated volume changes (thousand m^3)		0	67	26	18	27.3	50.7
The difference between the measured and calculated water volume in each time period		35.3	40.9	44.3	25.1	36.4	64.4
Exchange with groundwater (thousand m^3)		37.8	37.2	39.1	39.7	43.7	39.4
Water leakage from the lake floor on a monthly scale (thousand m^3)				39.4			

Uniform reed masses at Ovan Lake provide essential habitats for wildlife refuge, bird nesting, fish breeding, and amphibian and reptile life. Among the key wildlife, the great reed warbler and moorhen are vital breeding species dependent on reed masses and stable water levels for reproduction, making them particularly vulnerable to water shortages and nesting area drying. Pike establish small territories within and around reed areas, aggressively defending them, while common carp seek shelter in these reed zones for protection from predators. The lake and surrounding habitats also support species like Grebes, which rest briefly in this safe environment during migration, as well as waterfowl such as Mallards, Teals, Great Cormorants, Herons, Sandpipers, and birds of prey, which are drawn to the wetland as a stopover along their migration route.

Ovan Lake also serves as a critical habitat for local amphibians and reptiles, supporting them in spawning, feeding, and hibernation. The second stage of analysis identified Ovan Lake's critical ecological functions, as summarized in Table 5. Among these, the breeding of the great reed warbler in reed areas was selected as the key ecological indicator, reflecting the habitat's health and providing a conservation umbrella for other species. This selection upholds the environmental integrity of Ovan Lake, reinforcing both biodiversity and habitat conservation. The choice of the great reed warbler and reed habitats as ecological indicators considers their combined international, national, ecological, tourism, and economic value. Additionally, the lake's flow depth was deemed appropriate for sustaining favorable habitat conditions for these indicator species, supporting the broader ecological balance within Ovan Lake.

Relationship between selected ecological indicators and hydrological conditions of Ovan Lake

Establishing the correlation between hydrological conditions and specific ecological indicators is essential for determining the Environmental Water Requirements (EWR) of lakes. To maintain habitat suitability for selected indicators—such as wetland depth, area, and volume—it is necessary to define their relationship with hydrological conditions. This relationship is crucial for ensuring optimal hydrological conditions for other ecological functions. For Ovan Lake, appropriate hydrological conditions were identified to support the presence of Common reed and to facilitate the breeding of migratory waterfowl in the reeds and along the lake's margins. The Common reed vegetation provides critical habitat for wildlife reproduction and refuge; its reduction or absence would likely diminish both the ecological and economic value of the lake.

As an integral component of the aquatic ecosystem, the Common reed occupies portions of the lake's water zone, and fluctuations in its volume and biomass over time can greatly impact its ecological functions. This plant also plays a vital role in ecosystem purification and maintaining ecological balance, marking it as one of the wetland's most crucial elements. Algae, serving as primary producers, further contribute to this wetland's ecological structure. Migratory birds that breed within the wetland depend on the reeds for nesting, selecting parts of the reed with specific structure and height suited to each species. While birds skillfully choose nest locations, the presence of water within the reeds and along the lake's edges—leading toward drier areas—can be a critical factor in limiting suitable nesting sites.

Table 5
Checklist of Important Ecological Functions for Ovan Habitat.

Ecological function	Connection with water requirement	Related species	Descriptions

1	Wildlife habitat	It is a breeding habitat for vertebrates and a place for resting and recuperating migratory birds and a place for hatching birds, especially a place for resting and recuperating a large number of migratory birds.	great reed warbler, moorhen, marsh frog, pike, and common carp	The water depth of 30-40 cm in the margins of the wetland, especially around the reed lands, provides suitable conditions for the regeneration of the vertebrates of the wetland.
2	Providing shelter for wildlife	The presence of a reed mass next to a wide water area provides a suitable shelter for wildlife.	Breeding birds, passing birds, common carp, reptiles and amphibians	A water area of more than 7 ha with a water depth of more than 40 cm, along with a mass of straw aquatic plants in the margins and a large mass of aquatic plants submerged in the water body can be a suitable shelter for wildlife.
3	Bird breeding place	The presence of water and vegetation provides the basis for nesting. Also, water prevents the direct presence and access of fishermen and hunters to the nests.	great reed warbler and moorhen	Reed lands offer safe nesting grounds for waterfowl and terrestrial birds. The water depth of 30-40 cm in the center and along the edges protects nests from invaders.
4	Habitat for fishes	A suitable habitat for fishes and their spawning	Pike and common carp	Common carp and pike thrive in water that is 40-50 cm deep, has good quality and quantity
5	Habitat and spawning ground of amphibians	The presence of water, vegetation, shelter, etc. provides the breeding ground for amphibians in the wetland.	marsh frog, treefrog, and green toad	Vertebrates need at least 20-30 cm of water in wetlands with aquatic plants for spawning. These conditions also provide shelter and easy access for predators.
6	Areas under the management of the environmental protection organization	Shooting and hunting are prohibited	Under the protection of Environmental Organizations	The area of this freshwater lake reaches 8 and sometimes 9 ha during high water. This wetland is a part of the prohibited shooting and hunting area of eastern Alamut.

The presence of adequate hydrological conditions, such as maintaining water depths of 50 to 70 cm adjacent to and extending from the reed beds to the drier sides of the wetland, helps deter invasive species and enhances breeding success for species that cannot defend themselves. By ensuring these optimal conditions, Ovan Lake can sustain its most critical environmental functions, creating a suitable habitat that supports key ecological processes and promotes the well-being of native and migratory species reliant on the wetland.

Sustainable management through flow regime restoration and holistic ecological assessment

To maintain optimal conditions in wetland ecosystems, it is recommended to adjust water flow to closely mirror the natural flow regime rather than optimizing it solely for one or a few species. This approach supports biodiversity and preserves the wetland's eco-hydrological stability over the long term. The holistic method operates on the premise that sustaining the natural hydrological regime will keep the ecosystem at its best if maintained at appropriate times. For Ovan Lake, the priority is to retain the natural flow regime to comprehensively meet the lake's water needs under ideal conditions. Here, the optimal ecological level is the lake's maximum water volume that prevents overflow at the outlet. When water overflows, it obstructs access to Zarabad village, contrary to holistic principles that aim to balance benefits for all stakeholders. To address this, a study was conducted to analyze rainfall patterns with 2-, 5-, and 10-year return periods in the watershed. Based on the findings, a free height of 5 cm was allocated for storage in the lake reservoir, with the lake depth during overflow at 95 cm. Using the lake's surface-volume-height curve and its ecological level, the surface area and volume of Ovan Lake can be determined under optimal ecological conditions.

To prevent further impacts during periods of water scarcity, establishing a threshold limit for Ovan Lake's minimum ecological water volume is essential. Analysis focused on biodiversity index species and critical ecological functions has shown that the relationship between the great reed warbler and Common reed is of utmost importance. Common reed is distributed throughout the lake, except for a small eastern section accessible to tourists annually. A decline in reed coverage or its desiccation would severely threaten breeding birds, including the great reed warbler and moorhen, which depend on the reeds for nesting. These birds are vulnerable to disturbances from human presence and animals like jackals.

To support breeding, maintaining a water depth between 50 and 70 cm near the reeds, with a reed cover width of around 20 m, is ideal, particularly for the great reed warbler's breeding season in March. For fish species like pike and common carp, a water depth of 50–70 cm below the reeds provides an optimal spawning ground in March, which may extend throughout the year as water levels fluctuate.The minimum ecological level was defined considering lake morphology and fish population density, corresponding to a 50 cm water depth. Using the lake's surface-volume-height curve and the ecological level, the lake's surface area and volume under minimum ecological conditions can be calculated. Table 6 outlines the values of water level, area, and volume for both desired and minimum ecological conditions.

Table 6

Levels, Area, and Volume of the Lake in Desired and Minimum Ecological Conditions.

Ecological condition	Lake water level (m)	Total area (ha)	Total volume (thousand m^3)
Desired	1799.9	8.83	241
Minimum	1799.6	7.67	207

Based on the ecological conditions established for minimum and optimal levels, the intermediate range between these two was defined as acceptable. Consequently, the monthly water requirements were estimated based on lake volume, as illustrated in Fig 7. December, January, and February were excluded from the estimation due to favorable balance input conditions and the freezing of the lake surface.

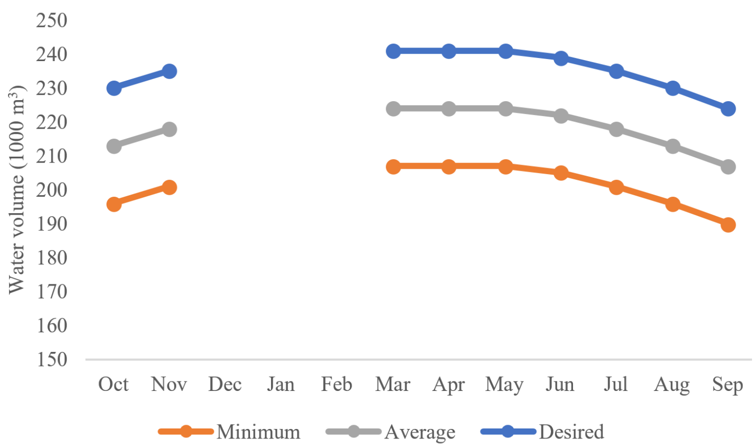

Figure 7. Surface-height and Volume-height Curves of Ovan Lake.

Adjusting the water requirement of the lake in different weather scenarios according to the simulation of the long-term statistical period of the water system

Meteorological and climate studies for the region informed an assessment of the water balance equation across various scenarios, incorporating hydrologic components such as monthly average rainfall and evaporation under drought, normal, and wet conditions. When inflow exceeds the lake's maximum capacity, surplus water overflows from its southwestern side, flowing toward the valley. The lake's maximum capacity is determined by the critical riparian level and the highest volume the lake can contain, while the initial water volume at the start of the water year is taken as the lake's water volume at summer's end.

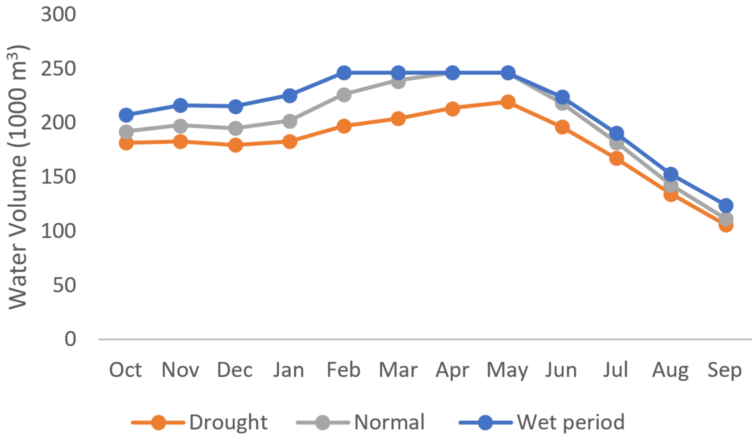

Figure 8. Ovan Lake Water Volume in Drought, Normal, and Wet Period Scenarios.

In drought conditions, the limited water resources make it challenging to meet the lake's water needs for maintaining favorable ecological conditions. Consequently, water requirements should align with the ecological thresholds appropriate for each scenario. Achieving optimal conditions may not be feasible in drought periods, where only the minimum ecological standards might be sustained. To estimate the water needed to reach the targeted levels under drought, normal, and wet scenarios, the monthly and annual lake water volume was compared against minimum, acceptable, and optimal conditions, respectively. The corresponding water shortages for each scenario were calculated, as shown in Fig 9.

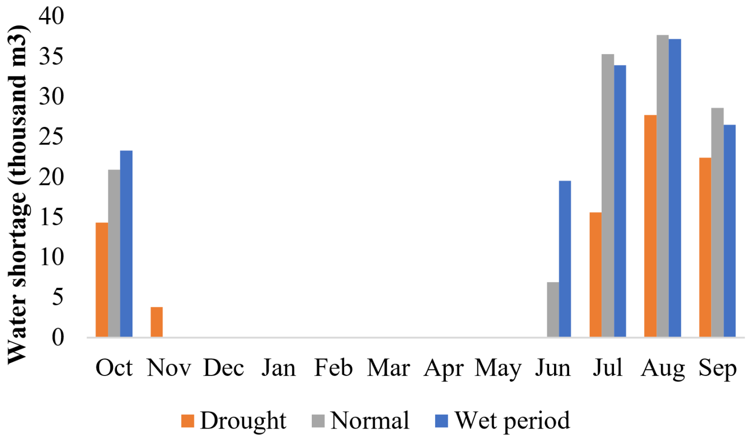

Figure 9. The Required Water in Ovan Lake to Meet the Water Needs in Different Scenarios.

The findings indicate that to maintain Ovan Lake's ecological balance and stability across different hydrological scenarios, increasing inflow sources is essential. A stream located north of the lake, currently used for irrigating agricultural lands and arbors, sometimes diverts part of its flow into the lake, presenting a viable additional water source. It is recommended to optimize irrigation systems and manage agricultural water rights concerning this stream to support sustainable water input for Ovan Lake.

Conclusion

Lakes are vital ecosystems that foster connections between terrestrial and aquatic life, supporting diverse species and acting as biodiversity hotspots. They sustain ecological health through intricate nutritional and ecological relationships. Recognizing the environmental water requirements (EWRs) of lakes is fundamental for conservation, restoration, and minimizing ecological damage. This paper assesses the EWRs of Ovan Lake using a holistic approach that combines hydrological and ecological methods. Discharge patterns were analyzed across drought, normal, and wet conditions, followed by an assessment of biodiversity, ecological functions, and interactions between the lake's flora and fauna relative to its water needs.

In alignment with Integrated Water Resources Management principles, an optimal ecological balance was identified to reflect the lake's health and provide suitable habitats for its restoration. Experts evaluated biodiversity, ecological roles, and interdependencies between species. The hatching success of the great reed warbler, an aquatic migratory bird, was selected as an ecological index for monitoring, given its sensitivity to water level changes, trophic role, measurability, and the availability of census data. Maintaining Ovan Lake's natural flow regime emerged as a priority, ensuring sufficient water provision and managing water levels to prevent overflow at the lake's outlet. A critical relationship was noted between the large reed cuckoo and the Common reed, forming a nesting habitat in a 20-meter strip around the lake. Reductions in reed cover or partial desiccation would threaten bird nesting and lake health. Recommended measures include maintaining a water depth of 50–70 cm at the base of the reeds and a reed cover width of 20 meters extending towards the lake's dry borders to support breeding conditions for wetland species. A minimum volume of 207,000 m^3 and an optimal volume of 241,000 m^3 were deemed necessary to sustain Ovan Lake's ecological balance, promoting the lake's essential functions and supporting its resident species. Understanding and meeting lakes' environmental water demands, as illustrated by this study on Ovan Lake, are crucial for effective ecosystem conservation. Sustainable development must account for aquatic ecosystem health, watershed value, and climate resilience to protect natural resources and support biodiversity for the long term.

CrediT authorship contribution statement

Parnian Yazdani and Morteza Karimi developed the theoretical formalism, performed the analytic calculations and performed the numerical simulations. Hadi Modaberi supervised the project.

Declaration of competing interest

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

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