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An evaluation of the ecological security of the Dongting Lake, China

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ABSTRACT

Evaluation of lake ecological security is important for sustainable management of lakes and regional ecological environment construction. Dongting Lake is the second largest freshwater lake in China; its ecological security directly threatens the ecological security of the middle and lower reaches of the Yangtze River. In this paper, the ecological security evaluation index system of the Dongting Lake is constructed, including target layer (first order), criterion layer (second order), and index layer (last order). The target layer is the ecological security of the lake, the standard layer includes five indicators, and the index layer includes 11 indicators. The comprehensive evaluation method is used to evaluate the ecological security of the Dongting Lake by assessing all indexes of every layer. The weight of each index is determined by analytic hierarchy process. The evaluation results showed that the ecological security score of the Dongting Lake is 58 points, belonging to sub-security level. At present, the Dongting Lake has problems of low ecological water level, reduced lake surface area, eutrophication, and reduced lake storage capacity. Therefore, in future, the industrial and domestic pollution sources should be controlled, and the carrying capacity of water environment should be improved.

Keywords: Lake ecological security; Evaluation; Index; Weighting and scoring; The Dongting Lake

1. Introduction

Lakes have many functions, such as regulating river runoff, developing irrigation, providing water sources for industrial and drinking, breeding aquatic life (AL), communicating with shipping, improving regional ecological environment, and developing mineral resources. However, the rapid development of economy and population brings great pressure to the lake environment. Large amounts of nitrogen and phosphorus nutrients as well as toxic and harmful pollutants enter into lakes and reservoirs, which may increase algal risk in lakes [1,2].

In China, the total freshwater storage capacity of lakes is 226 billion m^3, accounting for 8% of the total amount of freshwater resources. A number of large and medium-sized lakes in China have the problem of ecosystem degradation, and 60% of large reservoirs are eutrophic. Some lakes have lost their ecological function of providing drinking water source. In short, human activities around lake basins have seriously exceeded the ecological carrying capacity of lakes [3].

The Dongting Lake, the second largest freshwater lake in China, covers an area of 18,780 km^2, which is an important commodity grain-, cotton-, oil-, and fish-producing region of Yangtze River Basin. The ecological security of the Dongting Lake directly threatens the ecological security of the middle and lower reaches of the Yangtze River. With the increase of population, industrial enterprises, and small towns in the Dongting Lake area, the increasing pollution loads from point source and non-point source leaded to water contamination have become a prominent environmental problem in the Dongting Lake area [4]. During years of 1990–1995, the east Dongting Lake has received about 240 million tons effluents of urban and industrial wastewater per year. In recent years, although some measures have been taken to control water contamination, there is still about 150 million tons of wastewater being discharged into the Dongting Lake every year. In 2006, the water quality (WQ) of all the water samples in the Dongting Lake exceeded the National Class III Water

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Standard (Environmental Quality Standards for Surface Water [GB3838-2002]), 10% and 90% of which belonged to the National Class IV Water Standard and National Class V Water Standard, respectively [5]. Therefore, it is necessary to evaluate the ecological security of the Dongting Lake and put forward corresponding measures to protect the ecological environment of the Dongting Lake.

Lake ecological (LE) security refers to lakes' good natural ecological conditions and lakes' function providing sustainable social services (SSs). The lakes' natural ecological conditions include the physics, chemistry, and ecology of lakes, and their conditions are described by the physical, chemical, and biotic integrity of lakes; the lakes' function of SSs means that lakes have the capacity to provide services to human society continuously. LE security evaluation [6] refers to the evaluation of physical integrity (hydrological integrity and physical form [PF] integrity), chemical integrity, biological integrity, and service function integrity of lakes as well as their mutual compatibility.

In some countries in Europe and the United States, the aim of LE security evaluation is to the lake watershed management. Assessing the health status and development trend of lake ecosystem and identifying their stress state can provide a reliable management tool for the scientific evaluation of LE restoration effects and the determination of the priority of LE restoration measures (Table 1).

The researches on LE security evaluation in China have been focused on the Yellow River, the Yangtze River, and the Pearl River Basins, with contents focusing on the analysis of ecological indexes. Researchers as well as China's

Table 1
Security evaluation indexes of lakes of different countries

Biological index	Europe	The composition and quantity of phytoplankton and the biomass per unit area; the composition and quantity of large plants and benthic plants; the composition and quantity of benthonic invertebrates; the composition, quantity and age structure of fish, etc.
	USA	Attached diatom; phytoplankton (algae); zooplankton; benthic macroinvertebrates; algae density (chlorophyll-a); invasive species
	Japan	The living condition of organisms around the lake; the condition of waterside plants; the habitat and living condition of birds and other small animals; the habitat and living condition of fish; the living condition of benthos
Physical index	Europe	Water quantity and dynamics characteristics; residence time; connection with underground water bodies; change of lake depth; the number, structure, and substrate of lakebed; lakeshore structure, etc.
	USA	The coverage and structure of habitat in lakeside zone; the coverage and structure of habitat in shallow water; human disturbance in lakeside zone
	Japan	Water quantity condition (whether the water quantity is enough in sunny weather); natural flow ratio (how many natural water quantity in the lake without being affected by human beings); bank condition (natural or artificial); the moving obstacles of fish and other organisms (whether there are buildings obstructing the moving of organisms); the inflow and outflow water quantity of outer lake basin.
Chemical index	Europe	Transparency; thermal condition; oxidation condition; salinity; acidification; nutritional status. Specific pollutants (pollution caused by all major pollutants; pollution caused by other substances discharged into the water)
	USA	Nutrients (total nitrogen and total phosphorus,); dissolved oxygen, temperature, pH, turbidity, buffer capacity, salinity, mercury content in sediment
	Japan	COD or BOD (the amount of organic matter excreted in human daily life); transparency; fecal coliforms; ammonia nitrogen; odor; dissolved oxygen
Landscape and recreation index	Europe	
	USA	Fishing; swimming
	Japan	Landscape (feel) (whether the waterside landscape is coordinated); visual (whether the garbage is heaped by the water); touch (do you feel good when you touch the bottom of the river); smell (whether the water smells good); hearing (whether the sounds heard by the water are comfortable); geographical resources of history and culture (whether there is history and culture related to the river evaluation, whether it is developed); difficulty and easiness of being near water (whether it is safe and easy to be near water); utilization of residents (whether walking around the lake, or carrying out recreational activities); economic activities (whether it is used for tourism, industrial and agricultural water, shipping, etc.); environmental activities (whether residents and other people use the evaluated river to carry out water environment learning and conservation activities)

river basin organizations have put forward some evaluation index systems and evaluation methods [7–12]. In LE security evaluation, the domestic researches pay attention to the ecological health and service function security of lakes and emphasize the harmony between people and water. Most of the scholars suggest that a secure lake is a lake with a balance between natural function and social function [13–16]. In this study, based on the physical, chemical, and biological integrity of lakes and SS function integrity, an ecological security evaluation index system of the Dongting Lake was established, including target layer, criterion layer, and index layer, to evaluate the ecological security of the Dongting Lake (Table 2).

2. Materials and methods

2.1. Description of the study area

The Dongting Lake, located between E 111°14′–113°10′ and N 28°30′–30°23′ at the south bank of Jingjiang River and the northern side of Hunan province, is the second largest freshwater lake in China with an area of 18,780 km^2. The Dongting Lake consists of the East Dongting Lake, the South Dongting Lake, and the West Dongting Lake (including Muping Lake and Qili Lake). The climate in the Dongting Lake area is north subtropical humid with an annual average temperature of 16.4°C–17°C and an annual precipitation of 1,100–1,400 mm, half of which is concentrated in spring (from April to June) and mostly is heavy rain and rainstorm [17–19].

The Dongting Lake water mainly comes from Xiangjiang River, Zijiang River, Yuanjiang River, and Lijiang River as well as the distributaries of Songzi estuary, Taiping estuary and Ouchi estuary, and flows out to form Chenglingji (Qili Mountain) [20]. Hudu River, with a total length of 137.7 km, after flowing through Mituo Temple, Huangjinkou, Zhakou, Haungshantou Controlling Gate, and Dongjiadang to Anxiang River of new mouth Songzi East Branch after being diverted at Taiping estuary, it flows into Lishui River spillway in Xiaojiawan. Songzi River, a spillway diverted into the lake by the distributary of Songzi estuary, is divided into two branches [21]. The two branches are further divided into three branches in Hunan province. The East Branch is also called Dahukou River, with a total length of 42 km; the Middle Branch is also called Zizhiju River, with a total length of 28.9 km; the West Branch is also called Huanhuan River, with a total length of 35.5 km. Ouchi River, located at Ouchi estuary of Jingjang River, discharges the water and sand of the Yangtze River into the Dongting Lake and consists of a main stream and three tributaries, with a total length of 360 km. The main stream, namely the East Branch, flows into the East Dongting Lake, with a total length of 101 km; the West Branch is also called Anxiang River, with a total length of 70 km; the Middle Branch flows into the South Dongting Lake, with a total length of 98 km; another river known as Tuojiang River, which connects Ouchi estuary East Branch with the South Dongting Lake, with a total length of 43 km. Tiaoxian River, flows out of Shishou city in Jiangjiachong to enter Huarong County, Hunan province, and is divided into west and north branches in Hongdu town, Yanhe County. The North Branch flows into the East Dongting Lake, with a total length of 60 km (Fig. 1).

The soil in the Dongting Lake area is predominated by red loam and paddy soil, accounting for more than 70% of the total area of soil [22]. The vegetation in the Dongting Lake area is limnophyte and beach plants, and the vegetation groups in the Dongting Lake area show a zonal distribution pattern according to vegetation moisture gradient change. From the lakebed of shallow lake to land, the following vegetation zones are distributed in proper order: the first is submerged aquatic vegetation; the second is floating-leaved aquatic vegetation; the third is emergent aquatic vegetation; the forth is swamp meadow vegetation; and the fifth is beach woody deciduous broad-leaved forest. The average number of phytoplankton in the Dongting Lake is 91.5 × 10^4 pcs/L, with a large range between 18.2 and 329.4 × 10^4 pcs/L in different areas. The main reason may be that high sediment content, low transparency, and large variation range of the water level of the Dongting Lake are harmful to algae growth. There are 90 species of zooplanktons and 67 species of zoobenthos, with an average density of 114 pcs/m^2. About 12 orders, 22 families, and 116 species of fish were recorded in the Dongting Lake. In the Dongting Lake, rare species, including first-grade state protection animals such as *Lipotes vexillifer*, Chinese sturgeon, and paddlefish and second-grade state protection animals such as *Neomeris phocaenoides* and *Myxocyprinus asiaticus*, have ever lived [23]. However, due to the habitats of them in the Dongting Lake were disturbed by human development activities, *Lipotes vexillifer*, Chinese sturgeon, paddlefish, and *Neomeris phocaenoides* are hardly seen, and *Myxocyprinus asiaticus* is occasionally seen, but their numbers have been significantly reduced.

The main water pollution sources in the Dongting Lake are the domestic wastewater derived from the residents around the Dongting Lake, industrial wastewater, pesticides, and anti-schistosomiasis drugs. There is about 150 million tons of wastewater being discharged into the Dongting Lake every year.

2.2. Research methods

2.2.1. Determination of the evaluation indexes

The ecological security evaluation index system of the Dongting Lake was established referred to the National Technical Document for River and Lake Health Evaluation (Health Evaluation Index, Standard and Method of Lakes) (experimental work) (Edition 1.0), including 1 target layer, 5 criterion layers, and 13 evaluation indexes (Fig. 2).

Minimum ecological water level (ML) of the lake is the lower limit of ecological water level, which is the lowest water level to maintain the normal operation of lake ecosystem [24]. If the water level is lower than the ML for a long time, the lake ecosystem will be seriously degraded. River flow condition (RFC) can be represented by the duration of river drying up, the decrease of annual runoff, and the annual standard rate of WQ [25]. Aquatic area shrinking rate (ASR) refers to the phenomenon of sustained decline in lake water level and continued decrease in water area and water storage capacity due to human activities. Dissolved oxygen (DO) was very important to aquatic animals and plants, high or low concentrations of DO will be harmful to aquatic organisms, and 4–12 mg/L is

Table 2
Security evaluation index of each lake basin

	Subitem	The Yangtze River	The Huanghe River	Taihu Lake	The Huaihe River	Songliao Basin	The Pearl River	The Haihe River
Index	1. Hydrology (water quantity)	The satisfaction degree of demand ecological water	Bankfull flow, environmental flow, environmental water quantity and instantaneous minimum flow		Minimum ecological water guarantee rate	Water level, flow, flow velocity	Ecological flow guarantee rate (%)	Relative drying up length and days, relatively drying up days, annual average flow rate
	2. Terrain	River connectivity	Channel elevation			Connectivity		
	3. Physical and chemistry (water quality)	The ratio up to the standard of water quality, soil and water loss ratio of water function zone	18 items of water quality, new added five items of water source	Nemero index	The ratio up to the standard of water quality of rivers and lakes, eutrophication index of lakes	10 items of water quality	21 items, eutrophication evaluation of reservoir	Water pollution index
	4. Aquatic life	The wetland reservation rate, index of biotic integrity of fish, survival of rare aquatic animal	Wetland, fish status	Nutrient index of chlorophyll-a, quantity of algae, number of protozoa, number of annelids	Index of aquatic life diversity	Biological monitoring indexes such as phytoplankton, planktonic animal, benthos, fish species and three-farm distribution, chlorophyll, riparian vegetation as well as community diversity, ecological integrity, survival status of rare aquatic organisms and other index	Epiphytic diatoms; reservoirs: zooplankton, phytoplankton.	River biodiversity (identified from the diversity of fish and plankton), floodplain vegetation coverage
	5. Function (social economic index)	Blocking rate of Schistosomiasis transmission, retention rate of excellent river regime, guarantee rate of navigable depth, measure improvement rate of flood control works, utilization ratio of water resources.		Reclamation intensity, entrance flow rate, fitness of flood control standard, flood control project execution, standard rate of water source, guarantee rate of water supply of port mouth, success rate of purse seine control, development and utilization ratio of shoreline		Development and utilization degree of water resources, groundwater depth (exploitation rate), the ratio up to the standard of water quality in water function zone		
Evaluation method	No	No	No	No	No	No	Yes, triangular diagram	Yes, comprehensive score

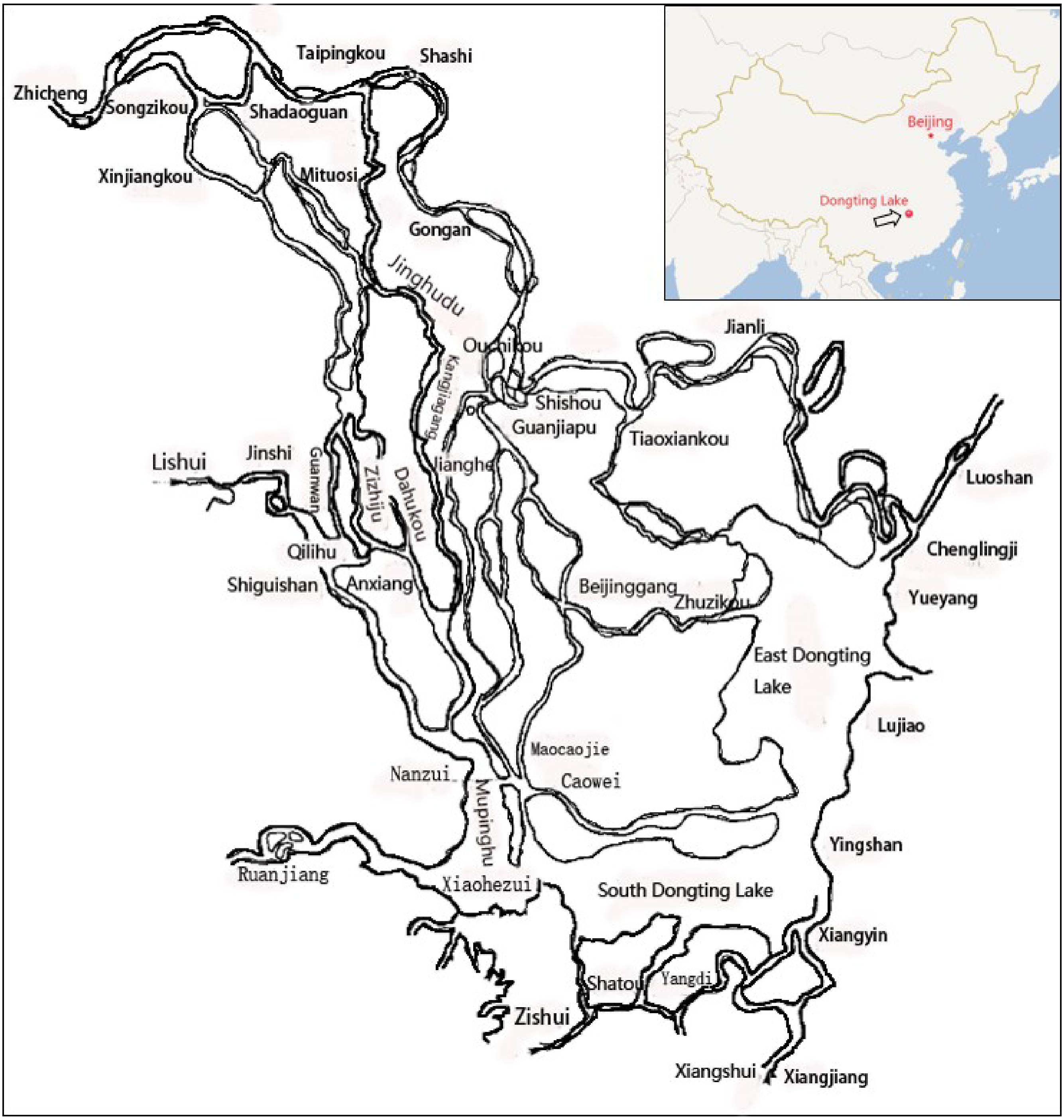

Fig. 1. Geographical map of the study area.

considered as the appropriate DO value. Oxygen-consuming pollutant (OCP) is an organic pollutant, which may cause reduction of DO concentration in water, including permanganate index (COD_{Mn}), 5-d biochemical oxygen demand (BOD_5), and ammonia nitrogen. Eutrophication (EU) refers to nutrients concentration, production capacity, and transparency of lake. Phytoplankton population (PHP) is an important index of lake conditions. Phytoplankton had short growth cycle, is sensitive to environmental changes, and the change of its biomass and population structure can reflect the status and change of lakes well. Macrophytes (MPH) coverage is an important part of lakeshore zones and is important for lake pollutant buffering and water purification. Fish loss index (FOE) refers to the ratio of fish species in the lake to historical reference fish species in the lake, which reflects the loss of top species in the lake ecosystem. Water resources utilization (WRU) is expressed by the utilization ratio of water resources and refers to the percentage of water supply in the lake basin

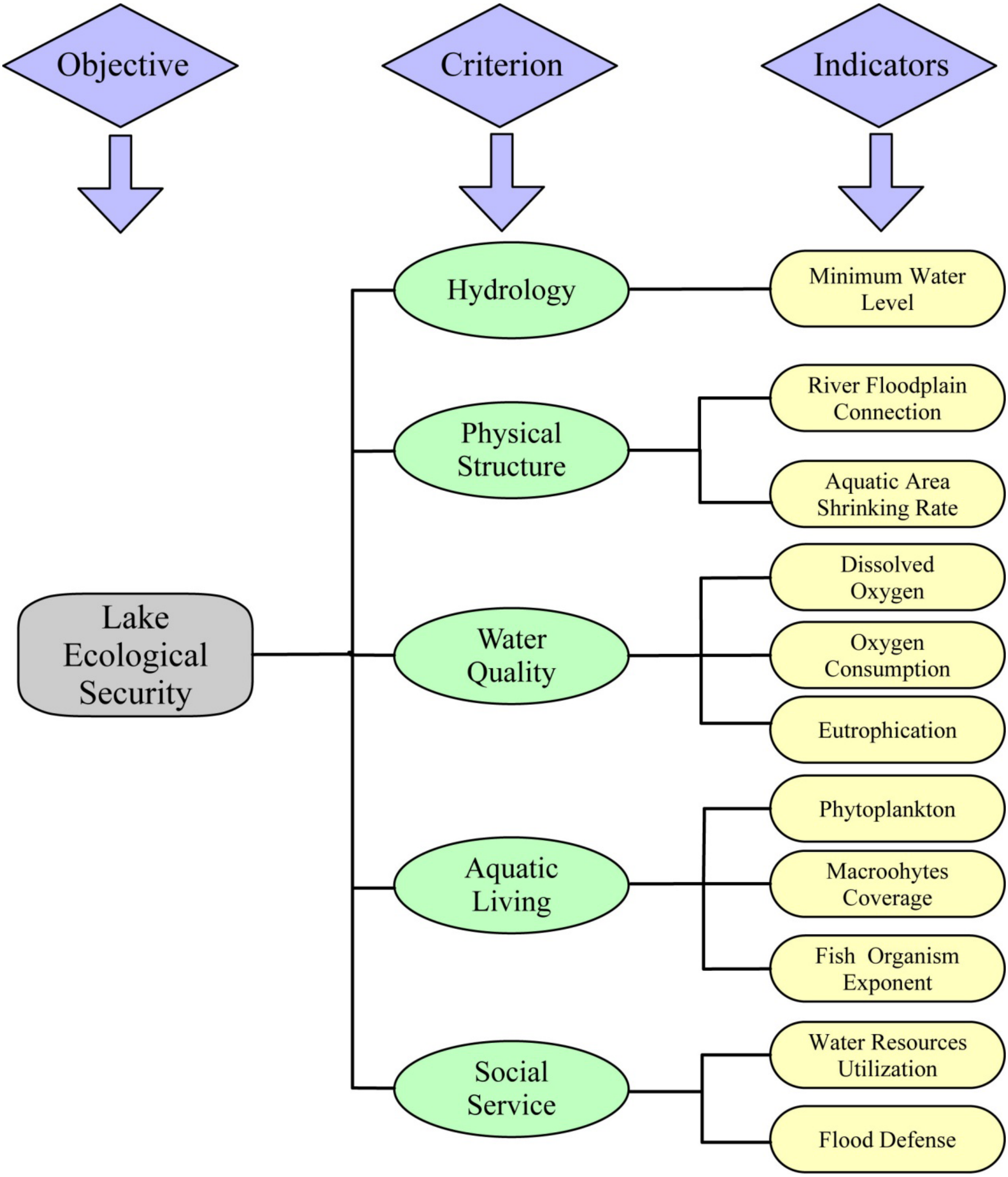

Fig. 2. Structure of the ecological security evaluation index system of the lake.

to the total water resources quantity in the lake basin, which reflects the influence of the economic and social activities in the lake basin on water resources quantity, as well as the development degree of the lake basin. Flood defense (FLD) refers to the flood control of the lake, which can reduce the flood control pressure of the upper reaches, peak discharge of the lake, and flood pressure of the lower reaches by retaining flood with lakes (Fig. 2).

2.2.2. Evaluation standard and method of the indexes

2.2.2.1. Hydrology The ML of the Dongting Lake is determined according to history natural water level data. The ML of the lake for many years under the natural conditions is considered as the ML. The ML of the Dongting lake under the natural conditions is calculated by using the measured average ecological water levels of 90% guaranty rate of nine water level stations, including Chenglingji, Yueyang, Lujiao, Yingtian, Yangliutan, Ruanjiang, Xiaohezui, Nanzui, and Shiguishan water level stations in 1980–1989, and the ML of each representative water level station for consecutive 3, 7, 14, 365, 30, and 60 d was analyzed (Fig. 3).

The scoring (HDr) of hydrology (HD) layer is calculated by the following formula:

$$\text{HDr} = \frac{1}{n}\sum_{i=1}^{n}\text{MLr}_i \quad (1)$$

Here, HDr is the scoring of HD, MLr_i is the scoring of the satisfaction degree of ML of the *i*th water level station, and *n* is the number of water level stations in the study area.

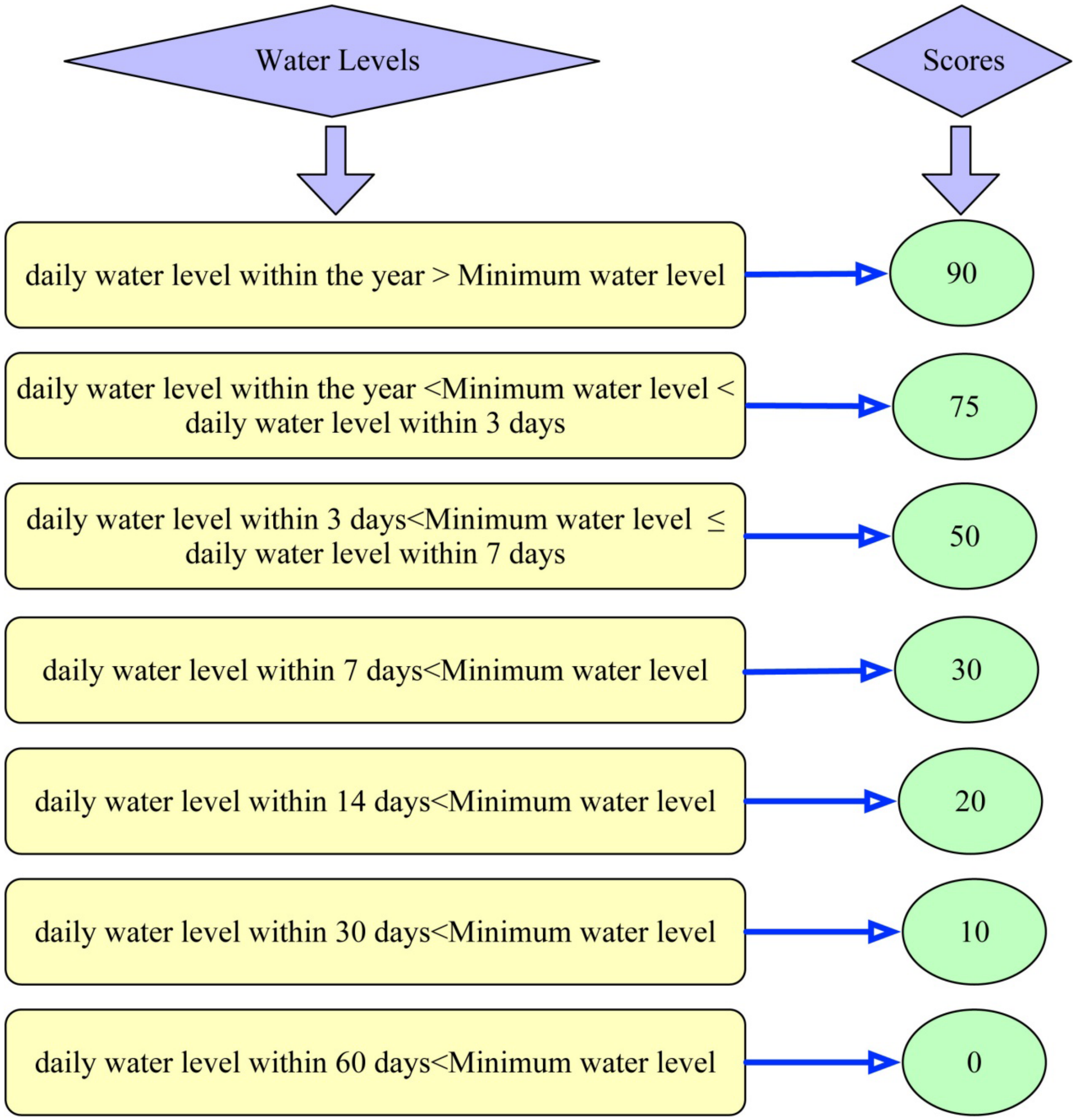

Fig. 3. Evaluation standard for the satisfaction degree of ML of the lake.

2.2.2.2. Physical form RFC mainly evaluated the flow between the rivers around the lakes and the lakes. The scoring of RFC is calculated by the following formula:

$$\mathrm{RFC} = \frac{\sum_{n=1}^{N_s} W_n R_n}{\sum_{n=1}^{N_s} R_n} \tag{2}$$

Here, N_s is the number of rivers around the lakes; R_n is the annual surface water resources of rivers around the lake in the evaluation year (10^4 m^3/y), and the surface water resources of outflow rivers are calculated according to the measured outflow water quantity; W_n is the scoring of the flow condition of the *n*th river, which is determined according to Table 3. For the duration of river drying up, the ratio of the inflow water quantity of rivers around the lake to the annual average measured annual runoff as well as the ratio up to the standard of WQ of inflow rivers are scored, and the worst condition was used to determine the score of the flow condition of each river around the lake and RFC was the comprehensive score of the flow condition of rivers around the lake (Table 3).

The ASR is calculated by the following formula:

$$\mathrm{ASR} = 1 - \frac{A_C}{A_R} \tag{3}$$

Here, A_C is the water surface area of the lake in the evaluation year; A_R is the historical reference water surface area of the lake, considering that the large-scale reclamation of lakes in China occurred in 1950s–1980s, the historical reference water surface area of the lake in the year before the 1950s should be selected; and ASR is the aquatic area shrinking rate of the lake area (Table 3).

The scoring of PF criterion layer is calculated by the following formula:

$$\mathrm{PFr} = \mathrm{RFCr} \times \mathrm{W_{RFC}} + \mathrm{ASRr} \times \mathrm{W_{ASR}} \tag{4}$$

Here, PFr is the scoring of PF, RFCr is the scoring of RFC, ASRr is the scoring of ASR, and W_{RFC} and W_{ASR} are the weights of RFC and ASR, respectively.

2.2.2.3. Water quality The DO adopted the annual average concentration of 12 months of the evaluation year and is averaged according to the flood and non-flood seasons. The scorings of DO in the flood and dry seasons are calculated respectively, and the lowest scoring is considered as the scoring of WQ (Table 4).

The scoring of OCP is considered as the average scorings of COD_{Mn}, BOD_5, and ammonia nitrogen, which are calculated in the flood and non-flood seasons, respectively, according to the annual average concentration of 12 months of the evaluation year, and their lowest scorings are used as the scorings of COD_{Mn}, BOD_5, and ammonia nitrogen, respectively, whose average is used as the scoring of OCP.

$$\mathrm{OCPr} = \frac{\mathrm{CODMNr} + \mathrm{BODr} + \mathrm{NH_3Nr}}{3} \tag{5}$$

Here, OCPr is the scoring of OCP; $COD_{Mn}r$, BODr, and NH_3Nr are the scorings of COD_{Mn}, BOD_5, and ammonia nitrogen, respectively.

The scoring of EU, including total phosphorus, total nitrogen, chlorophyll-a, COD_{Mn}, and transparency, is calculated respectively in accordance with the provisions of the Technical Regulations for Surface Water Resources Quality Assessment (SL395) (Table 5). The EU of the lake and reservoirs is evaluated using index method, and the formula is as follows:

$$\mathrm{EI} = \sum_{(n=1)}^{N} E_n / N \tag{6}$$

Here, EI is eutrophication index, E_n is the scoring of evaluation item, and N is the number of evaluation items.

The minimum value of DOr, OCPr, and EUr is used as the evaluation standard of WQ criterion layer.

$$\mathrm{WQr} = \mathrm{Min}(\mathrm{DOr}, \mathrm{OCPr}, \mathrm{EUr}) \tag{7}$$

Table 3
Determination and evaluation standard of the indexes of PF of the lake

Smoothness	Blocking time for river drying up (month)	The ratio of the inflow water quantity to the annual average measured annual runoff	The ratio up to the standard of water quality of inflow rivers	Scoring of the smoothness of rivers around the lake (W_n)	Range of RFC scoring	Description	Atrophy ratio of lake area	ASR scoring
Completely blocked	12	0%	0%	0	0–20	Very poor connectivity	5%	100
Seriously blocked	4	10%	20%	20	20–40	Poor connectivity	10%	60
Blocked	2	40%	40%	40	40–60	Common connectivity	20%	30
Very smooth	1	60%	80%	70	60–80	Good connectivity	30%	10
Smooth	0	70%	100%	100	80–100	Excellent connectivity	40%	0

Table 4
Scoring standard of OCP of the lake

DO (mg/L) (>)	DO scoring standard of OCP	Permanganate index (mg/L)	Oxygen demand of BOD_5 (mg/L)	Ammonia nitrogen (NH3-N) (mg/L)	OCP scoring
7.5	100	2	3	0.15	100
6	80	4	3.5	0.5	80
5	60	6	4	1	60
3	30	10	6	1.5	30
2	10	15	10	2	0
0	0				

Table 5
Evaluation standard and scoring standard of EU of the lake

EU classification (EI = eutrophication index)		Scoring of evaluated items (E_n)	Total phosphorus (mg/L)	Total nitrogen (mg/L)	Chlorophyll (α) (mg/L)	Permanganate index (mg/L)	Transparency (m)	EI value	EU scoring
Poor EU (0 ≤ EI ≤ 20)		10	0.001	0.020	0.0005	0.15	10	10	100
		20	0.004	0.050	0.0010	0.4	5.0	42	80
Mild EU (20 <EI ≤ 50)		30	0.010	0.10	0.0020	1.0	3.0	45	70
		40	0.025	0.30	0.0040	2.0	1.5	50	60
		50	0.050	0.50	0.010	4.0	1.0	60	50
EU	Slight EU (50 < EI ≤ 60)	60	0.10	1.0	0.026	8.0	0.5	62.5	30
	Moderate EU (60 < EI ≤ 80)	70	0.20	2.0	0.064	10	0.4	65	10
		80	0.60	6.0	0.16	25	0.3	70	0
	Severe EU (80 < EI ≤ 100)	90	0.90	9.0	0.40	40	0.2		
		100	1.3	16.0	1.0	60	0.12		

Here, WQr is the scoring of WQ criterion layer, DOr is the scoring of DO, OCPr is the scoring of OCP, and EUr is the scoring of EU.

2.2.2.4. Aquatic life The PHP is expressed by algae density, which is evaluated using direct scoring method. According to the survey data by Jin et al. [26], the annual average of algae in the lake varies between 10×10^4 and 10×10^7 pcs/L in 1980s–1990s. The scoring standard of PHP is shown in Table 6.

The MPH evaluated the total coverage of the non-alien species of floating plants, emergent plants, and submerged plants and is determined using direct evaluation and scoring method by experts.

The FOE is determined using historical background survey method. By using the FOE in the 1980s, a statistical analysis and evaluation of the number of fish species in the lake is conducted. Expert consultation and investigation are then carried out to determine the history background of fish in aquatic ecoregion where the lake is located and establish the investigation and evaluation expectation of FOE. The formula of the evaluation method of FOE is as follows:

$$\mathrm{FOE} = \frac{\mathrm{FO}}{\mathrm{FE}} \tag{8}$$

Here, FOE is fish loss index, FO is the number of fish species in the evaluated lake (excluding alien species), and FE is the number of fish species in the evaluated lake before the 1980s. The scoring standard of FOE is shown in Table 6.

The formula of the scoring of AL criterion layer is as follows:

$$\mathrm{ALr} = \mathrm{PHPr} \times W_{\mathrm{PHP}} + \mathrm{MPHr} \times W_{\mathrm{MPH}} + \mathrm{FOEr} \times W_{\mathrm{FOE}} \tag{9}$$

Here, ALr is the scoring of AL criterion layer, PHPr is the scoring of PHP, MPHr is the scoring of MPH, FOEr is the scoring of FOE, and W_{PHP}, W_{MPH}, and W_{FOE} are the weights of PHP, MPH, and FOE, respectively.

2.2.2.5. Social service The WRU is expressed by the utilization ratio of water resources and the formula is as follows:

$$\mathrm{WRU} = \frac{\mathrm{WU}}{\mathrm{WR}} \tag{10}$$

Here, WRU is the water resources utilization of the lake basin, WR is the water resources of the lake, and WU is the water utilization of the lake.

Table 6
Evaluation standard and scoring standard of AL of the lake

Algae density (10^4 pcs/L)	Scoring	MPH coverage	Description	FOE	Scoring standard of FOE
40.00	90.00	0.00	No such vegetation	1.00	100.00
100.00	75.00	0%–10%	Sparse vegetation	0.85	80.00
200.00	60.00	10%–40%	Moderate coverage	0.75	60.00
500.00	40.00	40%–75%	Heavy coverage	0.60	40.00
1,000.00	30.00	>75%	Extremely heavy coverage	0.50	30.00
2,500.00	10.00			0.25	10.00
5,000.00	0.00			0.00	0.00

There is an international agreement that the reasonable limit of WRU is 30%–40%, even if rainwater resources are used sufficiently, the WRU should not be higher than 60%. The scoring model of WRU is a parabola, at 30%–40% the scoring of WRU is the highest (each lake basin can be appropriately amended according to its characteristics), at too high (60%) or too low (0%), the scoring of WRU is 0. The formula of the scoring of WRU is as follows:

$$\text{WRUr} = a\times\left(\text{WRU}\right)^2 + b\times(\text{WRU}) \tag{11}$$

Here, WRUr is the scoring of WRU, WRU is the water resources utilization of the evaluated lake, and *a* and *b* are the coefficients, with a = 1,111.11 and *b* = 666.67.

The scoring of FLD, including scoring of fitness of flood control standard, flood control project execution (FLDE), storage capacity coefficient, flood venting capacity (FLDV), flood regulating capacity, flood control benefit, and flood loss rate, is calculated respectively. In this paper, the FLDE and FLDV are used as the indexes of FLD. The FLDE refers to the ratio of the length of the flood control dam reaching the flood control standard to the total length of the flood control dam (Table 7). The FLDV refers to the ratio of the allowable flood storage capacity of the lake to the planned flood storage capacity of the lake. The formulae are as follows:

$$\text{FLDE} = \frac{\text{BLA}}{\text{BL}} \tag{12}$$

$$\text{FLDV} = \frac{\text{VA}}{\text{BL}} \tag{13}$$

Here, BLA is the length of the flood control dam reaching the flood control standard, BL is the total length of the flood control dams, VA is the storage capacity of the lake, and VP is the planned flood storage capacity of the lake.

The formulae of the scoring of FLD are as follows:

$$\text{FLDEr} = \text{FDE}\times 100$$

$$\text{FLDVr} = \text{FDE}\times 100 \tag{14}$$

$$\text{FLDr} = \text{FLDEr}\times W_{\text{FLDE}} + \text{FLDVr}\times W_{\text{FLDV}}$$

Table 7
Scoring standard of FLDE and FLDV of the lake

Scoring	100	75	50	25	0
Flood control project execution (FLDEr)	95%	90%	85%	70%	50%
Flood venting capacity (FLDVr)	100%	90%	75%	60%	50%

Here, FLDr is the scoring of FLD, FLDEr is the scoring of FLDE, FLDVr is the scoring of FLDV, and W_{FLDE} and W_{FLDV} are the weights of FLDE and FLDV, respectively.

The formula of the scoring of SS criterion layer is as follows:

$$\text{SSr} = \text{WRUr}\times W_{\text{WRU}} + \text{FLDRr}\times W_{\text{FLDR}} \tag{15}$$

Here, SSr is the scoring of SS criterion layer, WRUr is the scoring of WRU, FLDVr is the scoring of FLDV, and W_{WRU} and W_{FLDR} are the weights of WRU and FLDR, respectively.

2.2.3. Ecological security evaluation method of the lake

Based on the scoring of HD, PF, WQ, AL, and LE, the scoring of ecological security of the lake is calculated combined with LE and SS, the scoring of the ecological security evaluation method of the lake is obtained. The formula of the scoring of ecological security of the lake is as follows:

$$\text{LSI} = \text{LEI}\times W_{\text{LE}} + \text{SSI}\times W_{\text{SS}} \tag{16}$$

The formula of the scoring of lake ecological integrity index (LEI) is as follows:

$$\text{LEI} = \text{HDr}\times W_{\text{HD}} + \text{PFr}\times W_{\text{PF}} + \text{WQr}\times W_{\text{WQ}} + \text{ALr}\times W_{\text{AL}} \tag{17}$$

Here, LSI is the scoring of lake security index, LEI is the scoring of LE integrity index, SSI is the scoring of services, and W_{LE} and W_{SS} are the weights of LE and SS, respectively. HDr is the scoring of HD criterion layer, PFr is the scoring of PF, WQr is the scoring of WQ, ALr is the scoring of AL, and

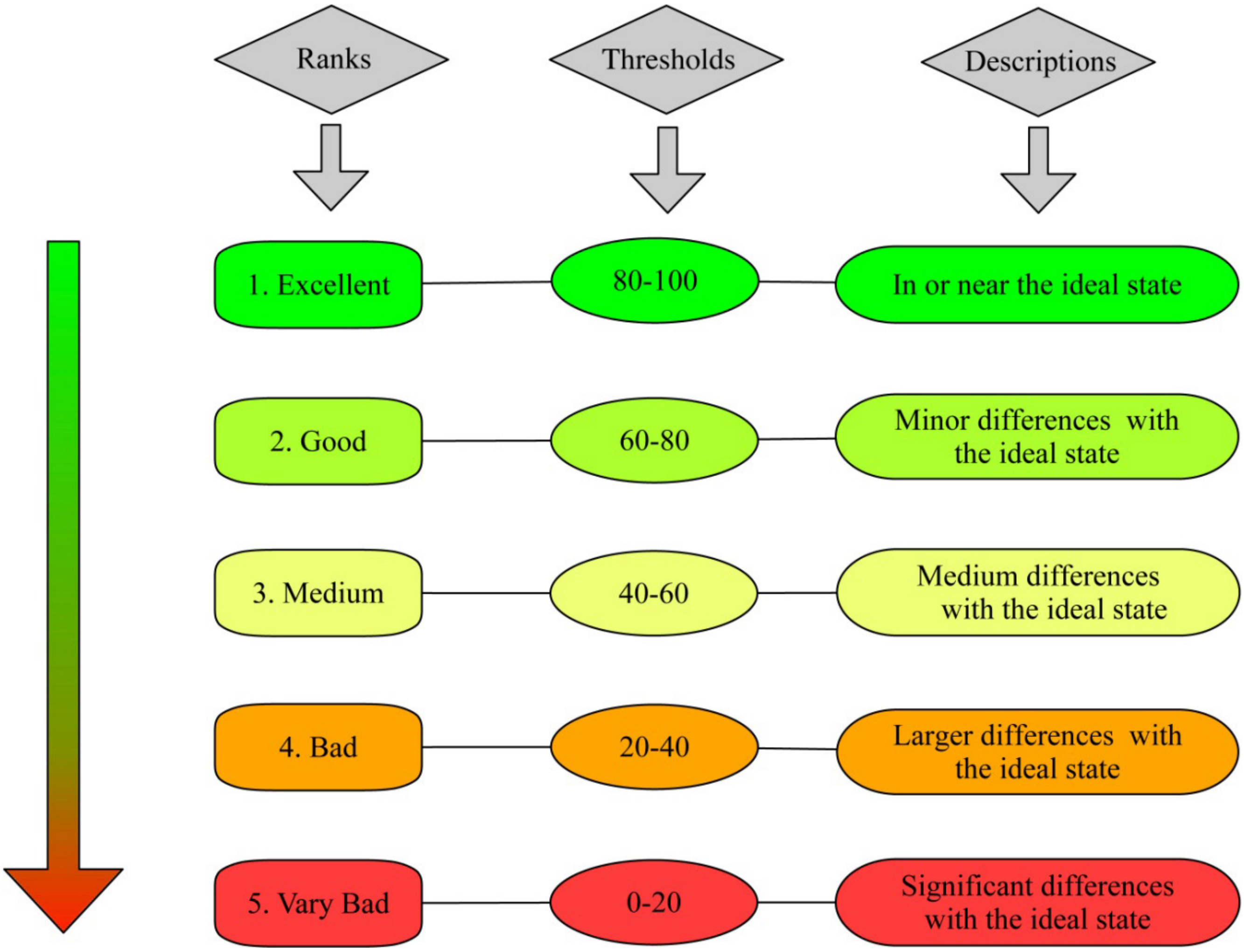

Fig. 4. Classification of lake security evaluation.

W_{HD}, W_{PF}, W_{WQ}, and W_{AL} are the weights of HD, PF, WQ, and AL, respectively.

The ecological security evaluation of the lake is conducted using classification index scoring method, and LSI is obtained using progressive weighting and comprehensive scoring method. LSI is divided into five levels (Fig. 4), including ideal, secure, sub-secure, grave, and highly grave.

2.2.4. Determination of the index weight

Each index is determined using analytic hierarchy process, which refers to that the weight between each index of the index layer and its criterion layer is obtained by solving the characteristic vector of judgment matrix. Finally, the weight between the criterion layer and target layer is obtained using weighted sum method.

3. Results and discussion

3.1. Security evaluation results of the Dongting Lake

The results showed that only Chenglingji had a high ML score of 100 points; Nanzui water level station had an ML score of 10 points; other water level stations had a low ML score of 0 point. Therefore, the HD criterion layer score was 12.2 points.

The PF criterion layer score was low with 39.29 points. The comprehensive RFC score was 78.58 points, indicating that the RFC of the Dongting Lake was good, because complex water systems and numerous dam works. As recommended by the experts, the duration of river drying up, with a score of 70 points, was "smooth" due to that the dam works have little blocking time for large river drying up. For Xiangjiang River, Zijiang River, Yuanjiang River, and Lijiang River, their annual average inflow water quantity was 146 billion m^3, and their annual average runoff was 185.7 billion cm^3, accounting for 89.3% of the annual average measured annual runoff of inflow rivers, with a score of 100 points. According to the actual monitoring results, the average ratio up to the standard of WQ of the lake and large inflow rivers was 74.31%, with a score of 65.73 points. The ASR score of the Dongting Lake was 0 point. The maximum water area of the Dongting Lake was 4,350 km^2 in 1949 and 2,291 km^2 in 2008 through remote sensing image analysis. The lake atrophy ratio was up to 47.33% (Fig. 5).

The WQ criterion layer score of the Dongting Lake was 47.97 points. Among which, the EU score was the lowest

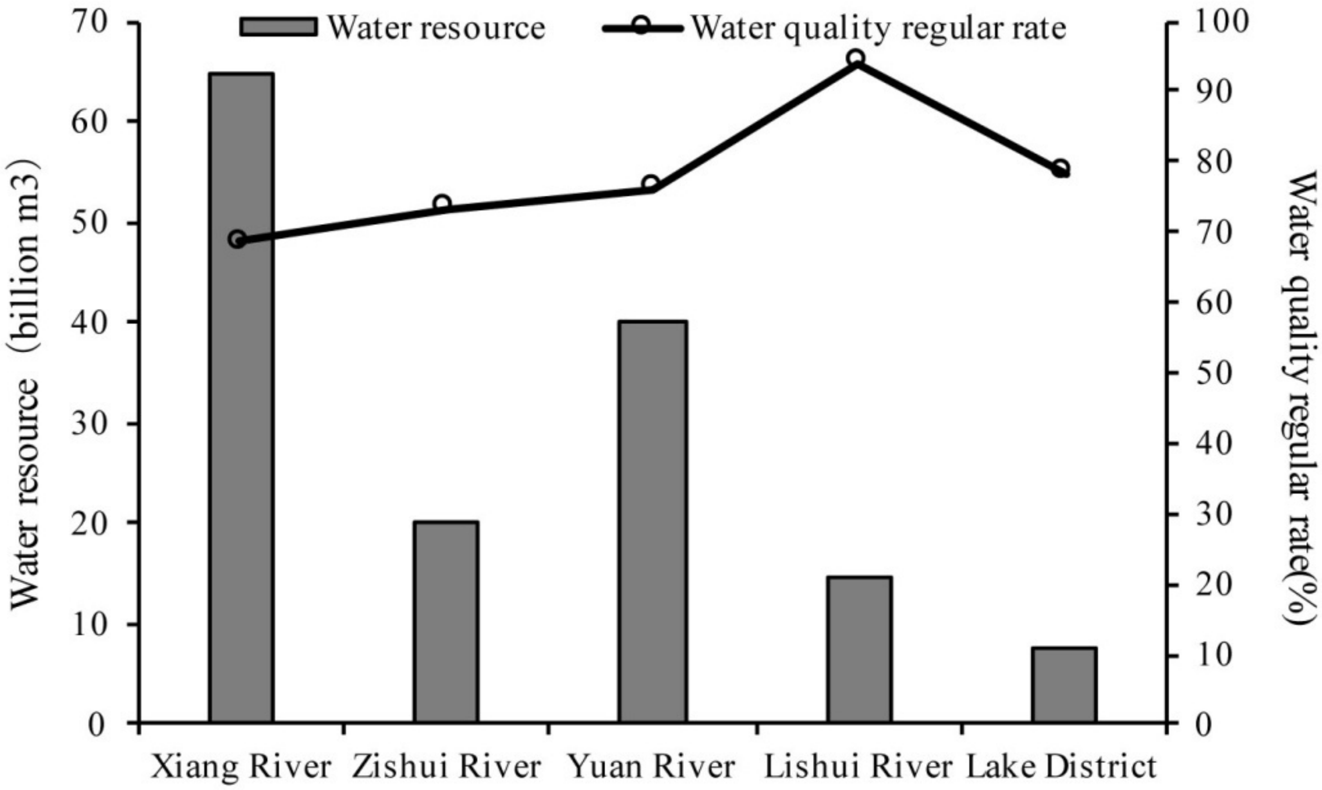

Fig. 5. Water resources quantity and ratio up to the standard of water quality of inflow rivers of the Dongting Lake.

with 47.97 points. The average concentration of DO in the Dongting Lake was 5.7 mg/L in September and 10.0 mg/L in December, with a score of 74 points. The average concentration of COD_{Mn}, BOD_5, and ammonia nitrogen was 3.7, 0.6, and 1.9 mg/L in September, respectively, and 3.1, 0.3, and 1.4 mg/L in December, respectively, with a score of 83, 4, and 100 points, respectively.

The AL criterion layer score of the Dongting Lake was 89.5 points. According to the monitoring results of the algae density of the Dongting Lake in 2004–2006, in these 3 years the average algae density of the Dongting Lake was $14.83–18.29 \times 10^4$ pcs/L, and the PHP score was 90 points. The Dongting Lake is China's largest reed-producing area, with a reed area of 800 km^2, accounting for about 40% of the total area of wetlands. The MPC score was 75 points. The number of fish species in the Dongting Lake was 104 in the 1970s [27], and 109 in 2002–2008.

The SS criterion layer score of the Dongting Lake was 63.22 points. In 2008, the WR of the Dongting Lake was 153.5 billion m^3, the WU of the Dongting Lake was 31.6 billion m^3, and the WRU of the Dongting Lake was 20.6%, and the WRU score was 90 points. The FLD score was 36.43 points. In the Dongting Lake area, there was a flood control dam with a total length of 4,427.88 km, and the flood control dam reaching the flood control standard had a total length of 3,468.79 km, so the FLDE was 78.34%. The FLDV score was 71.15 points. The total effective storage capacity of the Dongting Lake was 16.381 billion m^3; in 2020, the flood control capability was enhanced thanks to reservoirs and the Three Gorges Project in the upper reaches of the Dongting Lake. The planned flood storage capacity of the Dongting Lake was about 27.94 billion m^3. The FLDV was 58.62%. The FLDV score was 21.55 points.

The LEI score of the Dongting Lake was 55.7 points, so the LSI score of the Dongting Lake was 58 points, belonging to sub-security level (Fig. 6).

3.2. Ecological problems of the Dongting Lake

The Dongting Lake is the formerly first largest freshwater lake in China, covers an area of 6,000 km^2, and ever enjoyed the reputation of "Eight Hundred Dongting Lake." However, because the ecological water level of the Dongting Lake in the dry season is difficult to meet, the uneven spatial and temporal distribution of water resources of the Dongting Lake leads to the ecological water level of the Dongting Lake is difficult to meet. Because of two floods occurred in 1860 and 1870, Ouchi estuary and Songzi River bursted their banks to allow the distributaries of four estuaries of Jingjiang River to flow into the Dongting Lake. Jingjiang River poured out large amounts of sediment into the Dongting Lake every year (accounted for more than 80% of the total inflow sediment quantity) to deposit in the Dongting Lake, in addition, the large area of lake reclamation appeared, thus, the area and volume of the Dongting Lake shrink and the lake floor elevation continuously rises year by year. According to history data, the natural lake area of the Dongting Lake was near 6,000 km^2 in 1852 and was reduced to 4,350 km^2 in 1949. By 1995, the natural lake area of the Dongting Lake dropped to 2,625 km^2, and the volume of the Dongting Lake was reduced from 29.3 to

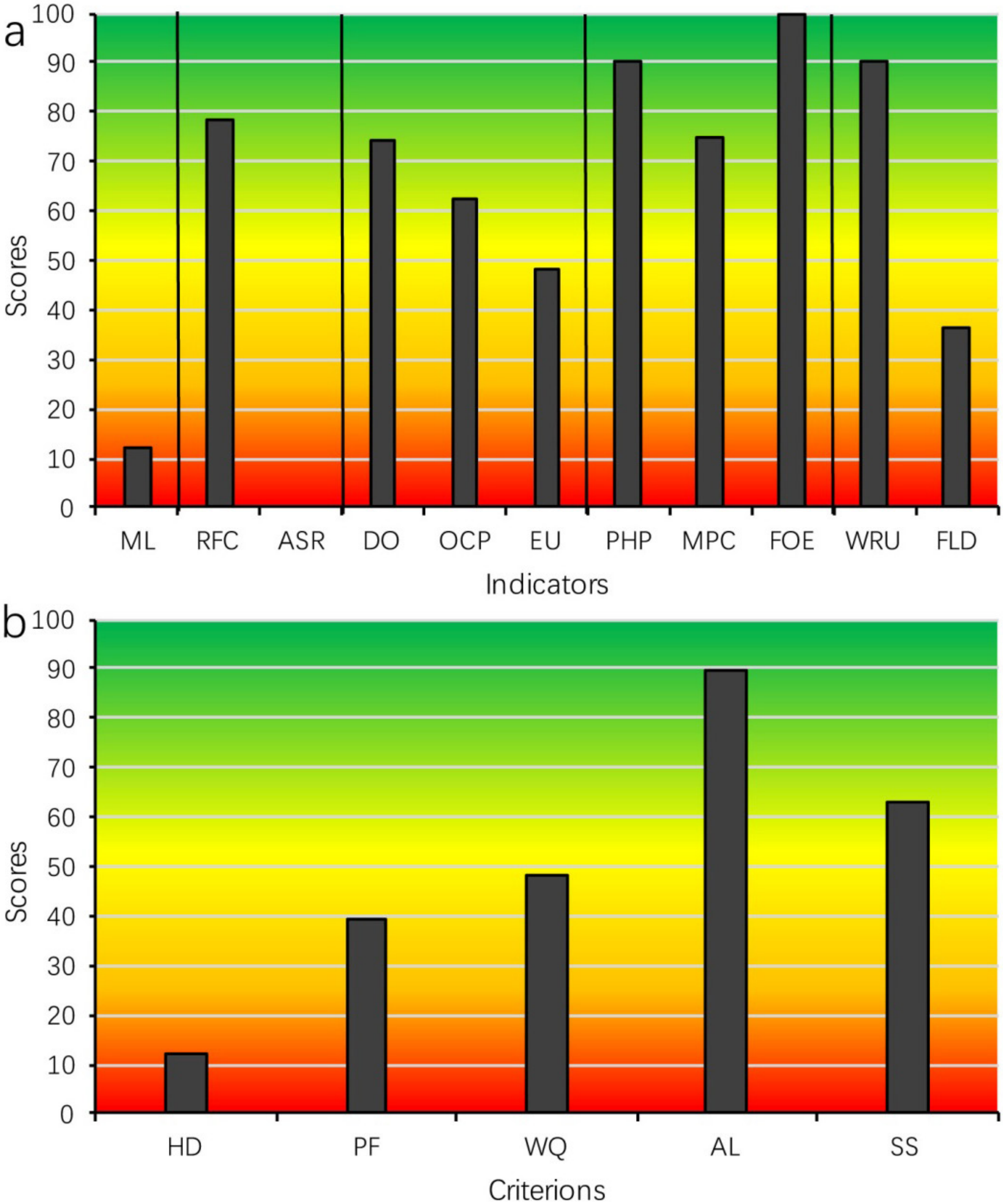

Fig. 6. Ecological security evaluation results of the Dongting Lake (a: score of the index; b: score of the criterion layer).

16.7 billion m^3; by now, the Dongting Lake has been reduced to the second largest freshwater lake in China from the first largest freshwater lake in China. In 2008, the largest water area of the Dongting Lake was reduced to 2,291 km^2.

Water pollution of the Dongting Lake is an unignored problem. After the 1970s and 1980s, the emission of various harmful pollutants derived from industry, agriculture, and prevention of schistosomias caused serious deterioration of the water environment quality of the Dongting Lake. The investigation showed that a total of 39 factories, mainly mills and chemical fertilizer factories, discharge polluted wastewater to the Dongting Lake. The water pollution in the West Dongting Lake topped the list, followed by the East Dongting Lake and the South Dongting Lake. The South Dongting Lake was a mixed type of mild EU and mild EU–EU. Among the EIs, total phosphorus, total nitrogen, and transparency have been in the state of mild EU.

The AL criterion layer score of the Dongting Lake was high, showing that the fish and algae in the Dongting Lake were in good condition. During 1960s–1980s, the duck species in the Dongting Lake decreased sharply and increased gradually after the 1990s. Up to now, there are 28 duck species, close to the duck species in the 1960s. However, the species richness of the East Dongting Lake and the South Dongting Lake decreased, as some species that are sensitive and non-resistant to ecological environment change have disappeared. In the Dongting Lake area, in 1963, the "Four Artificial Fish" (black carp, grass carp, silver carp, and bighead carp) accounted for 21% of fish catches, while the fish settling in the lake such as carp, crucian carp, and catfish accounted for about 63% of fish catches; in 1981, the proportion of the "Four Artificial Fish" dropped to 14.1%, while the proportion of the fish settling in the lake increased to 63.7%; in 1999, the proportion of the half-migratory fish in rivers and lakes dropped to about 10%, and the proportion of the "Four Artificial Fish" dropped to 9.3%, while the proportion of the fish settling in the lake such as carp, crucian carp, and catfish increased up to 86.1%. In 2006, a sampling survey of fish catches showed that the proportion of the "Four Artificial Fish" dropped further to 5.4%. In addition, in the past 50 years, the population of the typical migratory fish such as Chinese sturgeon, shad, eel, and mullet decreases rapidly, some of which are endangered.

The FLDV of the Dongting Lake was as low as 58.62%. In the 1990s, from Chenglingji to Hankou reach to the Dongting Lake, there were serious siltation, river blocking, unsmooth flood discharge and rising water level. The maximum water level of each water level station was 1.81–1.88 m higher than the designed water level of the flood control dam. The constant rising water level of rivers and lakes exacerbated the threat of flood disaster to the Dongting Lake area.

4. Conclusion

In this paper, an ecological security evaluation index system of the Dongting Lake was constructed, including 1 target layer, 5 criterion layer, and 11 evaluation indexes, and each evaluation index, criterion layer, and target layer was scored, and the ecological security of the Dongting Lake was evaluated using progressive weighting and comprehensive scoring method. The evaluation results showed that the ecological security score of the Dongting Lake was 58 points, belonging to sub-security level. The indexes affecting the ecological security of the Dongting Lake included low ecological water level, reduced lake surface area, and EU. At present, the Dongting Lake has ecological environment problems such as aggravated flood disaster, frequent biological disasters, increased water pollution load, and degraded biological resources. There were many factors causing the ecological degradation of the Dongting Lake, which were mainly summed up as follows: (1) Human activities such as overfishing resources and excessive exploitation and utilization of water resources were the main factors for the ecological degradation of the Dongting Lake; (2) Water pollution caused the deterioration of fish habitat, which affected the growth of fish and even led to the death of fish; (3) The continuous construction of hydraulic structures, box dams, and fish banks in the Dongting Lake area impeded the migration of fish and affected the fish reproduction and fish population supplement, leading to the decline of migratory fish in rivers and lakes. Therefore, in future, the emission of industrial and domestic pollution sources should be controlled and the carrying capacity of water environment should be improved.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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