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The aquatic ecological health-state assessment and the influencing mechanism of Poyang Lake

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ABSTRACT

Context. Freshwater lakes are still facing a series of problems, e.g. a decline in water quality, and a decrease in biodiversity. Thus, assessing the state of aquatic ecological health of the lake has drawn widespread attention from scholars both at home and abroad. **Aims.** This study aims to assess the state of aquatic ecological health of Poyang Lake and analyse the influencing factors. **Methods.** The long-term (2007–2018) site-monitoring data were analysed on the basis of the extension–evaluation method and correlation-analysis method. **Key results.** The results showed that the aquatic ecological health was mainly '*good*', and remarkable seasonal differences were observed. The seasonal order of relative aquatic ecological health could be expressed as the wet season being better than the dry season, whereas the rising season was similar to the retreating season. And the pollutant discharged into the lake was found to be the key factor, and the hydrological conditions led to seasonal differences in the state of aquatic ecological health of Poyang Lake. **Conclusions.** Consequently, scholars and policymakers should focus on both nutrient concentrations and hydrological conditions, which are the key factors influencing the aquatic ecological health of Poyang Lake. **Implications.** The results of this study have provided a theoretical and practical basis of the causes of ecological deterioration and should help with ecological-health protection of the large lakes connected with the Yangtze River.

Keywords: aquatic ecological health assessment, extension–evaluation method, eutrophication level, *good*, hydrological conditions, influencing mechanism, Poyang Lake, seasonal variations.

Introduction

Freshwater ecosystems are facing a whole series of environmental problems, for instance, the gradual decline of water quality, loss of biodiversity and the ecological degradation of the lakes. The aquatic-ecosystem health assessment for lakes has drawn widespread attention from scholars and environment administrators at home and abroad (Xu *et al.* 2001; Qi *et al.* 2018; Bacigalupi *et al.* 2021; Hartig *et al.* 2021; Wu *et al.* 2022). Assessing the ecological status of lakes can provide a theoretical basis for identifying the main causes of the impaired conditions, and thus propose regulations and recommendations for environmental protection.

Poyang Lake, the largest freshwater lake in China, is an essential resource for human existence and sustainable socioeconomic development because of providing crucial functions, such as fresh water, agricultural irrigation, water transport, fishing and recreation. However, water quality has suffered accelerating degradation, as a result of enhanced anthropogenic disturbances, including rapid urbanisation, sanding, agriculture and so on. Poyang Lake has become moderately eutrophic since the 1980s, and it has had a persistent decline in water quality in recent years, accompanied by a significant increases in total nitrogen and total phosphorus concentrations (Li *et al.* 2020). Furthermore, the structure and function of the lake ecosystem may be altered accordingly because water quality could have direct and indirect effects on the response of the lake to environmental changes. The lake has experienced frequent seasonal droughts in spring and winter in recent years, which has significant ecological implications for the drainage area (Yang 2012; Wu *et al.* 2019). According to a survey on birds in the spring of 2011 and relevant studies, white cranes, the rare birds initially feeding in the shallow water, were first found to migrate to the marshland to feed and inhabit because of habitat changes in Poyang Lake in this period. Moreover, a significant increasing trend in the size and diversity of migratory bird populations has been observed (Jia *et al.* 2013; Wu *et al.* 2014). Spring droughts may be catastrophic for fish. The fish spawns when the flowing water and aquatic plants stimulate the sexual gland. However, fish reproduction is severely affected if the water plants are directly exposed to bright sunlight over spring droughts. The aquatic communities of Poyang Lake have been subjected to notable declines in abundance ratio and biological diversity in recent years (Cai *et al.* 2014; Liu *et al.* 2015). Cyanobacterial blooms have become more common, the diversity of benthic animals has declined, and the value of ecosystem services has significantly decreased (Cai *et al.* 2014; Liu *et al.* 2015; Li Q *et al.* 2021, Li B *et al.* 2022). Poyang Lake is unique in its dramatic water-level (WL) variation and free connection to the Yangtze River. Thus, the ecosystem structure and function of Poyang Lake have greater notable spatial–temporal variations than do other isolated lakes (Zhang L *et al.* 2014; Liu *et al.* 2015; Zhang YH *et al.* 2016).

As a natural lake connected to the Yangtze River, eutrophication is still the most widespread pressure, and hydromorphological pressures are also important factors causing lowered ecological status. In a study conducted by Li *et al.* (2020), the annual mean total nitrogen (TN) and total phosphorus (TP) concentrations showed significant upward trends from the 1980s to 2018. It is has been reported that topography changes caused by sand mining will bring increased impacts on the hydrological features of Poyang Lake, such as flow velocity (Qi *et al.* 2019). Poyang Lake is a complex ecosystem, and the ecological status is combined by many factors.

Given the above, assessing the state of aquatic ecological health of Poyang Lake and analysing the influencing mechanism of aquatic ecological health are of great practical value for identification of the causes of aquatic ecological degradation and for ecological decision-making to protect the ecosystem of Poyang Lake. In the present study, the extension–evaluation method was used to assess the state of ecological health and the influencing mechanism for aquatic ecological health in Poyang Lake was analysed. The findings of the current study could help in identifying the causes of ecological health degradation and will have implications for protection of the water environment of Poyang Lake.

Materials and methods

Study area and data sources

Poyang Lake is the largest freshwater lake in China and also one of the two existing lakes that are freely connected to the longest river in China, namely, the Yangtze River (the other Dongting Lake). As a typical floodplain lake, Poyang Lake has marked intra-annual and inter-annual water-level variations. Thus, Poyang Lake shows a unique picture that looks like a river and a lake during the dry and wet seasons respectively. In addition, Lake Poyang has an average hydraulic retention time of 20.9 days (Zhu and Zhang 1997). The populations in the drainage area of Poyang Lake have been continuously expanding in recent years. Meanwhile, the water quality of Poyang Lake has been deteriorating (Cheng and Li 2006; Gao and Jiang 2012), and a sharp decrease in biodiversity and ecological degradation was observed accordingly (Jia *et al.* 2013). Notably, the yearly water-quality observations from 2007 to 2018 obtained from the Poyang Laboratory for Wetland Ecosystem Research (PLWER) were computed by seasonal–monthly observations (at least six sampling sites, for some years, only in the wet season; Table 1). Moreover, the hydrological data were collected from Jiangxi Hydrological Bureau.

Methods

The extension–evaluation method, which is based on extension mathematics, is commonly used to solve uncertain and contradictory problems from both qualitative and quantitative perspectives (Cai *et al.* 1997). To achieve this goal, a multi-indicator assessment model is usually established, and the object of concern is comprehensively characterised (Wong and Hu 2014). The method has found an increasingly wide utilisation in various fields (e.g. evaluation of water quality, river ecosystem-health evaluation and water-resources sustainability estimate) and has been shown to be efficient in dealing with incompatibility problems (Wong and Hu 2014; Deng *et al.* 2015; Wang *et al.* 2019; Li *et al.* 2020). For this method, the attributive standard (e.g. lake ecological-health standard) was described by an interval, not by a single numeric value, whereas in the fuzzy and grey evaluation methods, the value of the standard is regarded as a numeric single value. That is to say, compared with fuzzy mathematics and the grey correlation analysis method, extension assessment converts the indicators from single definite values into intervals to better meet the needs. Thus, the extension–evaluation method is available to deal with the complexities and uncertainties in complicated systems, e.g. in the lake ecological-health valuation processes, for which uncertainty is a fundamental issue.

For the extension–evaluation method, $j_0(p)$ is the grade of aquatic ecosystem health. Grades 1, 2 and 3 represent '*good*',

Table 1. Summary of variables and number of sites sampled in a given month and year in Poyang Lake.

Year	Month and sites	Data
2007	October, 24 sites	Physical, chemical and biological variables (SD, TN, TP, COD_{mn}, Chl-*a*, phytoplankton biomass and macrozoobenthos)
2008	June, 35 sites	
2012	January, April, July and October, 15 sites	Physical, chemical and biological variables (SD, TN, TP, COD_{mn}, Chl-*a*, phytoplankton biomass and macrozoobenthos)
2013	January, April and October, 15 sites; July, 68 sites	
2014	January, April and October, 15 sites; July, 68 sites	
2018	January, April, July and October, 6 sites	
1999, 2007, 2008, 2012, 2013, 2014, 2018	January–December, seven sites (Xingzi, Duchang, Hukou, Kangshan, Wucheng, Tangyin and Boyang)	WL

SD, Secchi disc depth (water transparency); TN, total nitrogen; TP, total phosphorus; COD_{mn}, chemical oxygen demand; Chl-*a*, chlorophyll-*a*; WL, water level.

'*moderate*' and '*poor*' respectively. $J^*(p)$ is the accurate health status of the aquatic ecosystem. $J^*(p) - j_0(p)$ was determined to characterise the tendency of the health status of the aquatic ecosystem. The more positive the value is, the higher is the tendency grade; the more negative the value is, the lower is the tendency grade. If $j_0(p)$ is 1 and $J^*(p)$ is 1.4, $J^*(p) - j_0(p)$ is 0.4. Therefore, the accurate health status of the aquatic ecosystem for the site is 1.4, belonging to Grade 1, with a tendency of Grade 2. The weight is constructed by simple correlative function on the basis of the index data. The weight of aquatic-ecosystem health-assessment factors have a dynamic characteristic; that is, even if factors are the same, the weight will also alter with the different factor values, even if the indicator values are the same, the weight will also alter with the different relationships among indicators. The extension assessment conducted in the current study was programmed with R software (ver. 4.1.2, R Foundation for Statistical Computing, Vienna, Austria, see https://www.r-project.org/). Spearman rank correlation, which was used to investigate relationships between indicators and the grade of aquatic ecosystem health in different states, was performed using the SPSS statistical package for Windows (ver. 17.0, see https://www.ibm.com/au-en/products/spss-statistics). On the basis of literature (Zhang *et al.* 2019), the evaluating indicator system for aquatic ecological-health assessment contains the following six indicators: the biomass ratio of cyanobacteria to diatom (CB:DB), eutrophication index (TLI), macrozoobenthos species diversity index (DI), biotic index of macrozoobenthos species (BI), the difference with the lowest water-level average value in the dry season (LWLa-D), and the difference with the mean water-level average value in the rising season (MWLa-R). The aquatic ecological health was categorised into three groups, namely, *good*, *moderate* and *poor* (Table 2).

Given that Poyang Lake is characterised by seasonal flood pulse and considerable alteration regarding hydrodynamic conditions, water quality as well as aquatic species, the interannual average values of biological and physicochemical parameters of 15 monitoring sites in four seasons (January, April, July and October) in 2014 were calculated for the entire Poyang Lake to gain a broadened understanding of the overall aquatic ecological health and the seasonal aquatic ecological health, i.e. dry (January), rising (April), wet (July) and retreating (October) seasons.

Results and discussion

The aquatic ecological health of Poyang Lake

The overall health of the aquatic ecosystem in Poyang Lake

The overall aquatic ecological health of Poyang Lake is shown in Fig. 1. In 2014, most of the 15 sample sites were *good* (70%); $J^*(p) - j_0(p)$ indicated that the tendency of the health of the aquatic ecological environment in the 15 sites was *moderate* (80%). In summary, the overall health of the aquatic ecosystem in the lake was *good* and tended to be *moderate*. This finding is essentially in agreement with the results of previous studies of aquatic ecological-health assessment in the Poyang Lake wetland (Zhang *et al.* 2016; Qi *et al.* 2018).

Table 2. The aquatic ecological assessment indexes and thresholds of Poyang Lake.

Health status indicators	CB/DB	DI	MWLa-R	BI	LWLa-D	TLI
Good	≤0.4	≥2	−1.03 m to 1.05 m	0 to 5.5	−0.76 m to 0.76 m	≤40
Moderate	0.4 to 0.6	1 to 2	1.05 m to 1.52 m, −1.50 m to −1.03 m	5.5 to 6.5	0.76 m to 1.18 m, −0.76 m to 1.18 m	40–50
Poor	≥0.6	0 to 1	<−1.50 m, >1.52 m	6.5 to 10	<−1.18 m, >1.18 m	≥50

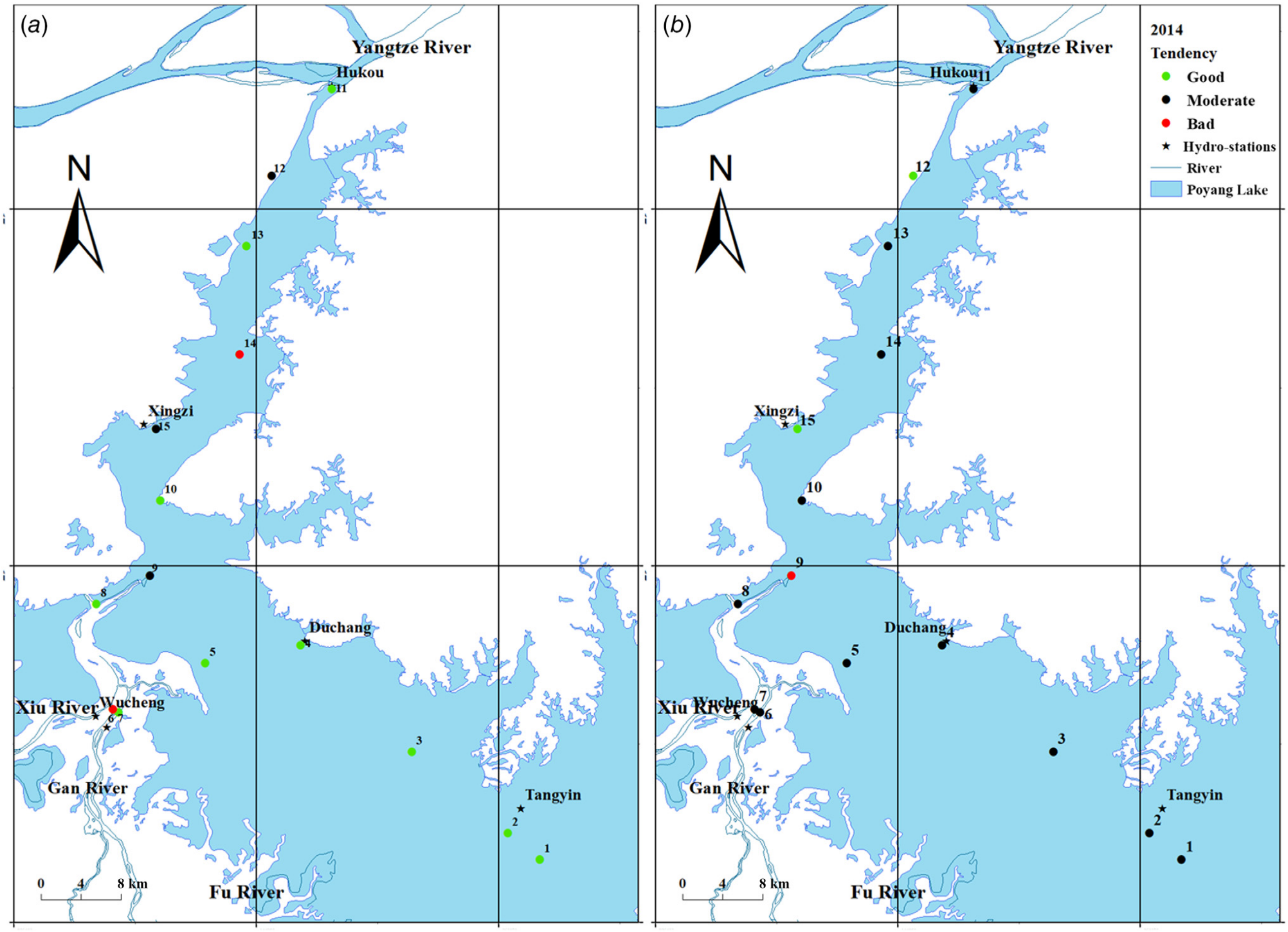

Fig. 1. Aquatic ecological health (*a*) and health tendency (*b*) of Poyang Lake, in 2014.

Seasonal variations in the health of the aquatic ecosystem

The aquatic ecological health in four seasons, i.e. dry–rising–wet–retreating periods, in 2014, in Poyang Lake is presented in Fig. 2. Seasonally, the health was determined *moderate* in dry and wet seasons. In more than 50% of the 15 sampling sites, the health in the wet season was better than that in the dry season. Conversely, the health in rising and retreating seasons were *good*. The seasonal order of relative aquatic ecological health could be expressed as July (wet season or summer) was better than January (dry season or winter), whereas April (rising season or spring) was similar to October (retreating season or autumn).

The influencing mechanism of the aquatic ecological health of Poyang Lake

Eutrophication level was a key factor influencing the aquatic ecological health of Poyang Lake

The evaluation weight of the aquatic ecological health of Poyang Lake from 2007 to 2018 are shown in Fig. 3. From a weighted point of view, TLI had a higher weight, indicating that lake eutrophication was the key factor for the aquatic ecological health of Poyang Lake, which was almost following the previous reports that it had constantly suffered from contamination and higher eutrophication levels since the 1980s (Cheng and Li 2006; Gao and Jiang 2012). For biotic-component indicators, the weight of BI and DI were greater than that of CB:DB. These results can be explained by a decreasing biodiversity and a degrading ecosystem function in Poyang Lake. A previous study reported that the biodiversity of macrozoobenthos has sharply declined, but the biomass has remained almost unchanged in Poyang Lake since the 1990s (Ouyang *et al.* 2009). These findings suggest that the changes in the aquatic ecological health of Poyang Lake have had a dramatic impact on macrozoobenthos. The mean hydraulic retention time of Poyang Lake is only 20.9 days (Zhu and Zhang 1997) and previous studies have indicated that phytoplankton biomass and assemblage structure patterns in Poyang Lake may be affected by altering its seasonal hydrology (Liu *et al.* 2015). Thus, the smaller weight of CB:DB was largely due to the free connectivity between Poyang Lake and the Yangtze

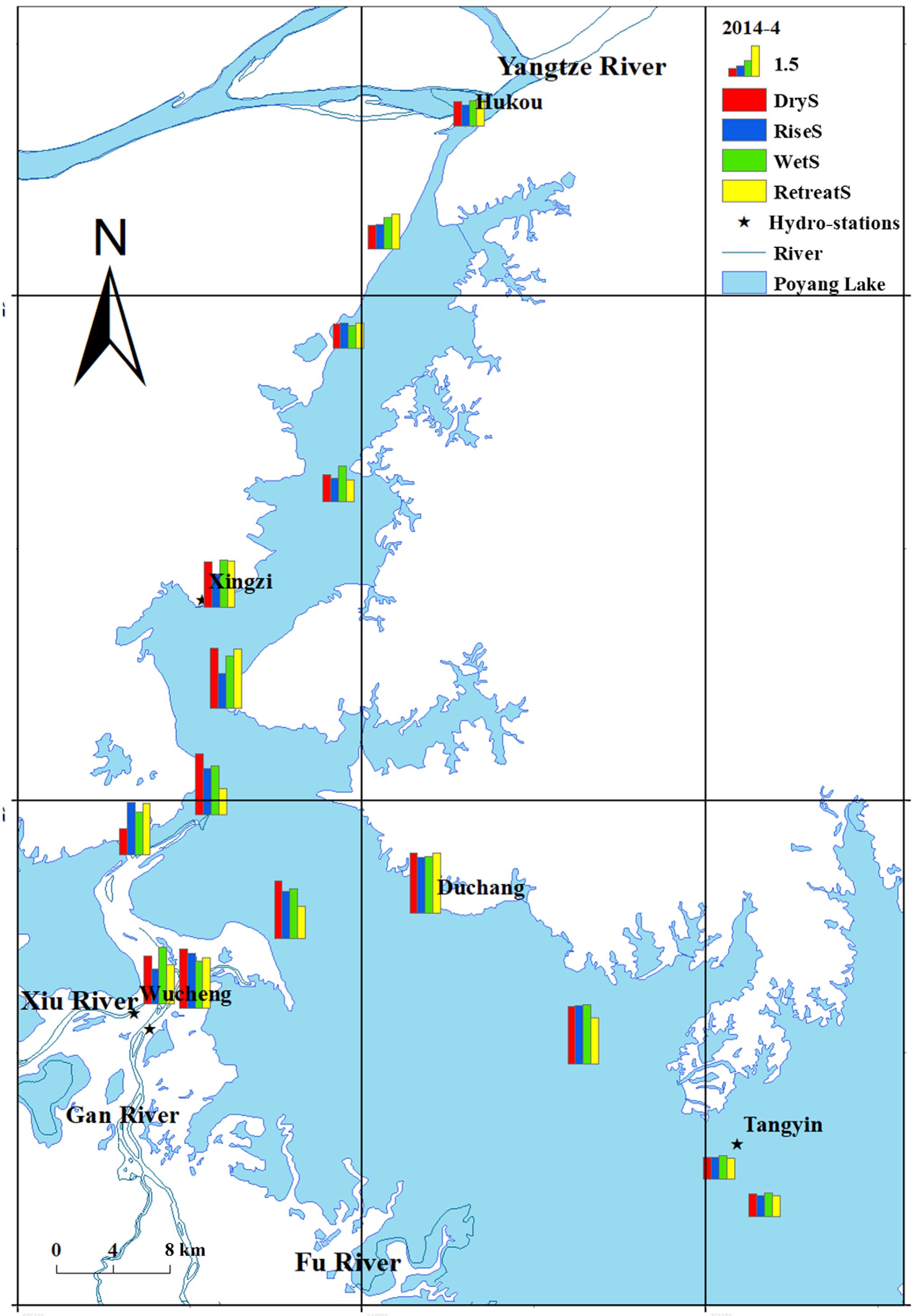

Fig. 2. The aquatic ecological assessment results of Poyang Lake in four seasons in 2014.

River. The faster the water velocity, the fewer the cyanobacteria. The weight of hydrological indicators were larger. However, the weight of both LWLa-D and MWLa-R fluctuated dramatically, indicating that the water-level fluctuations (WLFs) were another primary influencing factor of the aquatic ecological health of Poyang Lake.

To sum up, the aquatic ecological health of Poyang Lake was not only controlled by the degree of eutrophication in Poyang Lake, but also by the hydrological and hydrodynamic conditions, the interaction between the Yangtze River and Poyang Lake, and so on. Eutrophication level was the key factor.

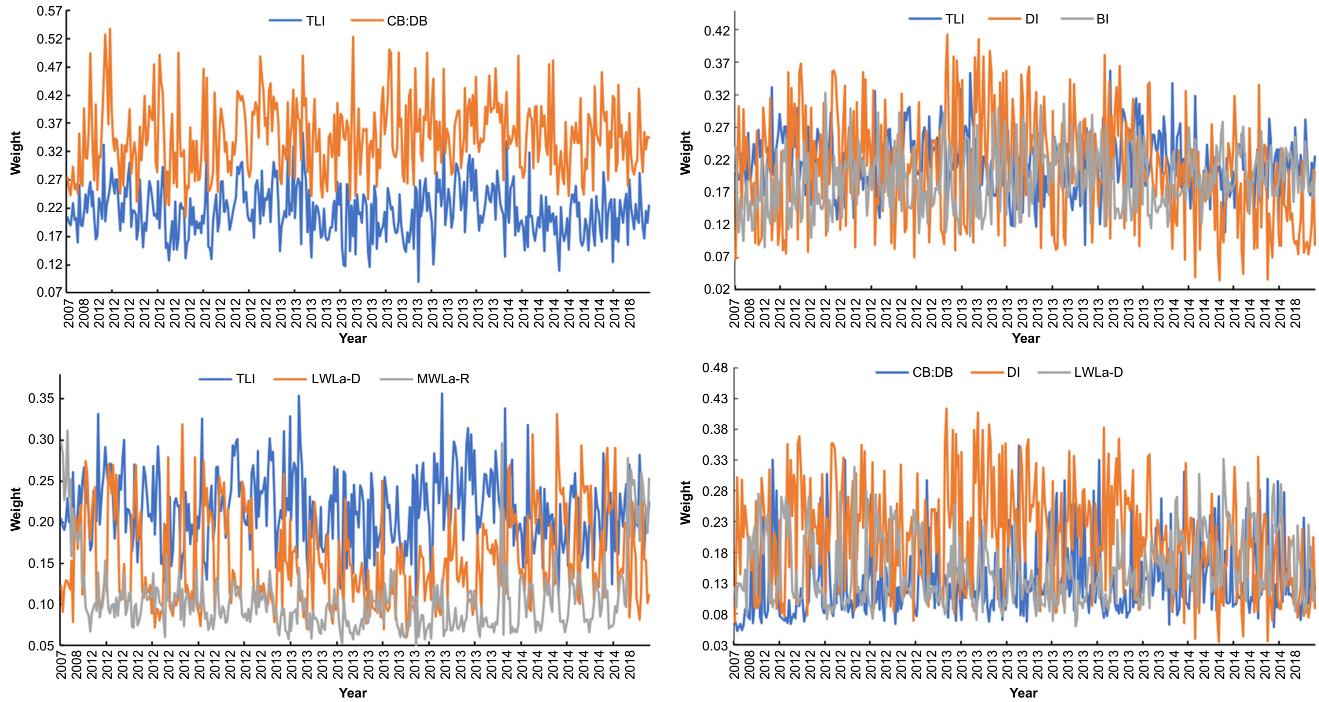

Fig. 3. The extension assessment weight of TLI *v.* CB:DB, TLI *v.* DI *v.* BI, TLI *v.* LWLa-D *v.* MWLa-R, CB:DB *v.* DI v. LWLa-D.

The analysis of weight also showed that the extension assessment method outperformed the reflection of objective fact. The contributions were as follows: the weight of the aquatic ecological health-assessment factors have a dynamic characteristic (i.e. the weight will also alter with the different data of factors even if factors are the same and the weight will also alter with the different relationships among indicators even if the same evaluation data were used) and the evaluation results of lake aquatic ecological health must be different. Therefore, this method could effectively distinguish the major contributors to the aquatic ecological health of Poyang Lake. So it is inferred that it can be effectively applied to lake ecosystem-health assessment, especially for Poyang Lake, which has considerable seasonal WLFs.

The results of a Pearson correlation analysis between the grade of aquatic ecological health and the indicators are presented in Table 3. Moreover, Table 3 shows that the influencing factors are spatially different across the different states of ecological health. The correlation coefficients indicated in Table 1 show that TLI and LWLa-D ($P < 0.01$) are significantly related to the grade of aquatic ecological health, whereas DI, BI, MWLa-R and CB:DB do not show statistical significance for all samples. For *poor* samples, TLI is statistically highly significant with the grade of aquatic ecological health, and the coefficient is negative, which means that the change of lake eutrophication plays an important role in distinguishing between *good* and *poor* aquatic ecological health for Poyang Lake.

The correlations between indicators varied for different health states. However, TLI had a significant correlation with all other indicators regardless of the grade of health. For all samples, TLI had a highly significant correlation with CB:DB, DI and LWLa-D. For *good* samples, TLI had a highly significant correlation with CB:DB and DI. For *moderate* samples, TLI had a highly significant correlation with CB:DB, LWLa-D and BI. For *poor* health samples, TLI had a highly significant correlation with CB:DB and DI. As shown in Table 3, TLI had a significant effect on biotic or hydrological indicators, which further influenced the aquatic ecological health of Poyang Lake. Thus, the above findings indicated that TLI had a direct or indirect effect on the ecological health of Poyang Lake.

Seasonal variabilities in the ecological health of Poyang Lake owing to changes in hydrological conditions

Hydrological conditions influence the aquatic ecological health of Poyang Lake mainly through WLFs. WLFs affect the aquatic ecological health in Poyang Lake through the following two aspects: first, WLFs directly affect the nutrient concentration (Wu *et al.* 2017), which, in turn, may cause an effect on the aquatic ecological health (Li *et al.* 2020). Second, WLFs directly influence the health of aquatic creatures in the lake (Qian *et al.* 2016). Fig. 4 shows the variation trend of TLI and the mean WL of Xingzi station across different seasons from 2007 to 2018. The figure shows that the higher the WL is, the lower is the TLI, and the lower the WL is, the higher is the TLI. And TLI exhibited a significant negative correlation with the WL.

Table 3. Correlations of indicators for different states of ecological health (*good*, *moderate* and *poor*).

Item		TLI	CB:DB	DI	BI	LWLa-D	MWLa-R	Grade
All samples	TLI	1						
	CB:DB	−0.236**	1					
	DI	−0.400**	−0.276**	1				
	BI	−0.095	−0.096	−0.390**	1			
	LWLa-D	−0.064	−0.216**	−0.317**	−0.1	1		
	MWLa-R	0.222*	−0.253**	−0.271**	−0.085	−0.144*	1	
	Grade	−0.318**	−0.119*	0.174*	−0.11	0.331**	−0.107	1
Good samples	TLI	1						
	CB:DB	−0.211*	1					
	DI	−0.481**	−0.347**	1				
	BI	−0.025	−0.179	−0.445**	1			
	LWLa-D	0.144	−0.284**	−0.316**	0.058	1		
	MWLa-R	0.177	−0.167	−0.247*	−0.025	−0.111	1	
	Grade	−0.031	−0.058	−0.104	0.03	0.383**	−0.087	1
Moderate samples	TLI	1						
	CB:DB	−0.254*	1					
	DI	−0.358**	−0.392**	1				
	BI	−0.263**	−0.123	−0.209*	1			
	LWLa-D	−0.065	−0.142	−0.210*	−0.304**	1		
	MWLa-R	0.267**	−0.200*	−0.290**	−0.088	−0.163	1	
	Grade	−0.103	0.003	0.079	−0.247*	0.248*	0.011	1
Poor samples	TLI	1						
	CB:DB	−0.396**	1					
	DI	−0.297**	−0.099	1				
	BI	−0.077	−0.047	−0.452**	1			
	LWLa-D	0.01	−0.176	−0.528**	−0.016	1		
	MWLa-R	0.189	−0.379**	−0.260**	−0.126	−0.096	1	
	Grade	−0.326**	0.138	0	0.014	0.09	−0.005	1

Correlations are significant at: *, $P < 0.05$; **, $P < 0.01$.

The results of the Pearson correlation analysis showed that the WL was significantly and negatively correlated with the seasonal aquatic ecological health in 2014 (Fig. 5). For example, the WL of Xingzi was relatively higher in July 2014 than in other months and was associated with a healthier aquatic ecological state. However, the WL of Xingzi was lower in January 2014, which corresponded to a less healthy aquatic ecological state. Some previous studies have noted the impacts of low WL in dry seasons on the ecological degradation of the lake in recent years. The dry season has been prolonged to a certain extent in Poyang Lake from 2003; i.e. the dry season arrives earlier than before in Poyang Lake, and the low WL persists longer during the dry season (Zhang Q *et al.* 2011; Min and Zhan 2012). Such a change has a dramatic impact on the growth of wetland vegetation and succession of population structure. In 2013, the dry season arrived 40 days earlier than in previous years, resulting in an extensive area of green grass. The habitats of fish and migratory birds were also jeopardised. The first sighting of overwintering white cranes feeding in the grassland in large numbers was reported from 2010 to 2011 (Jia *et al.* 2013). A low WL in the dry season can cause severe vegetation degradation in the wetlands of Poyang Lake, as well as other problems, e.g. a sharp decrease in submerged vegetation and invasion of alien species (Hu *et al.* 2010). Poyang Lake has experienced aggravating spring droughts from 2003 (Min and Zhan 2012). Among the top 10 years in terms of severity of spring droughts in the past 60 years, were the 5 years after 2000 (i.e. 2004, 2005, 2008, 2009 and 2011). Spring droughts may be disastrous for the reproduction of fish because the fish spawn in spring when the sexual gland is stimulated by the flowing water and aquatic plants (Zhu and Peng 2010; Mu *et al.* 2022). In addition, as the habitat quality deteriorates, the quality of

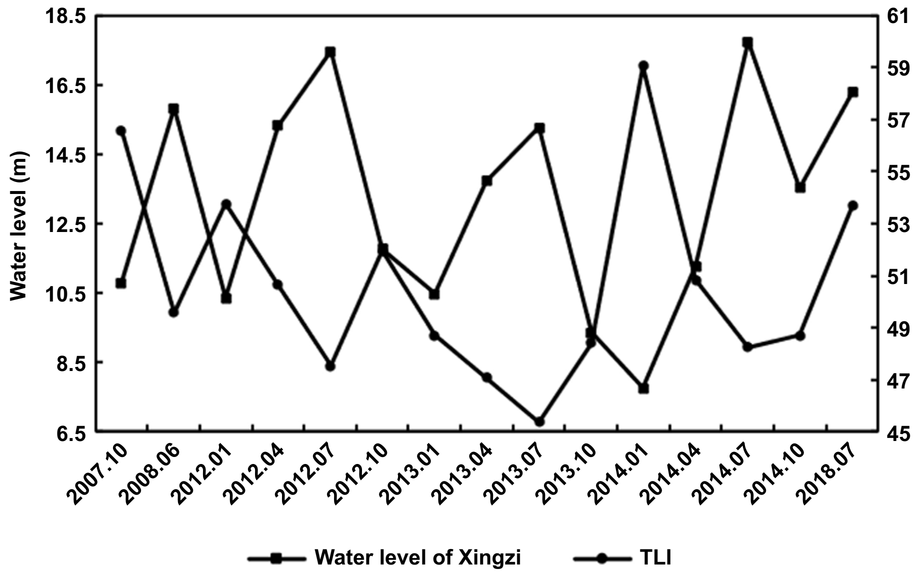

Fig. 4. TLI and the mean WL of Xingzi station in different seasons from 2007 to 2018.

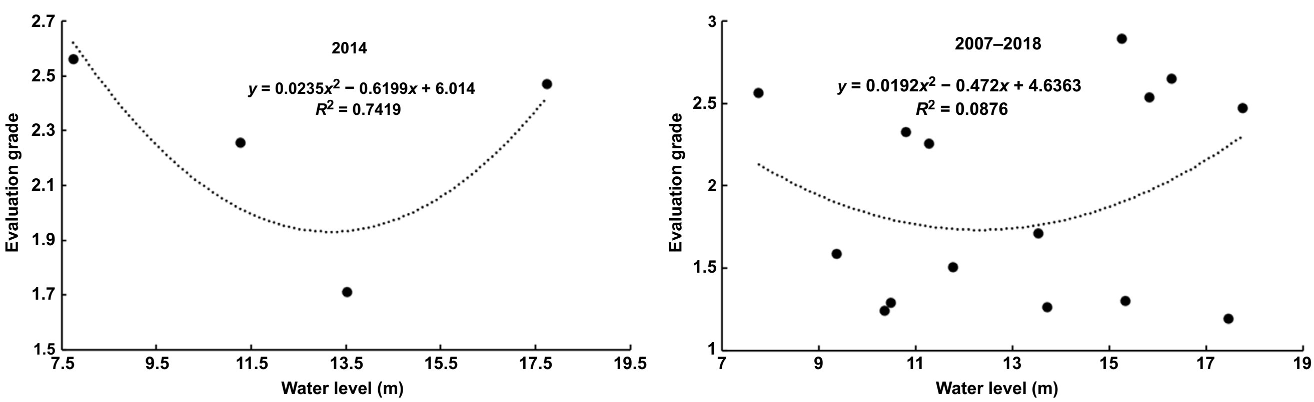

Fig. 5. The relationship between the aquatic ecological health-assessment results and the WL in Poyang Lake.

fish resources declines. Thus, younger fish and those with smaller body sizes now account for a larger proportion of the fish community (Zhang ZY *et al.* 2011).

However, only a weak correlation was observed between the aquatic ecological-assessment results and the WL from 2007 to 2018. The reasons were two-fold: first, the significant correlation between the grade of aquatic ecological health and WL in 2014 was a coincidence. The WL was only weakly correlated with the grade of aquatic ecological health. Second, the number of monitoring sites and samples was limited, resulting in errors. On the basis of the relationship between the WL of Xingzi and TLI, we infer that the WLFs had a direct impact on the degree of eutrophication of Poyang Lake, which further affected the water quality and hence the aquatic ecological health. On the whole, the WLFs directly influenced nutrient concentrations in Poyang Lake, which further affected the water quality and hence the aquatic ecological health. Furthermore, because of the influence of the complex hydrological and hydrodynamic conditions, the mechanism influencing the aquatic ecological health of Poyang Lake was complex.

A previous study has indicated that WLFs are the most vital factor leading to seasonal variability of water quality and the biomass of aquatic organisms (Yao *et al.* 2015; Li Y *et al.* 2019; Liu *et al.* 2019; Li B *et al.* 2020). Moreover, hydrodynamic conditions, human activities and the river–lake relationship of the Yangtze River also have an important impact on the aquatic ecological health of Poyang Lake. In addition, the current study was trying to make only a preliminary exploration on these topics.

Conclusions

In the present study, the extension assessment method was applied to assess the aquatic ecological health of Poyang

Lake and the influencing mechanism was discussed. The results showed that the aquatic ecological health was mainly *moderate* in 2014 and remarkable seasonal differences in the aquatic ecological health of Poyang Lake were observed. The seasonal order of relative aquatic ecological health could be expressed as July (wet season or summer) being better than January (dry season or winter), whereas April (rising season or spring) was similar to October (retreating season or autumn). TLI was an important factor influencing state of aquatic ecological health. Thus, the eutrophication level was a key factor influencing the aquatic ecological health of Poyang Lake. Hydrological conditions contributed, to a certain degree, to seasonal variabilities in the state of aquatic ecological health of Poyang Lake. A finer grading of the health of aquatic ecosystems was obtained by the extension method. In addition, this method could effectively distinguish the major contributors to the health of the aquatic ecosystem in Poyang Lake. The findings of the current study identified the causes of ecological-health degradation and can provide basis for water-environment protection of Poyang Lake.

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Data availability. The data that support this study will be shared upon reasonable request to the corresponding author.

Conflicts of interest. The authors declare that they have no conflicts of interest.

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