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Evolution and restoration of water quality in the process of urban development: a case study in urban lake, China

Shuhe Ruan · Yujia Hong · Yanhua Zhuang

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Abstract Urban development has positive and negative effects on the evolution of enclosed lake water quality. This study aims to quantitatively analyze the water quality evolution of a typical urban lake, the Sha Lake, in the process of urban development. The land use degree comprehensive index (I) was calculated to reveal the level of urban development; water quality index (S_{mid}) and eutrophication index (T_{mid}) were used to evaluate the water quality changes by fuzzy comprehensive-quantifying assessment (FCQA) method. The urban construction process and the water quality changes in 2000–2018 in the Sha Lake Basin were divided into three stages: (1) in 2000–2006, with the slow urban development, water quality remained stable and the degree of eutrophication improved slightly; (2) in 2007–2009, I increased rapidly to reach 300, S_{mid} and T_{mid} increased from 90.62 to 92.83 and 75.06 to 87.52, respectively. Water quality deteriorated because of the failure to implement environmental protection measures in time; (3) in 2010–2018, although urban development reached a high level ($I > 300$), the water network connection project, dredging project, exogenous pollutant control, and sewage pipe network renovation since 2009 were critical measures to improve water quality for a long time. Due to the lag effect on improving water quality, the implementation of environmental protection measures should be synchronized with or even before urban construction. The research results can provide a scientific basis for the urban lake water environment protection in the process of urban development.

Keywords Lake evolution · Water quality · Eutrophication · Urban construction · Non-point source (NPS) pollution

Introduction

Urban lakes have ecological functions such as maintaining urban biodiversity, regulating urban temperature, regulating runoff, flood prevention, and disaster reduction. Urban development not only changes the natural landscape pattern but also has a great impact on lake areas, lake water quality, and water quantity. On the one hand, rapid urban development caused

S. Ruan · Y. Zhuang (✉)
Hubei Provincial Engineering Research Center of Non-Point Source Pollution Control, Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences,
Wuhan 430077, People's Republic of China
e-mail: zhuang@apm.ac.cn

S. Ruan · Y. Zhuang
University of Chinese Academy of Sciences,
Beijing 100049, People's Republic of China

Y. Hong
Wuhan Britain-China School, Wuhan 430034,
People's Republic of China

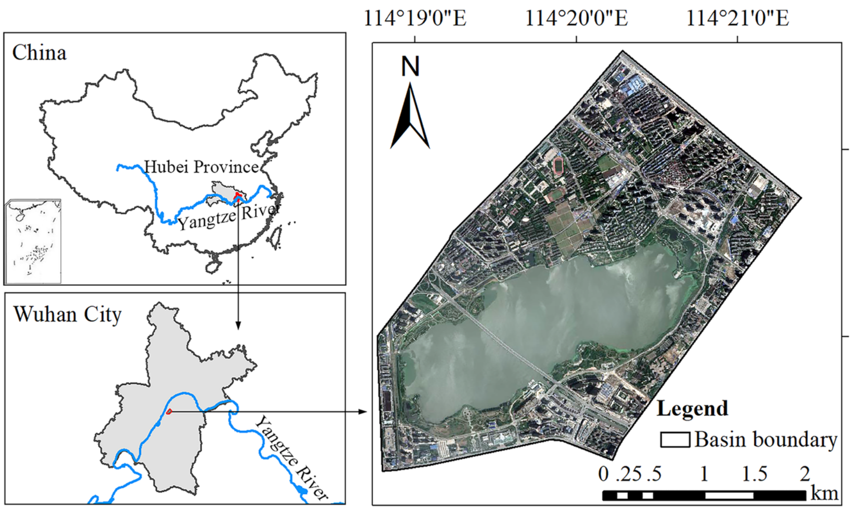
Y. Hong
Wuhan Foreign Languages School, Wuhan 430022,
People's Republic of China

urban lakes, especially enclosed lakes, to face a series of environmental problems such as urban non-point source pollution, area reduction, and sharp decline in biodiversity. For example, the area of East Lake in Wuhan decreased by 2.17 km^2 in 2000–2013, and the average annual decrease was 0.17 km^2 (Chen et al., 2015). On the other hand, the construction and improvement of regional infrastructure and investment in environmental protection have played a positive role in improving the water environment (Yu et al., 2003). For example, the "six major projects" (sewage interception around the lake, rural non-point source control, ecological restoration and construction, improvement of the river into the lake, ecological dredging and other endogenous pollution control, and water diversion and water saving in outer basins) implemented in the Dianchi Lake since 2005 had reduced the proportion of pollution loads into the lake from 50% in 2005 to 30% in 2013 (He et al., 2015).

Affected by human activities, urban lake water quality is undergoing long-term changes and development. To evaluate the water quality, many methods have been developed, such as the Bayesian discrimination (BD) (Huang et al., 2019; Qian et al., 2018), the gray correlation analysis (GCA) (Chen et al., 2016), and the fuzzy comprehensive assessment (FCA) (Onkal-Engin et al., 2004; Wang, 2002; Zhu & Lu, 2019). Among them, FCA can solve the problem that information is fuzzy and evaluation objective is restricted by many factors and has been widely used (Ding et al., 2017). FCA uses the principle of maximum membership (MMP) to assess the environmental quality level (Shen et al., 2005), and it is impossible to quantitatively compare inter-year environmental quality changes through specific indicators. At the same time, when using the FCA method, if any one of the key parameters has extreme changes, the evaluation results will be contradictory (Liou & Lo, 2005). The fuzzy comprehensive-quantifying assessment (FCQA) method combines traditional FCA with quantitative evaluation, and the evaluation results are convenient for quantitative comparison in a certain period (Yang et al., 2011).

Wuhan, the capital of Hubei Province in central China, is famous for the title of "city of hundreds of lakes." Among 166 lakes in Wuhan, 40 are located in the central urban area (Wu et al., 2019). Most urban lakes in Wuhan are facing the problems of area reduction, eutrophication, and deterioration of water quality (Wu & Xie, 2011; Zhou et al., 2019). As a typical urban lake in the central Wuhan (Fig. 1), Sha Lake is about 307.8 ha and the water depth is 2–2.5 m. The total area of the Sha Lake Basin is about 997.19 ha, which was determined according to both hydrology and ground object boundary of the region (Zeng et al., 2012). In 1995–2015, lake reclamation and other urban construction activities had reduced the area of the Sha Lake by 47.35% (Deng et al., 2017). According to the "Environmental Quality Standards for Surface Water of China (GB 3838-2002)", the water quality standard of the Sha Lake is class IV. And the corresponding functions of the Sha Lake are urban rainfall regulation, scenery, and recreation based on the "Surface Water Environment Functional

Fig. 1 Location of the Sha Lake in China



Zoning of Wuhan City". However, the actual water quality classification of the Sha Lake was class V, and the eutrophication level of the Sha Lake was moderate eutrophication in recent years (Luo et al., 2021). Meanwhile, the average transparency of the Sha Lake was 0.35 m in 2018 based on the site monitoring. The Sha Lake witnesses the urban development and is representative for urban lake research and conservation.

How to maintain the long-term stability of lake water quality in the process of rapid urban development is an important issue for urban lake protection. Taking Sha Lake as an example, this study amis to analyze the urban development process in the Sha Lake Basin in 2000–2018, quantitatively evaluate the water quality of the Sha Lake in 2000–2018, and discuss the relationship between urban development and water quality changes of the Sha Lake. The results can provide a reference for the improvement and maintenance of urban lake water quality.

Method and materials

Data sources

The research data included remote sensing images and water quality data. Remote sensing images were used for land use classification and chlorophyll-a concentration inversion from Landsat data (https://earthexplorer.usgs.gov/) and Google Earth images (https://www.google.com/earth/) in 2000–2018. The water quality data of Sha Lake were obtained from long-term monitoring, including dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total phosphorus (TP), total nitrogen (TN), and chlorophyll-a in 2000–2018.

Methods

Land use classification

Based on supervised classification and visual interpretation, the remote sensing images were used to classify the land use types of the Sha Lake Basin in 2000–2018. Land use types of the Sha Lake Basin were divided into construction land, unutilized land, farmland, green land, and water. The classification and statistical analysis were implemented in ENVI 5.3 and ArcGIS 10.2.

Land use degree assessment

Land use degree reflects the natural attributes of the land and the comprehensive influence of natural and human factors on land use. The land use degree comprehensive index (I) was calculated to reveal the level of urban development from the perspective of land use. The calculation formula of I was as Eq. (1) (Zhuang & Liu, 1997). The greater the I is, the higher the land use degree is. $I \leq 200$ represents a low land use degree; $200 < I \leq 300$ represents a medium land use degree; and $300 < I \leq 400$ represents a high land use degree, and construction land becomes the main land use type. The changes of I indicate the state of urban development. The increase of I indicates that urban construction is in development, and the decrease of I indicates that urban construction is in decline.

$$I = \sum_{i=1}^{n} A_i \times C_i \times 100 \quad I \in [100, 400] \tag{1}$$

where I is the land use degree comprehensive index, A_i is the grading index of the i-th level land use in the region, C_i is the percentage of the area of the i-th level land in the region, n is the number of land use levels, and the value of land use classification is shown in Table 1.

Fuzzy comprehensive-quantifying assessment

FCQA method was used to quantitatively evaluate the water quality of the Sha Lake (Li et al., 2009; Yang et al., 2011). In this study, the DO, BOD, COD, TP, and TN were selected to calculate the water quality index (S_{mid}); the TP and TN were selected to

Table 1 Land use grading assignment

Grading index	Land use type
1	Unutilized land
2	Green land, grassland, and water
3	Farmland
4	Construction land, residential land, and road traffic land

calculate the eutrophication index (T_{mid}). S_{mid} and T_{mid} were calculated in the same way (Eqs. (2)–(3)). For S_{mid}, each index was divided into 5 levels according to the Chinese surface water environmental quality standard (GB3838-2002). And for T_{mid}, each index was divided into 11 levels according to the technical rules of the National Comprehensive Water Resources Planning. In particular, the S_{mid} and T_{mid} values in 2001–2003 were obtained by equal interval interpolation due to the lack of monitoring data.

$$\begin{cases} S_{mid} = \sum_{j=1}^{m} b_j \cdot C_{mid(j)} \\ T_{mid} = \sum_{j=1}^{m} b_j \cdot C_{mid(j)} \end{cases} \tag{2}$$

$$b_j = \sum_{i=1}^{n} w_i \cdot u_{ij} = \sum_{i=1}^{n} \frac{x_i/s_i}{\sum_{i=1}^{n} (x_i/s_i)} \cdot u_{ij} \tag{3}$$

$$u_{ij} = \begin{cases} 1, & 0 \le x_i < v_1 \\ \frac{v_2 - x_i}{v_2 - v_1}, & v_1 \le x_i < v_2, \quad j = 1 \\ 0, & x_i \ge v_2 \end{cases}$$
$$u_{ij} = \begin{cases} 0, & x_i < v_{j-1} \ or \ x_i \ge v_{j+1} \\ 1 - u_{j-1(x)}, v_{j-1} \le x_i < v_j \\ \frac{v_{j+1} - x_i}{v_{j+1} - v_j}, v_j \le x_i < v_{j+1} \end{cases}, \quad j = 2, 3, ..., m-1$$
$$u_{ij} = \begin{cases} 0, & 0 \le x_i < v_{j-1} \\ 1 - u_{i(j-1)}, v_{j-1} \le x_i < v_j, \quad j = m \\ 1, & x_i \ge v_j \end{cases} \tag{4}$$

where $C_{mid(j)}$ is the j-level evaluation standard, $C_{mid(j)}$=[55,65,75,85,95] for S_{mid}, and $C_{mid(j)}$=[0,10,20,30,40,50,60,70,80,90,100] for T_{mid}; b_j is the parameter calculated by fuzzy algorithm; m is the number of grades, 5 and 11 for S_{mid} and T_{mid}, respectively; w_i is the weight of the i-th index; x_i is the monitoring value of the i-th index, mg/L; s_i is the average value of evaluation standard for i-th index, mg/L; u_{ij} is the membership degree of the i-th index at the j-th level, and was calculated by Eq. (4); and v_j is the standard value of the evaluation index under the j-th level, mg/L.

Remote sensing inversion of chlorophyll-a concentration

Chlorophyll-a concentration is an intuitive index to evaluate the eutrophication of the water body (Wang et al., 2015). The remote sensing inversion technology of chlorophyll-a has been developed to make up for the lack of measured data. The empirical model (Eq. (5)) was used to simulate the chlorophyll-a concentration in Sha Lake. The inversion was implemented in ENVI 5.3.

$$Chla \propto (R_{\lambda 1}, R_{\lambda 2}, R_{\lambda 3}, R_{\lambda 4}, R_{\lambda 5}, R_{\lambda 6}) \tag{5}$$

where $Chla$ is the chlorophyll-a concentration (μg/L) and $R_{\lambda 1}$–$R_{\lambda 6}$ are the surface reflectance of remote sensing image bands 1–6, respectively.

Results and discussion

Urban construction in the Sha Lake Basin

Land use changes in the Sha Lake Basin

Based on remote sensing interpretation data, the ratio of various types of land use in the Sha Lake Basin in 2000–2018 was calculated. The results showed that the percentage of construction land area increased from 35.27% to 63.82% and the percentage of water area decreased from 50.47% to 27.68%. The main land use type change in the Sha Lake Basin was the conversion of water to construction land. With the urban development of the basin, the area of roads and green land increased with the needs of infrastructure construction; farmland showed a significant reduction trend, and had been converted into construction land; and unutilized land referred to transitional land use types in the process of transforming other land use types to construction land, which was prone to soil erosion and caused urban non-point source pollution. And the change of unutilized land in the Sha Lake Basin was fluctuating.

On the whole, land use in the Sha Lake Basin had changed significantly in 2000–2018. The water area showed a clear shrinking trend (Fig. 2). The entire lake was reduced to a certain extent in both

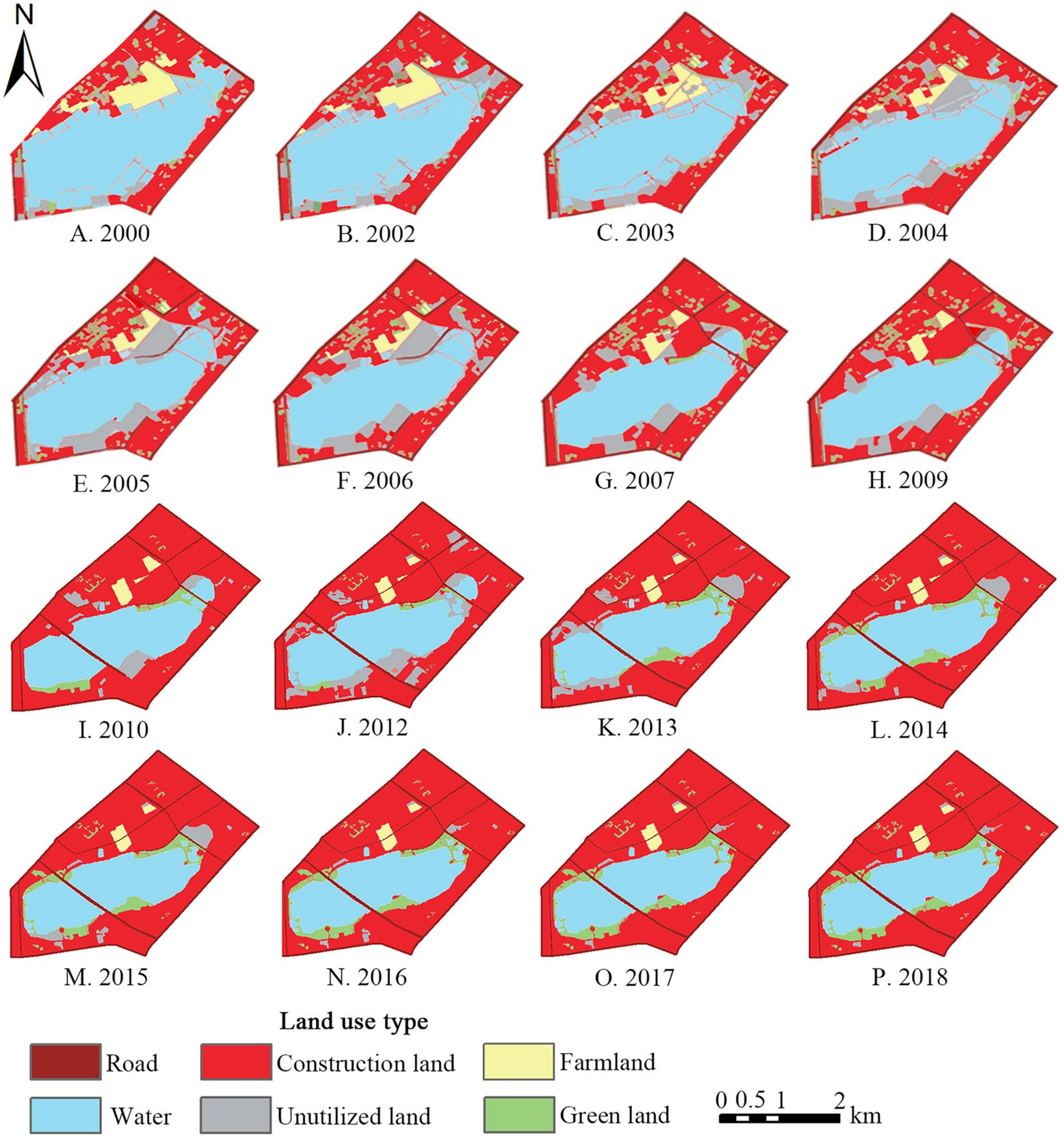


Fig. 2 Distribution of land use of the Sha Lake Basin in 2000–2018

the vertical and horizontal directions. The shape of the Sha Lake had changed greatly. The occupied areas of the Sha Lake were mainly distributed in the north and south of the lake; the decrease of farmland area was mainly related to the development of real estate along the lake in recent years; the unutilized land fluctuated and was mainly distributed in the northeast and south of the lake; and with the decrease of water and farmland area, construction land increased significantly.

Urban construction process in the Sha Lake Basin

The *I* value had increased from 271.45 in 2000 to 328.25 in 2018, an increase of 56.80 units, indicating the rapid urban development of the Sha Lake Basin in the past 20 years. According to the change rate of *I*, the urban construction process in the Sha Lake Basin could be divided into three stages (Fig. 3a).

(1) Stage I: slow urban development period (2000–2006).

I slowly increased from 271.45 to 276.87. In this period, the changes of land use types in the Sha Lake Basin were mainly manifested as the transformation of farmland in the north of the Sha Lake and water in the south into unutilized land.

(2) Stage II: rapid urban development period (2007–2009).

I increased from 297.84 to 300.30, and urban construction entered a period of rapid development. During this period, with urban development, land use changes in the Sha Lake Basin were mainly manifested in the mutual transformation between construction land and unutilized land. In 2007, the intensity of real estate development on the northeast of the Sha Lake had increased, and about 70 hm^2 of unutilized land were converted into urban construction land, which resulted in a significant increase of 20.97 units in *I* compared with 2006.

(3) Stage III: highly urban development period (2010–2018).

I increased from 319.58 to 328.25, and urban construction reached a high level. The construction land area reached 63.82% of the basin area in 2018. In 2010, *I* suddenly increased to 319.58. This was because most of the unutilized land in the

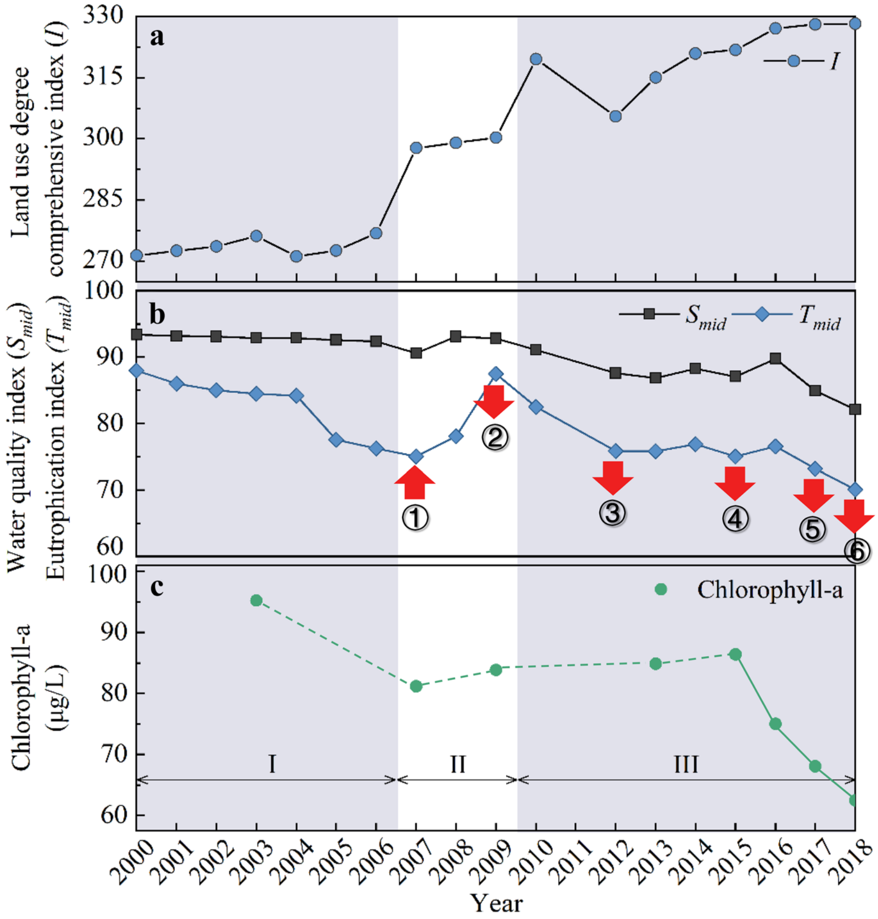


Fig. 3 Trends of urban development and water quality change in the Sha Lake Basin in 2000–2018: **a** land use comprehensive index, **b** water quality index and eutrophication index, and **c** chlorophyll-a concentration. ① in 2007, prohibition of pisciculture; ② in 2009, East Lake Ecological Water Network Connection Project and dredging project of Sha Lake; ③ in 2012, artificial wetland (Shahu Park); ④ in 2015, Lake Protection Regulations of Wuhan; ⑤ in 2017, greenway by the Sha Lake; ⑥ in 2018, Sha Lake Water Environment Enhancement Exogenous Pollution Control Project and Sewage Pipe Network Maintenance and Renovation Project

Table 2 Evaluation results of the Sha Lake water quality by FCQA

Year	FCQA						
	I (b_1)	II (b_2)	III (b_3)	IV (b_4)	V (b_5)	S_{mid}	Class
2000	0.02	0	0	0.08	0.90	93.40	V
2004	0.02	0	0.02	0.07	0.88	92.86	V
2005	0.03	0	0	0.11	0.86	92.60	V
2006	0.03	0	0	0.14	0.83	92.37	V
2007	0.04	0	0.03	0.23	0.70	90.62	V
2008	0.03	0	0.03	0.02	0.92	93.09	V
2009	0.02	0	0.04	0.05	0.89	92.83	V
2012	0.14	0	0.02	0.13	0.70	87.61	IV
2013	0.15	0	0.10	0.03	0.72	86.85	IV
2014	0.13	0	0.03	0.10	0.74	88.27	IV
2015	0.14	0	0.06	0.10	0.70	87.09	IV
2016	0.08	0.02	0.05	0.01	0.83	89.79	IV
2017	0.22	0	0	0.11	0.67	84.97	IV
2018	0.27	0	0.05	0.10	0.57	82.12	IV

I (excellent), $50 \le S_{mid} \le 59$; II (good), $60 \le S_{mid} \le 69$ III (ordinary), $70 \le S_{mid} \le 79$; IV (poor), $80 \le S_{mid} \le 89$; V (bad), $90 \le S_{mid} \le 100$

Sha Lake Basin was completely transformed into construction land in 2010. Since 2012, the planning and construction of the Sha Lake Park transformed part of the construction land and water in the southern area near the lake into unutilized land. Therefore, *I* in 2012 was lower than in 2010. With the completion of the construction, the unutilized land near the lake became construction land, and *I* increased rapidly.

Water quality change of the Sha Lake

The results of FCQA were shown in Table 2 and Table 3. Lower S_{mid} and T_{mid} indicated better water quality and lower eutrophication. In the past 20 years, the S_{mid} decreased from 93.40 in 2000 to 82.12 in 2018, T_{mid} decreased from 87.96 in 2000 to 70.08 in 2018, and chlorophyll-a concentration decreased from 95.26 μg/L in 2003 to 62.49 μg/L in 2018. On

Table 3 Evaluation results of eutrophication status of the Sha Lake by FCQA

Year	FCQA												
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	T_{mid}	Class
2000	0	0	0	0	0	0	0.10	0.01	0	0.79	0.11	87.96	Severe
2004	0	0	0	0	0	0	0	0.21	0.16	0.63	0	84.17	Severe
2005	0	0	0	0	0	0	0	0.27	0.70	0.03	0	77.57	Moderate
2006	0	0	0	0	0	0	0	0.38	0.62	0	0	76.22	Moderate
2007	0	0	0	0	0	0	0	0.49	0.51	0	0	75.06	Moderate
2008	0	0	0	0	0	0	0	0.19	0.81	0	0	78.06	Moderate
2009	0	0	0	0	0	0	0	0	0.25	0.75	0	87.52	Severe
2012	0	0	0	0	0	0	0	0.41	0.59	0	0	75.86	Moderate
2013	0	0	0	0	0	0	0	0.42	0.58	0	0	75.79	Moderate
2014	0	0	0	0	0	0	0	0.31	0.69	0	0	76.88	Moderate
2015	0	0	0	0	0	0	0	0.50	0.50	0	0	75.04	Moderate
2016	0	0	0	0	0	0	0	0.34	0.66	0	0	76.56	Moderate
2017	0	0	0	0	0	0	0	0.68	0.32	0	0	73.23	Moderate
2018	0	0	0	0	0	0	0.02	0.95	0.03	0	0	70.08	Moderate

Oligotrophic, $0 \le T_{mid} \le 30$; mesotrophic, $30 \le T_{mid} \le 50$; light eutropher, $60 \le T_{mid} < 70$; moderate eutropher, $70 \le T_{mid} < 80$; severe eutropher, $80 \le T_{mid} \le 100$

the whole, the water quality of Sha Lake had experienced a process of deterioration to improvement in the past 20 years. The study had shown that the eutrophication state of the Sha Lake decreased from severe eutrophication to moderate eutrophication in 2014–2016, which supported our results (Luo et al., 2021). The change in T_{mid} was more obvious than the change in S_{mid} during the study period. For instance, in 2007–2009, I increased by 0.83%, and S_{mid} and T_{mid} increased by 2.45% and 16.60%, respectively; in 2009–2012, I increased by 1.76%, and S_{mid} and T_{mid} decreased by 5.62% and 13.33%, respectively. This indicated that eutrophication was more sensitive to land use change, and the impact of urban construction on lake water quality was mainly nitrogen and phosphorus pollution.

The water quality deterioration of the Sha Lake was mainly related to the rapid urban development. And the water quality improvement was mainly attributed to environmental protection measures, including decreasing exogenous input, reducing lake endogenous release, and enhancing water self-purification capacity. According to the urban development process, the changes in the water quality of the Sha Lake could be divided into three stages (Fig. 3b and c).

(1) Stage I: stable period (2000–2006).

During this period, S_{mid} and T_{mid} continued to decrease from 93.40 to 92.37 and 87.96 to 76.22, respectively, and the chlorophyll-a concentration was 95.26 μg/L in 2003, which indicated a bad water quality and a severe/moderate eutrophication level of the Sha Lake. With a slow development of urban construction, the water quality of the Sha Lake showed a steady improvement trend and the eutrophication level had improved slightly.

(2) Stage II: deteriorative period (2007–2009).

S_{mid} increased from 90.62 to 92.83, T_{mid} increased from 75.06 to 87.52, and chlorophyll-a concentration increased from 81.18 μg/L to 83.86 μg/L during this period. The water quality of Sha Lake was deteriorated, especially that the eutrophication level increased from moderate to severe. As urban construction had entered a period of rapid development in 2007–2009, domestic sewage was the main pollution source of the Sha Lake. With the sudden increase in I value in 2007, the S_{mid} and T_{mid} decreased in 2007 and then increased from 2008, indicating that urban construction showed a negative effect on water quality in the short term. Simultaneously, some environmental protection measures had been taken, such as the prohibition of pisciculture in 2007, the East Lake Ecological Water Network Connection Project and the dredging project in 2009. East Lake Ecological Water Network Connection Project and dredging project implemented in 2009 were critical ways to improve water quality during this period. Connected with the Yangtze River and the East Lake, the Sha Lake was transformed from an enclosed lake to an open

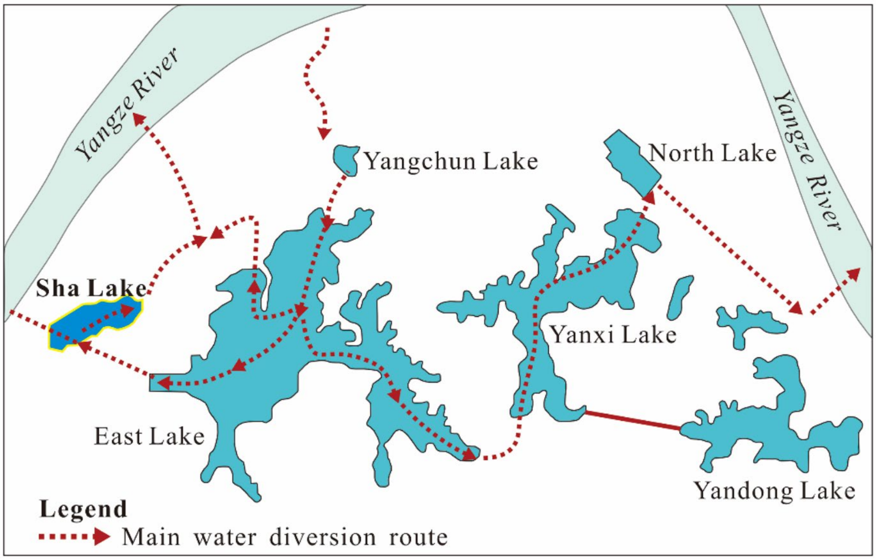


Fig. 4 Schematic diagram of East Lake Ecological Water Network Connection Project in Wuhan

lake by East Lake Ecological Water Network Connection Project (Fig. 4). The water network connection was a useful and critical measure for water resource allocation, water ecological restoration, and water quality improvement (Yang et al., 2019; Yu et al., 2020). It was conducive to increasing water flow, improving hydrodynamic circulation and self-purification capacity, and preventing pollutant accumulation in the lake (Cui et al., 2009; Wang et al., 2016). Through the completely water exchange between the lake and the Yangtze River, the water quality of Sha Lake had been improved (Luo et al., 2021). Simultaneously, the dredging project of the Sha Lake was implemented. Removal of sediment could effectively reduce the lake endogenous release and the storage of pollutants in the water body, and water quality would be improved until 1–2 years after the project finished (Björk et al., 2010; Jing et al., 2019; Wu et al., 2008). The results indicated that the combination of water network connection and dredging project had improved water quality in a long time. However, due to the failure to implement these measures in time and the incomplete infrastructure during the rapid urban development, water quality still deteriorated during this period.

(3) Stage III: improving period (2010–2018).

S_{mid} decreased from 91.07 to 82.12, T_{mid} decreased from 82.51 to 70.08, and chlorophyll-a concentration decreased from 84.91 μg/L to 62.49 μg/L during this period. Urban construction reached a high level and supporting environmental protection measures had been followed up. The environmental protection measures implemented in 2009 showed effects in this period. In addition, other measures were implemented from 2012. In 2012, the construction of Shahu Park was started, and the artificial wetland was formed around the lake, which could intercept pollutants into the lake and improve water self-purification capacity. In 2015, the "Lake Protection Regulations of Wuhan" was promulgated to strictly regulate the management system and occupation of lakes. In 2016, due to the construction of a large number of residential communities in the south and northwest of Sha Lake, the increase of regional population, accumulation of urban garbage, and the increase of domestic sewage discharge caused the water quality to be a little worse than that in 2015. In 2017, the basic construction of the communities, parks, and greenways in the southern part of the Sha Lake had been completed (Fig. 5), and the ecological environment had been significantly improved. Among them, the greenways by the Sha Lake could filter and reduce pollutants into the lake, thereby reducing non-point source pollution. In 2018, the Sha Lake Water Environment Enhancement Exogenous Pollution Control Project and Sewage Pipe Network Maintenance and Renovation Project were implemented. The former could control both point and non-point source pollution of the Sha Lake Basin. And the latter could control the non-point source pollution in the process of pollution occurrence. At present, a high-standard interception system had been built in the Sha Lake catchment area, 100% of the dry weather flow did not flow into the lake, and 33% of the catchment area had completed the diversion of rainwater and sewage (Wu & Chen, 2020).

Fig. 5 Current situation of ecological landscape of the Sha Lake (taken in 2020)

Conclusion

The water quality of the Sha Lake under the process of urban development was quantitatively evaluated in 2000–2018. The overall water quality of the Sha Lake was improved. Corresponding to the period of urban development, the water quality changes of the Sha Lake experienced three periods: stable period, deteriorative period, and improving period. Urban development had both positive and negative effects on water quality. In the period of slow urban development, there was little influence on lake water quality, and water quality remains stable. In the period of rapid urban development, due to the failure to implement effective environmental protection measures in time, the water quality still deteriorated. In the period of high urban development, the implementation of a series of environmental protection measures since 2009 came into effect and had improved water quality.

Rapid urban development causes the deterioration of water quality in a short time, and effective environmental protection measures can improve water quality for a long time. Due to the lag effect on improving water quality, the implementation of environmental protection measures should be synchronized with or even before urban construction. Water network connection is a critical measure for enclosed urban lake water quality improvement, which can accelerate water circulation and enhance water self-purification capacity. Reduction of exogenous and endogenous pollutants, such as dredging project and sewage pipe network maintenance and renovation, can also reduce the pollutants into the lake and the pollutants released from the lake sediment. The research results can provide a reference for urban lake protection under the conditions of economic and social development.

Author contribution YZ: conceptualization; YZ, SR and YH: methodology and data analysis; SR and YH: investigation; SR and YZ: writing, reviewing, and editing; YZ: funding acquisition.

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Data availability The remote sensing data analyzed during the current study are available in the repositories: Landsat data (https://earthexplorer.usgs.gov/) and Google Earth data (https://www.google.com/earth/).

Declarations

Conflict of interest The authors declare no competing interests.

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