



# Insights into spatiotemporal variations of the water quality in Taihu Lake Basin, China

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**Abstract** Taihu Lake Basin is highly developed but suffers from perennial water shortages due to pollution. Most studies have been limited to examining the water quality in specific areas, but few have investigated the entire basin. This study was based on official water quality data obtained from 565 sites in the monitoring network, thereby covering the entire basin. The water quality spatiotemporal variations were explored by statistical analysis, and the precise spatial distribution of the main pollutants was analyzed by heat maps. Only 29.09% of the water quality assessment results showed “drinkable,” whereas 28.63% showed “moderate” and “severe” pollution. The “severe” proportion had a significant declining

trend ( $R^2=0.933$ ) and was affected by the variations of nitrogen that was related to rainfall and anthropogenic activities. The water quality spatial variation was most likely related to anthropogenic influence and land use. The water quality in the developed and densely populated urban areas was poor, especially in downtown Shanghai.  $\text{NH}_3\text{-N}$ , TN, TP,  $\text{BOD}_5$ , COD,  $\text{COD}_{\text{Mn}}$ , and DO were the main pollutants that affected the water quality.  $\text{NH}_3\text{-N}$  and TN were major reduction targets.  $\text{NH}_3\text{-N}$  was the main pollutant that deteriorated the water quality in most densely populated urban areas. Many lakes and reservoirs were highly polluted with TN. Controlling domestic sewage may be effective to improve the water quality. This study makes up for the limited research on the water quality spatiotemporal variations in the entire Taihu Lake Basin and provides beneficial information

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and suggestions for decision-making regarding the water management.

**Keywords** Water quality · Spatial–temporal variation · Eutrophication · Taihu Lake Basin

## Introduction

Water resources play a significant role in maintaining ecological health, human survival, and sustainable social development. However, the degradation observed in quality of surface water has long been a global issue. Pollutants from domestic, urban, and industry, such as chemicals, sewage, fertilizer, pesticide, and heavy metals in the aquatic ecosystem, has caused drinking water scarcity and damage to the health of environment, human, and the aquatic habitat (Adeleke et al., 2017; Chen et al., 2019). In general, the water environment in highly developed and densely populated areas faces greater pressure in terms of balancing water resources with agricultural irrigation, population, economic growth, and urban development (Li et al., 2019) and is therefore of particular concern.

Taihu Lake Basin is a well-known plain river network area in China and is dotted with lakes. The area has one of the highest population densities in China, which is accompanied by the fastest economic growth. Shanghai, Hangzhou, and Suzhou are all international metropolises that are located in the basin. However, in the process of rapid economic growth, the water bodies in Taihu Lake Basin have borne a heavy burden of pollution for years. This basin suffers from a perennial water shortage induced by pollution (Zhu, 2003). Since massive cyanobacterial blooms caused a drinking water crisis in Wuxi in 2007 (Yang et al., 2009), the Chinese government has begun to invest to strengthen the environmental governance. After years of environmental management, the government indicated that the water quality in the basin continued to improve, but the total amount of pollution discharge was still higher than that allowed (NDRC, 2013; Taihu Basin Authority of MWR, 2014, 2015, 2016, 2017). Due to the many factors caused by social development, it is difficult for the water environment of Taihu Lake Basin to fundamentally improve in a short period of time (Hu et al., 2014).

To safeguard the sustainable development of Taihu Lake Basin and relieve water shortage in the future, it is necessary to elaborate on the water quality spatiotemporal variations. Moreover, water quality spatiotemporal variations were related to the variations in water quality parameters, such as nutrient and organic matter from natural or domestic, agricultural, and industrial sources (Lintern et al., 2018; Adeleke et al., 2019a). Therefore, in order to manage the water quality, it is also necessary to identify the pollutants and the possible sources and factors of them that caused the water quality deterioration in different period and locations. Such information will provide reference for making more applicable decisions on the water quality management and can also help assess the effectiveness of past governance.

Numerous studies have explored the water quality spatiotemporal variations in Taihu Lake Basin. Most of these studies have focused on Taihu Lake (Zhu, 2009; Zhu et al., 2018) and the rivers that significantly affect the lake (Wang et al., 2011, 2015; Yi et al., 2016). Liu et al. (2020) found that the northwestern of Taihu Lake was the most heavily polluted area, and the main pollution sources were agricultural runoff and domestic sewage there. Zhang et al. (2017) studied the water quality in the northwestern upstream and found severe nutrient pollution in the cities Wuxi and Changzhou in winter and spring. Vadde et al. (2018) analyzed the southwestern inflow rivers of Taihu Lake and found that wastes from non-point sources negatively affected the quality of local rivers and Taihu Lake. These studies indicate that the quality of Taihu Lake is mainly affected by external pollution from the inflow rivers. Additionally, the water quality in the downstream basin was poor. Wang et al. (2019a) identified severe total nitrogen pollution in the downtown and northern suburbs of Shanghai. These studies are important for improving the water quality of Taihu Lake, the rivers surrounding Taihu Lake, and the downstream basin.

However, studies investigating the entire Taihu Lake Basin are limited because of its vast area, the different regional management mechanisms, and the difficulty in establishing a water quality monitoring network over the entire basin. The basin covers three provinces as well as Shanghai City. Thus, it is difficult for researchers to obtain detailed water quality monitoring data for the entire basin. Wu et al. (2018) set 96 monitoring sites along the main rivers in Taihu

Lake Basin to assess the water quality using modified water quality index. However, there are strong correlations between water quality and the structure and connectivity of river network (Deng, 2019). So it is necessary to monitor and evaluate the water quality in the tributaries of the main rivers, if a comprehensive understanding of water quality status is to be achieved while ensuring the development of the areas through which these rivers pass.

Our study aims to determine the water quality status over entire Taihu Lake Basin to identify issues and provide suggestions, based on the data from the monitoring network constructed by 565 sites. The paper included the following: (1) the overall water quality status of Taihu Lake basin, including the proportions of drinkable water and water with different pollution levels; (2) the spatial and temporal variations of the water quality; and (3) the main water quality parameters that deteriorated the water quality and their spatiotemporal variations and pollution status. Our study makes up for the limited research on the current water quality status of the entire Taihu Lake Basin and provides beneficial information and suggestions for decision-making in terms of water management in this basin, as well as in other developed and densely populated areas.

**Materials and methods**

**Description of the study area**

Taihu Lake Basin (30°7'19" to 32°14'56" N, 119°3'1" to 121°54'26" E) is located in the Yangtze River Delta and covers a total area of 36,895 km<sup>2</sup>. The basin comprises parts of the Jiangsu, Zhejiang, and Anhui provinces as well as the Shanghai municipality (Fig. 1a). Taihu Lake is located at the center, with a surface area of 2338 km<sup>2</sup>. The total length of the rivers in the basin is approximately 120,000 km (Taihu Basin Authority of MWR, 2013). The basin has a subtropical monsoon climate, with a mean annual temperature and precipitation of 14.9–16.2 °C and 1177 mm, respectively, and approximately 60% of the precipitation is concentrated in wet season (May to September) (NDRC, 2013). In 2018, Taihu Lake Basin had a population density of 1654 persons/km<sup>2</sup>, which was 11 times higher than the national average; the basin contributed 9.7% of China’s GDP and had

an urbanization rate greater than 70% (Taihu Basin Authority of MWR, 2018a). Except for urban areas, the main types of land cover in the basin are farmland and water bodies (Gao et al., 2017). Forest is distributed in the western hills of the basin (Fig. 1b).

**Data source and description**

The study was based on monthly water quality data that were obtained from the monitoring network constructed by 565 sites covering 193 rivers, 10 lakes, and seven reservoirs in the basin (Taihu Basin Authority of MWR, 2018b). The water quality data covered the period January 2018 to December 2018, which were obtained from the Water Resources Quality of Taihu Lake Basin and Southeast Rivers’ Important Water Functional Zones Report (Taihu Basin Authority of MWR, 2018b) (hereinafter referred to as “the Report”). Taihu Basin Authority released the data ([www.tba.gov.cn/](http://www.tba.gov.cn/)). In 2018, the Report published the water quality assessment results for all 380 water functional zones (determined by the government) in Taihu Lake Basin for the first time, providing information about the water quality grade, exceeding standard parameters, and exceeding standard multiples of the exceeding standard parameters in each functional zone. Before and after 2018, the Report provided assessment results of only 108 functional zones and lacked information on exceeding standard multiples. The more complete data for 2018 can therefore aid in a comprehensive analysis of the water quality.

According to the Report, 23 parameters were selected for the water quality assessment, and five additional parameters were selected to assess the drinking water functional zones (Table 1). Single

**Table 1** Parameters used in water quality assessment

Parameters
23 Parameters: temperature, pH, dissolved oxygen (DO), permanganate index (COD <sub>Mn</sub> ), chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD <sub>5</sub> ), ammonia nitrogen (NH <sub>3</sub> -N), total phosphorus (TP), total nitrogen (TN), copper (Cu), zinc (Zn), fluoride, selenium (Se), arsenic (As), mercury (Hg), cadmium (Cd), hexavalent chromium (Cr <sup>6+</sup> ), lead (Pb), cyanide, volatile phenol, petroleum, anionic surfactant, sulfide
5 Additional parameters: sulfate, chloride, nitrate, iron, manganese

**Table 2** Water quality grades and levels and descriptions of them

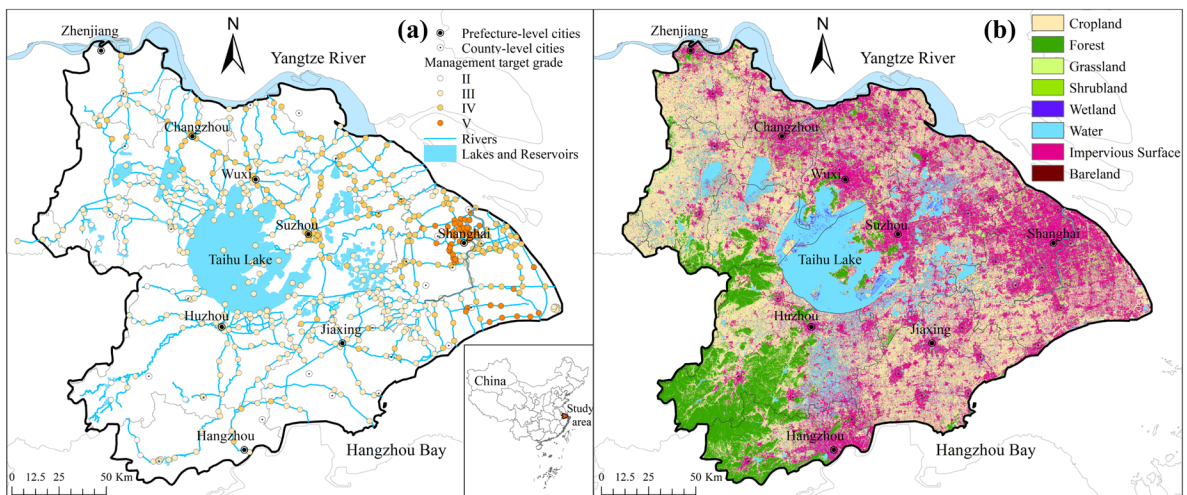
Water quality grade	Water quality status	Water quality level	Description
Grade I	Excellent	Drinkable	National nature reserve, river sources
Grade II	Excellent	Drinkable	First-class protected areas, drinking water sources
Grade III	Good	Drinkable	Second-class protected areas, drinking water sources
Grade IV	Mildly polluted	Mild	Human body non-direct contact water, industrial water
Grade V	Moderately polluted	Moderate	Agricultural and landscape water
Inferior to grade V	Severely polluted	Severe	Wastewater inferior to Grade V

factor assessment method was used to assess the water quality. Using this method, the water quality grade of an object is determined by the grade of the parameter with the worst water quality in terms of all the parameters chosen for assessment. Although this method cannot provide a comprehensive water quality status of an object, the worst status is revealed. That is more conducive to pollution control. The water quality assessment standards used in the Report refer to the Environmental Quality Standards for Surface Water (GB 3838–2002) (MEE, 2002), in which six water quality grades were established: Grades I–III indicate water that is suitable for drinking; grade IV, grade V, and inferior to grade V indicate polluted water. According to GB 3838–2002 (MEE, 2002), descriptions of each water quality grade are shown in Table 2. The Methods for Surface Water Environmental Quality

Assessment (trial) (MEE, 2011) defined the water quality status of each grade, according to which surface water quality can be reclassified into four levels, namely, “drinkable” (grade I–grade III), “mild” (grade IV), “moderate” (grade V), and “severe” (inferior to grade V), as shown in Table 2. One or more sites were set in each functional zone, producing the total of measurement 565 sites (Fig. 1a) within the 380 water functional zones. Each water functional zone has a management target grade that of a site is considered the same as its functional zone (Fig. 1a).

### Basic concepts and statistical analysis

In this part, some concepts and statistical calculations for water quality are introduced.



**Fig. 1** **a** Study area, the 565 sites with their management target grades. **b** The landcover at 10-m resolution derived from Gong et al. (2019) (data download web URL: <http://data.ess.tsinghu-a.edu.cn/fromglc2017v1.html>)

*Concept 1: the proportion of each water quality grade*

For the six water quality grades in Table 2, we calculated the proportions of each grade in terms of months, dry season and wet season, and year 2018 to analyze the water quality temporal variations. The proportion of water that is of a particular quality grade in a specific month is defined as the proportion of the total sites that has been assigned that grade (Eq. (1)). The proportion of water that is considered a specific grade in a season and a year is defined as Eqs. (2) and (3), respectively.

$$MPC_{gm} = \frac{\sum_{j=1}^J C_{gjm}}{J} \times 100\% \tag{1}$$

$MPC_{gm}$  represents the proportion of water that is of grade  $g$  in month  $m$ .  $j$  is the  $j^{th}$  site. If the water quality grade at the  $j^{th}$  site in month  $m$  is  $g$ , then  $C_{gjm} = 1$ ; otherwise,  $C_{gjm} = 0$ .  $J$  is the number of sites.

$$SPC_{gs} = \frac{\sum_m MPC_{gm}}{n} \tag{2}$$

$$APC_g = \frac{\sum_{m=1}^{12} MPC_{gm}}{12} \tag{3}$$

$SPC_{gs}$  represents the proportion of water that is of grade  $g$  in season  $s$ , and  $n$  is the number of months that comprise the season  $s$ .  $APC_g$  represents the annual proportion of grade  $g$ .  $m$  is a month in a period. A year consists of twelve months.

*Concept 2: exceeding standard parameters*

To prevent and control water pollution, the government set a management target grade for each water functional zone (Fig. 1a). The exceeding standard parameter is defined as that a parameter whose concentration exceeds the acceptable limit corresponding to the management target grade of the functional zone in a single factor assessment, according to the Technological Regulations for Surface Water Resources Quality Assessment (SL395-2007) (MWR, 2007). The management target grade of most sites is grade III (Fig. 1a). If the concentrations of some parameters at some sites exceed the acceptable limits corresponding

to grade III, the water quality levels of the sites are inferior to “drinkable.” It indicates that the sites are polluted and the pollutants are the exceeding standard parameters. Moreover, the water quality grades of the sites are determined by the grades of the parameters with the worst water quality, according to single factor assessment method. Therefore, the parameters with the worst water quality should be the major reduction targets of the sites. Table S1 lists the acceptable limits corresponding to grade I–grade V for certain parameters, which are specified by GB 3838–2002 (MEE, 2002).

*Concept 3: concentration of a parameter*

The Report did not provide the concentrations of the parameters of each functional zone, but it provided the exceeding standard multiples for the exceeding standard parameters. According to Concept 2, exceeding standard parameters are pollutants in water functional zones. The concentrations of them can determine the water quality grades and are related to Concept 1. SL395-2007 (MWR, 2007) defined that an exceeding standard multiple is

$$FB_i = FC_i / FS_i - 1 \tag{4}$$

In a functional zone,  $FB_i$  is the exceeding standard multiple of the exceeding standard parameter  $i$ ,  $FS_i$  represents the acceptable limit corresponding to the management target grade of the functional zone, and  $FC_i$  represents the concentration of parameter  $i$ . Therefore, the concentration of exceeding standard parameter  $i$  can be calculated as follows:

$$FC_i = (FB_i + 1) \times FS_i \tag{5}$$

If a parameter was not the exceeding standard parameter in the functional zone, we estimated the concentration of it. If the water quality grade of the functional zone was worse than or equal to the management target grade, the concentration was assigned by the median of the concentration range of the management target grade of the zone. If the water quality grade of the functional zone is better than the management target grade, the concentration is assigned by the median of the concentration range of the water quality grade of the zone. Furthermore, the quality levels of parameters are also classified into “drinkable,” “mild,” “moderate,” and “severe.”

**Table 3** Concentration range ( $\text{mg}\cdot\text{L}^{-1}$ ) of each water quality level for certain parameters

Parameter	Drinkable	Mild	Moderate	Severe
$\text{NH}_3\text{-N}$	$\leq 1.0$	$\leq 1.5$	$\leq 2.0$	$> 2.0$
TN (lake, reservoir)	$\leq 1.0$	$\leq 1.5$	$\leq 2.0$	$> 2.0$
TP (river)	$\leq 0.2$	$\leq 0.3$	$\leq 0.4$	$> 0.4$
TP (lake, reservoir)	$\leq 0.05$	$\leq 0.1$	$\leq 0.2$	$> 0.2$
$\text{BOD}_5$	$\leq 4.0$	$\leq 6.0$	$\leq 10$	$> 10$
COD	$\leq 20$	$\leq 30$	$\leq 40$	$> 40$
$\text{COD}_{\text{Mn}}$	$\leq 6.0$	$\leq 10$	$\leq 15$	$> 15$

The concentration range of each water quality level for certain parameters (Table 3) is defined based on Table S1.

Besides, in order to improve the efficiency of pollution control, the proportion of the number of times the parameters in Table 1 exceeded the standards in 2018 were counted to extract the main exceeding standard parameters that deteriorated the water quality in the basin. We mapped the exceeding standard sites of each main exceeding standard parameter in different seasons to analyze the spatial distribution and pollution status of the parameters. Moreover, heat maps were applied to illustrate where exceeding standards often occurred in different seasons.

Heat map is a widely applied method for visualizing complex spatial patterns (Chang & Zhao, 2017). Heat maps can show locations in which higher densities of geographic entities occur, such as areas with dense population, and can also reveal areas with a higher density of the occurrence of a phenomenon, such as the risk of disaster (Liu et al., 2019), and travel demand (Chang & Zhao, 2017). We created heat maps using the kernel density tool in ArcGIS 10.2, which calculates the density of point features in a neighborhood around those point features to create an interpolated density surface. The predicted density at a new  $(x,y)$  position is determined as follows:

$$\text{Density} = \frac{1}{(\text{radius})^2} \sum_{i=1}^n \left[ \frac{3}{\pi} \cdot \text{pop}_i \left( 1 - \left( \frac{\text{dist}_i}{\text{radius}} \right)^2 \right)^2 \right] \quad (6)$$

The new position  $(x, y)$  is taken as the center coordinate point for drawing a circular neighborhood, and  $\text{radius}$  represents the search radius within which to calculate density.  $i = 1, \dots, n$  are the input points (i.e., the exceeding standard sites of a main parameter

in this study) and only include points in the sum if they are within the radius distance of the  $(x,y)$  location.  $\text{dist}_i$  is the distance between point  $i$ , and the  $(x,y)$  position, and  $\text{dist}_i < \text{radius}$ .  $\text{pop}_i$  is the weight of point  $i$ . In this study, the weight is the number of times a parameter exceeded the standard at its exceeding standard site. The heat maps reveal areas in which a higher density of exceeding standards occurred.

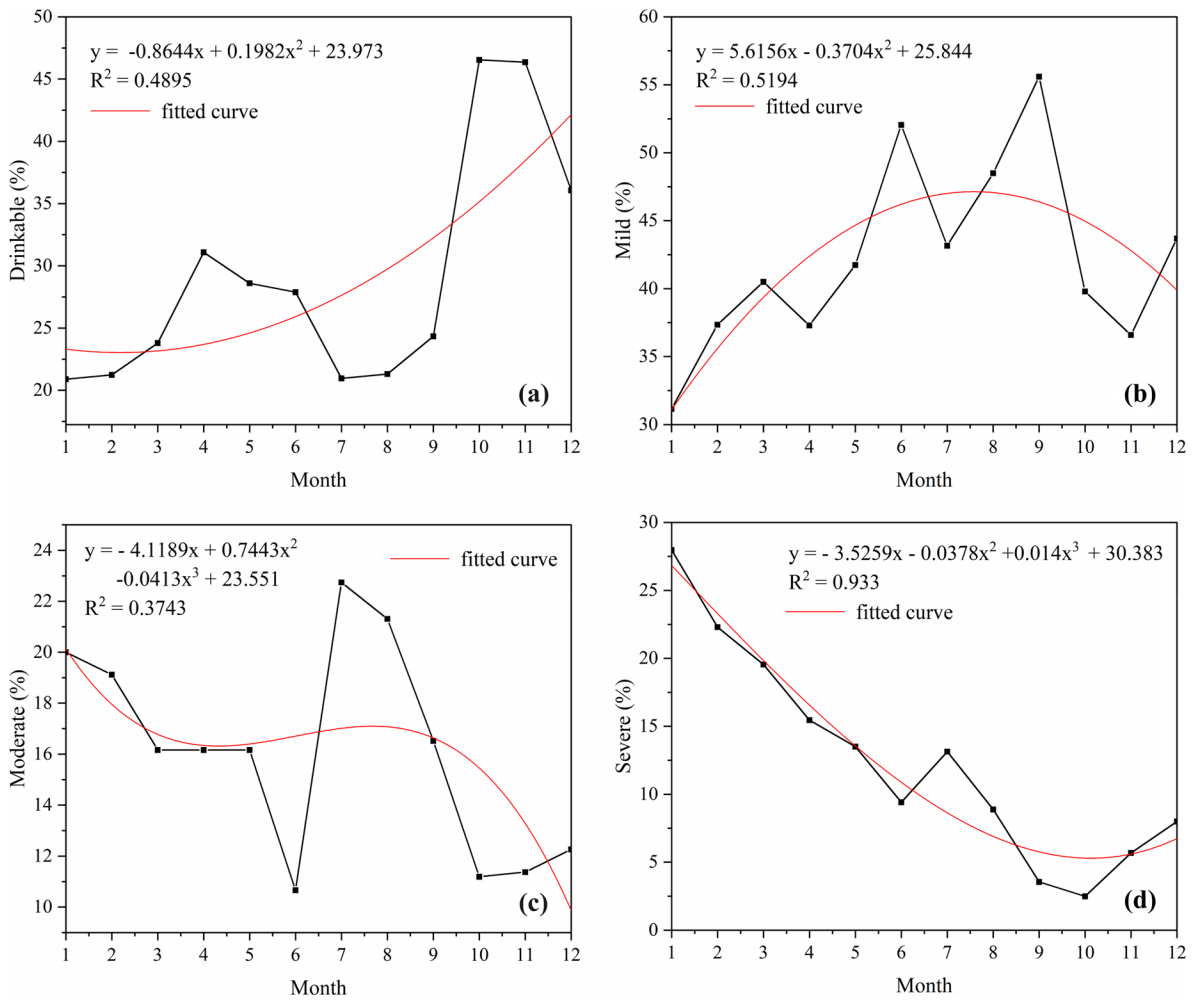
## Results

The proportions of water quality levels for different period

The proportion of each water quality level (“drinkable,” “mild,” “moderate,” “severe,” Table 2) in the twelve months is calculated by Eq. (1), and the results are shown in Table 4. To find the trend of variation in the monthly proportions of different water quality levels, we fitted the trend lines using math functions. Experimentation with a variety of mathematical fitting functions (quadratic, cubic, complex curve, power, logarithmic, exponential, and logistic functions) indicated that the cubic function had the highest coefficient of determination  $R^2$ . The trend lines for the four water quality levels are shown in Fig. 2, which shows that “drinkable” water had a rising trend, while “severe” had a declining trend from January to December during 2018. In particular, the temporal variation trend for “severe” was obvious, as the  $R^2$  for it reached 0.933. Neither “mild” nor “moderate” level showed any obvious trends. Moreover,

**Table 4** Proportions of water quality levels (%) in twelve months

Month	Drinkable	Mild	Moderate	Severe
January	20.89	31.15	20.00	27.97
February	21.24	37.35	19.12	22.30
March	23.80	40.50	16.16	19.54
April	31.08	37.30	16.16	15.45
May	28.60	41.74	16.16	13.50
June	27.89	52.04	10.66	9.41
July	20.96	43.16	22.74	13.14
August	21.31	48.49	21.31	8.88
September	24.33	55.60	16.52	3.55
October	46.54	39.79	11.19	2.49
November	46.36	36.59	11.37	5.68
December	36.06	43.69	12.26	7.99



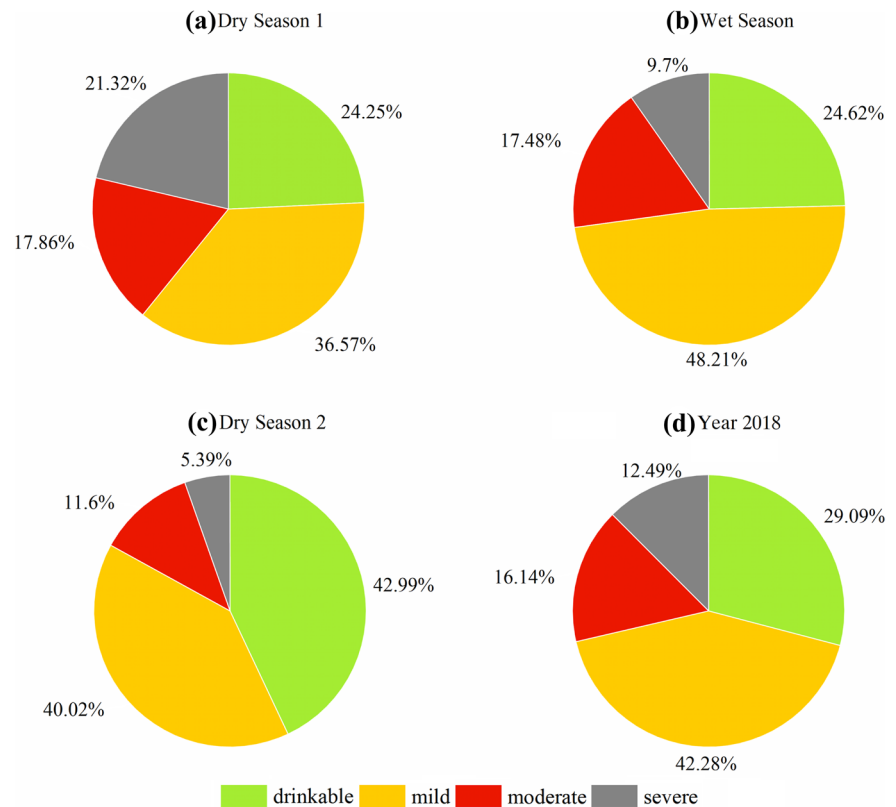
**Fig. 2** The temporal variation trends in the different water quality levels: **a** “drinkable,” **b** “mild,” **c** “moderate,” **d** “severe”

when the sum of “severe” and “moderate” proportions increased, the “drinkable” proportion decreased, and vice versa. The relationship between “drinkable” and “severe and moderate” is like a seesaw, suggesting that to increasing “drinkable” water proportion, we may need to strengthen the governance of “moderate” and “severe” water. Besides, except for October and November, the proportion of “mild” was higher than the other levels in all months, especially it exceeded 50% in June and September. Thus, for most of the months, mildly polluted was the general water quality status in Taihu Lake Basin.

Some factors affecting the water quality are climate and other natural factors. For instance, the heavy rainfall increases surface runoff and water volume, and

the intense microbial activity with high temperature accelerates the degradation of pollutants, resulting in the variations of the concentrations of pollutants in rivers and lakes (Tian et al., 2019). Researchers have found that there were differences in the water quality status in dry and wet seasons (Mei et al., 2014; Passos et al., 2021). We calculated the proportions of each water quality level (Table 2) in dry and wet seasons by Eq. (2) to find the seasonal variations of the water quality in the basin (Fig. 3). This can indicate the differences in the water quality status under different rainfall and temperature conditions. According to the regulations of Taihu Basin Authority (Taihu Basin Authority of MWR, 2018c), from May to September, the period is wet season, and the dry season consists of

**Fig. 3** Water quality temporal variations in the seasons for **a** dry season 1 (January to April), **b** wet season (May to September), **c** dry season 2 (October to December); **d** the water quality status for year 2018



the other months. Figure S1 shows the monthly precipitation and temperature in Taihu Lake Basin in 2018. However, from October to December, the “drinkable” proportion was clearly higher than that from January to April, and the “severe” and “moderate” proportions were clearly lower than those from January to April (Table 4). Therefore, the dry season was divided into dry season 1 (January to April, before wet season) and dry season 2 (October to December, after wet season) to avoid conflating the two different water quality status in the subsequent analysis.

Figure 3 illustrates the water quality for the different seasons. As can be seen from Fig. 3, the “drinkable” proportion was the highest in dry season 2 (42.99%), and it was almost equal in dry season 1 and wet season. The “mild” proportion increased from dry season 1 to wet season. The proportion of “moderate” was almost equal in dry season 1 and wet season, and it was the lowest in dry season 2. The “severe” proportion was the highest in dry season 1 (21.32%); however, it declined clearly during wet season and was the lowest in dry season 2. It can indicate that the “severe” proportion was affected by rainfall. In summary, the water quality in

Taihu Lake Basin was the worst in dry season 1 and was improved in wet season and the best in dry season 2.

As shown in Fig. 3e, in 2018, the proportion of “drinkable” water was only 29.09%, while the proportion of polluted water reached 70.91%. The proportions of “mild,” “moderate,” and “severe” water were 42.28%, 16.14%, and 12.49%, respectively. It can be seen that drinking water resources in Taihu Lake Basin were insufficient. The proportion of “mild” water was the highest, indicating that mildly polluted was the general water quality status in Taihu Lake Basin. The sum of “moderate” and “severe” was 28.63%, which was only 0.46% lower than the proportion of “drinkable.” Therefore, it is necessary to strengthen the management of the moderately and severely polluted water in Taihu Lake Basin.

The distribution of water quality levels in different seasons

The seasonal water quality levels of the 565 sites were used to analyze the water quality spatial variations in different seasons. Grade I–inferior to Grade V are



**Table 5** Conversion between mean water quality grade and water quality level

Mean water quality grade	Water quality level
1.0 < to ≤ 3.0 (grade I < to ≤ grade III)	Drinkable
3.0 < to ≤ 4.0 (grade III < to ≤ grade IV)	Mild
4.0 < to ≤ 5.0 (grade IV < to ≤ grade V)	Moderate
5.0 < to ≤ 6.0 (grade V < to ≤ inferior to grade V)	Severe

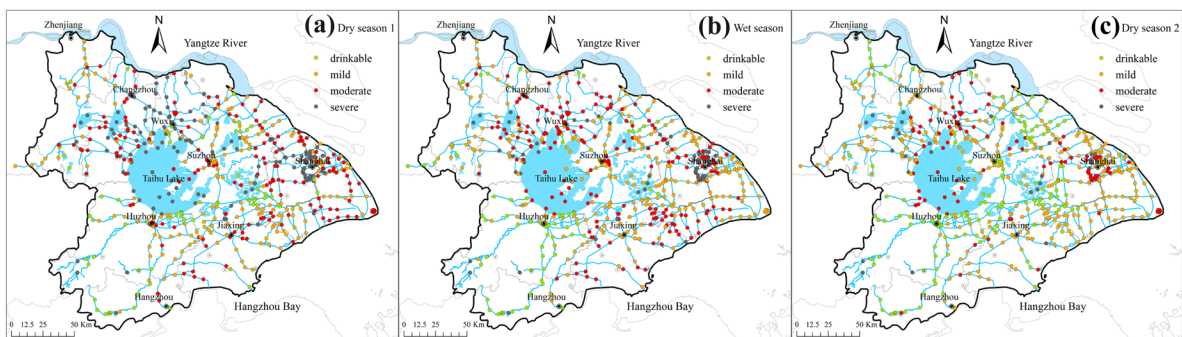
represented by the corresponding Arabic numerals 1–6, respectively. The seasonal water quality grade of a site was the mean value of all monthly water quality grades of the site in the season. The mean value may be a non-integer value, but it can be converted to the corresponding water quality level (Table 5) for describing the water quality succinctly. Figure 4 shows the distribution of the water quality for Taihu Lake Basin in dry season 1 (January to April), wet season (May to September), and dry season 2 (October to December).

As can be seen from Fig. 4, the spatial distribution of water quality in Taihu Lake Basin was not uniform during the study period. For lakes and reservoirs, the water quality of the northwestern Taihu Lake; the lakes locating in northwestern basin (e.g. Tao Lake and Ge Lake); Dianshan Lake; and the Fushi, Laoshikan, Duihekou, and Qingshan reservoirs locating in southwestern basin was almost “severe” and worse than the other lakes and reservoirs in all seasons. The water quality of the rest parts of Taihu Lake was “severe” and “moderate” in dry season 1 but was improved a bit in the other seasons, especially the “mild” quality level in eastern Taihu Lake.

For the river sites, most of the sites with “severe” quality were distributed in downtown Shanghai and the urban areas of Wuxi and Changzhou in dry season 1, and they were still distributed in downtown Shanghai in wet season and dry season 2. The sites with “moderate” quality were mainly distributed in the urban areas of most cities and most of the suburbs of developed cities (i.e., Shanghai, Wuxi, Changzhou, and Suzhou) in dry season 1. In wet season, in addition to most of the areas of Taihu, the water quality in the urban areas of Wuxi and Changzhou also changed from “severe” to “moderate.” Moreover, the water quality of some urban areas and suburbs was improved to “mild.” However, the water quality of the agriculturally developed suburbs locating in Jiaxing and southwestern Shanghai was deteriorated to “moderate.” In dry season 2, the sites with “moderate” quality were mainly distributed in the urban areas of Wuxi and Shanghai, and the water quality of many suburbs and urban areas was improved to “mild” and even “drinkable.” The water quality was the worst in dry season 1 and was improved in wet season and the best in dry season 2. It can be seen that the seasonal spatial variations in the water quality corresponded to the seasonal variations in Fig. 3. Besides, the sites with “drinkable” quality were distributed in water conservation and forests in general, for instance, the forests locating in southwestern basin.

The main exceeding standard water quality parameters

The above analysis has provided details concerning the overall status and spatiotemporal variations in the



**Fig. 4** The distribution of water quality levels in different seasons for **a** dry season 1, **b** wet season, and **c** dry season 2

water quality of Taihu Lake Basin. However, which water quality parameters affected and deteriorated the water quality has not been identified. To answer this question, the proportions of the number of times the parameters in Table 1 exceeded the standards in 2018 were counted, respectively. For a parameter, the proportion is the number of exceeding standard assessment results to the total number of assessment results during a period. According to the Report, TN was only measured in lakes and reservoirs. The assessment standard of TP for rivers is different from that for lakes and reservoirs (Table S1) (MEE, 2002), so the proportions of the number of exceeding standard times of TP (river) and TP (lake, reservoir) were calculated separately.

Table S2 shows that the proportions of the number of exceeding standard times of ammonia nitrogen ( $\text{NH}_3\text{-N}$ ), total phosphorus (TP), total nitrogen (TN), five-day biochemical oxygen demand ( $\text{BOD}_5$ ), chemical oxygen demand (COD), permanganate index ( $\text{COD}_{\text{Mn}}$ ), and dissolved oxygen (DO) were clearly higher than the other parameters. Therefore, these parameters are considered the main exceeding standard parameters in the basin.  $\text{NH}_3\text{-N}$ , TN, and TP are nutrients.  $\text{BOD}_5$ , COD, and  $\text{COD}_{\text{Mn}}$  are indicators of organic pollution. DO indicates the oxygen content in water. Besides, iron (Fe) and manganese (Mn) were the additional pollutants in drinking water functional zones, because the proportions of them (Table S2) were clearly higher than the other additional parameters (Table 1) which were used to evaluate the drinking water functional zones.

The proportions of the number of exceeding standard times of the main exceeding standard parameters for different seasons and year 2018 are shown in Table 6. As can be seen, the proportions of the number of exceeding standard times of TN (lake, reservoir) and TP (lake, reservoir) reached above 70% in the year. It indicated that there was widespread eutrophication in lakes and reservoirs. In addition, the proportions of the number of exceeding standard times of  $\text{NH}_3\text{-N}$ , TN (lake, reservoir), and DO varied significantly with the seasons. As shown in Table 6, the proportions of the number of exceeding standard times of  $\text{NH}_3\text{-N}$  and TN (lake, reservoir) in dry season 1 were significantly higher than wet season. The proportion of the number of exceeding standard times of DO in wet season was significantly higher than dry seasons 1 and

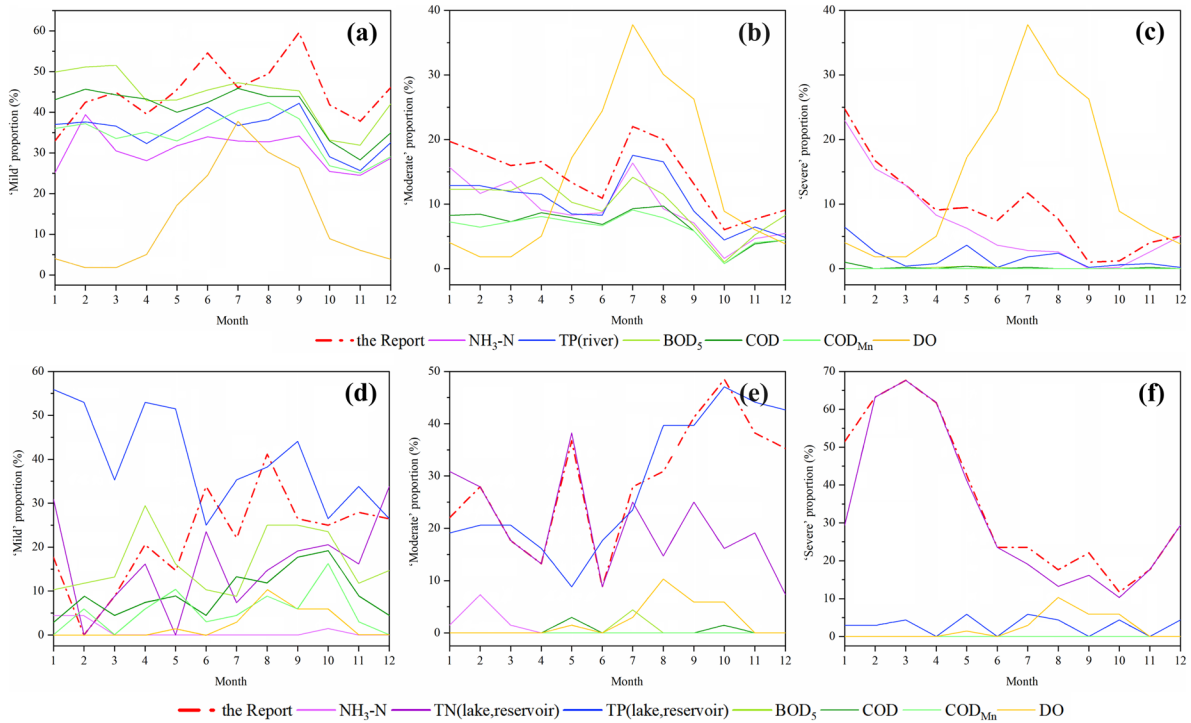
**Table 6** The proportions of the number of exceeding standard times of the main exceeding standard parameters (%) in different seasons and year 2018

Parameter	Dry Season 1	Wet Season	Dry Season 2	Year 2018
$\text{NH}_3\text{-N}$	32.62	11.47	7.46	17.53
TN (lake, reservoir)	94.85	61.77	59.31	72.18
TP (river)	18.90	18.47	8.82	16.21
TP (lake, reservoir)	73.53	69.71	77.94	73.04
$\text{BOD}_5$	25.58	19.18	13.44	19.88
COD	14.67	13.89	7.99	12.68
$\text{COD}_{\text{Mn}}$	6.38	8.60	4.56	6.85
DO	2.79	24.37	5.74	12.52

2. Besides, except for TP (lake, reservoir) and DO, the proportion of the number of exceeding standard times for each parameter was the lowest in dry season 2, which might cause the better water quality in dry season 2.

The variations in water quality are dominated by the variations in the concentrations of pollutants (Lintern et al., 2018). The proportions of “severe,” “moderate,” and “mild” for the monthly concentrations of the main exceeding standard parameters were counted based on their concentration ranges of each quality level in Table 3. Because of the different assessment standards for TP (lake, reservoir) and TP (river) (Table S1), the above calculation was applied to 497 river sites and 68 lake and reservoir sites, respectively. Moreover, the monthly proportions of the water quality levels for the 497 sites and the 68 sites (“the Report” red lines in Fig. 5) are calculated by Eq. (1), respectively. The results are shown in Fig. 5. According to SL395-2007 (MWR, 2007), the exceeding standard multiple of DO does not require calculation, so DO concentrations cannot be calculated by Eq. (5). We used the monthly proportions of the number of exceeding standard times of DO to replace the proportions of the pollution levels.

According to single factor assessment method, the water quality level of a site is determined by the quality levels of the parameters with the worst water quality. As can be seen, for rivers, only the variation in the “severe” proportion of  $\text{NH}_3\text{-N}$  was similar to that in the “severe” proportion, especially in dry seasons (Fig. 5). For lakes and reservoirs, only the



**Fig. 5** The proportions of “mild,” “moderate,” and “severe” for the monthly concentrations of the main exceeding standard parameters for **a–c** 497 river sites and **d–f** 68 lake and reservoir sites

variation in the “severe” proportion of TN (lake, reservoir) was similar to that in the “severe” proportion. The “severe” proportions of NH<sub>3</sub>-N and TN (lake, reservoir) were higher than the other parameters, respectively. Therefore, NH<sub>3</sub>-N and TN should be major reduction targets of the river sites and lake and reservoir sites with “severe” quality, respectively. In addition, the monthly “moderate” proportions in July and August were clearly higher than the other months (Fig. 2). The “moderate” proportion of TP (river) was also higher than the other parameters in July and August, and the variation trend of it was similar to that of the “moderate” proportion (Fig. 5). It indicated that TP should be a reduction target of the river sites with “moderate” quality, especially in July and August. In addition, except for TN (lake, reservoir) and TP (lake, reservoir), the proportions of “severe” and “moderate” of the other parameters for the lake and reservoir sites were low, indicating that TN and TP were the main pollutants in lakes and reservoirs.

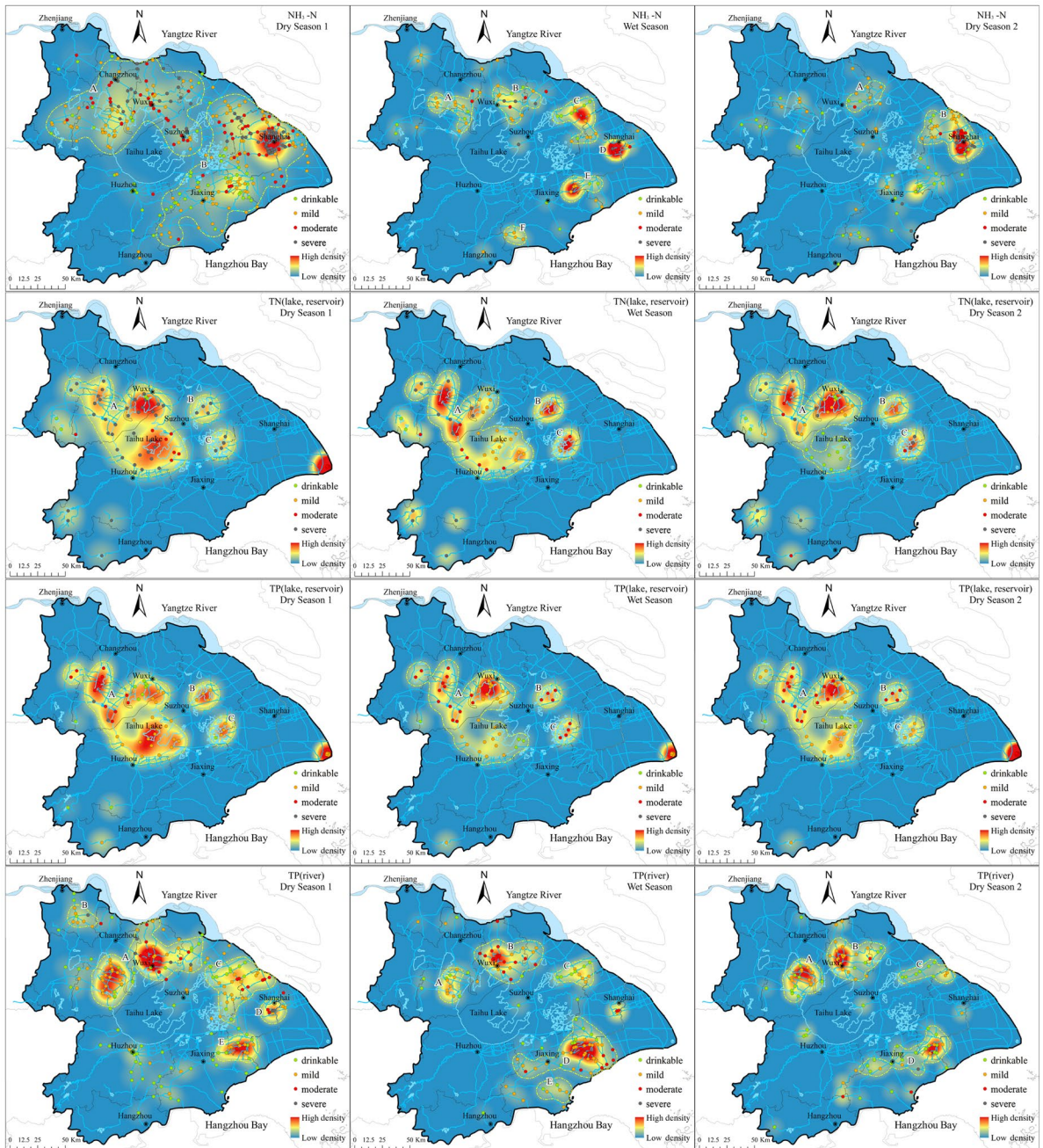
The precise spatial distribution and pollution status of the main exceeding standard parameters

In order to better control pollution, this section analyzes the precise spatial distribution and pollution status of the main exceeding standard parameters, which were the main pollutants that affected and deteriorated the water quality in Taihu Lake Basin. According to SL395-2007 (MWR, 2007), if the exceeding standard rate of a parameter is over 20% at a site in a period, the site is considered to be the exceeding standard site of the parameter in the period. The exceeding standard rate of a parameter is the number of exceeding standard results to the total number of assessment results at the site in the period. Compare the mean concentration in the period with Table 3 to determine the pollution level of the parameter at the site.

In dry and wet seasons, the spatial distribution and pollution levels for the exceeding standard sites of each main exceeding standard parameter are shown

in Figs. 6 and 7. We used the proportion of the number of exceeding standard times to describe the pollution status of DO for each exceeding standard site. Furthermore, the high densities represented by warm colors in heat maps (Figs. 6 and 7) were used to

illustrate areas in which a higher density of exceeding standards occurred in different seasons. The heat areas are marked with letters in heat maps. Besides, due to less number of exceeding standard times and low concentration each exceeding standard time, the

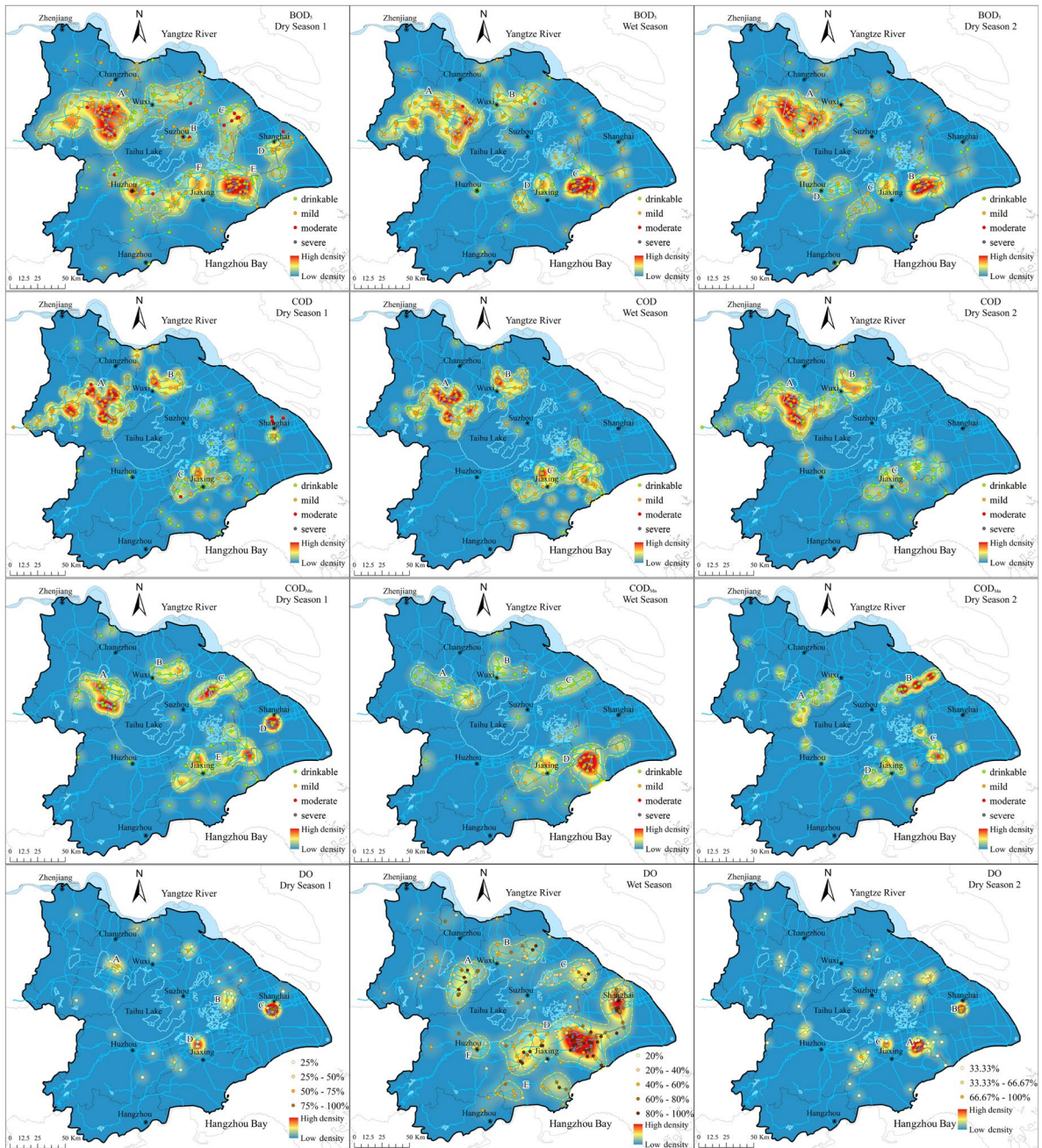


**Fig. 6** The precise spatial distribution and pollution status of seasonal exceeding standard sites for NH<sub>3</sub>-N, TN (lake, reservoir), TP (lake, reservoir), and TP (river)

mean concentrations of some sites corresponded to “drinkable” in Figs. 6 and 7.

For NH<sub>3</sub>-N, the pollution status was serious in dry season 1, but it was weakened in wet season and dry season 2. In dry season 1, many exceeding standard

sites with “moderate” and “severe” pollution level were distributed in the north and east of heat area A and the north of heat area B, which were the densely populated and developed urban areas (i.e., most of the urban areas of Shanghai, Wuxi, Changzhou, and



**Fig. 7** The precise spatial distribution and pollution status of seasonal exceeding standard sites for BOD<sub>5</sub>, COD, COD<sub>Mn</sub>, and DO; the proportion of the number of exceeding standard times of DO (%) was used to describe the pollution status of each site

Suzhou). In particular, downtown Shanghai showed high aggregation of “severe” sites with the highest density of exceeding standard occurrence. By contrast, in the southwest of heat areas A and B (i.e., the agriculturally developed suburbs locating in Wuxi, Changzhou, and southwestern Shanghai, and the developing Jiaxing city), the pollution levels of most exceeding standard sites were “mild” and “drinkable.” As can be seen, although agriculture is the primary source of nitrogen (Yu et al., 2019), the  $\text{NH}_3\text{-N}$  pollution was higher in densely populated and developed urban areas in Taihu Lake Basin. After dry season 1, the pollution status in most of the urban areas was weakened, indicating that rainfall has a great impact on  $\text{NH}_3\text{-N}$ . This was one of the reasons for the improvement of water quality in some urban areas in wet season (Fig. 4).

Many lakes and reservoirs in the basin suffered from eutrophication. For TN (lake, reservoir), in dry season 1, almost all lake and reservoir sites exceed the standards every month, and most of them were “severe.” In wet season and dry season 2, the pollution and the density of exceeding standard occurrence in the western heat area A (i.e., the northwestern Taihu Lake, and the lakes in the northwestern basin such as Tao Lake and Ge Lake) were higher than the other lake areas. In addition, the TN pollution level of the Fushi, Laoshikan, Duihekou, and Qingshan reservoirs in the southwestern basin was almost “severe” in all seasons. For TP (lake, reservoir), the distribution of heat areas was similar to that of TN (lake, reservoir). In all seasons, the pollution level in northwestern heat area A (i.e., the northwestern Taihu Lake, and the lakes in the northwestern basin) was “moderate” and higher than that in the other areas of heat area A which was changeless “mild.”

For TP (river), the pollution status in the urban areas of Wuxi (the eastern heat area A in dry season 1, and heat area B in the other seasons) was worse than the other areas and had high density of exceeding standard occurrence. In addition to Wuxi, the exceeding standard sites were distributed in the urban areas of eastern Suzhou (heat area C in all seasons) and the south of downtown Shanghai. The agriculturally developed suburbs locating in Wuxi and southwestern Shanghai had high densities of exceeding standard occurrence in all seasons. As can be seen, agricultural runoff is an important source of TP (river) in this basin. However, the TP pollution in urban areas was higher, especially in dry season 1.

For  $\text{BOD}_5$ , the main pollution level of the exceeding standard sites in all seasons was “mild.” The exceeding standard sites were mainly distributed in suburbs in all seasons, such as the suburbs locating in Wuxi, Changzhou, southwestern Shanghai, Jiaxing, and Huzhou. The suburbs locating in Wuxi, Changzhou, and southwestern Shanghai had high densities of exceeding standard occurrence in all seasons. Besides, there were many exceeding standard sites in the urban areas of Wuxi, Suzhou, Shanghai, and Huzhou in dry season 1.

For COD, the suburbs locating in Wuxi and Changzhou (i.e., heat area A) had the highest density of exceeding standard occurrence in all seasons, followed by the urban areas of Wuxi and the suburbs of Jiaxing. Compared with the other cities,  $\text{BOD}_5$  and COD in Wuxi exceeded the standards in almost all seasons, indicating that the organic pollution control should be strengthened there. For  $\text{COD}_{\text{Mn}}$ , except for the “mild” sites locating at heat area B in wet season (i.e., Jiaxing and the southwestern suburbs of Shanghai), the main pollution levels of the exceeding standard sites were “drinkable” in all seasons.

In wet season, the exceeding standard sites of DO were clearly more than dry seasons. The proportions of the number of exceeding standard times of many sites were higher than 40%, which were mainly distributed in the lower reaches of rivers leading to lakes and main streams (e.g., Taihu Lake, the Huangpu River, the Beijing-Hangzhou Canal, and Hangzhou Bay).

## Discussion

### Temporal variation of water quality

Our study indicated that the proportion of “drinkable” water in Taihu Lake Basin in 2018 was insufficient and strengthening the governance of “severe” and “moderate” water may be effective to improve it. Seasonal variations in water quality are dominated by variations in the concentrations of pollutants, which are related to seasonal variations in the sources (e.g., fertilizer application) and climate (Lintern et al., 2018). The “severe” proportion had a significant declining trend ( $R^2=0.933$ ), and the seasonal proportion reduced clearly from dry season 1 to wet season (Fig. 3).  $\text{NH}_3\text{-N}$  and TN (lake, reservoir) were the major

reduction targets for the sites with “severe” quality, because the variation trends of the proportions of the number of exceeding standard times and the “severe” proportions of them were similar to the “severe” proportion (Table 6 and Fig. 5). As can be seen, rainfall has a great impact on  $\text{NH}_3\text{-N}$  and TN (lake, reservoir). Xu et al. (2019) found that sewage outfalls (point sources) had the strongest contribution in  $\text{NH}_3\text{-N}$  concentration in dry season; but the effects of them were weakened in wet season because the increased rainfall diluted the concentration. Moreover, the high concentration of nitrogen was also related to stronger agricultural activities in dry season 1 (Wu et al., 2014; Xu et al., 2007; Zhang et al., 2017). For the river sites with “moderate,” Fig. 5 indicated that TP should be a reduction target, especially in July and August when the rainfall was heavy (Fig. S1). The variation in TP is related to agricultural land proportion, population density, and rainfall (Mainali & Chang, 2018). The surface runoff that was generated by increased rainfall caused a large amount of granular TP in soil to flow into the water bodies (Lintern et al., 2018).

Figure 3 shows that “mild” was the general water quality status in Taihu Lake Basin, and the proportion increased from dry season 1 to wet season. This trend was similar to the variation of the proportion of the number of exceeding standard times of DO (Table 6). DO may be one of the reasons for the seasonal variation in “mild” proportion. The high water temperature in wet season leads to a low dissolving capacity for DO and more DO to be consumed by active microorganisms (Paerl, 2006; Li et al., 2012). Low DO concentration led to water deteriorate and damage to the health of aquatic population (Singh et al., 2009). The exceeding standard sites of DO were mainly distributed in the lower reaches of rivers leading to lakes and main streams. In general, lower reaches flow more slowly than upper reaches, resulting in a longer time for oxygen-demanding pollutants to be decomposed by consuming oxygen (Wang et al., 2019b). However, there were almost no obvious seasonal variations in the pollution status of  $\text{BOD}_5$ , COD, and  $\text{COD}_{\text{Mn}}$  (Table 6, Figs. 5 and 7), indicating that organic matter were more affected by anthropogenic factors than natural factors. Besides, in dry season 2 (October to December), the “drinkable” proportion was 42.99% and higher than the other seasons. After the accumulation of rainfall during wet season, the water volume and the maximum load of pollutants

that can be accommodated in water body increased, and thus the water quality was improved in dry season 2 (Wang et al., 2019c).

#### Spatial variation of water quality

TN and TP were the main pollutants that deteriorated the water quality in lakes and reservoirs. In all seasons, the water quality in the northwestern Taihu Lake, the lakes locating in northwestern basin such as Tao Lake and Ge Lake, and Dianshan Lake was almost “severe” (Fig. 4). The concentrations of TN and TP of these lakes were almost “severe” level (higher than  $2 \text{ mg}\cdot\text{L}^{-1}$ ) and “moderate” level ( $0.1 \text{ mg}\cdot\text{L}^{-1}$  to  $0.2 \text{ mg}\cdot\text{L}^{-1}$ ), respectively (Fig. 6). It can be seen that TN and TP pollution status in those lakes did not weaken with increasing rainfall and may be more affected by anthropogenic activities. The water quality in Tao Lake and Ge Lake was largely affected by local developed agriculture and aquaculture (Xie et al., 2017; Zhang et al., 2017; Zhong et al., 2014). The water quality of Taihu Lake is mainly affected by pollution from the inflow rivers, and the main pollution sources of the northwestern lake were agricultural pollution and domestic sewage (Liu et al., 2020). Qin et al. (2019) indicated that the external factors for the unsatisfactory decrease in nutritional load in Taihu Lake included economic development pressures, looser standards for the discharge effluent from sewage treatment plants, and the lack of initiative in terms of the collection and treatment of non-point source pollution. In addition, the Fushi, Laoshikan, Duihekou, and Qingshan reservoirs locating in southwestern basin was severely polluted by TN in all seasons (Fig. 6), because of external pollution from their inflowing rivers (Hu et al., 2016; Shi et al., 2015).

The water quality spatial variation of rivers was most likely related to anthropogenic influence and landuse. The water quality in the developed and densely populated urban areas (i.e., most of the urban areas of Shanghai, Wuxi, Changzhou, and Suzhou) was poor. As can be seen from Figs. 6 and 7,  $\text{NH}_3\text{-N}$  was the main pollutant in the above urban areas in dry season 1 and of downtown Shanghai in the other seasons. High  $\text{NH}_4^+$  concentrations indicate the discharge of human excreta and domestic sewage (Gao et al., 2019). TP (river),  $\text{BOD}_5$ , and COD were also the main pollutants in the urban areas of Wuxi. The closest land use to rivers has a great impact on water

quality (Lian et al., 2021). Li et al. (2019) found that the increased population and GDP of Taihu Lake Basin were the direct dominant factors for increased concentrations of nitrogen and phosphorus. Table S3 shows the population density and GDP of the cities in the basin. Therefore, the  $\text{NH}_3\text{-N}$  and TP (river) pollution status of the developed and densely populated urban areas was worse than the developing cities and suburbs. Lian et al. (2018) also found that social and economic development, urbanization, and population density were the main impact factors on nitrogen. This is why downtown Shanghai had highly aggregated “severe” sites and the highest density of exceeding standard occurrence of  $\text{NH}_3\text{-N}$ .

However, the water quality in water conservation and forests was “drinkable” in general, because of the relatively weak anthropogenic activities (Wu et al., 2018). Moreover, forests can intercept surface runoff and reduce the sewage that enters rivers (Gu et al., 2019; Mainali & Chang, 2018).

The water quality in the agriculturally developed suburbs (i.e., the suburbs locating in Wuxi, Changzhou, southwestern Shanghai, and Jiaxing) and the industrial developed suburbs (i.e., the suburbs of eastern Suzhou) was worse than the other suburbs. Similar to the urban areas of Wuxi, the main pollutants in the suburbs of eastern Suzhou were  $\text{NH}_3\text{-N}$ , TP (river), and  $\text{BOD}_5$  (only in dry season 1). Different from the urban areas, the main pollutants in the agriculturally developed suburbs were organic matter ( $\text{BOD}_5$ , COD,  $\text{COD}_{\text{Mn}}$ ), TP (river), and  $\text{NH}_3\text{-N}$  (only in dry season 1) with “mild” pollution level. The sources of organic matter are domestic sewage, aquaculture sewage, and industrial wastewater (Song et al., 2011; Zhang et al., 2009; Han et al., 2020). The suburbs locating in Wuxi and Changzhou had high densities of exceeding standard occurrence of  $\text{BOD}_5$  and COD (Fig. 7). In addition to farming and aquaculture, secondary industries also developed there. The sewage discharged from families, aquaculture, and industries such as chemical, printing and dyeing, steel, food, and paper (Guo et al., 2021; Yan et al., 2012) increased the organic pollution there. In addition, due to the agricultural runoff generated by the heavy rainfall in wet season, TP pollution in the suburbs locating in southwestern Shanghai and Jiaxing increased (Fig. 6) (Lintern et al., 2018). Moreover, DO concentrations reduced significantly in those areas (Fig. 7). This may be why their water quality was deteriorated in wet season (Fig. 4).

### Management implications for improving the water quality

Increasing domestic, agricultural, and industrial demand for water and wastewater discharged without adequate treatment, resulting in surface water degradation (Adeleke et al., 2019b). The government should manage pollution sources and reduce the discharge of sewage.  $\text{NH}_3\text{-N}$  was the main pollutant in most of the densely populated urban areas; and lakes and reservoirs with the worst water quality were severely polluted with TN. The two parameters should be major reduction targets in water management, especially in dry season 1. The primary sources of nitrogen include agricultural runoff and domestic sewage (Yu et al., 2019), but Jiao et al. (2015) pointed out that domestic sewage caused greater harm to the environment of Taihu Lake Basin. Moreover, the exceeding standard sites of  $\text{BOD}_5$  were distributed in many urban areas and suburbs (Fig. 7). Li et al. (2019) indicated that urbanization and the rise in living standards were among the reasons for increased  $\text{BOD}_5$  pollution. Therefore, the government should strengthen the control of domestic sewage discharge. On the one hand, the illegal sewage outfalls should be rectified due to their strong contribution in  $\text{NH}_3\text{-N}$  concentration in dry season (Xu et al., 2019). On the other hand, in order to reduce sewage discharge, the government need to raise the public water conservation awareness, enact stricter sewage treatment standards, and apply more effective treatment technology. For instance, activated carbon is the most effective adsorbent known for wastewater treatment (Adeleke et al., 2019b). As can be seen, the water quality in developed Suzhou and Hangzhou was better than that in developed Shanghai, Wuxi, and Changzhou (Fig. 4). This may be due to effective governance in recent years, such as strict sewage collection and treatment and water diversion projects (Tu et al., 2016; Wang et al., 2016; Zhao et al., 2016). Moreover, applying fertilizer abstemiously and developing modern sustainable farming (Qin et al., 2019) are effective to control agricultural runoff. Besides, although industrial pollution has been strictly control in the basin in recent years (Zhang et al., 2017), more sewage treatment plants should be constructed, and industrial restructuring should be boosted in the suburbs and Wuxi city.



## Conclusions

Our study analyzed the spatiotemporal variations and the main exceeding standard parameters of the water quality in the rivers, lakes, and reservoirs of Taihu Lake Basin using water quality data from 565 sites, which were released by the Taihu Basin Authority in 2018. Our findings reveal that (1) of all the water quality assessment results in 2018, only 29.09% met the drinking water standards, whereas 70.91% was polluted (the proportions of “mild,” “moderate,” and “severe” were 42.28%, 16.14%, and 12.49%, respectively). Mildly polluted was the widespread water quality status in the basin; (2) the “severe” proportion had a significant declining trend ( $R^2=0.933$ ) from January to December. It was the highest in dry season 1 (January to April) and dropped significantly during wet season (May to September), indicating that the “severe” proportion was affected by rainfall. The water quality was the worst in dry season 1 and was improved in wet season and the best in dry season 2 (October to December); (3) the water quality spatial variations were most likely related to anthropogenic influence and land use. The water quality in the developed and densely populated urban areas (i.e., the parts of Shanghai, Wuxi, Changzhou, and Suzhou) was poor, especially in downtown Shanghai. The water quality in the northwestern Taihu Lake, the lakes in northwestern basin, and Dianshan Lake was almost “severe” in all seasons. The water quality in the agriculturally or industrial developed suburbs was worse than the other suburbs. The water quality in water conservation and forests was the best. (4)  $\text{NH}_3\text{-N}$ , TN, TP,  $\text{BOD}_5$ , COD,  $\text{COD}_{\text{Mn}}$ , and DO were the main exceeding standard parameters that deteriorated the water quality in Taihu Lake Basin. Reducing the discharge of  $\text{NH}_3\text{-N}$  and TN is important to decrease the “severe” level water.  $\text{NH}_3\text{-N}$  and TN were also affected by rainfall. Moreover,  $\text{NH}_3\text{-N}$  was the main pollutant that deteriorated the water quality in most of the densely populated urban areas; and lakes and reservoirs with the worst quality were severely polluted with TN. Therefore,  $\text{NH}_3\text{-N}$  and TN are major reduction targets in pollution control, especially in dry season 1 (January to April). Strengthening the discharge and sources control of domestic sewage is one of the effective ways for improving the water quality in urban areas and suburbs. Our study can make up for the limited research on the water quality variations

in the entire Taihu Lake Basin and provides beneficial information on water quality status and suggestions for the generation of more applicable decisions regarding water management in this basin.

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**Data availability** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Competing interests** The authors declare no competing interests.

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