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Current status and characteristics of urban landscape lakes in China

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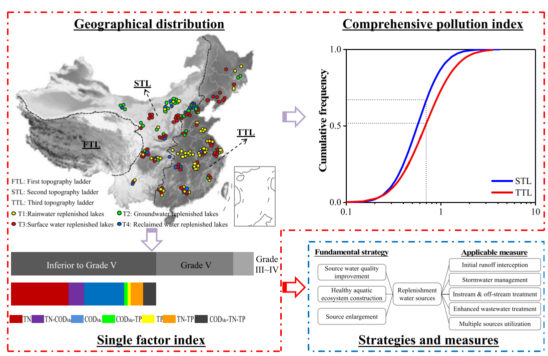
HIGHLIGHTS

- 189 urban landscape lakes (ULLs) in 26 provinces over China were investigated.
- These ULLs were diagnosed according to replenishment condition and water quality.
- Several indices were compared for characterizing landscape water quality.
- Water transparency (SD) was found to correlate well with public perception.
- SD was evidenced as suitable indicator for characterizing the quality of ULLs.

GRAPHICAL ABSTRACT



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ABSTRACT

Urban landscape lakes (ULLs) are important environmental elements in most cities. In order to understand the current situation of ULLs in China and formulate proper strategies to improve their landscape quality to meet public desire for water-front enjoyment, a study was conducted of 189 ULLs widely distributed in 26 provinces of China, based on existing data and field surveys. These ULLs were firstly categorized according to their topographic features, climatic zones, and water replenishment sources. Lake water quality was evaluated considering both single factors and a comprehensive pollution index (CPI). Results show that if the Chinese Surface Water Quality Standard was used as the sole criteria, about 60% of the ULLs investigated could not meet the lowest requirement. Excessive total nitrogen (TN) concentration was the most limiting factor especially when reclaimed water was the replenishment source. The differences in topographic and climatic conditions to a certain extent affected the availability of replenishment water sources but no significant correlation was identified with the single water quality factors or CPI. However, when public satisfaction was introduced in the evaluation of the ULLs' landscape effect, it was found that the water transparency in terms of Secchi Depth (SD) correlated well with people's appreciation of water landscape.

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1. Introduction

Urban landscape lakes (ULLs) are important in creating urban water landscape environments and providing water-front enjoyment for the public (Stoianov et al., 2000). Numerous ULLs are distributed in urban areas varying in geographical location, climatic condition and morphological features, especially in China. These water bodies are characterized by small surface area, shallow depth, and low flow rate, contributing to weak self-purification capacity and low resilience to environmental disturbances (Chen et al., 2013a; Henny and Meutia, 2014). As most ULLs are closed or semi-closed ecosystems, water replenishment is essential to maintain normal ecological water level and promote the renewal of water body (Chen and Qian, 2016). The combination of these factors makes ULL management very challenging: eutrophication and water pollution often result in deterioration of landscape quality and breakdown of the eco-environment. Therefore, the situations and characteristics of ULLs must be scientifically understood before effective management and protective achievement of corresponding environmental services can be put on a sustainable development path.

Several studies have been conducted relating the current status and characteristics of ULLs on assessment of pollution by eutrophication (Li et al., 2011; Wei et al., 2011), heavy metals and toxic organic compounds (Chen et al., 2017), and remedies to restore ULLs quality (Dunalska et al., 2015). Some studies confirmed ULLs were prone to eutrophication, which is a common consequence of deteriorating water quality characterized by high nutrient levels, low water transparency, and excessive growth of algal (Henny and Meutia, 2014; Li et al., 2011; Zhao et al., 2015). Protection and restoration of ULL water quality fall into three main categories: physical methods (e.g., water replenishment optimization and artificial aeration) (Chen et al., 2013b; Xiong et al., 2016), chemical methods (e.g., flocculation, precipitation, and chemical alga-killing) (Łopata et al., 2013; Yamagishi et al., 2017), and biological methods (aquatic plants, ecological floating bed, biomanipulation, and constructed wetlands) (Chen et al., 2013a; Waajen et al., 2016; Wang et al., 2018a, 2018b). Water replenishment is an effective method to improve ULL water quality, and its efficiency depends on the quality and quantity of replenishment water sources, which varied from reclaimed to surface water. Owing to the shortage of urban water resources, current researches mainly focused on the utilization of reclaimed water as a potential alternative source of ULLs, claiming advantages such as stability and controllability (Yi et al., 2011; Zhao et al., 2015). Unfortunately, the significantly high nutrient concentrations in reclaimed water from wastewater treatment plants (WWTPs) bring about high algae growth potential. Hydraulic regulation and control, specific replenishment schemes and ecological measures such as treatment by constructed wetland can be adopted to restrict excessive algae growth by increasing the dilution effect and decreasing the nutrient supply effect (Ao et al., 2018; Li et al., 2014; Qin et al., 2013). Nonetheless, the present studies were conducted either at the single lake or at metropolitan level. Consequently, little is known on the overall characteristics and spatial differences of ULLs in China at the national level. Additionally, in the broader picture of comprehensive management and landscape assurance, a better understanding of the differences between ULL replenishing sources is crucial.

Furthermore, objective quality is of vital significance in the environmental monitoring, evaluation and management of ULLs. In China, lake water quality evaluation usually refers to the Surface Water Environment Quality Standard (GB3838-2002) in which surface waters are categorized to five grades according to the purposes of water uses. Grade I to Grade III, respectively, are excellent, good, and fine source waters for drinking water supply, while Grade IV and Grade V, are only applicable to industrial and agricultural/landscape waters, respectively (Li et al., 2014; Liu et al., 2008; Zhao et al., 2015). The standardized parameters primarily deal with the concerns on the physical, chemical, and bacteriological quality of water sources. Regarding the applicability of such standards to ULLs, there are increasing doubts and discussion. One major concern is on the true landscape feature of water which closely relates to human perception (Smith et al., 2015), and another is the restriction of conventional water sources for the impoundment and replenishment of many ULLs in water deficient regions. In fact, nowadays in China most cities have been making effort to build artificial ULLs or restore historical water landscape. In such cases, the ULLs do not have their own natural catchment areas and totally depend on artificial water supply. In addition to diverting water from available surface and/or groundwater sources, development of alternative sources becomes a common practice, such as by reclaimed water use or implementing rainwater harvesting and supply systems (Wang et al., 2018b; Jia et al., 2014). Using the current surface water quality standard as the sole criteria for ULL water quality control may heavily restrict alternative water use for the purpose of replenishment or result in adoption of excessive measures for water quality improvement.

Facing the above-mentioned problems, a national scale investigation was conducted on the current condition of ULLs in China. By existing data collection and field surveys in summer 2016, first-hand information was obtained for diagnosing 189 ULLs in 26 provinces, covering diverse geographic locations, different climatic conditions, and various replenishment water sources. Attention was paid to the landscape effects of these ULLs and the suitable index for characterizing landscape water quality.

2. Materials and methods

2.1. Study area

Fig. 1 shows the locations of the 189 ULLs selected for this study, as well as information on topographic and climatic features, and replenishing water source types. The Chinese territory generally shows a topographic feature of decreasing ground elevation from northwest to southeast and can be categorized into three topographic ladders, namely the first ladder (FTL) with elevation >4000 m above sea level, the second ladder (STL) descending from 4000 m to 500 m, and the third ladder (TTL) with elevation <500 m (Ding et al., 2015; Zhao et al., 1995). The climate generally varies with ground elevation to a large extent and can be featured by four climatic zones, namely the humid zone with annual rainfall >800 mm (generally higher than the average annual evaporation depth), the semi-humid zone with annual rainfall of 800–400 mm (also generally higher than the average annual evaporation depth), the semi-arid zone with annual rainfall of 400–200 mm (generally lower than the average annual evaporation depth) and the arid zone with annual rainfall <200 mm (completely lower than the average annual evaporation depth) (Zhang et al., 2016a, 2016b).

The water surface areas of the selected ULLs ranges from 0.2 to 645 ha, of which only 5 ULLs are larger than 500 ha and with natural catchment areas, while others with smaller water surface areas are artificially restored or built ULLs which solely depend on water supply from available sources for replenishment. The average water depth of these ULLs ranges between 0.5 and 12 m, and only 11 of them are on average deeper than 5 m. To facilitate data analysis, the investigated ULLs were divided into large, medium and small groups according to water surface area. The numbers of large (>35 ha), medium (5–35 ha), and small (<5 ha) sized ULLs are 48 (25.4%), 92 (48.7%), and 49 (25.9%), respectively. These ULLs are regularly replenished by rainwater (T1) associated with rainwater harvesting, storage and supply facilities, groundwater (T2), surface water (T3), and reclaimed water (T4) from urban wastewater treatment systems. The morphological information of each ULL was collected either from existing documents and confirmed by field survey and analysis of the latest satellite map. The data on the operation and management of each ULL, including replenishment water source, frequency, and amount, were provided by local authorities and/or managerial offices.

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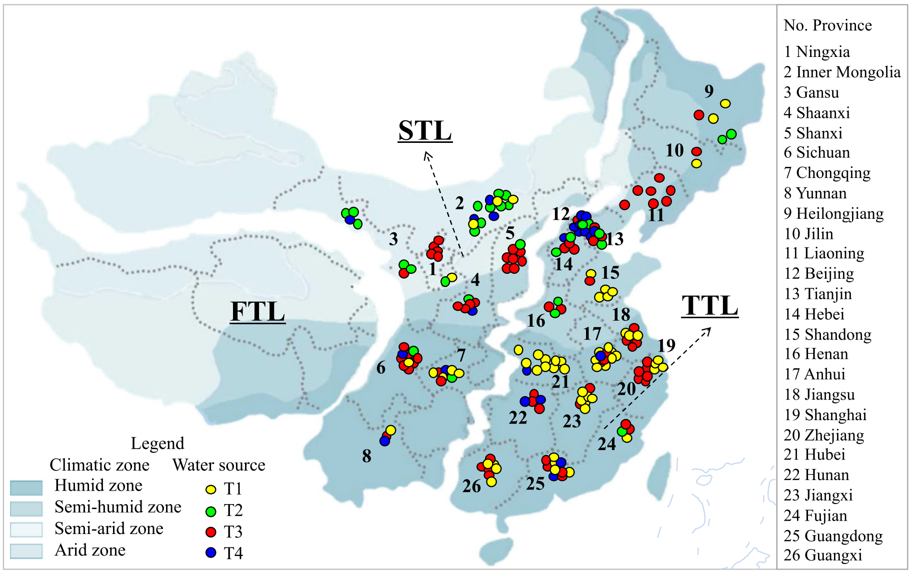

Fig. 1. Geographic locations and water replenishment sources of 189 urban landscape lakes in China. (FTL: the first topography ladder, STL: the second topography ladder, TTL: the third topography ladder. T1: rainwater replenished lakes, T2: groundwater replenished lakes, T3: surface water replenished lakes, T4: reclaimed water replenished lakes.)

Table 1 summarizes the distribution of the ULLs investigated in this study and related information.

2.2. Field survey

For the 189 ULLs, field survey was carried out in summer 2016, including water quality tests and questionnaire survey.

2.2.1. Water quality tests

In-situ water quality monitoring was conducted using portable meters for measurement of pH, temperature, salinity and dissolved oxygen, and water transparency was assessed with a Secchi Disk (SD). Water samples were collected for analyzing chemical oxygen demand (COD_{Mn}), ammonium (NH_4^+-N), total nitrogen (TN) and total phosphorous (TP) by Pack Test (Kyoritsu Chemical-Check Lab. Corp., Japan) which is a professional easy-to-use onsite water quality checker, and its reliability has been confirmed by Kyoritsu Chemical-Check Lab through many fieldworks across several countries (Kikuchi et al., 2010). Following the Chinese standard methods (MEP, 2002c), water samples were collected thrice on three consecutive days in the study duration. According to the size of surface area, the quantity of water holding, and the conditions of water replenishment and retreat, sample sites were set at 4 to 5 locations almost evenly distributed along the lake surface where sufficient water depth could be confirmed. Therefore, the

Table 1
Distribution of the ULLs in 26 provinces in China.

No	Province	Number	Topographic ladder	Climatic zone	Replenishment source
1	Ningxia	5	STL	Arid	T3
2	Inner Mongolia	14	STL	Semi-arid	T1, T2, T4
3	Gansu	9	STL	Arid/semi-arid	T1, T2, T3, T4
4	Shaanxi	6	STL	Semi-humid	T2, T3, T4
5	Shanxi	8	STL	Semi-humid	T2, T3
6	Sichuan	10	STL	Humid	T1, T2, T3, T4
7	Chongqing	8	STL	Humid	T1, T2, T3, T4
8	Yunnan	3	STL	Humid	T1, T3, T4
9	Heilongjiang	5	TTL	Semi-humid	T1, T2, T3
10	Jilin	2	TTL	Semi-humid	T1, T3
11	Liaoning	7	TTL	Humid/semi-humid	T3
12	Beijing	12	TTL	Semi-humid	T2, T3, T4
13	Tianjin	8	TTL	Semi-humid	T2, T3, T4
14	Hebei	6	TTL	Semi-humid	T2, T3, T4
15	Shandong	6	TTL	Semi-humid	T1, T3
16	Henan	4	TTL	Semi-humid	T2, T3
17	Anhui	12	TTL	Humid	T1, T3, T4
18	Jiangsu	7	TTL	Humid	T1, T3
19	Shanghai	6	TTL	Humid	T1, T3
20	Zhejiang	4	TTL	Humid	T3
21	Hubei	12	TTL	Humid	T1, T3, T4
22	Hunan	5	TTL	Humid	T3, T4
23	Jiangxi	8	TTL	Humid	T1, T3
24	Fujian	4	TTL	Humid	T1, T2, T3
25	Guangdong	10	TTL	Humid	T1, T3, T4
26	Guangxi	8	TTL	Humid	T1, T3

STL: the second topography ladder; TTL: the third topography ladder; T1: rainwater; T2: groundwater; T3: surface water; T4: reclaimed water.

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number of samples from a single lake was between 12 and 15. Copper samplers each with 500 mL water volume were used for sampling at a depth of 0.5 ± 0.2 m below the water surface.

2.2.2. Questionnaire survey

To understand public perception on whether or not the lake supported the designated use, an on-site survey questionnaire was conducted through face-to-face interviews. Aside from their demographic information, participants were asked to report their preferred activities on the lakes; their concerns about the lake's landscape effect as connected to water color, odor, clarity, hydrocoles and hydrophytes. Finally, participants were asked their opinion regarding environmental improvements related to lake uses and ways to improve the lake environment (Kawamura and Fukushima, 2017). Their evaluations of lakes were subsequently reported based on a standard level of satisfaction using the Likert Scale from 1 to 5: 1-dislike a lot, 2-dislike, 3-neutral, 4-like and 5-like a lot (McCormick et al., 2015).

A total of 3780 valid questionnaires were collected, with a participation rate of 100%. The questionnaire passed Cronbach's alpha reliability analysis with a value of 0.938. Comparisons of participants' gender, age and occupation with level of satisfaction were conducted using a *t*-test with SPSS Statistics 22.0 (IBM Corporation, Armonk, NY, USA). We then calculated the average level of satisfaction for the 189 ULLs.

2.3. Methods for water quality evaluation

The single factor index method and comprehensive pollution index (CPI) method were adopted to evaluate ULL water quality. Single factor index was applied to determine the overall water quality of ULLs investigated by the worst index. The P_i can be expressed as follows:

$$P_i = C_i / S_i \quad (1)$$

where P_i is the single factor index of the pollutant i; C_i is the measured concentration of pollutant i (mg/L); S_i is the standard permissible concentrations of pollutant i according to the surface water quality standard (mg/L). The items in the standard are divided into five categories, where Grade I to Grade III are good for drinking water supply, and Grade IV and Grade V are applicable to industrial and agricultural/landscape waters, respectively.

Given the combined effect of pollutants, CPI was used to evaluate the comprehensive pollution degree of water quality. The CPI is calculated according to Eq. (2):

$$CPI = \frac{1}{n}\sum_{i=1}^{n} P_i \quad (2)$$

where, CPI is the comprehensive pollution index of pollutants; n is the number of pollutants; P_i is the single factor index of pollutant i. The permissible concentrations of each pollutant (S_i) referred to the lowest threshold value (Grade V) in the surface water quality standard. The pollutant level can be classified into six categories: CPI ≤ 0.20, clean; 0.21–0.40, sub-clean; 0.41–0.70, slight polluted; 0.71–1.00, moderately polluted; 1.01–2.00, heavily polluted; CPI > 2.0, severely polluted.

2.4. Data analysis

Analysis of similarities (ANOSIM) was performed to test for the differences among the water quality of ULLs with different replenishment water sources using the Bray-Curtis index. Each ANOSIM produces an R-statistic, which indicates whether the differences are more related to types of replenishment water sources (R value is close to 1) or to differences within a water replenishment type (R value is close to 0) (Sánchez-Montoya et al., 2012). The number of Monte Carlo permutations was set at 999. Pair-wise ANOSIM comparison was used to distinguish possible contrasting effects among different water replenishment types. In addition, normality test was conducted and data showed a skewed distribution (Shapiro-Wilk test, $p < 0.05$). The possible differences in water quality parameters among different water replenishment types were detected using a Kruskal-Wallis test. Kruskal-Wallis test was also applied to determine the differences in CPI between topography ladders, and to explore the relationship between levels of public satisfaction and SD. We used Pearson's correlation analysis to identify the association between public satisfaction and SD, and used linear regression model r^2 to test the power of SD to predict public satisfaction as a relative estimate of the reliability.

3. Results and discussion

3.1. Overview of lake water quality

The water quality of 189 ULLs evaluated by single factor index is illustrated in Fig. 2. According to the current surface water quality standard, 8.5% (16/189) were classified as Grade III~IV, 31.7% (60/189) as Grade V, while approximately 60% of lakes were inferior to Grade V (Fig. 2a), highlighting ubiquitous water pollution. Further analysis (Fig. 2b) indicated that the deterioration of lakes inferior to Grade V can be ascribed in most cases to excessive TN (68.1%, 77/113), followed by COD_{Mn} (49.6%, 56/113) and TP (22.1%, 25/113). For the majority of lakes (69.0%, 78/113), only one water quality parameter exceeded the prescribed threshold value (25 in STL and 53 in TTL), while for the other lakes (31.0%, 35/113), multiple water quality parameters exceeded the threshold values simultaneously (9 in STL and 26 in TTL). As shown in Fig. 2b, 10.6% (12/113) of lakes suffer from TN and COD_{Mn} pollution, 8.8% (10/113) from TN and TP pollution, 2.8% (3/113) from COD_{Mn} and TP pollution, and 8.8% (10/113) from TN, TP, and COD_{Mn} pollution, implying that the ULLs in China are subjected to diverse problems, and in addition to surface water quality standard, other landscape water quality indicators may need to be considered.

Regarding water temperature, dissolved oxygen, and salinity, all the in-situ measurement data were within the ordinary ranges of surface waters and no apparent differences were found between ULLs in different areas or with different replenishing conditions.

3.2. Effect of geographic locations

Fig. 3 indicates that one third of the ULLs investigated distribute in the STL, while two thirds distribute in the TTL. This phenomenon may be attributed to the spatial patterns in topography and natural resources, which further influence the spatial agglomeration of economic development and population distribution (Guan et al., 2018; He et al., 2017). The relatively flat terrain, affluent rainfall and resources endowment of the TTL make for the formation of numerous low-lying terrains, which were enlarged and modified to create ULLs during the urbanization process. In addition, the excellent natural conditions of TTL contribute to the development of local economy and denser population. To satisfy the public requirements for water landscape, many ULLs were constructed by artificial excavation. Therefore, compared with the STL, more ULLs distribute in the TTL, particularly in the Middle-Lower Yangtze Plain (42.9%).

Meanwhile, spatial agglomeration of ULLs reveals a heterogeneous pollution level. ULLs in the STL displayed an average CPI value of 0.69, meaning they were slightly polluted. COD_{Mn} was identified as the critical pollutant. ULLs in the TTL displayed an average CPI value of 0.85, falling into the moderately polluted category. Here, TN and COD_{Mn} were identified as the critical pollutants. ULLs found in the TTL displayed poorer water quality than those in the STL. As shown in Fig. 3, CPI cumulative frequency distribution was 33.0% and 48.1% for ULLs in the STL and TTL, respectively, casting them into moderately and heavily polluted levels (CPI > 0.7), respectively. Kruskal-Wallis analysis further confirmed significant differences in the pollution status of ULLs between the two ladders ($F = 4.80$, $df = 1$, $p = 0.03$). This may be related with the local economy development and population density, as well as

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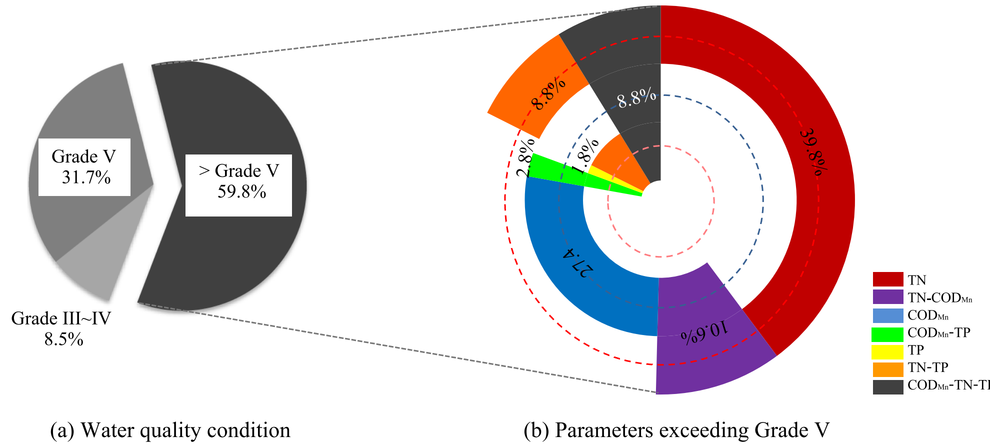

Fig. 2. Results of single factor index evaluation.

replenishment water sources. Besides, insufficient or poor water quality replenishment sources, developed economy and dense population exposed ULLs in the TTL to more intensive anthropogenic impacts such as point- and non-point-source pollution, which consequently degraded the water quality (Zhou et al., 2017).

ULL pollution varied from low to severe (Fig. 3), in the same topography group. In the STL, the pollution level of lakes in the Inner Mongolia Plateau (CPI = 0.85) was higher than those in the Loess Plateau (CPI = 0.62) and Yunnan-Guizhou Plateau (CPI = 0.64). The Kruskal-Wallis test identified the differences in CPI among three regions in STL were not significant ($F = 1.61$, $df = 2$, $p > 0.05$). In the TTL, lakes in the Middle-Lower Yangtze Plain suffered more serious pollution problems (CPI = 0.82). These differences are associated with various factors including the physical characteristics of lakes, geographical condition, socioeconomic development, availability of replenishment water, management levels, etc.

3.3. Effect of replenishment water sources

As shown in Fig. 1, ULLs replenishing water come from rainwater, groundwater, surface water, and reclaimed water, accounting for 30.2%, 15.3%, 41.3%, and 13.2%, respectively. The distribution of ULLs replenished with different water sources presents prominent spatial heterogeneity, which can be attributed to the geographic and climatic conditions. The ULLs in the STL replenished with rainwater (T1), groundwater (T2), surface water (T3) and reclaimed water (T4) accounted for 15.8%, 28.6%, 42.9%, and 12.7%, while those in the TTL accounted for 37.3%, 8.7%, 40.5%, and 13.5%, respectively. Surface

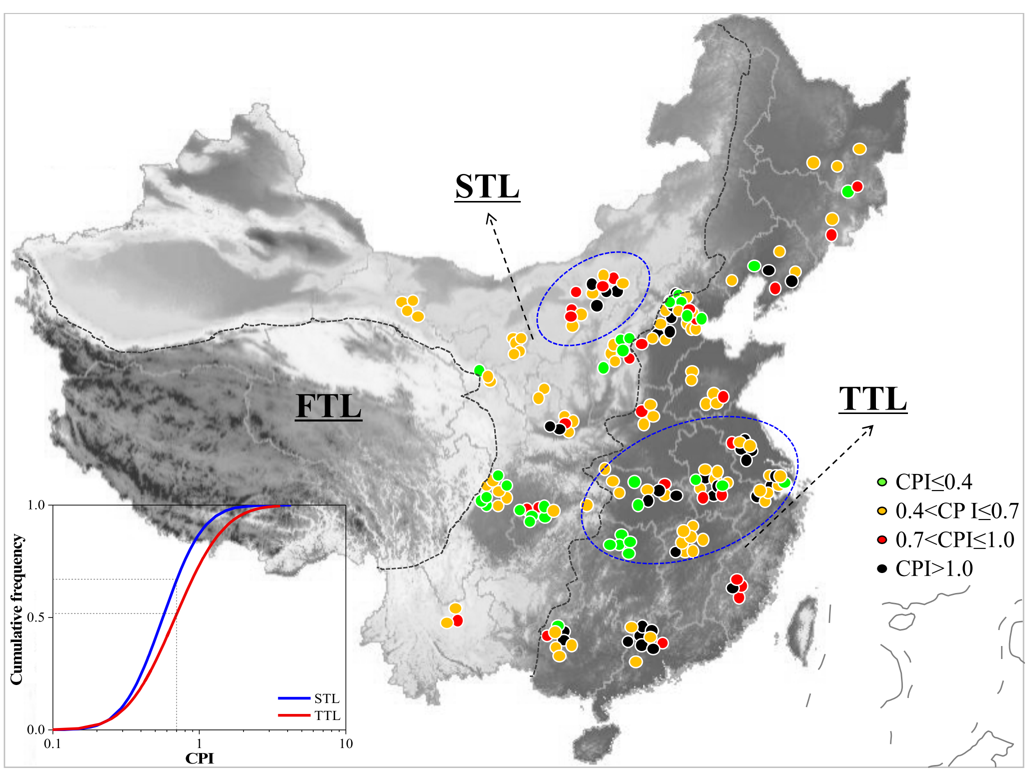

Fig. 3. Spatial distribution of pollution status in 189 urban landscape lakes (The ellipse at STL denotes lakes in the Inner Mongolia Plateau, and the other at TTL denotes lakes in the Middle-Lower Yangtze Plain). The inserted graph shows the cumulative frequency of CPI in STL and TTL.

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water is the most ubiquitous replenishment water source in both the STL and TTL. Nonetheless, due to the uneven geographic distribution of water resources (surface water increases from west to east) and to precipitation patterns in China (rainfall increases from north to south), ULL replenishment presented significant differences between the two ladders, with higher proportions of T2 in the STL and T1 in the TTL. More specifically, T1 (52.6%) was mainly distributed in the Middle-Lower Yangtze Plain, in the humid zone with abundant rainfall. On the other hand, in water-deficient areas, T2 and T4 accounted for considerable proportions, with 89.7% of T2 in the Inner Mongolia Plateau and 64.0% of T4 in the North China Plain. Reclaimed water and reuse rate are relatively high in the North China Plain, due to the developed local economies and population densities (Zhang et al., 2016a, 2016b). Correspondingly, the reuse of reclaimed water to replenish ULLs is popular in this region. However, in the Inner Mongolia Plateau, the low level of regional socioeconomic development hinders local wastewater reuse progress, and low rainfall in semi-arid and arid zone impedes the availability of rainwater, which lead to replenishment using groundwater (Chang et al., 2013; Su et al., 2016).

Fig. 4 illustrates the boxplots of COD_{Mn}, NH_4^+-N, TN and TP for ULLs with different water replenishing sources. It can be observed that water quality varied greatly among ULLs with different replenishing methods. The average COD_{Mn} values varied from 12.9 to 15.3 mg/L, with the highest for T2 and lowest for T3. T2 water quality was apparently better than ULLs with other replenishment water sources, apart from COD_{Mn}, which was 15.0%, 18.6% and 4.8% higher than T1, T3 and T4, respectively. This may be related to the dominant distribution of T2 in water-deficient North China. Despite the excellent quality of groundwater, its low availability and relatively high evaporation rates prolong hydraulic retention time (HRT) and amplify the concentration effect of degraded waters in this region (Piao et al., 2010). The average NH_4^+-N values varied from 0.44 to 1.18 mg/L, with the highest for T3 and lowest for T2. The significantly higher NH_4^+-N value found in T3 may be primarily associated with the quality of surface water, which generally serves as the receiving system of effluent of WWTP with high NH_4^+-N value. Moreover, quite a few WWTPs do not comply with Chinese water quality standards for reuse (MEP, 2002a; Sun et al., 2016). The socioeconomic conditions of the area and its population density also influence T3 NH_4^+-N value, which is found to be twice as high in the TTL (1.48 ± 2.35 mg/L) than in the STL (0.61 ± 0.99 mg/L). This may be due to the vast discharge of WWTP in TTL. Average TN values varied from 2.14 to 3.35 mg/L, with the highest for T4 and lowest for T1. This is undoubtedly due to the quality of reclaimed water, which features as very high TN value (15 mg/L) (MEP, 2002b; Wang et al., 2018a, 2018b). Average TP values varied from 0.035 to 0.185 mg/L, with the highest for T1 and lowest for T2. This can be associated with geographical location, which results in heterogeneity in regional economic development. Both the atmospheric wet deposition and surface runoff are heavier polluted in economic developed areas, contributing to the deterioration of T1 (Hobbie et al., 2017; Zhu et al., 2016). This was evidenced by the markedly lower TP value of T1 in the STL (0.037 ± 0.023 mg/L) than that in the TTL (0.216 ± 0.384 mg/L), and the higher TP value of T1 in the Middle-Lower Yangtze Plain (0.244 ± 0.394 mg/L) than that in the Northeast Plain (0.158 ± 0.064 mg/L). Moreover, T1 TP values decreased from north to south in the STL, which depended on the higher utilization of high quality rainwater as replenishment water serves the water quality improvement of ULLs according to dilution effect (Huo et al., 2014; Paerl and Huisman, 2008).

ANOSIM results confirmed the overall differences in water quality of lakes with different replenishment water sources according to global value of R ($R = 0.158$, $p < 0.05$). Pair-wise comparisons detected significantly different water quality among T1, T3 and T4. The Kruskal-Wallis test identified significant differences of NH_4^+-N ($F = 4.45$, df = 3, $p < 0.05$) and TP ($F = 8.25$, df = 3, $p < 0.05$) among ULLs with different water replenishing sources. Hence, the quantity and quality of replenishment water have great influences over the state of ULLs (Ao et al., 2018). It can be inferred that ULL water quality depended much more on replenishment water sources than from geographic and climatic conditions. The latter to a certain extent affects the availability of replenishment water sources. In addition, the blue line in Fig. 4 denotes the threshold values of Grade V in the surface water quality standard. COD_{Mn} and TN values of many ULLs were higher than for Grade V standards, particularly in T4. More specifically, T1 and T3 were dominantly polluted by TN, T2 by COD_{Mn}, and T4 by COD_{Mn} and TN. The percentages of ULLs satisfied the lowest water quality requirement (Grade V) were 36.8% for T1, 41.4% for T2, 42.3% for T3 and 40.0% for T4. The majority of ULLs exceeded the lowest water quality requirement irrespective of the replenishment water, highlighting the necessity of optimizing replenishment strategies to maintain ecosystem health.

3.4. Public perception on landscape water quality

The *t*-test showed no significant correlation between satisfaction level and demographic details. Based on the perceived quality

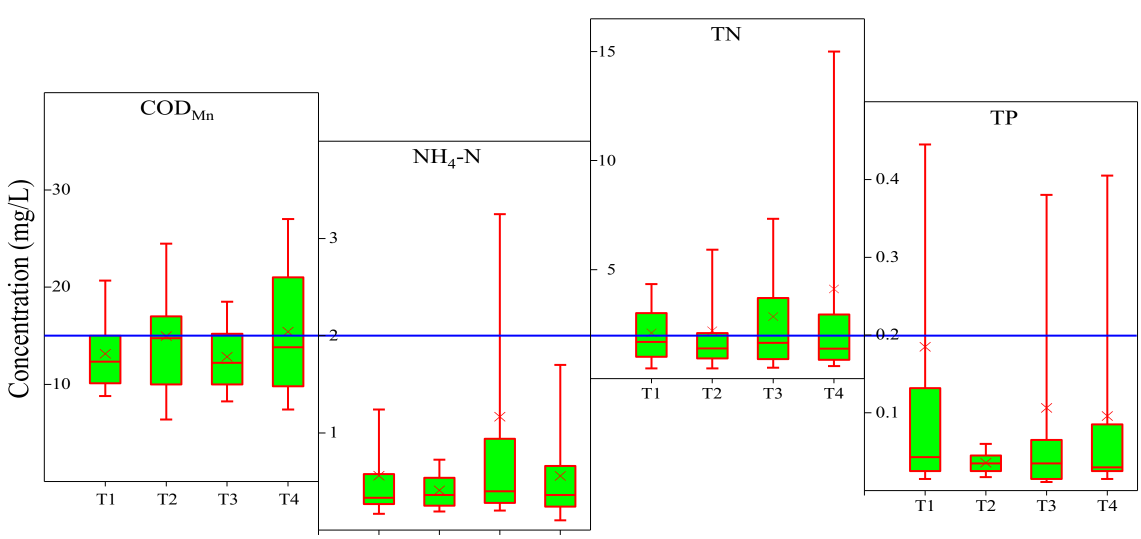

Fig. 4. Boxplots of COD_{Mn}, NH_4^+-N, TN and TP for ULLs with different water replenishing sources. (The blue line denotes the limits of Grade V standard. The cross denotes the average value.) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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questionnaire survey, 35.4% of ULLs fell into level 4 public satisfaction category. The remaining breakdown of perceived quality rating categories was as follows: 12.2% of ULLs were rated as level 5, 30.7% as level 3, 16.4% as level 2, and 5.3% as level 1. About 80% of the 189 ULLs studied were found to meet the public requirements for water landscape (satisfaction level ≥3), which was different from that of single factor index evaluation based on the surface water quality standard. Fig. 5(a) shows the relationship between public satisfaction and water quality category. All lakes within Grade III were perceived well, with a satisfaction level ≥4, and 92.9% of lakes within Grade IV were given satisfaction level ≥3. Even for lakes inferior to Grade V, 73.4% of lakes were given satisfaction level ≥3. This implies that there is a great inconsistency between the water quality requirements based on the surface water standard and the public perception of landscape water.

As shown in Fig. 5(a), the majority of lakes inferior to Grade V can still meet the public requirements. Hence, water quality evaluation based on the current surface water quality standard reflects ULL pollution status to a marginal extent, while failing to reflect the comprehensive ULL landscape quality. That is, the surface water quality standard cannot effectively discriminate between inferior water quality and water body function. This leads to uninformed environmental management and prevents the relevant authorities to improve water environment. It is therefore imperative to seek a more appropriate indicator to evaluate ULL landscape quality.

ULL landscape quality is closely related with people's perception, visual and olfactory aspects decisively affect public satisfaction level (Lee and Lee, 2015). In most conditions, the odor usually emerges following the deterioration of visual effect. As the visual effect is embodied by the transparency of water body, the perceived quality of ULLs can be evaluated by the SD. SD can be considered a comprehensive indicator, relating with water quality and reflecting people's perception of water landscape. As shown in Fig. 5(b), the relationship of SD and public satisfaction indicates that public satisfaction level is in a manner coincide with a gradient of SD, the lower the SD, the worse the public satisfaction. Pearson correlation analysis further confirmed SD and public satisfaction are strongly correlated ($r^2 = 0.956$, $p < 0.001$). The result is in line with previous studies (Lee, 2016; Smith et al., 2015).

Fig. 5(c) shows the relationship between SD and CPI. It is noticed that SD decreased gradually with the increase of CPI in a given SD range (SD < 0.5 m, 0.5 m ≤ SD < 1.0 m, SD > 1.0 m), and the decreasing amplitude increases with SD increase. However, the SD varied greatly at a certain CPI, and the variability decreased with the increase of CPI. It can be seen that SD can not only represent the ULL pollution status and discriminate between lakes with same pollution level, but also reflect the people's perception of water landscape. For these and the aforementioned reasons, SD holds great potential to characterize ULL landscape quality.

3.5. Strategies and measures for landscape water quality improvement

As shown in Figs. 2–5, from the viewpoint of surface water quality in general, such as following the Chinese surface water quality standard and the related CPI, about 60% of the ULLs investigated inferior to Grade V, the limit of allowable surface water quality. However, when we consider the visual satisfaction on landscape water based on the questionnaire survey and the water transparency in terms of SD, a majority of the ULLs with their quality inferior to Grade V were acceptable as urban landscape waters. According to the information obtained in our field survey, under the condition of no applicable national and/or local guidelines for ULLs management, most local agencies or water authorities responsible for ULL operation have tried to replenish the lakes following their experiences in accordance with the availability of water sources, such as adjustment of water replenishing frequency and amount for keeping the visual effect of the lake water as far as possible. This might be the main reason for the unclear relation between the data on visual satisfaction or SD and the replenishing water sources or major water quality parameters.

In the authors' previous study, we noticed that even using reclaimed water, which usually has high residual nutrient concentrations, as the sole replenishing water source, satisfactory landscape could be ensured if sufficient amount of the reclaimed water was available for a reasonable control of the HRT of the waterbody (Ao et al., 2018). Of course, the maximum HRT for a given urban lake varies with source water quality and the requirement of replenishing water frequency and amount would be different under different conditions. Generally speaking, regarding the four categories of source water discussed in this study, groundwater (T2) is usually of good quality, reclaimed water (T4) is with higher nutrient content, and rainwater (T1) that can be used for replenishing ULLs is usually very polluted with its initial runoff, while the surface water (T3) quality is diverse and variable between areas.

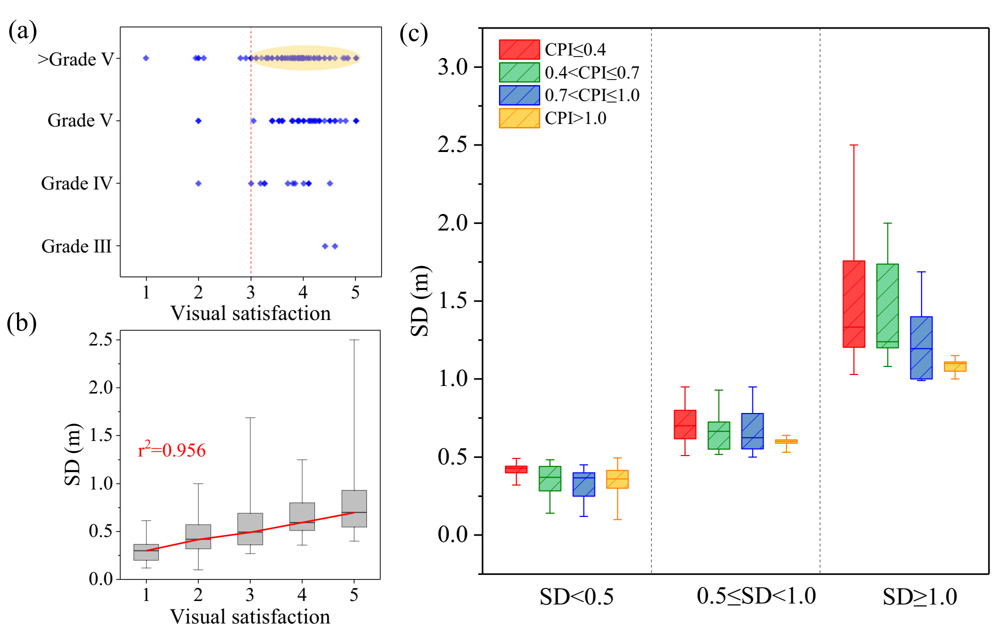

Fig. 5. The relationships between (a) public satisfaction and water quality; (b) public satisfaction and SD; (c) SD and CPI.

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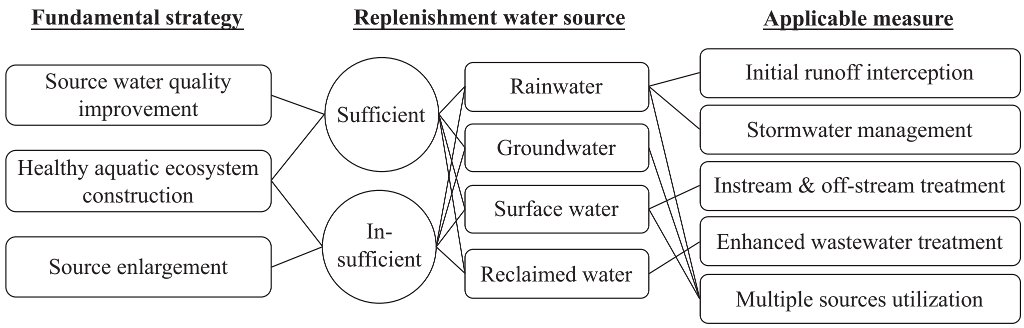

Fig. 6. Strategies and measures for landscape water quality improvement.

Based on the above understanding gained from the current study, a framework could be proposed as shown in Fig. 6 to assist decision-making on the fundamental strategies and applicable measures for urban landscape water quality improvement. Under the condition that replenishment water sources are sufficient, the key strategy would be source water quality improvement, while under the condition that replenishment water sources are insufficient, the key strategy would be source enlargement. Anyway, healthy aquatic ecosystem construction would be the common strategy under any circumstances, aiming at enhancing the self-purification capacity of the ULL (Wang et al., 2018b; Song et al., 2019). The applicable measures for water quality improvement may include initial runoff interception and stormwater management (Bach et al., 2010; Wang et al., 2018a) for rainwater, instream and off-stream treatment (Le et al., 2010; Qin, 2009) for surface water, and enhanced wastewater treatment (Deng et al., 2019) for reclaimed water. Rational and optimized utilization of multiple sources may be a combined measure for replenishment water source enlargement (Chen, 2008).

4. Conclusion

Current status and characteristics of ULLs in China were analyzed in this study based on a diagnosis of 189 ULLs widely distributed in 26 provinces. From the viewpoint that the landscape water quality closely relates to human sensory perception, the water transparency in term of SD, which may have comprehensively reflected the impacts of physical, chemical, biochemical, and even ecological factors on the aquatic appearance, was introduced in this study. It was found that, although the topographic and climatic features much influenced the availability of water replenishment sources and consequently the lake water quality as evaluated by single factors or CPI based on surface water quality standards, there were no significant correlative relationships between SD and water quality factors. However, SD correlated well with people's perception of water landscape according to the questionnaire survey data. It is thus suggestable to use SD as an alternative indicator for evaluating landscape water quality and assisting the formulation of strategies for aquatic landscape improvement. Although the proposal of such an indicator was based on current state of ULLs in China, it may also be useful for other countries and regions where shortage of natural water sources for ULL replenishment is also a restricting factor.

Declaration of competing interest

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

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