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Optimization for Cost-Effectively Monitoring Ecological Effects of Water Diversion on the Urban Drinking Water Sources in a Large Eutrophic Lake

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Due to the inputs of allochthonous pollutants and biological species from imported water, ecological effects of water diversion on urban drinking sources require long-term monitoring. Since spatial distributions of biological and environmental elements are always susceptible to water diversion, the monitoring specifications in water-receiving regions are always different from conventional ecological monitoring, especially in monitoring parameter selection and site distribution. To construct the method for selecting sensitive monitoring parameters and optimizing sites distribution in lakes, the large river-to-lake water diversion project, Water Diversion from Yangtze River to Lake Taihu in China, was taken as an example. The physicochemical properties and phytoplankton communities in the water-receiving Gonghu Bay and the referenced lake center were investigated and compared between the water diversion and non-diversion days in different seasons from 2013 to 2014. The comparative and collinearity analyses for selecting sensitive physicochemical parameters to water diversion, and the multidimensional scaling analysis based on the matrices of biological and sensitive physicochemical data, were integrated to optimize the monitoring in the water-receiving lake regions. Seven physicochemical parameters, including water temperature, pH, dissolved oxygen, total nitrogen, total phosphorus, chlorophyll a, and active silicate, were demonstrated to be sensitive to seasonal water diversion activities and selected for optimizing the site distribution and daily water quality monitoring. The nonmetric multidimensional scaling analysis results based on the data matrices of sensitive physicochemical parameters and phytoplankton communities were consistent for sites distribution optimization. For cost-effective monitoring, the sites distribution scheme could choose the optimizing results based on the Euclidean distance from 3.0 to 4.0 and the Bray-Curtis similarity from 40 to 60%. This scheme divided the Gonghu Bay into three water regions: the inflow river inlet, bay center, and bay mouth adjacent to the open water region. In each of the three regions, one representative site could be selected. If focusing on more details of each region, the standards with the Euclidean distance lower than 2.0 and the Bray-Curtis similarity higher than 60% should be considered. This optimization method provided an available way to fulfill the cost-effective long-term monitoring of urban drinking water sources influenced by water diversion projects.

Keywords: water diversion, drinking water sources, physicochemical parameters, phytoplankton community, cost-effective monitoring

INTRODUCTION

Water diversion projects, as popular engineering projects for water supply and environmental improvement, have been implemented in many countries for over several decades (Hu et al., 2008). Originally, water diversion projects, such as the California Water Diversion Project, Mississippi River Diversion Project, and China South-to-North Water Diversion Project, were mainly used for agricultural irrigation, industrial production, residential water use, and ecological water supplement (Li et al., 2011, 2013). Since the global lake eutrophication problem became prominent in the 1960s, water diversion also has been taken as an efficient way to improve hydro-environments and to deal with cyanobacterial blooms in drinking water sources in many eutrophic lakes such as Lake Green in the USA (Oglesby, 1968), Lake Veluwe in the Netherlands (Jagtman et al., 1992), and others (Lake Taihu, Lake Chaohu, Lake Dianchi, Lake Baiyangdian, etc.) in China (Hu et al., 2008; Zhai et al., 2010; Li et al., 2011, 2013; Zhang et al., 2016; Chen et al., 2017; Cao et al., 2018; Dai et al., 2018, 2020; Qu et al., 2020; Zhang et al., 2021). As an emergent measure for protecting drinking water security, ecological effects induced by allochthonous inputs of nutrients and exotic species in water diversion projects have been receiving extensive attention.

To reveal the ecological effects of water diversion projects on drinking water sources in lakes, long-term ecological monitoring work is necessary. The ecological monitoring procedure for rivers and lakes always has standard specifications for sampling sites, sampling time, monitoring parameters, and other procedures (Wang et al., 2013). However, due to the dynamic inflow discharges of water diversion and their influences on water currents, the distributions of ecological elements are always influenced by the inflow discharges, allochthonous elements, and the lasting time of water diversion activities (Li et al., 2013). Therefore, the monitoring specifications, especially the site location, should be different from that of the normal monitoring methods. For example, due to the mixing effects of water diversion in the water-receiving regions, the original spatial differences in concentrations of some physicochemical parameters among the adjacent sites during the non-diversion period might be eliminated by the water diversion (Dai et al., 2020). Moreover, the normal specification of lake ecological monitoring always has many physicochemical parameters (Wang et al., 2013), some of which may not be sensitive to the water diversion. Thus, to save monitoring costs, sensitive physicochemical parameters should be selected for the long-term monitoring of the ecological effects induced by water diversion.

The site layout optimization research in lakes is mainly related to water quality monitoring (Behmel et al., 2016; Jiang et al., 2020; Liu et al., 2020). To optimize the water quality monitoring networks in drinking water sources of lakes, site layout optimization methods are usually based on water quality parameters correlation coefficients (Wang et al., 2014), the kriging variance (Beveridge et al., 2012), chlorophyll a remote sensing (Kiefer et al., 2015), and multivariate statistical analysis like cluster and discriminant analysis (Kovács et al., 2015; Tanos et al., 2015). These methods always use one or several representative water quality parameters to calculate differences among sites. But only a few studies provided a method for selecting the representative water quality parameters, mainly using the principal component analysis and collinearity analysis (Wang et al., 2014). Moreover, for optimizing ecological monitoring works in lakes, biological communities should also be considered. However, few studies provide a targeted methodology for optimizing the layout of ecological monitoring sites in drinking water sources of lakes, especially influenced by water diversion projects (Lepono et al., 2003; Zhang, 2009).

Lake Taihu is the third largest eutrophic shallow lake in the most developed middle and lower reaches of the Yangtze River, China. Due to anthropogenic and climatic disturbances, cyanobacterial blooms and pollution-induced water shortage have become the dominant ecological problems in the Taihu Basin (Qin et al., 2010). The Water Diversion from the Yangtze River to Lake Taihu (WDYT) project has been given the obligation to relieve these ecological problems in the Taihu Basin (Hu et al., 2008). Although the WDYT can quickly enhance the water exchange capacity and alleviate the cyanobacterial blooms in some drinking water sources of Lake Taihu (Li et al., 2013), the allochthonous input of nutrients and other pollutants have also sparked controversies (Hu et al., 2010; Dai et al., 2018; Yao et al., 2018; Qin et al., 2019). Therefore, long-term and cost-effective monitoring work should be carried out to objectively evaluate ecological effects of this project. In this study, we proposed a targeted methodology for selecting sensitive biotic and abiotic parameters and optimizing the location of monitoring sites in the water-receiving regions of Lake Taihu. As the numerous and active biota in lakes, phytoplankton are vitally sensitive to lake conditions such as the trophic level and hydrodynamic disturbance (Guo et al., 2019), and thus are taken as the representative biological index in ecological monitoring (Padisak et al., 2006). The physicochemical parameters and phytoplankton communities in the drinking water sources in Gonghu Bay were measured during the water diversion periods in different seasons. Based on these monitoring variables, an integrated method, combining comparative analysis, collinearity analysis, and multivariate statistical analysis, was constructed for optimizing the ecological monitoring sites distribution in lakes. This study intended to provide an available method which is cost-effective for long-term

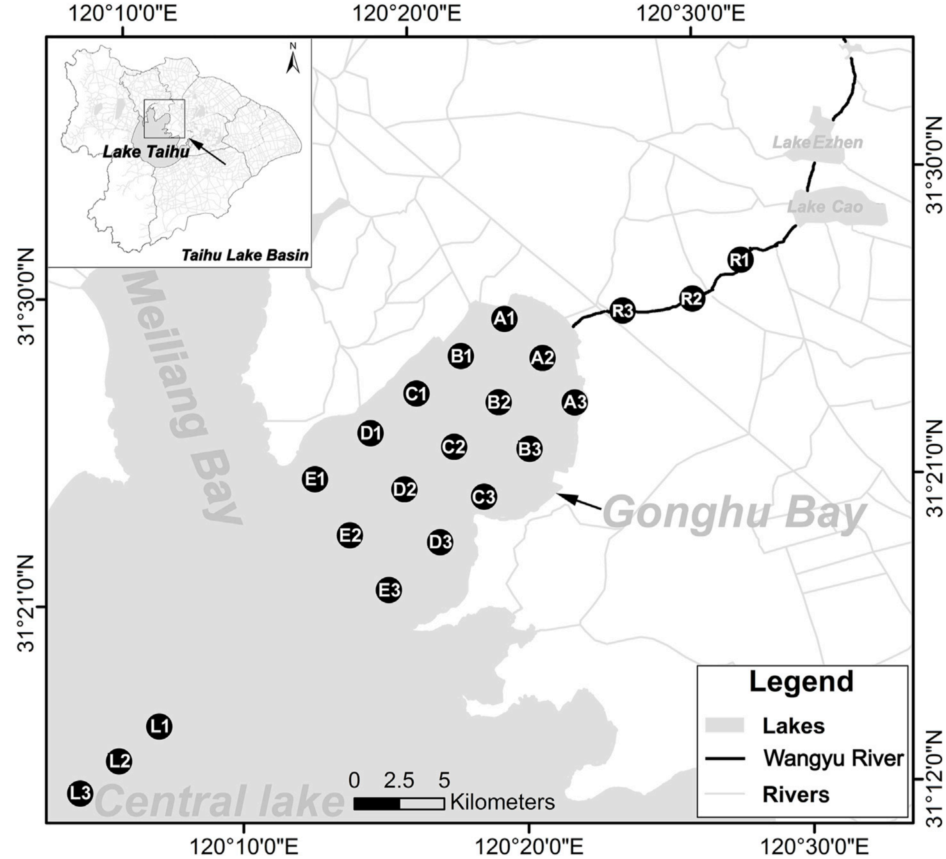

FIGURE 1 | The initial distribution of monitoring sites in Wangyu River, Gonghu Bay, and the lake center of Lake Taihu.

ecological monitoring, and thus could standardize the procedure of ecological monitoring for limnetic effects induced by water diversion projects.

MATERIALS AND METHODS

Study Area and Initial Monitoring Sites Distribution

Gonghu Bay, the northeastern part of Lake Taihu, is the main urban drinking water source for Wuxi city of the Taihu Basin and also the first water-receiving area connecting the main inflow channel of the Wangyu River and the central lake of Lake Taihu (**Figure 1**). It covers about 150 km^2 and has a multi-year average water depth of 1.8 m (Zhong et al., 2012). Due to the frequent serious cyanobacterial blooms in the north part of Lake Taihu from May to December in a year, Gonghu Bay is always threatened by *Microcystis* scums (Dai et al., 2018, 2020). According to the Technical Specifications Requirements for Environmental Monitoring of Surface Water and Waste Water (HJ/T 91-2002) issued by the Ministry of Ecology and Environment of P.R. China, we distributed the monitoring sites in a uniform grid with a 2.50 km distance among two sites in Gonghu Bay. We also laid three monitoring sites in Wangyu River and the central lake of Lake Taihu, respectively, (**Figure 1**). In Gonghu Bay, there were three site lines from the river mouth of Wangyu River to the central lake, of which two were along the west and east sides of Gonghu Bay, respectively. The other was of the central line of Gonghu Bay. Each line had five sites.

Water Sample Collection and Physicochemical Parameters Measurement

Since WDYT is always operated according to the water level of Lake Taihu (TBA, 2013). Once the water level of Lake Taihu is lower than the control water level for water supply which is ruled by the Taihu Basin Authority (TBA), the hydro-junctions in the Wangyu River will open to transfer Yangtze River water to Lake Taihu. Additionally, if Lake Taihu faces serious cyanobacterial blooms, the WDYT will also be urgently operated to relieve bloom disasters (Qin et al., 2010). Due to this reason, the WDYT has been regularly operated during the dry period in Taihu Basin from November to February year by year (TBA, 2013, 2014). In this study, we constantly monitored *in situ* on the middle days of July, August, November, and January from 2013 to 2014. Among these sampling days, the days of November and January in 2013 and July in 2014 were in the period without water

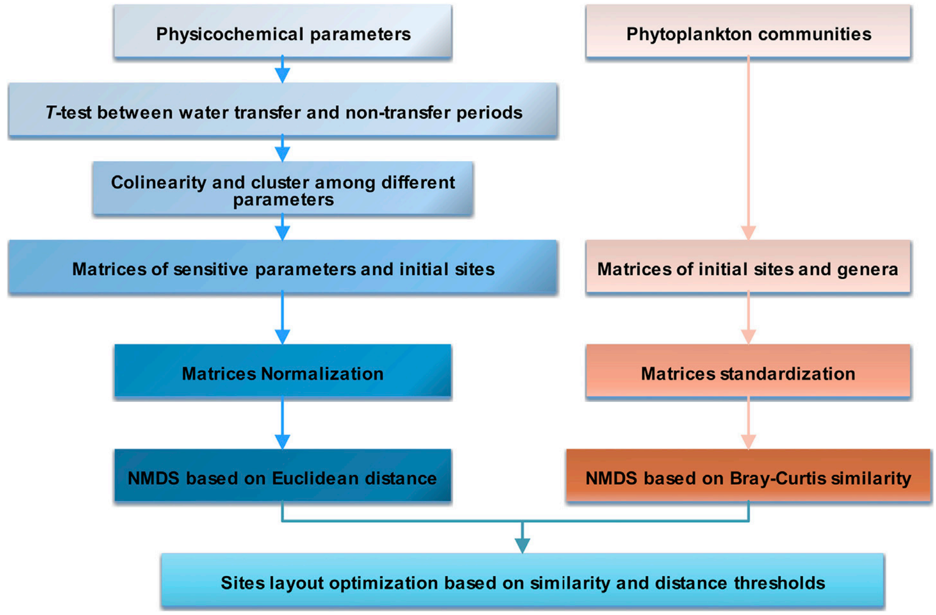

FIGURE 2 | The flow chart of sites optimization methodologies used in this study.

diversion, while the days in August of 2013 and November and January in 2014 were all in the water diversion period.

About a 2-L water sample (about 50 cm under the water surface) for each site was collected using the column water sampler. One liter was stored in a clean plastic bottle and used for measuring the physicochemical parameters in the laboratory in 24 h. Another 1-L water sample for each site was stored in a sterile plastic bottle and fixed with the 15 ml of 5% Lugol's iodine reagent (Jin and Tu, 1990), which was transported to the laboratory for phytoplankton community identification.

Physicochemical Parameters Measurement

Water temperature, pH, turbidity, and dissolved oxygen content were detected *in situ* using the Portable Multi-parameters Detection HQ30d (HACH, Shanghai, China) kit. The contents of total nitrogen (TN), total phosphorus (TP), ammonia (NH_3-N), nitrate (NO_3-N), soluble reactive phosphorus (SRP), permanganate index (COD_{Mn}), chlorophyll a (Chl a), and dissolved silicate (SiO_3-Si) were all measured in the laboratory according to the literature methods (Jin and Tu, 1990).

Phytoplankton Community Identification

After over 24 h of standing, the 1-L Lugol's fixed water sample for each site was concentrated to 50 ml in a sterile glass bottle using a separating funnel. Then, 0.1 ml of the concentrated sample was injected into the algae counting box and put in the Axiovert 200 (CARL ZEISS, Germany) optical microscope to uniformly capture 100 random views. This procedure was repeated three times for one sample. The cell abundances of phytoplankton species were identified according to the literature (Hu and Wei, 2006).

Optimization Methods

Sensitive Physicochemical Parameters Selection

The significance in physicochemical parameters between the periods of water diversion and non-diversion in the same month for different years was determined using the two-tailed *t*-test method (**Figure 2**) in the SPSS 16.0 statistic software (IBM, United States). The collinearities of the significant physicochemical parameters were tested by Pearson correlation analysis with the SPSS 16.0 software and were plotted using the R software. After this, the representative significant parameters without significant autocorrelation among them were selected to be the sensitive physicochemical parameters which would be further used for sites distribution optimization.

Sites Distribution Optimization

Nonmetric Multidimensional scaling analysis (NMDS) (Clarke and Gorley, 2006) was used to optimize the distribution and number of monitoring sites, based on the Euclidean distance of environmental data matrices and Bray-Curtis similarity of phytoplankton community matrices among initial monitoring sites, respectively, (**Figure 2**). The environmental data matrices were constructed by sensitive physicochemical parameters of the initial monitoring sites. The phytoplankton community matrices were constructed by the phytoplankton genera or species corresponding to the environmental data matrices. The threshold values, distinguishing sites revealing different ecological effects of water diversion, were selected as 1.0, 2.0, 3.0, 4.0, 5.0 of the Euclidean distance and 40, 50, 60, 70, 80% of the Bray-Curtis similarity, respectively. The NMDS biplots showing differences among sites on the water diversion days were plotted using the Primer-E software (Quest Research Limited, New Zealand) (Clarke and Gorley, 2006).

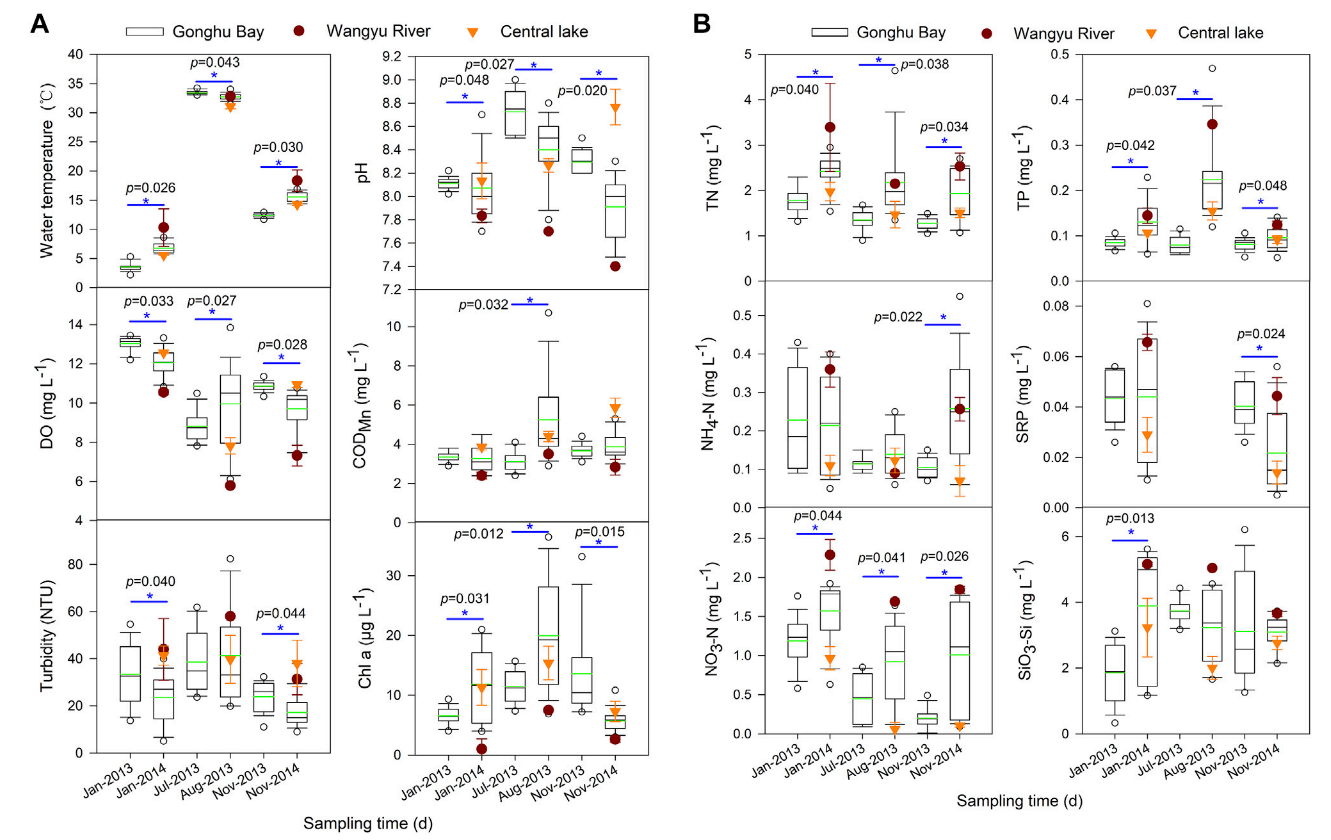

FIGURE 3 | The comparisons in mean values of the 12 physicochemical parameters between the same seasons during water diversion and non-diversion periods from 2013 to 2014 (DO, dissolved oxygen; SiO_3-Si, active silicate; NO_3-N, nitrate; NH_3-N, ammonia; TN, total nitrogen; TP, total phosphorus; Temp, water temperature; Chl a, chlorophyll a; COD_{Mn}, permanganate index; Jan, Aug, and Nov are the abbreviations of January, August, and November, respectively, the asterisk means significant difference in parameters between the water diversion and non-diversion periods in the same season; Significant *p* values between the water diversion and non-diversion periods in the same season are shown in the figure; the green line means the mean value in the physicochemical parameter from the 15 sites in the Gonghu Bay).

RESULTS AND DISCUSSION

Sensitive Physicochemical Parameters Determination

The investigated physicochemical parameters were differently sensitive to the water diversion in the three seasons (**Figure 3**). In the three seasons during 2013–2014, there were significant differences in the mean values of water temperature, DO, pH, Chl a, TN, NO_3-N, and TP in Gonghu Bay between the water diversion and non-diversion days. In some of the three seasons, significant differences were also found in the mean values of turbidity, COD_{Mn}, NH_3-N, SRP, and SiO_3-Si. Due to the lower contents of DO and pH (**Figure 3**) and the higher values of water temperature (**Figure 3**), TN, NH_3-N, NO_3-N, TP, and SiO_3-Si (**Figure 3**) in the Wangyu River on some of the water diversion days, the contents of water temperature, DO, pH, TN, NH_3-N, NO_3-N, TP, and SiO_3-Si were evidently different from those on the non-diversion days in the same season. Since the contents of turbidity in the Wangyu River and central lake were always higher than those in Gonghu Bay, this parameter was not sensitive to the water diversions in different seasons (**Figure 3**). The average contents of COD_{Mn} and Chl a in Gonghu Bay were more influenced by the growth of phytoplankton in Gonghu Bay, but the average content of Chl a was also lower on the water diversion days than that on the non-diversion days in autumn (**Figure 3**). The contents of SRP were also not sensitive to the water diversions in different seasons (**Figure 3**).

The collinearity analysis of the 12 monitored parameters on all six sampling days showed there were pronounced correlations among some of the physicochemical parameters (**Figure 4**). Based on the collinearities among the physicochemical parameters, seven physicochemical parameter groups were classified with the Pearson coefficient of 0.30: group A, COD_{Mn}, Chl a, and pH; group B, turbidity; group C: water temperature and TP; group D, DO; group E, TN and NO_3-N; group F, SiO_3-Si; group G, NH_3-N, and SRP (**Figure 5**). However, if selecting the higher Pearson coefficients, we could get more groups. Combining with the results of mean value comparisons and the convenience in data acquisition, seven physicochemical parameters, including water temperature, pH, DO, TN, TP, Chl a, and SiO_3-Si, were selected to be the sensitive physicochemical parameters used for sites distribution optimization and daily water quality monitoring.

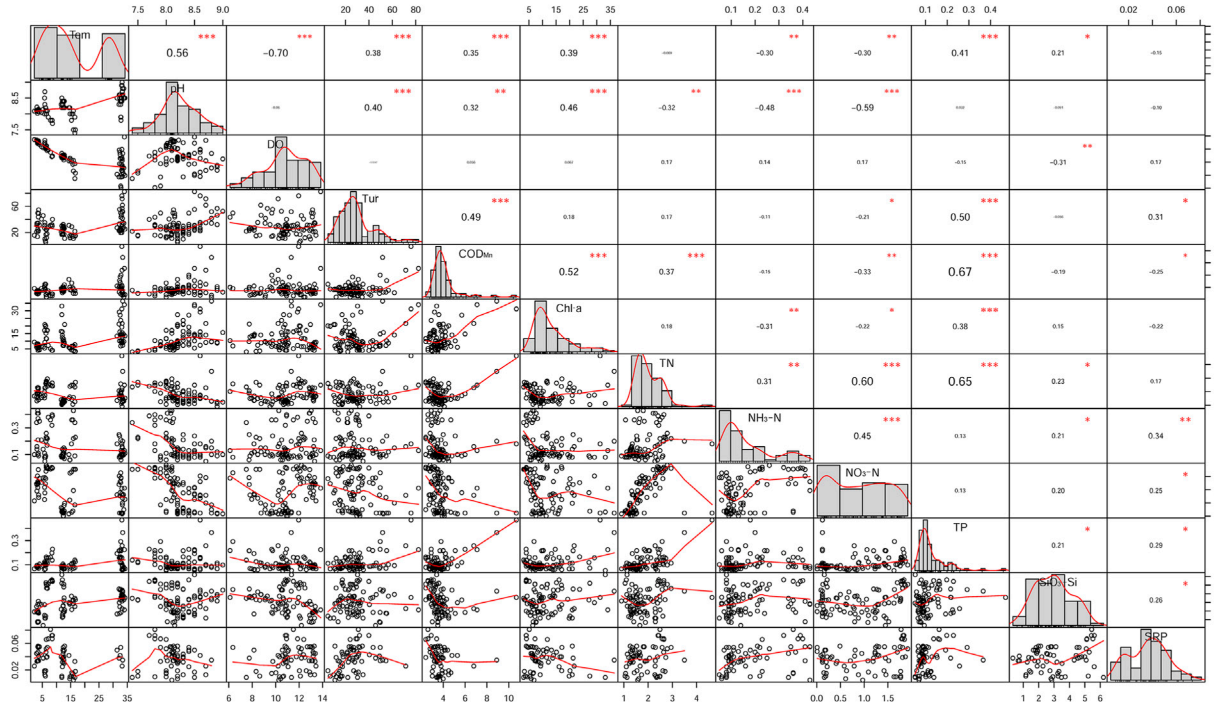

FIGURE 4 | The collinearity analysis of the 12 monitored physicochemical parameters on all six sampling days. [DO, dissolved oxygen; SiO_3-Si, active silicate; NO_3-N, nitrate; NH_3-N, ammonia; TN, total nitrogen; TP, total phosphorus; Temp, water temperature; Chl a, chlorophyll a; COD_{Mn}, permanganate index; the single asterisk represents significant correlations (Pearson correlation, $p \le 0.05$); the double asterisk means highly significant correlations ($p \le 0.01$); the triple asterisk means extremely significant correlations ($p \le 0.001$)].

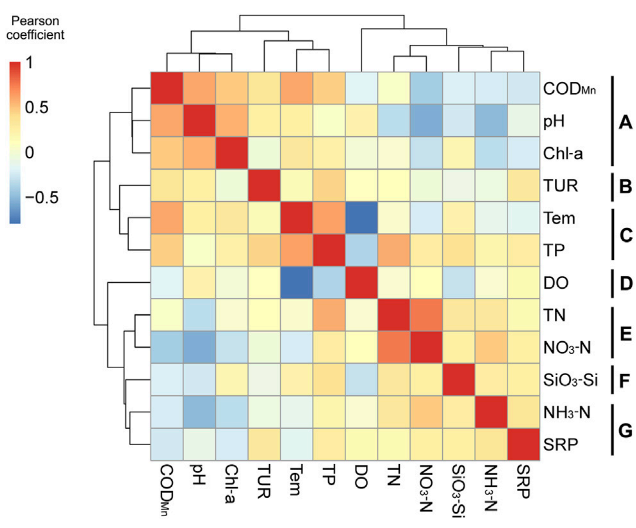

FIGURE 5 | The heatmap of Pearson correlations among the monitored physicochemical parameters in Gonghu Bay in the six sampling times. (The sample number of the Pearson correlation test is 90. DO, dissolved oxygen; SiO_3-Si, active silicate; NO_3-N, nitrate; NH_3-N, ammonia; TN, total nitrogen; TP, total phosphorus; Temp, water temperature; Chl a, chlorophyll a; COD_{Mn}, permanganate index).

The selected parameters represent different physicochemical features of the lake water.

Water temperature, reflecting seasonal and climate changes, is the basic physical parameter influencing characteristics of hydrodynamics, circulation of substance and energy, and life processes in lakes (O'Reilly et al., 2003; Elçi, 2008; Gudasz et al., 2010). The pH value is the comprehensive physicochemical index which reflects the dynamics of hydrogen ion determined by the contents of carbon dioxide, bicarbonate ion, and carbonate in water (Charlson and Rodhe, 1982). Due to the normally lower pH values in rivers than in lakes (Feng et al., 2017), the pH value which is always increased by the cyanobacterial blooms (Cao et al., 2016) in the water-receiving lake regions were decreased significantly. Dissolved oxygen is also a regular and critical environmental monitoring parameter which is easily obtained *in situ* using automatic monitoring equipment. The Chl a index represents not only the primary production but also the level of cyanobacterial blooms. Additionally, N, P, and Si are the basic elements of natural waters, and the nutrient parameters are also the normal monitoring indexes for drinking water sources (Wu et al., 2017). Finally, the selected physicochemical parameters not only reflected the sensitive characteristics of the physicochemical habitat in the water-receiving lake region, but also covered the most important monitoring water quality indexes for the drinking water sources.

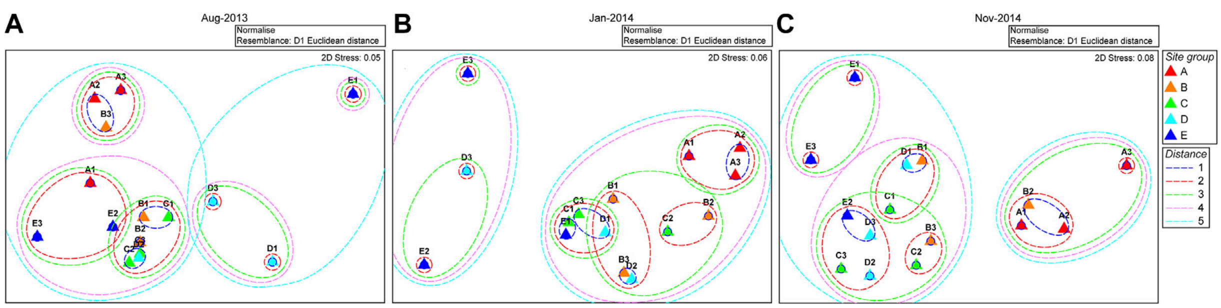

FIGURE 6 | The multi-scaling analysis biplots for monitoring sites in Gonghu Bay based on the Euclidean distance matrices of sensitive physicochemical parameters during the six sampling periods from 2013 to 2014. The classification of monitoring sites was based on three levels (1, 2, 3, 4, and 5).

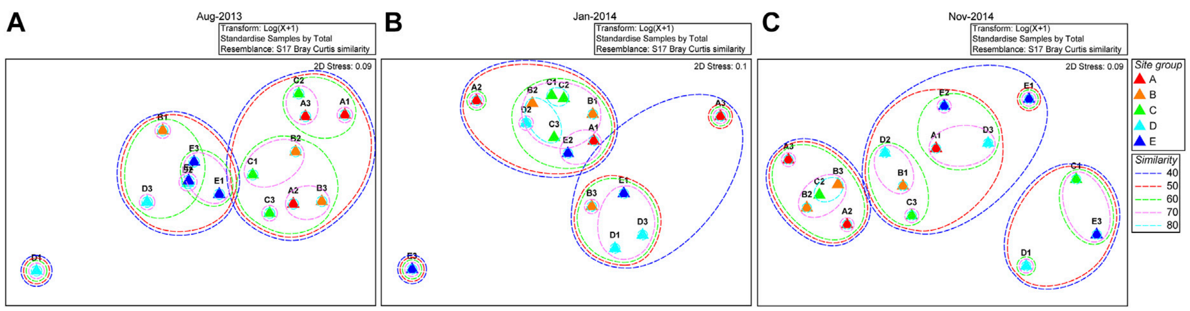

FIGURE 7 | The multi-scaling analysis biplots for monitoring sites in Gonghu Bay based on the Bray-Curtis similarity matrices of phytoplankton communities during the six sampling periods from 2013 to 2014. The classification of monitoring sites was based on three levels (40, 50, 60, 70, and 80%).

Sites Optimization Based on Matrices of Sensitive Physicochemical Parameters

The NMDS results based on the Euclidean distance matrices of the sensitive physicochemical parameters from 2013 to 2014 showed the pronounced differences among sites, with the gradient from the inflow river mouth of Gonghu Bay to the adjacent region between Gonghu Bay and the lake center on the water diversion days (**Figure 6**). The classification of sampling sites was different with different distance thresholds. Along with the increase of Euclidean distance, the number of site clusters decreased. At the 1.0 level of Euclidean distance, most of the sampling sites differed from each other on each water diversion day, while at the 5.0 level of Euclidean distance, only two site clusters were classified on the three water diversion days. Totally, at the Euclidean distance range from 3.0 to 4.0, three site groups were found in the inflow river mouth of Gonghu Bay, bay center, and the adjacent region between Gonghu Bay and the lake center during the water diversion periods, respectively (**Figure 6**). The Euclidean distance is the most popular dissimilarity index for measuring the distances among different environmental matrices (Hadjisolomou et al., 2018). In this current study, the classification result at the Euclidean distance range from 3.0 to 4.0 could reflect the heterogeneity in the spatial effect induced by water diversion. Therefore, based on the environmental matrices of sensitive physicochemical parameters, the sites distribution could be optimized which could also reflect the impacts of water diversion on the drinking water sources in lakes.

Sites Optimization Based on Phytoplankton Community Matrices

The NMDS on the Bray-Curtis similarity matrices of the phytoplankton communities showed obvious spatial heterogeneity in phytoplankton community structures on the three water diversion days of 2013–2014 (**Figure 7**). At the similarity level of 80%, the phytoplankton community in different sites was significantly different. The ecological structure of Gonghu Bay is complicate with the algae-dominated west region and the macrophyte-dominated east region (Gao et al., 2017). Moreover, the lake currents of some water regions in Gonghu Bay are sensitive to the disturbance induced by wind and water diversion activities (Lv, 2013). Therefore, the phytoplankton habitat in Gonghu Bay presented obvious spatial heterogeneity, which might be an important reason for the significant differences in phytoplankton communities among different sites at the similarity of 80%. However, from 60 to 40% of the similarity levels, most of the adjacent sites were grouped together and shaped several site groups in the inflow river mouth of Gonghu Bay, center, and the adjacent region between Gonghu Bay and the central lake during the water diversion periods,

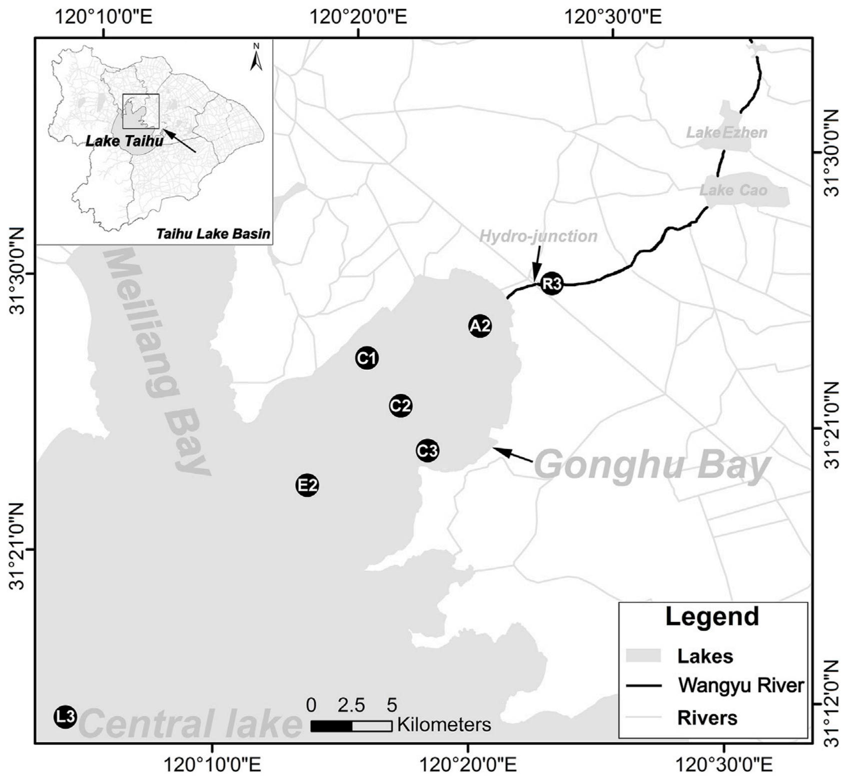

FIGURE 8 | The most cost-effective sites distribution in Wangyu River, Gonghu Bay, and the lake center of Lake Taihu.

respectively, (**Figure 7**). Consistent with the results of the NMDS analysis on sensitive physicochemical properties of water samples, the spatial distribution of the phytoplankton communities in Gonghu Bay during the water diversion days was similar. The similar distribution pattern for both the phytoplankton communities and their physicochemical habitats was demonstrated by some previous studies (Li et al., 2019; Kutlu et al., 2020). In this study, the thresholds for the cluster indices were determined to optimize the sampling sites distribution, which was alternative according to the monitoring requirements.

Determination of Sites Distribution Optimization and Methodology Application

In view of the above NMDS analysis results, taking into account the spatial distribution of monitoring sites and ecological functions of monitoring areas, the optimization of monitoring sites for the ecological effects of the water diversion project was optimized. The representative monitoring sites that can reflect the ecological effects of water diversion in Gonghu Bay were initially selected. Among them, the distance between every point in Gonghu Bay was optimized from the original 2.5–5 km.

As the only monitoring point of the Wangyu River, site R3 should be preserved to represent the characteristics of inflow water. As the most sensitive water area to water diversion activities, site A1 that linked the Wangyu River inlet and Gonghu Bay is also preserved. During the periods of water diversion, the physicochemical and biological elements of Gonghu Bay showed an evident spatial gradient along the Wangyu River inlet to the mouth of Gonghu Bay, so three monitoring sites (A2, C2, and E2) are preserved along the center line of Gonghu Bay. As a reference water area, lake center regions retained the original L3 monitoring site. The east and west regions of Gonghu Bay are two different types of ecosystems, and the southeast monsoon has a greater impact on Lake Taihu in the summer. Therefore, the monitoring sites (C1 and C3) were preserved for the east and west regions, respectively (**Figure 8**).

From the monitoring costs perspective, the sites layout scheme could choose the optimizing results based on the Euclidean distance of 3.0–4.0 or the Bray-Curtis similarity from 40 to 60%. This scheme divided Gonghu Bay into three water regions with the distance gradient far from the inflow river mouth. In each of the three regions, one representative site could be located. However, if focusing on more details of each region, the standards with the Euclidean distance lower than 2.0 and the Bray-Curtis similarity higher than 60% should be considered. At the same time, the marginal effect of the biological diversity of the shoreline ecosystem in lakes and the impact of wind directions in different seasons in Lake Taihu should be taken into consideration. The most representative monitoring sites in the monitored area should be selected in different seasons.

CONCLUSION

Based on the two-tailed *t*-test and collinearity analysis, the six physicochemical parameters including pH, DO, turbidity, TP, NO_3-N, and SiO_3-Si were demonstrated to be sensitive physicochemical parameters that could be used for sites distribution optimization in Gonghu Bay. The sites distribution optimization method is available to the case study of Gonghu Bay influenced by the WDYT. The NMDS analysis results based on the Euclidean distance of physicochemical matrices and the Bray-Curtis similarity of phytoplankton communities were consistent. From the monitoring costs perspective, the sites distribution scheme could choose the optimizing results based on the Euclidean distance from 3.0 to 4.0 and the Bray-Curtis similarity from 40 to 60%. This scheme divided Gonghu Bay into three water regions of the Wangyu River inlet, center, and mouth of Gonghu Bay. In each of the three regions, one representative site could be located. However, if focusing on more details of each region, the standards with the Euclidean distance lower than 2.0 and the Bray-Curtis similarity higher than 60% should be considered. At the same time, the marginal effect of the biological diversity of the shoreline ecosystem in lakes and the impact of wind directions in different seasons in Lake Taihu should be taken into consideration. The most representative monitoring sites in the monitored area should be selected in different seasons.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

JD: Conceptualization, Investigation, Formal analysis, Writing—Original Draft ZF: Revision and Editing XW: Project administration, Funding acquisition SW: Supervision, Project administration, Funding acquisition YZ: Formal analysis FW: Investigation AG: Investigation XL: Investigation, Resources SZ: Writing—Review and Editing.

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