SPATIOTEMPORAL DYNAMICS OF AMMONIA NITROGEN AND ITS RESPONSE TO INFLOW RIVER BASED ON RANDOM FOREST MODEL IN NORTHWEST TAIHU LAKE, CHINA

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Abstract. Inflow rivers have crucial impact on lake eutrophication. Ammonia nitrogen (NH_4^+–N) in inflow rivers have tightly coupled relationships with water quality in Lake Taihu, China. Based on the monthly concentrations from 2009 to 2015, this study focused on the spatiotemporal dynamics of NH_4^+–N in northwest Taihu Lake and utilised random forest (RF) model to simulate its response to inflow rivers. Results indicated that (1) in northwest Lake Taihu, the spatiotemporal distribution patterns of NH_4^+–N concentrations are distinct, and river inputs were the major source of NH_4^+–N loadings. (2) Scenario simulation results in RF models indicated that the inflow loads should be controlled under 6427.38, 3248.01, 2206.92 and 1107.58 ta^{-1} for the protective targets. (3) In 2015, NH_4^+–N concentrations in four lake regions and NH_4^+–N loads from inflow rivers were consistent with the simulation results in RF models. The NH_4^+–N concentrations decreased approximately 6%, 34%, 44.44% and 6.67% in North Zone and Zhushan, Meiliang and Gonghu Bays, respectively, despite reduction in external NH_4^+–N loads by 8.99%, 11.41%, 51.38% and 62.87%. This study provides further understand on quantifying the reduction of nutrient loading from inflow rivers and governing Lake Taihu or other typical eutrophic lakes.
Keywords: eutrophication, inflow river, load reduction, NH_4^+–N, Taihu Lake, water quality

Introduction

With urbanisation development and population expansion, a large number of ecologically important freshwater bodies have experienced harmful water quality degradation and algal blooms, which have been a national concern in the recent decades (Schindler and Hecky, 2009; Qin et al., 2015; Wu et al., 2016). Previous research suggests that lake eutrophication is driven by physical, chemical and biological parameters and land use influences, including sediment dredging, aquatic organisms and hydrodynamic conditions (Wang et al., 2011; Bian et al., 2016). A great amount of nutrients and other contaminants enter lakes from river inputs, which are the main pollution route among all the influencing factors and considerably affecting the aquatic environment and ecosystem heath of lakes (Rao and Schwab, 2007; Chen et al., 2011; Juma et al., 2014). Studies have found that the pollutant input from inflow rivers has a

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meaningful effect on the nutrient concentration with certain relationships (Zhang et al., 2016).

As one of the five largest fresh lake and a long-term eutrophic water body in China, many efforts have been undertaken by researchers and government entities to restore the Lake Taihu since 1990, including sediment dredging, wetland construction, water transfer projects, the use of macrophytes and so on (Hu et al., 2010; Li et al., 2011a, 2013). Researchers have shown that increasing the amount of pollutant discharge into the lakes is crucial, and efforts to control the nutrient input from the catchment of Lake Taihu are essential (Chen et al., 2003; Qin et al., 2007; Wang et al., 2011). In addition to light, temperature and salinity, nitrogen (N) and phosphorus (P) are the most common factors of limiting algal growth and relevant control has been widely implemented to address eutrophication in many freshwater system (Nixon, 1995; Schindler and Vallentyne, 2008; Conley et al., 2009; Suttle and Harrison, 2010; Xu et al., 2010, 2015). With the tendency of being co-limited by N and P in Lake Taihu, evidence suggests that the lake has been in a nutrient-imbalance condition owing to focusing more on P reduction rather than together these two elements (Paerl, 2009; Lewis et al., 2011; Tang et al., 2016). In general, the pollution level of nitrogen and phosphorus is indicated by total nitrogen (TN) and total phosphorous (TP), and some studies have estimated the TN reduction in Lake Taihu and its inflow rivers (Du et al., 2017). Meanwhile, ammonia nitrogen (NH_4^+–N) is one of the three main forms of TN in natural water, and studies have indicated that NH_4^+–N has tightly coupled relationships with TN and water quality in Lake Taihu Basin (Liang et al., 2008; Ferard and Blaise, 2013). Therefore, this study focuses on the spatiotemporal dynamics of NH_4^+–N and its response to inflow river. In the interactional study of eutrophication, hydrodynamics and ecosystem in various freshwater bodies, lots of mathematical modelling approaches have been extensively applied to simulate the flow, water quality, spatiotemporal pattern of hydrodynamics and so on (Rasmussen et al., 2009; Min and Wise, 2010; Zhang et al., 2017). For instance, Mike21, a two-dimensional mathematic model, has been usually used to calculated aquatic environment capacity and total emission reduction according to aquatic environmental functions and targets (DHI, 2007; Zhu et al., 2013; Zhang, 2017). Several empirical models, such as the Wisconsin Department of Natural Resources' (WDNR) Wisconsin Lakes Modelling Suite, Seepage Lake Model and BATHTUB, have been previously developed and tested for predicting eutrophication-related water quality conditions in complex lakes and reservoirs (USEPA, 2000, 2010; WDNR, 2004; MPCA, 2006). However, these methods usually have certain data requirements or index restrictions (Wang et al., 2005). Random forest (RF) is a new machine learning algorithm and is combined with a predictor of multiple decision trees. It was proposed as a new soft computing method (Breiman et al., 1984). The RF has been developed to optimise predictive performance because of its several advantages, including a limited number of user defined parameters and the capability to model nonlinear relationships; reduce overfitting; remain robust despite of missing data and outliers; manage qualitative and quantitative variables; and evaluate, summarise and interpret final models (Breiman, 2001; Friedman, 2001; Friedman and Meulman, 2010). Over the past years, RF has been successfully applied to simulate soil organic carbon stocks, suspended sediment concentration, NO_2 concentration and nutrient concentrations (such as chemical oxygen demand); during these simulations, RFs have high tendency (Francke et al., 2008; Were et al., 2015; Rodriguez-Galiano et al., 2015; Ye et al., 2018; Muthukrishnan et al., 2018; Marttila et al., 2018; Kaminska, 2019).

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The present work took the northwest Lake Taihu as an example for the analysis. Generally, this study aims to (1) analyse the temporal and spatial variations in NH_4^+–N in the lake and its inflow rivers; (2) develop RF model to simulate the correspondence between the NH_4^+–N concentrations in the lake and its inflow rivers; and (3) address the water quality in the northwest Lake Taihu response to the river inflow.

Materials and Methods

Study area

As the third largest freshwater lake in China, Lake Taihu is situated in Southeast Jiangsu Province and the lower reach of the Yangtze River Basin with a surface area of 2338 km^2 and drainage area of 36500 km^2 (Lake Taihu Basin Authority, 2012). Lake Taihu is the main drinking water source for its neighbouring residents despite being heavily polluted and inferior to Grade V in GB3838-2002 (Bai et al., 2009). With the deterioration of environment and water quality, it has caused serious pollution in the lake ecosystems and algal blooms have long been frequency and concerning phenomenon, especially northwest part of the lake, and rivers flowing into Lake Taihu are the crucial factor (Qin et al., 2008; Tao et al., 2018). Excessive nutrients from inflow rivers are the major source of pollutant loadings to the lake and subsequently lead to spatial heterogeneity (Li et al., 2013; Liu et al., 2017). Lake Taihu has a tanglesome river and channel network, and more than 200 rivers at different scales are connected to it (Zhang et al., 2014). As shown in *Fig. 1*, the inflow rivers are primarily located in the northwest regions, covering North Zone, Zhushan Bay, Meiliang Bay and Gonghu Bay, and the outflows in the eastern and southern part of the lake (Du et al., 2017; Li et al., 2019). Inflow rivers in northwest Lake Taihu contribute the most water discharge and nearly 80% of COD, N and P to the lake (Zhang and Chen, 2011). Eutrophication studies in Lake Taihu have often focused on P because it is the most universal limiting nutrient and is thus typically targeted for loading reduction (Morton et al., 2003; Niu et al., 2004; Schindler, 2006; Lewis and Wurtsbaugh, 2008). Nevertheless, it is fundamentally important and cannot be ignored to control N inputs. Therefore, the present work focuses on the NH_4^+–N concentrations in northwest Lake Taihu and its inflow rivers based on the monthly monitoring data covering the period of 2009–2015.

Data analysis

Monthly NH_4^+–N concentrations of inflow rivers and of northwest Lake Taihu during the period of 2009–2015 were provided by Jiangsu Province Hydrology and Water Resources Investigation Bureau. The locations of the monitoring sites distributed across northwest Lake Taihu and its inflow rivers are shown in *Fig. 1*. These monitoring stations were located by GPS, and water samples were collected monthly from 2009 to 2015, from approximately 1 m below the water. The samples were then delivered to a laboratory by cryopreservation, and their correlation processing, such as the sampling, preservation, transportation and analysis, were performed within 24 h. All the samples were measured three times, and results were expressed in average. All chemical analyses followed the standards established by the State Environmental Protection Bureau of China.

For the convenience of describing the influences of the inflow rivers, Lake Taihu was divided into seven sub-areas (*Fig. 1*), namely, North Zone, Zhushan Bay, Meiliang Bay,

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Gonghu Bay, Southwest Zone, Central Zone, East Epigeal Zone and Dongtaihu Bay (Hu et al., 2008; Li et al., 2011b). This study focuses on the NH_4^+-N concentration in northwest Lake Taihu and thus included only the sub-lakes of North Zone, Zhushan Bay, Meiliang Bay, Gonghu Bay and their inflow rivers. In view of data availability and the links between the sub-lakes and their inflow rivers, corresponding sites were selected, as shown in *Fig. 2*.

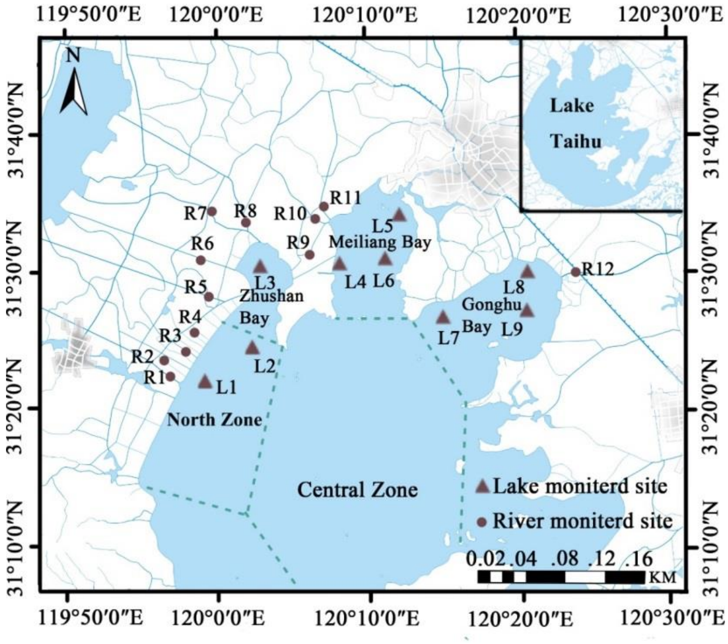

Figure 1. *Study area and its monitoring sites*

Model description

A RF model is made up of a number of simple (binary) decision trees, which were predetermined by a subset of predictors with the random selection strategy and grown on a bootstrap sample of the training set (Breiman, 2001). An RF makes no any additional assumptions about either the dependent or independent variables and could describe nonlinear and linear relationships (Cutler et al., 2007). The final model predictions are the average of the forest predictions and this method has been successfully used in analysis of many fileds (Maraqa et al., 2007; Paliwal and Patra, 2011). Despite the optimise predictive performance and wide potential, the complex relationship between pollutant concentrations and ambient conditions couldn’t be provided and satisfactory descripted in this model (Khan et al., 2017; Kaminska, 2019).

Three important parameters, the number of trees to grow in the forests (ntree), the number of randomly selected predictor variables at each node (mtry) and the minimal number of observations at the terminal nodes of the trees (nodesize), must be specified in the RF model. Ntree is the most important one since its determination of the strength of each individual tree and correlation among trees (Peters et al., 2008). The random in an RF is performed by randomizing the observed subsets and mtry candidate variables both, which influence the tree and the split creation in the tree respectively. Mulitdimensional step function is produced by each individual tree, which results in that the average of the individual tree is a multidimensional step function, namely the whole

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prediction of the forest. The multidimensional step function can predict smooth function as it has large number of sample values (Gromping and Ulrike, 2009).

In order to determine the fitting quality of each model, several possible error functions were computed and considered in the present work. As one of the basic measures to estimate a model's goodness of fit, the coefficient of determination R^2 is fundamental and the value ranges between <0, 1>. The closer it is to 1, the smaller are the differences between the empirical values and the estimated values.

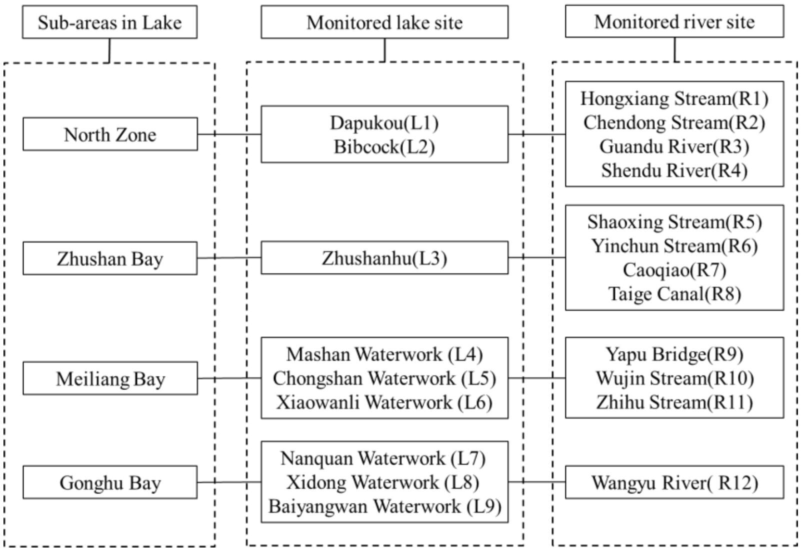

Figure 2. *Sampling stations in Lake Taihu and its inflow rivers*

Model scenarios

Developing effective and feasible nutrient reduction targets is necessary to improve trophic status and reduce bloom potentials. According to the Environmental Quality Standards for Surface Water in China (GB3838-2002) (*Table 1*), two nutrient reduction modeling scenarios were con-ducted to assess water quality response to nutrient load reductions in this study (*Table 2*).

Table 1. *The standard of NH_4^+–N in the Environmental Quality Standards for Surface Water in China (GB3838-2002) (mg/L)*

	Class I	Class II	Class III	Class IV	Class V
NH_4^+–N (≤)	0.15	0.5	1.0	1.5	2.0

Table 2. *Nutrient reduction scenarios and Water quality targets*

	North Zone	Zhushan Bay	Meiliang Bay	Gonghu Bay
Scenario 1	Class III	Class III	Class II	Class II
Scenario 2	Class II	Class II	Class I	Class I

There is a possibility that water circumstances could be altered by climate change in the future which is not easy to control. Although the answers are clearer now that nutrients, light, temperature and hydrodynamic force have all have been shown to

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influence formation of cyanobacterial blooms, the mechanism of a specific cyanobacterial bloom remains unknown (Qin et al., 2013). For example, temperature, precipitation and the distribution the runoff water have significant effect on the ammonium concentration and they are so complex and hard to predictable (Qin et al., 2010; Paerl et al., 2014). However, anthropogenic nutrient reduction to control water quality in lake is a direct and potentially achievable step that can be taken (Paerl et al., 2011; Xu et al., 2015). The two scenarios were made according to the water quality targets for the northwest Taihu Lake in the Master Plan of Integrated Regulation of Water Environment and the Water Function Zoning of the Lake Taihu Basin.

Results and Discussion

Spatiotemporal distribution of NH_4^+–N in northwest Lake Taihu

The northwest Lake Taihu area is the most contaminated and has yet to be studied in detail. Thus, it was selected for the analysis of the spatial and temporal changes that occurred in 2009–2015. The spatiotemporal distribution of NH_4^+–N in North Zone, Zhushan Bay, Meiliang Bay and Gonghu Bay are detailed as follows.

In the northwest Lake Taihu, the spatiotemporal distribution patterns of nutrient concentrations are distinct. In general, ammonia concentration tends to decrease gradually from 2009 to 2015 (*Fig. 3*).

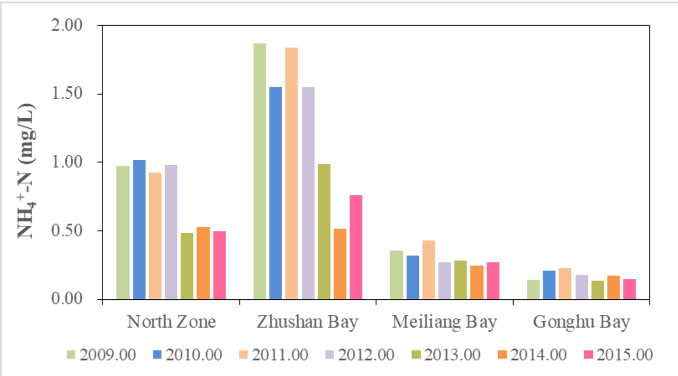

Figure 3. *Yearly mean values of NH_4^+–N concentration in northwest Lake Taihu*

The North Zone and Zhushan Bay were the two heavily polluted areas, whereas Gonghu Bay was in the best and cleanest condition. The range of NH_4^+–N concentration in the North Zone and Zhushan Bay was 0.5–2.5 mg/L, whereas those in Meiliang Bay and Gonghu Bay were approximately 0.5 mg/L (*Fig. 4*). The Environmental Quality Standards for Surface Water in China (GB3838-2002) has indicated that the NH_4^+–N concentration in the North Zone and Zhushan Bay is classified as Class III–V, and that in the other two lake regions is classified as Class I or II; this classification indicates that the further consideration of the limiting nutrient in the North Zone and Zhushan Bay is important prior to other lake regions. The NH_4^+–N content in the four seasons (that is, Winter: December, January and February; Spring: March, April and May; Summer: June, July and August; and Autumn: September, October and November) in northwest Lake Taihu were calculated (*Table 3*). The standard deviations of monthly mean values of NH_4^+–N concentration in northwest Lake Taihu in *Fig. 4* are 0.52, 0.8,

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0.1 and 0.09, separately. The results showed that season had a considerable effect on the NH_4^+–N concentration of northwest Lake Taihu, which was remarkably higher in winter and spring than those in other seasons. In the studied area, the NH_4^+–N concentration was the highest in winter. Therewith, the concentration started gradually decreasing in spring. Finally, it dropped to the minimum value in the summer or autumn. The seasonal tendency in the four regions was similar and especially evident in the North Zone and Zhushan Bay. The variations of concentrations in different seasons were in accordance with the change trend of air temperature. The solubility of ammonia nitrogen in water decreases with temperature increasing. What's more, these winter maxima possibly arise from (1) around lake, surface and subsurface catchment inputs are high in the non-growing season; (2) nutrients are concentrated in lower water levels; and (3) microbial activity is low due to low temperatures (Wang et al., 2017). It also may due to the relationships between ammonium loadings and rainfall, that's precipitation had a summer maximum and a fall minimum and followed an inverse seasonal cycle compared to NH_4^+–N concentrations (Nõges et al., 2007).

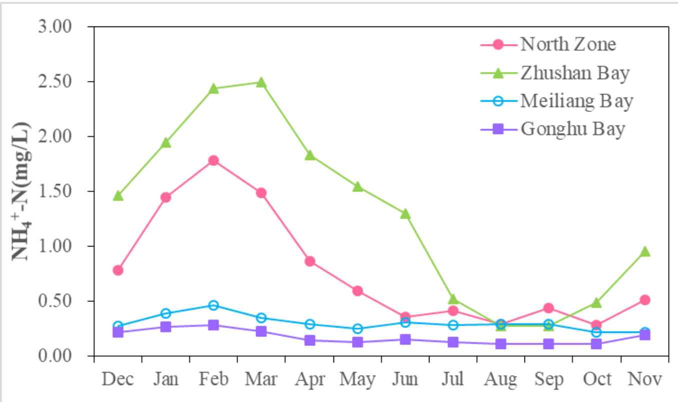

Figure 4. *Monthly mean values of NH_4^+–N concentration in northwest Lake Taihu*

Table 3. *Monthly mean values of NH_4^+–N concentration in northwest Lake Taihu (mg/L)*

	North Zone	Zhushan Bay	Meiliang Bay	Gonghu Bay
Winter	1.34	1.96	0.38	0.26
Spring	0.98	1.95	0.30	0.17
Summer	0.35	0.70	0.29	0.13
Autumn	0.41	0.57	0.24	0.14

NH_4^+–N input from inflow rivers in northwest Lake Taihu

The annual NH_4^+–N loads to the northwest Lake Taihu from its tributaries mean a large amount of nutrients and pollutant. Besides Gonghu Bay, NH_4^+–N concentrations of inflow rivers in the regions were classified as Class IV–V or worse. By contrast, the water quality of inflow rivers in Gonghu Bay was relatively good. The NH_4^+–N concentrations in the main inflow rivers in northwest Lake Taihu directly affected the northwest lake regions from 2009 to 2015, as shown in *Fig. 5*. The R^2 values of these scatter diagrams are all approximately 0.70 (that is, 0.763, 0.775, 0.641 and 0.758), and $p<0.01$ (*Fig. 5*). In conclusion, river inputs are the major source of NH_4^+–N loadings to the northwest Lake Taihu, and water quality in the lake is closely related to that in

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inflow rivers. Declining water quality in inflow rivers have a considerable influence on lake restoration, and NH_4^+–N concentrations evidently decrease with the reduction of inflow load.

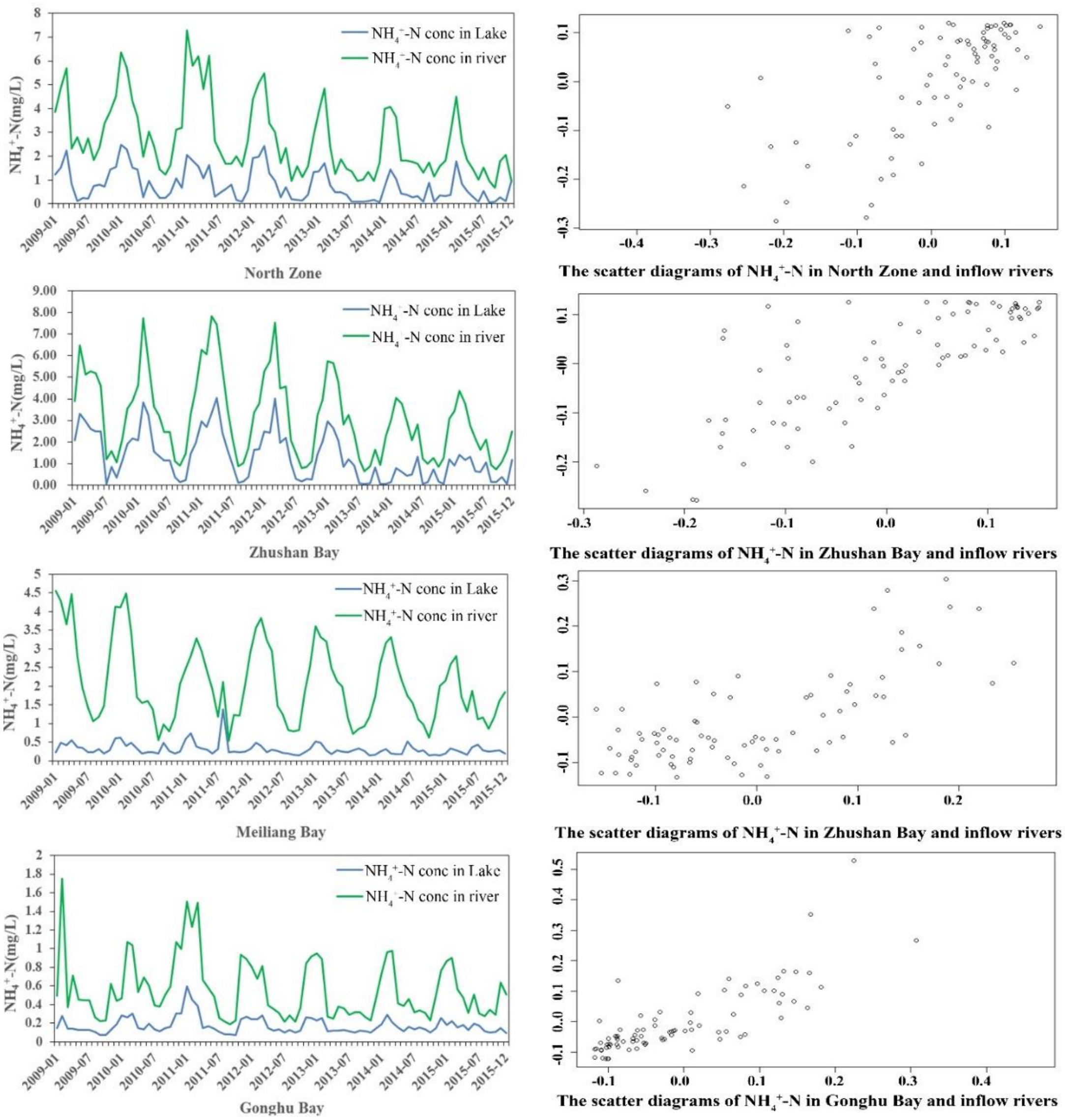

Figure 5. *Monthly mean values of NH_4^+–N concentration in northwest Lake Taihu and its inflow rivers from 2009 to 2015 and the scatter diagrams in corresponding regions*

System response to nutrient reduction

Simulated results in RF model

By using the acquired monitoring data, the RF model set up the forecast model between the water quality of monitoring sites in the lake (NH_4^+–N concentrations) and its inflow rivers (NH_4^+–N loads). Given the relatively small dataset, every one of the seventh data were extracted as the testing stage, whereas the others are randomly assigned as the training stage after sorting the monthly monitoring data during 2009-2014, thereby ensuring that the RF model was fully calibrated. Then the data of

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2015 in the inflow rivers were the independent validation set and used to test the model. The simulation results showed that the values of R^2 in the training stage of NH_4^+-N were 0.87, 0.95, 0.73 and 0.97 in the RF model for the four pairs of lake and river stations. Meanwhile, the values of R^2 in the testing stage of NH_4^+–N were 0.53, 0.52, 0.57 and 0.58 in the RF model. Moreover, the data of 2015 in the inflow rivers were used to the established model to stimulate the water quality in the lake. As shown in *Fig. 6*, the relationships between the measured NH_4^+–N concentration and those predicted by the RF are proved to have good curve fitting characteristics. Consequently, the established RF model had a relatively high precision, and the forecast model could be used in the next step of stimulating the scene of water quality in the northwest Taihu Lake.

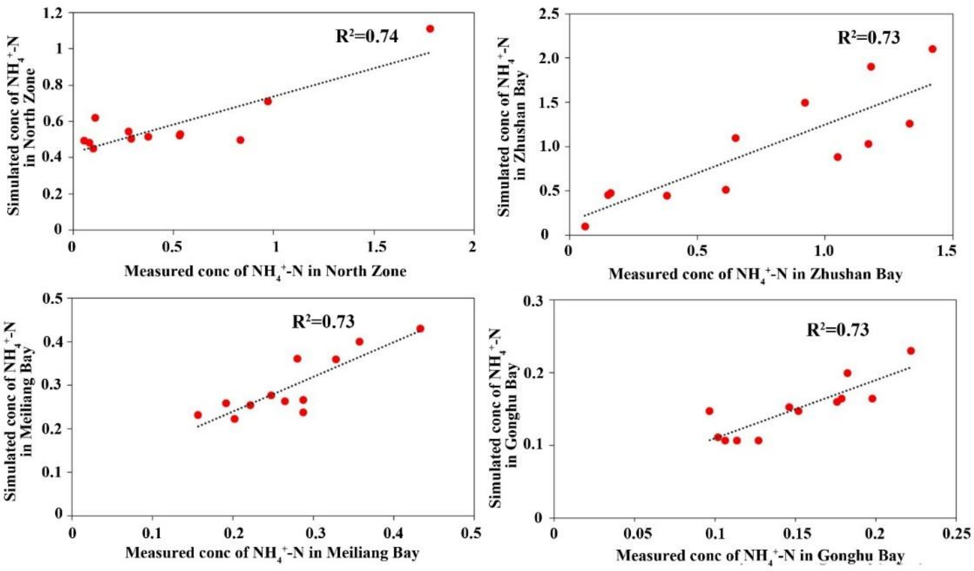

Figure 6. *Measured and simulated NH_4^+–N concentration in 2015 in the RF model (mg/L)*

The Master Plan of Integrated Regulation of Water Environment of Taihu Basin, which was ratified by the State Council in 2008 and revised in 2013, had proposed the control targets of water quality indices in the lake (TN–Class V) for agricultural irrigation purpose. In addition, the Chinese State Council ratified the Master Plan of Integrated Regulation of Water Environment and the Water Function Zoning of the Lake Taihu Basin, thereby initiating the comprehensive treatment of the water environment in the basin. On the basis of the master plan, the NH_4^+–N protective goals of the North Zone and Zhushan Bay belong to Class Ⅲ, and those of Meiliang Bay and Gonghu Bay belong to Class Ⅱ. As mentioned in Section 3.1, research has shown that NH_4^+–N concentrations in the North Zone and Zhushan Bay were classified as Class III–V, whereas those in other two lake regions were classified as Class I or II. The setting of the NH_4^+–N concentration in the lake as the target value should continuously debug the NH_4^+–N concentration in the inflow rivers and allow the target value to be predicted in the debugged RF models (*Table 4*). Consequently, for the protective targets in the Master Plan of Integrated Regulation of Water Environment and the Water Function Zoning of the Lake Taihu Basin [Scenario 1: North Zone and Zhushan Bay (Class Ⅲ), Meiliang Bay and Gonghu Bay (Class Ⅱ)], the inflow loads should be

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controlled under 6427.38, 3248.01, 2206.92 and 1107.58 $t\,a^{-1}$, respectively. The total NH_4^+–N loads in the northwest Lake Taihu should be maintained under 12989.89 $t\,a^{-1}$. To achieve better water quality goal in Scenario 2 [North Zone and Zhushan Bay (Class Ⅱ), and Meiliang and Gonghu Bays (Class I)], the inflow loads in the North Zone , Zhushan Bay, Meiliang Bay and Gonghu Bay should be maintained under 3304.64, 2466.53, 615.26 and 281.93 $t\,a^{-1}$, respectively. The total NH_4^+–N loads from the northwest Lake Taihu should be maintained under 6668.37 $t\,a^{-1}$.

Table 4. *Water quality goals in the lake and statistics of water quality values in different scenarios*

Sub-lake	Water functional zone	Scenario 1		Scenario 2	
		Goal in lake (mg/L)	Inflow loads (ta^{-1})	Goal in lake (mg/L)	Inflow loads ($ta^{-1)}$
North Zone	Conservation areas of Lake Taihu	1.0 (III)	6427.38	0.5 (II)	3304.64
Zhushan Bay	Conservation areas of Zhushan Lake	1.0 (III)	3248.01	0.5 (II)	2466.53
Meiliang Bay	Conservation areas of water scenery	0.5 (II)	2206.92	0.15 (I)	615.26
Gonghu Bay	Conservation areas of drinking water source	0.5 (II)	1107.58	0.15 (I)	281.93

Influences of loads on NH_4^+–N

The overall results indicated that the NH_4^+–N concentrations evidently decreased with the inflow loads in the lake regions. In 2015, the NH_4^+–N loads from inflow rivers were less than the standards in Scenario 1, and the NH_4^+–N concentrations in the four lake regions agreed with the simulation results in RF models in *Table 5*, that's the NH_4^+–N concentration in the North Zone and Zhushan Bay were classified as Class Ⅲ and Meiliang Bay and Gonghu Bay were classified as Class Ⅱ, which once again proved the practicability of the simulated results of the RF models. The NH_4^+–N concentrations in the four lake regions achieved the basic goals in the Master Plan of Integrated Regulation of Water Environment and the Water Function Zoning of the Lake Taihu Basin. Under 8.99% reduction of inflow loads in the North Zone, the water quality in this region could be suitable to Class Ⅱ. Similarly, the NH_4^+–N loads from the inflow rivers of the North Zone, Zhushan Bay, Meiliang Bay and Gonghu Bay should be reduced by nearly 8.99%, 11.41%, 51.38% and 62.87%, respectively, for better water quality in the lake regions (the NH_4^+–N concentrations decreased by approximately 6%, 34%, 44.44% and 6.67%, respectively). The total NH_4^+–N loads from the inflow rivers of northwest Lake Taihu should be maintained under 6668.37 $t\,a^{-1}$, which is 20.96% lower than that in 2015.

Table 5. *Mass budgets for NH_4^+–N in inflow rivers in northwest Lake Taihu and load reductions in two scenarios in contrast to the situation in 2015*

	NH_4^+–N loads from inflow rivers	NH_4^+–N concentrations in the lake regions	In comparison to Scenario 1	In comparison to Scenario 2
North Zone	3627.83	0.53 (III)	−77.17%	+8.91%
Zhushan Bay	2784.15	0.76 (III)	−16.66%	+11.41%
Meiliang Bay	1265.52	0.27(II)	−74.39%	+51.38%
Gonghu Bay	759.31	0.16(II)	−45.87%	+62.87%

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Conclusions

In the present study, monthly NH_4^+–N water quality data in inflow rivers and corresponding sub-lake were used to analyse the NH_4^+–N distributions in northwest Lake Taihu. RF models were constructed to simulate the correspondence between the NH_4^+–N concentrations in the lake and its inflow rivers in different scenarios.

In the northwest Lake Taihu, the spatiotemporal distribution patterns of nutrient concentrations are distinct, and river inputs were the major source of NH_4^+–N loadings to the northwest Lake Taihu. The North Zone and Zhushan Bay were the most seriously polluted among the lake areas, whereas Gonghu Bay was the cleanest region. In winter and spring, NH_4^+–N concentrations were significantly higher than in summer and autumn, and seasons had a significant effect on the NH_4^+–N concentrations of northwest Lake Taihu. In the RF models, the R^2 and relationships between measured NH_4^+–N concentrations and those predicted by the RF proved that the established RF models had a relatively high precision and that the forecast model could be used in the further stimulation of the scene of water quality in northwest Taihu Lake. In 2015, the NH_4^+–N loads from inflow rivers were less than the standards in Scenario 1, and the NH_4^+–N concentrations in the four lake regions agreed with the simulation results in RF models. For the protective targets [Scenario 1: North Zone and Zhushan Bay (Class Ⅲ), Meiliang Bay and Gonghu Bay (Class Ⅱ)], the inflow loads should be controlled under 6427.38, 3248.01, 2206.92 and 1107.58 $t\,a^{-1}$, respectively. To achieve better water quality goal for North Zone and Zhushan Bay (Class Ⅱ), Meiliang Bay and Gonghu Bay (Class I), the inflow loads should be maintained under 3304.64, 2466.53, 615.26 and 281.93 $t\,a^{-1}$, respectively. The nutrient reduction scenarios showed that NH_4^+–N concentrations decreased by approximately 6%, 34%, 44.44% and 6.67% in the North Zone, Zhushan Bay, Meiliang Bay and Gonghu Bay, despite the reduction of external NH_4^+–N loads by 8.99%, 11.41%, 51.38% and 62.87%, respectively.

Eutrophication and algal blooms are worldwide environmental issues in lakes and the eutrophication process and forming mechanisms of algal blooms are particularly complicated in shallow lakes due to the strong lake–land, air–water and water–sediment interactions (Qin et al., 2007). This study provides further understand on the water quality distribution pattern in Lake Taihu, quantifying the reduction of nutrient loading from inflow rivers and governing Lake Taihu or other typical eutrophic lakes. However, only the northwest Lake Taihu Basin was studied instead of the entire lake, and only monthly NH_4^+–N monitoring data during 2009–2015 were utilised as modelling variables instead of using other indices. Additional water quality indices and theoretical explorations are still needed in future works. Thus, stricter external nutrient managements and other ecological restoration tools must still be considered and investigated for the water environment recovery and protection in the Taihu basin. Under the control of exogenous nutrients, the variation characteristics and distribution of nutrient concentration in eutrophicated shallow lakes are closely related to the hydrodynamic process of shallow lakes and the action of underlying lake flow (Jing et al., 2000). At the same time, submerged plants can contain the dynamic suspension process of sediments, absorb nutrients in water and sediments, reduce the load of nutrients, and purify the water quality of lakes (Jöbgen et al., 2004; Wang et al., 2019). Therefore, it also shows that it is not enough to govern Taihu lake only by controlling external pollution, and the treatment of internal pollution of Taihu lake also needs to be strengthened.

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