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Variation analysis of long-term TN concentration and influencing factors in Miyun reservoir in China

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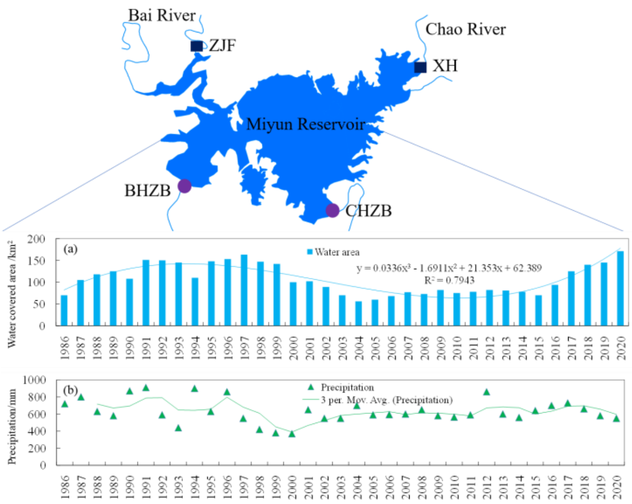
Graphical abstract



Abstract

The total nitrogen (TN) is the key indicator for the eutrophication of Miyun Reservoir. Base on the long-term series of remote sensing, hydrological and water quality observation data, this paper comprehensively analyzed the trend of water quality especially the TN concentration and its influencing factors over 30 years in Miyun reservoir. The development trends of the TN concentration during the 14th Five Year Plan Period were predicate with the designed water quality scenarios simulations. The results showed that the water covered area of Miyun reservoir was reduced from 1986 to 2004 and enlarged from 2004 to 2020, and the smallest water covered area was about 56.4km2 in 2004 while the largest was about 170.7km2 in 2020. For the regional rainfall and artificial water storage, the inflow of Miyun reservoir is much greater than the water intake, and this is the main reason for the water covered area increased. From 1988 to 2020, TN contents in the inflow water of Chaohe river and Baihe river were generally in upward trends, with annual upward rates of 0.16 mg/L and 0.05 mg/L at the 99% confidence levels separately. However, the TN concentrations from Chaohe river and Baihe river presented downward trends for the recent 5 years. And this is own to the emission control and river ecological control measures in the upstream basin of Miyun reservoir. From 1988 to 2020, the annual averaged TN concentration of the main dams in Chaohe and Baihe (BHZB and CHZB) was 1.10±0.32 mg/L and 1.17±0.31 mg/L respectively and in recent 5 years, and significant positive trends were also identified at both two stations with the steadily rising the water level and volume in Miyun reservoir. The lightly increase of TN concentration in recent years in Miyun reservoir was the comprehensive results of external input and self purification capacity. Based on the MIKE21 model of four scenario simulations, the TN concentration of Miyun reservoir will meet the class II water quality level (China's Environmental Quality Standards for Surface Waters, GB3838-2002) under the comprehensive implementation of rural domestic source control and agricultural non-point emission control measures in the upstream basin of Miyun reservoir during the 14th Five Year Plan period.

Keywords: Miyun reservoir, water covered area, total nitrogen concentration, MIKE21, Mann–Kendall

1. Introduction

Nitrogen is one of the potential factors of eutrophication (Xia *et al.,* 2020). When nitrogen, phosphorus and other nutrient elements are enriched in closed or semi closed water bodies such as reservoirs, lakes and bays, it will cause the proliferation of algae and other aquatic plants, decrease dissolved oxygen and deteriorate water quality (Huang *et al.,* 2021). Since the 21st century, due to human disturbance and climate change, the concentration of Nitrogen in surface water has increased all over the world (World Resources Institute, 2011), which has brought problems water quality deterioration such as eutrophication and drinking water safety special for the reservoirs constructed for drinking water supply and irrigation water provision (Wang *et al.,* 2017). Natural factors and human disturbance have aggravated stream runoff variations and water quality deterioration (Shrestha *et al.,* 2012). For the concentration of total Nitrogen (TN), the increase of water flow can not only dilute pollutants, but also carry more loads into the water (Qin *et al.,* 2018). Agricultural activities will increase the release of nitrogen, but if certain ecological measures are taken, the release of TN can be reduced to a certain extent (Li *et al.,* 2013). In addition, coexistence relationships between water quantity and water quality were also should be fully considered and the nitrogen concentration in water was often accompanied by the changes of other water pollutants (Cai *et al.,* 2011; Wang *et al.,* 2015).

Beijing, the capital of China, is one of the largest cities in the world and a city with scarce water resources (Wang *et al.,* 2008). The industrial, agricultural and municipal water mainly comes from Miyun reservoir and the South-to-North Water Transfer Project. The ecological protection of Miyun reservoir plays an irreplaceable role in ensuring the water source safety of the capital and the ecological and urban sustainable development of Beijing (Li *et al.,* 2013). In recent years, Miyun reservoir is facing the problem of non-attainment TN concentration, especially the relatively higher concentration of TN in the inflow river, which aggravates the risk of eutrophication in the reservoir area (Xu *et al.,* 2020). In 2020, except for TN, the basic projects of Miyun reservoir meet the requirements of class II standard in the environmental quality standard for surface water (GB 3838-2002), while the annual averaged TN concentration was in class IV standard (Miyun Ecological Environment Bureau, 2021). From time perspective, there were lots of single year research about TN concentration in Miyun, but these studies were scattered and lack of long-time scale analysis (Qin *et al.,* 2018; Zhang *et al.,* 2020). The limited research about TN concentration in recent 30 years was focused on the inflow water of Chaohe river and Baihe river of Miyun reservoir (Wang *et al.,* 2020).

Although Miyun reservoir has carried out a series of water bloom prevention and control work in recent years, and the shortage of water resources has been alleviated after the South-to-North Water Transfer Project since 2014, the water shortage has not been fundamentally improved, and the contradiction between human and water demand is still prominent in Beijing (Wang *et al.* 2014, 2020). Therefore, the comprehensive evaluation and analysis of the water quality in Miyun reservoir is of great significance for controlling water eutrophication and providing scientific water environment management in the upstream basin of Beijing and Hebei regions. Based on long-term series of remote sensing and water quality data, this study creatively constructed the coupling model of hydrodynamic and water quality and multiple time series statistical algorithms of Miyun reservoir, to comprehensively analyze the Long-term TN concentration and influencing factors in Miyun Reservoir in Beijing, China.

2. Materials and methods

2.1. Study area

The Miyun Reservoir is located in northeast of Beijing, Miyun County, 65 km away from downtown Beijing. The Miyun reservoir was built in September 1958 and completed in September 1960, with a maximum storage capacity of 4.375×108 m^3, a total reservoir area of 224 km^2 and a maximum water covered area of 188 km^2 (Wang *et al.,* 2020). After completion of the largest water conservancy project in North China, the main functions of Miyun Reservoir are flood control, irrigation water provision, and drinking water supply in Beijing (Gebel *et al.*, 2014; Wang *et al.*, 2015).

The upstream basin of Miyun reservoir includes Beijing and Hebei (shown in Figure 1), which is divided into Chaohe River Basin and Baihe River Basin. The total area of the upstream basin of Miyun reservoir is about 15840 km^2, including 4500 km^2 in Beijing, 11340 km^2 in Hebei Province and 1276.5 km^2 in Miyun district. The Chaohe and Baihe Rivers are the main rivers flowing into the Miyun Reservoir, and the area of Chaohe and Baihe rivers watershed is 6716 km^2 and 9072 km^2 separately (Beijing Miyun statical yearbook, 2020).

The Miyun reservoir is located in a warm temperate continental monsoon semi-arid and semi humid climate, with an average annual precipitation of 480 mm. The precipitation of Miyun reservoir is mainly from June to August (Wang *et al.*, 2008). The Chaohe and Baihe Rivers are the twin rivers situated in the Miyun Reservoir Basin. The average volume of flow in Chaohe and Baihe rivers is 268 and 438 million cubic meters annually (Zhang *et al.*, 2014). In recent decades, the runoff of the upstream basin of Miyun reservoir has gradually decreased (Wang *et al.*, 2015). From 1960 to 2014, the runoff of Baihe river and Chaohe river was decreasing by 3.24$m^3 \cdot S^{-1}$ (10a) $^{-1}$ and 1.60 $m^3 \cdot S^{-1}$ (10a) $^{-1}$ respectively (Qin *et al.*, 2018).

The total population of Miyun Reservoir Basin is 900 thousand and the agricultural population accounts for 91.7% (Li *et al.*, 2013; Zhang *et al.*, 2020). The industry in the study area is mainly agriculture and the industrial foundation is relatively weak. There are few industrial point sources in Miyun Reservoir Basin and the Miyun reservoir is mainly affected by domestic sewage, agricultural non-point sources and other factors (Zhang *et al.*, 2020). The main types of vegetation in Miyun Reservoir Basin are forest land, grassland and cultivated land and the broad-leaved forest fields and natural grassland account for 39.37%, 17.65%, 14.23% respectively (Yang et al, 2009; Zhang *et al.*, 2020). The per capita area of agricultural cultivated land in Miyun Reservoir Basin ranges from 0.05 to 0.1 hectares and the treatment rate of rural domestic sewage in the basin in 2020 is 46.9%-28.9% respectively (Ministry of ecological environment, 2021).

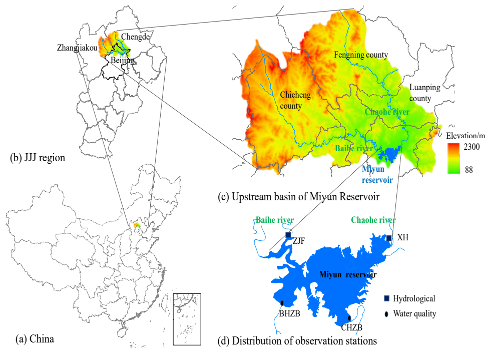


Figure 1. Location of the study area of the Miyun Reservoir Basin and observation stations

The hydrological data such as water flow (WF), water covered area (WA), water level (WL), and water volume (WV) were obtained from the "Hydrological Year Book" provided by the Miyun Reservoir Administration Office and Beijing Municipal Water Affairs Bureau (http://nsbd.swj.beijing.gov.cn/dzxsksq.html). The meteorological data such as precipitation (Precip) and air temperature (T) was downloaded from the meteorological data sharing network (http://www.cma.gov.cn/2011qxfw/2011qsjgx/). The land use data is from the data center of resources and Environmental Sciences, Chinese Academy of Sciences (https://www.resdc.cn/). The TN concentration and other water quality observation data were from Miyun Reservoir Management Office and Qingyue Open Environment Data Center (https://data.epmap.org/page/index). The water quality index was monitored once a month. The total nitrogen and nitrate nitrogen were determined by QuikChem injection analyzer of Lachat company in the United States and the detection ranges of TN and nitrate nitrogen were 0.2-10 mg/L and 0.1-20 mg/L respectively. The sampling and analysis were based on the "Environmental Quality Standards for Surface Water" of China (GB 3838—2002) (State Environmental Protection Administration, 2002).

2.2. Water remote sensing

The annual water covered area data from 1986 to 2020 of Miyun reservoir was derived from the Landsat satellite data download form the website of the United States Geological Survey (USGS). Remote sensing image data was received by MSS (multispectral scanner), TM (thematic mapper) and OLI (operational land imager) with the spatial resolution 30 m (Wang *et al.*, 2008).

The normalized difference water index (ENDWI) was calculated to extract the water covered area of Miyun reservoir. This method considers the different transmissivity and absorption of water in different bands, and applies the band ratio of numerical difference and numerical sum as the identification basis of water body (Mcfeeters, 1996). The NDWI uses reflected near-infrared radiation and visible green light to enhance the presence of water feature while eliminating soil and terrestrial vegetation features (Gautam *et al.*, 2015). The ENDWI of water body is mainly distributed between -0.42 and -0.16. In EQ1, Green represents the green band, corresponding to the second band of TM image data and the third band of OLI image data; NIR is the near infrared band, corresponding to the 4th band of TM image data and the 5th band of OLI image data; MIR represents the mid infrared band, corresponding to the 5th band of TM image data and the 6th band of OLI image data. The ArcGIS 9.3 was applied for mapping and remote sensing image processing.

The equation of the Normalized Difference Vegetation Index is:

$$ENDWI = \frac{Green - MIR}{Green + NIR} \quad (1)$$

2.3. MK method for temporal diagnostics

The Mann Kendall (MK) test is applied to analyze the trend and detect the tipping point in a long-term series data and is carried out by the software of SPSS 13 (SPSS Inc.) in this study. The MK test is a nonparametric method and is less affected by outliers and missing values (Mann, 1945; Kendall, 1975). It assumes no particular underlying distribution and is widely applied on hydro-meteorological data analysis (Silva *et al.*, 2015).

The MK trend statistic Z is defined as follows:

$$\begin{cases} Z = (S-1)/\sqrt{n(n-1)(2n+5)/18}(S>0) \\ Z = 0(S=0) \\ Z = (S+1)/\sqrt{n(n-1)(2n+5)/18}(S<0) \end{cases} \quad (2)$$

In the equation, S is the standard normal statistical variable of a series *x*, and *n* is the number of independent random variables or the length of the data set. When Z>0, it represents an upward trend; when Z<0, it indicates a downward trend. |Z|>1.28, |Z|>1.64, and |Z|>2.32 show that significant trends are identified at the significance confidence level of α=90%, α=95%, and α=99%, respectively.

In addition to mutation detection or the aberrance in a time-series, the time sequence is constructed as $x_1, x_2, ..., x_n$, and the order sequence r_i is constructed; then calculate the cumulative number of $x_i > x_j$ (1≤j≤i).

$$S_k = \sum_{i=1}^{k} r_i (k = 1, 2, \ldots, k) \quad (3)$$

Assuming that a set of time series consists of random independent variables, the statistics UF_k is defined as follows:

$$UF_k = \frac{S_k - E(S_k)}{\sqrt{Var(S_k)}} \quad (4)$$

In the equation, UF_k is a standard normal distribution; $E(S_k)$ and $Var(S_k)$ are the mean and variance of the data set. The new test statistic UB_k is given by rearranged the series in an opposite order. When $UF_k = UB_k$, the aberrance point was identified near the intersection period under the confidence level α.

2.4. GFM for water quality statistical prediction

Gray forecast model (GFM), proposed by Deng can effectively deal with the data with small sample size and irregular variations (Liu and Deng, 2000). Grey system contains some known information, while some information is unknown (Ju-Long, 1982). The GFM model applies the accumulation operator to process the random data and then generate a series of continuous and regular data sequences. By establishing the differential equation of time target sequence, the GFM prediction is realized.

The accumulation method used in the traditional grey model is the first-order differential equation (GM (1,1)) and the accuracy of GM (1,1) is much improved through the continuous study of the grey model (Wang and Lu, 2020). Assume that the original observation sequence is $X^{(0)}$:

$$X^{(0)} = \left\{x^{(0)}(1), x^{(0)}(2), \cdots, x^{(0)}(n)\right\} \quad (5)$$

After the original observation sequence accumulated, a new sequence ($X^{(1)}$) with continuous upward trend is obtained.

$$X^{(1)}=\left\{x^{(1)}(1),x^{(1)}(2),\cdots,x^{(1)}(n)\right\} \quad (6)$$

$$X^{(1)}(k)=\sum_{i=1}^{k}X^{(0)}(i) \quad (7)$$

$$(k=1,2,\cdots,n)$$

By establishing a first-order linear differential method, the EQ6 and EQ7 are further analyzed.

$$\frac{dX^{(1)}}{dt}+aZ^{(1)}=b \quad (8)$$

$$\hat{x}^{(1)}(\mathrm{t}+1)=\left[x^{(0)}(1)-\frac{b}{a}\right]\mathrm{e}^{-at}+\frac{b}{a}(t=0,1,\cdots,n-1) \quad (9)$$

$$\hat{x}^{(0)}(t+1)=\hat{x}^{(1)}(t+1)-\hat{x}^{(1)}(t) \quad (10)$$

In the formula, a or b is the parameter to be estimated by the least square method;t is the time; $\hat{x}^{(1)}(t+1)$ $\hat{x}^{(0)}(t+1)$ is the predictions calculated by the $\hat{x}^{(1)}(t+1)$ in EQ.10

2.5. MIKE21 for water quality numerical simulation

In this study, the two-dimensional flow model Mike21 was applied to simulate the changes of hydrodynamics and water quality of Miyun reservoir. MIKE 21 is the most functional simulation tool for two-dimensional water physical, chemical or biological processes and is widely applied for hydrodynamic and water quality simulation of lakes, reservoirs, estuaries, coasts and oceans (DHI, 1964). The equations solved in MIKE21 are:

$$\frac{\partial \mathrm{h}}{\partial t}+\frac{\partial(Hu)}{\partial x}+\frac{\partial(Hv)}{\partial y}=0 \quad (11)$$

$$\frac{\partial \mathrm{u}}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial h}{\partial x}-fv+g\frac{u\sqrt{u^2+v^2}}{C^2H}=0 \quad (12)$$

$$\mathrm{UF_k}=\frac{\mathrm{S_k}-\mathrm{E(S_k)}}{\sqrt{\mathrm{Var(S_k)}}} \quad (13)$$

$$\mathrm{UF_k}=\frac{\mathrm{S_k}-\mathrm{E(S_k)}}{\sqrt{\mathrm{Var(S_k)}}} \quad (14)$$

where h represents the water level; H represents the water depth; u and v represent the flow velocity component in the x and y directions, respectively; f represents the Coriolis force coefficient; C represents the Chezy coefficient; T represents time; G represents the acceleration of gravity; P represents the pollutant concentration; K_x and K_y represent the dispersion coefficient in the x and y directions, respectively; and M represents the source item.

The calculation boundary of Miyun reservoir was converted to CGCS2000 3 Degree GKZone 39 according to longitude and latitude. The unstructured triangular grid is used to mesh Miyun reservoir, and the side length of the grid is controlled to be 100m, with a total of 26934 calculation grids. The operation type of dry and wet boundary was advanced dry and wet boundary. The buried depth of dry boundary was set to 0.005m; the buried depth of fluctuation boundary was set to 0.05 m; the buried depth of wet boundary was set to 0.1 m; the eddy viscosity coefficient was set to a fixed value of 0.28; and the bottom roughness was set to 32. The study took the water level of 148.95 m on January 1st, 2019 as the initial water level. The dispersion coefficient of water quality was 5 m/s, and the degradation coefficient was a time-varying sequence dfs0 file.

The source and sink items of the hydrodynamic model of Miyun reservoir included Chaohe river, Baihe river, the inflow of rainfall, the drainage of Chaohe and Baihe river main dam, water intake and evaporation outflow of the ninth water plant. The source sink term of the water quality model was based on the hydrodynamic source sink term, without considering the impact of evaporation on TN concentration. The 2019 year was the calibration period and the 2020 year was the verification and prediction period. The initial and boundary concentrations of water quality in Miyun reservoir wee set as the sampling concentrations in January 2019.

3. Results and discussion

3.1. Long-term variation of water covered area

As shown in Figure 2, the water covered area of Miyun reservoir was the smallest, about 56.4km^2 in 2004 and it changed to be the largest, about 170.7 km^2 in 2020 during 1986~2020 from the dynamic satellite remote sensing maps. The water covered area was less than 70 square kilometers in 1986 and increased to be the largest in 1997, up to 161.1 km^2. From 1998 to 2004, the water covered area began to shrink, and by 2004, the water covered area was the smallest, only 56.4 km^2. From 2005 to 2020, the water covered area of Miyun Reservoir increased gradually especially during 2015~2020. Since 2015, Miyun reservoir also undertook the task of regulating and storing the water from the South-to-North Water Transfer Project. In 2020, the water covered area of Miyun reservoir was the largest, 170.7 km^2; it was 65.2 km^2 higher than the average value from 1986 to 2019, with an increase of 22.0 km^2 compared with 2019.

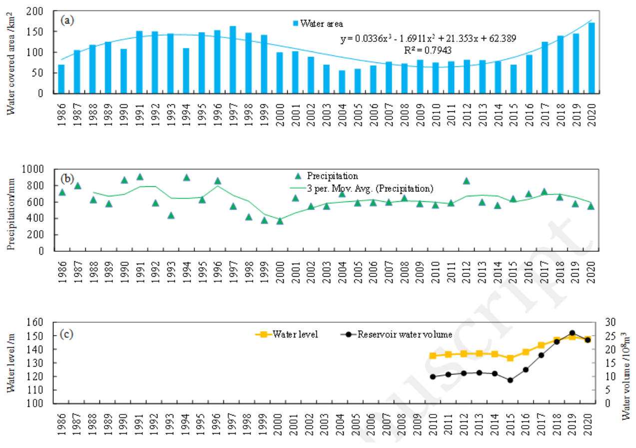


Figure 2. Long-term variation of annual averaged water covered area (a), precipitation (b), water level, and water volume (c) in Miyun reservoir

Natural precipitation and human use have significant impacts on the water area and volume of Miyun Reservoir. Since 2010, the water area of Miyun Reservoir remotely sensed by satellite and the measured reservoir water volume was significantly correlated, with the Pearson's correlation coefficient R 0.961 (P=0.000, α=0.01). Additionally, the Pearson's correlation coefficient R between water covered area and water level was 0.965 (P=0.000, α=0.01). To some extent, it proved from the side that the results of surface water covered area data based on satellite remote sensing were reliable and acceptable.

The water covered area of Miyun reservoir is closely related to precipitation and man-made water intake. On one hand, the precipitation has increased in recent years and the precipitation from May to September contributes greatest to the reservoir water storage. On the other hand, with the South-to-North Water Transfer Project, the water intake of Miyun reservoir has also prominently decreased. The inflow greater than the water intake due to regional rainfall and artificial water storage was the main reason for the increase of water covered area.

This study explored an appropriate way of monitoring water covered area by satellite remote sensing techniques in the Miyun reservoir over 30 years. The traditional water covered area monitoring method depends on in situ measurements and these point sampling methods are costly and time consuming while the satellite remote sensing method can effectively monitor spatial and temporal variations of water covered area and is more capable of supplying rapid and seasonal information (Wang *et al.*, 2008). With the improvement of spatial and spectral resolution in sensors, satellite remote sensing information is widely applied to monitor and evaluate water coverage areas.

3.2. Long-term variation of water quality

The long-term variation of inlet and outlet TN concentrations at different stations in Miyun reservoir were given in Figure 3 and Table 1. From 1988 to 2020, the TN contents in the inflow water of Chaohe river (CHRK) and Baihe river (BHRK) were 4.77±1.72 mg/L and 2.04±0.70 mg/L respectively; while the annual averaged TN concentrations of Chaohe main dam (CHZB) and Baihe main dam (BHZB) were 1.10±0.32 mg/L and 1.17±0.31 mg/L respectively. From 1988 to 2020, the TN contents at CHRK and BHRK were generally in upward trends, with annual upward rates of 0.16 mg/L and 0.05 mg/L, and both rising rates passed the MK significance test (α=0.01); moreover, the rising rate at BHRK was relatively gentle, while it was relatively fierce at CHRK. The variations of TN concentration at CHZB from 1988 to 2020 did not pass the MK significance test, while it increased slightly from 1988 to 2020, with an annual increase rate of 0.01mg/L (α=0.05) at BHZB.

The TN concentration at CHRK was higher than that of BHRK, while the TN concentration of CHZB was slightly lower than that of BHZB. The Pearson's correlation coefficient of TN concentration between CHZB and CHRK, BHRK were 0.141 (P = 0.434) and 0.062 (P = 0.732) respectively while the Pearson's correlation coefficient of TN concentration between BHZB and CHRK, BHRK were 0.326 (P=0.064) and 0.390 (P=0.025, α=0.05) respectively. Compared with CHZB, the TN concentration at BHZB was more significantly affected by Baihe inflow concentration (BHRK). Most notably, the TN concentration at CHRK decreased from 8.0 mg/L in 2016 to 6.6 mg/L in 2020, and the TN concentration at BHRK decreased from 4.4 mg/L in 2016 to 2.5 mg/L in 2020. Overall, under the comprehensive implementation of emission control and river ecological control measures in the upstream basin, the inlet water concentration of TN showed a downward trend in recent 5 years.

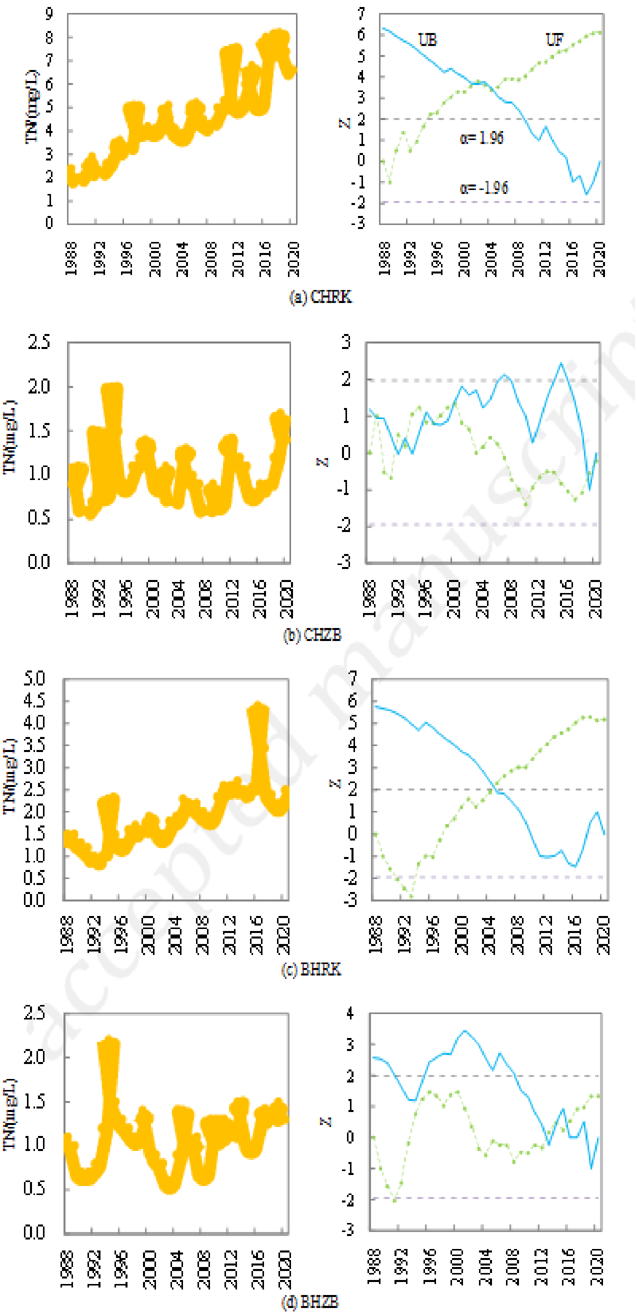


Figure3. Long-term variation of TN concentration and the Mann Kendall mutation analysis at different stations in Miyun reservoir

For the mutation point of TN concentration, the TN concentration at CHZB fluctuated greatly before 2000, and there were multiple mutation points in the confidence interval. In general, from 2000 to 2020, significant positive trend of TN concentration at CHZB was identified, with an annual upward rate of 0.02 mg/L (α=0.1). From 2000 to 2020, the trend of TN concentration at BHZB was not obvious. The abrupt change of TN concentration at BHZB mainly occurred around 2015 from the Mann Kendall test. From 2015 to 2020, the annual increase rate of TN concentration at BHZB was 0.04 mg/L (α=0.1). Thus, in recent 5 years, the TN concentration fluctuated and increased lightly in Miyun reservoir at both BHZB and CHZB stations with the steadily rising the water level and volume. At present, the TN concentration at CHZB or BHZB have been above 1.50 mg/L (class Ⅳ according to the GB3838—2002) in some monitoring periods and the water environment quality was in moderately eutrophication.

This study further comprehensively analyzed the relationships between TN concentration and water covered area, water level, water storage and precipitation in Miyun reservoir. As shown in Table 2, the TN concentration increased with the decrease of water inflow. The decrease of flow rate reduces the dilution of water pollutants and enhances the leaching and evaporation. The TN concentration of Miyun reservoir mainly comes from Chaohe river basin compared with Baihe river basin. Zhang *et al.* (2019) pointed that the Chaohe river basin has large population density and high degree of agricultural intensification; thus, the scouring of rainfall runoff makes a large amount of chemical fertilizer and livestock manure flow into the river and finally into the Miyun reservoir. The main pollutants of Chaohe river were TN and TP, which were mainly affected by agricultural non-point sources and primary industry activities while the main pollutants of Baihe river are TP and organic matter, which were mainly affected by the domestic sources and primary industry (Yang *et al.*, 2009).

In recent 20 years, the population and economic activities in Chaohe and Baihe river basins have increased significantly, and the water consumption and water pollution discharge have increased (Xu *et al.*, 2020). The increase of agricultural, livestock and poultry breeding pollutants were the main reason for the increase of TN in inflow rivers (Li *et al*., 2013). Due to the great increase in the area of paddy fields and irrigated land, agricultural water consumption accounts for more than 90% of the total water consumption (Zhang *et al.*, 2019). In addition, the construction of multiple reservoirs in the upstream of Miyun reservoir has led to a significant reduction in runoff (Li *et al.*, 2013). Various regional human activities and water conservancy and soil conservation measures led to a significant reduction in runoff (Bao *et al.*, 2012). Li *et al.* (2013) pointed out that in the past 20 years, regional human activities have gradually increased, and water conservancy and soil conservation measures have not changed the increasing trend of TN and the decrease of runoff has enlarged this effect. Although the implementation of "Capital Water Resources Sustainable Utilization Planning in the Beginning of 21st Century" increased the areas of water and soil conservation in Miyun watershed in recent years (Li *et al.*, 2008), the inflow water concentration in the river was always higher than that in the in Miyun reservoir.

In our study, the Pearson's correlation analysis also indicated that the TN concentration in Miyun reservoir was in certain positive correlation with water volume, water covered area and water level. These hydrological observation variables were essentially affected by the precipitation and runoff from the upstream. The impact of inflow TN concentration in the reservoir was much higher than the self purification effect, which will result in a slight increase in the concentration in the Miyun reservoir. Xu *et al.* (2020) found that both N losses and N accumulation had similar decreasing trends while the N input was higher and decreased more quickly than the N output during 2001-2017 to the cropping system in Miyun County. The rising water level resulting in inundating the forest land and grassland, nitrogen will be released and lead to the increase of TN concentration in water body in Miyun reservoir (Zhang *et al.*, 2019). Groundwater recharge and atmospheric nitrogen deposition will also affect the nitrogen balance of Miyun reservoir (Li *et al.*, 2013). Through the above analysis, the TN concentration of Miyun reservoir was greatly affected by the upstream water quality; livestock and poultry breeding and agricultural planting were the main pollution sources while the contribution of domestic and industrial pollution was much lower. Due to the higher incoming water concentration than the reservoir area, incomplete self-purification and consumption of the reservoir, the TN concentration in Miyun reservoir presented a continuous upward trend in recent years. Compared with other estuarine and lake (reservoir) tributary areas, limited long-term studies were conducted to Miyun Reservoir due to difficult data sampling in water source protection area. Nevertheless, most of the data applied in our study was from the statistical yearbook of Miyun County Government, and increasing published articles and scientific research project cooperation. These multi-source data are helpful to analyze the changes and causes of TN concentration in Miyun Reservoir in recent years. It is worth noting that the data from these sources may be of rough quality. Moreover, due to the lack of water quality and hydrological observation data at different temporal and spatial scales, the influencing mechanism of TN concentrations were not analyzed deeply. However, taking the Miyun Reservoir, the important water source in Beijing, China as the research area, this study developed an integrated nonparametric water quality diagnosis approach to analyze the spatio–temporal variations of TN concentrations and provided technical means for the follow-up pollution control and sustainable improvement of ecological environment in Miyun reservoir.

3.3. Water quality simulation and prediction

The water quality in the western section of Miyun reservoir (BHZB) was slightly higher in the eastern section (CHZB) during the monitoring period. Thus, our study further simulated and predicted the variations of TN concentration under different scenarios at BHZB station.

The TN concentration of Miyun reservoir mainly comes from Chaohe and Baihe rivers, which is mainly affected by agricultural sources, livestock and poultry breeding and living non-point sources and the combination of different vegetation under the influence of rainfall runoff can reduce the TN to a certain extent (Ongley *et al.*, 2020; Chen *et al.*, 2019).

Table1. Mann Kendall test for long-term variation of TN concentration at different stations in Miyun reservoir

Station	Period	n	Mean	SD	K	Z	Trend	α
CHRK	1988-2020	33	4.77	1.72	0.16	6.20	Upward trend detected(inlet)	0.01
CHZB	1988-2020	33	1.10	0.32	0.00	0.46	No significant trend(outlet)	-
	2001-2020	20	1.07	0.28	0.02	1.37	Upward trend detected(outlet)	0.10
BHRK	1988-2020	33	2.04	0.70	0.05	5.45	Upward trend detected(inlet)	0.01
BHZB	1988-2020	33	1.17	0.31	0.01	1.94	Upward trend detected(outlet)	0.05
	2015-2020	6	1.31	0.17	0.04	1.32	Upward trend detected(outlet)	0.10

Table2. Relationship between TN concentrations and water area, water level, water storage, precipitation and T in Miyun reservoir

Station	Period	Pearson	WL	WV	WA	Precip	WQ	T
CHZB	2010-2020	R	0.596	0.602	0.506	-0.125	-0.317	0.094
		P	0.053	0.050	0.112	0.715	0.342	0.783
		α	-	-	-	-	-	-
BHZB	2010-2020	R	0.504	0.475	0.398	-0.270	-0.030	0.363
		P	0.114	0.140	0.226	0.421	0.931	0.272
		α	-	-	-	-	-	-

In order to further simulate and reduce the TN concentration in the reservoir area, in our study, for the MIKE21 model, the basic scenario was to set the TN input concentration of Chaohe and Baihe rivers in Miyun reservoir as the annual averaged values in 2020 respectively. The first scenario was the living reduction scenario, considering the management of rural sewage pollution reduction in the basin. As the previous analysis, the treatment rate of rural domestic sewage in the basin in 2020 is 46.9%-28.9% respectively (Ministry of ecological environment, 2021). In the first scenario, for the rural areas in the basin, especially in Hebei province, centralized sewage treatment facilities will be established, and the sewage treatment plants that have been established should be improved and upgraded. The second scenario was agricultural emission reduction scenario. In this scenario, the livestock and poultry breeding within 1000m on both sides of the basin will be relocated and planting within 50m from both banks of the Chaohe and Baihe rivers should be prohibited on the basis of the policy of returning farmland to forests. The third scenario was to take emission reduction measures simultaneously based on the second and the third scenarios. Considering the factors such as population, land use and sewage treatment, the TN load of Miyun reservoir was about 634-3706 t/a in 2020 and the inflow boundary concentration of TN was reduced by about 0%, 10%, 15%, 25% respectively in 2021 in the four scenarios in MIKE21.

In order to evaluate the model performance, our study further analyzed the MIKE21 model calibration and validation, as shown in Figure 4. During model calibration in 2020, the absolute errors of simulated and measured water levels at ZJF and XH stations were within 0.01-0.62m, and the relative error range was 0.03-0.48%; the correlation coefficients of the measured and calibrated water flow at two stations were 0.989 and 0.991 respectively. The correlation coefficients between the measured and verified values of TN, DO concentrations and WT at BHZB from January to December 2020 were 0.82, 0.90 and 0.99 respectively and the root mean square errors were 0.163 mg/L 1.115 mg/L and 0.972℃ respectively. As a whole, the established local parameterized of the two-dimensional coupling model of hydrodynamic and water quality model were generally acceptable.

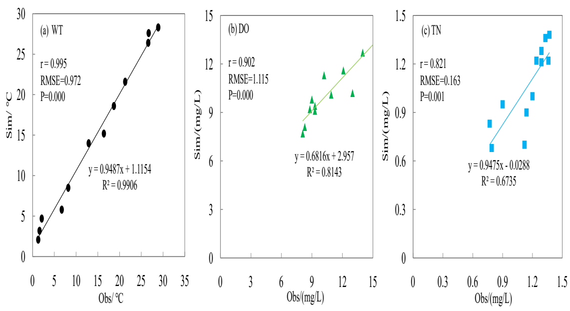


Figure4. Comparison and verification of simulated and measured values of water temperature, dissolved oxygen and total nitrogen in Miyun reservoir at BHZB station based on MIKE21 model

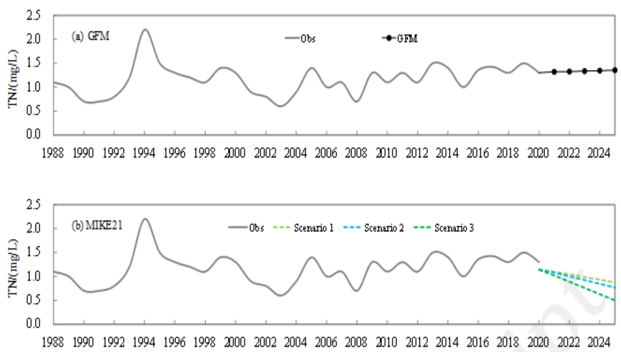


Figure5. The predicted total nitrogen in Miyun reservoir at BHZB station based on MIKE21 and GFM model

For the GFM, the absolute value of relative error was 0.5% ~ 18.7%, and the precision grade of the model was grade 2, which is more suitable for predicting the inter-annual variation of TN concentration in Miyun reservoir. The TN concentration predicted by GFM increased from 1.32 mg/L in 2021 to 1.36 mg/L in 2025 with the averaged concentration of 1.34 mg/L during the 14th Five Year Plan period (Figure 5). From four scenario simulations based on the MIKE21 model, as shown in Table 3, the TN concentration predicted during the 14th Five Year Plan period was 0.96,0.88,0.69 mg/L. As a result, it will need 10 years, 7 years and 5 years to reach the class II water quality target for TN concentration in the first, second and third scenario respectively; that is, during the 14th Five Year Plan period, the TN concentration of Miyun reservoir will better than or meet the class II water quality standard (0.5mg/L, GB3838—2002) under the scenario of comprehensive implementation of rural domestic source control and agricultural non-point emission control measures in the upstream basin. In addition, it will need 14 years, 10 years and 6 years to reach the class II water quality target for TN concentration in the first, second and third scenario respectively superimposed on the statistical model GFM. Therefore, the obvious improvement of TN concentration in Miyun reservoir cannot be changed in a short time. The degradation mechanism of TN is a complex process, which is affected by comprehensive factors such as physics, chemistry, biology and meteorology. In this study, the treatment measures focused on the research of living sources, agricultural sources and river ecological construction. In the future, it is necessary to comprehensively consider the impact of meteorological factors and the water transfer of South-to-North Water Transfer Project. Therefore, there were some uncertainties in the model simulation, but the two-dimensional water quality simulation by MIKE21 can make better prediction and provide some supports for water pollution prevention and control in improving water quality for Miyun reservoir. The application of the MIKE21 model in Miyun reservoir can also provide reliable means and experience for the treatment of other eutrophic lakes in China.

Table 3. The statistics of the predicted total nitrogen under different scenario hypothesis predictions in Miyun reservoir based on MIKE21 model

Scenarios	Predictions (mg/L)	Annual reduction rate/(mg/L)	Time required for class II objectives (year)	Time required for class II objectives (year) overlying GFM
Basic Scenario	1.14	-	-	-
Scenario 1	1.10	0.056	10 (2030)	14 (2034)
Scenario 2	1.08	0.078	7(2027)	10(2030)
Scenario 3	1.02	0.130	5(2025)	6(2026)

4. Conclusions

In recent 30 years, the water quality in the upper reaches of Miyun reservoir is unstable and the traceability of TN is a difficult and hot topic in current research. According to the previous studies, the rainwater runoff, livestock and poultry breeding and agricultural planting in the upstream basin were the main sources and greatly influenced the TN concentration in Miyun reservoir. Meanwhile, the sewage infrastructure of Miyun reservoir is not perfect and accurate. The existing towns and villages are mainly concentrated in the upstream of Miyun reservoir and the existing sewage station has been difficult to meet the actual treatment needs. Therefore, the higher inflow concentration leads to the obvious increase of TN concentration in Miyun Reservoir in recent years.

During the 14th Five Year Plan period, if strong water source protection and water ecological supervision measures are not taken, the problem of nonattainment TN concentration in Miyun reservoir is becoming serous and the improvement of total nitrogen in Miyun reservoir could not be changed in a short time especially during the 14th Five Year Plan period.

This study creatively constructed the coupling model of hydrodynamic and water quality of Miyun reservoir, comprehensively analyzed the variation of water quality and purposefully carried out water quality scenario prediction of Miyun reservoir in Beijing. This research provided a scientific basis for decision making for ecological protection of the Miyun reservoir. Results indicated that from 1986 to 2020, the water covered area of Miyun reservoir was the smallest, about 56.4km^2 in 2004 and changed to be the largest, about 170.7km^2 in 2020 from the dynamic satellite remote sensing maps. The inflow greater than the water intake was the main reason leading to the increase of water area. From 1988 to 2020, the TN content in the inflow water of Chaohe river and Baihe river generally showed an upward trend, with an annual upward rate of 0.16 mg/L and 0.05 mg/L at the 99% confidence level while the inflow TN concentration had shown a certain downward trend in recent 5 years. The emission control and river ecological control measures in the upstream basin played a certain effect in recent 5 years. In recent 5 years, significant positive trends were also identified at both BHZB and CHZB stations with the steadily rising the water level and volume in Miyun reservoir. The lightly increase of TN concentration in recent years in Miyun reservoir was the comprehensive results of external input and self purification capacity.

Reducing the concentration of TN of the inflow water of Chaohe river and Baihe river is the key for the water quality improvement of Miyun Reservoir. In order to improve the water quality of Miyun Reservoir during the 14th Five Year Plan period, it is necessary to focus on total nitrogen reduction in Miyun reservoir basin. The main suggestions are as follows:

(1) Reduce the inflow TN concentration. The main measures include: reasonably adjust the industrial layout and the agricultural structure, change the mode of agricultural production, reduce the use of chemical fertilizers and pesticides, and control agricultural non-point source pollution; promote the construction of ecological bank protection and riverside constructed wetlands in the upper reaches of Baihe and Chaohe rivers in order to improve the water quality of incoming rivers.

(2) Enhance water pollution control measures. Strengthen the construction, upgrading and transformation of urban sewage treatment facilities to avoid direct discharge of domestic sewage into rivers; strengthen the collection and harmless treatment of garbage in villages and towns to reduce the agricultural non-point source pollution.

(3) Deepen joint prevention and governance of regional river basins. Establish and improve the compensation mechanism for regional ecological protection in Beijing and Hebei including exploring the establishment of the benefit area charging mechanism horizontally, improving the transfer payment policy vertically, and exploring the ecological product value realization mechanism such as the compensation distribution mechanism; promote joint water conservation actions and deepen the joint construction with Hebei Province.

(4) Strengthen refined and intelligent management. Establish an intelligent reservoir management system. Based on the existing monitoring data, make full use of information technology and mathematical model to carry out flood forecasting, water quality safety and eutrophication early warning, so as to improve the emergency response and disposal capacity of the Miyun reservoir. Carry out TN source analysis in the basin, and investigate and evaluate the environment and management status on an annual basis.

(5) Enhance the awareness of water and ecological conservation in the basin. Strengthen publicity and education to improve the understanding of water environment protection. Strengthen the publicity and popularization of documents such as the comprehensive plan for ecological and environmental protection of Chaohe and Baihe rivers Basin. Strive to form an atmosphere in which everyone consciously contributes to the protection of clean, hygienic and safe water quality.

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Author Contributions

Bingfen CHENG and Quanjie ZHU designed the study, performed data analysis and wrote the manuscript. Other coauthors contributed to the research design, proofreading and revision

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