Water quality in relation to land use in the Junshan Lake watershed and water quality predictions

Jiangang Lu, Haisheng Cai, Xueling Zhang and Yanmei Fu

ABSTRACT

Changes in human-dominated spatial patterns of land use are the main driving factors of water quality evolution in watersheds, and the quantitative impact of land use changes on water quality is currently a focus of lake ecology research. Using the Junshan Lake Basin as a study area, this paper quantitatively analyzes the response relationships between the water quality parameters, land use, and socio-economic factors in the study area from 2005 to 2019 and predicts the water quality in 2035 based on land and space planning scenarios. The results show the following. (1) The land use structure of the Junshan Lake Basin has changed significantly over the last 15 years. The basic trend is an increase in settlement and wetland areas in the basin and a decrease in water, cropland, forest, and grassland areas. (2) Settlement areas play the role of a 'source' for the total phosphorus (TP) and ammonium-nitrogen (NH_3-N) pollution load, and cropland areas play the role of a 'sink' for the TP, NH_3-N, and chemical oxygen demand (COD_{Mn}) pollution load. (3) The main land use type in the Junshan Lake Basin is cropland, which accounts for more than 40% of the total, and the water quality in the lake is affected not only by non-point source pollution but also by the regional Gross Domestic Product (GDP), total population, and per capita disposable income. According to the water quality prediction and analysis, the concentrations of TN and TP in Junshan Lake will meet the Class IV water quality standard in 2035, and the concentrations of dissolved oxygen (DO) and COD_{Mn} will meet the Class II standard. This study is significant for the management and control of the water environment in the Junshan Lake Basin.

Key words | Junshan Lake Basin, land use, socio-economic factors, water quality

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HIGHLIGHTS

- Quantitatively analyzes the response relationships between the water quality parameters, land use, and socio-economic factors in the study area.
- Reveals the relationship between the "source" or "sink" of the impact of construction land and cropland in the study area on water quality.
- According to the quantitative expression obtained in this paper, the water quality of the study area in 2035 is predicted.

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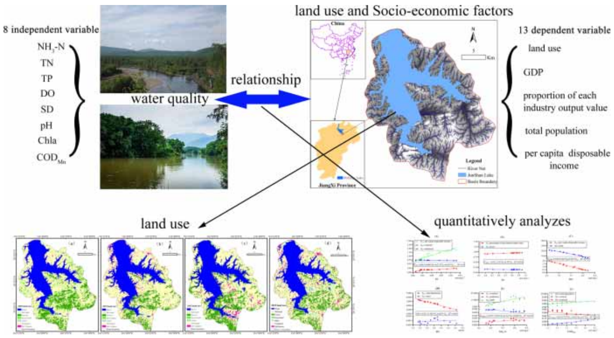
GRAPHICAL ABSTRACT



INTRODUCTION

The ecological environment provides a foundation for human survival and social development. Land use structure and land cover changes have a large impact on the global ecological environment via factors such as the climate (Calijuri *et al.* 2015), hydrology (Mello *et al.* 2018), biodiversity (Luisa Martínez *et al.* 2009), and soil (Horel *et al.* 2015). The evolution of the environmental water quality under the influence of human activities has been a main difficulty and bottleneck in global watershed management (Horel *et al.* 2015; He & Wu 2019; Mahmoodi 2019; Wu & Lu 2019) and has become one of the main factors affecting the safety of the water ecology in watersheds. Multiple studies have shown that changes in the human-dominated spatial pattern of land use are a major driving factor in water quality evolution in watersheds (Griffith 2002; Calijuri *et al.* 2015; Zhao *et al.* 2015; Mwaijengo *et al.* 2020).

Since the 1970s (White 1976; Rimer *et al.* 1978), scholars have hypothesized that changes in the land use spatial pattern will bring about certain environmental effects. In the 1990s (Arnold & Gibbons 1996; Wear *et al.* 1998), several scholars began to study the correlations between the land use structure and water quality concentrations. In the last 20 years, multiple scholars have analyzed the relationship between land use structure changes and water quality on three scales, the entire watershed (Singh *et al.* 2010; Qadir & Singh 2019), the sub-basin (Ullah *et al.* 2018; Twisa *et al.* 2020), and the buffer zone (Sliva & Williams 2001; Li *et al.* 2009), combined with landscape ecology, meteorology, hydrology, and other factors (Shrestha *et al.* 2018). The water quality indicators studied include total nitrogen (TN), biochemical oxygen demand (BOD), total phosphorus (TP), chlorophyll-a (Chla), fecal coliform (FC), total suspended solids (TSS), electrical conductivity (EC), turbidity, nitrate-nitrogen (NO_3^--N), nitrite-nitrogen (NO_2^--N), pH, and anions (SO_4^{2-}) (Osborne & Wiley 1988; Schoonover & Lockaby 2006; Zhao *et al.* 2015; Sadeghi *et al.* 2020; Tahiru *et al.* 2020), and a large amount of meaningful research results have been generated. For example, the expansion of farmland and city areas has had a positive effect on the increase in the concentration of TP (Wang *et al.* 2014); water temperature and flow are important indicators that affect the concentration of the water quality (Mello *et al.* 2018); and grassland and forest areas are negatively correlated with the concentrations of NO_3^--N and SO_4^{2-} in water (Zhao *et al.* 2015). When studying the response relationship between the land use structure and the water quality, it is still under debate as to which specific scale should be adopted to draw conclusions with the highest reliability. For example, Li *et al.* believe that the land use structure of the riparian zone has a significant influence on the concentration of the water quality (Li *et al.* 2009), while other scholars believe that the change in the land use type over the entire watershed provides a better explanation for changes in the water quality indexes (Wang *et al.* 2014). Some scholars believe that the water quality will degrade when the impervious surface area in a basin reaches 10% and that the water quality will degrade significantly when it reaches 20–30% (Beck *et al.* 2016). However, the specific relationships between the land use structure and the water quality indexes are difficult to quantify and express for the following three reasons. (1) The research scale may be too large or too small. That is, if the scale is too large, there may be many sources of interference, while if the scale is too small, the conclusions obtained may be too one-sided. (2) At present, several studies have obtained quantitative expressions; however, these are only study-specific expressions of water quality indexes and the proportion of specific land use types (Tran *et al.* 2010; Beck *et al.* 2016). The conclusions of these studies therefore have certain limitations. In addition, socio-economic factors have not been included even though the growth of the population and economy can reflect changing trends in the water quality (Dube *et al.* 2014). Moreover, even with increases in the settlement area, the pollutants produced by different industries may differ. In the interpretation of land use, the accuracy of the land use type interpretation meeting the requirements is a great challenge. (3) There are too few years of data available, and long time series data are needed to obtain reliable quantitative expressions.

Junshan Lake is the largest freshwater lake in Jinxian County in China. In the last 10 years, the scale of the farming of Junshan Lake hairy crabs has changed from regional scales to encompassing the entire lake. The water quality in the lake has subsequently attracted much attention. In view of this, this paper focuses on the Junshan Lake Basin and interprets the land use data from 2005 to 2019 using ENVI software. The study then combines this with the socio-economic development data over the same period, collects water quality data for the corresponding years, and reveals the quantitative relationships between the water quality indicators and other factors. Finally, combined with the 'Jinxian County Land and Space Master Plan (2019–2035)' (http://www.jinxian.gov.cn/), the water quality in 2035 is predicted.

STUDY AREA

Junshan Lake (116° 15′–116° 21′ E, 28° 23′–28° 39′ N) is located in northwest Jinxian County, Nanchang City, Jiangxi Province, China. It is the largest internal lake in Jinxian County and the largest freshwater lake at the county level in China at present (Yuan *et al.* 2019). Junshan Lake was originally part of Poyang Lake (the largest freshwater lake in China) and was separated from Poyang Lake by the construction of a dam in 1959 (Zhang *et al.* 2015). After the partition, the water flow slowed, the water self-purification ability weakened, and the water ecosystem changed significantly. Junshan Lake supplies more than 70% of the water resources for development and the people living in Jinxian County. It is forbidden to open sewage outlets into the lake except in the case of aquaculture. The Junshan Lake Basin has a tropical monsoon humid climate with abundant rainfall. The basin area is 518 km^2 (Figure 1), which accounts for approximately 1/3 of the total area of Jinxian County. It is associated with eight townships, has a water surface area of 185–210 km^2, and is approximately 25 km long and 5 km wide, with a greatest depth of 6.5 m and an average depth of 4.3 m. The annual average temperature in the region is 17.1 °C, and the average annual precipitation is 1,075 mm. The average annual sunshine time is 2,063 h, and the average annual wind speed is 3 m/s, with a dominant southeast wind. Junshan Lake was originally famous for its rich produce, such as turtles, mandarin fish, and silver fish, and is now primarily used for breeding river crabs, which constitutes a 'pollution-free aquaculture base in the Jiangxi Province'. Since 2010, the intensity of aquaculture in the lake has increased each year, the non-point source pollution has intensified, and the water nutrition level has notably increased.

METHODS

Water quality, population, and economic growth data

Water quality data from 2005 to 2009 in the study area was collected from the literature (Hongchao *et al.* 2010; Wuming *et al.* 2016), and water quality data from 2010 to 2019 was collected from the website of the Jiangxi Provincial Department of Ecology and Environment (http://sthjt.jiangxi.gov.cn/). The data collected include TP, TN, NH_3-N, COD_{Mn}, Chla, pH, DO, SD, a total of eight water quality indicators, and the concentrations of COD_{Mn} and Chla in 2006, TP in

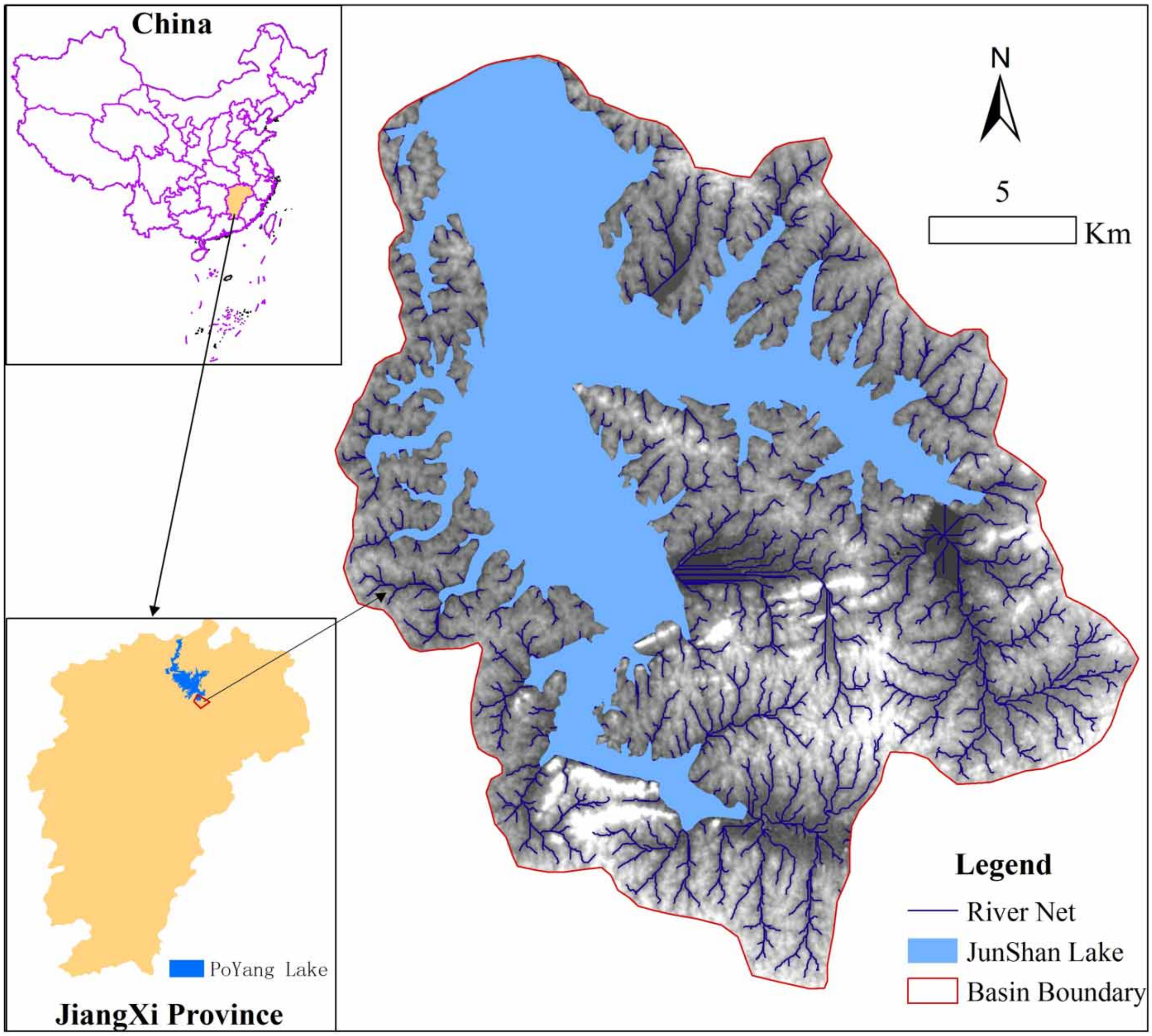


Figure 1 | Location of Junshan Lake.

2008, and NH_3-N in 2011. The concentration of Chla and the pH in 2017 are missing; therefore, an interpolation method was adopted to supplement these data. Population and economic growth data were obtained from the 'Jinxian County Social Statistics Yearbook' (http://tjj.nc.gov.cn/).

Land use data

Landsat TM data for December 2005, September 2010, November 2015, and October 2019 were downloaded (http://bjdl.gscloud.cn/help/detail/news/85). After data clipping, the data were processed using the 'Radiometric Calibration' and 'Quick Atmospheric Correction' tools in 'The Environment for Visualizing Images' (ENVI) software. The data were then combined with historical images from Google Earth to visually correct and interpret the land use data in the study area (the separability coefficients between the samples were all above 1.9). As shown in Figure 2, the study area was divided into seven types of land use: water, wetland, cropland, settlement, forest, grassland, and other. If a remote-sensing interpretation of the land use data was carried out in a given year, the accuracy could be difficult to guarantee; however, the possibility of large changes in the land use types in two adjacent years is relatively small.

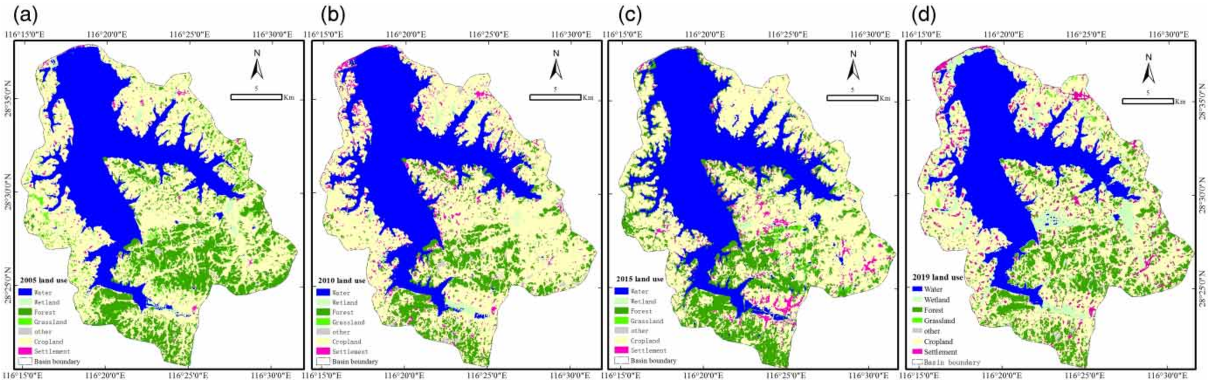


Figure 2 | Land use patterns in the Junshan Lake Basin from 2005 to 2019.

In this study, combining the development and construction of land with relevant data from the China Land and Resources Bulletin over the years (http://www.mnr.gov.cn/sj/tjgb/), the proportion of various types of land use in other years was obtained via linear interpolation. For example, based on data from 2005 and the variation range from 2005 to 2010, the proportion of settlement area increased by 10% in 2006, 50% in 2007, 80% in 2008, and 90% in 2009; meanwhile, the proportion of cropland area increased by 10% in 2006, 20% in 2007, 50% in 2008, and 80% in 2009.

Using the above steps, the proportions of water (X1), forest (X2), wetland (X3), grassland (X4), settlement (X5), cropland (X6), and other (X7) areas, regional Gross Domestic Product (GDP) (X8, unit: 100 million CNY), percentage of agricultural output value (X9), percentage of industrial output value (X10), percentage of service industry output value (X11), total population (X12, unit: 10,000 people), and per capita disposable income (X13, unit: 10,000 CNY), a total of 13 dependent variable data, and TP, TN, NH_3-N, COD_{Mn}, Chla, pH, DO, and transparency (SD), a total of 8 independent variable data, were collected.

Data analysis method

After collecting the water quality data, the annual average concentration of each water quality indicator in each year was obtained using statistical methods (mean, standard deviation, and coefficient of variation), with the water quality indexes as the independent variable and the other factors as dependent variables. First, a single water quality index was preliminarily screened for its Pearson correlation with the other dependent variables; the dependent variables with correlation coefficients of <0.3 were then removed (Xu *et al.* 2020), followed by a stepwise linear regression analysis. If the VIF value of the independent variable was >5, a correlation analysis was conducted for the variable. After deleting the data with strong correlations, the stepwise linear regression model was rerun (Marshall & Randhir 2008). All the data processing in this paper was completed using 'Statistical Product and Service Solutions (SPSS) 21' software.

RESULTS

Quantitative changes in land use in the Junshan Lake watershed

The analysis indicated that, in the last 15 years, the main land use structures in the study area were water and cropland (Figure 3). The proportion of the water body area decreased slightly but remained at approximately 30%. The proportion of wetland area increased yearly, from 2.7% in 2005 to 11.3% in 2019. The proportion of cropland area decreased from 49.2% in 2005 to 41.3% in 2019. The proportion of settlement area increased from 0.86% in 2005 to 4.8% in 2019. The forest area also decreased, from 16.2% in 2005 to 12.8% in 2019. The grassland area decreased every year, from 2.9% in 2005 to 0.98% in 2019. Even though the proportion of 'other' areas has been less than 0.5% over the years, the increase in its

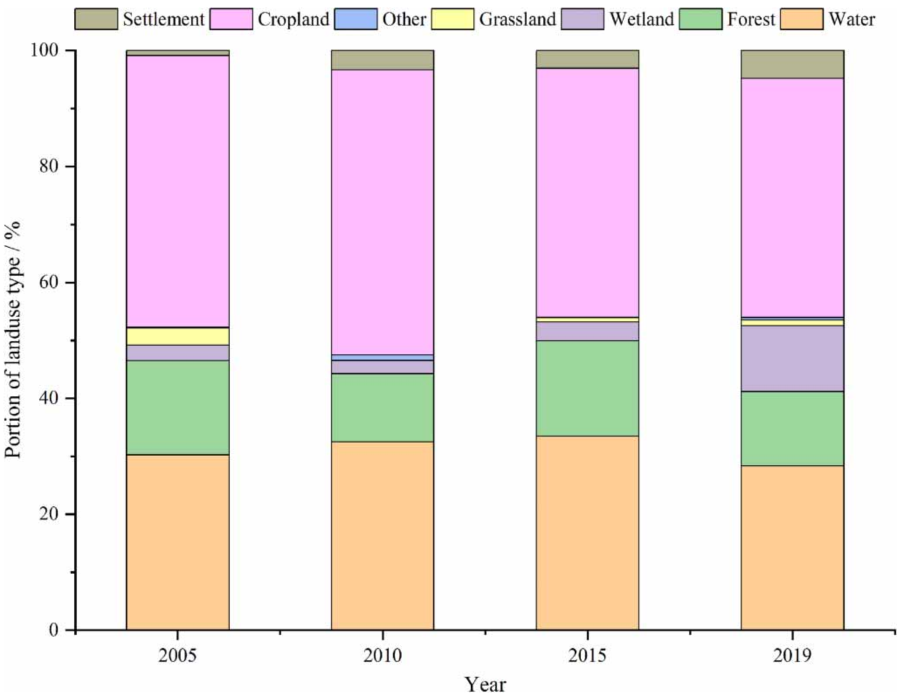


Figure 3 | Proportion of different land uses from 2005 to 2019.

proportion has been relatively large, from 0.2% in 2005 to 0.5% in 2019.

Analysis of the land use transfer matrix in the Junshan Lake watershed

A land use transfer matrix can comprehensively and specifically express the specific characteristics of the land use type change during a certain period (Mello *et al.* 2018). It is convenient for researchers to understand the specific direction of each type of land use in the initial stage, and such matrixes can explain the changes in the area of each land use type during a research period (Nagendra *et al.* 2013). The land use transfer matrix of Junshan Lake from 2005 to 2019 is shown in Table 1.

From 2005 to 2019, 6.733% of the water body area was converted into wetland areas and 4.31% of the wetland area was converted into water body areas. This shows that there is a high frequency of conversion between water body and wetland areas and that the surface water resources in the study area have decreased. A total of 28.645% of the forest area was converted into cropland areas and 3% of the

Table 1 | Land use transition matrix in the Junshan Lake watershed (unit: %)

		2005						
Period	**Land use type**	**Wetland**	**Water**	**Forest**	**Settlement**	**Other**	**Cropland**	**Grassland**
2019	Wetland	85.959	6.733	1.745	2.487	3.835	13.964	4.9
	Water	4.31	92.91	0.023	0.081	0	0.18	0
	Forest	0.797	0.01	63.807	1.072	10.067	4.856	5.934
	Settlement	2.247	0.068	3.014	86.957	3.739	7.231	3.121
	Other	0.705	0.023	1.368	0.222	10.067	0.351	0.461
	Cropland	5.943	0.255	28.645	9.039	71.045	71.997	82.487
	Grassland	0.039	0.001	1.4	0.142	1.246	1.421	3.097

The numbers in the table indicate the percentage of the initial land use types converted into the final land use types.

cropland area was converted to settlement areas, indicating that the reduction of the forest area was one of the main reasons for the deterioration of the water quality in Junshan Lake. Another obvious change during this period was the conversion of cropland areas to settlement areas: 7.23% of the cropland area was converted into settlement areas, which was the main reason for the substantial increase in the settlement area during this period. In addition, 82.48% of the grassland area was converted into cropland areas, which indicates that grassland is a land use type with very frequent land use changes. This series of changes shows that, between 2005 and 2019, there were frequent changes between cropland, forest, and grassland areas in the Junshan Lake watershed. Therefore, human activities, such as agriculture and forest management, are important factors affecting land use changes in the study area.

Variation characteristics of water quality indicators

In this study, the annual average water quality data over the years were used for the analysis (Figure 4). The results indicate that, except for the pH, the water quality in the study area deteriorated significantly over the last 15 years. Overall, the water quality in 2005 met the Class II standard in the 'Surface Water Environmental Quality Standard (Ministry of Ecology and Environment the People's Republic of China 2002),' in terms of a single water quality index, and the concentrations of COD_{Mn} and DO met the Class I standard. The water quality in 2019 in the study area as a whole met the Class III standard, in terms of a single water quality index, COD_{Mn} met the Class II standard, and the concentration of TP met the Class IV standard.

Correlation analysis of the water quality indicators and other factors

When establishing the stepwise regression model, it was found that the R^2 of the regression equation established by pH and Chla was too small ($R^2 < 0.6$); therefore, the establishment of the regression model was not completed. However, the stepwise regression effects of the other six water quality indicators were better and the significance level was <0.05 (Figure 5). These results indicate that the cropland area was significantly negatively correlated with TP, NH_3-N, and COD_{Mn}, the settlement area was significantly positively correlated with TP and NH_3-N, the per

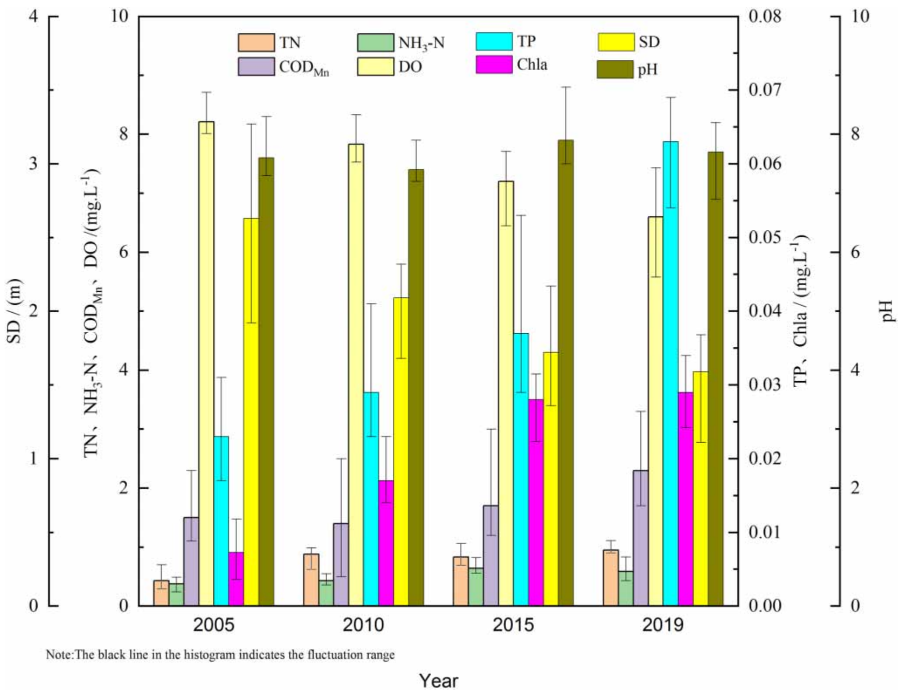


Figure 4 | Annual average water quality of Junshan Lake from 2005 to 2019. The black line in the histogram indicates the fluctuation range.

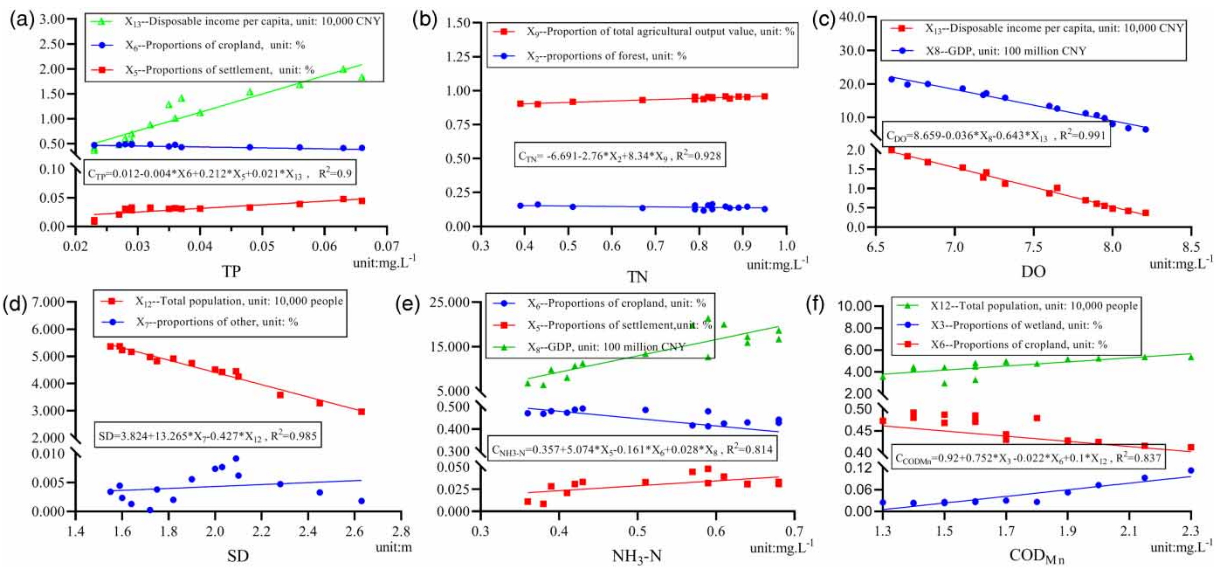


Figure 5 | Results of the stepwise linear regression.

capita disposable income was significantly negatively correlated with DO and significantly positively correlated with TP; the total population was significantly negatively correlated with SD and COD_{Mn}, and GDP was positively correlated with NH_3-N and DO.

Water quality forecast for Junshan Lake in 2035

Quantitative relationships between the six water quality indicators and the other dependent variables were found in the previous section. The projected proportions of various types of land use in the Junshan Lake watershed in 2035 were obtained from the 'Jinxian County Territory-Space Master Plan (2019–2035)'. Following the collected social and economic development data of the Junshan Lake watershed over the last 15 years, linear regression was used to predict the social and economic data for the study area in 2035 (the total population is the ratio of the planned construction land area to the per capita construction land area in 2035). The results are shown in Table 2. Following the derived quantitative relationships between the water quality parameters and the other dependent variables (Figure 5), the data in Table 2 were substituted into the relationships to obtain the predicted values of the water quality factors for Junshan Lake in 2035. The results are given in Table 3.

DISCUSSION

Over the last 15 years, with the implementation of a series of national and local policies and the rapid growth of the population and economy, the land use in the Junshan Lake Basin has changed dramatically. The basic trend is an increase in the construction land and wetland areas in the basin and a decrease in the water, cropland, forest, and grassland

Table 2 | Predicted values of various dependent variables in the Junshan Lake watershed in 2035

Dependent variables	Water	Forest	Wetland	Grassland	Other	Cropland	Settlement	GDP/(100 million CNY)	Percentage of agricultural output value	Per capita disposable income /(10,000 CNY)	Total population /(10,000 people)
Value	0.3012	0.1233	0.1054	0.0108	0.0012	0.4077	0.0504	39.483	0.9699	3.8274	5.653

Figures without units in the table indicate proportions.

Table 3 | Predicted values of the water quality parameters in Junshan Lake in 2035

Parameter	TP/(mg·L^{-1})	TN/(mg·L^{-1})	DO/(mg·L^{-1})	SD/(m)	NH_3-N/(mg·L^{-1})	COD_{Mn}/(mg·L^{-1})
Value	0.10	1.058	6.99	1.43	1.65	1.56

areas. The attenuation of the water resources coincides with the deterioration of the water quality in the study area. From the perspective of changes in land use, with the continuous development of industrial and agricultural policies in Jinxian County, cropland and forest areas in the study area will continue to be converted into settlement areas; the expansion trend of settlement areas is very obvious. However, with the large-scale afforestation project in the basin, the decrease in the forest area will be slowed and the unused land area will gradually decrease. The grassland area decreased by more than 60% from 2005 to 2019 (Figure 3), which indicates that cropland, forest, and grassland areas are being rapidly transformed. The large-scale expansion of the settlement area in the watershed mainly impinged on the cropland, forest, and grassland areas.

Figure 5 reveals the relationships between the water quality indexes, land use types, and socio-economic factors. We can see that the construction land area has a significant positive correlation with NH_3-N and TP, indicating that construction land is a main source of water quality deterioration. Construction land represents the most intensive area of human activity and can change the nature of the underlying surfaces. Impermeable surfaces lead to an increase in surface runoff, while the interception and absorption of pollutants is weakened, leading to an increase in the concentration of organic matter and nutrients in the water. This decreases the water quality, which is consistent with existing conclusions (Li *et al.* 2008). In this study, the cropland area was negatively correlated with TP, NH_3-N, and COD_{Mn}, which is contrary to existing research conclusions (Meneses *et al.* 2015). This may be due to the development of aquaculture in the study area over the last 10 years, causing the change in the cropland area to have only a small effect on the water quality. In addition, socio-economic factors, such as per capita disposable income, GDP, or total population, were introduced into the quantitative expressions of the three water quality indicators, which shows that the quantitative response relationships with the water quality cannot be revealed from the change in the land use type alone and should be analyzed on the basis of the land use type combined with other factors. However, the per capita disposable income in this paper was not subdivided into urban per capita disposable income and rural per capita disposable income. This is because the administrative regions involved in the study were all townships and more than 90% were rural households. With the support of a series of policies, Junshan Lake has been vigorously developing aquaculture over the last 10 years and has experienced obvious economic growth. Therefore, the driving effect of the social and economic factors on the water quality cannot be ignored, which is the main reason why Junshan Lake was selected as the focus of this study.

Even though there are several studies predicting the water quality of rivers (lakes and reservoirs) based on quantitative expressions (Schoonover & Lockaby 2006; Li *et al.* 2009), most dependent variables are predicted according to previous trends (Marshall & Randhir 2008; Tran *et al.* 2010). In this paper, the land use type dependent variable data are scientific and reasonable combined with the land and space planning of the Junshan Lake watershed; however, the water quality prediction results show that the concentration of NH_3-N in 2035 will be higher than that of TN (Table 3), mainly because the R^2 in the formula is too low (Figure 5(e)). This indicates that the accuracy of the NH_3-N expression established in this paper needs to be further verified. However, the degradation of the water quality parameters was not considered in this quantitative relationship. Therefore, future research should focus on the coupling mechanism between land use and water quality and establish a physical model of this process.

The spatial scale effect is an important issue in the analysis of the relationship between water quality and land use; however, there is still controversy concerning the optimal spatial analysis scale (Seeboonruang 2012; Wang *et al.* 2014). While the uncertainty of the research scale involves the fact that the water quality pollutants are different from each other, the natural attributes of watersheds are also very different; therefore, it is difficult to find a unified research scale suitable for all watersheds. Some studies suggest that the relationship between the river water quality and the land use at the small watershed scale is more significant than that at the buffer scale (Chen *et al.* 2020); however, there is currently no clear conclusion concerning the scope of a small watershed. Most watershed areas in existing studies are larger than 1,000 km^2 (Marshall & Randhir 2008; Li *et al.* 2009; Wilson & Weng 2010). To determine the relationships between land use structure changes and water quality responses between the buffer zone and a small watershed, this paper examined the Junshan Lake watershed (with a watershed area of 518 km^2) and revealed quantitative response relationships between the water quality indexes and the land use and socio-economic factors using a large number of mathematical statistical methods.

CONCLUSIONS

(1) From 2005 to 2019, the cropland, forest, and grassland areas in the Junshan Lake Basin transformed quickly; the forest and cropland areas decreased significantly, and the construction land area expanded on a large scale.

(2) Overall, the water quality of Junshan Lake changed from Class II in 2005 to Class III in 2019. The concentration of TP increased the most, with the concentration of TP in 2019 being slightly lower than the Class III standard.

(3) Cropland area is significantly negatively correlated with TP, NH_3-N, and COD_{Mn}; settlement area is significantly positively correlated with TP and NH_3-N; per capita disposable income is significantly negatively correlated with DO and significantly positively correlated with TP; total population is significantly negatively correlated with SD and COD_{Mn}; and GDP is significantly positively correlated with DO and NH_3-N.

(4) The concentrations of TP and TN in Junshan Lake in 2035 are projected to meet the Class IV water quality standard, while the concentrations of DO and COD_{Mn} are projected to meet the Class II standard.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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