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Impacts of human activities and climate change on the water environment of Lake Poyang Basin, China

Xinyan Li[*], Lu Zhang, Guishan Yang, Hengpeng Li, Bin He, Yuwei Chen and Xuguang Tang

Abstract

Background: The global mean temperature has risen by 0.85 °C from 1880 to 2012, and this increase may even accelerate in the future. The surface temperatures of large inland water bodies worldwide have been rapidly warming since 1985 with an average rate of 0.045 ± 0.011 °C yr^{-1} and rates as high as 0.10 ± 0.01 °C yr^{-1}. The global climate change was responsible for an increased contribution of diffuse nutrient losses to the total nutrient loads in water bodies. More and more algae blooms were reported in inland water bodies. Lake Poyang, the largest freshwater lake in China, is experiencing a deterioration of water quality. Ganjiang River, as the longest river in the Lake Poyang catchment, plays an important role in linking between terrestrial and aquatic ecosystems. A large amount of N pollutants is transported through the Ganjiang River to Lake Poyang. It is important to study quantitatively human enhanced N (nitrogen) inputs and DIN (Dissolved Inorganic Nitrogen) exports through rivers in the background of global warming.

Results: In this paper, we estimate the inputs of nitrogen (N) and exports of dissolved inorganic nitrogen (DIN) from the Ganjiang River to Lake Poyang for the period 1995-2010 by using the Global NEWS-DIN model. Modeled DIN yields range from 1038 kg N km^{-2} yr^{-1} in 1995 to 150 kg N km^{-2} yr^{-1} in 2010, showing a decreasing trend. The study demonstrates a varied contribution of different N inputs to river DIN yields during the period 1995-2010. Biological N fixation contributes about 73.3 % of DIN yields before 2005, but the contribution decreases substantially to 28.4 % in 2010. Chemical N fertilizer application and animal manure N inputs together contribute 12.6 % of the river DIN yields, while atmospheric N deposition contributes an average of 5.5 % of DIN yields in the period 1995-2010. Sewage N inputs contributes an average of 5.2 % of DIN yields over the period 1995-2005, while the contribution increases remarkably to 69.7 % in 2010. The trophic state index (TSI) of Lake Poyang agrees well with modeled DIN yields from the Ganjiang River over the whole study period.

Conclusions: N inputs from nonpoint sources are approximately 10-54 times that from point sources. Almost all the diffuse DIN inputs were retained in the watershed before entering the lake Poyang. While about half of sewage N inputs were input to Lake Poyang as DIN from the Ganjiang River. Modeled DIN yield from Ganjiang River decreased after 2005 significantly, providing evidence for the recovering capacity of watersheds to retain DIN as inputs decrease as a direct result of human activities. The study also demonstrates a varied contribution of different N inputs to river DIN yields during the study period. The authors also point out that more attention should be kept on reducing sewage N discharge to Lake Poyang in the background of global warming.

Keywords: Dissolved inorganic nitrogen; Water environment; Ganjiang River; Lake Poyang basin; Global NEWS-DIN model; China

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Background

The global mean temperature has risen by 0.85 °C from 1880 to 2012, and this increase may even accelerate in the future (IPCC 2014). The global warming can significantly alter the regional hydrology and inflows to lake ecosystems (IPCC 2014). The changes in hydrological cycles caused by climate change, including precipitation, evapotranspiration, soil moisture, river flow, and groundwater, strongly influences environmental quality, aquatic ecosystem productivity, and chemical exports from the watersheds to lakes (Catherine et al. 2003; Mortsch et al., 2003). In the 1980s, the spring diatom bloom in Lake Erken in Sweden (59°25′N, 18°15′E) appeared earlier than in the 1970s and there was a five-fold increase in the summer abundance of the blue-green algae Gloeotrichia (Weyhenmeyer et al., 1999). Serious cyanobacterial blooms were reported in a number of European lakes during the warm summer of 2003 and there was evidence to suggest that some species have already extended their geographical range (Wiedner et al., 2007). By using nighttime thermal infrared imagery, Schneider and Hook (2010) reported that the surface temperatures of large inland water bodies worldwide have been rapidly warming since 1985 with an average rate of 0.045 ± 0.011 °C yr^{-1} and rates as high as 0.10 ± 0.01 °C yr^{-1}. Combing historical and paleolimnological data, Catherine et al. (2003) pointed out that climate change has contributed to diminish productivity in Lake Tanganyika over the past 80 years. The observed global climate change was responsible for an increased contribution of diffuse nutrient losses to the total nutrient load in water bodies (Bouraoui et al., 2004).

Rivers play a key role in linking between terrestrial and aquatic ecosystems. A large amount of N pollutants is transported through rivers to water bodies. As the most abundant and bioavailable form of N, Dissolved inorganic nitrogen (DIN) attracts more attention of scientists in recent studies (Dumont et al. 2005; Yan et al. 2010). It is reported that DIN yields from the Yangtze River to estuary increased evidently from 1970 to 2003 (Yan et al. 2010). The authors suggested that anthropogenically enhanced N inputs dominate river DIN yields in the basin. However, much uncertainty remains in the quantification of the impact of human activities on river DIN export (He et al., 2009, 2011).

Lake Poyang, located at the southern bank of the middle and lower reaches of the Yangtze River, is regarded as the largest freshwater lake in China. The water quality of Lake Poyang shows a decreasing trend in past 4 decades. According to the surface water environmental quality standard in China (GB3838-2002), the water quality is at Level I if the total nitrogen concentration (TN) of lake water is below 0.2 mg L^{-1}, it is at Level II if $0.2 < TN \leq 0.5$ mg L^{-1}, at Level III if $0.5 < TN \leq 1.0$ mg L^{-1}, at Level VI if $1.0 < TN \leq 1.5$ mg L^{-1}, at Level V if $1.5 < TN \leq 2.0$ mg L^{-1}, and at worse than Level V if $TN > 2.0$ mg L^{-1}. The Water quality of lake Poyang was at Level I in the early 1980s and at Level II ~ III in the 1990s (Liu, 1987; Wan and Jiang, 2005). When it comes to the 21st Century, the water quality of Lake Poyang deteriorated continuously. It changed from Grade II ~ III in 2001 to Grade IV ~ V in 2009 (Wu et al., 2011). The deterioration of lake water quality has been a threat to the survival of aquatic organisms. The estimated population of Siberian Crane in the Lake Poyang region decreased from 2760 in 2006 to 2495 in 2011 (Barter et al., 2006; Jia et al., 2013).The annual average dry season in the 2000s is 175 days, which is longer than that in any previous decades. Especially in recent years, extreme drought events in Poyang Lake basin occurred frequently (Liu et al., 2014). Many researchers pointed out the damage of rainfall reduction in the Lake Poyang basin (Min and Zhan, 2012; Liu et al., 2014). In 2011, Lake Poyang suffered from a terrible drought, leading to serious degradation of lake wetlands ecosystem. The lake area in the dry seasons was only 10 percent of that in the wet seasons. Because of drought, the number of fishes decreased sharply causing enormous economic losses to fishermen. Due to the sharp decline in water level of the lake, the wintering migratory birds to Lake Poyang wetland were facing feeding difficulty. Therefore, the number of migratory waterbirds to Lake Poyang in 2011 winter clearly decreased (Wang et al., 2013). The catastrophic flood during July-August 1998 in the Yangtze River basin significantly reduced density and biomass of *Potamogeton malaianus*, *Vallsineria spiralis* and *Carer cinerascens* (Cui et al., 2000). There have been large amounts of research on hydrology, biology and water environment of Lake Poyang in recent years (Ye et al. 2013; Wang et al., 2013). However, there is little data available for tracing the trajectory of DIN flux in the basin over a relative long period.

This study is the first to model the exports of DIN from the Ganjiang River to Lake Poyang in the period 1995-2010 based on quantitative analysis of N cycling. Findings from this study should provide a better understanding of the N cycling under changing human pressures and climate change.

Methods

Study area

The Ganjiang River watershed is located in the south of Lake Poyang Basin, Jiangxi, China (Fig. 1). The Ganjiang River is the largest river of Lake Poyang basin and flows into Lake Poyang and the Yangtze River. The sampling
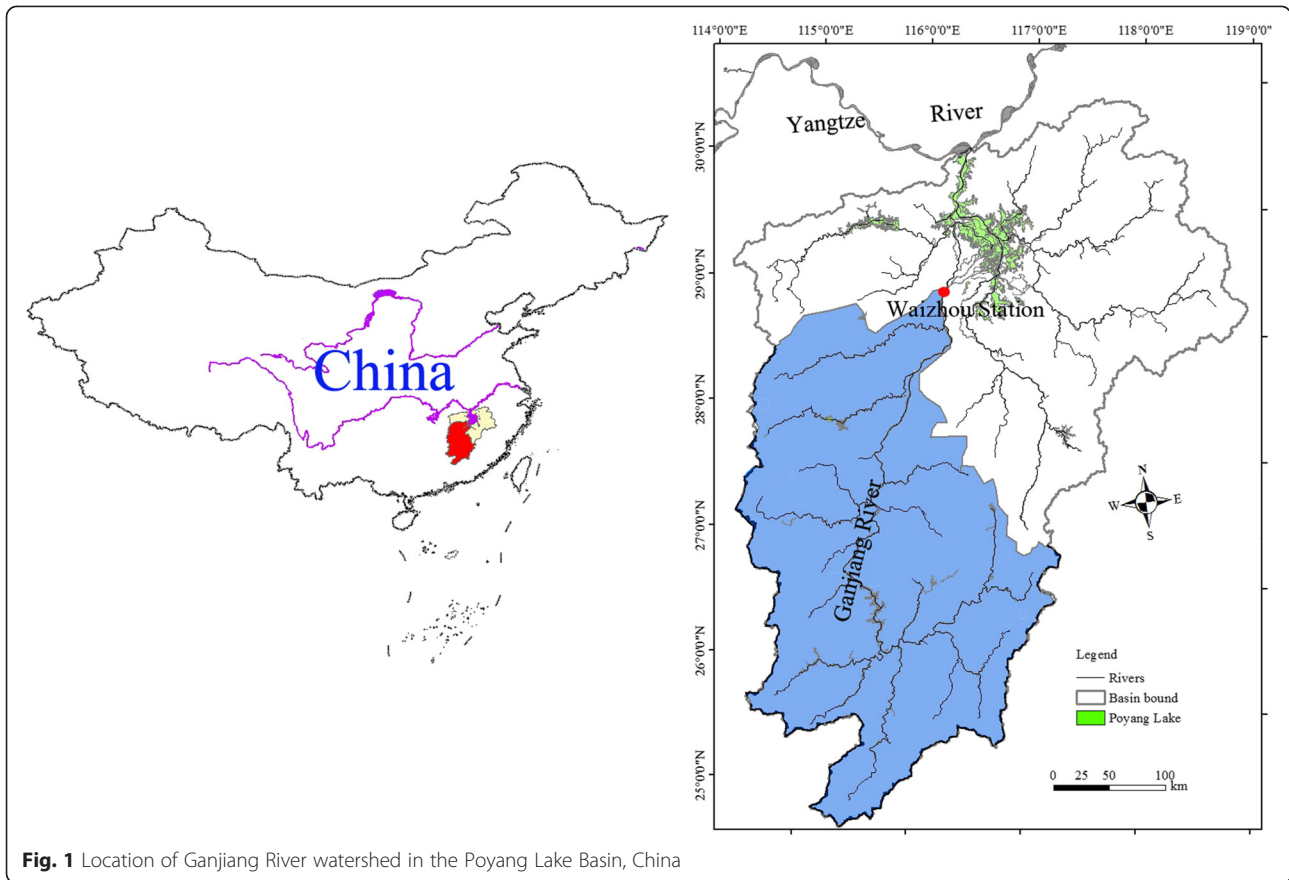
Fig. 1 Location of Ganjiang River watershed in the Poyang Lake Basin, China

location for this study was Waizhou gauging station located at the mouth of Ganjiang River (Fig. 1). The Ganjiang River drains a total area of 11.23×10^4 km^2 and has an average annual discharge of 686.5×10^8 m^3 per year at the sampling location. The Ganjiang River watershed belongs to a subtropical wet climate zone with an annual mean temperature of 17.5 °C and annual mean precipitation of 1680 mm (Ye et al., 2013). The annual mean temperature clearly increased (blue circle, Fig. 2),

while the annual mean precipitation varied slightly in recent 20 years (red square, Fig. 2).

Riverine DIN flux estimate

To estimate annual DIN export from the Ganjiang River in 1995-2010, the widely applied global NEWS-DIN model was utilized (Dumont et al. 2005; Mayorga et al. 2010).
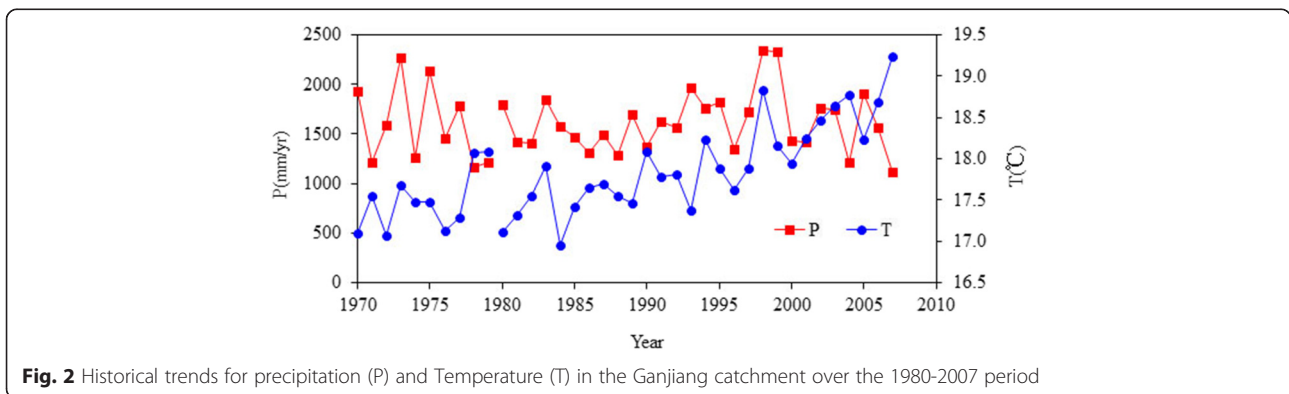

Fig. 2 Historical trends for precipitation (P) and Temperature (T) in the Ganjiang catchment over the 1980-2007 period

Table 1 Parameters Used in the Global NEWS-DIN Model

Model Parts	Parameters	Units	Parameters Explanation
Hydrology coefficients	Runoff	m yr-1	Water runoff
	Q_{rem}	0-1	Fraction of consumptively use water removed from the river
	D_{din}	0-1	Fraction of N retained by reservoirs
Point sources	GDP	U.S.\$ indiv.$^{-1}$	Gross domestic product as purchasing-power parity
	Pop_{Dens}	indiv. km^{-2}	Population density
	R	0-1	Fraction of N removed by sewage treatment
	I	%	% of population connected to sewage system
Diffuse sources	TN_{fe}	kg N km^{-2} yr^{-1}	TN applied as fertilizer
	TN_{ma}	kg N km^{-2} yr^{-1}	TN applied as animal manure
	TN_{fix}	kg N km^{-2} yr^{-1}	TN fixed by natural and agricultural fixation
	TN_{dep}	kg N km^{-2} yr^{-1}	TN deposited via atmospheric deposition for Waizhou Station drainage area
	TN_{exp}	kg N km^{-2} yr^{-1}	TN exported from the basin as crop harvest
	FE_{ws}	0-1	Fraction of N exported from landscape to the rivers as DIN
	RSD	0-1	The ratio of watershed N surplus against N input

NEWS-DIN model

Definitions of all the parameters used in this model are given in Table 1. NEWS-DIN can be summarized as follows:

$$DIN_{yield} = FE_{riv}\left(DIN_{sew} + FE_{WS} \bullet TN_{diff}\right) \quad (1)$$

Where DIN_{yield} is modeled annual DIN load per river basin; FE_{riv} is a river export fraction representing the fraction of total point and nonpoint DIN inputs to the river that exported as DIN (0-1); DIN_{sew} is DIN from sewage point sources to rivers; FE_{WS} is a watershed export fraction representing the fraction of total nitrogen (TN) from nonpoint sources in the watershed that leaches to rivers as DIN; TN_{diff} is net total nitrogen from nonpoint sources that is mobilized from the watershed soils and sediments. Almost all basin-scale N input and river export terms (including DIN_{yield}, DIN_{sew}, and TN_{diff}) are expressed as total N mass load per year normalized by basin area at Waizhou Station (WZS), expressed in kg N km^{-2} yr^{-1}.

Point source (DIN$_{sew}$)

As described by Dumont et al. (2005), an indirect approach was used to calculate total N input into rivers from point sources (TN_{sew}, kg N km^{-2} yr^{-1}) as

$$TN_{sew} = \left(1 - TN_{frem}\right) \bullet I \bullet \left(H \bullet E_N\right) \quad (2)$$

In which E_N is the per capita N emission as human waste, H is population density, I is the fraction of the population that is connected to a sewage system, and TN_{frem} is the fraction of TN in sewage influent that is removed by wastewater treatment. E_N is estimated using an empirical function of per capita gross domestic

product (GDP) that is based largely on protein consumption; this relationship was updated by Van Drecht et al. (2009) to use per-purchasing parity GDP (GDP_{ppp}) rather than market-exchange-rate GDP (GDP_{mer}) as originally formulated (Dumont et al., 2005; Van Drecht et al., 2003). Data on provincial GDP_{mer} and population (including urban and rural) come from Jiangxi Statistical Yearbooks (Jiangxi National Bureau of Statistics, 1996-2010); basin-aggregated GDP_{mer} was converted to GDP_{ppp} using the annual ratio of national GDP_{mer} to GDP_{ppp} values for Jiangxi (World Bank, 2001). The fraction of total population connected to sewage systems (I) is estimated as the ratio of urban and total population living in the basin (%).

Diffuse source (TN$_{diff}$)

The total amount of diffuse source nitrogen that is mobilized annually (TN_{diff}) is estimated as

$$TN_{diff} = TN_{fe} + TN_{ma} + TN_{fix} \quad (3)$$
$$+ TN_{dep} - TN_{exp}$$

All terms are in kg N km^{-2} yr^{-1}; the definition of each term is given by Yan et al. (2010) and Li et al., (2011).

TN_{fe} is defined as the ratio of yearly N fertilizer application and basin area. Data of N fertilizer application and forms in the basin are available in the Jiangxi Statistical Yearbooks (Jiangxi Statistical bureau, 1996-2010). The data of all N fertilizer forms were converted into element N to estimate N fertilizer input.

TN_{ma} is calculated as animal manure N input divided by WZS drainage area. Animal manure N input is the product of yearly animal populations and N excretion rates by animal category. Animal categories summarized

in this article include pigs, cattle, sheep, horses, and poultry. Data of these animal populations comes from Jiangxi Statistical Yearbooks (Jiangxi Statistical bureau, 1996-2010). The mean stock of animals by category includes standing livestock animals at the end of a year and animals slew during that year. Considering the fact that slain animals no longer produce manure, the number of slain animals is corrected with the factor c (c = 0.542), representing the time during which slain animals were part of the living stock (Yan et al., 2010).

N_2 fixation (TN_{fix}) refers to the sum of symbiotic N fixation by cultivation of N fixation by microorganisms in both managed and natural ecosystems. N fixation input is estimated by multiplying the rate of fixation (kg N ha^{-1}) for each natural ecosystem by its area within the basin. The legume crops are grouped as soybeans, peanuts, and green-manure crops in the basin. Nonlegume crops include all the other vegetation except the legume crops and rice. The differences between the natural and manmade forest (grassland) are ignored in this article. The N fixation rates are given by Yan et al. (2003).

Atmospheric N deposition rates (TN_{dep}) (including dry and wet deposition of NH_3 and NO_y) of forestland and farmland in Ganjiang River watershed were calculated according to the research obtained by others based on monitoring (Fan et al., 2007; Lv and Tian, 2007; Wang et al., 2008; Yang et al., 2009; Li et al., 2011). Since atmospheric NH_3 sinks to the ground in a short distance, only atmospheric NO_y deposition is considered in this study. TN_{dep} is estimated as

$$TN_{dep} = F_{NOy} \bullet A_i \qquad (4)$$

Where, TN_{dep} is atmospheric $NO_y^- N$ deposition, kg; F_{NOy} is the flux of atmospheric $NO_y^- N$ deposition, kg N ha^{-1}; A_i is land area in ha; the parameter of i represents forestland and farmland.

Watershed export
The watershed export fraction (FE_{WS}) represents an aggregate of all processes leading to retention of diffuse N inputs during transport to the surface water (Dumont et al., 2005). It is defined as

$$FE_{WS} = e \bullet R \qquad (5)$$

Where R is runoff (m yr^{-1}) and e is set at 0.94, based on a global calibration described by Mayorga et al. (2010).

River system retention
DIN retention terms in river systems include estimates for denitrification, removal via consumptive water use, and loss in reservoirs. The river export term (FE_{riv}) is

then calculated as the multiplication of the export fractions corresponding to each of these terms. Full details are presented by Dumont et al. (2005), Mayorga et al. (2010) and Yan et al. (2010).

$$FE_{riv} = (1-D) \bullet (1-Q_{rem}) \bullet (1-L_{den}) \qquad (6)$$

DIN retention in reservoirs (D) within a watershed is estimated as a function of characteristics for each reservoir: mean reservoir depth (m), discharge intercepted by dams (km^{-3} yr^{-1}), and change in water residence time due to the construction of reservoirs (days).

$$D = \frac{1}{Q} \bullet \left[\sum_{i=1}^{n} 0.8845 \bullet \left(\frac{DEPTi}{Rti} \right)^{-0.3677} \right] \bullet Q_i \qquad (7)$$

Where $DEPT_i$ is reservoir depth, m, R_{ti} is water residence time (years), and i is the reservoir identification number within a watershed (i = 1, 2, ..., n). Q_i is the discharge intercepted by dam i, km^3 yr^{-1}; Q is the total discharge, km^3 yr^{-1}. Data of the variables and completion years for 5 artificial reservoirs in Ganjiang River watershed were compiled to calculate D.

$$Q_{rem} = \frac{Q_{irr} + Q_{div}}{Q_{nat}} \qquad (8)$$

Source contributions
The contributions of sewage inputs and each diffuse source to DIN yields at WZS are estimated by isolating the respective terms in Eq(1). The sewage contribution is calculated as the point-source DIN input to rivers (DIN_{sew} in Eq(1)) multiplied by the river export term (FE_{riv}) (Yan et al., 2010). The contribution of each diffuse source to DIN yield is calculate as

$$\begin{aligned} DIN_{fix}\% = FE_{riv} \bullet FE_{ws-fit} \bullet TN_{fix} \bullet 100 \\ \bullet \left[1 - 0.23 \bullet TN_{exp} / \left(TN_{fe} + TN_{ma} + 0.23 \bullet TN_{fix} \right) \right] / DIN_{yield} \end{aligned} \qquad (9)$$

$$\begin{aligned} DIN_{fe}\% = FE_{riv} \bullet FE_{ws-fit} \bullet TN_{fe} \bullet 100 \\ \bullet \left[1 - TN_{exp} / \left(TN_{fe} + TN_{ma} + 0.23 \bullet TN_{fix} \right) \right] / DIN_{yield} \end{aligned} \qquad (10)$$

$$\begin{aligned} DIN_{ma}\% = FE_{riv} \bullet FE_{ws-fit} \bullet TN_{ma} \bullet 100 \\ \bullet \left[1 - TN_{exp} / \left(TN_{fe} + TN_{ma} + 0.23 \bullet TN_{fix} \right) \right] / DIN_{yield} \end{aligned} \qquad (11)$$

$$\begin{aligned} DIN_{dep}\% = FE_{riv} \bullet FE_{ws-fit} \bullet TN_{dep} \bullet 100 \\ \bullet \left[1 - TN_{exp} / \left(TN_{fe} + TN_{ma} + 0.23 \bullet TN_{fix} \right) \right] / DIN_{yield} \end{aligned} \qquad (12)$$

Measured DIN export from watershed
Measured DIN yield was obtained as follows:

$$DIN_{mea} = Q \cdot C / A \qquad (13)$$

DIN_{mea} is measured DIN yields at WZS, kg N km^{-2} yr^{-1}; Q is measured discharge at WZS, 10^7 m^3 yr^{-1}; C is measured DIN (referring to NO_3^--N and NH_4^+-N) concentration at WZS, mg L^{-1}; A is watershed area, km^2.

River water samples were collected once every two months (n = 96 sampling times total) at Waizhou gauging station from 1995 to 2010 (Fig. 1) by Hydrology Bureau of Jiangxi Province. The concentration of NO_3^- in water sample was determined by the spectrophotometric phenol disulfonic acid method; NH_4^+ by spectrophotometric salicylic acid method (Duan et al., 2000). Data for daily river discharge at Waizhou station and daily precipitation and temperature in Nanchang city were obtained from the Hydrology Bureau of Jiangxi Province and China Meteorological Data Sharing Service System, respectively.

Model analysis
Paired Samples T Test Method was applied to test whether the difference between the modeled and measured values was significant at the level of $P = 0.05$ by using the software of IBM SPSS 19.0. A significant difference would indicate the model results did not agree well with the measured values. In that case, the model would have needed modification. If not, the global NEWS-DIN model could be applied in the Ganjiang River watershed to model the DIN export. Model Error (ME) (%), was calculated as

$$ME = (Mod - Mea) \cdot 100 / Mea \qquad (14)$$

Where Mod is modeled DIN export and Mea is measured DIN export for the watershed.

Trophic State Index (TSI)
Nitrogen content is one of the primary determinants of water body's trophic state index (TSI). Nutrients such as nitrogen and phosphorus tend to be limiting resources in standing water bodies, so increased nitrogen concentrations tend to result in increased plant growth, followed by corollary increases in subsequent trophic levels. TSI is calculated according to the formula,

$$TSI\left(\sum\right) = \sum W_j \cdot TSI_{(j)} \qquad (15)$$

Where, TSI is the comprehensive trophic state index of lakes. W_j is the relative weights of trophic state index of parameter j. $TSI_{(j)}$ represents the trophic state index of parameter j.

Annual data of TSI of Lake Poyang in the period 1995-2010 were obtained from Water Resources Bulletin of Jiangxi Province (http://www.jxsl.gov.cn/slgb/szygb/index.html).

Data resources
Data on social economic development, including GDP, population, urbanization rate, etc. and data of agricultural fertilization intensity, numbers of domestic animals and planting area of different crops were derived from the Statistical yearbooks of Jiangxi Province (1996-2011). Data of annual wastewater discharge were derived from Water Resources Bulletin of Jiangxi Province (1999-2011).

Results
Nonpoint and point sources N inputs
Based on statistical data, watershed N budgets were calculated by using watershed N balance model proposed by OECD (2001). It shows that the net N inputs from diffuse sources (TN_{diff}) are 10-54 times that of sewage N inputs over the period 1995-2010. Diffuse sources N inputs decrease from 4400 kg N km^{-2} yr^{-1} in 1995 to 3300 kg N km^{-2} yr^{-1} in 2010 (Fig. 3). Among the diffuse N sources, biological N fixation is the largest contributor, accounting for about 45.4 % ~ 48.3 % of total N inputs, showing a slightly variation over the period 1995-2010. Chemical N fertilizer application is the second largest contributor, accounting for about 26.0 %-30.3 % of total N inputs. Fertilizer N application decreases considerably from 55.9×10^7 kg in 1995 to 43.4×10^7 kg in 2010 over the period 1995-2010 (Fig. 3). Atmospheric N deposition and manure N inputs contribute altogether with 24.7 % of total N inputs, showing a slightly variation over the period 1995-2010. Sewage N inputs increases remarkably from 82 kg N km^{-2} yr^{-1} in 1995 to 321 kg N km^{-2} yr^{-1} in 2010.

Contribution of different N input sources
The contributions of different N sources input to DIN yields in the Ganjiang River watershed for the period 1995-2010 were estimated (Fig. 4). Biological N fixation accounts for about 73.3 % over the period 1995-2005, but after this interval it decreases quickly to 28.4 % in 2010. Fertilizer N application was the second largest contributor to DIN yield; it accounts for about 11.7 % of DIN yields over the period 1995-2005. After this period it decreased sharply to 1.2 % in 2010. Manure N and atmospheric N input together account for about 10 % of DIN yields in the period 1995-2005, but they both decreased significantly to smaller than 1 % in 2010. The percentage of sewage N input against DIN yields varies substantially. It accounts for about 5 % over the period 1995-2005, but after this interval it increases quickly to 69.7 % in 2010. For all N input sources, it indicates that biological N fixation has dominated N inputs over the period 1995-2007, but after that it was exceeded by sewage N input gradually (Fig. 4).
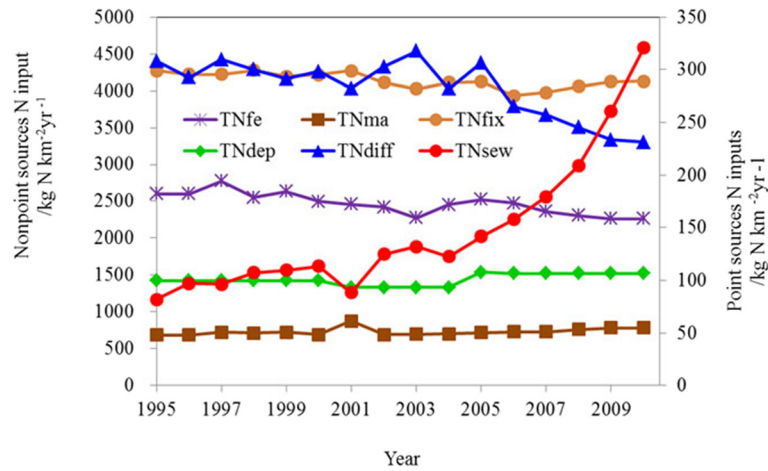
Fig. 3 Diffuse and sewage N inputs over the period 1995-2010

Sewage N inputs have been the biggest contributor to DIN yields for Ganjiang River since 2008.

Diffuse and sewage DIN inputs changes

As shown in Fig. 5, N inputs from nonpoint sources are much higher than those from point sources. The former are approximately 10-54 times the later. But as for DIN inputs, nonpoint DIN inputs decrease continuously especially after the year 2005. It decreases to 68.3 kg N km^{-2} yr^{-1} in 2010. Sewage DIN inputs increase continuously over the period 1995-2010. It increases from 40.0 kg N km^{-2} yr^{-1} in 1995 to 156.8 kg N km^{-2} yr^{-1} in 2010, showing a relative consistent changing trend with sewage TN input. The ratio of DIN and total N inputs from nonpoint sources varies from 2.1 % to 25.5 % in the period 1995-2010. The ratio of DIN and total N inputs from

point sources is about 48.8 %. It indicates that almost all the diffuse DIN inputs were retained in the watershed before entering the Lake Poyang. While about half of sewage N inputs were input to Lake Poyang as DIN from Ganjiang River.

Changes of Trophic State Index (TSI) of Lake Poyang

As shown in Fig. 6, we can see that TSI of Lake Poyang changed between 37 and 49. It decreased from 42 to 39 in 1995-1999, and it increased continuously to 49 in 2005, before decreasing to 44 in 2010. The valley value occurred in 1998, 1999, 2000 and 2002, indicating a strong dilution effect in these flood years. The value of TSI decreases remarkably after 2005, which agrees well with the modeled and observed DIN export from the Ganjiang River.
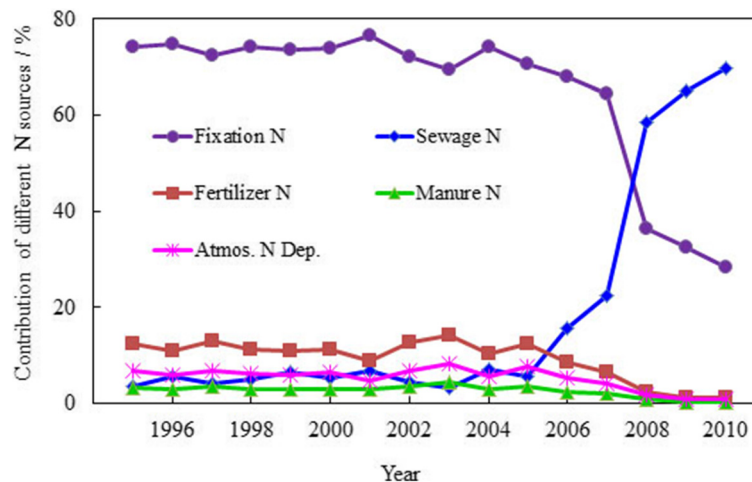

Fig. 4 Contributions of different N input sources to river DIN yields in the Ganjiang River watershed during the period 1995-2010
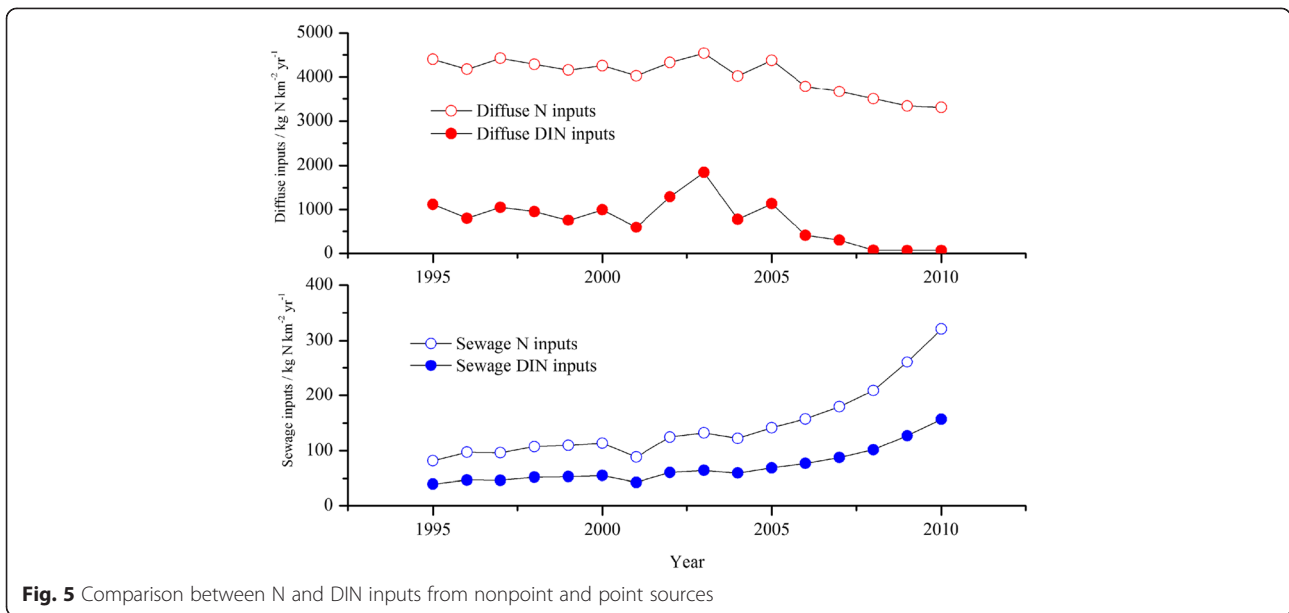
Fig. 5 Comparison between N and DIN inputs from nonpoint and point sources

Discussion

Reduction of nonpoint N sources inputs

During 1995-2010, the N fertilizer application in the watershed decreases significantly. The rapid decrease of N fertilizer application could be attributed to natural disasters and reduction of cropland. In the summers of 1998 and 2002, the Yangtze River basin suffered from flood disasters, which severely affected the agricultural production in Jiangxi Province. The fertilizer N application had declined since 1998. In Jiangxi Province, the policy of returning farmland to forest was carried out continuously in 2001-2003. About 13.3×10^4 ha and 21.3×10^4 ha farmland were returned to forestland in 2002 and 2003, respectively, covering over 60 counties throughout the province. Accordingly, the fertilizer N application decreased sharply. The lowest value of fertilizer N application occurred in 2003. After that the fertilizer N application increased to meet people's need

Fig. 6 Annual changes of TSI from April to September of Lake Poyang in the period 1995-2010

for food in the next two following years. Accordingly, TN export by harvesting decreased remarkably in 2001-2003 (Fig. 3). After 2005, with the acceleration of industrialization process, more and more farmers moved to cities to live and work. Due to the lack of labor force in the countryside and the reduction of farmland, inputs from fertilizer N application decreased year by year.

Some advanced production technology was applied in agriculture and some excellent crop varieties were promoted to increase crop yields, leading to the growth of N export by harvesting. More than half of N was exported by harvesting on average during the period 1995-2010 in the Ganjiang River watershed. Due to the decrease of anthropogenic N inputs and growth of N export by harvesting, the net N surplus in agriculture decreased remarkably in the period 1995-2010.

Increase of sewage N input driven by urbanization

The economy in the Ganjiang River watershed has quickly developed in the period 1995-2010. The gross domestic product was 4.6×10^{10}\$ (1\$ = 6.8 RMB) in 2010, with an increase of about seven times from that in 1995. In 1995-2010, the total number of population increased from 1.65×10^7 in 1995 to 1.97×10^7 in 2010, with an average annual growth rate of 1.2 % (Jiangxi Statistical Yearbook 2011). The urbanization rate continuously increased from 17.2 % in 1995 to 35 % in 2010. The growth of population and urbanization process will undoubtedly lead to sharp increase of wastewater discharge. According to Statistical Bureau of Jiangxi Province (1996-2011), the wastewater discharge in the Ganjiang River watershed increased from 1.1×10^{12} kg in 1995 to 3.1×10^{12} kg in 2010. Accordingly,
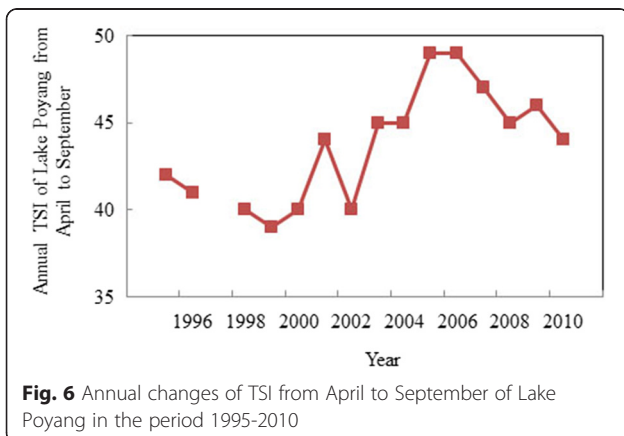
sewage N inputs increased significantly from 6.8×10^6 kg in 1995 to 26.8×10^6 kg in 2010. Although sewage treatment ratio increased significantly in recent years, N removal fractions were very low due to the lack of advanced treatment facilities. As a result, a large portion of untreated sewage was discharged directly into surface water, contributing to sewage N pollution in the estuary to Lake Poyang. Under the background of global warming, as the demand for water is increasing, sewage discharge from urban and rural areas will increase continuously. The contribution of sewage discharge to DIN yield for the Ganjiang River Watershed will continue to increase based on the Global NEWS-DIN model.

DIN yield decrease

Rivers play an important role in delivering nutrients from landscape to water bodies. As the longest river in Lake Poyang basin, Ganjiang River transports a great deal of nutrients to lake, which affects the lake trophic status greatly. According to Yan et al. (2010), the fraction of N lost from landscape to rivers as DIN (FE_{WS}) should increase over time along with the increasing input of newly nitrogen driven by human activities, and vice versa. The fluctuation of DIN yield in 1995-2005 indicates that anthropogenic N input is relatively steady. The decrease of DIN export for Ganjiang River in 2005-2010 reflects the decrease of N input and the enhancement of retaining DIN for landscape in the watershed.

Soils that contain high N levels can become a primary source of dissolved N in runoff, and thus contribute to the degradation of surface water quality (Edwards and Daniel 1993). The capacity to store N can ultimately become saturated as N inputs into the watershed increase beyond the requirements of the ecosystem. As the N saturation is reached, N retention within the watershed can be expected to decrease rapidly due to the inability of terrestrial ecosystems to utilize further N additions. Accordingly, the fraction of N lost from landscape to rivers as DIN should decrease over time following the decreasing N inputs driven by human activities. The forest has a strong ability to fix nitrogen. The Jiangxi Province government gave much importance to afforestation as its forest cover increased from 50 % in 1995 to 63 % in 2010. The forest ecosystem plays a vital role in improving the capacity of landscape to storing N. In this article, FE_{ws-fit} (the fitted fraction of N lost from landscape to rivers as DIN) varied slightly in 1995-2005, while it decreased significantly in 2006-2010, providing evidence for the recovering capacity of watersheds to retain N as inputs decreased as a direct result of human activities.

Climate change Impacts on river runoff, nutrients flux and atmospheric N deposition

An increase in water temperature alters the rate of operation of some key chemical processes in water. Also, changes in intense precipitation events impact the rate at which materials are flushed to rivers and lakes, and changes in flow volumes affect dilution of loads (Kundzewicz et al. 2008). The average annual temperature in recent 5 years (2006-2010) is 0.5 °C higher than that in 1995-2005. While the average annual precipitation in 2006-2010 is 215 mm lower than that in 1995-2005. The warming and drying climate reduces the water volumes in the watershed, and thus reduces the dilution capacity of Lake Poyang.

Key consequences of declining water quality due to climate change include increasing water withdrawals from low-quality sources; greater pollutant loads from diffuse sources due to heavy precipitation (via higher runoff and infiltration); water infrastructure malfunctioning during floods; and overloading the capacity of water and wastewater treatment plants during extreme rainfall (Kistemann et al., 2002). Recent studies show that climate plays a dominant role in changing basin hydrology and runoff in the Lake Poyang basin (Guo et al., 2008; Ye et al., 2013). The measured DIN yield is highest in the 1998 flood year, which indicates that the increase of precipitation, especially the increased frequency of summer storms is the main reason for the increase of runoff. Runoffs measured at most gauging stations in the Lake Poyang basin show increasing trends, but monthly variations are obviously different. The monthly variability of runoff may indicate a change of seasonal climate regime. The increase of annual runoff was primarily affected by climate change for the whole catchment (Ye et al., 2013). However, nowadays, little work has been conducted to quantify the effects of climate change on the water environment of Lake Poyang due to the lack of data on water quality in the basin.

The atmospheric NO_y^--N deposition mainly comes from coal combustion (Tian et al., 2001). Under the background of global warming, the rapid growth in energy consumption leads to the growth of NO_y emission in China (Tian and Hao, 2003; Wang et al., 2012). High emissions produce high deposition. Consequently, atmospheric N deposition has increased considerably over the past 16 years (Liu et al., 2013).

Uncertainty analysis
DIN model performance
Comparison of modeled versus measured DIN yields indicates that NEWS-DIN's predictive capacity is quite high, but varies from year to year. It shows that the differences between modeled and measured values are not significant at the level of $P = 0.05$ by using Paired Samples T Test method in the software of IBM SPSS 19.0,

Fig. 7 Modeled and Measured DIN yield for Ganjiang River
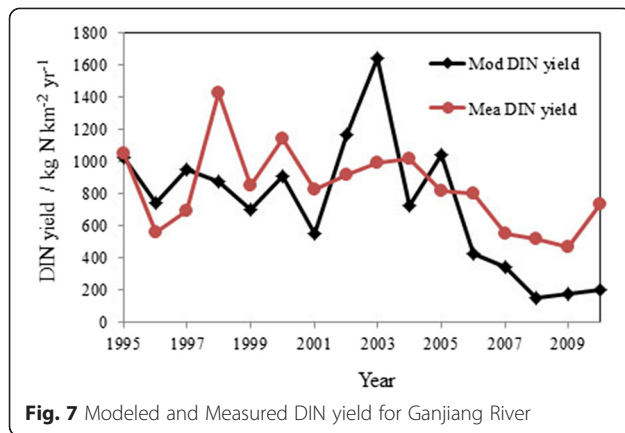
with a 95 % confidence interval over the period 1995-2010 (n = 16, P = 0.234). Model errors vary from -63.8 % ~ 66.9 % with the average value of -10.8 %.

Modeled DIN yield from Ganjiang River varies from 151 kg N km^{-2} yr^{-1} to 1645 kg N km^{-2} yr^{-1} in 1995-2005, not showing remarkable changing trend (Fig. 7). However, it decreases significantly after 2005 and shows the same changing trend with measured values. In this case, modeled values are evidently lower than measured ones, which indicates that the model underestimates the DIN export for the Ganjiang River in the period 2005-2010. Moreover, the model does not catch the peak value of river DIN yield in the 1998 flood year.

From Fig. 7, we see that the modeled DIN yield is different from measured DIN yield in 2001-2004. That is because the TN exports, which accounts for about 46 %-62 % of diffuse TN inputs, show abnormal variations in 2001-2004 (Fig. 3). In 2003, an extreme drought hit the whole Lake Poyang basin causing severe food reduction. In 2003, the rice yield in Jiangxi Province reached its lowest limit, which was 1.3×10^{10}kg. Simultaneously, the policy of returning farmland to forestland was carried out in whole province during 2001-2003 leading to the decrease of cultivated land area. Therefore, TN export by harvesting decreased significantly in these three years. The FE$_{ws\text{-}fit}$ plays a decisive role in the calculation of DIN yield for the Ganjiang River in the Global NEWS-DIN model. It is calculated based on the positive relationship with RSD (Eq(16)). According to Wang et al. 2014, the R^2 (determination coefficient) of the equation is 0.41, which indicates that RSD can only explain 41 % of the variation of FE$_{WS\text{-}fit}$. The model still needs adjustment considering other factors.

Watershed N retention

In the Global NEWS-DIN model, FE$_{WS}$ is calculated as a simple function of runoff only, which does not exhibit long-term trends (Yan et al., 2010). In this article, we calculated an adjusted FE$_{WS}$, that is FE$_{WS\text{-}fit}$, by using

the watershed export coefficient model proposed by Wang et al. (2014) (Eq(6)). The model is defined as
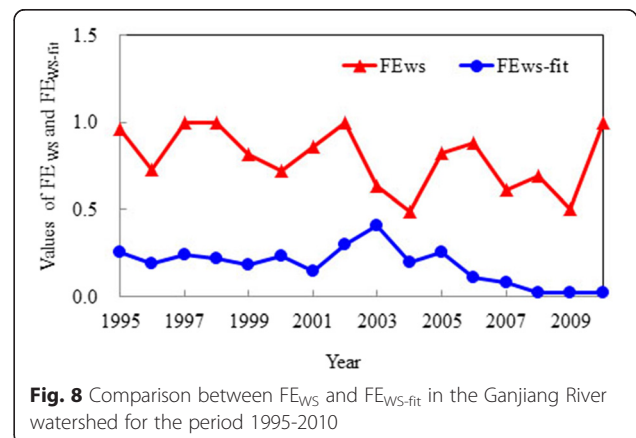
$$FE_{WS-fit} = 2.75(RSD) - 1.09 \qquad (16)$$

Where, RSD represents the ratio of watershed N surplus against N input in the Ganjiang River watershed (Wang et al., 2014). It indicates that the lesser RSD is, the higher the capacity of watershed retention for nonpoint DIN inputs (1- FE$_{WS\text{-}fit}$).

Comparison between FE$_{WS}$ and FE$_{WS\text{-}fit}$ (fitted or adjusted FE$_{WS}$) is shown in Fig. 8. It shows that, while FE$_{WS\text{-}fit}$ are substantially lower than FE$_{WS}$ in the period 1995-2010, they show the same decreasing trend, providing evidence for the recovering capacity of watersheds to retain N as nonpoint inputs decrease as a direct result of human activities. Variation of FE$_{WS}$ and FE$_{WS\text{-}fit}$ indicates that leaching and runoff from agricultural soils to surface water is not constant.

Denitrification

Denitrification is a critical process regulating the removal of bioavailable nitrogen (N) from natural and human-altered systems (Seitzinger et al., 2006). In the Global NEWS-DIN model, DIN loss by denitrification during river transport is estimated as a simple function of drainage area, which does not exhibit long-term change trends (Dumont et al., 2005). However, the uncertainty lies in how the rates of denitrification will change as hydrology and geomorphology varythroughout the river network (Seitzinger et al., 2006). How rates of denitrification will respond to the varying loading of N in the watershed and how nutrient removal processes scale across the broad range of stream sizes that comprise river networks still remains uncertain (Fisher et al., 2004; Wollheim et al., 2006; Yan et al., 2012).

Fig. 8 Comparison between FE$_{WS}$ and FE$_{WS\text{-}fit}$ in the Ganjiang River watershed for the period 1995-2010

Conclusions

Based on the quantitative analysis of nitrogen balance within the Gangjiang River watershed, the inputs of N and exports of DIN from Gangjiang River to Lake Poyang for the period 1995-2010 was estimated, by using the Global NEWS-DIN model. It shows that N inputs from nonpoint sources are approximately 10-54 times that from point sources. Almost all the diffuse DIN inputs were retained in the watershed before entering the lake Poyang. While about half of sewage N inputs were input to Lake Poyang as DIN from the Ganjiang River. Modeled DIN yield from Ganjiang River decreased after 2005 significantly, providing evidence for the recovering capacity of watersheds to retain DIN as inputs decrease as a direct result of human activities. The values of TSI (Trophic State Index) of Lake Poyang agree well with modeled DIN yields from the Ganjiang River. The study also demonstrates a varied contribution of different N inputs to river DIN yields during the study period. In the period 1995-2005, biological N fixation was the largest source of DIN yields, with a contribution ranging from 69.6 % to 74.7 %. But after such interval, this contribution decreased significantly to 28.4 % in 2010. Animal manure N inputs and atmospheric N inputs together accounted for about 10 % of the total DIN yields in the period 1995-2005, showing a relatively stable trend. Sewage N inputs accounted for about 5.3 % of DIN yields prior to 2005, but this account increased significantly to 69.7 % in 2010. The impact of climate change on the water environment of Lake Poyang was not clear due to lack of data on water quality in the basin. However, it plays a dominant role in changing basin hydrology and runoff in the Lake Poyang basin. More attention should be paid to reducing sewage N discharge to Lake Poyang in the background of global warming.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

XL carried out the river DIN export study, participated in the sequence alignment and drafted the manuscript. *LZ* provided some important data and methods guidance. *GY* and *HL* conceived of the study, and participated in its design and coordination. *BH* participated in the design of the study and the data processing. *YC* helped to draft the manuscript. *XT* performed the statistical analysis. All authors read and approved the final manuscript.

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