Simulation of nitrogen and phosphorus pollution in typical agricultural and forested basins as well as relevant reduction effect based on SWAT model

Wu Li, Chen Zhe, Liu Hui-ying and Wang Dun-qiu

ABSTRACT

Non-point source nitrogen and phosphorus pollution is a critical threat to aquatic ecosystems and a potential risk to drinking water safety. To precisely control nitrogen and phosphorus pollution in the river basin, in this study, we identified key pollution areas of the river basin, analyzed the main characteristics of pollution sources as well as their contribution to the river basin pollution, and conducted simulation analysis on reduction measures based on the SWAT model. The results showed the following. (1) The simulation effect of the calibrated model was good, and sub-basins 3, 39 and 96 were the key source areas, the main sources of pollution were combined pollution from livestock and poultry breeding and planting industry. (2) Crops had the largest input and output for both nitrogen and phosphorus, the output of which was 6,137.8 t/a and 562.4 t/a respectively. The urban point sources had the highest output rates of nitrogen and phosphorus, 75.7% and 67.5% respectively. (3) With the optimal combination of reduction measures, nitrogen and phosphorus were reduced by 1,438.9 t and 85.3 t respectively, i.e., the reduction rates were the highest. The reduction effect for total nitrogen was better than that for total phosphorus.

Key words | agricultural and forested basins, nitrogen and phosphorus pollution, reduction, SWAT

Wu Li
Chen Zhe
Wang Dun-qiu (corresponding author)
Guangxi Key Laboratory of Environmental Pollution Control Theory and Technology, College of Environmental Science and Engineering,
Guilin University of Technology,
Guilin 541004,
China
E-mail: *wangdunqiu@sohu.com*

Liu Hui-ying
Yongzhou Hydrology and Water Resources Investigation Bureau of Hunan Province,
Yongzhou 425000,
China

Wu Li
Environmental Protection Bureau of Yongzhou Economic and Technological Development Zone,
Yongzhou 425000,
China

HIGHLIGHTS

- Using local census data of pollution sources based on SWAT model.
- Identifying the key pollution sources through the characteristics of main pollution source and output.
- Using data of pollution sources examining contribution rate and output rate.
- The reduction effects of different reduction measures were compared.
- Using long-term hydrology, water quality data rate and validation, the result of model is reliable.

INTRODUCTION

The protection of water resources is essential for local social and economic development. To strengthen the protection of water resources in river basins, industrial point source pollution in major river basins of China has been effectively controlled. However, non-point source pollution is still a serious problem, which has significantly compromised water quality, and made the governance of river basins more difficult (Chen *et al.* 2016; Wang *et al.* 2019). The non-point source nitrogen and phosphorus pollutants are mainly from agricultural and urban pollution sources, among which the urban pollution sources include living pollution sources and industrial pollution sources in urban hubs and scattered rural areas. Agricultural pollution sources may be divided into livestock and poultry breeding, agricultural

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planting, and aquaculture, from which the time, route, quantity and category for pollution are uncertain. However, if their spatial distribution can be reflected accurately, the managers of river basins may accurately locate the key areas for governance. Therefore, some hydrological models, such as the HSPF model, AGNPS model and SWAT model, have been widely applied. The SWAT model takes into account soil type, land type, climate, and vegetation type, and its simulation results are characterized by strong temporal sequence and significant spatial distribution (Wang *et al.* 2020). Many scholars all over the world have studied regional non-point source pollution load and relevant distribution characteristics utilizing the hydrology–hydrodynamics–water quality linkage simulation function of the SWAT model, and accurately located the key source areas of relevant basins (Song *et al.* 2013; Chen *et al.* 2015). Analyzing the main characteristics of pollution sources and calculating the contribution rate of the pollution sources to the water quality pollution in relevant basins based on a comprehensive investigation of pollution sources may provide technical support for accurate formulation of policies concerning the basins. Previous studies have used output coefficients to calculate the input of nitrogen and phosphorus pollutants, so as to simulate the contribution and output rate of pollution sources, which often caused a great deviation from the actual situation (Mockler *et al.* 2017; He *et al.* 2019a, 2019b; Hua *et al.* 2019). Nitrogen or phosphorus pollution is closely related to rainfall runoff process, soil type, vegetation type, agricultural production mode (fertilizer application, tillage mode, etc.) and agricultural management measures. At present, many river basins have implemented different management measures, which have caused a great difference in nitrogen and phosphorus load reduction. Generally, the managers take the optimal integrated management measures dependent on local conditions, e.g. the optimal management measures for the Mary River Basin summarized by Richards *et al.* (2008), by which the phosphorus load was reduced by 50%. Wojciechowska *et al.* (2019) studied different management measures and policies in three small basins. In addition, for regions with serious soil and water loss, the prevention and control of soil and water loss and nutrient loss are often considered together in management measures for relevant basins, so as to make a comprehensive strategy (Niraula *et al.* 2012; Himanshu *et al.* 2019). In this study, a simulation of non-point source nitrogen and phosphorus pollution in the Yongzhou Basin of Xiangjiang River was carried out using local census data of pollution sources (from the second national census of pollution sources carried out recently) and farmland survey data (from the latest farmland quality survey report) based on the SWAT model, and three major goals for basin management and control were realized: (1) the key pollution areas of the river basin were identified; (2) the main characteristics of basin pollution sources and their contribution to the basin pollution were analyzed; (3) specific reduction measures were put forward, and the reduction effect was simulated. This study may be taken as a reference for effective control of nitrogen or phosphorus pollution in typical agricultural and forested basins, and especially the analysis of the presented key source areas, the apportionment of the sources in the basin and nitrogen and phosphorus pollution control countermeasures may support local initiatives better to protect the source of Xiangjiang River.

OVERVIEW OF THE STUDY REGION

Overview of the region

The study region is located on the upper reaches of the Xiangjiang River. Xiangjiang River is the largest river in Hunan Province, and a major tributary of the Yangtze River as well. It originates from Haiyang Mountain, Lingchuan County, Guangxi Zhuang Autonomous Region in the west, and Wild Dog Ridge, Lanshan County, Hunan Province in the east. Its total length is 948 km, and the area of the basin is 94,700 km^2. As a basin with the most abundant water resources and the highest development and utilization rates, it belongs to the Dongting Lake system and is dominated by a subtropical monsoon climate, with long-term average annual precipitation of 1,200–1,900 mm, and annual average temperature at 17.6–18.6 °C. Red soil and yellow soil are its main soil types, with perennial average sunshine between 101.5 and 113 $kcal/cm^2$.

Planting conditions

In this study region, double-season rice, maize, and oilseed rape are the main crops. To simulate soil nitrogen and phosphorus loss with farmland runoff, it is assumed that the double-season rice is planted in paddy fields and single-season maize in upland fields every year. The main fertilizers are nitrogen fertilizers and compound fertilizers. Urea with nitrogen content of 46% is the main nitrogen fertilizer while for the compound fertilizers, mainly a fertilizer containing nitrogen, phosphorus and potassium, 15% content for each, is adopted. For double-season rice and maize, there are base fertilizer and topdressing fertilizer for each season of rice. The application of fertilizers for the main crops is as shown in Table 1.

STUDY METHODS

Database construction

The database for the SWAT model was divided into two categories: spatial database and attribute database. All spatial data were converted into the projection coordinate system: WGS_1984_UTM_Zone_49N; after that the data of meteorological, land use type, soil type and the daily load of urban point sources and livestock and poultry breeding pollution sources were used for simulation, likewise the hydrology and water quality data were used for model calibration and verification respectively. See Table 2 for the names, parameters and sources of the main data.

Model construction and land use distribution

In this study, ARCSWAT was used to perform DEM image recognition, calculate the catchment area of the basin, extract the river network and delimit the sub-basin. Based on the thresholds of land use type, soil type and slope division set as 10%, 10% and 15%, the total basin area was 18,633.6 km^2, and the basin was divided into 115 sub-basins and 818 HURs. There were eight types of land in the study region. The land use types that covered the largest areas were forest land, paddy field and dry land, of which the areas were 11,393.5 km^2, 3,186.8 km^2 and 2,057.2 km^2 respectively, accounting for 89.3% of the total basin area of the study region together. The study region is a typical region dominated by agriculture and forestry, as shown in Figures 1 and 2.

Table 1 | Application of chemical fertilizers for the main crops

Category	Rice		Agricultural land
	Early rice	Late rice	Crop
Nitrogen fertilizer (kgN·ha^{-1})	10.8	9.5	10.6
Phosphate fertilizer (kgP·ha^{-1})	4.6	3.7	5.1

Soil type distribution

The soil type map reflects the spatial distribution of soil in the study region. This study utilized HWSD data downloaded from the FAO website to extract a 1:1,000,000 soil type map of Yongzhou, effective numerical range: 11,333–11,927. Some attribute data can be found through the HWSD_DATE database, and the rest of the data can be calculated by SPAW software. Thus, the soil database can be established (Figure 3).

MODEL CALIBRATION AND EVALUATION OF THE MODEL

Model calibration

In this study, the SUFI method of SWAT-CUP software was used for sensitivity analysis of model parameters, in which 71 parameters related to runoff and nitrogen or phosphorus cycle were selected for iterative modelling with the Global Sensitivity Analysis method. The parameters with the highest sensitivity are as shown in Table 3.

Evaluation of the model

In the study, the coefficient of determination (R^2) and Nash–Sutcliffe efficiency coefficient (Ens) were selected as the indexes for evaluation of the model. The coefficient of determination (R^2) reflects the correlation between simulated value and actual value of the model. The larger R^2, the better the consistency between the simulated value and the actual value. The Nash–Sutcliffe efficiency coefficient (Ens) represents the overall efficiency of model simulation.

Table 2 | Parameters required for SWAT model database establishment

Type		Format	Data type	Source	Remarks
Spatial data	Digital elevation model	GRID	Elevation data	Geospatial data sites	STRM with 12 m × 12 m resolution
	Land use type	GRID	Land use type	Resource and Environmental Science Center, Chinese Academy of Sciences	Land use map with resolution of 1 km × 1 km
	Soil type	GRID	Soil distribution type	Resource and Environmental Science Center, Chinese Academy of Sciences	Soil type map with resolution of 30 m × 30 m
Attribute data	Meteorological data	TXT table	Daily rainfall, the maximum and minimum mean temperature, daily radiation, wind speed, relative humidity, evaporation capacity, etc.	China Meteorological Data Network	Term of data for Dao County and Lengshuitan station: 2000–2019
	Hydrology and water quality data	EXCEL table	Monthly runoff, nitrogen and phosphorus concentrations	Yongzhou Hydrographic Bureau	Term of data: 2000–2019
	Pollution source data	EXCEL table	Data of pollution sources from urban point sources, livestock and poultry breeding, and planting industry	Yongzhou Ecological Environment Bureau	Data from the second national census of pollution sources
	Data on crops and fertilizers	Word file	Crop species, fertilization data, agricultural management measures	Yongzhou Agricultural and Rural Bureau	Farmland quality survey report
	Soil data		Hydrologic characteristics, density, electrical conductivity as well as physical and chemical properties of soil	Scientific Data Center for Cold and Arid Regions	HWSD soil texture data set
	Management measures		Planting pattern as well as fertilization dosage and time	Field survey and relevant statistical yearbook	

The closer the value to 1, the better the suitability of the model simulation. The formulas for calculation of R^2 and Ens are as follows:

$$R^2 = \left[\frac{\sum_{m=1}^{n}(O_m - \bar{O})(P_m - \bar{P})}{\sum_{m=1}^{n}(O_m - \bar{O})^2 \sum_{m=1}^{n}(P_m - \bar{P})^2}\right]^2$$

$$Ens = 1 - \frac{\sum_{m=1}^{n}(O_m - P_m)^2}{\sum_{m=1}^{n}(O_m - \bar{O})^2}$$

where O_m = the measured value for the mth time, $\bar{O}$ = the average measured value during the entire simulation period, P_m = the simulated value for the mth time, $\bar{P}$ = the average simulated value during the entire simulation period.

Usually, R^2 and Ens should be combined for evaluating the model parameter calibration. Generally speaking, as long as both $R^2 > 0.6$ and Ens > 0.5 are satisfied, the simulation results are acceptable (Moriasi *et al.* 2015). To avoid errors caused by the zero of many variables in the initial operation stage of the model, the first five years were selected as the warm-up period of the model, so as to improve the accuracy of the model. Spatially, the data from Dao County station and Lengshuitan station were selected for calibration in the upstream and downstream respectively, and the data were calibrated in sequence from the upstream to the downstream. The flow rate was calibrated first, and then the ammonia nitrogen and total phosphorus were calibrated (Zhao *et al.*2017).

Runoff, ammonia nitrogen and total phosphorus simulation: Dao County station took the years 2005–2017 as the period for calibration while Lengshuitan station took the years 2012–2017 as the period for calibration. At the same time, the years of 2018 and 2019 were taken as the

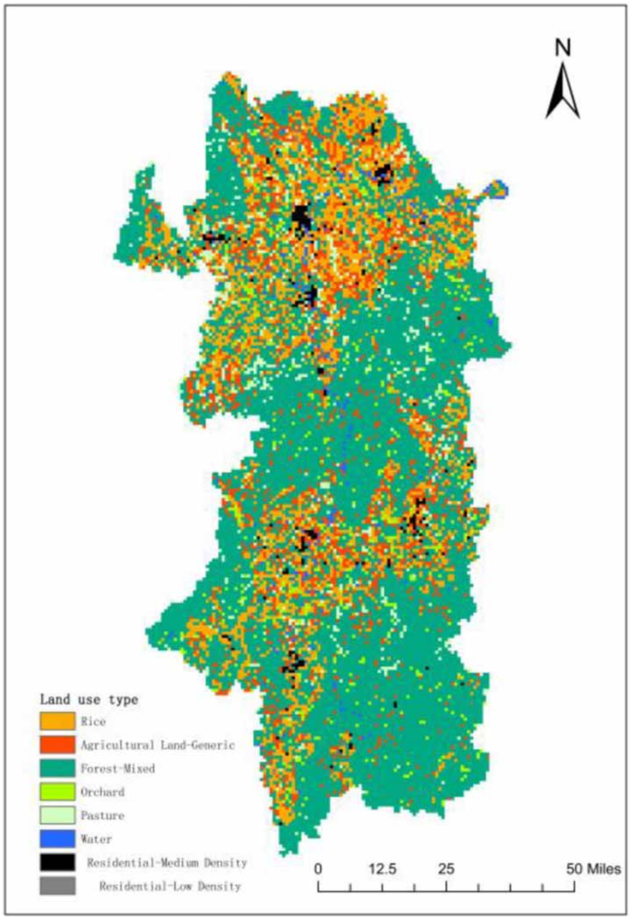

Figure 1 | Land use types in Yongzhou Basin of Xiangjiang River in 2018.

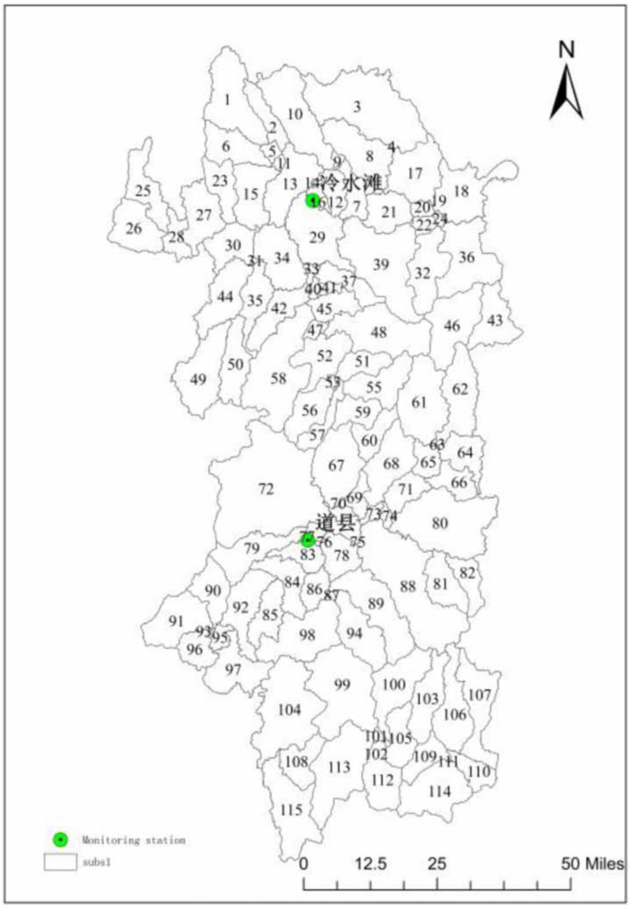

Figure 2 | Division and station distribution of Yongzhou Basin of Xiangjiang River in 2018.

validation period. For simulation accuracy values of runoff, ammonia nitrogen and total phosphorus of the two stations, see Figure 4. $R^2 > 0.68$ and Ens > 0.61 for runoff, ammonia nitrogen and total phosphorus of the two stations indicated that the SWAT model was suitable for Yongzhou Basin of Xiangjiang river, and Lengshuitan station is better than Dao County station in simulation accuracy.

RESULTS AND DISCUSSION

Analysis of characteristics of main pollution sources

There were a total of 363 urban point sources as the pollution sources in the study region, including 18 centralized sewage treatment plants in urban areas, 143 centralized sewage treatment facilities in rural areas (used for statistics of rural domestic sewage emissions), 202 industrial enterprises (with wastewater discharged directly into the river channel), and 2,758 livestock and poultry farms above the designated scale. In the region, the total nitrogen emission load was 12,927.12 t/a, the total phosphorus emission load was 1,501.82 t/a, the total nitrogen emission load and the total phosphorus emission load for the planting industry were 9,464.1 t/a and 864 t/a respectively, for livestock and poultry farms above the designated scale were 2,362.29 t/a and 575.66 t/a respectively, and for point sources in urban areas were 1100.73 t/a and 64.32 t/a respectively. The top six total nitrogen and phosphorus inputs from high to low in Yongzhou Basin of Xiangjiang River are as shown in Table 4 and Table 5. The maximum sub-basin inputs of total nitrogen and total phosphorus were 796.01 t and 88.49 t respectively, and the top three sub-basins for total

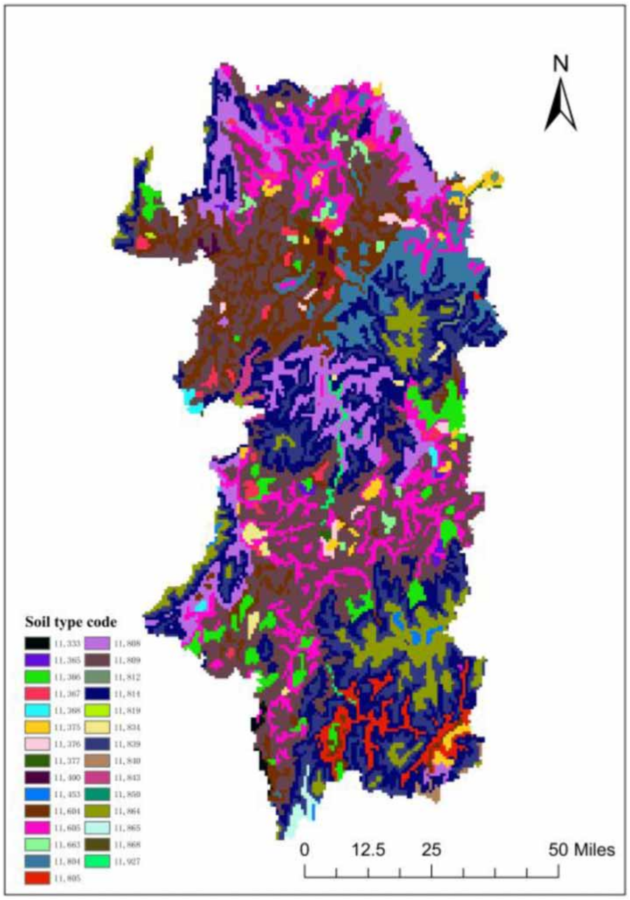

Figure 3 | Soil type map of Yongzhou Basin, Xiangjiang River in 2018.

nitrogen input were sub-basins 3, 72 and 39. Therefore, sub-basins 3 and 39 are the most centralized areas for output of total nitrogen and total phosphorus. The top three sub-basins for total phosphorus input were sub-basins 3, 39 and 104. Sub- basin 3 is located in the northwest of Qiyang County, including 13 urban point sources, two centralized sewage treatment plants and 143 livestock and poultry farms above the designated scale. For the planting industry, livestock and poultry breeding, and urban point sources, the total nitrogen input accounted for 68.49%, 19.89%, and 11.62% respectively, and the total phosphorus input accounted for 56.25%, 38.22%, and 5.54% respectively. The main sources of pollution are the combined pollution from the planting industry, livestock and poultry breeding, and urban point sources, mainly of the planting industry and livestock and poultry breeding. Sub-basin 39 is located in the northeast of Lingling District, including six urban point sources, and 80 livestock and poultry farms above the designated scale. For the planting industry, urban point sources, and livestock and poultry breeding, the total nitrogen emission load accounted for 74.52%, 0.11% and 25.37% respectively, and the total phosphorus emission load accounted for 49.28%, 0.27% and 50.45% respectively. The main sources of pollution were the combined pollution from the livestock and poultry breeding and the planting industry, mainly from livestock and poultry breeding.

Table 3 | Evaluation of model simulation results of the study region

Runoff parameter	Definition of parameter	N parameter	Definition of parameter	P parameter	Definition of parameter
ESCO	Soil evaporation compensation coefficient	GW_REVAPMN	Net flow coefficient of shallow groundwater	ERORCP	Phosphorus enrichment rate
CN2	SCS runoff curve number	ERORGN	Nitrogen permeability coefficient	BIOMIX	Biomixing efficiency coefficient
CN_K2	Effective hydraulic conductivity of main channel bed	CN2	SCS runoff curve number	PPERCO	Phosphorus infiltration coefficient
GW_REVAPMN	Net flow coefficient of shallow groundwater	SHALLST_N	Nitrate concentration in the basin discharged to the channel through groundwater	PHOSKD	Soil phosphorus distribution coefficient
SURLAG	Surface runoff lag coefficient	NPERCO	Nitrogen permeability coefficient	AI2	Proportion of P in the biomass of algae
ALPHA.BF	Base flow coefficient	AI6	Nitrogen portion in the biomass of algae	CH_OPCO	Organophosphate concentration in channel

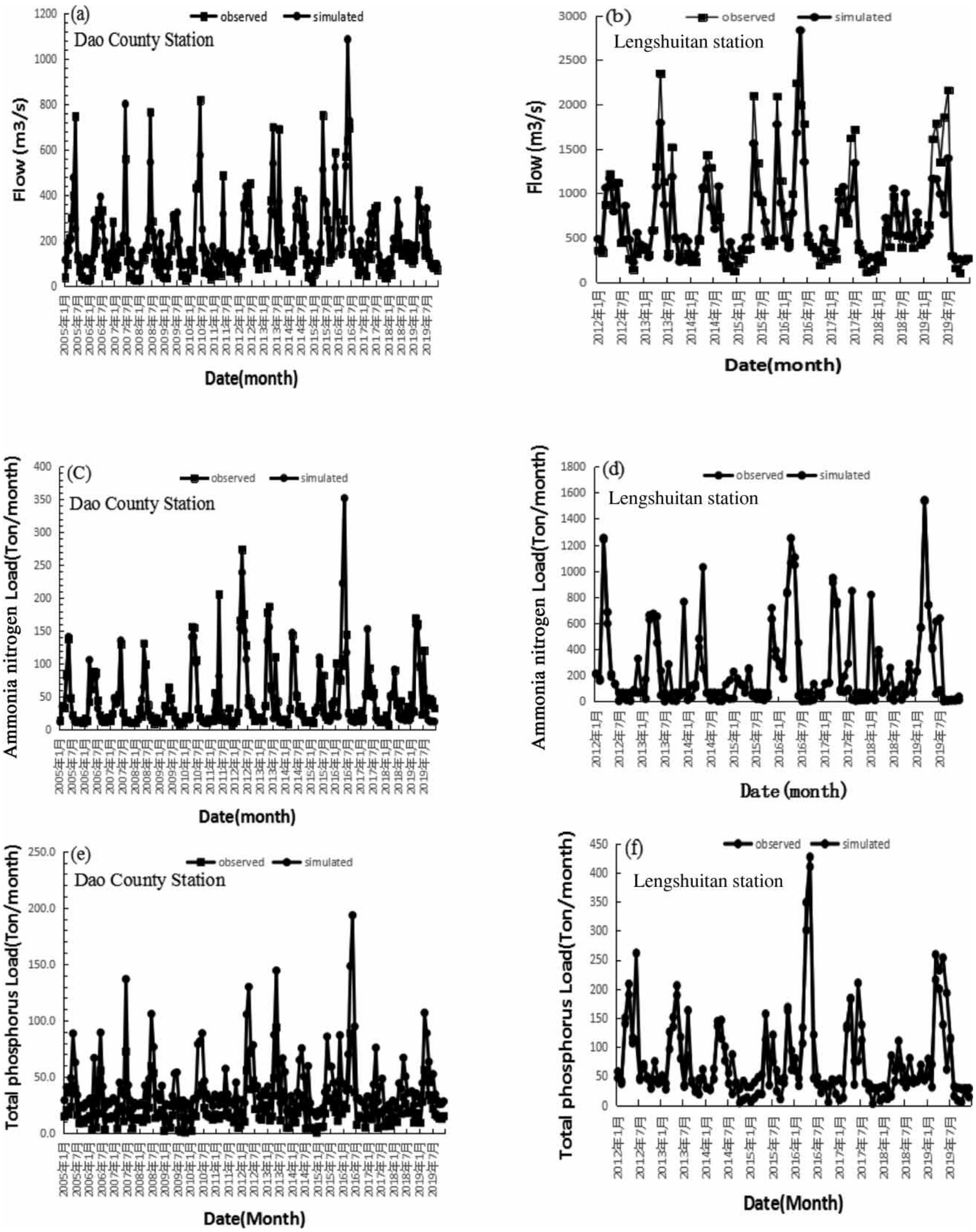

Figure 4 | Calibration and verification results of runoff, ammonia nitrogen and total phosphorus in Lengshuitan station and Dao County station.

Table 4 | Total nitrogen emission and its proportion in the Yongzhou Basin of Xiangjiang River

Sub-basin code	Crop cultivation/t	Point source in town/t	Livestock pollution/t	Total nitrogen emission/t	Proportion of crop cultivation(%)	Proportion of point source in town(%)	Proportion of livestock and poultry breeding (%)
3	545.20	92.46	158.35	796.01	68.49	11.62	19.89
29	293.60	0.53	98.26	392.39	74.82	0.14	25.04
39	360.26	0.53	122.63	483.41	74.52	0.11	25.37
72	454.30	1.32	67.96	523.57	86.77	0.25	12.98
80	298.97	125.27	56.69	480.93	62.16	26.05	11.79
104	259.33	4.74	140.46	404.53	64.11	1.17	34.72

Note: Crop-planting emissions in each sub-basin = emissions load for planting industry × farmland area/total area of sub-basin.

Table 5 | Total phosphorus emissions and proportion in the Yongzhou Basin of Xiangjiang River

Sub-basin code	Crop cultivation/t	Point source in town/t	Livestock pollution/t	Total phosphorus emission/t	Proportion of crop cultivation(%)	Proportion of point source in town (%)	Proportion of livestock and poultry breeding (%)
3	49.77	4.90	33.82	88.49	56.25	5.54	38.22
29	26.80	0.06	19.66	46.52	57.62	0.13	42.25
39	32.89	0.18	33.67	66.74	49.28	0.27	50.45
72	41.48	0.18	17.80	59.46	69.75	0.31	29.94
80	27.29	4.49	15.31	47.09	57.96	9.53	32.51
104	23.68	0.33	40.35	64.35	36.79	0.51	62.70

Note: Crop-planting emissions in each sub-basin = emissions load for planting industry × farmland area/total area of sub-basin.

Analysis of spatial distribution characteristics concerning output intensity of nitrogen and phosphorus pollution

Due to the fact that the census data of pollution sources were based on year 2017, the model output results select 2017 data for analysis. The spatial distribution concerning input and output intensity of total nitrogen and total phosphorus in the whole basin is as shown in Figure 5(a) and 5(b). The sub-basins with large pollution load input and output are mainly distributed in the main stream of Xiangjiang River and its north tributary. The output intensity of total nitrogen and total phosphorus reached 0.44–15.52 kg·ha^{-1} and 0.02–1.41 kg·ha^{-1} respectively. Sub-basins 98–103 in the upstream basin of Xiaoshui River were less polluted, the total nitrogen output intensity was less than 2.90 kg·ha^{-1}, and the total phosphorus output intensity was less than 0.28 kg·ha^{-1}. In the north basin, sub-basin 35 at the upper reaches of Xiangjiang River, sub-basins 21 and 39 at the lower reaches of Xiangjiang River, tributaries 2 and 3 of Luhong River, and sub-basin 96 in the southern basin were seriously polluted, with total nitrogen output intensity greater than 11.09 kg·ha^{-1}, and total phosphorus output intensity greater than 1.11 kg·ha^{-1}. Obviously, for sub-basins 3 and 39 in the north, both inputs and outputs of total nitrogen and total phosphorus were very high while for sub-basin 96 in the south, the key source area for nitrogen and phosphorus treatment in this basin, the outputs of total nitrogen and total phosphorus were very high. The reason why those sub-basins had very high outputs of total nitrogen and total phosphorus was that the livestock and planting industry developed rapidly, Moreover ineffective measures have been taken to reduce emissions by local government. For instance, Jianghua county (located around sub-basin 96) cooperated with Guangdong Wen's Food Group Co., Ltd, to introduce many large-scale pig breeding projects. According to the Statistical Yearbook, high-standard farmlands were completed in Yongzhou City every year.

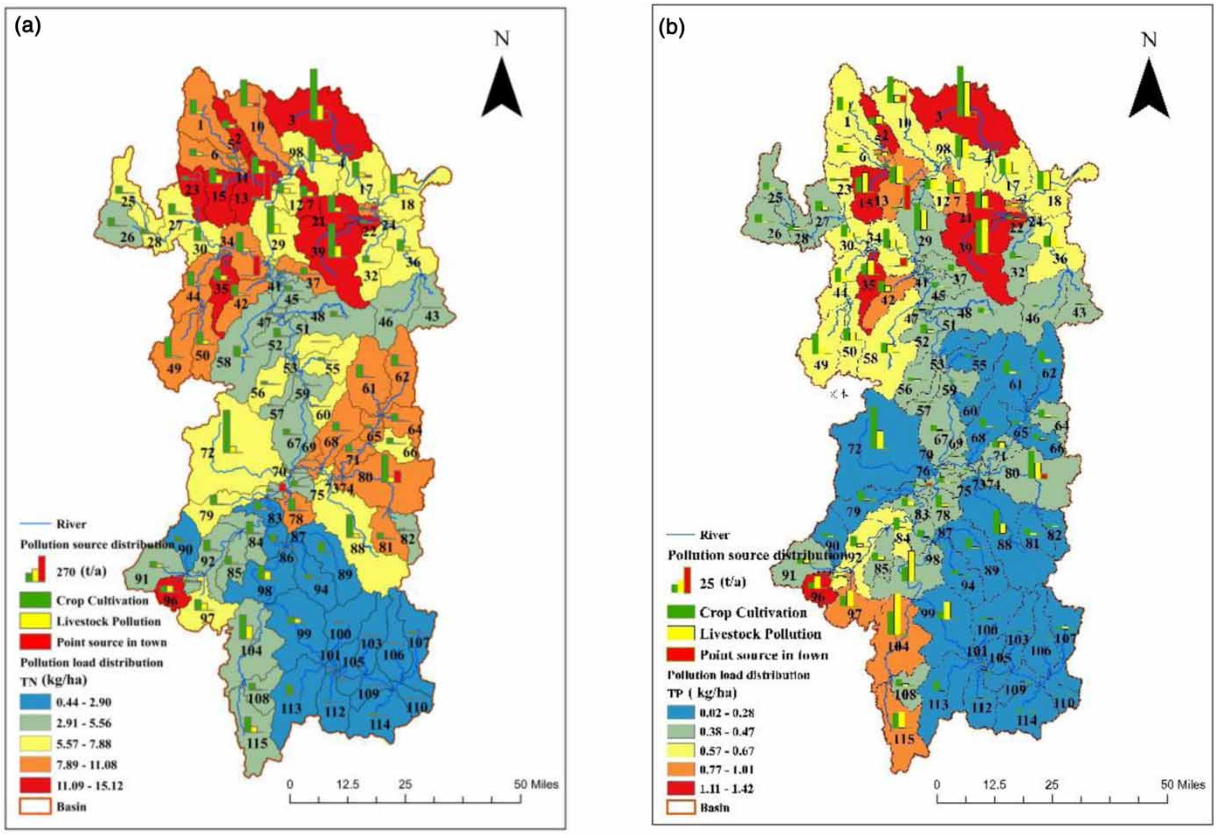

Figure 5 | (a) Spatial distribution of total nitrogen load in all basins in 2017. (b) Spatial distribution of total phosphorus load in all basins in 2017.

Analysis of output rate and contribution of nitrogen and phosphorus pollution

The pollution sources in the study region were divided into livestock and poultry breeding, crop cultivation and urban point sources. As shown in Table 6, for both total nitrogen input and total phosphorus input, crop cultivation ranked first (9,464.1 t/a and 864.0 t/a), livestock and poultry breeding ranked second (2,362.3 t/a and 575.7 t/a). For crop planting, livestock and poultry breeding and urban point sources, the pollution outputs (contribution rates) of the total nitrogen load model were 6,137.8 t/a (31.8%), 1,212.1 t/a (6.3%), and 833.5 t/a (4.3%) respectively, and of the total phosphorus load model were 562.4 t/a (25.5%), 242.4 t/a (11.0%), 43.4 t/a (2.0%) respectively, which were far lower than the background values and the values from other sources. The reason is that river background values and the contribution values from pollution sources of soil erosion and uncounted pollution sources were far greater than the obtained values. The total nitrogen output rates for pollution from crop planting, livestock and poultry breeding and urban point sources were 64.9%, 51.3% and 75.7% respectively, and the total phosphorus output rates for pollution from crop planting, livestock and poultry breeding and urban point sources were 65.1%, 42.1% and 67.5% respectively. Although the input of urban point sources was not high, the output rate was still high because of its direct discharge into the water body without soil and vegetation reduction, which was consistent with the results of Chen *et al.* (2015). The output rate of livestock and poultry breeding was the lowest. The reason may be that comprehensive utilization of agriculture reduced the output of relevant pollution sources (Zhang *et al.* 2014). The contribution rate of crop planting was the highest and the output rate of crop planting was also relatively high in the study region. The main reason for this was that the study region

Table 6 | Comparison table of total nitrogen and total phosphorus input and output of different pollution sources in 2017

	Input/t		**Output/t**		**Output rate/%**		**Contribution rate/%**	
	TN	**TP**	**TN**	**TP**	**TN**	**TP**	**TN**	**TP**
Background value and other sources	–	–	11,095.2	1,361.4	–	–	57.6	61.6
Crop source	9,464.1	864.0	6,137.8	562.4	64.9	65.1	31.8	25.5
Livestock and poultry breeding source	2,362.3	575.7	1,212.1	242.4	51.3	42.1	6.3	11.0
Town point source	1,100.7	64.3	833.5	43.4	75.7	67.5	4.3	2.0
Total	12,927.1	1,504.0	19,278.6	2,209.6	–	–	100	100

Note: Output rate = input/output; contribution rate = output of each pollution source/total output of pollution source.

was dominated by hills and mountains, where slope cultivation was prevalent and nutrient loss was caused by serious soil and water loss during rainfall (Zhao *et al.* 2017). Therefore, for this basin, the key for prevention and control is still fertilizer control in combination with soil erosion prevention and control, but joint control of livestock and poultry breeding and urban point sources is still necessary for reduction of nitrogen and phosphorus pollutants into the river.

Simulation of nitrogen and phosphorus pollution reduction

From 2020, global usage of chemical fertilizers will increase by 1.5% annually. However, the utilization rate of nitrogen and phosphorus fertilizers absorbed by crops is only 30%–50%. A large amount of leached nitrogen and phosphorus makes chemical fertilizers become the most important source of non-point source nitrogen and phosphorus pollution. Reducing chemical fertilizers is the fundamental measure for reduction of non-point source pollution (Tilman *et al.* 2002; FAO 2017). In terms of source control, the main reduction measure for livestock and poultry breeding is to use livestock and poultry manure as an organic fertilizer in the planting industry after being made hazard-free by treatment, which can not only reduce nitrogen and phosphorus pollutants directly discharged into the river, but also reduce the use of chemical fertilizers. This measure is also the key for nitrogen and phosphorus pollution control (Himanshu *et al.* 2019). According to a survey report concerning cultivated land quality in Yongzhou City of 2019, under the condition that the production increase of crops such as double-season rice and maize was guaranteed, the application amount of chemical fertilizers per mu was reduced by 2.47 kg/mu in 2018 as compared with that in 2019, and the application amount of chemical fertilizer will be reduced by 5% by 2020 through agricultural management measures, such as burying green manure, soil testing and formulated fertilization, returning straw to field, and replacing chemical fertilizers with organic fertilizers. At the same time, some studies showed that the application of resin-coated slow-release fertilizer and crop-specific fertilizer could reduce the usage of chemical fertilizers by 10%–25% without compromise of yield (Wu *et al.* 2002; Xu *et al.* 2002; Zhang *et al.* 2010). Therefore, this study set the fertilizer reduction rates at 5%, 10% and 20%. For comparison, the reduction rates for urban point sources and livestock and poultry breeding were set at 10% and 20% respectively. Because of the second three-year action plan for Xiangjiang River protection issued by the People's Government of Yongzhou City, the goal of the reduction rates for urban point sources and livestock and poultry breeding at 10% and 20% was feasible and practical. At present, emission reduction projects can be implemented such as by the retiring of livestock and poultry breeding in prohibited areas, building comprehensive utilization of manure in large-scale livestock and poultry farms and upgrading of sewage treatment facilities. As shown in Table 7, when the fertilizer reduction rate was set at 5%, the total nitrogen and total phosphorus of the basin were reduced by 288.4 t and 14.6 t respectively. Both reduction rates were greater than 20% for urban point sources and 10% for livestock and poultry breeding. When the fertilizer reduction rate was set at 20%, the total nitrogen and total phosphorus in the basin

Table 7 | Simulation of the reduction of total nitrogen and total phosphorus output under different reduction measures

	Urban point source emissions		Emissions from livestock and poultry breeding sources		Fertilizer application			The best combination of measures		
	Reduction 10% (A1)	Reduction20% (A2)	Reduction10% (B1)	Reduction 20% (B2)	Reduction 5% (C1)	Reduction10% (C2)	Reduction15% (C3)	Reduction20% (A1)	Reduction 20% (B2)	Reduction 15% (C3)
Total nitrogen reduction/t	16.2	82.1	103.1	210.6	288.4	596.5	1,146.2		1,438.9	
Total nitrogen reduction rate/%	0.1	0.4	0.5	1.1	1.5	3.1	6.0		7.5	
Total phosphorus reduction/t	1.8	5.4	12.8	26.3	14.6	28.9	53.6		85.3	
Total phosphorus reduction rate/%	0.1	0.2	0.6	1.2	0.7	1.3	2.4		3.9	

were reduced by 1,146.2 t and 53.6 t respectively, which were far greater than in urban point sources and livestock and poultry breeding of 20% reduction rate. The effect for total nitrogen reduction was better than for total phosphorus reduction, which was consistent with the results of Ma *et al.* (2016). The main reason why the reduction rate for livestock and poultry breeding was much lower than that for agricultural planting was that the pollution from livestock and poultry breeding below the designated scale was not included in the model in this study. Taking all the reduction measures into consideration, the optimal combination reduced total nitrogen and total phosphorus by 1,438.9 t and 85.3 t respectively. The larger the reduction rates for fertilizer application, livestock and poultry breeding and urban point sources, the lower the output of nitrogen and phosphorus pollution (Sun *et al.* 2013; Jang *et al.* 2016).

CONCLUSION

1. In the simulation period of Lengshuitan station and the calibration period and validation period of Dao County station, $R^2 > 0.68$ and Ens > 0.61 for runoff, ammonia nitrogen and total phosphorus. The simulation evaluation parameters met relevant requirements, which indicated that the SWAT model for Yongzhou Basin of Xiangjiang River had a good simulation effect.
2. The maximum inputs of total nitrogen and total phosphorus were 796.01 t and 88.49 t respectively; the output intensity of total nitrogen and total phosphorus reached 0.44–15.52 kg·ha^{-1} and 0.02–1.41 kg·ha^{-1} respectively; both sub-basins 39 at the lower reaches of Xiangjiang River and tributary 3 of Luhong River had total nitrogen output intensity greater than 11.09 kg· ha^{-1} and total phosphorus output intensity greater than 1.11 kg·ha^{-1}; as the key source areas for nitrogen and phosphorus treatment in this basin, both inputs and outputs of total nitrogen and total phosphorus were very high.
3. For both total nitrogen input and total phosphorus input, crop cultivation ranked first (9,464.1 t/a and 864.0 t/a), livestock and poultry breeding ranked second (2,362.3 t/a and 575.7 t/a). Crop planting had the highest pollution output and contribution rate of the total nitrogen load model, 6,137.8 t/a and 31.8% respectively; the nitrogen

and phosphorus output rates for pollution from urban point sources were the highest, 64.9% and 65.1% respectively, which indicated that chemical fertilizers are the most important source of non-point source pollution, and the application control of chemical fertilizers should also be combined with the control of livestock and poultry breeding and urban point source control.

4. In terms of source control, the reduction effect of chemical fertilizer application control was the best, and total nitrogen and total phosphorus could be reduced by 1,438.9 t and 85.3 t respectively, reduction rates: 7.5% and 3.9%. The effect for total nitrogen reduction was better than for total phosphorus reduction.

Nitrogen or phosphorus pollution is closely related to rainfall runoff process, soil type, vegetation type, agricultural production mode (fertilizer application, tillage mode, etc.) and agricultural management measures. Considering that terrace farming in typical agricultural and forestry basins is a common phenomenon, and soil erosion caused by terrace farming is closely related to water-body nitrogen and phosphorus pollution, it is therefore worthwhile to study the reduction effect of management measures such as medium-high planting, returning farmland to forest, and wetland buffer zone in the future. In addition, climate and land use patterns are also important factors affecting nitrogen and phosphorus pollution in the watershed.

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DATA AVAILABILITY STATEMENT

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

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