ORIGINAL ARTICLE

Hydrological status of the Dagu River Basin and management suggestions based on soil and water assessment tool multi-station calibration

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Abstract

Soil and water assessment tool (SWAT) model was used to calculate the runoff, nitrogen and phosphorus emissions in the Dagu River Basin from 2002 to 2012 and provided preliminary suggestions on environmental protection measures. Calibration on hydrological watershed parameters was obtained from data obtained from multiple representative stations. Cluster analysis was used to group all stations, and the parameters of different representative stations were applied to the entire geographical area to reflect the hydrological conditions of the basin. Additionally, the spatiotemporal changes and pollution source characteristics of nitrogen and phosphorus were analyzed. Anthropogenic sources—chemical fertilizer loss and livestock breeding—accounted for 49.9–29.6% of total nitrogen (TN) and 41.4% and 40.3% of total phosphorus (TP), respectively. Non-point sources accounted for 85.8% of the TN and 89.4% of the TP. Six landscape management practices were set up to evaluate the reduction effect on non-point source pollution loads, and comprehensive measures were proposed to reduce TN (TP) by ~70%. According to water quality model, the response relationship between river control and nutrient distribution in Jiaozhou Bay is calculated. Based on the findings, we propose an optimal control scheme for non-point source pollution in the Dagu River Basin and other similar basins.

Keywords Dagu River Basin · Soil and water assessment tool · Multi-station calibration · Water pollution · Environmental management

Introduction

Aquatic environments in China have been found to pose a threat to both human health and surrounding ecosystems as these have become heavily polluted. Research shows that the origin of water contamination has gradually shifted from point source to non-point source pollution worldwide (Novotny 1981; Pradhan et al. 2014). Owing to a significant investment in financial and human resources, the worsening problem of water pollution has been moderately curbed (Shen et al. 2017; Zhou et al. 2021). In the case of Jiaozhou Bay of China, water quality has not been improved from 2002 to 2016 (Qingdao Municipal Ocean and Fisheries Administration, 2002–2016). The significant disconnect

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between pollution reduction and water quality improvement can be attributed to the current calculation methods for land-based pollution discharges in Qingdao, which is limited to understanding point sources, such as industry and urban life, and does not include non-point sources, such as agriculture and rural life. Since 1960s, research on non-point source pollution has been performed, and it has gradually developed from the initial qualitative research to the current quantitative research (Wang et al. 2019a, b; Zou et al. 2020). Therefore, it is necessary to prioritize the research of effective pollution integration calculations in Dagu River Basin. A general plan for the protection and spatial utilization of Dagu River Basin was formulated in 2011 in Qingdao, and from 2013 to 2015 pollution control measures were implemented. The above watershed management measures of non-point sources also provide a good theoretical basis for our research.

Improving the Soil Conservation Service (SCS) Runoff Curve Method, the USLE Model laid the foundation for the quantitative verification of non-point source pollution load (Singh et al. 2010; Al-Juaidi 2018; Alewell et al. 2019; Xin et al. 2020). It also provided the basic module for many subsequent organic models. For example, the storage treatment overflow runoff model, urban storm water management model, HSP model, Japan's semidistributed water tank model, TOPMODEL, a semidistributed model developed in 1970s (Park et al. 2018; Palla et al. 2015; Yazdi et al. 2019; Huang et al. 2007; Beven et al. 2021), and Soil and Water Assessment Tool (SWAT) (Himanshu et al. 2019).

The SWAT model developed by Dr. Arnold for the Agricultural Research Institute in the 1990s is a non-point source pollution model, which simulates and expresses hydrological and pollution processes. SWAT can simulate long-term impact of meteorology, soil, land use, and operation management on runoff, pollutant load, and sediment loss in a watershed, but it cannot simulate the erosion process of a single rainfall (Wang 2003; Xiao 2010). SWAT is widely used to simulate the output of non-point source pollution and assess the effects of land use type change and environmental management measures on non-point source pollution (Himanshu et al. 2019; Arabinda Sharma et al. 2019). In the river basins of Xixi (Jinjiang River), Mayihe, Yuanshui, Fuxin, Beiru, Biliu, and Lancang, it has been used to study the output of non-point source pollution load (Zhang et al. 2010a, b; Li et al. 2013; Yu et al. 2018; Song et al. 2018; Yuan et al. 2020; Xu et al. 2020; Tang et al. 2021). SWAT has been proved to be accurately applicable to Chinese watersheds.

Dagu River is the largest river in Jiaozhou Bay, and the excess nitrogen and phosphorus are the main sources of pollutants (Li et al. 2018; Zhang 2021). Dagu River Basin is an important water source of Qingdao and the "core axis" of the territory. Therefore, it is important to study the nitrogen and phosphorus pollution and hydrological status of Dagu

River. For Dagu River Basin, Liu (2009) used the AnnAG-NPS model to simulate the output of nitrogen and phosphorus pollutants from non-point source and gave the simulation and prediction results of two different fertilization schemes. Pu et al. (2010) used the SWAT model to study the characteristics of non-point source nitrogen load and the response relationship with water quality of Jiaozhou Bay. Du et al. (2019) set up a system for hydrology simulation on the basis of the runoff data from 1986 to 2000 and adjusted sensitive parameters with SWAT-CUP (Calibration and Uncertainty Program for SWAT; 2019). However, the systematic understanding of pollution is still lacking. For example, the mock examination of the simultaneous migration and transformation of non-point source and point source pollutants is lacking in the same model framework, especially for the Dagu River Basin.

Previous research on SWAT model calibration and verification often focused on the fitting of one station over a long period of time (Karki et al. 2020; Li et al. 2021). The simulation efficiency can only explain the degree of interpretation of the model for the overall outlet of the basin and cannot fully represent the accuracy for the hydrological simulation of the whole basin. In this paper, four classic stations were selected for the long-term calibration of the runoff, nitrogen and phosphorus in the Dagu River Basin, and the universal applicability of these calibration parameters was verified by two field sampling measurements. Point source pollution is regarded as a fixed outlet with a certain longitude and latitude position, which is input into the SWAT model, and participates in the simulated migration and transformation process with non-point sources. The addition of point sources to improve accuracy has been cited by Yang et al. (2012) about the importance of identifying point sources of Nansha River pollution in estimating overall pollution. Thus, the quantity, distribution and composition of pollutant emission in the watershed can be described more accurately. Finally, on this basis, the environmental remediation measures of nitrogen and phosphorus pollution are studied in Dagu River Basin.

Materials and methods

Study area

Dagu River Basin originates from the west foot of Fushan in Zhaoyuan, Yantai City. It flows through Zhaoyuan, Laizhou, Pingdu, Laixi, Jimo and drains into Jiaozhou Bay in Matou village in Hexitun, Jiaozhou City (Fig. 1). It has a total length of 179.9 km and a total drainage area of 6131.3 km^2. The elevation of the basin is 6–639 m, and the average gradient of the main stream is 0.61 ‰. The northern part of Dagu River Basin is mountainous and has shallow hills. The southern part is a piedmont plain with depression
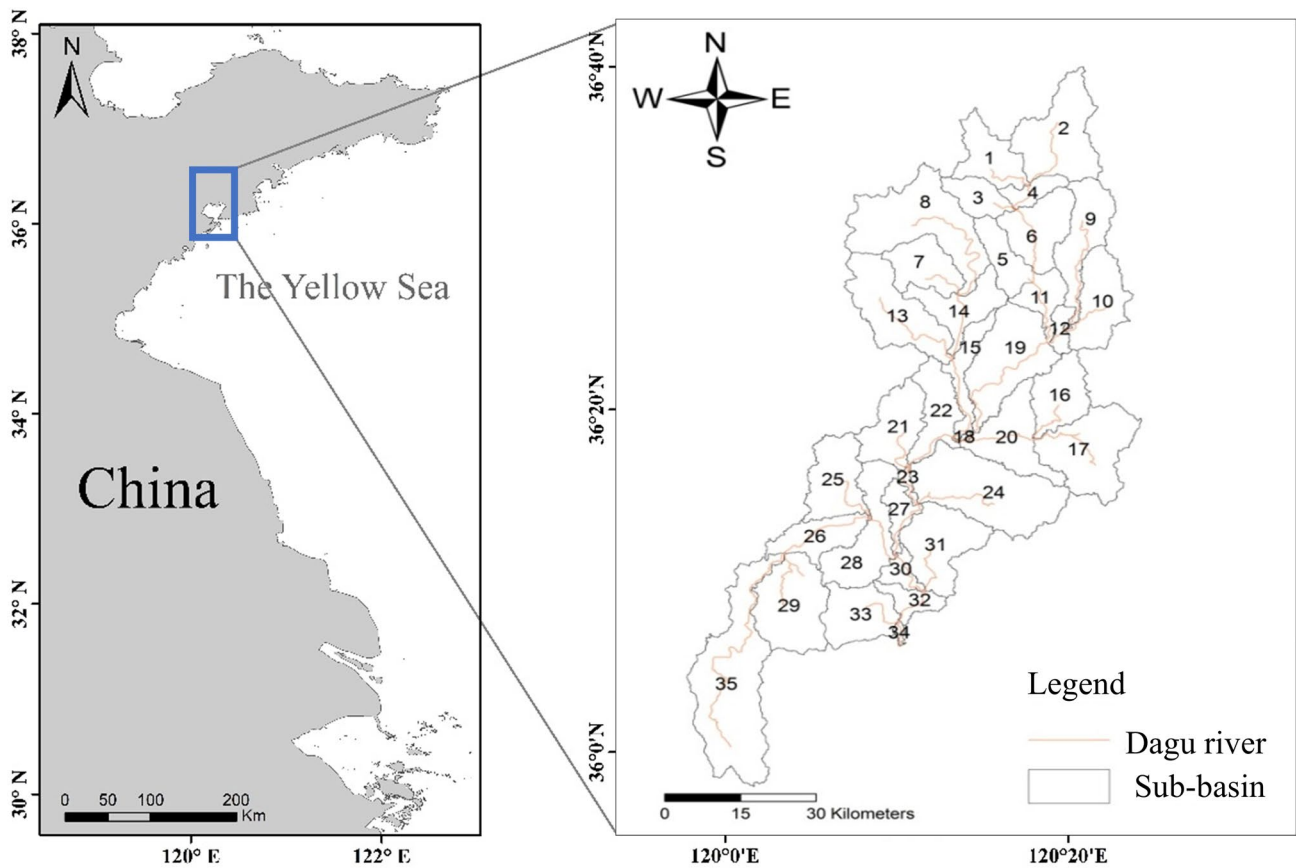
Fig. 1 Location map of the Dagu River Basin

areas. The mountainous, hilly, plain and low-lying areas in the basin account for 11.4%, 34.5%, 36.8% and 17.3% of the basin area, respectively. There are 27 towns (or sub-district offices) and more than 1480 villages along the main stream of Dagu River, with a population of 1.37 million, accounting for 57% of the total population in the basin. The annual runoff is mainly concentrated during the flood season from July to October, varying greatly from year to year, and the annual distribution is uneven.

Datasets

To perform simulation calculations, the SWAT model required spatial and attribute data (see Table 1). Spatial data used in this study included: digital elevation model (DEM), land use and soil type maps. Attribute data used in the model included data, such as land use type attribute data (land use parameter table) and soil attribute tables (chemical and physical attributes), meteorological, hydrological and water quality data (monitoring data of river basin monitoring section for many years) and pollution source investigation

data. Among them, meteorological data and soil attribute data were considered as the most important.

Overview of SWAT

In this paper, the experimental design of Dagu River Basin using SWAT2012 rev. 682 released Oct 20, 2021, will be carried out according to the steps of estimation, calibration, verification and application management (Fig. 2). SWAT model adopts modular structure and is mainly composed of three submodels: hydrological process submodel, soil erosion submodel and nutrient migration submodel. SCS model is adopted for the calculation of runoff,

$$Q = \frac{(p - 0.2s)^2}{p + 0.8s}$$

$$S = \frac{25400}{CN} - 254$$

Table 1 SWAT model basic data description

Item	Data name	Data type	Purpose	Source
Spatial data	DEM	GRID	It is the basis of hydrological process simulation to extract the distribution of drainage network, divide sub-basins, find the outlet and calculate the slope	(http://datamirror.csdb.cn/index.jsp)
	Land use map	GRID or.shp	Provide the spatial distribution information of land use types in the watershed	(http://westdc.westgis.ac.cn/)
	Soil type map	GRID or.shp	Provide the spatial distribution information of soil types in the watershed	(Harmonized World Soil Database, HWSD)
Attribute data	Land use type attribute table	.dbf	The vegetation growth, water consumption and surface runoff were calculated	–
	Soil attribute table	.sol and.chm	Calculation of soil flow and groundwater in Watershed	SPAW
	Meteorological Database	.dbf	Calculation of basin discharge and evaporation	CMADS V1.0
	Station distribution	.txt	Geographical location information of verification and calibration station	Qingdao Municipal Bureau of hydrology

SWAT uses the modified universal soil loss equation (MUSLE) to calculate soil erosion caused by rainfall and runoff.

$$\mathrm{sed} = 11.8 \left(Q \cdot q_{\mathrm{peq}} \cdot \mathrm{area}_{\mathrm{hru}} \right)^{0.56} \cdot K \cdot C \cdot P \cdot \mathrm{LS} \cdot \mathrm{CFRG}$$

See Table 1 for the explanation of the above formula parameters. The migration and transformation model of nitrogen and phosphorus nutrition is divided into soluble nitrogen and phosphorus and granular nitrogen and phosphorus. See Annex B and C, respectively.

Point source pollution is divided into industrial wastewater discharge and urban domestic sewage treatment plant input. For industrial point source pollution, sewage discharge data and specific distribution positions of industrial enterprises are obtained from Qingdao Yearbook and input into the model. For the nitrogen and phosphorus discharged by urban population, according to the septic tank discharge standard, Qingdao implements a class I standard, taking the total nitrogen emission coefficient as 11.5 g/(person * day) and the total phosphorus emission as 0.81 g/(person * day), and comprehensively estimating the point source pollution emissions in different sub-watersheds.

Calibration and validation of SWAT

Model validation following model calibration is essential because of the uncertainty of the model parameters, and some parameters are empirical (Kouchi et al. 2017). Only after the calibration and validation have attained a certain accuracy, can the model be applied to the corresponding watershed.

As the parameter calibration process of the SWAT model should be based on the actual physical process, the results of the sensitivity analysis were only used as a reference for the calibration process. In the actual calibration process, not all parameters were included in the calibration (Pang et al. 2010). The list of sensitivity parameters and sensitivity results determined by the SWAT is shown in Tables S1 and S2.

In this study, data were collected from two field sampling: 12 stations during a watershed survey in September 2011 and 2 stations during a small watershed survey from July to August 2012; the data from the two field sampling were used to validate the SWAT model data. The parameters used in the verification of the above stations were determined according to the calibration stations.

The parameters were selected based on a clustering analysis of hydrological conditions, runoff, nitrogen and phosphorous emissions of the stations. The clustering algorithm is realized by K_Means using Euclidean distance as the basis to distinguish the similarity between stations (Naz et al. 2022). Import geographical location, runoff, nitrogen, phosphorus and other hydrological parameters into SPSS 21 and select k_Means clustering. The number of iterations is adjusted to 20, and the number of clusters is determined according to the cluster pedigree (tree chart) in the result.

Model calibration was performed to obtain the optimal (minimum, maximum or moderate) parameter values of the objective function. Objective functions used in this study, included the relative error (Re), the coefficient of determination (R^2) and the Nash–Sutcliffe coefficient (Ens) (Moriasi et al. 2015; Zeckoski et al. 2015; Nash and Sutcliffe 1970). Each objective function is weighted to transform into single objective optimization problem through linear weighting
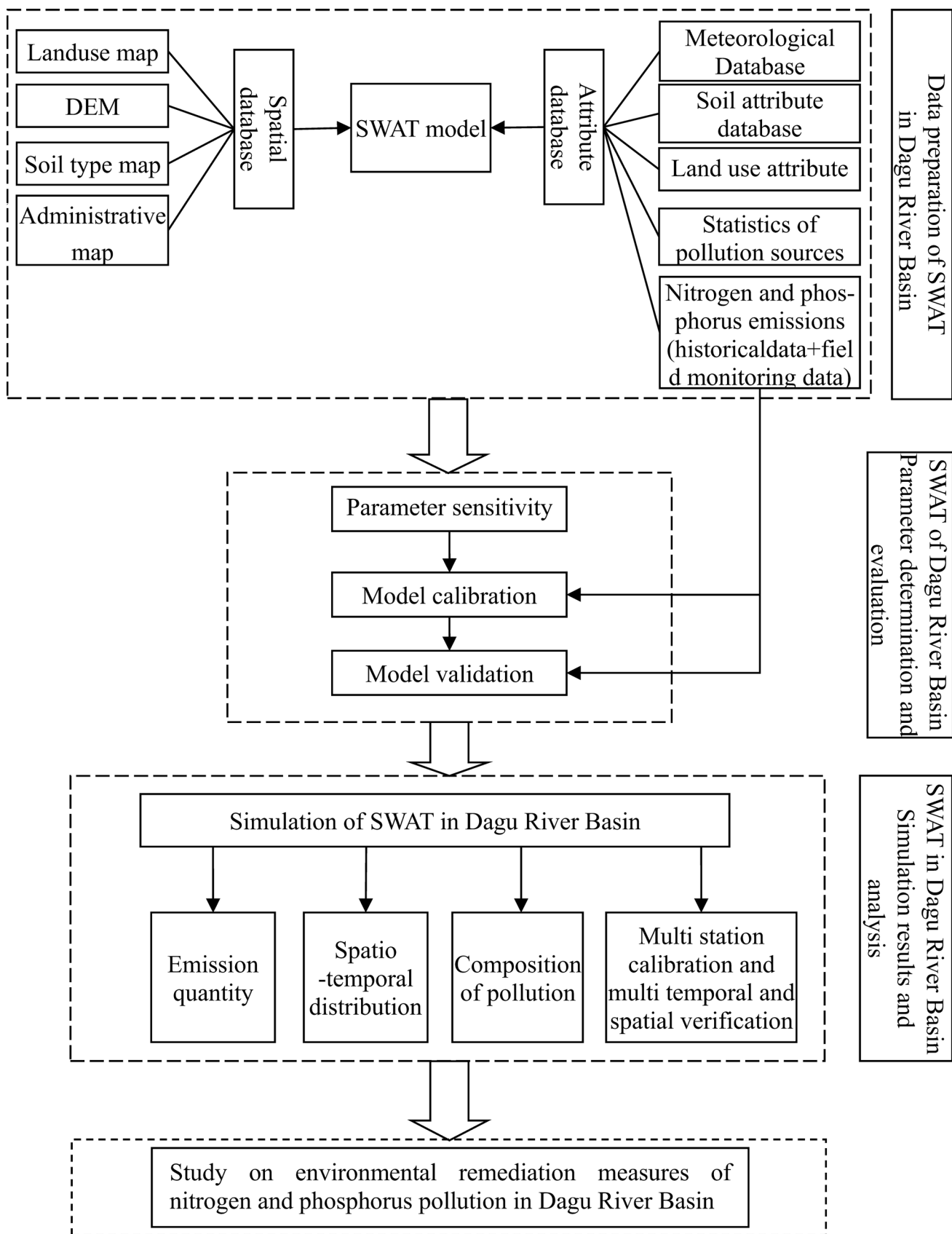
Fig. 2 Flow chart for SWAT simulation in Dagu River Basin

method. Use SUFI-2 algorithm in SWAT-CUP to conduct parameter hypercube sampling and plug-in optimization algorithm to find the optimal solution (Qi et al. 2020). They are used as a combination to optimize after data standardization as follows:

$$\mathrm{Obj}_{max}\left\{ \frac{1}{3} \cdot (-\mathrm{Re}) + \frac{1}{3} \cdot R^2 + \frac{1}{3} \cdot \mathrm{Ens} \right\}$$

For the hydrological parameters used in the simulation process of these 12 stations (Fig. S1), the parameters of 4 stations calibrated above are used correspondingly. For the corresponding relationship of stations, the distance in geographical location cannot represent the similarity of hydrological stations. Based on the historical hydrological data, cluster analysis was performed to obtain the relevant distance between stations; this was performed for grouping the stations. If the stations fell in the same category as the calibration station, the calibration station parameters were used. The results of cluster analysis are shown in Fig. S2.

Contribution rate of pollution sources

The main sources of pollution in Dagu River Basin are from agricultural, industrial, the service industry, local residents and environmental background discharges related to land use, physical and chemical soil properties, topography and climate (Dong et al. 2008 and Liang et al. 2014). This paper mainly discusses contribution rates of industrial and environmental background polluting discharges into the Dagu River Basin. In SWAT, the contribution rate was estimated by simulating whether the above pollution sources have corresponding inputs. The calculation formula is as follows:

$$\mathrm{TN}_X\% = \mathrm{TN}_X \cdot \left. 100 \middle/ \mathrm{TN}_{tot} \right.$$

$$\mathrm{TP}_X\% = \mathrm{TP}_X \cdot \left. 100 \middle/ \mathrm{TP}_{tot} \right.$$

$\mathrm{TN(P)}_x\%$: Ratio of nitrogen (phosphorus) from different sources to total nitrogen (phosphorus); $\mathrm{TN(P)}_x$: Nitrogen (phosphorus) yield from different sources (t); $\mathrm{TN(P)}_{tot}$: total nitrogen (phosphorus) yield (t).

Effect of different management reduction

For different pollution sources, different reduction ratios were initially set. The specific reduction rates were 10%, 30%, 50% and 70% for fertilizer application, livestock waste discharge, industrial discharge and rural domestic sewage discharge, respectively. The SWAT model was used to simulate the control of the above measures and point source to quantitatively analyze the effect of the above reduction rates on the reduction of nitrogen and phosphorus emissions in the Dagu River Basin.

Results

The SWAT model was used to calculate the runoff, nitrogen and phosphorus emissions in the Dagu River Basin.

Calibration and verification

Calibration period

Figure 3 compares the simulation and observation values of flow calibration and summarizes the results of various evaluation indexes. The Re of calibration was not more than 20%, and the R^2 and Ens were maintained above 0.8 (except Ens of Dongdingjia station). The calibration accuracy was found to be good (Moriasi et al. 2015) and met the calculation requirements.

Figure 4 compares the simulation results and observation values of TN calibration and summarizes the results of various evaluation indexes. The Re of calibration fluctuated between 10 and 30%, and the R^2 and Ens was maintained above 0.7. The fluctuation was large, and the simulation of Fanghongzha station was found to be the best. The calibration accuracy was found to be acceptable (Moriasi et al. 2015) and met the calculation requirements.

Figure 5 compares the simulation results and observation values of TP calibration and summarizes the results of various evaluation indexes. The Re of calibration fluctuated between 20 and 30%, and the R^2 was maintained above 0.9 (except Dongdingjia station). However, the performance of Ens was not satisfactory; the calibration accuracy was found to be acceptable to a certain extent (Moriasi et al. 2015) and met the calculation requirements.

Model verification of watershed survey data in 2011

Twelve stations in Dagu River Basin were investigated to determine the flow, source characteristics of nitrogen and phosphorus. Table S6 provides the station details, and Fig. S2 depicts the geographical location of the stations.

The observed data of discharge, nitrogen and phosphorus of 12 stations in the watershed survey in September 2011 were used as the validation data of SWAT model, and the validation results are as follows (Fig. 6).
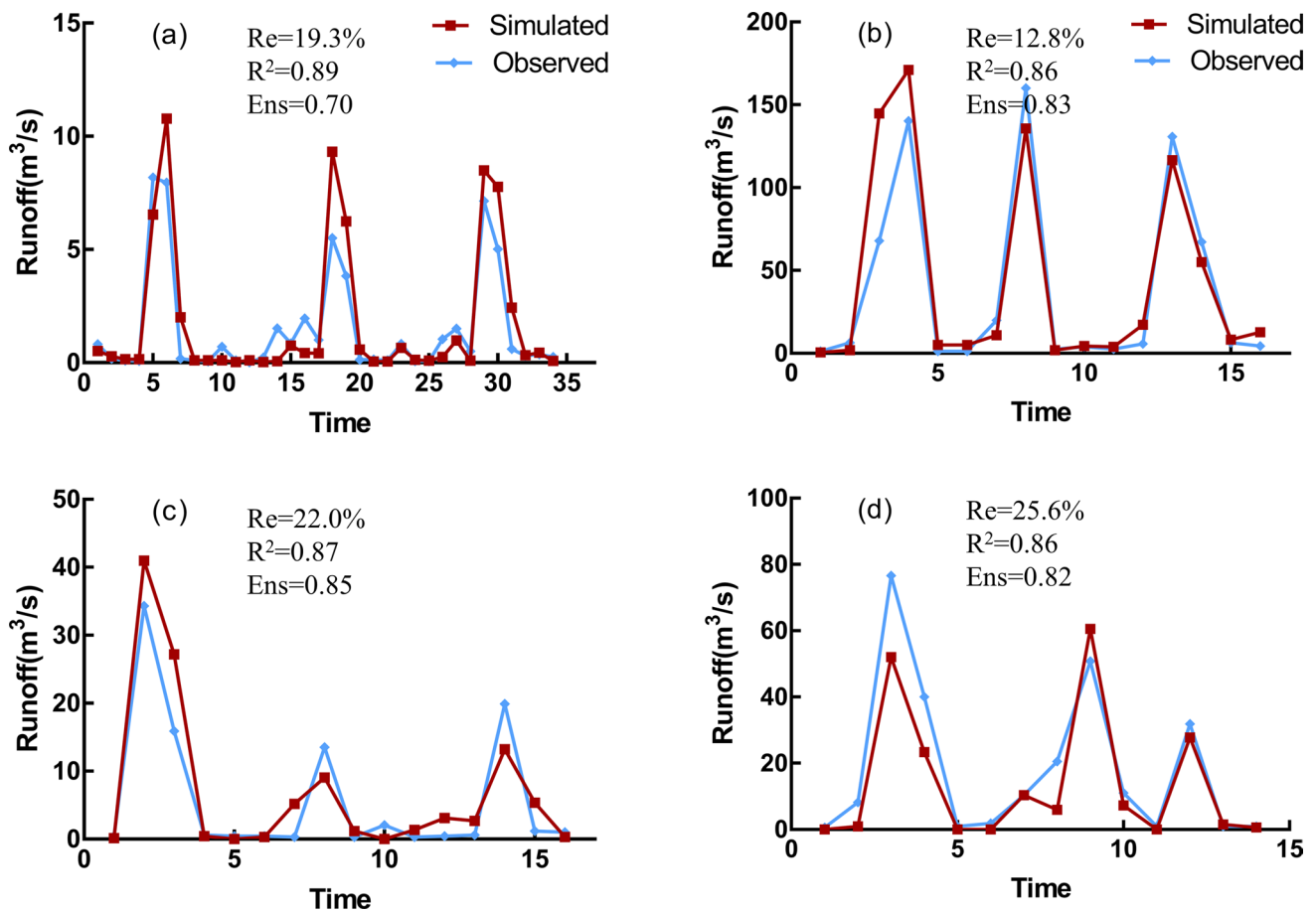
Fig. 3 Comparison of observed and simulated monthly runoff during calibration period at different stations: **a** Dongdingjia; **b** Zaochao; **c** Houlugezhuang; **d** Fanghongzha

Model verification of survey data of upstream small watershed in 2012

In addition to using the survey data in September 2011 to verify the SWAT model, we also utilized the survey data from July to August 2012 in the Dagu River Basin for 19 consecutive days to further verify the applicability of the parameters calibrated by SWAT model in the Dagu River Basin. The verification results included the verification of Dongdingjia and Xijujia stations (Fig. 7).

After verifying the SWAT calibration parameters, the calibrated SWAT parameters could be used for simulating the calculation of nitrogen and phosphorus emissions in Dagu River Basin (Liu et al. 2014).

After calibration and verification of the parameters, the final parameters of the SWAT model are listed in Table 2.

Different calibration parameters were adopted for different stations to ensure that the accuracy of the model was within the desired limit; this increased the regional pertinence for the model simulation, thereby increasing the simulation efficiency of runoff and nitrogen and phosphorus emissions.
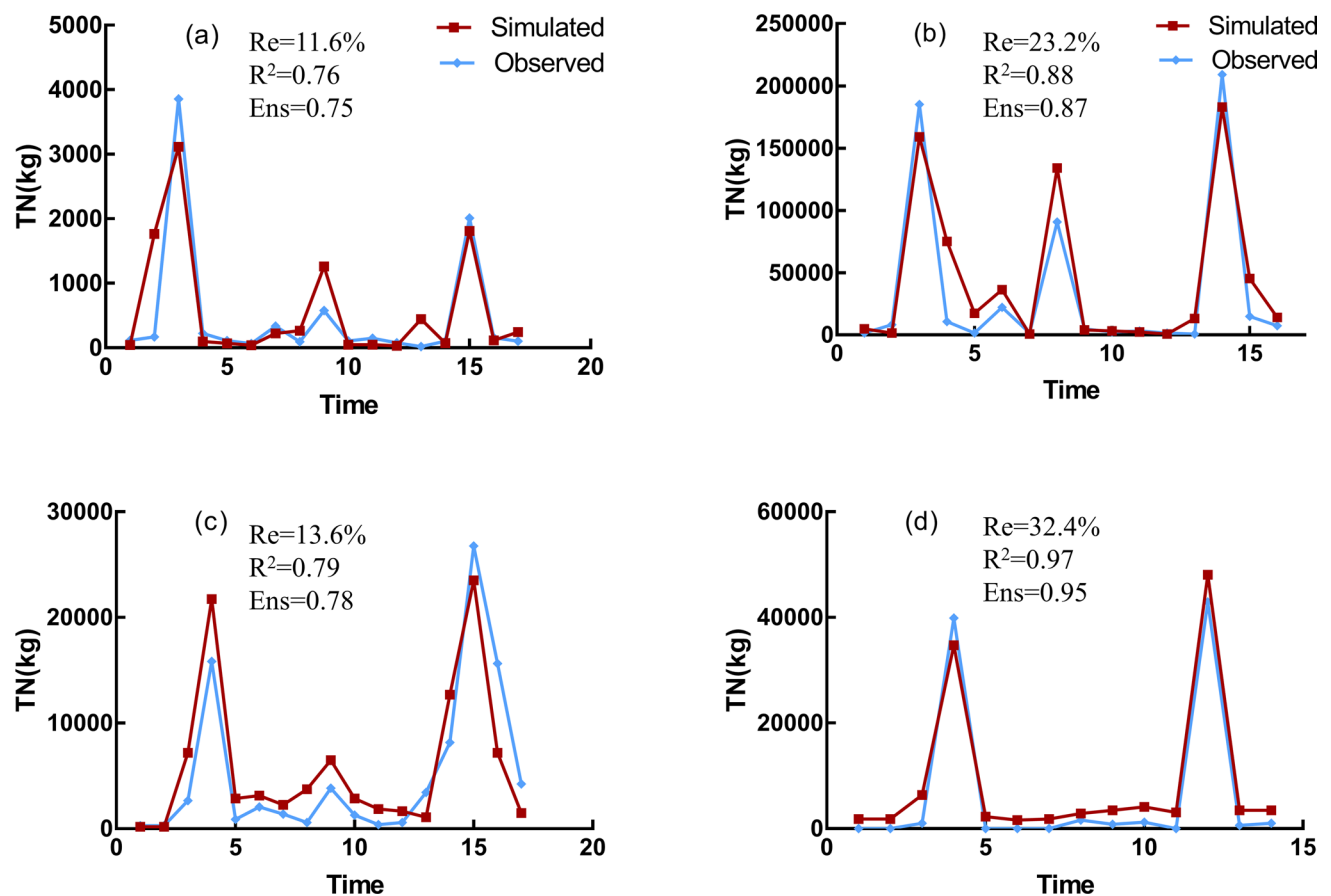
Fig. 4 Comparison of observed and simulated monthly TN during calibration period at different stations: **a** Dongdingjia; **b** Zaochao; **c** Houlugezhuang; **d** Fanghongzha

Characteristics of nitrogen and phosphorus emissions

Spatial distribution

The SWAT model simulated the annual total nitrogen (TN) and total phosphorus (TP) emissions of 35 sub-basins from 2002 to 2012. The results are summarized in Table S4. The results indicated that the TN and TP emissions within sub-watersheds vary significantly. The 8th-sub-watershed (Fig. 8) had the largest TN emission (292.68 t) which accounted for 9.51%; the smallest TN emission was obtained for the 18th-sub-basin (1.05 t emission) and accounted for 0.03% of the total. Six sub-watersheds (sub-watersheds 2, 8, 13, 17, 24 and 35) accounted for more than 5% of the TN emissions, and their area accounted for 35.6% of the total watershed area. The 8th-sub-watershed also had the largest TP emission (48.01 t), accounting for 9.98% of the total; the smallest TP emission was obtained for the 18th-sub-basin (0.19 t)

and accounted for 0.04%. There were only four sub-basins (8, 13, 24 and 35) whose TP emission accounted for more than 5%, and their area accounted for 26.2% of the total basin area. Further analysis found that the TN and phosphorus emissions of the sub-basins were positively correlated with the area of sub-basins except for individual sub-basins. Therefore, it was necessary to analyze the nitrogen and phosphorus emissions per unit area. Hence, the average emission density of nitrogen and phosphorus (expressed in kg/km^2) in 35 sub-basins of Dagu River Basin from 2002 to 2012 was simulated by the SWAT model. According to the comprehensive observation, the nitrogen and phosphorus output in the middle and upper reaches of Dagu River is high.

Temporal characteristics

In this study, the calibrated and validated SWAT simulation results were used to analyze the annual emissions and the monthly average variation characteristics of nitrogen
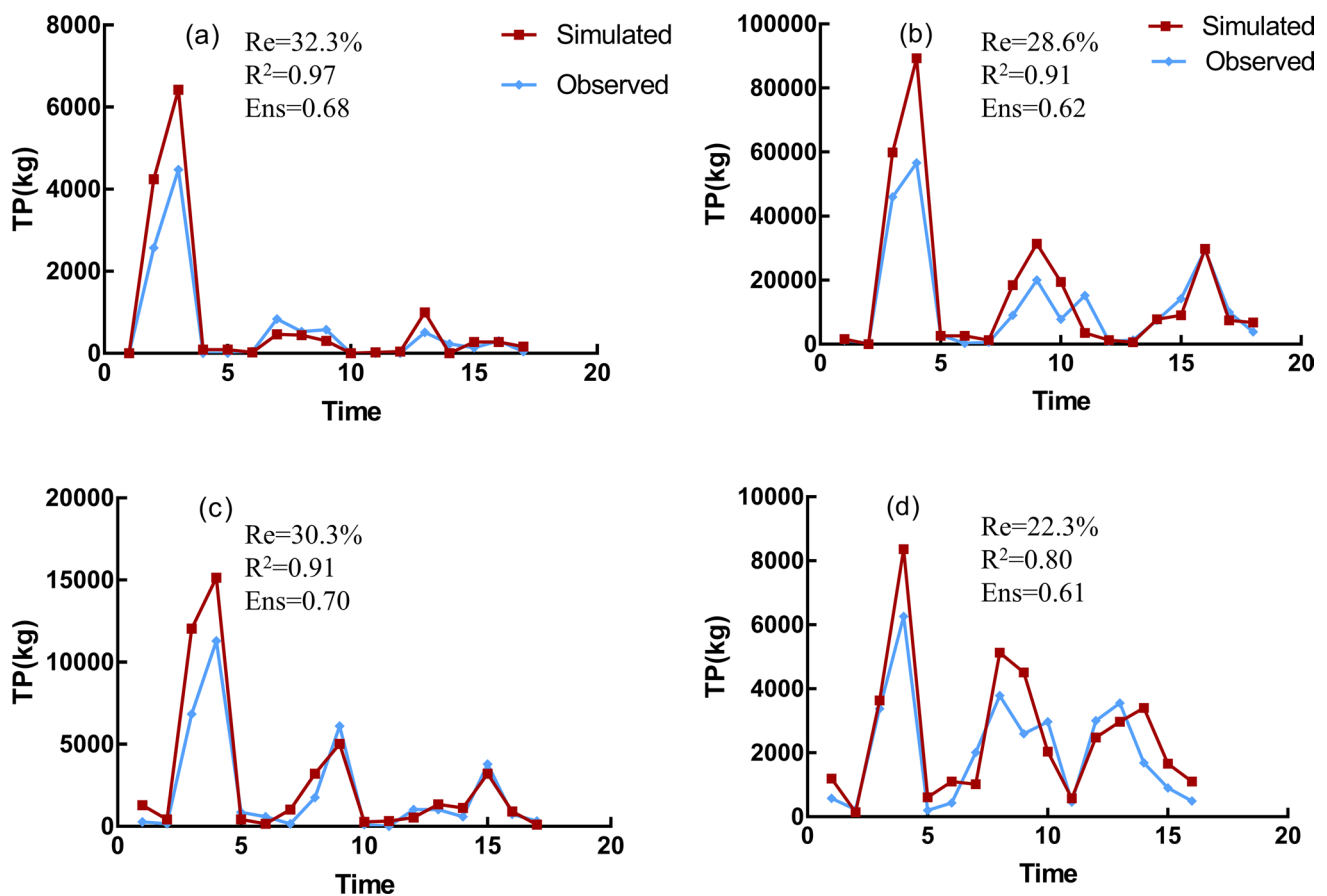
Fig. 5 Comparison of observed and simulated monthly TP during calibration period at different stations: **a** Dongdingjia; **b** Zaochao; **c** Houlugezhuang; **d** Fanghongzha

and phosphorus pollutants in Dagu River Basin from 2002 to 2012. From 2002 to 2012, the emissions of the organic, inorganic and TN initially increased and then decreased. This trend was consistent with the rainfall recorded in the Dagu River Basin. With the increase in rainfall, the emissions of organic, inorganic and TN also showed an increasing trend. Therefore, more attention should be given to pollution control during the wet season. However, the trend of organic, inorganic and TP emissions was discontinuous. In 2007, precipitation and phosphorus emissions were also significantly higher than those in other years, which demonstrated that rainfall was the key factor influencing phosphorus emissions. The annual variation trend of organic, inorganic and TP emissions was similar to that of nitrogen (Fig. 9).

The average monthly emissions of organic nitrogen, inorganic nitrogen and TN show an inverted "V" shape. The emissions of organic nitrogen, inorganic nitrogen and TN mainly come from the flood season (July to September), accounting for 74.4%, 75.7% and 75.6% of the annual emissions, respectively. During the dry season (January to

March) emissions accounted for only 3.1%, 1.2% and 1.5% of the total annual emissions, respectively.

The average monthly emissions of organic, inorganic and TP show an inverted "V" shape, which is basically the same as that of nitrogen. The emissions of organic phosphorus, inorganic phosphorus and TP primarily occurred during the flood season and accounted for 79.6%, 84.6% and 84.3% of the annual emissions, respectively. The dry season emissions accounted for only 4.5%, 1.1% and 1.2% of the total annual emissions, respectively. Thus, rainfall was a key factor affecting monthly phosphorus emissions.

The monthly average nitrogen and phosphorus were similar to the results obtained from other studies (Li et al. 2013; Zhang et al. 2010a, b). This may be attributed to the utilization of large amount of chemical fertilizers before June to improve the yield of crops. Under the effect of rainfall during the flood season, a large amount of chemical fertilizer are washed into the river channel, thus causing the surge in nitrogen and phosphorus during the flood season. In addition, however the use of chemical fertilizers has been curbed in October, during the harvest time of crops and the coverage degree of underlying surface of the watershed
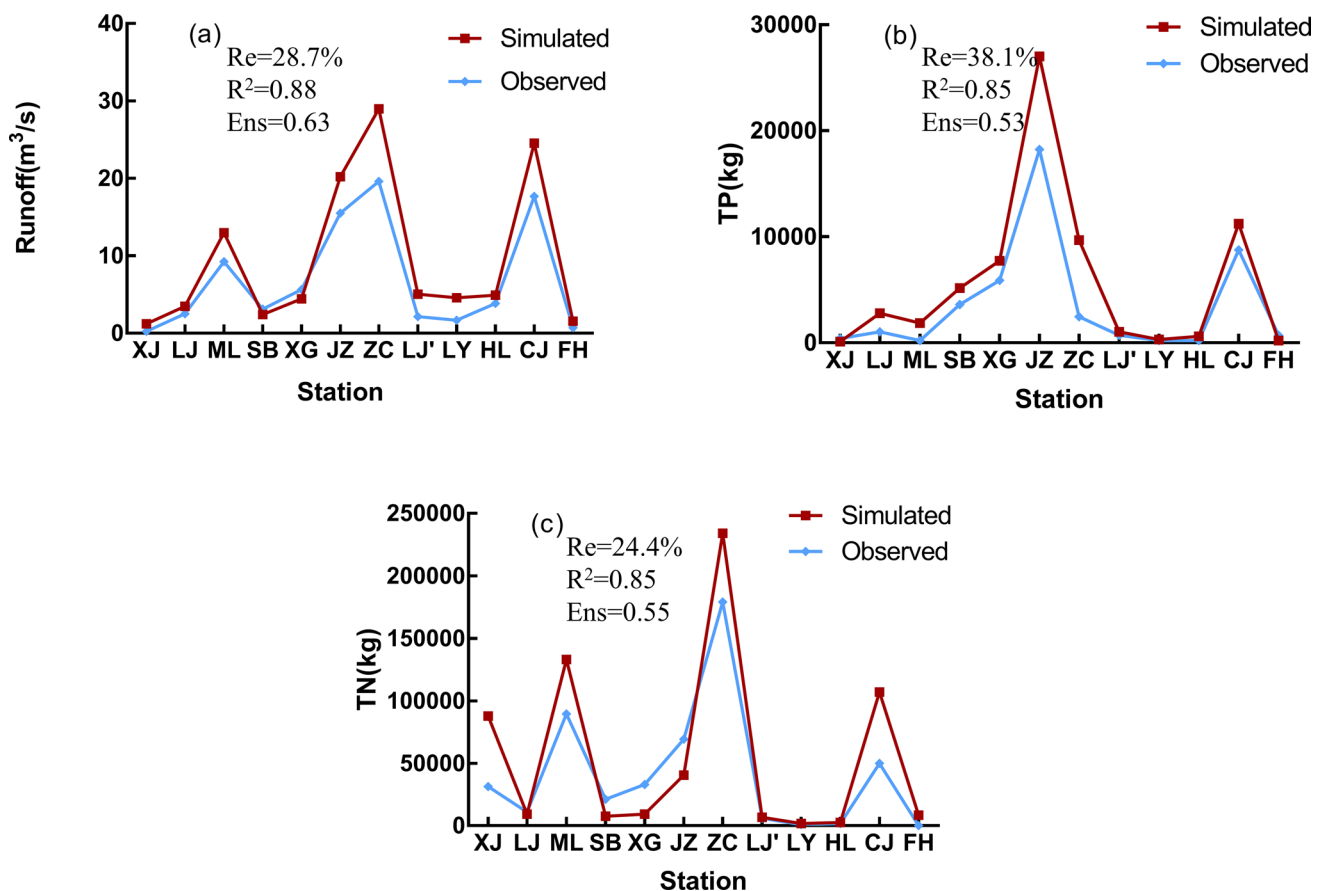
Fig. 6 Comparison between observed and simulated values of each verification station: **a** runoff; **b** TP; **c** TN

changes dramatically, which leads to a large loss of soil and water, nitrogen and phosphorus. This indicated that the loss of nitrogen and phosphorus in Dagu River Basin was not only related to precipitation, but also closely related to agricultural management methods, such as the use of chemical fertilizer and harvest season.

Compositional characteristics

Pollution sources can be divided into point and non-point source. Non-point sources account for 85.8–89.4% of the TN, and phosphorus discharged from the Dagu River Basin (Fig. 10a), respectively. Pollution sources can be also categorized into man-made and natural sources, among which man-made sources include agricultural activities and industrial emissions. Man-made sources account for the vast majority of nitrogen and phosphorus emissions in the Dagu River Basin. The pollution caused by nitrogen and phosphorus emissions can be effectively controlled and prevented through certain ways, such as reducing the application and improving the utility of chemical fertilizers, centralized livestock breeding, reducing resident sewage effluents. Furthermore, natural emissions cannot be ignored for nitrogen

and phosphorus emissions in Dagu River Basin (Fig. 10b), which can be reduced by modifying land use types according to the local terrain conditions (such as returning farmland to forest).

The anthropogenic sources of nitrogen and phosphorus pollutants in Dagu River Basin include chemical fertilizer loss, livestock breeding, human activity (urban and rural life) and industrial emissions. Figure 10c and d shows the contribution rate from different sources. The primary anthropogenic sources of TN and TP in the Dagu River Basin are chemical fertilizer loss and livestock breeding. They accounted for 49.9% and 29.6% of the TN and 41.4% and 40.3% of the TP, respectively. Residents' life (urban life and rural life) accounted for 17% of the TN and 13.3% of the TP emissions. The proportion of industrial emissions of TN (3.6%) and TP (5.0%) was the smallest. In conclusion, the pollution control system was improved, and the key pollution sources were found to be from chemical fertilizers and livestock breeding. Hence, there is a need to improve the efficient cultivation of the agricultural farming system and the centralized treatment of livestock and poultry excretion.
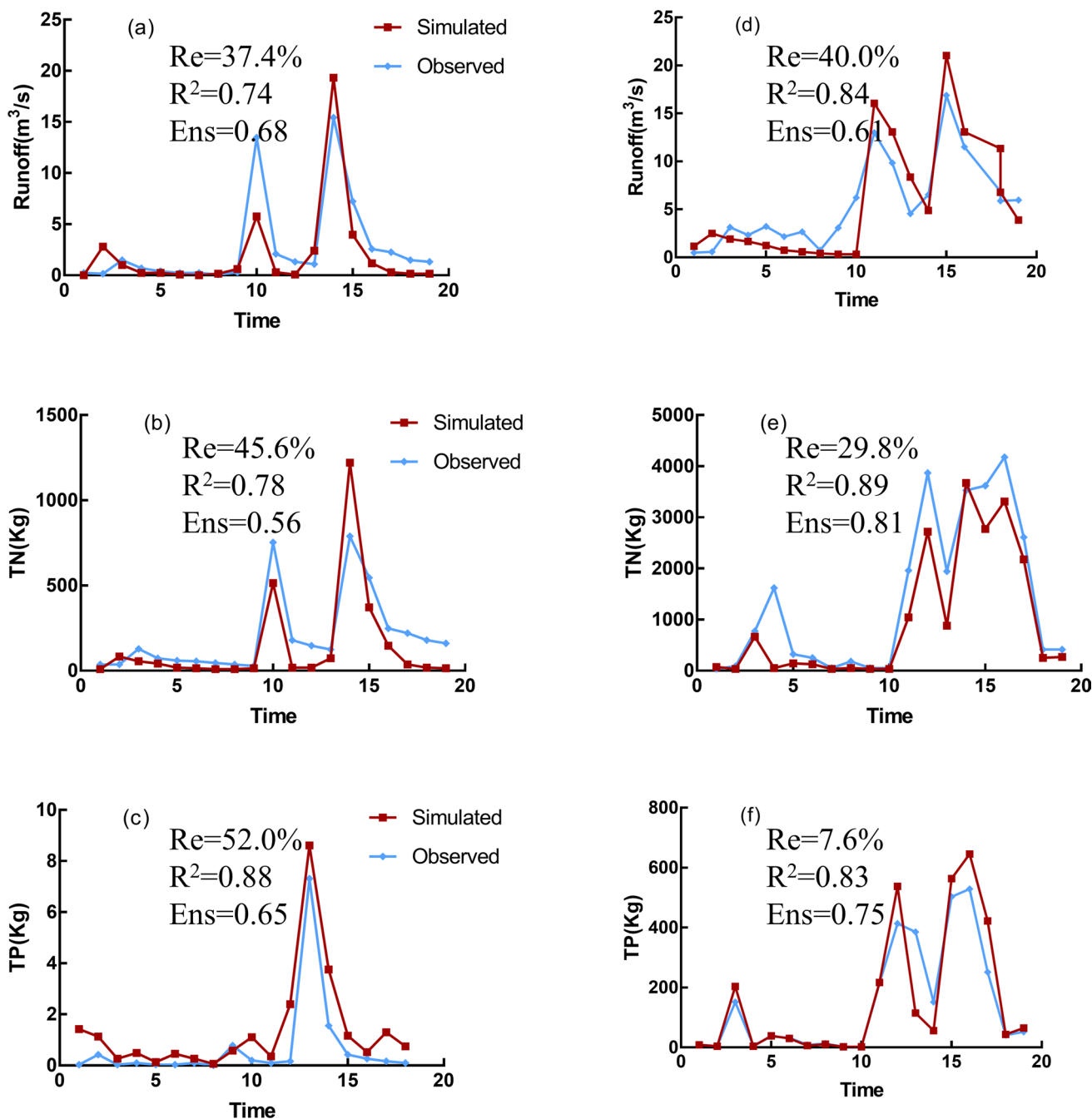
Fig. 7 Comparison between monitored and simulated values in continuous investigation Dongdingjia: **a** runoff, **b** TN, **c** TP; Xijujia: **d** runoff, **e** TN, **f** TP

Environmental management measures

Simulation effect of different remediation measures

According to the pre-set reduction ratios of various measures, the impact on TN and TP emissions was simulated, and the results are shown in Table 3.

Simulation evaluation of reduction measures based on planning

Based on the simulation results of different proportion reduction measures of chemical fertilizer use, livestock waste emissions, rural domestic sewage effluents and industrial emissions, the reduction of TN and TP emission from the Dagu River under specific measures of different sources

Table 2 Final values of calibration parameters

| Parameter	Meaning	File position	Value range	Actual value			
				DD	ZC	HL	FH
CN2	Runoff curve number	.mgt	0–100	91.7	59–91.7	59–92	83–92
ESCO	Soil evaporation compensation factor	.hru	0–1	0.5	0.5	0.2	0.4
Rchrg_dp	Permeability coefficient of deepwater storage	.gw	0–1	0.9	0.92	0.78	0.83
GWQMN	Shallow groundwater runoff coefficient	.gw	0–5000	4500	3500	4800	4200
Alpha_Bf	Base flow α coefficient	.gw	0–1	0.89	0.80	0.62	0.82
USLE_P	Water and soil conservation measures and factors	.mgt	0.1–1	0.52	0.6	0.52	0.52
SURLAG	Lag coefficient of surface runoff	.bsn	0–10	4	4	4	4
Ch_K2	Effective water conductivity of river channel	.rte	0.01–500	288.9	288.9	158.2	256
NPERCO	Nitrogen permeability coefficient	.bsn	0–1	0.07	0.07	0.07	0.07
PPERCO	Phosphorus permeability coefficient	.bsn	10–17.5	13.14	13.14	13.14	13.14

See Table S3 for station abbreviations
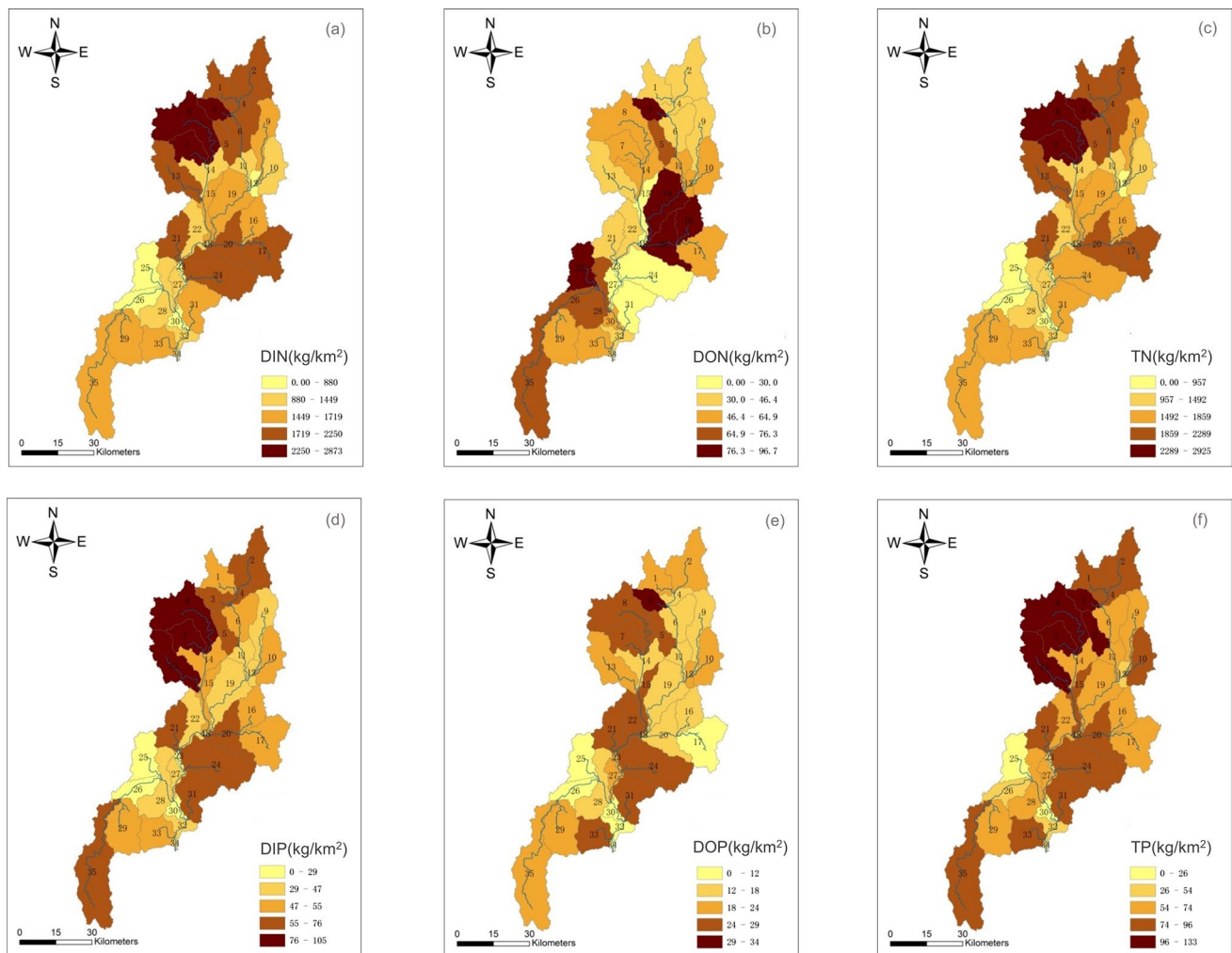
Fig. 8 Annual average emission density of nitrogen and phosphorus in sub-basins of Dagu River Basin: **a** DIN, **b** DON, **c** TN, **d** DIP, **e** DOP, **f** TP
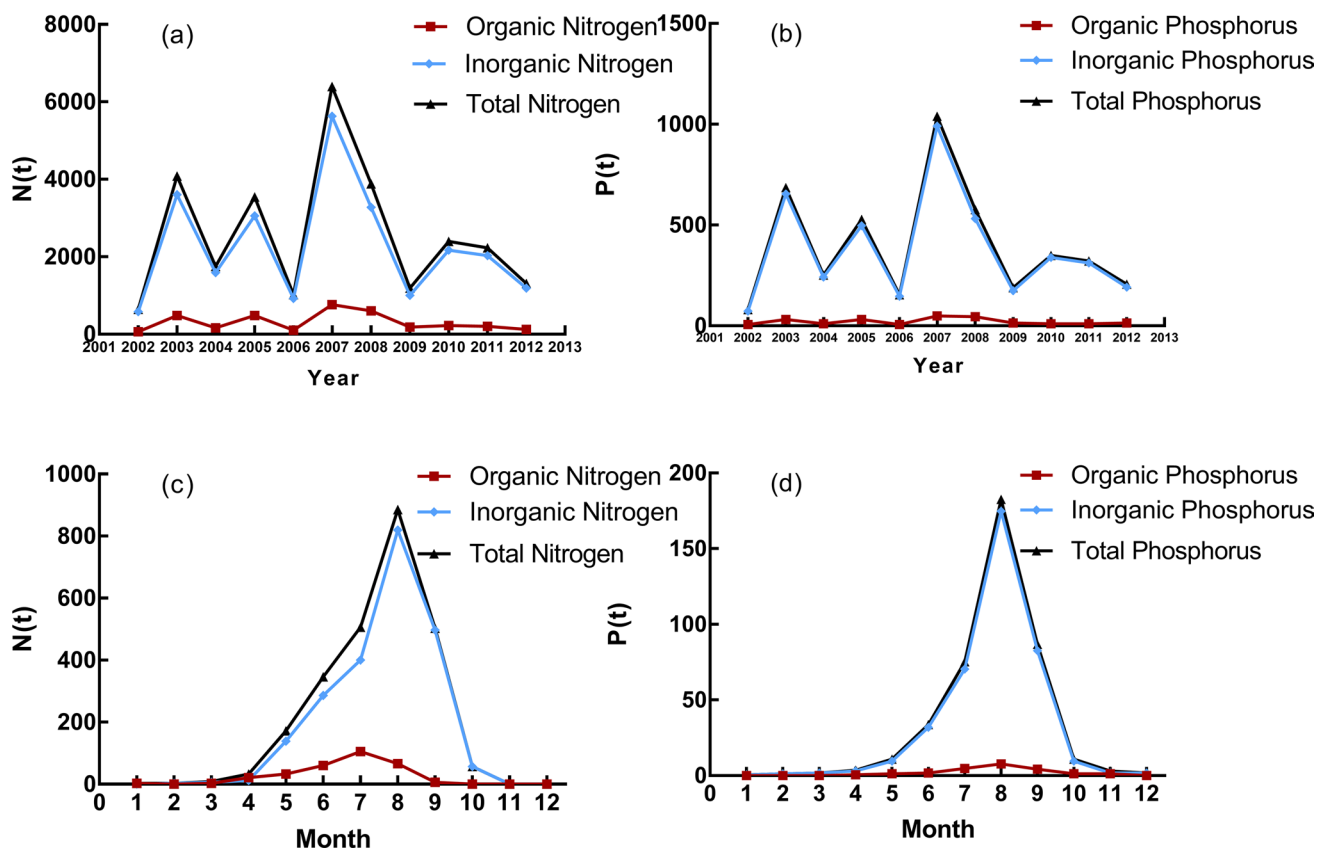
Fig. 9 Annual and monthly average emissions of nitrogen and phosphorus in Dagu River Basin from 2002 to 2012: **a** interannual nitrogen change; **b** interannual phosphorus change; **c** monthly average nitrogen change; **d** monthly average phosphorus change
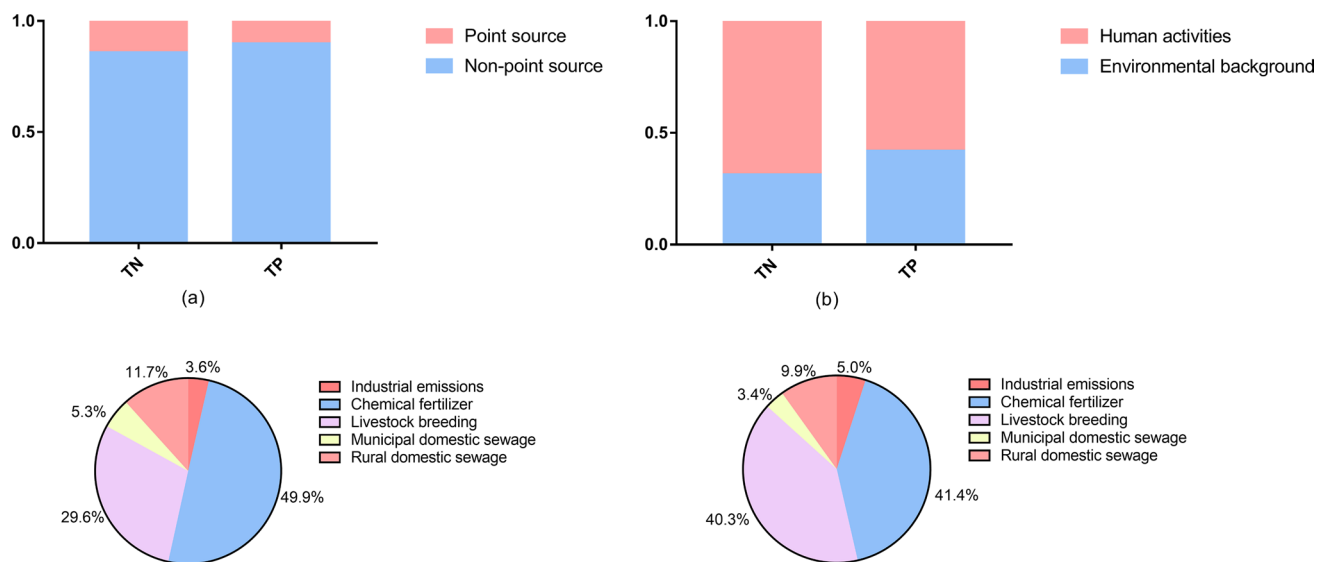
Fig. 10 Analysis of the characteristics of pollution source composition: **a** the composition of point source and non-point source, **b** the composition of pollution source, **c** composition of anthropogenic sources about TN, **d** composition of anthropogenic sources about TP

Table 3 Simulation results of various measures

Scenario		10% reduction		30% reduction		50% reduction		70% reduction	
		Simu/t	R-rate (%)	Simu/t	R-rate (%)	Simu/t	R-rate (%)	Simu/t	R-rate (%)
FE	TN	2517.34	3.21	2257.82	13.18	1946.40	24.62	1585.93	37.73
	TP	398.17	2.08	353.48	12.56	329.10	19.38	278.72	29.67
LB	TN	2551.60	1.68	2418.47	6.81	2249.52	13.32	2097.70	19.17
	TP	398.13	2.01	371.68	8.52	348.44	14.24	315.98	22.23
IE	TN	2559.91	1.36	2482.57	4.34	2431.44	6.31	2366.04	8.83
	TP	402.93	0.83	395.21	2.73	390.78	3.82	382.65	5.82
RL	TN	2579.11	0.62	2537.33	2.23	2491.65	3.99	2450.13	5.59
	TP	404.31	0.49	400.33	1.47	394.80	2.83	390.17	3.97

FE, chemical fertilizer; LB, livestock breeding; IE, industrial emissions; RL, rural life; Simu/t, simulation/t; R-rate, reduction rate

Table 4 Measures based on planning

Measures		Explanation
1	50% reduction in chemical fertilizer	The proportion set according to the national recommended dosage
2	70% reduction in chemical fertilizer	The proportion set according to the recommended dosage in developed countries
3	70% reduction in livestock emissions	The proportion set for converting livestock waste into organic fertilizer
4	Rural life cut by 70%	The proportion set by connecting rural domestic sewage to municipal sewage pipe network for sewage interception
5	50% reduction in industrial emissions	The ratio set for upgrading from secondary to primary emissions
6	Returning 30% farmland to forest	Implementation of returning farmland to forest in hilly areas of the upper reaches
7	Comprehensive measures	Measure 1. 3, 4, 5 and 6

(Table 4) was analyzed in detail according to the environmental protection and spatial utilization plan of the Dagu River Basin. From the analysis, it was found that chemical fertilizer would decrease to 50–70% (the reduction proportion is set according to the national recommended dosage and the recommended dosage of developed countries). Nitrogen and phosphorus emissions from livestock would decrease by 70% (of which the nitrogen and phosphorus emissions from livestock will be converted into organic fertilizer). Nitrogen and phosphorus emissions from rural domestic sewage will be reduced by 70% (the proportion set by the rural domestic sewage connected to the municipal sewage pipe network). Industrial nitrogen and phosphorus emissions will be reduced by 50% (the secondary discharge is upgraded to the primary discharge). The impact results of the implementation of the '30% of returning farmland to forest in the hilly forest area' were calculated by the nitrogen and phosphorus emission density of different land use modes (Liang et al. 2014).

Figure 11 demonstrates that the implementation of chemical fertilizer reduction, livestock waste reduction or returning farmland to forest in hilly areas could achieve significant results. Measure 7 shows that the comprehensive reduction measures can effectively achieve the effect of environmental remediation, which can reduce 79.14% of the TN and 69.02% of TP in Dagu River Basin.

According to the three-dimensional water quality model in Jiaozhou Bay (Lu et al. 2017), average concentration distribution of TN and TP in summer was calculated in Jiaozhou Bay before and after combination measure 7. Figure 12 shows that the environmental combination management measures for Dagu River are helpful to the control of TN and TP level in Jiaozhou Bay, especially in the verified summer period with frequent algal blooms. From Fig. 12a and c, it can be seen that under the initial scenario, the horizontal distribution concentration of nitrogen and phosphorus in Jiaozhou Bay gradually decreases from near shore to far shore, while after the implementation of measure 7, the distribution trend is basically unchanged, but the concentration values near and far shore are lower than the initial values. For the horizontal distribution of nitrogen in the sea area, in the initial scenario, the nitrogen concentration in the sea area of Jiaozhou Bay is generally higher than 0.2 mg/l, while the overall concentration is lower than 0.1 mg/l after the implementation of measure 7. For the horizontal distribution of phosphorus in the sea area, after the implementation of measure 7, the concentration in the nearshore decreased significantly, mostly below 0.07 mg/l, and the effect of decline in the far shore was not obvious.

Fig. 11 Reduction of total nitrogen and phosphorus emissions under different measures: **a** TN, **b** TP


(a)

(b)
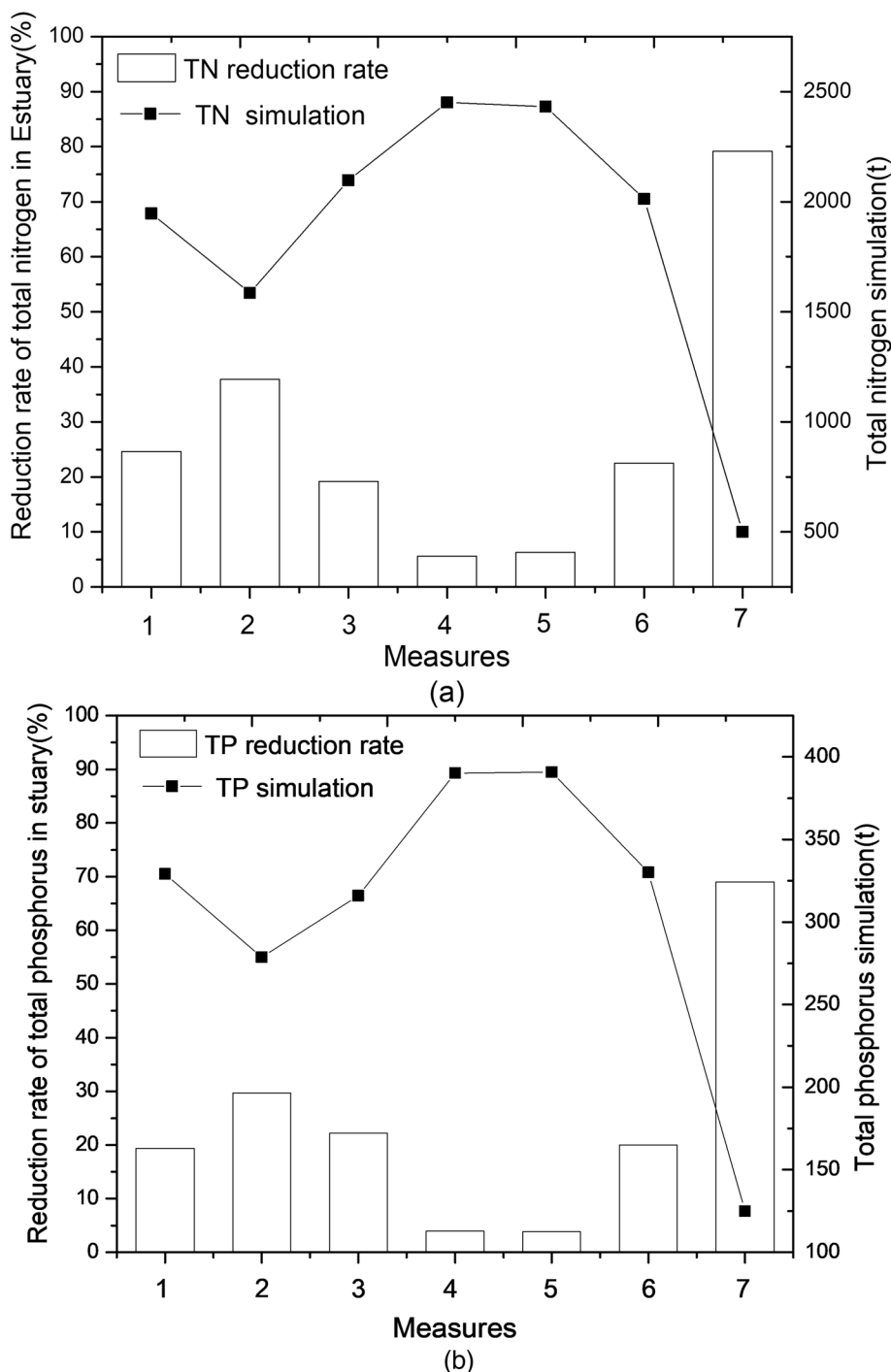
Discussion

Discussion on spatial density of nitrogen and phosphorus

In this study we found that the spatial distribution of inorganic and organic nitrogen emission density varied greatly in the Dagu River Basin. The inorganic nitrogen emissions mainly came from the upper reaches, while the organic nitrogen emissions mainly came from the middle reaches of Dagu River Basin. The reason for the difference may be that there are a lot of grasslands in the upper reaches, which meant that there was no discharge of industrial organic sewage. In contrast, the intensive human activities in industrial manufacturing caused the discharge of high organic nitrogen sewage in the middle reaches (Ham et al. 2003; Kusliene et al. 2015). As for phosphorus, it can be seen that the emission density of inorganic phosphorus was much higher than
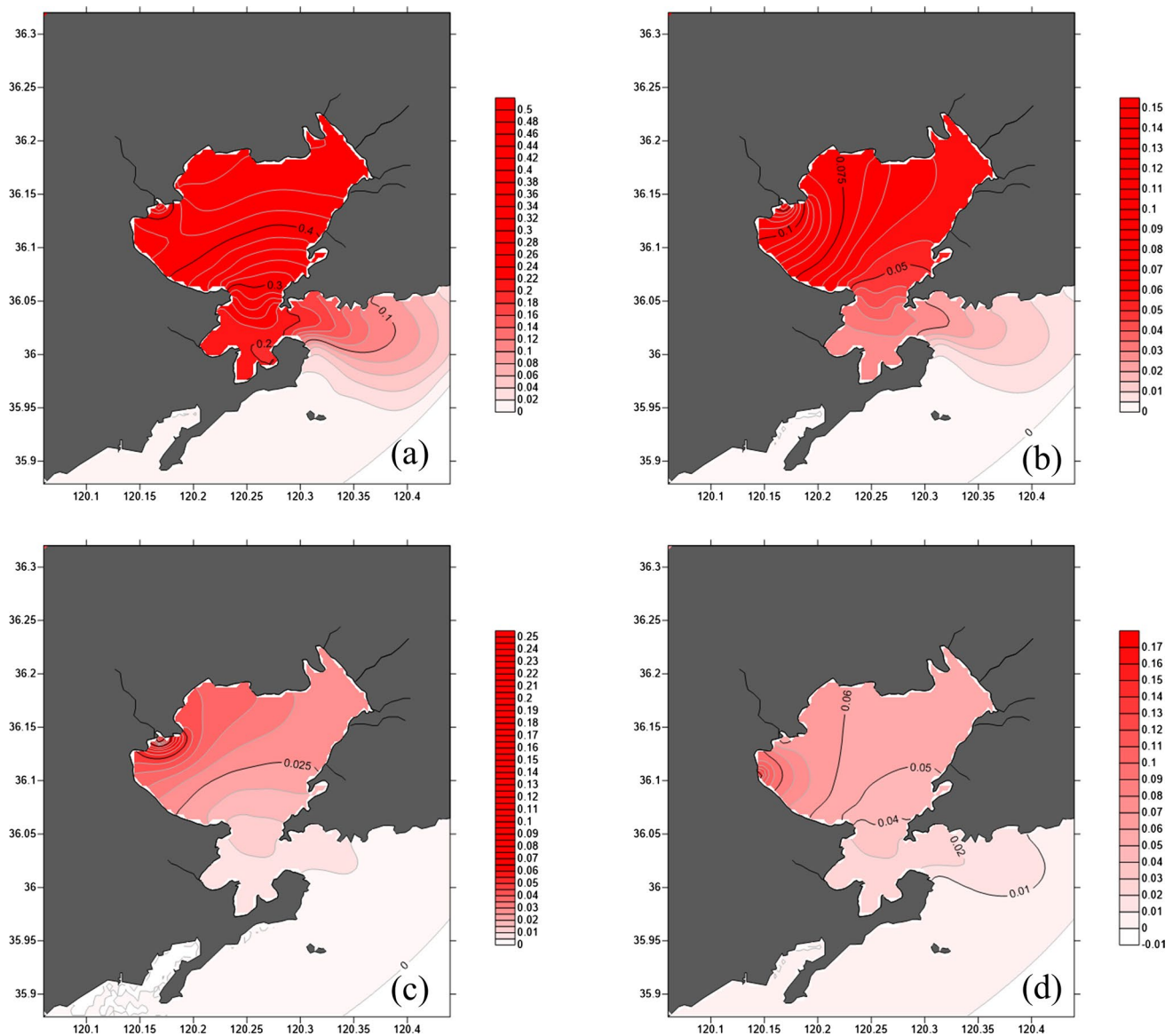
Fig. 12 Concentration distribution of TN and TP under different situations in Jiaozhou Bay, TN: **a** present situation, **b** after measure 7; TP: **c** present situation, **d** after measure 7

that of overall organic phosphorus. Hence, inorganic phosphorus should be targeted for phosphorus control in Dagu River Basin (Jia et al. 2016). Therefore, different pollution control measures should be taken for different areas, especially for different land use patterns.

It was also found that nitrogen and phosphorus emissions in the Dagu River Basin had a significant difference in their spatial distribution. The regions with higher nitrogen and phosphorus emission density in the Dagu River Basin were concentrated in the upper reaches, which is consistent with the field survey results from September 2011. The spatial difference of nitrogen and phosphorus emission density in the Dagu River Basin was closely related to the spatial distribution of rainfall, topography, land use and soil in the Dagu River Basin.

From the distribution of soil types (Fig. S3), the leached soil was mainly distributed in the middle reaches of the river, and the clay soil was mainly distributed in the upper reaches of river. The clay content of leached soil was high, which lead to significant emissions of organic nitrogen and phosphorus in corresponding areas. The higher content of inorganic matter in clay soil leads to higher emission density of inorganic nitrogen and inorganic phosphorus in the upper reaches of Dagu River (Liao et al. 2009). Figure S4 depicts that the rainfall in the Dagu River Basin gradually decreased from south to north. On the whole, TN and TP showed a

decreasing trend from north to south, as the natural area in the upstream was completely affected by rainwater scouring runoff. Most of the downstream was artificial surface, which is mostly controlled by the sewage discharge system. In conclusion, the amount of nitrogen and phosphorus emissions in each sub-watershed of the Dagu River Basin is influenced by the interaction of rainfall, topography, land use and soil types (Jiang et al. 2020).

Optimum combination of different measures

Based on the reduction of TN and TP and changes of the key emission sources in the Dagu River Basin with different measures, it can be concluded that the implementation of comprehensive measures (reducing fertilizer application by 50%, livestock and poultry breeding by 70%, rural residents' lives by 70%, urban residents' lives by 50% and turn 30% of cultivated land into forests), is effective for nitrogen and phosphorus remediation measures in the Dagu River Basin. This is consistent with results of the study by Zou (2008) that indicated that returning farmland to forest offered the best reduction effect in the upper reaches of Dagu River (Zou et al. 2008). In addition to the above measures, TN and TP can reach a reduction rate of up to 70%. These measures will provide valuable data support for comprehensive management of the Dagu River Basin in the future.

When the target of TN and TP output reduction control of Dagu River is reached, it can be found that the nutrient level of Jiaozhou Bay also has a response reduction. The response relationship between river emission reduction and bay emission reduction can be quantified according to the water quality model method used in this paper.

Conclusion and prospect

In this study, the SWAT model was used for data adaptation calculations and a multi-station calibration of parameters to better simulate the quantitative characteristics and spatial–temporal distribution of nitrogen and phosphorus emissions in the Dagu River Basin. The point source pollution and non-point source pollution were integrated in the same framework through the reasonable transformation method to study the migration and transformation of nitrogen and phosphorus pollution. Further the quantitative characteristics of nitrogen and phosphorus emissions were obtained with high accuracy.

Multiple station data were used to calibrate historical hydrological data, including discharge, nitrogen and phosphorus emissions based on which we propose that multi-station calibration is needed to reflect the overall hydrological status of the whole basin and improve the accuracy of global or partial hydrological simulation. According to the

selected representative stations, a series of suitable values of sensitive parameters were determined by relative deviation, Ens and other optimization standards. Further, the combination of the above sensitive parameters was verified by two field experiments, which were consistent with the actual hydrological conditions of the Dagu River. Based on cluster analysis method, the results of local station calibration could be used for the entire watershed and the final results with multiple verification can also be used for hydrological prediction and simulation in the future.

The primary sources of nitrogen and phosphorus emissions in the Dagu River Basin were from anthropogenic and natural sources. Anthropogenic sources were the predominant sources of nitrogen and phosphorus emissions; these emissions accounted for 69–58% of the total emissions. Further analysis showed that the main anthropogenic sources of TN and TP in Dagu River Basin were chemical fertilizer loss and livestock breeding, which accounted for 49.9% and 29.6% of TN and 41.4% and 40.3% of TP, respectively. Non-point sources accounted for 85.8% of the TN and 89.4% of the TP in Dagu River Basin. Future research and management should focus on the prevention and control of non-point source pollution.

The findings of this study demonstrate that chemical fertilizer reduction, scientific livestock breeding management, especially returning farmland to forest, are effective environmental control measures in the Dagu River Basin.

Land use types vary temporally, so it cannot match the meteorological data completely. Although land use patterns vary little in a short period of time, the mismatch problem may lead to different division of hydrological units in the model simulation. The relevant parameters of land use classification in the USA are also not the same as those in the study area, which is also one of the error sources in the application of the model. The SWAT model is suitable for long-term non-point source simulation, but it requires decades of monitoring data for calibration and verification. However, focusing on the characteristics of the combination of on-site monitoring and model simulation, long-term calibration and verification was not evaluated. Furthermore, due to the lack of sediment data, this study did not consider sediment parameters for calibration. It is also necessary to collect the spatial data and monitoring data of the Dagu River Basin and focus our attention to improving the spatial resolution of the data obtained. Sediment calibration should also be performed based on sediment monitoring data. Addressing these issues may enable the SWAT modeling to be more effectively applicable for the Dagu River Basin.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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