Quantifying the impact of human activities on water quality based on spatialization of social data: a case study of the Pingzhai Reservoir Basin

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ABSTRACT

In water pollution source research, it is difficult to quantify the impact of human activities on water quality. Based on pollution load theory and the concept of spatialization of social data, this study integrates land-use type, slope gradient, and spatial position, and uses the contribution of human activities to quantify the impact of farmland fertilizers, livestock and poultry wastes, and human domestic pollution on water quality in the study area. The results show that livestock manure is the largest source of total phosphorus (TP) and total nitrogen (TN) discharges in the research area, and domestic pollution is the largest source of chemical oxygen demand (COD) discharges. The total equal standard pollution load (as well as the load of each pollution source and its pollutant amount) is the highest in the Nayong River Basin and the lowest in the Baishui River Basin. The contributions of human activities to TP and TN have similar spatial distributions. The impact of human activities on COD discharge is minimal. The quantitative results of this model are basically consistent with the actual conditions in the Pingzhai Reservoir Basin, which suggests that the model reasonably reflects the impact of human activities on the water environment of the basin.

Key words | basin water environment, contribution, human activities, spatialization, water quality

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INTRODUCTION

Deterioration of river water quality has become a major environmental problem. The quality of water is closely related to human activities in a river basin (Li *et al.* 2004). The impact of human activities on water quality may stem from both point and non-point sources (Xia *et al.* 2013). As point source pollution has been effectively controlled and managed, the impact of non-point-source pollution on water quality has become increasingly prominent (Yan *et al.* 2013). In recent years, agricultural non-point-source pollution has been the main reason for water quality deterioration (Volk *et al.* 2016; Tong *et al.* 2017). In China, non-point-source pollution mainly includes farmland chemical fertilizers, livestock and poultry waste, urban runoff pollution, farmland solid waste, and rural domestic pollution (Liang *et al.* 2010). These pollution sources are directly caused by human activities in a river basin. Thus, defining the impact of human activities on the quality of water and quantifying the influential factors have attracted significant attention from researchers in the field of basin water management.

Researchers around the world have investigated the relationship between river water quality and human activities in a river basin (Billen *et al.* 2001; Huang *et al.* 2014; Chang *et al.* 2015; Zhang *et al.* 2018). Previous studies mainly used three methods. The first method is to construct an evaluation index system that measures the intensity of human activities by considering various factors including

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population, agricultural activities, social and economic development, and land-use structure. Then, this method establishes a regression model between water quality parameters and evaluation indicators (Castillo *et al.* 2000; Cheng *et al.* 2015) or calculates human activity intensity indices (Wang *et al.* 2009b) to evaluate river water quality. The second method is a pollution load method, which is used to quantitatively evaluate the impact of point and non-point pollution sources on the water environment; examples of this type of method include the equal standard pollution load (Gao *et al.* 2010; Yan *et al.* 2016) and the output coefficient model (Tong *et al.* 2017). The third method is to use mechanistic models to simulate the river water quality under the influence of human activities (Hasan *et al.* 2012), which have been widely applied in non-point-source pollution simulations (Volk *et al.* 2016; Yasarer *et al.* 2016). Among the above quantitative methods, the first two are based on clear evaluation ideas, the data are primarily from statistical yearbooks and are thus easy to obtain, and the methods are easy to implement. However, these methods neglect the complex migration and transformation processes of non-point-source pollution, and therefore measurement accuracy is usually lower than that of the third method. In the third method, the model mechanism is clear and the measurement accuracy is high, but the model parameter values are difficult to obtain.

Due to these shortcomings, this study introduces the concept of spatialization. Based on pollution load theory, this work considers various impact factors, such as land-use type, slope gradient and population density, and proposes a quantitative human activity model based on spatialization. The model expresses the degree to which human activities contribute to a pollutant discharge per unit area, thereby quantifying the extent to which human activities affect water quality in the basin. The pollution load model is mainly based on statistical socio-economic data and uses geographic data and simulation technology to achieve social data spatialization (Bai *et al.* 2013), which helps quantify the impact of human activities on water quality in the basin. At present, spatialization of socioeconomic data, such as population (Bai *et al.* 2013) and GDP (Xiao *et al.* 2018), is common, whereas spatialization of pollution load data is rare. The Pingzhai Reservoir is located at the starting point of the Yuzhong Water Conservancy Project in Guizhou Province and is an important source of irrigation and drinking water. The karst landforms in the Pingzhai Reservoir are widely distributed, accounting for 71% of the total area of the basin. Therefore, this study uses the ecologically fragile Pingzhai Reservoir Basin as the research area to explore the impact of major pollution sources (and human activities) on the water quality of the basin. Quantifying the contribution of human activities to pollutant discharges has important theoretical and practical significance.

RESEARCH AREA OVERVIEW AND DATA

The Pingzhai Reservoir is located in the middle of the Sancha River in Wujiang. It is the starting point of Guizhou's first large-scale cross-regional and cross-basin long-distance water conservancy project (Qianzhong Water Conservancy Project) approved by the State Council of China. The project carried out a river closure in 2011 and gated water storage in 2015. The normal water level of the Pingzhai Reservoir is 1,331 m, and the total storage capacity is 1.089 billion m^3. The Pingzhai Reservoir Basin (Figure 1) lies between 105°05′42″–105°30′50″ E and 26°28′55″–26°43′12″ N. The area is a leaf-shaped basin with a total area of 684.08 km^2 that covers Nayong County, Zhijin County, Liuzhi Special Zone and Shuicheng County, including 11 townships (streets). The terrain in the basin is complex. The terrain is high in the northeast and low in the southwest. The maximum elevation is 2,273 m, and the elevation difference is 1,091 m. The karst landforms are widely distributed. This area has a subtropical monsoon climate; it is mild and humid year round with abundant rainfall. The total population is 318,000 (end of 2016), and most areas are used for agriculture and animal husbandry.

The socioeconomic data used in this study mainly came from the 2017 yearbooks of Bijie City, Liupanshui City, and Nayong County, as well as the National Economic and Social Development Bulletin. The data applied from these yearbooks were supplemented by questionnaires and interviews. We calculated the data for this basin using area ratios. This study obtained land-use data from November 2017 Sentinel-2 images (https://scihub.copernicus.eu/) and combined these data with national census data and field

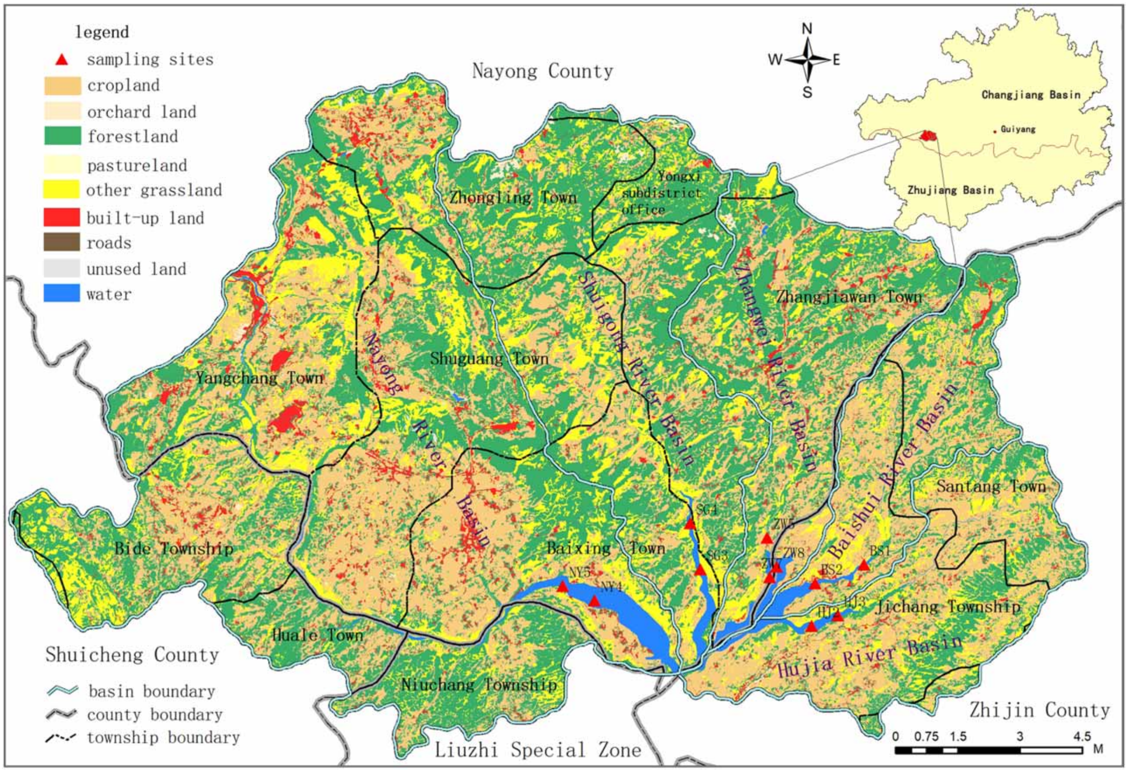

Figure 1 | Location of the study area and land use map.

surveys. Land-use types were divided into nine categories: cropland, orchard land, forestland, pastureland, other grassland, built-up land, roads, unused land, and water based on research needs (Figure 1). The slope gradient data were extracted from the 30 m Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) data through the ArcGIS-3D Analyst tool. The slope gradient data were divided into four ranges: 0°–8°, 8°–15°, 15°–25°, and higher than 25°. The water quality data of the research area adopted the measured value of the water area near the drainage outlet. The sampling points of Nayong River Basin were NY4 and NY5, those of Shuigong River Basin were SG3 and SG4, those of Zhangwei River Basin were ZW7 and ZW8 (ZW5 as a supplement), those of Baishui River Basin were BS1 and BS2, and those of Hujia River Basin were HJ2 and HJ3. Details are shown in Figure 1. The sampling position of the water sample was 0.2–0.5 m below the surface of the water. After collection, the water sample was stored in a portable cooler and taken back to the laboratory for determination within 24 h. Total phosphorus (TP) was determined by ammonium molybdate spectrophotometry, total nitrogen (TN) by alkaline potassium persulfate digestion–ultraviolet spectrophotometry, and chemical oxygen demand (COD) by rapid digestion spectrophotometry.

CONSTRUCTING THE HUMAN ACTIVITY QUANTITATIVE MODEL USING SPATIALIZATION

Introduction to the conceptual model

The quantitative model of human activity is based on the idea of social data spatialization and pollution load theory. The model aims to quantitatively evaluate the impact of human activities on river water quality and to visualize the evaluation results. The basic principle is to consider the research basin as consisting of many spatial units with various human activities that result in different land-use types. By calculating the contribution of human activities to the discharge of different pollutants in each spatial unit, we present the impact of human activities on river water quality spatially. For the Pingzhai Reservoir Basin, we performed the following procedures. (1) By considering the basin area and the sizes of land-use patches, the spatial unit of this study was determined to be 100 m × 100 m. The entire basin had a total of 69,318 units (cells). (2) The towns and townships in the basin were mostly based on agriculture, and there were few industrial and mining enterprises. Therefore, this study focused on agricultural non-point-source pollution (which has the widest sources of pollution), such as farmland fertilizers, livestock and poultry waste, and human domestic pollution. The fertilizers were mainly used on cropland, orchard land, and pastureland. Since the contributions of land-use types with different slope gradients to pollutant discharge are different, we introduced the slope gradient correction coefficient when dealing with cropland, orchard land, and pastureland. Livestock and poultry farming were mainly on residential land. Although manure can be used as fertilizer for farmland, only cropland near residences actually received manure fertilizer due to large slope gradients and fragmentation of the land. Therefore, the impact of livestock and poultry farming on cropland was not considered separately, and its data spatialization was included in built-up land and other grassland. Human domestic pollution was mainly on built-up land excluding roads. Since different population densities contribute differently to pollutant discharges, the population density correction factor was introduced when estimating the domestic pollution load of built-up land. (3) The rural population of Pingzhai Reservoir is large; therefore, the urbanization level is relatively low and the urban sewage treatment capacity is small. Most domestic sewage is directly discharged in a decentralized manner. Thus, the centralized treatment of urban sewage was not considered, and the domestic pollution of townships and rural areas in the study area was calculated as non-point sources. (4) Since the three types of pollution sources do not affect the water area, forestland, or unused land in the spatialization process, all the forestland, water area, and unused land cells in the spatial unit were replaced with 'none', indicating that, for our purposes, human activity had no impact. (5) We used TP, TN and COD as indicators for pollutants.

Calculation method

The contribution of human activities to a certain pollutant discharge was defined as the discharge of a certain pollutant by human activities in each cell divided by the total discharge of the basin. The equations are as follows:

$$K_{ij} = E_{ij} \Big/ \sum_{j=1}^{m} E_{ij} \tag{1}$$

$$E_{ij} = E_{ij\,\mathrm{fertilizer}} + E_{ij\,\mathrm{livestock\,and\,poultry}} + E_{ij\,\mathrm{domestic}} \tag{2}$$

Here, K_{ij} represents the contribution of human activities to the ith pollutant discharge in the jth cell; E_{ij} is the discharge of the ith pollutant from different human activity sources in the jth cell, including chemical fertilizer application, livestock and poultry farming, and domestic pollution; and m is the total number of basin cells.

Fertilizer application

Fertilizer pollution is caused by the application of large amounts of chemical fertilizers in agricultural production, which pollute the water, soil, and atmosphere (Zhu 2007) with nitrogen and phosphorus pollutants (Yan *et al.* 2016). According to statistics, the average utilization rates of nitrogen, phosphate and potassium fertilizers in China are 30–45%, 10–20%, and 40–60%, respectively. The fertilizer application efficiency is low, and the application of nitrogen fertilizer is disproportionate to phosphate fertilizer and potassium fertilizer (Zhu 2007; Wang *et al.* 2009a). The quantitative method for the discharge of pollutants caused by chemical fertilizer application was as follows:

$$E_{ij\,\mathrm{fertilizer}} = \left(\sum_{n=1}^{4} (A_{jn} \times S_n)\right) \times Q_{i\,\mathrm{fertilizer}} \times P_{i\,\mathrm{fertilizer}} \tag{3}$$

$$Q_{i\,\mathrm{fertilizer}} = \Big(M_{\mathrm{nitrogen\,fertilizer}} + M_{\mathrm{composite\,fertilizer}} \times 0.15 + M_{\mathrm{phosphate\,fertilizer}} \times 0.185\Big) \times 20\%/A_{\mathrm{basin}} (i \text{ is TN}) \tag{4}$$

$$Q_{i\,\mathrm{fertilizer}} = (M_{\mathrm{phosphate\,fertilizer}} + M_{\mathrm{composite\,fertilizer}} \times 0.5) \times 15\%/A_{\mathrm{basin}} (i \text{ is TP}) \tag{5}$$

Here, $E_{ij\,\text{fertilizer}}$ is the discharge of the ith pollutant from fertilizer application in the jth cell. A_{jn} is the area of cropland, orchard land, and pastureland within a certain slope gradient range in the jth cell. S_n is the slope gradient correction coefficient with reference to the suitability of cropland in the relative index model of land use (Chen *et al.* 2001). The reciprocal of the suitability of each slope gradient range is the slope gradient correction factor (Table 1, with adjustment as needed). The larger the value, the easier the movement of pollutants; thus, the greater the discharge. The grading of the slope gradient is indicated by n. $Q_{i\,\text{fertilizer}}$ is the movement of the ith pollutant of fertilizers in a unit area. The calculation method is based on the literature and is determined according to the actual situation in the study area (Wang *et al.* 2009a; Yan *et al.* 2016). $M_{\text{nitrogen fertilizer}}$, $M_{\text{phosphate fertilizer}}$, and $M_{\text{composite fertilizer}}$ are the amounts of application (expressed as amounts of pure chemicals) of nitrogen fertilizer, phosphate fertilizer, and composite fertilizer, respectively, in 2018. A_{basin} is the basin area. $P_{i\,\text{fertilizer}}$ is the equal standard pollution load ratio of the ith fertilizer pollutant (Ye & Bian 2005; Gao *et al.* 2010), which is the threshold concentration of pollutants referring to the water standard of Class III in GB3838-2002 (TN $1\,\text{mg}\cdot\text{L}^{-1}$, TP $0.2\,\text{mg}\cdot\text{L}^{-1}$, and COD $20\,\text{mg}\cdot\text{L}^{-1}$).

Livestock and poultry manure

In the study area, livestock and poultry are raised by individual rural households and there are few large-scale farms. The livestock in the study region include cattle (beef source), sheep, pigs and poultry. Most livestock and animal wastes directly enter the environment without proper treatment. The quantitative representation of pollutant discharge caused by livestock manure was calculated as follows:

$$E_{ij\,\text{livestock and poultry}} = (Z_j + Z_{j\,\text{grass}}) \times Q_{i\,\text{livestock and poultry}} \times P_{i\,\text{livestock and poultry}} \tag{6}$$

$$Q_{i\,\text{livestock and poultry}} = \sum_{n=1}^{4} (M_n \times N)/A_{\text{basin}} \tag{7}$$

Here, $E_{ij\,\text{livestock and poultry}}$ is the discharge of the ith pollutant from livestock and poultry in the jth cell. Z_j is the area of built-up land in the jth cell. $Z_{j\,\text{grass}}$ is the area of grassland in the jth cell (excluding pastureland). $Q_{i\,\text{livestock and poultry}}$ is the discharge per unit area of the ith pollutant in the livestock and poultry pollution source. M_n is the number of livestock of the nth type; n is the type of livestock and poultry. According to the actual situation of the study area, we selected cattle, sheep, pigs, and poultry. N is the pollutant content (kg/year) in the excretion (discharge) of each animal/poultry per year, which is determined from the literature (Department 2002; Zhu 2007) (Table 2). A_{basin} is the same as stated previously. $P_{i\,\text{livestock and poultry}}$ is the equal standard pollution load ratio of the ith pollutant in the livestock and poultry pollution source.

Domestic pollution

Domestic pollution is mainly from domestic sewage and human waste (Gao *et al.* 2010). The quantitative representation of pollutant discharge caused by domestic pollution was calculated as follows:

$$E_{ij\,\text{domestic}} = Z_j \times J \times Q_{i\,\text{domestic}} \times P_{i\,\text{domestic}} \tag{8}$$

$$Q_{i\,\text{domestic}} = (Q_{i\,\text{domestic sewage}} + Q_{i\,\text{human waste}})/A_{\text{basin}} \tag{9}$$

$$Q_{i\,\text{domestic sewage}} = M_{\text{population}} \times N \tag{10}$$

$$Q_{i\,\text{human waste}} = M_{\text{population}} \times N \tag{11}$$

Here, $E_{ij\,\text{domestic}}$ is the discharge of the ith pollutant from domestic pollution in the jth cell. Z_j is the area of built-up land in the jth cell. J is the population correction coefficient, which is determined by the population density of the basin and the average population density ratio of the counties (Nayong County, Zhijin County, Liuzhi Special Zone, and

Table 1 | Slope gradient correction coefficient

Slope gradient grading	Slope gradient range	Correction coefficient
1	0°–8°	1
2	8°–15°	2
3	15°–25°	3
4	>25°	4

Table 2 | Pollutant content of excreta per animal/person per year (kg/year)

	Livestock and poultry farming (headcount)						Domestic pollution (per person)	
	Cow dung	Cow urine	Sheep manure	Pig manure	Pig urine	Poultry manure	Domestic sewage	Human waste
TP	8.61	1.46	0.45	1.36	0.34	0.115	0.16	0.524
TN	31.9	29.2	2.28	2.34	2.17	0.275	0.56	3.06
COD	226.3	21.9	4.4	20.7	5.91	1.165	5.99	19.8

Shuicheng County). It was calculated as 1.78. The total population of the river basin was obtained through the investigation of each village committee. $Q_{i\,\text{domestic}}$ is the discharge per unit area of the ith pollutant in the domestic pollution source. $Q_{i\,\text{domestic sewage}}$ and $Q_{i\,\text{human wastes}}$ are the discharge per unit area of the ith pollutant in the domestic sewage and human waste, respectively. $M_{\text{population}}$ is the regional population. N is the pollutant content (kg/year) in the excretion (discharge) of each person per year. A_{basin} is the same as described above. $P_{i\,\text{domestic}}$ is the equal standard pollution load ratio of the ith pollutant in the domestic pollution source.

RESULTS AND ANALYSIS

Pollutant discharges in the study area

In Table 3, the TP, TN, and COD discharges in the study area accounted for 3.85%, 17.91%, and 78.24%, respectively. Of the pollution sources, chemical fertilizers, livestock and poultry manure, and domestic pollution accounted for 4.35%, 49.35%, and 46.30%, respectively. Livestock and poultry manure had the largest amount of pollutants and were the largest sources of TP and TN discharge. The contributions to TP and TN discharges were 50.43% and 49.40%, respectively. Domestic pollution was the largest source of COD discharges, contributing 50.72% to total COD discharge. The chemical fertilizers were mainly nitrogen and phosphorus pollutants, and the contributions to TP and TN discharges were 22.21% and 19.50%, respectively.

Table 3 | Total nitrogen, total phosphorus and COD discharges from three sources in the study area (unit: ton/year)

Category	TP	TN	COD	Total
Fertilizer application	176.42	721.46	–	897.88
Livestock and poultry manure	400.62	1,827.53	7,965.82	10,193.97
Domestic pollution	217.41	1,150.60	8,197.26	9,565.27
Total	794.44	3,699.59	16,163.08	20,657.12

Due to the differences in agricultural structure and population distribution in different river basins, there were significant differences in the pollution load generated by chemical fertilizers, livestock and poultry manure, and domestic pollution (Table 4). The total equal standard pollution load was the largest in the Nayong River Basin, reaching 4,201.92 t·a^{-1}, which was followed by the Shuigong River Basin. The smallest load was in the Baishui River Basin, reaching only 659.06 t·a^{-1}. These three pollution sources and three associated pollutants had the largest equal standard pollution loads in the Nayong River Basin. This was because this basin has the largest area and population, and the agricultural and livestock farming are well developed. Conversely, the Baishui River Basin had the smallest equal standard pollution load, which was due to its small geographic area and population, as well as unfavorable (deep valley) terrain.

In the entire basin, livestock manure was the largest pollution source, followed by domestic pollution and chemical fertilizers; the three sources accounted for 49.87%, 31.22%, and 18.91%, respectively, of the total equal standard pollution load. Regarding pollutants, the percentage of TP discharge was higher than that of TN and COD; these three pollutants accounted for 46.84%, 43.63%, and 9.53%, respectively, of the total equal standard pollution load.

The comprehensive impact of human activities on water pollutants in the basin

The quantitative model was used to comprehensively evaluate the TP, TN, and COD discharges in the upper reaches of

Table 4 | Comparison of equal standard pollution loads of three main pollution sources in each basin of the study area (unit: ton/year)

	Pollution source			**Pollutant**			
Basin	**Fertilizer application**	**Livestock and poultry manure**	**Domestic pollution**	**TP**	**TN**	**COD**	**Total**
Hujia River Basin	120.49	530.90	285.30	433.78	408.53	94.38	936.69
Baishui River Basin	85.48	376.65	196.93	305.51	287.44	66.11	659.06
Zhangwei River Basin	192.44	456.31	270.60	468.79	365.59	84.97	919.35
Shuigong River Basin	369.24	850.81	542.90	809.46	789.45	164.05	1,762.95
Nayong River Basin	835.90	2,014.24	1,351.78	1,954.69	1,848.58	398.65	4,201.92
Total	1,603.56	4,228.90	2,647.50	3,972.22	3,699.59	808.15	8,479.97

the Pingzhai Reservoir. The larger the contribution, the greater the contribution of human activities to water pollutants in the basin and the stronger the impact of human activities on river water quality. In order to make the results easy to compare, the calculated contribution of each cell was enlarged 69,318 times. According to the standard deviation, the contribution was divided into five categories, indicating that human activities had a very weak, weak, moderate, strong, or very strong impact on river water quality.

There were no significant differences in the impacts of chemical fertilizers, livestock manure and domestic pollution on TP and TN discharges. The contributions of the three human activities showed similar spatial distribution characteristics (Figures 2 and 3). The maximum contribution to TP discharges was 2.97. Similarly, the maximum contribution to TN discharges was 3.52. In the Nayong River Basin, strong impacts due to human activities were mainly distributed in Zhongling Town in the north, Yangchang Town and Bide Township in the west, and the banks of Baixing Town in the east. These areas are densely populated with concentrated cropland. In the Shuigong River Basin, strong impacts from human activities occurred

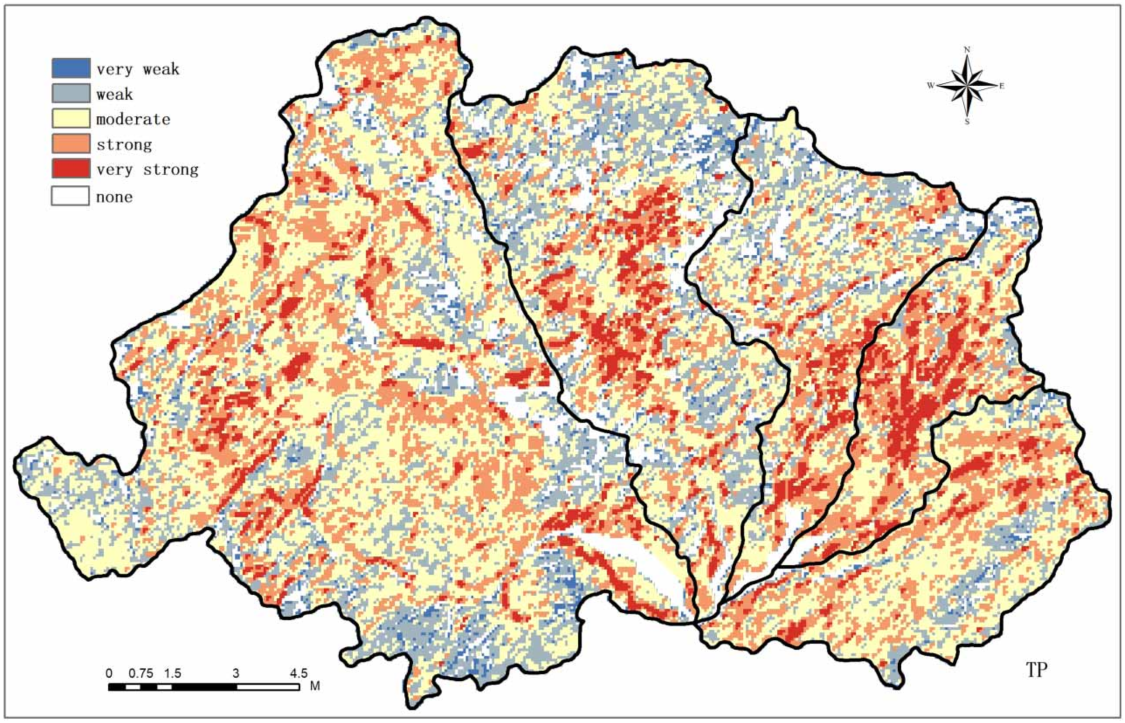

Figure 2 | Contribution of human activities to TP discharges in the study area.

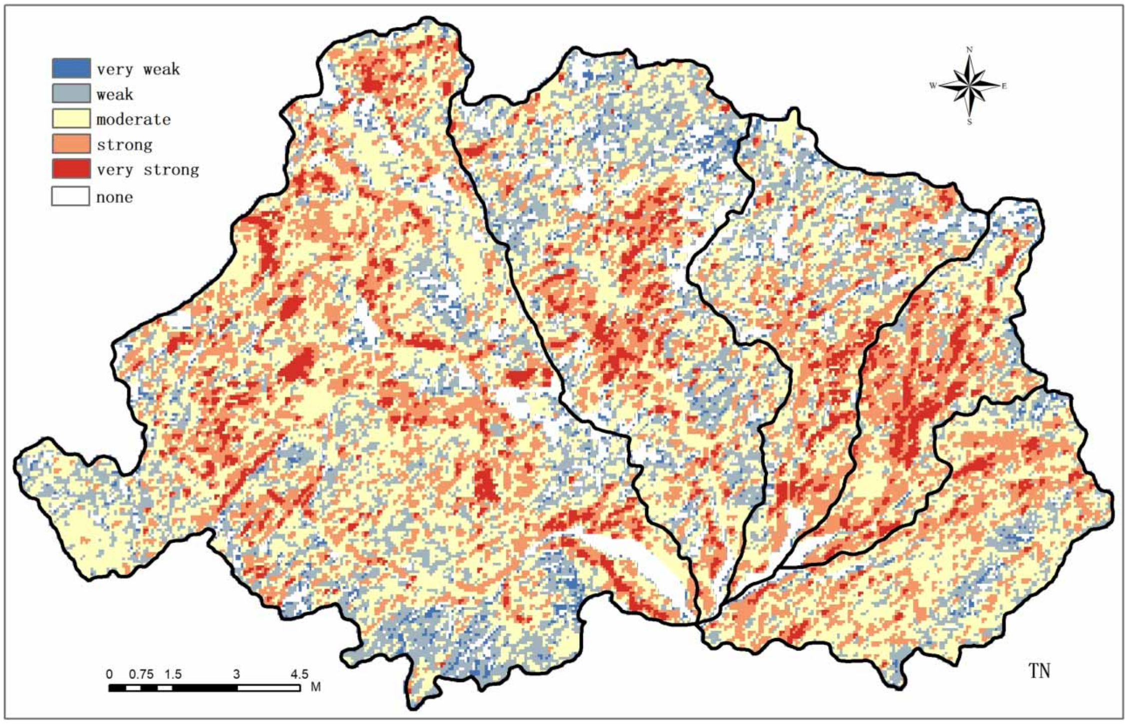

Figure 3 | Contribution of human activities to TN discharges in the study area.

mainly in the middle of the basin. The north is dominated by forests and grasslands, and the impact of human activities was small. Similarly, the northern part of the Zhangwei River Basin is dominated by forestland, and the impact of human activities was small. In the central and southern canyons, the slope gradient of cropland is large, and the impact of human activities was classified as strong and very strong. The Baishui River Basin has mountains and valleys, and the cropland is mostly distributed on the slopes. The impact of human activities was strong and very strong in this region. In the Hujia River Basin, the impact of human activities was moderate; impact in the north was stronger than in the south. The areas with the largest to the smallest TP and TN discharges per unit area were as follows: Baishui River Basin, Hujia River Basin, Nayong River Basin, Zhangwei River Basin, and Shuigong River Basin.

The impacts of the three human activities on COD discharges were mainly very weak and weak across the entire study basin; there was a maximum contribution of 13.96. The strong human activities are shown by the dots in Figure 4. The distribution in this region was uneven; it was mainly concentrated in the densely populated areas of the Nayong River Basin. The largest COD discharge per unit area was in the Nayong River Basin, followed by the Shuigong River Basin, Zhangwei River Basin, and Hujia River Basin. The smallest COD discharge per unit area was in the Baishui River Basin.

DISCUSSION

Model reasonableness discussion

Due to the lag in non-point-source pollution in the basin, the rationality of the spatial quantification results of the model was indirectly determined by comparing the measured values of TP, TN, and COD concentrations in the outlet waters in November 2018 with the total contributions of human activities to pollution in each basin. Two sampling points (Figure 1) were arranged for each of the five drainage areas, and the average value was taken as the measured value of each drainage area. The sum of contributions of human activities to pollution in each basin was the sum of

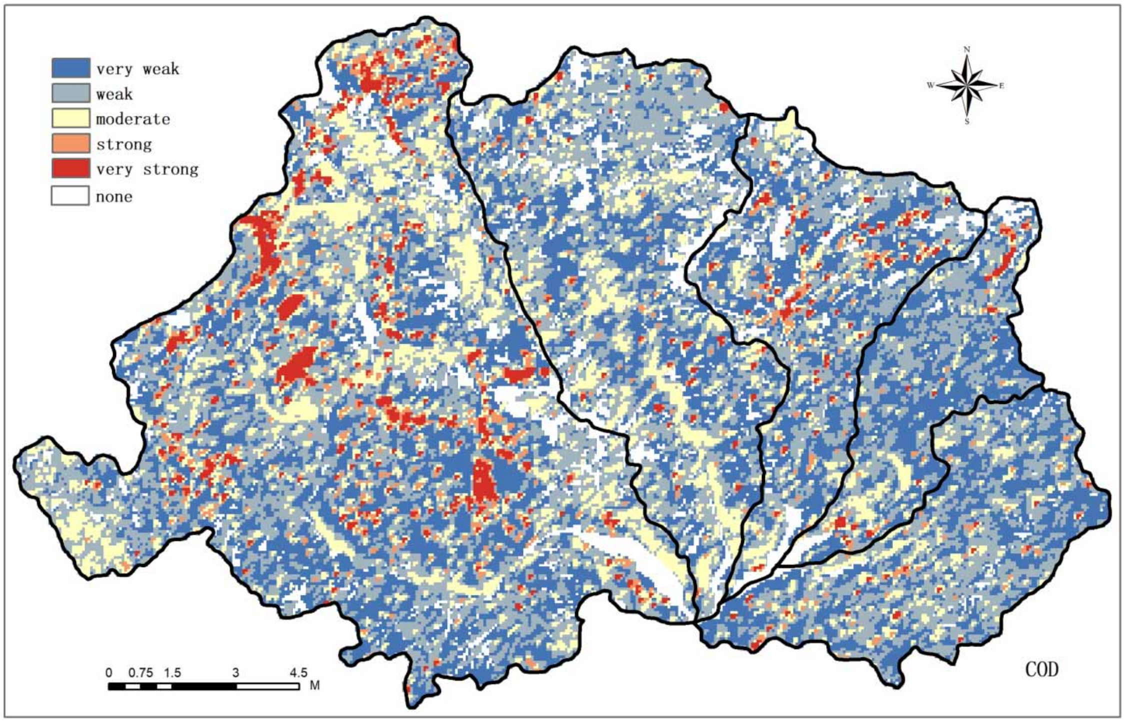

Figure 4 | Contribution of human activities to COD discharges in the study area.

contributions (K) of human activities in each spatial unit of the basin. In order to facilitate the comparison, the measured data for water quality parameters and the contribution of human activities to pollution were standardized by min–max, and the results are shown in Figure 5.

As shown in Figure 5, the total contribution of human activities to pollution in Baishui River Basin was low, while the measured concentrations of TP, TN, and COD were high, showing some inconsistency, which is mainly caused by the small basin area. As shown by Figures 2 and 3, the effects of human activities on TP and TN discharges in Baishui River Basin were strong and extremely strong, respectively, which is consistent with the measured TP and TN concentrations. The spatial quantification results of the model could reflect the impact of human activities on TP and TN concentrations in the water environment of the basin, but the response relationship to COD concentration was not significant.

The contribution of human activities to the discharges of TP, TN, and COD in the Hujia River Basin and Nayong

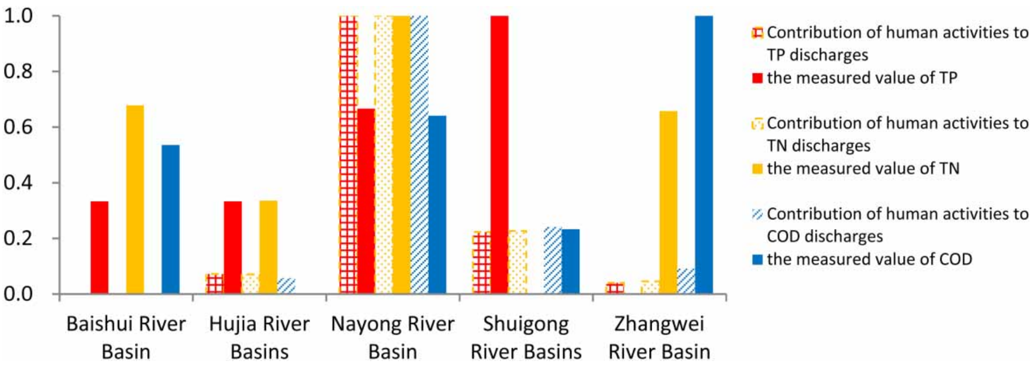

Figure 5 | Contributions of human activities to pollution and measured values of TP, TN, and COD in each basin.

River Basin was largely consistent with the measured TP, TN and COD concentration changes. The smaller the contribution of human activities, the lower the concentration of pollutants. The greater the contribution of human activities, the higher the concentration of pollutants. The contribution of human activities to pollutant discharges in Shuigong River Basin was consistent with the measured TN and COD concentration changes, which was different from that of TP.

The contribution of human activities to pollutant discharges in Zhangwei River Basin was consistent with the measured TP concentration, which was different from that of TN and COD. The two sampling points (ZW7 and ZW8) of Zhangwei River Basin were located at the outlet of the underground river. Comparing the measured values of TN and COD at the sampling points (ZW5) of the surface river of Zhangwei River showed that the TN concentration at ZW5 was 16.6% lower than that at ZW7, 11.1% lower than that in ZW8, and the COD concentration at ZW5 was 41% lower than that at ZW7 and 58.7% lower than that at ZW8, which was consistent with the low contribution of human activities in Zhangwei River Basin. Therefore, it can be concluded that the contribution of human activities to pollutant discharges in Zhangwei River Basin was consistent with the measured value. The complicated dual structure of the surface underground and water environment in the karst area is one of the causes of the local differences.

Model applicability discussion

The quantitative model proposed in this study took a human activity perspective and comprehensively evaluated the extent to which water quality in the basin was affected by human activities. The study aimed at promoting coordinated development of human socio-economic factors and the ecological environment in the basin by rationally managing human activities. The problems of water quality in river basins are often caused by a variety of human activities. At present, there are only three kinds of human activities considered in the model, all of which are agricultural non-point pollution sources. This quantitative model of human activities has strong application potential; however, additional human activities must be considered in order to improve the model in future studies.

The model quantified the impact of human activity as a value between 0 and 1. The sum of the contributions from all grids in the entire study area was 1. Therefore, the more cells, the smaller the contribution of a single cell. In order to simplify the comparison, the cells were enlarged. The process of spatial quantification was based on land-use types, as land use/cover change (LUCC) is the most significant indicator of human influence on nature and is also an important indicator of hydrological and water environment changes (Yan *et al.* 2013). Land-use patterns and their changes have a profound impact on natural environmental systems (e.g., hydrological development, ecological development) (Zhang 2011). This study mainly considered the direct impacts of human activities on cropland, orchard land, grassland (including pastureland), and built-up land (excluding roads), and did not consider forestland and water bodies and unused land. These land-use types were not considered because forestland may affect water quality parameters, especially those with a negative correlation with COD (Zhang *et al.* 2016).

The model quantified three kinds of human activities: chemical fertilizer application, livestock and poultry manure pollution, and domestic pollution. Livestock manure was the largest pollution source with its equal standard pollution load being the highest; it also had the largest impact on TP and TN. It should be noted that the size of livestock and poultry farming in the study was calculated using data from the township yearbooks. Most of the statistics were from large-scale livestock and poultry farming; thus, the actual size of livestock and poultry farming in this region needs to be investigated. As a result, the calculated results were higher than the real values and this issue will be addressed in a future study. Domestic pollution was the second largest source of pollution in the basin and the largest source of COD. The model was applied to built-up land (excluding roads) because this was the main area for human activities (and human activities had the largest impact on built-up land). When quantifying the application of fertilizers, we introduced the slope gradient correction coefficient because agricultural land (cropland, orchard land, and pastureland) with different slope gradients can contribute differently to various water bodies (Chen 2014). The larger the slope gradient, the larger the contribution. The total equal standard pollution load, as well as the load of each pollution source and its pollutant amount, in the

Baishui River Basin was the smallest. However, the contribution of human activities in this basin was very high. In particular, the impacts on TP and TN discharges in this basin were classified as strong and very strong, respectively. The main reason for this result was that the agricultural land in this area had large slope gradients.

CONCLUSIONS

The quantitative model used in this study used the contribution of human activities to quantitatively evaluate the comprehensive impacts of three kinds of human activities on water quality in the basin. The model integrated the spatial characteristics of land-use types to present the impacts of human activities on the water environment system in the basin.

Among the three pollution sources in the study area, livestock and poultry manure were the greatest pollution sources with the largest equal standard pollution load. Livestock and poultry manure were also the largest sources of TP and TN. Domestic pollution was the largest source of COD. The total equal standard pollution load, as well as the load of each pollution source and its pollutant amount, was the largest in the Nayong River Basin and the smallest in the Baishui River Basin.

There was little difference in the impacts of human activities on TP and TN discharges. The contributions of these discharges showed similar spatial characteristics. The areas with strong and very strong impacts were concentrated in the central part of the Baishui River and Shuigong River Basins, in the mid-southern part of the Zhangwei River Basin, in the northern part of the Hujia River Basin, in the northern part of the Nayong River Basin (Zhongling Town), in the west part of Yangchang Town, in Bide Township, and in the areas along the two banks of the reservoir in the eastern part of Baixing Town. These areas were densely populated and had concentrated or steep-sloped croplands. There was a small impact of human activities on COD discharges. Areas with strong impacts were scattered and unevenly distributed, and mainly occurred in the densely populated areas of the Nayong River Basin.

After analyzing pollutant discharge per unit area, we found that the impacts of human activities on TP and TN discharges were the largest in the Baishui River Basin, followed by the Hujia River Basin and Shuigong River Basin. The impact of human activities on COD discharges was the largest in the Nayong River Basin, followed by the Shuigong River Basin and Zhangwei River Basin, while it was the lowest in the Hujia River Basin and Baishui River Basin.

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