Study on spatial distribution of pollutants and total amount reduction in the Duliujian River (Tianjin, China)

Qiongqiong Liu, Dan Liu, Yan Zhang, Yanxi Wang and Meinan Xing

ABSTRACT

The Duliujian River is the largest river in the downstream area of the Haihe River. In order to further clarify the main pollutant load and load contribution of the basin, and analyze the watershed pollution control unit, key pollution sources and their spatial distribution characteristics, this study divides the control unit of the basin, which is based on the digital elevation model (DEM), and applies the expansion template of Arc Map–Arc Hydro tools software. On the basis of water environment capacity and total maximum daily load (TMDL) theory, water quality standards are set in accordance with the requirements of the water body function. Considering seasonal influence and the pollution load contribution rate, a total pollution load control plan and a load optimization allocation plan are proposed, in order to realize the distribution of pollution load among point source, non-point source and safety margin. According to the calculations, TMDL of chemical oxygen demand (COD) and NH_3-N in the flood season (June–September) in the Duliujian River is the largest, about 27,005 kg/d and 2,296 kg/d, respectively. During the dry season (December–March), the reduction of COD and NH_3-N is the largest, reaching 50.74% and 90.14%, respectively. And Duliujian River is dominated by non-point source pollution.

Key words | Arc GIS technology, control unit, non-point source, pollution load, TMDL

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INTRODUCTION

Rivers are one of the natural resources that are vital to the sustainability of life. However, the intensification of urbanization has destroyed the water quality of rivers. Sources of river pollution are classified into point source (PO) and non-point source (NPS) (Santhi *et al.* 2006; Che Osmi *et al.* 2016). PO is pollution that can identify the source. Conversely, NPS is diffuse pollution that occurs in a wide area and is not easily attributed to a single source (León *et al.* 2001; Wu & Chen 2013; Che Osmi *et al.* 2016). PO and NPS pollution has seriously deteriorated river water quality. More and more wastewater discharge into rivers and assimilation capacity has a greater impact on river water quality (Mohamed 2008). In order to understand the extent of watershed pollution better, it is necessary to comprehensively analyze the pollution load of the river basin. This is an important means of identifying the priority areas of pollution control in the basin, and it is also the key technical support for total pollutant control.

The Duliujian River is in the downstream area of the Haihe River, which is located in the coastal area where the agricultural irrigation ditch is developed. According to the survey, the main sources of pollution in the basin include sources of life, agricultural sources, industrial point sources and historical sources of pollution. At present, there is a lack of systematic quantitative research on the contribution of important pollution sources within the basin, and there is a lack of comprehensive research on the emission characteristics of the main source pollution and the spatial distribution of emission intensity. Water quality models are often used as water quality planning tools for managing

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watersheds (Hossain *et al.* 2013), analyzing and predicting changes in rivers, and indicating the relationship between pollution and river conditions (Zainudin *et al.* 2010). In addition, model analysis can create scenario analysis for decision-making processes (Hassan 2005; Song & Kim 2009; Zhao *et al.* 2013), and load-reduction scenarios are important for environmental impact assessment (Wang *et al.* 2015), and predicting river water quality is also important for proposing defensive strategies to maintain river health. Therefore, the modeling process helps to improve water quality and water quality management. Total maximum daily load (TMDL) means that the maximum amount of contaminants allowed to enter the water body does not exceed the water quality standard (Petersen *et al.* 2008). Flow duration curves (FDC) (Ganora *et al.* 2016), load duration curves (LDC) (Kim *et al.* 2015; Ha *et al.* 2016) and time-series analysis are commonly used to evaluate watershed conditions in TMDL studies (Kang *et al.* 2011). TMDL is derived from WLA (point source waste load distribution), LA (non-point source load distribution) and MOS (safe margin of future development) (Zhang & Yu 2004).

In recent years, China has carried out research on water environment capacity, water function zoning, water quality mathematical models, comprehensive planning for water pollution prevention and control in drainage basins, and sewage permit management systems. Many developed countries have also successively carried out research on water quality management technologies for water pollution conditions, such as the total control of the Rhine in the EU (Huisman *et al.* 1997), the total control plan for Tokyo Bay (US EPA 1999), Ise Bay and Laihu Inland Sea in Japan (Committee to Review the New York City Watershed Management Strategy Water Science & Technology Board 2000), and the US TMDL plan (Electronic Code of Federal Regulations 2003). A TMDL plan has been widely applied in China in recent years. Some basins have begun to be used for water body management according to the TMDL principle and have achieved good results. Xing & Chen (2005) described the detailed process and basic content of TMDL development. Tao *et al.* (2013) used the BOD index of Shenzhen Bay as the research object and studied the TMDL in point sources, non-point sources and sub-watersheds that affect the water quality through the EFDC model. On the basis of summarizing the basic content of TMDL, Liang *et al.* (2004) proposed that China should pay attention to the effective combination of a TMDL plan and other control methods on the management of non-point source pollution.

Based on the water environment capacity and TMDL theory of the basin, this study divides the basin control units by means of Arc GIS technology, and proposes a pollution load estimation method. The main pollutant load and its contribution rate for each control unit in the basin are measured quantitatively from six aspects, including direct-row enterprises, sewage treatment plants, farmland runoff, livestock and poultry breeding, aquaculture and rural life. And we also discuss the management of water-quality-based discharge permits in order to provide a basis for effective management and control of pollution sources in the river. By calculating TMDL and considering factors such as safety thresholds and seasonal changes, control measures are proposed for the concentration and quantity of point and non-point source pollutants in the basin, in order to guide the entire basin to implement the best watershed management plan.

METHODS

Study area

Duliujian River is located in Tianjin, China. It is an important flood control line, which belongs to the artificial excavation of the flood channel. The total length is about 67 km and the channel width is about 1 km. The water depth of most river sections is generally no more than 1 m. It is also the main source of replenishment for Beidagang Wetland, an important stop for migratory birds migrating from north to south in East Asia. The Duliujian River is criss-crossed, including six first-class rivers. It is connected to 20 primary tributaries, which are connected with 98 secondary tributaries, as shown in Figure 1.

Sewage outlets are a link between water functional areas and onshore pollution sources, and the results of their investigation and monitoring are the basis for accurately verifying the discharge of pollutants and the total amount entering the river. Through the analysis of the water system map of Tianjin, combined with a site survey, it is

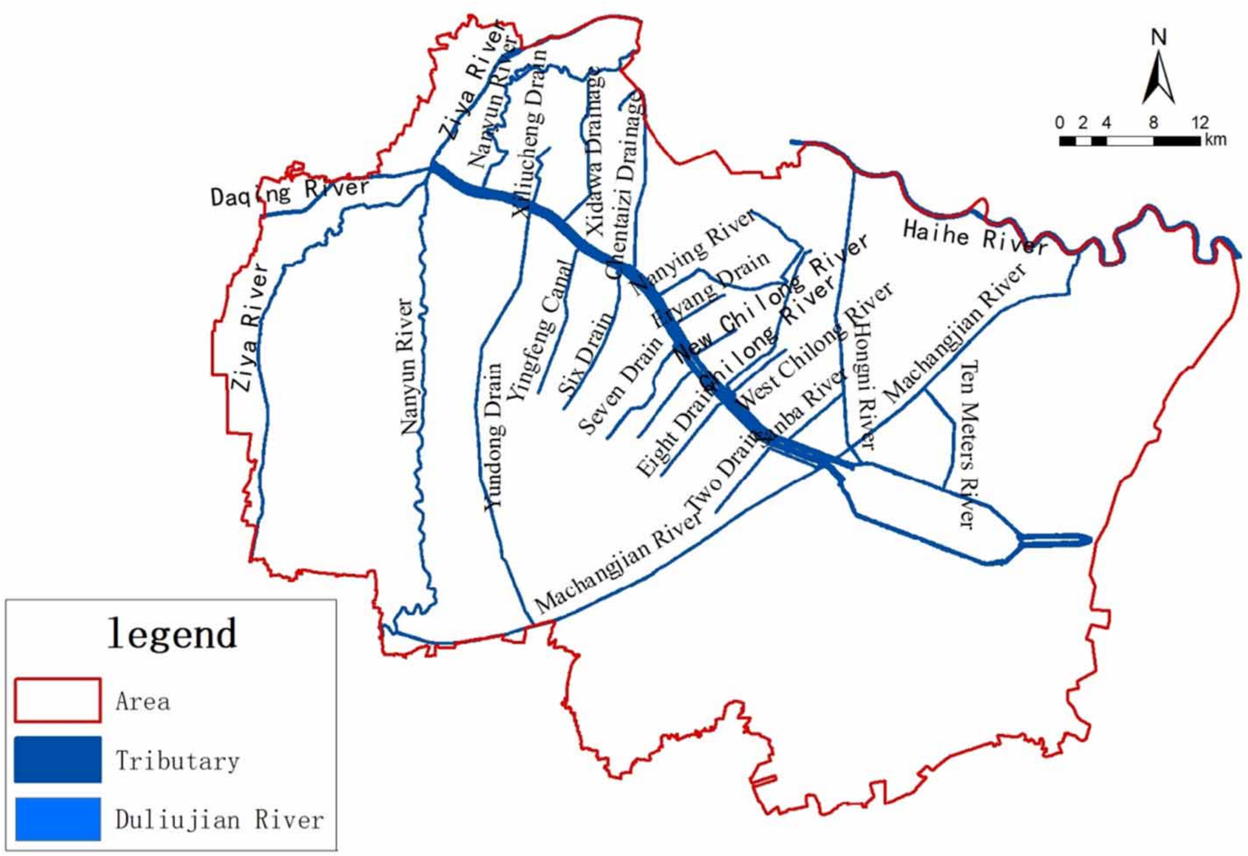

Figure 1 | Overview of the tributary and control section of the Duliujian River.

determined that there are 27 sewage outlets along the riverside of the Duliujian River, as shown in Figure 2.

Arc Map's extended template Arc Hydro tools software were used to process the digital elevation model (DEM) data of Duliujian River. Due to the fact that this basin is located on the plain, its channels are criss-crossed with bifurcation or reticulation. Moreover, based on the principles of administrative boundaries and easy management, the division of control units adopts a combination of administrative areas and catchment areas, which is to merge sub-watersheds within the same administrative area and water quality goals. Finally, we divided the watershed into 37 sub-watersheds and six control units, as shown in Figure 3.

Pollution source survey methods and accounting basis

According to the specific conditions of the Duliujian River, through the water quality monitoring, and access to the *Tianjin Statistical Yearbook*, combined with the discharge status of water production and living water sources, the four main pollutants chemical oxygen demand (COD), NH_3-N, total nitrogen (TN) and total phosphorus (TP) are selected. Among them, COD was measured by the dichromate method or chloride ion calibration method. NH_3-N was measured by the Nessler's reagent colorimetric method or salicylic acid spectrophotometry. TN was measured by gas-phase molecular absorption spectrometry. TP was measured by continuous flow–spectrophotometric detection of ammonium molybdate.

Among the sources of pollution in Duliujian River, there is point and non-point source pollution. Point source pollution mainly includes in-line enterprises and sewage treatment plants in the basin. Non-point source pollution includes agricultural water, rural domestic sewage, livestock and poultry wastewater, and aquaculture wastewater. Therefore, when calculating the total pollutants in the basin, the

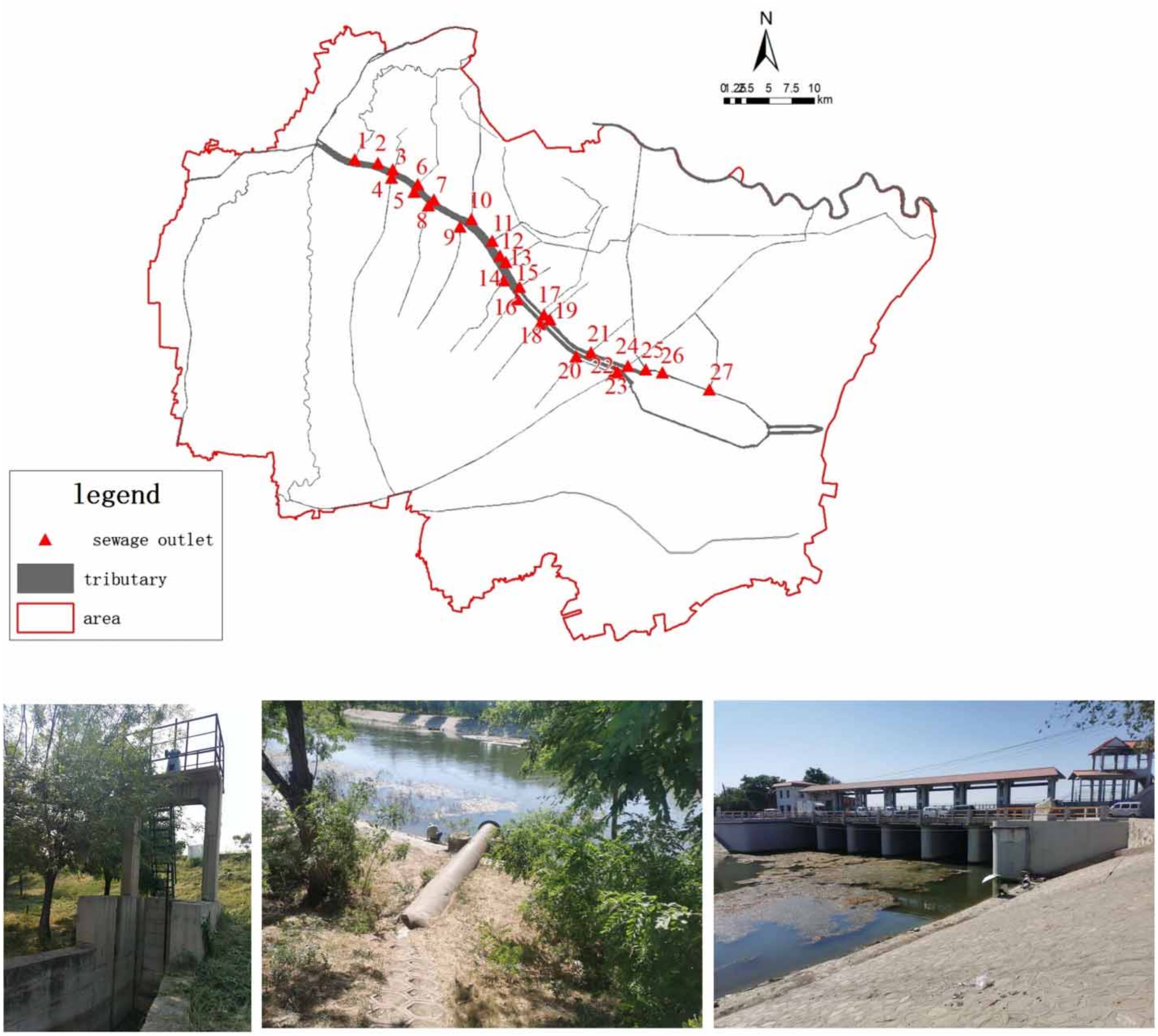

Figure 2 | Overview of the sewage outlet of the Duliujian River.

above-mentioned pollution sources are included. The period of sampling is from January to December in 2017, once a month. The total amount of pollutants in the basin is:

$$W = \Sigma(WLA_i + LA_i) = \Sigma(C_e \times V_e \times N) + (F_i \times K_f + P_i \times K_p + L_i \times K_l + A_i \times K_a)\ (i = 1, 2 \cdots\cdots)$$

In the formula, WLA_i is the total amount of point source pollution load in the i-th sub-basin. LA_i is the total non-point source pollution load of the i-th sub-basin. C_e is the point source pollutant discharge concentration, V_e is the point source pollutant discharge, N is the number of operating days. F_i is the farmland area of the i-th sub-basin, K_f is the farmland discharge coefficient. P_i is the number of rural residents in the i-th sub-basin, K_p is the rural living discharge coefficient. L_i is the amount of livestock and poultry farming in the i-th sub-basin, K_l is the discharge coefficient of livestock and poultry breeding. A_i is the aquaculture production of the i-th sub-basin, and K_a is the aquaculture discharge coefficient.

The method of data collection is mainly through the actual monitoring of the water quality and consulting the statistical yearbook. *Tianjin Statistical Yearbook* is a large-

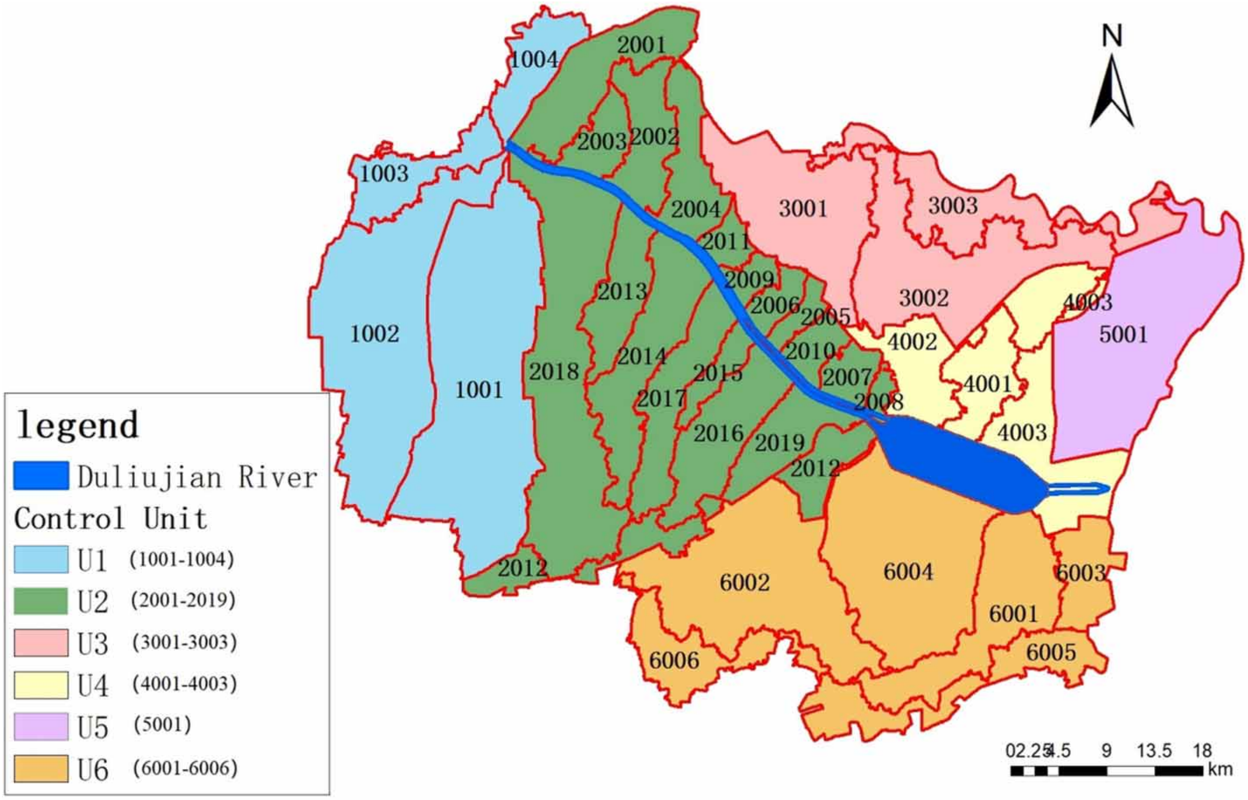

Figure 3 | Division of sub-basins and control units in the study area.

scale informational reference book that comprehensively reflects the national economic and social development of Tianjin. Publication began annually with the first issue in 1984 to form a series. With its rich and informative statistical data, this book has become the most authoritative tool for all sectors of society to understand Tianjin and know Tianjin. This book provided great help to our research.

The discharge coefficient and the river entry coefficient are shown in Table 1. The coefficients of farmland cultivation and rural residents' partial pollutant discharge refer to the coefficients provided in the *National Technical Guidelines for the Assessment of Water Environmental Capacity*. Part of the pollution factor for livestock and poultry breeding is the relevant pollution factor for North China in the *Manual of Sewage Coefficients and Pollution Discharge Coefficients of Livestock and Poultry Breeding* in the First National Pollution Source Survey. The aquaculture pollutant discharge coefficient refers to the coefficient provided in the *First National Pollution Source Survey of Aquaculture Pollution Source Pollution Factor Manual*. The river inflow coefficient for agricultural non-point sources refers to the Calculation of Beijing–Tianjin–Hebei Environmental Carrying Capacity project of the Environmental Planning Institute of the Ministry of Environmental Protection.

This study is based on the water environment capacity of the basin and TMDL theory. It mainly focuses on three aspects, including: (1) accounting for pollution load – The non-point source part is obtained by simulation calculation using a watershed non-point source mathematical model; (2) safety margin – considering the uncertainty of the allowable discharge load, it is required to reserve a certain percentage of the load as a safety margin; (3) emission distribution – distribute the discharge load to each pollution source.

The river water quality model uses mathematical methods to describe the laws of dilution, diffusion and self-purification produced by pollutants entering natural rivers. The basin environment model has gradually become a key method to solve the problem of total discharge–water quality response.

Table 1 | Sewage discharge coefficient and inlet river coefficient

Type		Sewage coefficient COD	NH_3-N	TN	TP	Coefficient of entering the river (%)
Farmland ($kg·hm^{-2}·a^{-1}$)		150	30	26.72	2.12	10
Rural life ($kg·p^{-1}·a^{-1}$)		14.6	1.46	4.38	0.88	25
Livestock ($g·h^{-1}·d^{-1}$)	pig	30.78	2.07	5.34	0.43	7
	cow	461.48	25.15	66.12	10.66	7
	cattle	243.56	16.85	16.85	1.19	7
	chicken	1.08	0.05	0.05	0.02	7
	sheep	4.4	0.57	0.57	0.45	7
Aquatic products ($g·kg^{-1}$)	carp	11.507	2.629	11.581	2.269	90
	grass carp	19.596	2.310	0.384	0.105	90
	squid	1.672	0.431	2.629	0.702	90
	shrimp	27.022	1.277	0.813	0.066	90
Direct enterprise						70
Sewage treatment plant						80

Note: There is no discharge coefficient for direct-row enterprises and sewage treatment plants, and the total pollutant discharge is calculated according to the point source pollutant discharge concentration and sewage discharge flow rate.

In this study, the calculation of the environmental capacity of the Duliujian River was divided into three cases:

1. Dry season – modeling according to reservoir-type river. In the low-flow period, the sluice and dam of the Duliujian River is closed, which can be regarded as a reservoir-type channel.
2. Flat water period – calculated according to the one-dimensional water quality model of the river. During the water transfer period, due to the upstream water flow and the effect of water transfer, the gates need to be opened from time to time, and the Duliujian River can be regarded as a completely mixed river.
3. Flood season – calculated according to the one-dimensional water quality model of the river. During the flood season and the water diversion period, due to the impact of precipitation and water diversion, the gates need to be opened from time to time. The Duliujian River can be regarded as a completely mixed river.

TMDL calculation in the Duliujian River

Due to climate reasons, most of the rivers in the northern regions of China are seasonal. In order to prevent flood drainage and water storage irrigation, multi-level dams are generally built on these rivers to control the flow of water. The Duliujian River is a river controlled by dams. During the water transfer period (April–November) and the flood season (June–September), due to the influence of upstream water, water transfer and precipitation, the gates need to be opened from time to time, and the river can be regarded as a general river channel. However, in the dry season (January–February), the dam is closed because there is no external adjustment, and the river can be regarded as a reservoir-type river. Therefore, in view of the above characteristics, referring to the water quality model provided in the *National Technical Guidelines for Water Environmental Capacity Verification* (the following Equations (1)–(5)), this study is divided into three cases when calculating the water environment capacity of the Duliujian River.

The dry season is modeled by a reservoir channel.

$$TMDL = W = (C_s - C_0)V/\Delta T + kVC_s + qC_s \tag{1}$$

In the formula, ΔT is the dry water period (d) – if the water level changes greatly during the year, it may take 60–90 days, if it is stable all year round, it may take 90–150 days; q is the amount of drainage (m^3/s) discharged from the lake water during safe volume; V is the volume of the river (m^3); C_s is the allowable concentration of pollutants; C_0 is the current concentration of pollutants; and k is the pollutant attenuation coefficient (d^{-1}).

The flat water period and the flood season are calculated according to the one-dimensional water quality model of the river. The receiving water model is divided into a steady-state model and a dynamic model. Combined with the characteristics of the single-flow river system and hydrological situation, the one-dimensional steady-state water quality model is used for calculation:

$$u\frac{\partial C}{\partial x} = D\frac{\partial^2 C}{\partial x^2} - KC \tag{2}$$

In the formula, u is the average flow velocity of the river section (m/s); C is the pollutant concentration (mg/L); x is the longitudinal distance along the river section (m); D is the longitudinal dispersion coefficient of the river (m^2/s); and K is the degradation coefficient of pollutants (d^{-1}).

For different water pollution control modes, the calculation of water environment capacity under one-dimensional steady-state conditions has two methods: segment head and segment tail control methods. The segment tail control method can control the water quality of the downstream section to reach the water quality target of the functional section, so that the water environmental load capacity at the head of the section can be reversed. The water environment load capacity model of the one-dimensional segment tail control method is as follows:

$$\begin{aligned} TMDL &= W \\ &= 0.0864\{Q_0(C_s - C_0) \\ &\quad + \sum_{i=0}^{n-1} C_s\left[Q_{i+1}\left(\exp\left(-\frac{KL_i}{86400U_i}\right)\right) - 1\right] + q_{i+1}\} \end{aligned} \tag{3}$$

In the formula, W is the water environmental load capacity (t/d); Q_0 is the incoming water flow rate (m^3/s); C_s is the control section water quality standard (mg/L); C_0 is the incoming water pollutant concentration (mg/L); Q_{i+1} is the river flow at the $(i+1)$-th node (m^3/s); K is the pollutant degradation coefficient (d^{-1}); L_i is the length of the i-th river (m); U_i is the average flow rate for the i-th river section design (m/s); and q_{i+1} is the sewage flow rate at the $(i+1)$-th node (m^3/s).

The pollutant degradation coefficient K is an important parameter for calculating the pollution capacity of a water body. The degradation coefficients of different pollutants, water bodies and environmental conditions are different. The degradation of COD, NH_3-N and TP in water is generally considered to be in accordance with the first-order reaction kinetics equation. The calculation formula is:

$$K = 86.4\,(\ln C_1 - \ln C_2)\;U/\mathrm{L} \tag{4}$$

In the formula, C_1 and C_2 are the pollutant concentrations in the upper and lower sections of the river section (mg/L); U is the average flow velocity of the river section (m/s); L is the spacing of the upper and lower sections of the river section (km); and K is the comprehensive degradation coefficient of the river (d^{-1}).

According to the survey and statistics, the average flow rates of the Duliujian River in the dry season, the flat water period and the flood reason were 0.002 m/s, 0.018 m/s and 0.021 m/s, respectively. The pollutant degradation coefficient K of the river in the dry season (December–March), the flat water period (April-May, October–November) and the flood season (June–September) are calculated, and in the dry season K is negative, which means unreasonable. At this time, K can be calculated by the relationship among the degradation coefficients of different water periods. The K values under different water temperatures are estimated as follows:

$$K_T = K_{20} \cdot 1.047^{(T-20)} \tag{5}$$

In the formula, K_T is the K value at T°C (d^{-1}); T is water temperature (°C); and K_{20} is the K value at 20 °C (d^{-1}).

The detailed degradation coefficients are shown in Table 2.

RESULTS AND DISCUSSION

Current status of watershed pollution

According to the survey and statistics of pollution sources, the amount of COD, NH_3-N, TN and TP in the point source are 2,204 t/a, 299 t/a, 461 t/a and 16 t/a. The amount of COD, NH_3-N, TN and TP in the agricultural

Table 2 | Comprehensive degradation coefficient of COD and NH_3-N in Duliujian River (d^{-1})

Reach	KCOD			KNH_3-N		
	Dry season	Flat water period	Flood season	Dry season	Flat water period	Flood season
Jinghong Gate–Wanjia Wharf	0.011	0.024	0.035	0.017	0.023	0.028
Wanjia Wharf–Workers' and Peasants' Gate	0.032	0.059	0.086	0.021	0.031	0.048
Mean	0.021	0.042	0.061	0.019	0.037	0.038

non-point source of the Duliujian River are 5,036 t/a, 574 t/a, 1,374 t/a and 232 t/a, respectively, which are 2.3, 1.9, 2.9 and 14.5 times those from the point source. As can be seen from Figure 4, the largest proportion of COD emissions is farmland planting, with a contribution rate of 28.13%, followed by livestock and poultry farming, with 24.15%. The contribution rates of COD emissions from rural life and inline enterprises are 13.61% and 11.29%, respectively. Among the NH_3-N discharged from the basin, farmland planting accounted for the largest proportion, with a contribution rate of 46.71%, followed by livestock and poultry farming and sewage treatment plants, with contribution rates of 14.74% and 13.31%, respectively. Urban runoff and aquaculture contributed less, at 0.87% and 2.73%, respectively. Among the TN and TP emission ratios, rural life contribution rates are the highest, at 29.19% and 43.42%, respectively. Livestock and poultry farming and direct-row enterprises contribute less.

Contaminant sensitivity analysis is used to assess the sensitivity of the water environment in the study area between production and socio-economic activities, in order to clarify the regional differentiation of environmental pollution sensitivity, and to identify priority control areas. According to the emission intensity of COD, NH_3-N, TN and TP pollutants from six types of pollution sources in the Duliujian River, the pollution sensitivity of the basin is divided into four levels, namely highly sensitive area, moderately sensitive area, mildly sensitive area and insensitive area. As shown in Figure 5, pollutant emissions in the western and southwestern parts of the basin are at a higher

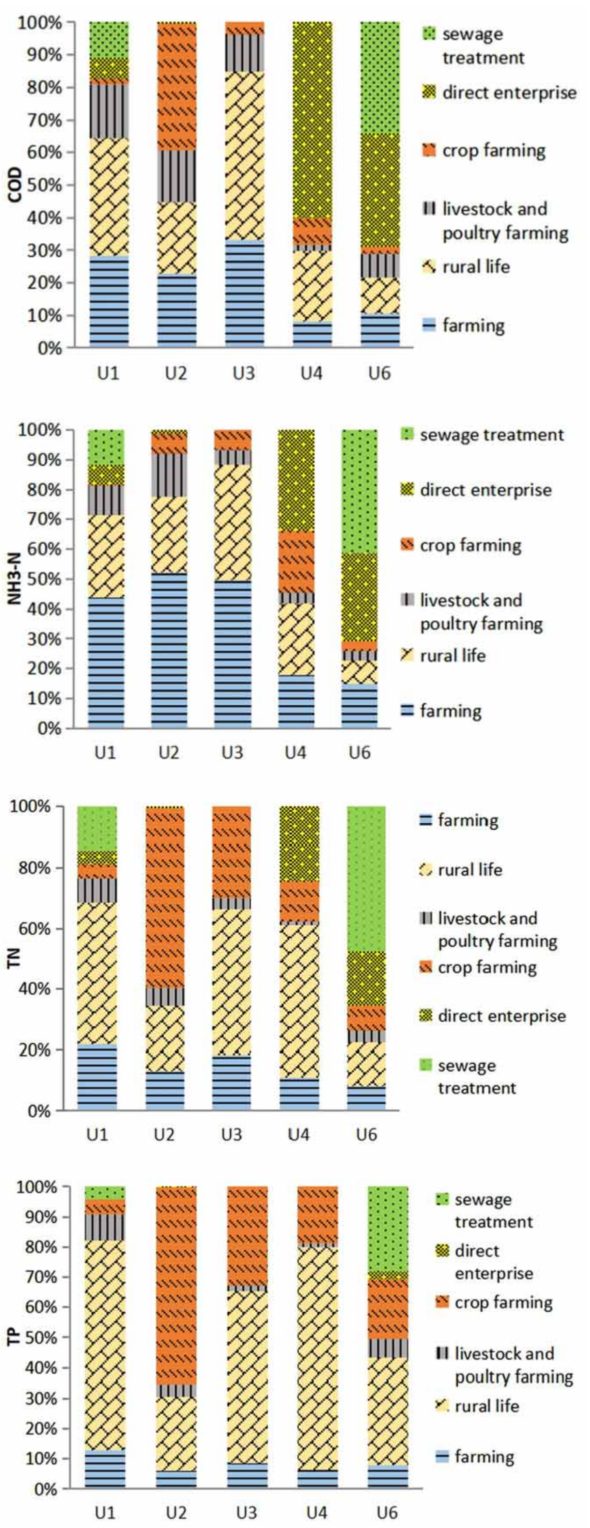

Figure 4 | Proportion of pollution sources of the Duliujian River.

level, while pollutants in the northern and eastern parts are at a lower pollution level. The density of livestock and poultry farming in the western and southwestern parts of the basin is high, the rural population is relatively large, and the agriculture is relatively developed, resulting in large regional agricultural non-point source pollution emissions. Furthermore, some important rivers mainly flow through the region, so their pollutant emissions are relatively large. In the northern part of the basin, the density of livestock and poultry farming is low, rural residents are few, and there is a large area of salt fields in the eastern coastal areas. Therefore, there is less agricultural non-point source pollution in the region.

The discharge intensity data of 37 sub-basins in the Duliujian River are analyzed by the most commonly used system clustering and k-means method (Celebi *et al.* 2013). Combined with the intensity contribution of pollution sources in the basin space, the pollution source clusters are divided into seven types (Figure 6), which are the pollution-types of livestock and poultry breeding, rural life, farmland, aquaculture, enterprises, sewage treatment plants and comprehensive pollution. Among them, comprehensive pollution refers to three or more pollution sources in the basin, which account for a certain proportion.

The comprehensive pollution area is 1,708 km^2, accounting for 47.24% of the total drainage area. It is mainly distributed in the areas where the planting and aquaculture development in the western and southern parts of the basin is relatively balanced. The pollution sources are complex and are the most difficult in pollution control. The pollution area of the enterprise is 466 km^2, accounting for 12.89%. The rural pollution area is

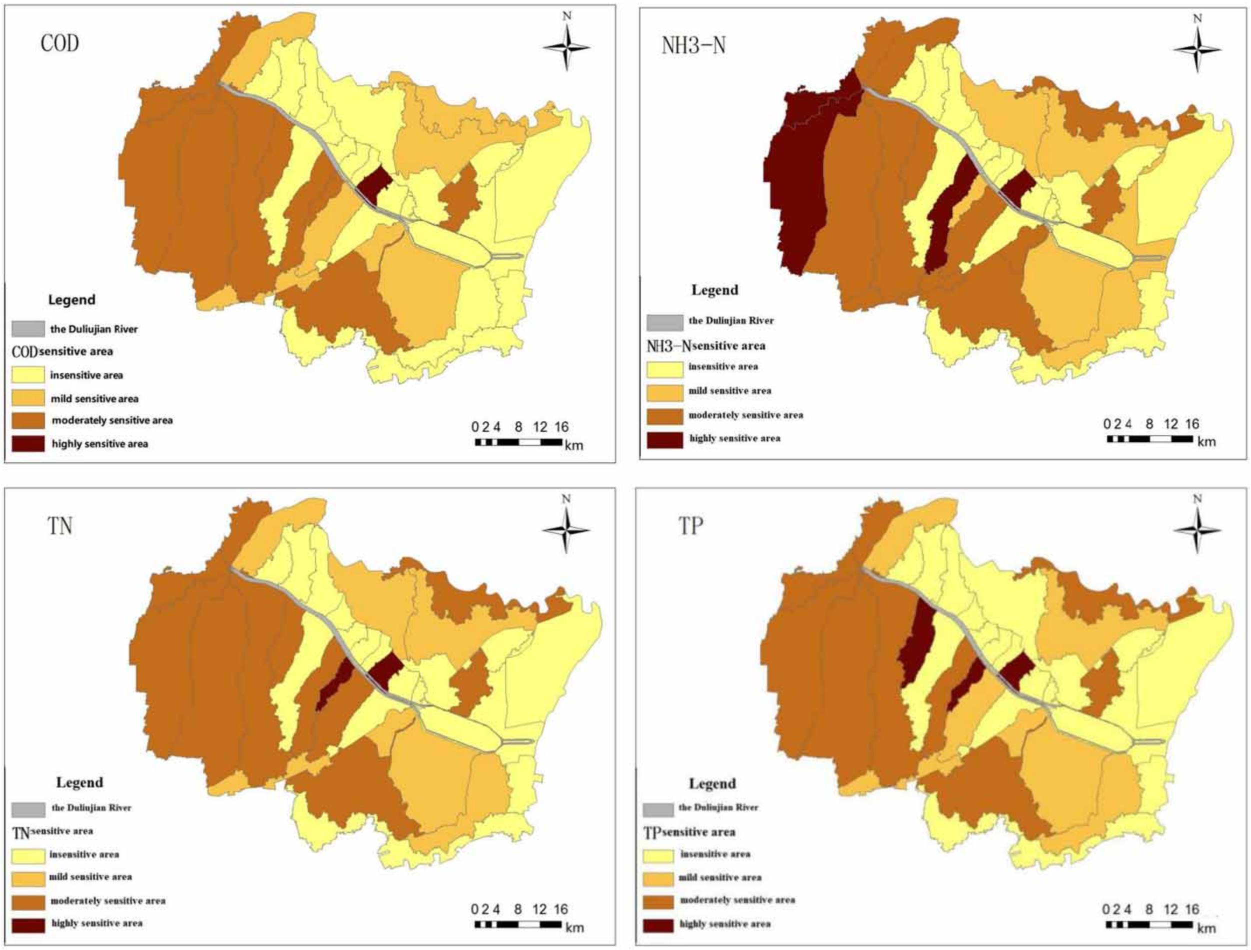

Figure 5 | Evaluation of pollution sensitivity in the Duliujian River.

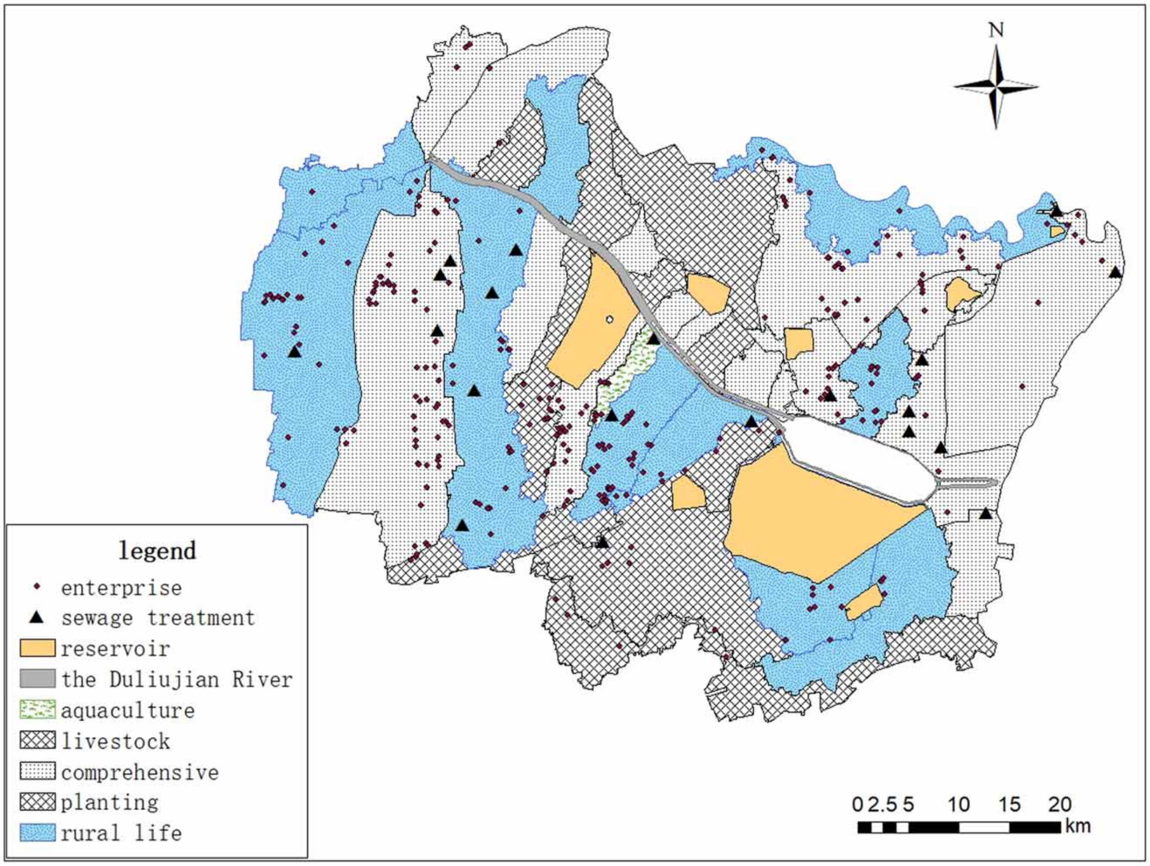

Figure 6 | Spatial distribution of pollution types in the Duliujian River.

362 km^2, accounting for 10.13%. And the aquaculture pollution area is the smallest (84 km^2), accounting for 2.3% of the entire area.

Calculation of TMDL

According to the characteristics of flow changes in the Duliujian River, TMDL is estimated. TMDL of COD and NH_3-N in the dry season (January–February) are about 11,408 kg/d and 958 kg/d, respectively; in the flat water period (April–May, October–November), TMD of COD and NH_3-N are about 22,369 kg/d and 1,543 kg/d, respectively; during the flood season (June–September), TMDL of COD and NH_3-N are approximately 27,005 kg/d and 2,296 kg/d, respectively. On the whole, the water quality of the Duliujian River in the flood period is worse than in the dry period. In the dry period, due to the small amount of precipitation and the decrease in the upstream water flow, the river water level drops and the flow velocity slows down, which is not conducive to the dilution and diffusion of pollutants, and the water environment capacity is greatly reduced compared with the abundant and peaceful periods. The main reason for the poor water quality during the flood period is that the precipitation is large, the runoff into the river increases, and the surface runoff carries a large amount of non-point source pollutants into the river, resulting in poor water quality. The river water volume during the flood period is greater than that during the dry period, and runoff influx will have a certain dilution effect on river pollutants. But the pollutant concentration during the flood period is higher than that during the low water period. The water quality in the flat water period exhibits similar pollution characteristics as in the flood period, and the concentration of nutrient salt pollutants is higher than in the dry period and less than in the flood period. The above shows that pollutants brought by runoff have a significant impact on the water quality of Duliujian River, as shown in detail in Table 3.

The agricultural non-point sources of pollution of the Duliujian River are calculated according to the dry season, the flat water period and the flood water period, which account for 15%, 30% and 55%, respectively. TMDL, the point source and the non-point source into the river are shown in Tables 4 and 5.

Total water pollution control in the Duliujian River

The core of total capacity control is to propose the total emission control requirements for water pollutants based on the water quality protection objectives. The existing total control research in China is limited to the calculation of total control targets, less involving the distribution between point source and non-point source pollution, and no comprehensive management at the basin scale. This study calculates the TMDL, and then distributes and reduces the pollution load. That is to say, the environmental capacity of the water body in the basin is determined first, and the point source and the non-point source pollution are initially allocated. Through analysis, it is then assigned to each sub-basin in detail to determine the amount of pollutant load that needs to be reduced under the premise of the water quality requirements. The formula for the total distribution of watershed pollutants is (Brady 2004):

$$\mathrm{TMDL} = \mathrm{WLA} + \mathrm{LA} + \mathrm{MOS}$$

In the formula, WLA is the allowable existing and future point source pollution load (kg/d); LA is the allowable

Table 3 | TMDL of COD and NH_3-N (kg/d)

				Dry season		Flat water period		Flood season	
Control unit	**Water body**		**Section name**	**COD**	**NH_3-N**	**COD**	**NH_3-N**	**COD**	**NH_3-N**
U1	Confluence Section of Duliujian River	Daqing River	Jinghong Gate	501	30	1,243	20	1,596	9
		Ziya River	Eleventh New Bridge	1,276	27	2,667	89	3,887	181
		Nanyun River	Eleventh New Bridge	690	14	1,443	48	2,103	202
		Total	–	2,467	71	5,353	157	7,586	392
U2	Jinghong Gate–Wanjia Wharf		Wanjia Wharf	6,893	628	11,960	912	14,015	1,311
U4	Wanjia Wharf–Workers' and Peasants' Gate		Workers' and Peasants' Gate	2,048	259	5,056	474	5,404	593
Total			–	11,408	958	22,369	1,543	27,005	2,296

Table 4 | Load statistics of COD (kg/d)

		Dry season			Flat water period			Flood season		
Control unit	**Water body**	**TMDL**	**Point source**	**Non-point source**	**TMDL**	**Point source**	**Non-point source**	**TMDL**	**Point source**	**Non-point source**
U1	Daqing River	501	0.23	298	1,243	0.23	596	1,596	0.23	1,114
	Ziya River	1,276	632	1,250	2,667	632	2,500	3,887	632	4,832
	Nanyun River	690	987	1,573	1,443	987	3,146	2,103	987	6,092
	Total	2,467	1,619	3,121	5,353	1,619	6,242	7,586	1,619	12,038
U2	Jinghong Gate–Wanjia Wharf	6,893	3,097	3,908	11,960	3,097	7,817	14,015	3,097	15,602
U4	Wanjia Wharf–Workers' and Peasants' Gate	2,048	1,305	369	5,056	1,305	738	5,404	1,305	1,890
Total		11,408	6,022	7,399	22,369	6,022	14,797	27,005	6,022	29,530

Table 5 | Load statistics of NH_3-N (kg/d)

		Dry season			Flat water period			Flood season		
Control unit	**Water body**	**TMDL**	**Point source**	**Non-point source**	**TMDL**	**Point source**	**Non-point source**	**TMDL**	**Point source**	**Non-point source**
U1	Daqing River	30	0.06	43	20	0.06	86	9	0.06	158
	Ziya River	27	95	164	89	84	328	181	80	608
	Nanyun River	14	165	217	48	130	434	202	118	804
	Total	71	260	424	157	214	848	392	198	1,569
U2	Jinghong Gate–Wanjia Wharf	628	622	399	912	460	797	1,311	406	1,490
U4	Wanjia Wharf–Workers' and Peasants' Gate	259	98	56	474	98	113	593	98	220
Total		958	980	879	1,543	772	1,758	2,296	702	3,278

existing and future non-point source pollution load (kg/d) and MOS is the margin of safety (kg/d), taking 5% of TMDL.

According to the pollution load distribution formula, the load allowed to be distributed by the main pollutants in the Duliujian River is the value of TMDL minus MOS. Tables 6 and 7 show the allowable distribution loads for COD and NH_3-N.

Tables 8 and 9 show the current pollution load, allowable distribution load and pollution reduction rate of COD and NH_3-N in each control unit. The COD allowable distribution load of control unit 1 (confluence section) in the dry season, flat water period and flood season is 2,335 kg/d, 5,085 kg/d and 7,207 kg/d, respectively, and the proportions to be reduced are 50.74%, 35.31% and 47.23%. Similarly, the NH_3-N allowed distribution loads are 67 kg/d, 149 kg/d and 372 kg/d, and the proportions to be reduced are 90.14%, 85.96% and 78.92%, respectively. Control unit 2 (Jinghong Gate–Wanjia Wharf) has a COD allowable distribution load of 6,548 kg/d, 11,362 kg/d and 13,314 kg/d in the dry season, the flat water period and the flood season, and the proportions to be reduced are 6.54%, −4.10% and 28.8%. The meaning of the negative value is that the permissible load of the river is greater than the current pollution load, indicating that the river section still has a certain water environment capacity, which does not need to be reduced. The NH_3-N allowable distribution loads are 597 kg/d, 866 kg/d and 1,245 kg/d, respectively, and the proportions to be reduced are 41.51%, 31.07% and 34.31%. The allowable distribution loads of COD in control unit 4 (Wanjia Wharf–Workers'

Table 6 | Allowable load of COD (kg/d)

			Dry season			Flat water period			Flood season		
Control unit	**Water body**		**TMDL**	**MOS**	**Allowable load**	**TMDL**	**MOS**	**Allowable load**	**TMDL**	**MOS**	**Allowable load**
U1	Confluence Section of Duliujian River	Daqing River	501	25.05	475.95	1,243	67.35	1,175.65	1,596	97.7	1,498.3
		Ziya River	1,276	63.8	1,212.2	2,667	133.35	2,533.65	3,887	194.35	3,692.65
		Nanyun River	690	34.5	655.5	1,443	72.15	1,370.85	2,103	105.15	1,997.85
		Total	2,467	132.1	2,334.9	5,353	267.65	5,085.35	7,586	379.3	7,206.7
U2	Jinghong Gate–Wanjia Wharf		6,893	344.65	6,548.35	11,960	598	11,362	14,015	700.75	13,314.25
U4	Wanjia Wharf–Workers' and Peasants' Gate		2,048	102.4	1,945.6	5,056	252.8	4,803.2	5,404	270.2	5,133.8
Total			11,408	579.15	10,828.85	22,369	1,118.5	21,250.55	27,005	1,350.25	25,654.75

Table 7 | Allowable load of NH_3-N (kg/d)

			Dry season			Flat water period			Flood season		
Control unit	**Water body**		**TMDL**	**MOS**	**Allowable load**	**TMDL**	**MOS**	**Allowable load**	**TMDL**	**MOS**	**Allowable load**
U1	Confluence Section of Duliujian River	Daqing River	30	1.5	28.5	20	1	19	9	0.45	8.55
		Ziya River	27	1.35	25.65	89	4.45	84.55	181	9.05	171.95
		Nanyun River	14	0.7	13.3	48	2.4	45.6	202	10.1	191.9
		Total	71	3.55	67.45	157	7.85	149.15	392	19.6	372.4
U2	Jinghong Gate–Wanjia Wharf		628	31.4	596.6	912	45.6	866.4	1,311	65.55	1,245.45
U4	Wanjia Wharf–Workers' and Peasants' Gate		259	12.95	246.05	474	23.7	450.3	593	29.65	563.35
Total			958	47.9	910.1	1,543	77.15	1,465.85	2,296	114.8	2,181.2

Table 8 | Load reduction targets of COD for each control unit in the Duliujian River

		Dry season			Flat water period			Flood season		
Control unit	**Water body**	**Current load (kg/d)**	**Allowable load (kg/d)**	**Reduction rate (%)**	**Current load (kg/d)**	**Allowable load (kg/d)**	**Reduction rate (%)**	**Current load (kg/d)**	**Allowable load (kg/d)**	**Reduction rate (%)**
U1	Daqing River	298	476	−59.73	596	1,176	−97.32	1,114	1,498	−34.47
	Ziya River	1,882	1,212	35.6	3,132	2,534	19.09	5,464	3,693	32.41
	Nanyun River	2,561	656	74.39	4,134	1,371	66.84	7,079	1,998	71.78
	Total	4,740	2,335	50.74	7,861	5,085	35.31	13,657	7,207	47.23
U2	Jinghong Gate–Wanjia Wharf	7,006	6,548	6.54	10,914	11,362	−4.1	18,700	13,314	28.8
U4	Wanjia Wharf–Workers' and Peasants' Gate	1,675	1,946	−16.18	2,044	4,803	−134.98	3,195	5,134	−60.69
Total		13,421	10,829	19.31	20,819	21,251	−2.08	35,552	25,655	27.84

and Peasants' Gates) are 1,946 kg/d, 4,803 kg/d and 5,134 kg/d in the dry season, the flat water period and the flood season. The NH_3-N allowable distribution loads are 246 kg/d, 450 kg/d and 563 kg/d. There is still a certain water environment capacity in this section. The allowable distribution load of COD and NH_3-N is greater than the current pollution load into the river.

Management of sewage outlets based on pollutant discharge permit

At present, total control is based on the total amount of pollutant discharge targets in China, and is not directly linked to the water environment capacity. Instead, it is determined by the pollutant discharge volume, the concentration, type, quantity of pollutants, the level of local economic development, the level of environmental technology control and the local total control indicators. Therefore, despite the implementation of the sewage permit system, the water body is still unable to meet the water quality standards because it is not directly linked to the water environment capacity.

This study takes the single-flow reduction river basin as the research object, and analyzes and calculates the current status of water pollution sources through data collection and compilation. According to the actual situation of the

Duliujian River, the water environment capacity in the dry season, the flat water period and the flood season is calculated based on TMDL. And the total pollution load of each pollution source is distributed through the calculation results to determine the allowable emissions and reductions of each control unit and sub-basin. Figure 7 is the sewage control and control technology system based on the pollutant discharge permit.

In summary, the water quality of the Duliujian River in the flood season is worse than in the dry season and the flat water period. The main reason for the poor water quality during the flood season is that the precipitation is large, the runoff into the river increases, and the surface runoff carries a large amount of non-point source pollutants into the river (Jing *et al.* 2013). It shows that pollutants brought by runoff have a significant impact on the water quality of Duliujian River. The water quality in the dry season mainly reflects the point source pollution, while the water quality in the flood season mainly reflects the impact of non-point source pollution. Therefore, it shows that the Duliujian River is dominated by non-point source pollution.

Table 9 | Load reduction targets of NH_3-N for each control unit in the Duliujian River

		Dry season			Flat water period			Flood season		
Control unit	**Water body**	**Current load (kg/d)**	**Allowable load (kg/d)**	**Reduction rate (%)**	**Current load (kg/d)**	**Allowable load (kg/d)**	**Reduction rate (%)**	**Current load (kg/d)**	**Allowable load (kg/d)**	**Reduction rate (%)**
U1	Daqing River	43	29	33.72	86	19	77.91	158	9	94.59
	Ziya River	259	26	90.1	412	85	79.48	688	172	75.01
	Nanyun River	382	13	96.52	564	46	91.91	922	192	79.19
	Total	684	67	90.14	1,062	149	85.96	1,767	372	78.92
U2	Jinghong Gate–Wanjia Wharf	1,020	597	41.51	1,257	866	31.07	1,896	1,245	34.31
U4	Wanjia Wharf–Workers' and Peasants' Gate	154	246	−59.77	211	450	−113.41	317	563	−77.71
Total		1,859	910	51.04	2,530	1,466	42.06	3,981	2,181	45.21

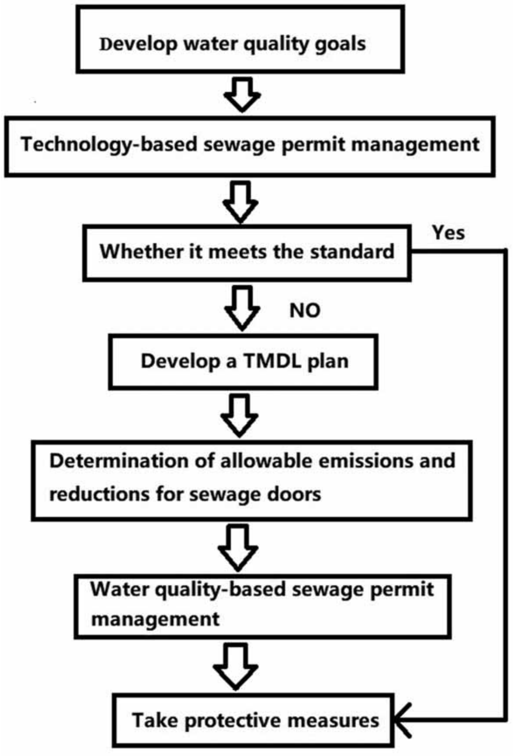

Figure 7 | Sewage outlet control technology system based on pollutant discharge permit.

CONCLUSION

This paper comprehensively considers the relationship among the water, inflow sewage outlet and land pollution sources, and uses the control unit as the way to calculate and allocate the total capacity based on TMDL theory. According to the water body function requirements, the water quality standards are set, and under the conditions of seasonal influence, we propose a sewage discharge port and a total watershed load control plan including point source and non-point source, as well as a load optimization distribution plan. Based on the calculation of water environment capacity, combined with the contribution rate of point source and non-point source pollution load, the distribution of pollution load among point source, non-point source and safety margin is realized. At the same time, the allowable distribution amount and reduction amount of each control unit and sub-basin are calculated. Therefore, the maximum allowable emission is determined, and the sewage control system is established with the pollutant discharge permit as the core. The ability of water bodies in different control units to accept pollutants is different and is determined by the characteristics of the river section within the control units. Through the implementation of the management and control technology of this research, the water quality targets of the assessment sections in the Duliujian River have been achieved. The annual average value of each water quality index reached $COD \leq 15$ mg/L and $NH_3\text{-}N \leq 2$ mg/L. Compared with the main water quality indicators in 2014, the average annual improvement was greater than 15%.

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