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Identifying the major pollution sources and pollution loading status of Qiputang River in Taihu Lake basin of China

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ABSTRACT

A proper understanding on the pollution sources and pollution loads of a water body is essential for its pollution control. Taihu Lake basin of China is an environmentally sensitive area. Currently, most of the river systems in this region are severely polluted, but information about these rivers is still lacking. Here, we present a comprehensive investigation into the pollution status of a typical river in Taihu Lake basin, Qiputang River, by using chemical oxygen demand (COD) and ammonia (NH_4^+–N) as two major evaluation indexes. The major pollution sources, actual pollution loads, as well as the expected pollution carrying capacity were estimated via model simulation and calculation. The results show that the orders of pollution load are: for COD, urban domestic non-point source (NPS) > industrial NPS > wastewater treatment plant (WWTP) effluent > rural domestic NPS > agriculture NPS > livestock NPS; for NH_4^+–N, agriculture NPS > urban domestic NPS > WWTP effluent > industrial NPS > rural domestic NPS > livestock NPS. Thus, urban domestic NPS, industrial NPS, agriculture NPS and WWTP effluents are the major pollution sources of the river, accounting for 84.17% of the total COD load and 87.1% of the total NH_4^+–N load. Pollution overloading is severe for the river, especially for No. 4~ sections where the overloading of COD and NH_4^+–N reached up to 748.1 and 422.3%, respectively. Thus, more future efforts of pollution control should be devoted to these sources and areas. This work presents a simple and useful way to investigate into the pollution situation of complex river systems, and offers valuable information on river pollution situation of Taihu Basin, which may help policy-makers and planners in implementing more effective and practical pollution control strategies.

Keywords: Pollution load; Pollution carrying capacity; Nonpoint sources; Modeling; Overload

1. Introduction

Taihu Lake basin is one of the most developed, densely populated regions of China; meanwhile, it is also a severely polluted area [1,2]. In the past decades, accompanied with a rapid urbanization and industrialization, there has been a growing discharge of pollutants to waters in this area. This has directly led to water quality deterioration and frequent outbreaks of cyanobacterial blooms, seriously threatening the ecology, human health, and local economic development [3–5].

It has been recognized that the identification of major pollution sources and estimation of pollution

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overloads plays a key role in the management of receiving waters. Despite the numerous load estimation methodologies in the literature, there has been many difficulties in accurately identifying the major pollution sources and quantifying the pollution loads as well as the pollution carrying capacity of rivers, attributed to great complexity and variation in pollution discharge scenario and river characteristics [6–9]. Especially, information about the pollutant discharge characteristics and pollution overloading in the Taihu Lake region is still scarce by far [7,10], which has significantly limited the water management practice in this region.

The pollution sources can be approximately categorized into two classes: point sources (PS) and non-point sources (NPS). The NPS, particularly those from agriculture and industrial activities, have been recognized a significant source of water nutrient pollution [11–14]. This is especially true for the Taihu Lake region of China, where chemical fertilizers are consumed in large amount, and discharge of insufficient treated industrial wastewater discharge are still serious [15,16]. This work aims to offer a comprehensive evaluation on the PS and NPS pollution discharge status of the Taihu Lake region, by taking Qiputang River as a case study. To this end, the pollution load emission along the river was surveyed and estimated, and a relatively simple hydraulic model was adopted to simulate the pollution transmission processes in the river. Here, to simplify the calculation, two major pollution indexes, chemical oxygen demand (COD) and ammonia (NH_4^+–N), were chosen for the evaluation. The model coefficients were determined based on the local pollution production and release characteristics. This study may also offer valuable references for pollution control of other similar river systems in China and other developing countries.

2. Study area and pollution status

2.1. Study area

There are abundant river systems in Taihu Lake region. Among the many rivers, Qiputang River is a typical and most important one, with multi-functions of flood control, diversion, shipping, and water purification. It connects the Yangtze River (the longest river in China) and Yangchenghu Lake, with a total length of 48 km (see Fig. 1). The river width and the river bed elevation are 20–30 m and 0.5–2.0 m, respectively. There are three major cities with highly-developed industries in this area, namely Changshu, Kunshan and Taicang. Qiputang River is now suffering from

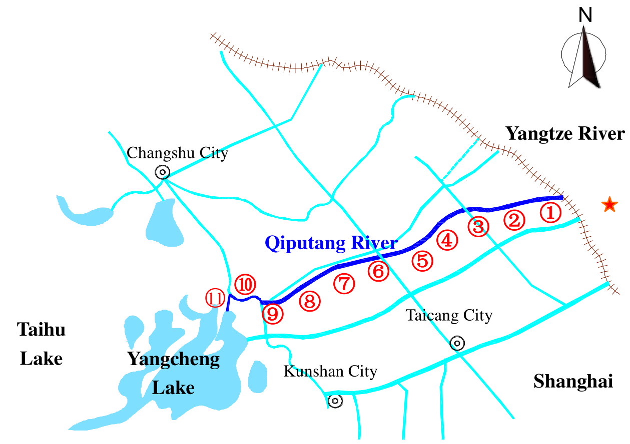

Fig. 1. Geographical location of Qiputang River and distribution of major river reaches (the numbers with circle refers to different river reaches from the Yangtze River border to the Yangcheng Lake border).

severe pollution, attributed to a considerable pollution discharge from the huge number of industrial enterprises and farms along the river. The overall river course varies significantly in hydraulics, section characteristics, and pollution scenario at different reaches. In addition, it interconnects and exchanges pollutants with six adjacent rivers.

2.2. Present water quality and pollution discharge status

A survey of the river water quality and the major pollution sources along the river was performed from March to December, 2010. Water samples from 38 sampling points were collected in March and August 2010, respectively. The average values of the water quality data in these two months were used to evaluate the water quality of Qiputang River. The concentrations of COD and NH_4^+–N were measured following the Standard Methods [17]. The distributions of COD and NH_4^+–N among these sampling points in 2010 are shown in Fig. 2. The monitoring data show that the water quality of most of the river sections belongs to Class V or V+ (the poorest quality) according to China's environmental quality standards for surface water [18]. Especially, the NH_4^+–N concentrations reached up to 1.2 mg/L, indicating an entrophic type of pollution. The water quality varies with seasons and river sections.

In addition, the pollution discharge loads along the river was also surveyed in order to understand the present pollution load status. The water quality at 30 major drain outlets, which range from wastewater treatment plant (WWTP) to industrial sources, villages,

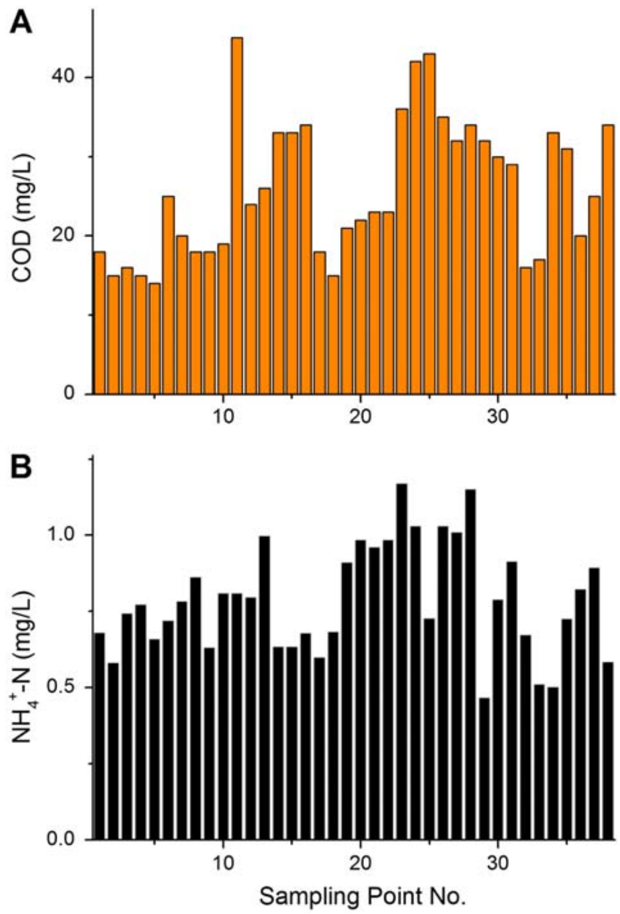

Fig. 2. (A) COD and (B) NH_4^+–N concentrations at 38 sampling points of Qiputang River in 2010.

and to livestock plants, was measured (data not shown). There is uneven distribution of pollution discharge along the river, with the COD concentration varies significantly from 33.9 to 397 mg/L and NH_4^+–N from 0.1 to 67.5 mg/L in 2010. Nevertheless, these data demonstrate that there is considerable pollution discharge in the Qiputang River region.

3. Modeling and calculation

3.1. Pollution load estimation

Analog to other rivers, the pollution load of Qiputang River mainly comes from two parts: PS (i.e. effluent of WWTPs) and NPS. Currently, there are two small-scale WWTPs in this area; the pollution load from these NPs can be easily obtained by calculating the flow rate and pollutant concentration of the WWTP effluent. In contrast, estimation of NPS pollution load is complex and a careful selection of pollution coefficients is needed to meet the practical situation. A field survey shows that the major NPS of Qiputang River include: (1) uncollected wastewater from some dispersed industrial enterprises; (2) uncollected urban domestic wastewater; (3) rural domestic wastewater; (4) pollution from agriculture NPS; and (5) livestock wastewater. Such NPS are characterized by large number, high discharge amount, and dispersed distribution, which arouse difficulties for pollution evaluation and control. Several evaluation criteria were proposed below according to common practice and local practical situation to estimate the pollution load from these NPS.

3.1.1. Uncollected industrial NPS wastewater

Along the river, there are about 100 pollutant discharging industrial enterprises. About 50% of the enterprises have drain pipes connected to municipal wastewater treatment plants and subject to centralized treatment, thus this part of industrial effluent is considered as PS. The other 50% of the industrial effluent (after primary treatment) is discharged directly into Qiputang River and can be considered as NPS. The effluent COD was estimated as 120 mg/L based on Grade III of local industrial discharge criteria.

3.1.2. Uncollected urban domestic wastewater

A fraction of urban domestic wastewater is uncollected and discharged directly to the river. The pollution load of such urban domestic wastewater NPS, W_{ud} (t/a), is calculated according to the following equation:

$$W_{ud} = (W_{udd} - \theta_u) \times \beta_u \tag{1}$$

Here, W_{udd} refers to the annual total discharge amount of urban domestic wastewater (t/a). It can be estimated by $W_{udd} = N_u \times \alpha_u$, where N_u is urban population (cap), α_u is the annual urban per capita pollutant discharge coefficient (60–100 g-COD/cap/*a* and 4–8 g-NH_4^+–N/cap/*d*); θ_u refers to the ratio of urban domestic wastewater subject to centralized treatment (calculated as 50%); and β_u is the urban river load ratio (taking 0.49 for COD and 0.86 for NH_4^+–N according to the local situation).

3.1.3. Rural domestic wastewater

Similar with urban domestic wastewater, the pollution load from rural domestic wastewater W_{rd} (which are almost all directly discharge into the river) can be estimated as,

$$W_{rd} = W_{rdd} \times \beta_r \tag{2}$$

where W_{rdd} and β_r are the total discharge amounts of rural domestic wastewater and rural river load ratio, respectively. $W_{rdd} = N_r \times \alpha_r$, in which N_r is rural population (cap), α_r is the rural per-capita pollutant discharge coefficient [40 g-COD/(cap.d) and 2 g-NH_4^+–N /(cap.d)]; β_r takes 0.37 for COD and 0.24 for NH_4^+–N.

3.1.4. Agriculture wastewater

Agriculture NPS pollution mainly come from fertilizers and pesticides in farmlands. The agriculture pollution load W_a can be estimated as,

$$W_a = W_{ad} \times \beta_a \times \gamma_a \tag{3}$$

where M_{ad} is the total discharge amount from agriculture source and M_{ad} = farmland area × pollutant discharge coefficient. The discharge coefficients are: 15 g-COD/(m^2.a); 3 g-NH_4^+–N/(m^2.a). β_a is the agriculture load ratio (taking 0.1–0.3), and γ_a is the correction factor (taking 1.2–1.5).

3.1.5. Other NPS

In addition to the above NPS, other NPS pollution loads can be calculated following similar procedures. For example, the discharge coefficient of livestock wastewater takes 0.5–0.8.

Thus, total NPS pollution loads (W_{NPS}) can be estimated by adding up all the above fractions.

3.2. Pollution carrying capacity estimation

Pollution carrying capacity indicates the upper extent of a water body to receive and self-eliminate pollution. In light of the already severely polluted water of Qiputang River, it would make no sense to calculate the present pollution carry capacity because theoretically no pollution discharge should be allowed at all. Therefore, this work attempts to estimate the pollution carrying capacity that can be attained since an improvement of the water quality to Class III are expected in the near future (i.e. by 2015 according to China's water management planning). Here, the pollution carrying capacity of different reaches of Qiputang River is estimated based on the hydraulic and pollutant discharge characteristics and its target water quality of Class III. To facilitate the calculation, the river network is generalized and divided into 11 reaches according to the pollution load distribution and location. The distribution of the 11 reaches is shown in Fig. 1. The following generalization principles are adopted: the minor branches are equalized to single river section or nodes at the premise of not changing the overall water carrying and storage capacity. According to this principle, all the confluence of the rivers or branches of Qiputang River can be generalized into three rivers: Shitoutang, Yantietang, and Zhangjiagang River for the calculation. The river cross-section is regarded as trapezoid. The river bed width and slope coefficient are 25.0 and 3 m, respectively.

The pollutants would undergo complex processes of dilution and degradation when entering into the river. Therefore, it is critical to understand the dilution effects as well as the fate and distribution of pollutants in receiving water. Model simulation offers a useful tool to explore into this process. Attributed to the relatively low flow rate of the river, a first-order hydraulic model was appropriate for the calculation. The following assumptions are made for the simulation: (1) pollutants mixed completely and immediately at the section where the drain outlet is located and (2) pollutant concentration only changes in flow direction; all the discharge outlets distribute evenly along each reach. As thus, the pollutant abatement process can be described by the Streeter–Phelps equation [19]:

$$C_x = C_0 \exp\left(-K\frac{x}{u}\right) \tag{4}$$

where C_x is the pollutant concentration at certain point (x) of the river flow direction (mg/L), C_0 is the pollutant concentration at the section of drain point (mg/L), x is the longitudinal distance from the drain point (m), u is the designed average flow rate of the section (m/s), and K is the abatement coefficient. The K value takes 0.06–0.3 d^{-1} according to the local industrial criteria [20] and common practice.

The pollutant concentration at the section of drain point is calculated as,

$$C_0 = \frac{C_R \cdot Q_R + C_E \cdot Q_E}{Q_R + Q_E} \tag{5}$$

where Q_R and C_R are the flow rate (m^3/s) and pollutant concentration of upstream water (mg/L), respectively; Q_E and C_E are the flow rate and pollutant concentration of wastewater from the drain outlet, respectively.

According to Eqs. (4) and (5), the pollution carrying capacity (W) for each river reach can thus be calculated by the following equation:

$$W = 31.54 \times \frac{C_s - C_0 e^{-K\frac{L}{u}}}{1 - e^{-K\frac{L}{u}}}(QKL/u) \tag{6}$$

where C_s is the target pollutant concentration (mg/L); Q is the flow rate of the reach (m^3/s); and L is the length of the river reach (m).

The flow rate Q (m^3/s) and water level Z (m) of each river section is calculated according to the Saint-Venant equation set [21], as follows:

$$\begin{cases} \frac{\partial Q}{\partial x} + B_W \frac{\partial Z}{\partial t} = q \\ \frac{\partial Q}{\partial t} + 2u\frac{\partial Q}{\partial x} + (gA - Bu^2)\frac{\partial A}{\partial x} + g\frac{n^2|u|Q}{R^{4/3}} = 0 \end{cases} \tag{7}$$

where t is the time from discharge; n is the roughness coefficient; A is the section area; B_w is the river width; R is the hydraulic radius; and q is the sidestream flow rate.

A discretization transformation of the above equation set yields:

$$\begin{cases} C_i Z_i + C_i Z_i - Q_i + Q_{i+1} = D_i \\ E_i Q_i + G_i Q_{i+1} - F_i Z_i + F_i Z_{i+1} = \psi_i \ldots (i = L1, L1+1, \ldots, L2-1) \end{cases} \tag{8}$$

Here, the major variables are calculated as follows:

$$C_i = B_{Wi+1/2}\frac{\Delta x_i}{2\theta \Delta t} \tag{9}$$

$$D_i = \frac{1-\theta}{\theta}(Q_i^j - Q_{i+1}^j) + C_i(Z_i^j + Z_{i+1}^j) + q_i\frac{\Delta x}{\theta} \tag{10}$$

$$E_i = \frac{\Delta x_i}{2\theta \Delta t} - 2u_{i+1/2}^j + \frac{g\Delta x_i}{2\theta}\left(\frac{n^2|u|}{R^{4/3}}\right)_i^j \tag{11}$$

$$F_i = \left(gA - Bu^2\right)_{i+1/2}^j \tag{12}$$

$$G_i = \frac{\Delta x_i}{2\theta \Delta t} - 2u_{i+1/2}^j + \frac{g\Delta x_i}{2\theta}\left(\frac{n^2|u|}{R^{4/3}}\right)_{i+1}^j \tag{13}$$

$$\psi_i = \frac{\Delta x_i}{\theta \Delta t}Q_{i+1/2}^j + \frac{2(1-\theta)}{\theta}u_{i+1/2}^j(Q_i^j - Q_{i+1}^j) - \frac{1-\theta}{\theta}(gA - Bu^2)_{i+1/2}^j(Z_{i+1}^j - Z_i^j) + \frac{\Delta x_i}{\theta}(u^2\frac{\partial A}{\partial x})_{i+1/2}^j \tag{14}$$

In the above equations, the subscript $i+1/2$ refers to the mean value functions at i and $i+1$ point. The values of Q and Z can be obtained by finite difference method.

3.3. Overload calculation

Based on the above calculation results, the overload (W_{ol}) can be estimated as,

$$W_{ol} = W_{PS} + W_{NPS} - W \tag{15}$$

where W_{PS} and W_{NPS} are the pollution loads from PS and NPS, respectively.

4. Results and discussion

4.1. Major pollution sources

The overall COD and NH_4^+–N loads of Qiputang River from various sources are estimated as 2328.5 and 75.26 t/a. But different sources have uneven contributions to the pollution. As shown in Fig. 3, among the various NP and NPS, uncollected urban domestic wastewater is the largest contributor to COD load of Qiputang River, which accounts for 34.61% of the overall load; agriculture wastewater is the most important source of NH_4^+–N pollution, accounting for 24.57% of the overall NH_4^+–N load. These results are in consistent with other literature report [16,22]. The order of dominant pollutions types in COD load is estimated as: urban domestic NPS > industrial NPS > WWTP effluent > rural domestic NPS > agricul-

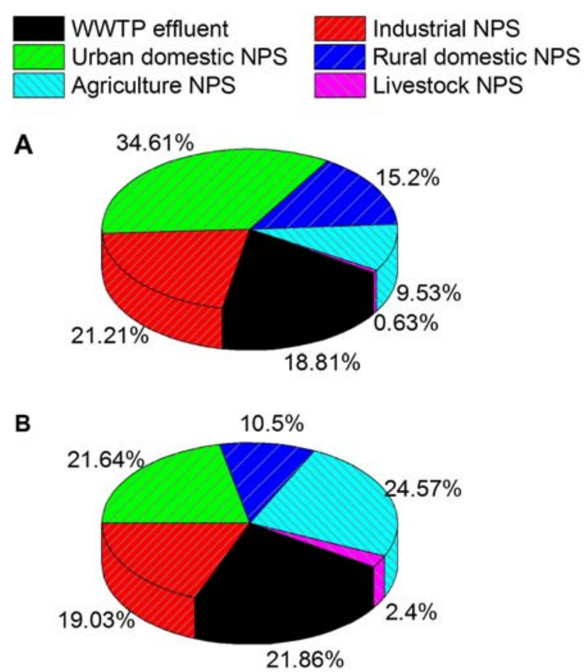

Fig. 3. Percentage of (A) COD and (B) NH_4^+–N loads of Qiputang River from different pollution sources.

Table 1
Pollution load and expected pollution carrying capacity of different reaches of Qiputang River in 2010

River reach no.	COD carrying capacity (t/a)	Actual COD load (t/a)	NH_4^+–N carrying capacity (t/a)	Actual NH_4^+–N load (t/a)
1	78.91	69.04	3.16	3.45
2	225	203.98	9.05	10.2
3	53.11	49.34	2.14	2.47
4	374.16	116.71	7.11	5.84
5	463.32	54.63	14.26	2.73
6	158.59	51.97	3.06	2.6
7	206.29	69.56	3.86	3.48
8	311.61	250.91	14.06	12.55
9	71.46	113.01	3	5.65
10	242	156.32	9.54	7.82
11	144.06	240.67	6.04	12.03

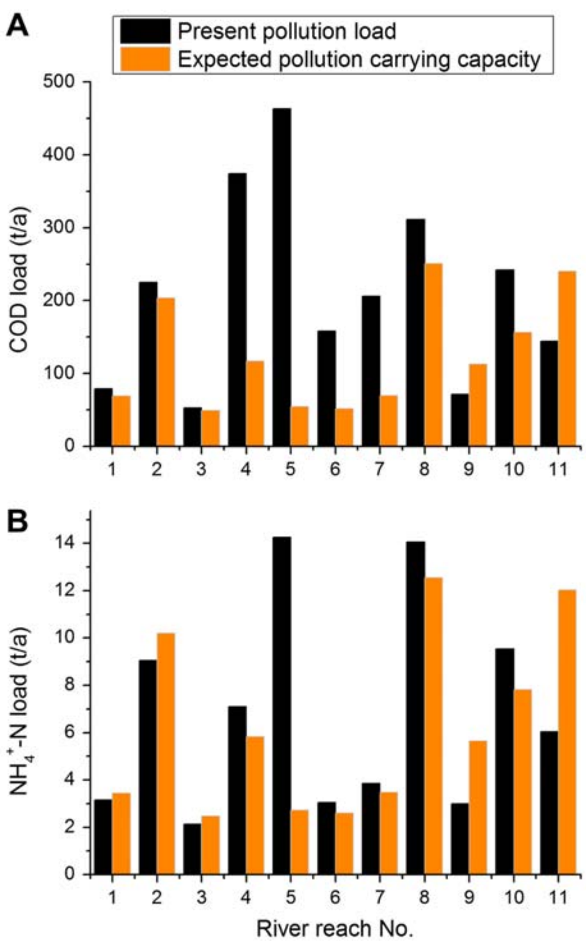

Fig. 4. Comparison of actual pollution load and expected pollution carrying capacity of Qiputang River for (A) COD and (B) NH_4^+–N in 2010.

ture NPS > livestock NPS. The order for NH_4^+–N load varies considerably, that is: agriculture NPS > urban domestic NPS > WWTP effluent > industrial NPS > rural domestic NPS > livestock pollution. Thus, the major pollution sources of Qiputang River are identified, including urban domestic NPS, industrial NPS, agriculture NPS, and WWTP effluents. These sources in together account for 84.17% of the total COD load and 87.1% of the total NH_4^+–N load in the river. Thus, future emphasis of water pollution control in this area should be put on urban domestic NPS, industrial NPS, and agriculture NPS. Of course, more stringent control on WWTP effluent, as a significant contributor of both COD and NH_4^+–N loads to Qiputang River, should continue to be pursued.

4.2. Expected pollution carrying capacity and pollution load

The present pollution loads and the expected pollution carrying capacity of each river reach are shown in Table 1 and Fig. 4. It can be clearly seen that both the pollution loads and the expected pollution carrying capacity vary significantly at different river reaches, confirming an uneven distribution of pollution discharge and river characteristics. Despite of all these differences, one common feature is that the present pollution loads overweigh the pollution carry capacities in most of the reaches. In this case study, the expected COD and NH_4^+–N carrying capacities of Qiputang River are 1376.1 and 68.81 t/a, respectively, while the overall loads of COD and NH_4^+–N reach 2328.5 and 75.3 t/a, suggesting an severe pollution overload state of the overall Qiputang River. This overloading is the most serious in No. 4–7 reaches. Particularly in No. 5 reach, the COD and NH_4^+–N overload reached 408.69 and 11.5 t/a, respectively, accounting for 748.1 and 422.3% of the maximum allowed values. Therefore, the wastewater treatment and pollution controlled should be especially strengthened for the pollution sources of these river reaches.

5. Conclusions

This study offers a comprehensive evaluation on the pollution sources and loading situation of Qiputang River. Among the various pollution sources, urban domestic NPS, industrial NPS, agriculture NPS and WWTP effluents are identified as major contributors to both COD and NH_4^+–N loads. The present pollution load and the expected pollution carrying capacity of each river reach were compared. The results clearly show a pollution overloading state of the overall river. This overloading is especially severe in No. 4–7 sections, where maximum overloading of up to 748.1% COD and 422.3% NH_4^+–N was observed. Therefore, the major pollution sources of these reaches should be the focus of future water pollution control. This evaluation method here presents a simple and useful way to investigate into the pollution situation of complex river systems, and may also provide references for pollution investigation of other rivers in China and other developing countries. In addition, this work offers valuable information on the pollution type and load of a typical river in Taihu Lake basin, which may help policy-makers and planners in implementing more effective and practical pollution control strategies.

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List of symbols

A — river section area
B_w — the river width
C_x — pollutant concentration at point (x) of the river flow direction (mg/L)
C_0 — pollutant concentration at the section of drain point (mg/L)
C_R — pollutant concentration of upstream water (mg/L)
C_E — pollutant concentration of wastewater from the drain outlet
C_s — target pollutant concentration (mg/L)
K — pollutant abatement coefficient
L — length of a river reach (m)
M_{ad} — discharge amount from agriculture source
n — roughness coefficient
N_u — urban population (cap)
N_r — rural population (cap)
q — sidestream flow rate
Q_R — flow rate of upstream water (m^3/s)
Q_E — flow rate of wastewater from the drain outlet
Q — flow rate of a river reach (m^3/s)
R — hydraulic radius (m)
t — time from discharge (s)
U — designed average flow rate of the section (m/s)
W — pollution carrying capacity
W_a — agriculture pollution load
W_{rd} — pollution load from rural domestic wastewater
W_{rdd} — discharge amount of rural domestic wastewater
W_{udd} — discharge amount of urban domestic wastewater (t/a)
W_{ol} — pollution overload
W_{PS} — pollution load from point sources
W_{NPS} — pollution load from non-point sources
x — the longitudinal distance from the drain point (m)
Z — water level (m)
α_r — rural per capita pollutant discharge coefficient
α_u — urban per capita pollutant discharge coefficient
β_a — agriculture load ratio n
β_r — rural river load ratio
β_u — urban river load ratio
γ_a — is the correction factor of agricultural load
θ_u — ratio of urban domestic wastewater subject to centralized treatment

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