Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2014.981678

57 (2016) 2903–2916
February

Taylor & Francis
Taylor & Francis Group

Application of WASP model and Gini coefficient in total mass control of water pollutants: a case study in Xicheng Canal, China

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Received 9 February 2014; Accepted 21 October 2014

ABSTRACT

The main objective of this study was to apply the water quality analysis simulation programme to develop total mass control of pollutant (TMCP) programmes by calculating the water assimilative capacities for chemical oxygen demand (COD) and ammonia nitrogen (NH_3-N) of a river that connects the Taihu Lake and the Yangtze River. Based on the distribution of water assimilative capacities, the geographical distribution of the pollutant permitted discharge load was validated by calculating the Gini coefficients for the economic, social and environmental efficiencies. According to the validation results, pollutant permitted discharge load was reallocated between townships and the rates of the reductions in pollutants for each township in the watershed were calculated. The water assimilative capacities of COD and NH_3-N of Xicheng Canal watershed were calculated as 4803 ton/yr and 186 ton/yr, respectively. The results for the reallocation of pollutant permitted discharge load between townships indicated that the reduction in COD was small, with only 11.2% reduction for Qingyang Town and 33.6% for Chengjiang Town. In contrast, the NH_3-N reductions of Yuecheng Town, Nanzha Town, Qingyang Town and Chengjiang Town were 52.9, 40.0, 61.4 and 54.5%, respectively, while the total reduction for Xicheng Canal watershed reached 53.5%. Based on the case, a new TMCP framework for allocating the pollutant permitted discharge loads in rivers was established, which not only combined the total mass of pollutant with the water quality but also took account for equity and efficiency in the allocation of pollutant permitted discharge loads.

Keywords: WASP; Gini coefficient; Water assimilative capacity; Pollutant permitted discharge load; Water quality

1. Introduction

Environmental problems associated with the rapid development of economies and societies have become increasingly severe in recent decades [1,2]. The control of surface water pollution has thus received more public attention. There are three main methods for current water quality management programmes, including the total maximum daily loads (TMDL) programme in the United States [3], the European Union water framework directive [4] and the total mass control of pollutant (TMCP) programme in China [5]. These three methods have the same basic concept in water quality management, and the TMDL framework is the most widely applied [6–8]. For water

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management, TMDL programmes have been implemented to analyse permit-trading policy [9] and have been further improved by considering both economic and social factors [10] to develop best management practices (BMPs) [3,11].

The application of a TMDL regulatory framework is usually carried out by calculating the water assimilative capacities of pollutants [12], which are defined as the maximum amounts of pollutants that the environment can hold for given environmental protection objectives, designated hydrological conditions and natural water backgrounds [13]. The water assimilative capacity can be calculated by water quality analysis model, including directly water quality simulations [14] and the establishment of mathematical models [15,16]. Considering lack of data and the complexity in establishing a mathematical model, a water quality model was chosen to calculate water assimilative capacity for the study. There are numerous models that have been used for environmental simulations [17], including the QUAL series, CE-QUAL, WATERSHEDS, AQUATOX, EFDC, WMS and WASP. The WASP model, which is composed of two modules (the one-dimensional hydrodynamic model (DYNHYD) and the water quality analysis model (WASP)) [18], can be used to simulate the quality of various water bodies [19,20]. Since it has a user-friendly interface and powerful functions, the WASP model was adopted to simulate and calculate water assimilative capacities in this study.

TMCP programmes have been an important project in water quality management in China and are often implemented by different administrative regions in order to clarify the responsibility. Because the watershed management is based on the combination of the administrative area and the ecological unit, the allocation of pollutant permitted discharge load in TMCP is generally determined by the administrative division of the watershed [21]. In the TMCP programmes, the pollutant permitted discharge loads were usually determined and allocated only based on the current pollutant discharge load of each administrative region. However, this kind of allocation has the advantage of convenient operation but does not respond to water quality improvement.

Taihu Lake is the third largest freshwater lake in China. With the increase in economic and social development in the area, an increasing amount of pollutants have been discharged into Taihu Lake, resulting in water pollution—eutrophication in particular. Algal blooms have become a serious environmental problem in the lake [22]. In order to improve the water quality of Taihu Lake, the traditional TMCP programme was applied in the Basin. Xicheng Canal, which flows through the city of Jiangyin in the Jiangsu Province, China, is an inflow river to the Taihu Lake and has a conspicuous effect on the water quality of the lake. However, the water quality of Xicheng Canal watershed does not meet the regulatory targets and it is essential to apply the TMCP programmes in the watershed. In order to improve the efficiency of pollutant reduction efforts, the levels of environmental protection and economic and social development should both be taken into account when assessing the water quality management programme for this watershed. Hence, this study combines the use of the Gini coefficient and the TMCP framework to examine the allocation of pollutant permitted discharge load between townships [23,24]. Two pollutants including COD and NH_3-N, which were main pollutants of TMCP programmes in China, were involved in the study. The application of WASP model in the TMCP framework was to calculate the water assimilative capacity to provide a foundation for the initial allocation of pollutant permitted discharge load, and the introduction of Gini coefficient was the guarantee for the equity in the reallocation of permitted discharge load. The objective of our study was to find out a way to enhance the economic development and to raise the efficiency of environmental protection based on the assurance of equality.

2. Materials and methods

2.1. Research area

Located at the north of Taihu Lake, Xicheng Canal, which is 37.4 km long, links the Taihu Lake in the south to the Yangtze River in the north. It has mainly been used for transport and as a comprehensively regulated river to guarantee flood control, irrigation,

Fig. 1. The location of the study area.

drainage and other hydrological attributes (Fig. 1). However, the water quality of the river has been deteriorating in recent years. The greatest threat to the river is the nutrient load, which exceeds the regulatory limit objectives for the river [22]. According to the water quality improvement programme of Taihu Lake, the nutrient load should be reduced to counter the eutrophication process and gradually improve water quality across the entire basin.

In this study, the area of Xicheng Canal watershed that was considered only involved in Jiangyin City including Chengjiang Town, Nanzha Town, Yuecheng Town and Qingyang Town, with a total area of 209.96 km^2 and population of 0.39 million.

2.2. Pollutant load allocation procedure

This study adopted the WASP model to calculate the water assimilative capacities of the COD and NH_3-N in Xicheng Canal watershed (Fig. 2). The initial pollutant permitted discharge load of each town was determined by the water assimilative capacities, and the pollutant load reduction was revised and reallocated by calculating Gini coefficients. First, a revised model with the social, economic and natural factors taken into account was established. Then, the initial allocation was carried out based on water assimilative capacities and the initial values of the Gini coefficients were calculated. If Gini coefficients were more than 0.2, the adjustment was applied, which provided a better comprehensive efficiency in terms of all three aspects mentioned above and an optimal allocation result. The adjustment was implemented over and over again until the values of the three Gini coefficients conformed to a value that was less than 0.2. The reallocation for pollutant permitted discharge load and the reduction rates in the study area were determined after adjustment.

2.3. WASP model for assimilative capacity

The water quality analysis and simulation programme (WASP) model can interpret and predict water quality cases in response to natural as well as man-made pollutions of diverse environments [25]. As a validated and flexible water quality model, WASP is widely used in assimilative capacity assessment [25,26]. The WASP model is composed of two modules, the DYNHYD and the WASP. The DYNHYD model solves the 1-D equation of continuity and momentum for a branching or channel-junction (link-node) computational network [27]. The flow velocity, channel length, the height and width of water surface are needed in the operation of DYNHYD model, which can provide the continuous data of the flows and other transport values, such as the channel volume and water flow [28]. The water quality model includes the eutrophication module (EUTRO) and the

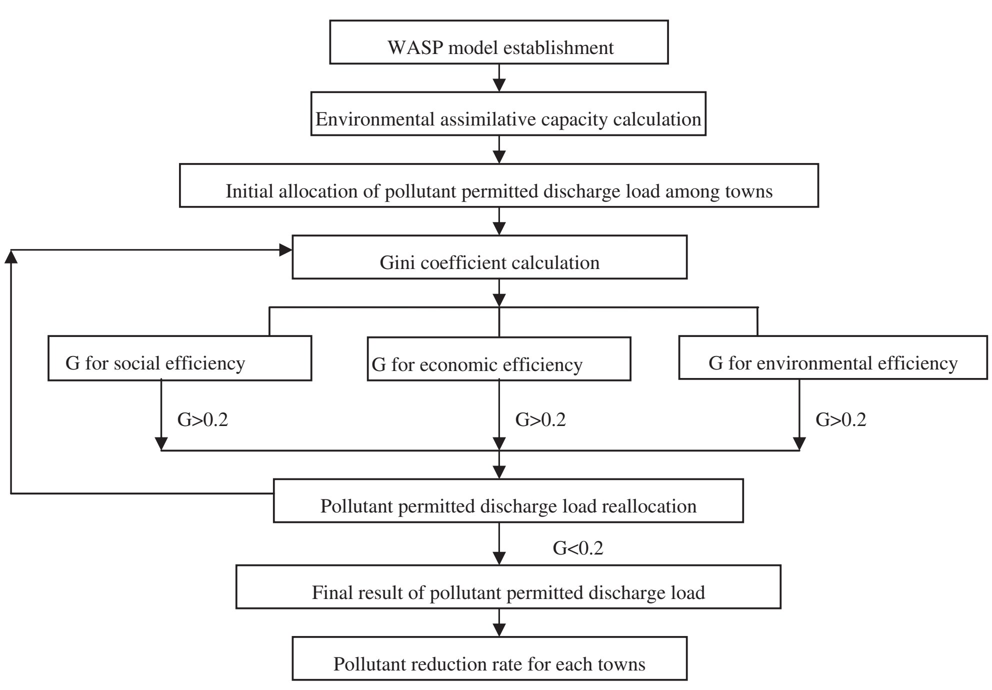

Fig. 2. The procedure for pollutant load allocation (*G* represents the Gini coefficient).

toxic pollutants module (TOXI). The EUTRO module is generally used to simulate nutrient enrichment, eutrophication and dissolved oxygen consumption processes in water, while the TOXI module focuses on the simulation of the migration and conversion of toxic pollutants in water [29]. The WASP version 7.3 was chosen for simulations in this study.

In a one-dimensional simulation of the WASP model, it is important to generalise the river networks. The principles applied for the river network generalisation were as follows [30]: (1) all of the main channels were considered as separate channels; (2) the secondary channels in parallel with each other which play delivery roles were generalised as one channel with equal discharge capacity, while the ones without a delivery function were generalised as the storage on land, such as small rivers, ditch ponds and lakes; (3) large lakes were generalised as storage nodes. According to these principles, the river network of Xicheng Canal was generalised (Fig. 3) and divided into 103 reaches. Each of reach was 0.5–0.7 km long.

Fig. 3. The generalised river network in study area.

To simplify the model, this study made three assumptions as follows: (1) all of the channels in the study were assumed to be one-dimensional straight rectangular channels and the convective dispersion, boundary sediment sorption, sediment release, evaporation and sedimentation, and dams and other structures to the water flow were neglected to revise; (2) the rivers were considered as a model case, and only the main point source and non-point source pollutions were taken into account, ignoring road transport, mining runoff and other impacts on the rivers. Point source pollutions were mainly composed of industrial wastewater and domestic sewage from municipal sewage treatment plants, and non-point source pollutions were mainly included agricultural runoff pollution, rural domestic pollution and livestock pollutions; (3) point source pollutants discharging into the river were regarded as continuous, while non-point source pollutants discharged into the corresponding river uniformly according to the length of each channel.

The parameter settings of the WASP model were diverse and had specific ranges summarised from an abundance of experiments and practical knowledge [31]. In order to find out the key parameters which had larger impacts on the calibration of WASP model, the sensitivity analysis method was applied [32]. Some coefficients such as BOD decay rate, nitrification rate and so on were indicated as the key parameters which had larger impacts on the model simulation [33]. Hence, the parameters that had the most drastic influence on the simulation result were calibrated first and then the other ones that needed fine adjustments.

Three indicators, the consistency index (d), the absolute error ($\bar{e}$) and the relative error ($\bar{f}$), were used to measure the overall effect of the model calibration. These were calculated with the following equations, Eqs. (1)–(3):

$$d = 1 - \frac{\sum_{i=1}^{n}(|A_i - B_i|^2)}{\sum_{i=1}^{n}(|A_i'| + |B_i'|)^2} \tag{1}$$

$$\bar{e} = \frac{\sum_{i=1}^{n}|A_i - B_i|}{n} \tag{2}$$

$$\bar{f} = \frac{\sum_{i=1}^{n}\frac{|A_i - B_i|}{B_i}}{n} \times 100\% \tag{3}$$

$$A_i' = A_i - \frac{\sum_{i=1}^{n} Ai}{n}, \; B_i' = B_i - \frac{\sum_{i=1}^{n} Bi}{n}$$

In the equations, n is the sample amount; A_i is the simulated value; and B_i is the observed value. The trial-and-error method of the WASP 7.3 model was used in water assimilative capacity calculation.

2.4. Gini coefficient method

The Gini coefficient was initially used for the quantitative evaluation of the income gap between the rich and poor. To date, it has also been widely used in environmental management fields [34,35], especially in the study of water assimilative capacity allocation [36,37].

As the main application of the environmental Gini coefficient is focused on the equality of measurements, this study tried to stress the consideration of efficiency based on equality validation through the indicator such as economic efficiency (E). Using the economic efficiency (E) as an economic indicator in the Gini coefficient evaluation system, the main point was to find out how much pollutant loads were generated by per unit of the gross domestic products (GDP) output. For instance, if the GDP generated per unit emission of pollutant load is large in some township, it implies that the township has high efficiency in terms of economic development and should therefore receive an appropriate bias in the allocation of pollutant permitted discharge load to ensure maximum fairness and efficiency in terms of both economic development and environmental protection.

For this study, the initial allocations of the pollutant permitted discharge load for COD and NH_3-N were based on water assimilative capacities which were calculated with the trial-and-error method of the WASP model. Then, the Gini coefficient for economic, social and environment efficiencies was calculated and valuated. The data of population were chosen as social indicator. The ratio of the GDP to the pollutant load was used as economic indicator, and the length of Xicheng Canal flowing through a certain township was chosen to be environmental indicator. The equation was established as follows:

$$W_i = W \times (\alpha_1 \cdot P_i + \alpha_2 \cdot E_i + \alpha_3 \cdot \delta_i) \quad (4)$$

where

$$P_i = P_i'/\sum_{i=1}^{n} P_i', \quad E_i = E_i'/\sum_{i=1}^{n} E_i', \quad \delta_i = \delta_i'/\sum_{i=1}^{n} \delta_i' \quad (5)$$

where W_i is the pollutant permitted discharge load allocated to the township; W is the pollutant permitted discharge load of the whole region; α_1 is the weight of the social factor; α_2 is the weight of the economic factor; and α_3 is the weight of the environmental factor.

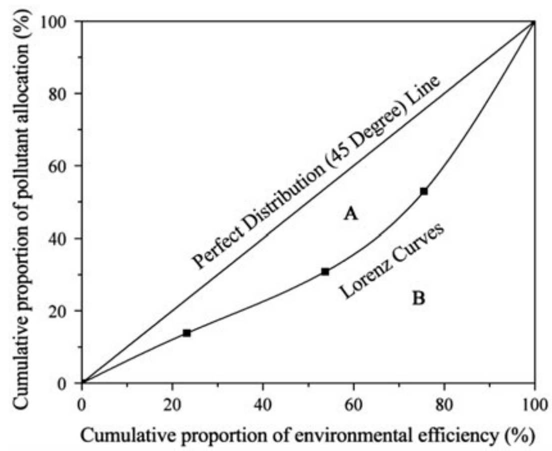

Fig. 4. The calculation of Gini coefficients with Lorenz curves.

The term P_i is the social efficiency coefficient of the township; E_i is the economic efficiency coefficient; and δ_i is the environmental efficiency coefficient.

The term P_i' is the population of the town; E_i' is the economic efficiency of each town; and δ_i' is the length of Xicheng Canal in each town.

The calculation of Gini coefficients for the economic, social and environmental efficiencies was conducted with the help of Lorenz curves (Fig. 4).

The Gini coefficient for environmental efficiencies was taken as an example. The Lorenz curves were built between the variation trend of pollutant allocations and environmental efficiency, and the value of $A/(A+B)$ was the Gini coefficient of the pollutant permitted discharge load allocation. Where A is the area between perfect distribution line and Lorenz curves and B is the area below the Lorenz curves. A high value of Gini coefficient indicates an inequitable allocation; therefore, small values are expected to be obtained to guarantee an equitable allocation of pollutant permitted discharge load.

2.5. Data source

In the study, the Jiangyin Statistics of the year 2007–2008 were used as the basis of the data. The water flow, water quality and meteorological data of the year of 2007–2008 were used for WASP model calibration and validation. However, the pollution sources were calibrated with the report data in 2007. For water assimilative capacity calculation, the 90% hydrological guarantee flow rate was adopted and the social and economic data were collected from the Statistical Yearbook of Jiangyin City (2007). The details and sources of the data were listed in Table 1.

Table 1
Data details and data sources in the study

Data	Details	Data source
Meteorological data	Daily temperature, wind speed and rainfall (from the year of 2007–2008)	Jiangsu Climate Center
Hydrological data	Water flow, water velocity (the year of 2007–2008, the 90% hydrological guarantee)	Taihu Lake Water Resources Administration Bureau
Watercourse data	River length, width and depth	Jiangyin Water Resources Bureau
Water quality data	Concentration of COD, NH_3-N, TP and TN of study rivers (from the year of 2007–2008)	Jiangyin Environmental Monitoring Station
Pollution source data	Pollution source of industrial, agricultural and domestic	The First Pollution Sources Census Report and the Environment Quality Bulletin
Social and economic data	Population, land area and GDP of each township in Jiangyin, 2007–2008	Statistical Yearbook of Jiangyin City (2007–2008)

3. Results and discussion

3.1. Water quality of the watershed

The water quality of Xicheng Canal is very important to the local communities and the water quality of the lake. The routine monitoring results showed that the indicators except NH_3-N, TN and TP of four sites in the watershed were stable and can be classified into Grade III to Grade IV most of the time according to Chinese National Environmental Quality Standards for Surface Water (GB3838-2002) (Table 2). However, there are times when the water quality of the watershed does not meet the standards. In addition, the concentration of NH_3-N, TN and TP exceeds the standards in most time. The mean concentration of TN in the four sampling sites was in the range of 3.96–6.47 mg/L, which was far exceeded the concentration of National Grade V (2.0 mg/L). The average concentration of NH_3-N was in 2.15 mg/L, which was worse than National Grade V (2.0 mg/L). And the concentration of TP was worse than other parameters as the highest concentration reached 1.51 mg/L in Sihe Bridge.

The concentrations of all pollutants in the watershed fluctuated during the year as shown in Fig. 5. Overall, the water quality of Sihe Bridge was worst and that of Huangtiangang was the best. The concentration of COD_{Mn} was stable for the most section of the watershed during the study year. The concentration of NH_3-N was highest in February and March and then declined in fluctuation in the following months. The concentration of TP was highest in April and then declined from May to August. However, the concentration of TN kept fluctuated throughout the year.

3.2. WASP model calibration and validation

The model could not automatically optimise itself because of the number of parameters. Therefore, it was important to choose appropriate parameter values based on practical data and the relevant literature. According to the calibration process, it was determined that the nitrification rate constant (k_{12}), the BOD decay rate constant (K_d) and the global reaeration rate constant (K_0) significantly affected the simulated results of the model [32,33]. These parameters were chosen to be coarse-tuning parameters. The BOD decay rate scale factor (R) and the temperature scale factor of a segment (RT) were observed to influence

Table 2
Water quality of the sampling sites in Xicheng Canal

Indicators	DO (mg/L)	COD_{Mn} (mg/L)	NH_3-N (mg/L)	TN (mg/L)	TP (mg/L)
Ximen Bridge	3.53	4.56	2.52	4.42	1.12
Sihe Bridge	3.05	6.64	2.69	6.03	1.51
Huangtiangang	4.61	3.51	1.31	3.96	0.59
Yuecheng Bridge	3.97	5.08	2.06	6.47	0.43
Average	3.79	4.95	2.15	5.22	0.91

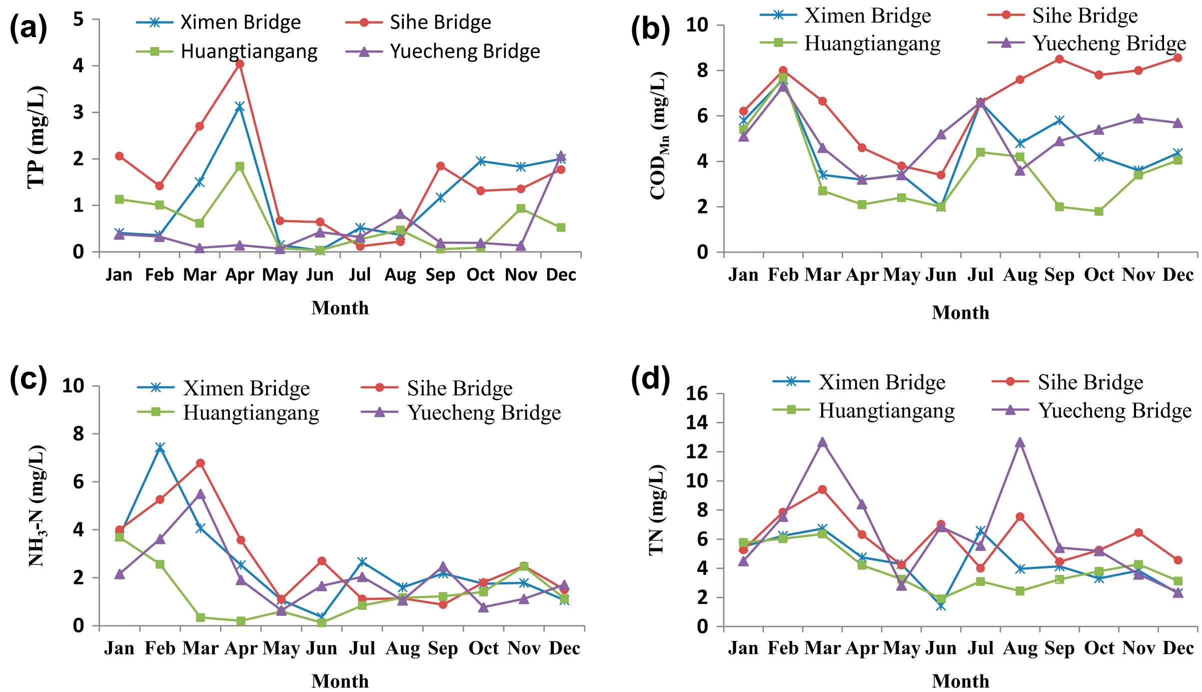

Fig. 5. Fluctuation of pollutant concentration in Xicheng Canal: (a) TP, (b) COD_{Mn}, (c) NH_3-N, and (d) TN.

the specific single river and were chosen to be fine-tuning parameters of the model. To achieve the final agreement between the simulated and observed values, an adjustment which first for coarse-tuning parameters and then for the fine-tuning parameters was carried out until the result met the objective level. The adjusted parameters are shown in Table 3, while the ones not listed were given the default values for the model parameters.

A further validation was made to assess the accuracy of the model simulation. Fig. 6 shows the results of simulated values and observed values of COD and NH_3-N after model calibration. Three indicators, the consistency index (d), the absolute error ($\bar{e}$) and the relative error ($\bar{f}$), were calculated according to Eqs. (1)–(3) and are shown in Table 4. The absolute error and the relative error were at acceptable levels [30], while the consistency index implied that the

Table 3
The calibrated parameters of the WASP model for the Xicheng Canal watershed

Parameters	Symbol	Unit	Model range	Calibrated value
Nitrification rate constant @20˚C	k_{12}	d^{-1}	0–10	0.27
BOD (1) decay rate constant @20˚C	K_d	d^{-1}	0–5.6	0.25
BOD (1) decay rate temperature correction coefficient	K_{1T}	–	0–1.07	1.065
BOD (1) half saturation oxygen limit	K_{COD}	mg/L	0–0.5	0.25
Nitrification temperature coefficient	K_{NT}	–	0–1.07	1.07
Half saturation constant for nitrification oxygen limit	K_{NO3}	mg/L	0–2	0.25
Minimum temperature for nitrification reaction	T_{min}	˚	0–20	3
Oxygen to carbon stoichiometric ratio	a_{oc}	–	0–2.67	2.67
Theta-reaeration temperature correction	r	–	0–1.03	1.03
Minimum reaeration rate	K_{omin}	d^{-1}	0–24	0.2
Global reaeration rate constant @20˚C	K_O	d^{-1}	0–20	0.35
BOD (1) decay rate scale factor	R	–	0–1	0.55–1.0
Temperature scale factor of a segment	R_T	–	0–1	0.45–1.0

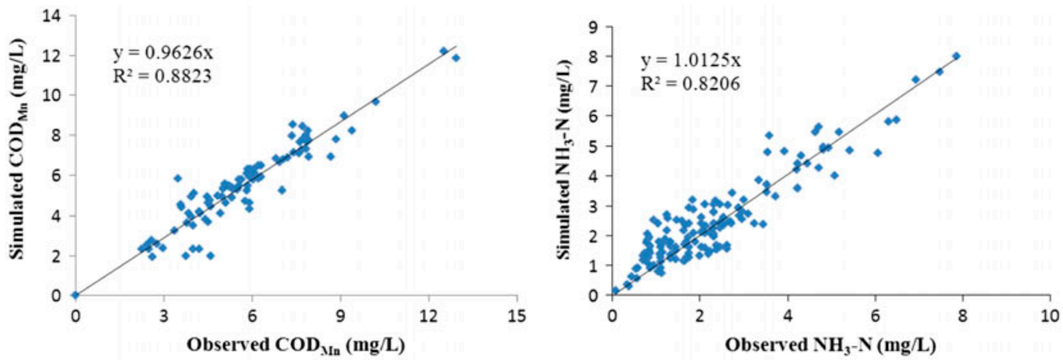

Fig. 6. Calibration results for COD and NH_3-N.

Table 4
Error analysis of the model calibration result

Index	d	$\bar{e}$	$\bar{f}\%$
COD	0.974	0.53	12.5
NH_3-N	0.945	0.52	31.8

simulation successfully maintained consistency between the simulated and measured values of COD and NH_3-N.

3.3. Water assimilative capacity

With the trial-and-error method of the WASP model under the 90% hydrological guarantee flow rate, water assimilative capacity for COD and NH_3-N of Xicheng Canal watershed was calculated. The results showed that the COD and NH_3-N capacity of the watershed is 4,803 ton/yr and 186 ton/yr, respectively. According to the river unit of each town, the initial spatial distributions of pollutant permitted discharge loads were given in Table 5.

3.4. Reallocation of pollutant permitted discharges load

In this case, the social efficiency, economic efficiency and environmental efficiency were considered as the main factors for determining the allocation of the COD and NH_3-N permitted discharge load in the watershed. There were three indicators for these efficiencies, including the population, the GDP per pollutant discharge load and the length of the canal, respectively.

According to Eq. (5), the efficiency coefficients for COD and NH_3-N permitted discharge load were calculated (Table 6). The results showed that Chengjiang Town had the highest efficiency coefficient which occupied 58.3% at social aspect and the rate of other three districts ranged from 10% to 18%. In terms of economic considerations, the four districts had similar COD efficiencies, which reached 30.5% in Nanzha Town, while for NH_3-N efficiency, Chengjiang Town was the most efficient at 37.9% and Yuecheng Town was the worst at 17.5%. Regarding their environmental efficiencies, Chengjiang Town also had the highest efficiency coefficient at 34.4%, while Qingyang Town had second highest at 26.9%, and Yuecheng Town and Nanzha Town were lower and similar.

The COD permitted discharge load allocation was validated by examining the Gini coefficients for the social, economic and environmental factors, which had values of 0.17, 0.45 and 0.15, respectively. The results showed that the initial allocation was relatively equitable in terms of social and environmental factors. But the Gini coefficient (G) for the economic factor exceeded the acceptable level, which indicated that

Table 5
Initial pollutant permitted discharge load of each town in the Xicheng Canal watershed

Township	COD permitted load (ton/yr)	NH_3-N permitted load (ton/yr)
Yuecheng Town	664	25
Nanzha Town	815	26
Qingyang Town	1,061	35
Chengjiang Town	2,263	100
Sum	4,803	186

Table 6
Efficiency coefficients for pollutant permitted load allocation

	Social			Economic						Environmental	
				COD			NH_3-N				
Township	P_I'(×10^4)	P_i (%)	GDP (10^8/a)	Load (t/a)	E_i'	E_i (%)	Load (t/a)	E_i'	E_i (%)	δ_i' (km)	δ_i (%)
Yuecheng Town	4.25	11.0	30.02	597.5	0.050	23.2	63.7	0.471	17.5	3.5	18.8
Nanzha Town	5.01	13.0	36.30	549	0.066	30.5	58.3	0.623	23.1	3.7	19.9
Qingyang Town	6.83	17.7	46.25	974.1	0.047	21.8	80.3	0.576	21.4	5.0	26.9
Chengjiang Town	22.45	58.3	201.63	3786.5	0.053	24.5	197.7	1.020	37.9	6.4	34.4
Sum	38.54	100	314.20	5907.1	0.217	100	400.0	2.690	100	18.6	100

the allocation was poor in terms of economic efficiency. According to the economic efficiency coefficients (E) shown in Table 6, Qingyang Town had the lowest E value while Nanzha Town had the highest one. Hence, an adjustment was carried out to reduce the allocation to Qingyang Town and appropriately increase the ones to Nanzha Town and the other two towns. However, the values of G for the social and environmental efficiencies were also altered by the adjustment. Therefore, they should be checked after each adjustment. The Gini coefficients of COD permitted discharge load allocation are given in Table 7, while the Lorenz curves are shown in Fig. 7.

The Gini coefficients of NH_3-N permitted discharge load allocation for the social, economic and environmental factors were 0.08, 0.21 and 0.30, respectively. The Gini coefficients of these three factors were at an acceptable level, although the one for the environmental factor was a little high at 0.30. Therefore, a moderate adjustment should be done. As the canal had the longest reach in Chengjiang Town, the environmental efficiency of this town was the highest; thus, a bias should be given to this town in terms of pollutant load allocation. The Gini coefficients of allocation are given in Table 7, while the Lorenz curves are shown in Fig. 8.

Reallocation for pollutant permitted discharge load was ended until G values were reduced to the acceptable level ($G < 0.2$). The final allocation of the pollutant permitted discharge load in Xicheng Canal watershed is given in Table 8. According to the water assimilative capacity of watershed, COD load should reduce 18.7% to meet water quality objectives. But the reduction task focused on Chengjiang Town which had to reduce 40.2% COD discharge load to meet the total mass control objective. In order to keep efficiency and equality of permitted discharge load allocation, we introduced Gini coefficient consisted of economic efficiency, social efficiency and environmental factor. After several reallocations, the COD reduction rate of Chengjiang Town fell from 40.2% to 36.6% while the reduction rate of Qingyang Town rose to 11.2%. The diffusion of responsibilities for COD reduction can effectively relieve the stress of pollution reduction in Chengjiang Town, and at the same time still achieve the water quality standard.

As Table 8 shows that the discharge load of NH_3-N had far exceeded the permitted load in the final allocation plan and the reduction rate of the whole watershed reached 53.5%, which indicated that the reduction of NH_3-N discharge load was the key task for water quality management of watershed.

Table 7
The Gini coefficients of pollutant permitted discharge load allocation

Gini coefficient		G-social	G-economic	G-environmental
COD	Before adjusting	0.17	0.45	0.15
	After adjusting	0.03	0.14	0.20
NH_3-N	Before adjusting	0.08	0.21	0.30
	After adjusting	0.13	0.12	0.20

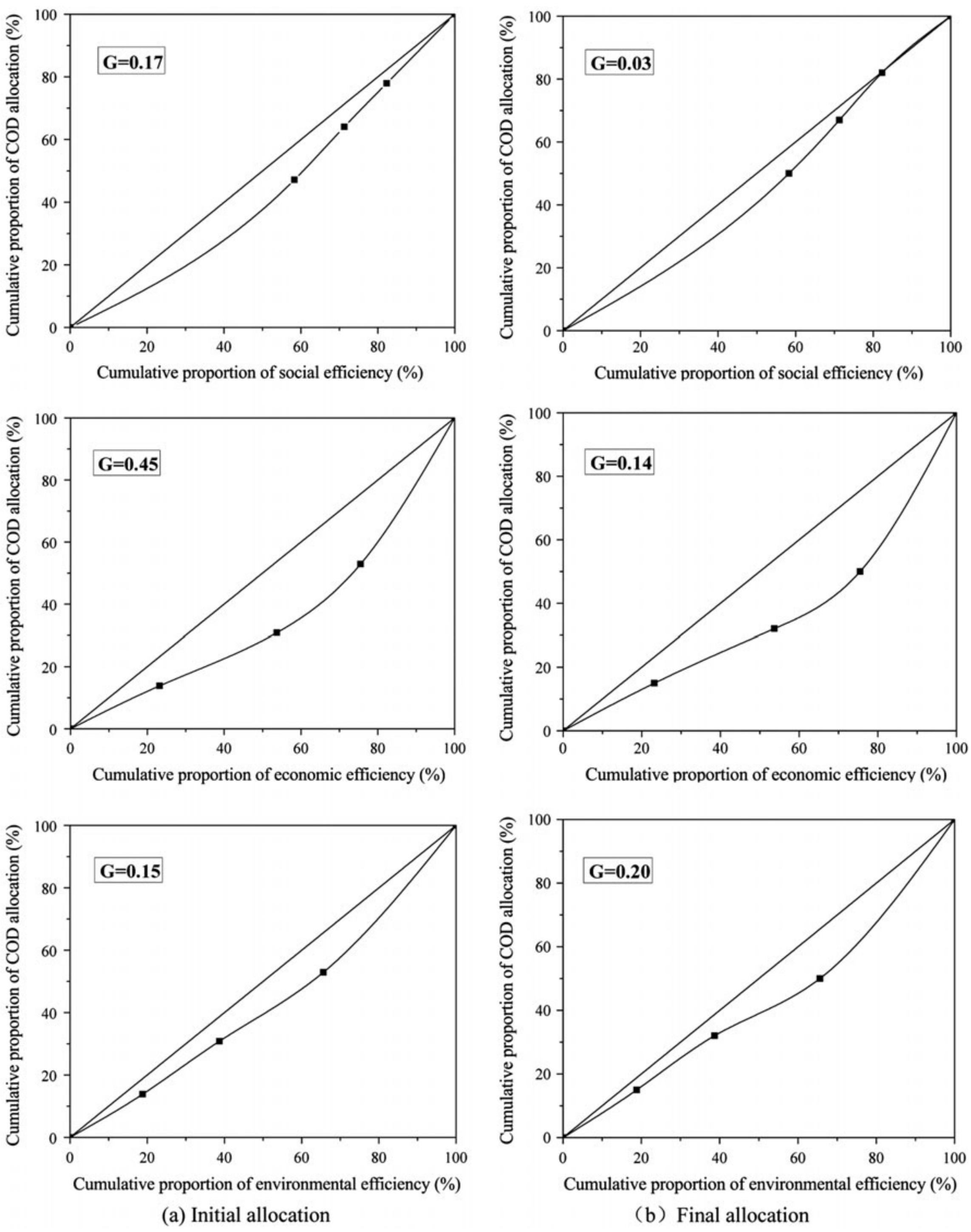

Fig. 7. The Lorenz curves for COD permitted discharge load allocation: (a) Initial allocation and (b) Final allocation.

According to initial allocation based on water assimilative capacity of each town, the NH_3-N reduction rate ranged from high to low as Yuecheng > Qingyang > Nanzha > Chengjiang and fluctuated between 49% and 61%. As the NH_3-N reduction rate of towns was relatively closed to each other, the first Gini coefficient was closed to 0.2 and only need fine adjustment to reach acceptable level. As final allocation results

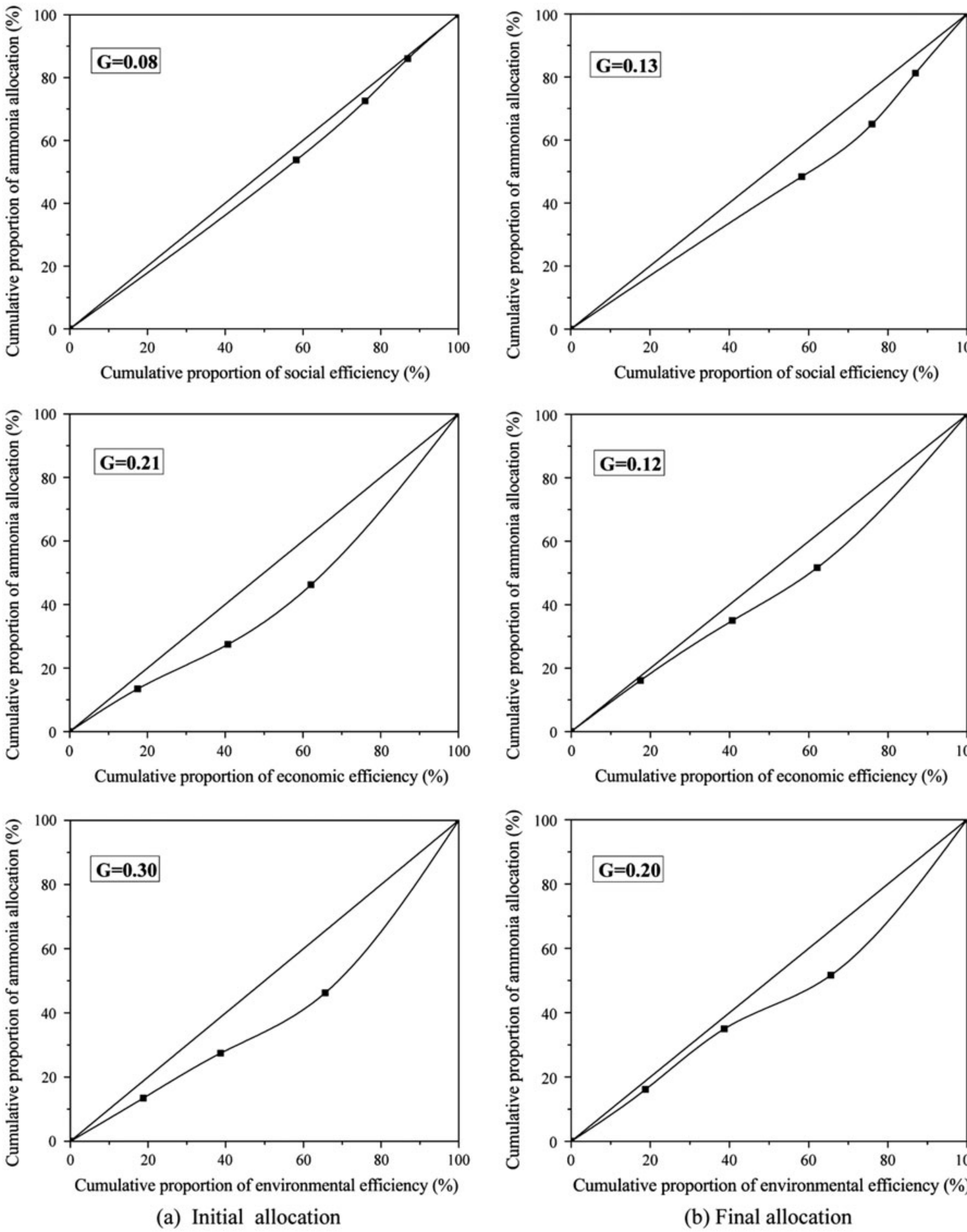

Fig. 8. The Lorenz curves for NH_3-N permitted discharge load allocation: (a) Initial allocation and (b) Final allocation.

showed that the NH_3-N reduction rate of Yuecheng Town fell from 60.8% to 52.9% and that of Nanzha Town fell from 55.4% to 40.0%. At same time, the NH_3-N reduction rate rose from 56.4% to 61.4% for Qingyang Town and from 49.4% to 54.5% for Chengjiang Town.

Table 8
The allocation results for pollutant permitted discharge load in the Xicheng Canal watershed

Township	Discharge load		Initial allocation				Final allocation			
			COD		NH_3-N		COD		NH_3-N	
	COD (yr/a)	NH_3-N (yr/a)	Permitted load (yr/a)	Reduction rate (%)	Permitted load (yr/a)	Reduction rate (%)	Permitted load (yr/a)	Reduction rate (%)	Permitted load (yr/a)	Reduction rate (%)
Yuecheng	597.5	63.7	664	0.0	25	60.8	720.5	0.0	30	52.9
Nanzha	549	58.3	815	0.0	26	55.4	816.5	0.0	35	40.0
Qingyang	974.1	80.3	1,061	0.0	35	56.4	864.5	11.3	31	61.4
Chengjiang	3,786.5	197.7	2,263	40.2	100	49.4	2,401.5	36.6	90	54.5
Sum	5,907.1	400	4,803	18.7	186	53.5	4,803	18.7	186	53.5

4. Conclusions

In this study, we try to make a new TMCP framework which allocated the pollutants permitted discharge load based on water assimilative capacity and validated the allocation based on equality and efficiency. Our TMCP was established using WASP model to calculate the water assimilative capacities of pollutants, which were the basis of initial pollutant permitted discharge load of each district. With a combination of the environmental, economic and social benefits, the Gini coefficient was introduced for the equality and efficiency in pollutant permitted discharge load allocation among districts.

In the case of Xicheng Canal, the water quality did not meet the objective of water quality management and the TMCP programmes was very essential. Based on the WASP model, the current pollutant discharge loads of COD and NH_3-N exceed the water assimilative capacities and the pollutant load reduction should be implemented in watershed management. The initial permitted discharge loads of COD and NH_3-N were determined by water assimilative capacities and reallocated with the guide of Gini coefficient. It was indicated that the reallocation of pollutant discharge load in each district was more equitable and closer to designated requirements, and the responsibilities of each district in environmental management were more harmonious with their economic and social development. According to the reduction plan, the NH_3-N load reduction was demonstrated to be a tough task in the future water quality management of Xicheng Canal.

To combine TMCP and Gini coefficient has created a better framework for the equitable allocation of pollutant permitted discharge load in different districts, which takes a comprehensive consideration of environmental, economic and social benefits. It can clearly demonstrate the responsibility of environmental management in different districts on the basis of equality. However, only the pollutant reduction plan was proposed, the economic and social measures were not involved in this study, which will also significantly affect the implementation of water management projects. Therefore, further research should focus on the allocation method which combines with local conditions and pollution control measurements.

Acknowledgements

This work was supported by the project of science and technology of Zhejiang Province for environmental planning team building (2012F20018) and the National Key Science and Technology Project: Water Pollution Control and Treatment (No. 2012ZX07506-006).

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