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A Hierarchical Approach for Inland Lake Pollutant Load Allocation: A Case Study in Tangxun Lake Basin, Wuhan, China

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ABSTRACT. Water pollution control is a challenging task in water resources management. It is widely believed that integrating efficiency and fairness of socio-economic factors is an effective solution for water problems of inland lake basins. In this paper, a hierarchical approach of Tri-level Pollutant Loading Allocation (TPLA) was developed for the optimal allocation of pollutant loading reduction. The top-down three levels allocation method adapted minimum marginal cost, Environmental Gini Coefficient (EGC) and water quality model to meet the set of water quality goal. The first level allocates pollution loading between point source and non-point source. The pollution loading in second level is allocated among all varieties of point sources based on minimum EGC method in terms of population and industrial added value, while the third level allocation is addressed in all sewage outlets. Tangxun Lake Basin, located in Wuhan, Central China, was selected as a case study, and COD_{Mn} was chosen as the representative pollution variable. Results show that the total COD_{Mn} loading reduction of point and non-point sources was allocated to 201.1 t/a and 24.1 t/a, respectively at the first level. Secondly, the districts within the lake basin are to cut off emission amounts to various extents. Results show that that the COD_{Mn} emission among the districts within the lake basin is more equally distributed by population than by industrial added value. Results also indicate that the impacts of inequality of population on COD_{Mn} emission are more likely to be relieved than that of industrial development in the lake basin. At the third level, the largest reduction amount of 142.21 t/a was found at Bee Jiaotou Plant outlet at Miaoshan District, followed by two outlets of 10.41 t/a in Zhifang District. Under this emission program, the COD_{Mn} concentration in the inner-lake region of the lake meet the water quality of grade III of the national standard. The TPLA model can provide an optimal pollutant loading allocation strategy that is easy to understand for stakeholders and flexible to apply in pollution loading allocation in inland lake basins.

Keywords: hierarchical approach, pollutant loading allocation, total pollutant control, lake basin, Tangxun Lake

1. Introduction

The deterioration of the water quality of inland lakes has been existing as a serious ecological and social problem in China, since many inland lakes often act as the main sources of drinking water, agricultural water, commercially fishery and recreational facilities (Huang et al., 2010; Huang et al., 2013). As the consequences of fast population growth and rapid economic development in China, a considerable amount industrial wastewater and domestic sewage were generated and dumped into inland lakes, leading to the decline of water quality including two major problems like black and odorous water bodies, and eutrophication (Miao et al., 2015; Huang et al., 2017). Besides, considering the slow water exchange of inland lakes, this makes lakes slower to be self-purified. Under these circumstances, pollutant loading control has become a prior and fundamental strategy of inland lakes environmental management for Chinese government (The State Counsil of China, 2015).

The goal of the pollutant loading control is to cut off the pollutant emission to meet the environmental capacity and maintain the water quality of the water body, namely the environmental capacity management (ECM) strategy, which was established and applied across the world in recent year (Chen et al., 1999; Haire, 2009; Mirchi, 2013). Similar concepts and strategies have been formulated aiming at water quality management, e.g. Total Maximum Daily Load (TMDL) (Haire, 2009), Water Framework Directive (WFD) (European Commission, 2000) and water quality target-oriented management (WQTOM) (Zhang et al., 2014), etc. Recently, the ECM strategies have also been widely applied in China to manage water quality and control the pollution of inland water bodies (Liu et al., 2014b; Wang et al., 2014; Liang et al., 2015).

The key component of ECM is optimal pollutant loading allocation (OPLA), which consists of two core parts, i.e., allowable pollutant loading calculation and pollutant loading allocation (Haire, 2009; Liang et al., 2015). Pollutant loading calcula-

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tion is to estimate the loading of pollutants generated in the lake basin, while pollutant loading allocation refers to the management strategy that could be directly implemented by stakeholders and decision-makers. When formulating the OPLA strategies, stakeholders often believe that the loading calculation should be precise and complex, while the method of loading allocation should be reasonable and easy to understand (Liang et al., 2015). This may probably due to that a robust pollution control strategy is often accompanied with a practical pollutant allocation strategy, which plays a pivotal role in environmental protection and watershed management. In this respect, a more understandable and realistic strategy is required for stake-holders and decision-makers. In the meantime, a relative precise calculation of pollutant loading is also needed in the decision formulation procedure, which could help supporting the implementation of the management strategy in a scientific and reasonable way. Therefore, there is still an increasing need to develop OPLA strategies that can achieve these two goals.

To achieve the goals of OPLA, a simulation-optimization approach has been generally considered as a vigorous way in formulating the management strategy (Xu, 2013; Xu et al., 2014; Huang et al., 2016). For instance, Burn and Yulianti (2001) applied genetic algorithms in waste-load allocation on the Willamette River in Oregon. Mujumdar and Vemula (2004) provided a simulation-optimization method that incorporated a fuzzy waste load allocation model, a water quality model (QUAL2E) and a genetic algorithm to address the waste load allocation problems in the Tunga-Bhadra River in South India. Yang et al. (2011) integrated an optimization model and QUAL2E model in investigating the natural assimilative capacity of a subtropical river system. Emami Skardi et al. (2014) integrated a multi-objective optimization tool with the Soil and Water Assessment Tool (SWAT) model and artificial neural network (ANN) model for optimal management of total suspended solids loading in the case study of Gharesou watershed in the northwest of Iran. The results of these studies formulated OPLA strategies that address the minimization of the total treatment cost and the inequity among the pollutant dischargers, which subjects to the satisfaction of water quality, economic development, and social demands. When the simulation-optimization procedure is done, pollution loading allocation strategies would be formulated based on the results, which are likely to be implemented in a hierarchical pattern. For instance, Zhang et al. (2012) established a regions-enterprises waste load allocation framework that optimize the total pollutant emission in the Xi'an-Xianyang Section of Weihe River according to the principles of efficiency and fairness. Liang et al. (2015) proposed a 5-level pollutant loading allocation system, in which pollutant load were allocated based on the characteristics of pollutant sources. A case study of Zhushan Bay of Taihu Lake was demonstrated to interpret the hierarchical pollutant load allocation strategy at levels of lakeshore, tributaries, local sources, point and non-point sources and various villages that contribute the most of the non-point sources pollution.

Yet, previous researches focused on the pollutant loading at river basin scale or in river systems (Huang et al., 2013; Kiedrzynska et al., 2014; Liu et al., 2014; Liang et al., 2015). Recently, pollution loading problems in inland lakes have raised increasing attention, while only a few studies on the application of OPLA have been performed in these areas. In the present study, we proposed a hierarchical approach that integrated the minimum marginal cost model, the environmental Gini coefficient model and a hydrodynamic and water quality model to optimize the pollution loading allocation in an inland lake basin. Tangxun Lake basin in Wuhan, one of the largest cities in central China, has been selected as a case study. The approach and the results of this study could be applied to other inland lake basins in the world that facing accelerating socio-economic development and accumulating pollution loading.

2. Methodology

2.1. Study Area

Tangxun Lake Basin, located between 30°22′ ~ 30°30′N and 114°15′ ~ 114°35′E in Central China (Figure 1), is the second largest lake in Wuhan City with a basin area of 240.4 km^2 and a mean water depth of 18.5 m. It is a typical urban shallow lake with a storage capacity of 32.85 million km^3, which suffers from an enormous amount of untreated wastewater and sewage discharge from the surrounding districts in Wuhan (Huang et al., 2010; Lv et al., 2011). According to the statistical report of "Wuhan Environmental Condition Bulletin, 2011", the water quality of the Tangxu Lake was classified as water quality Level Ⅳ of the *National Environmental Standard for Surface Water*. According to the Wuhan Environment Protection Agency (2011), the 26 sewage outlets with COD_{Mn} emission of 1357 t/a in 2011 are the main pollutant sources of Tangxun Lake Basin (Figure 1). Among the chemical substances of pollutant, permanganate index, abbreviated as COD_{Mn}, with the concentration of 9 mg/L in 2011 has been one of the main pollutants of concern of Tangxun Lake, which is 35% larger than the target value.

2.2. Tri-level Pollutant Loading Allocation (TPLA)

Pollutant loading allocation procedure of inland lake basin involves the whole processes of water pollution management of source emission reduction, process control and end treatment. Therefore, it needs to be economically efficient, technically feasible and socially fair (Liu et al., 2014). Consequently, a Tri-level Pollutant Loading Allocation (TPLA) model was proposed by integrating three methods, i.e., minimum marginal cost, Environmental Gini Coefficient (EGC) and lake hydrodynamic and water quality modeling. The TPLA for the case is a hierarchical approach that consists of 3 levels allocation (Figure 2). In the TPLA, the total loading is allocated to pollutant sources from the first-level to the third-level in this study. In the first-level allocation stage, we divide the total pollutant loading to two categories, i.e., inner source (IS) and exterior source. Inner source pollutant refers to those pollutants irritated within the water body, e.g., sediment-bound and particulate pollutants from lakebed, while pollutants from exterior sources consist of those from point sources (PS), non-point sources (NPS) and tributary sources (TS). PS refers to the pollution of sewage emission, while NPS is the addition of impurities into a surface water body

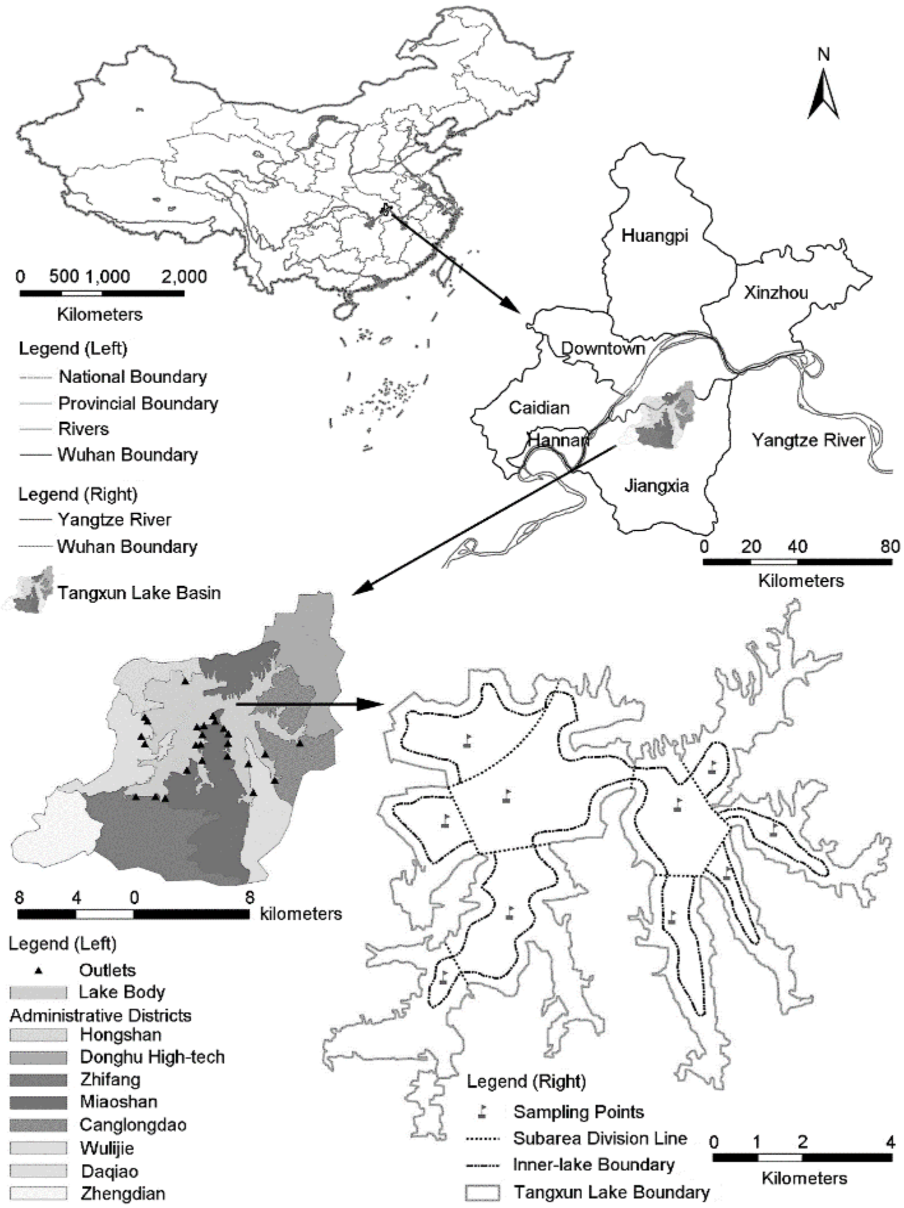

Figure 1. Sampling information of Tangxun Lake Basin.

or an aquifer, usually through an indirect route and from spatially diffuse sources (Zhu et al., 2015). Pollutants from tributary sources exist in those tributaries that transport water and pollutants from main river channel to lake water body. The second-level allocations stage main focuses on the point sources pollutants by various districts in the lake basin. This stage aims to achieve an environmental equity among the pollutants loading from every point source. In the third-level allocation stage, the goal of this stage is to maintain the concentration of the pollutants in the lake water body under the threshold of the drinkable water quality grade, defined by the Chinese Ministry of Environmental Protection (2002).

In the TPLA of the study case, pollutant loading are allocated by considering the constraints and the following four objectives: (i) the minimization of total pollutant, (ii) the minimization of total margin cost of disposing the point-source pollution and non-point source pollution, (iii) the minimization of the total EGC of pollution and socio-economic development within the Tangxun lake basin, (iv) water quality being no worse than grade Ⅲ (Chinese Ministry of Environmental Protection, 2002). Details of TPLA strategy for Tangxun Lake Basin are shown below.

(1) First-level Allocation

The first-level deals with the economic costs between the allocation of pollutants from inner sources and exterior sources. Pollutants from IS in the present study stand for those carried

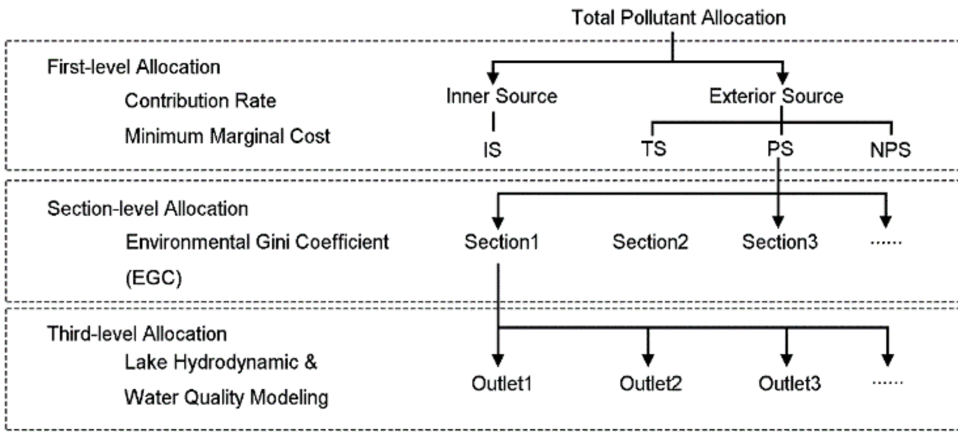

Figure 2. Tri-level pollutant loading allocation model for Tangxun Lake Basin.

by suspended sediment from the lakebed (Holbach et al., 2015). Exterior sources including point and non-point sources pollutants refer to those generated in the Tangxun Lake Basin, which are transported to the lake water body eventually. Tributary sources pollutants primarily stem from the Xunsi River that links the Tangxun Lake with Yangtze River in this case. Given that it is hard to quantify the pollution loadings precisely in most cases, we hold 5% of the allowable permitted assimilative capacity (APAC) for the safety margin (P_{margin}) in case of emergency (Ministry of Water Resources, 2010).

$$PR_{target} = P_{total} - APAC + P_{margin} = P_{total} - 0.95 \times APAC \tag{1}$$

where PR_{target} is the target amount of the pollution loading that needs to be reduced within the lake basin (t/a), P_{total} is the total amount of the pollution loading (t/a), *APAC* is the allowable permitted assimilative capacity of the lake water body (t/a).

The allocation of TS (PR_{TS}) and IS (PR_{IS}) were taken from PR_{target} according to their proportion in total pollution loading. Consequently, the sum amount of PS and NPS that should be cut off (PR_{PSNPS}) can be calculated as:

$$PR_{PSNPS} = PR_{target} - PR_{IS} - PR_{TS} \tag{2}$$

Considering the difference between the treatment costs of PS and NPS, the minimum marginal cost method was utilized for optimal economic efficiency (Mekaroonreung and Johnson, 2014; Ye et al., 2015), which can be defined as:

$$MIN \quad C(PR_{PS}, PR_{NPS}) = C(PR_{PS}) + C(PR_{NPS}) \tag{3}$$

$$s.t \begin{cases} PR_{PS} + PR_{NPS} = PR_{PSNPS} \\ 0 < PR_{PS} < PRL_{PS} \\ 0 < PR_{NPS} < PRL_{NPS} \end{cases} \tag{4}$$

where C(PR_{PS}) and C(PR_{NPS}) are the marginal cost of point source and non-point source pollutant treatment (10,000 yuan), PR_{PS} and PR_{NPS} are the reduction amount of point source and non-point source (t/a), and PRL_{PS} and PRL_{NPS} are the technical upper limit of treatment of point source and non-point source pollutant source (t/a).

To determine the marginal treatment costs of point source and non-point source, an exponential function was used (U.S. Environmental Protection Agency, 2004; Hernandez-Sancho and Sala-Garrido, 2008). In our case study of COD_{Mn} in Tangxun Lake Basin, their marginal cost functions can be expressed as (U.S. Environmental Protection Agency, 2004):

$$\begin{cases} C(PR_{PS}) = 59.2445 PR_{PS}^{\ -0.4337} \\ C(PS_{NPS}) = 4.6296 PS_{NPS}^{\ -0.29} \end{cases} \tag{5}$$

where C(PR_{PS}) and C(PR_{NPS}) are respective the marginal cost of COD_{Mn} treatment of point source and non-point source (10,000 yuan), PR_{PS} and PR_{NPS} are the amount of COD_{Mn} of point source and non-point source that need to be treated (t/a).

(2) Second-level Allocation

According to the report of Wuhan Environmental Protection Agency (2011) and a field survey by Yang et al. (2009), pollutant loading from point sources, particularly domestic and industrial pollutant emission, still contributes to the majority of the total loading of the Tangxun Lake. Therefore, the second level allocation aims at social fairness by controlling the proportion of *PS* loading of every loading section based on the Environmental Gini Coefficient (EGC) method, which is the extended application based on the Gini coefficient. The definition and calculation of Gini coefficient can be found in (Gini, 1912). This coefficient has been widely used to study the impacts of inequality, such as the impacts of income inequality on health (Ellison, 2002), or the impacts of income distribution on a carbon tax (Oladosu and Rose, 2007). Likewise, the EGC, which shares similar principles of Gini coefficient, has been widely used to reflect the impacts of inequality of population, GDP on pollution emission (Groves-Kirkby et al., 2009; Sun et al., 2010; Saha et al., 2018; Yu and Lu, 2018).

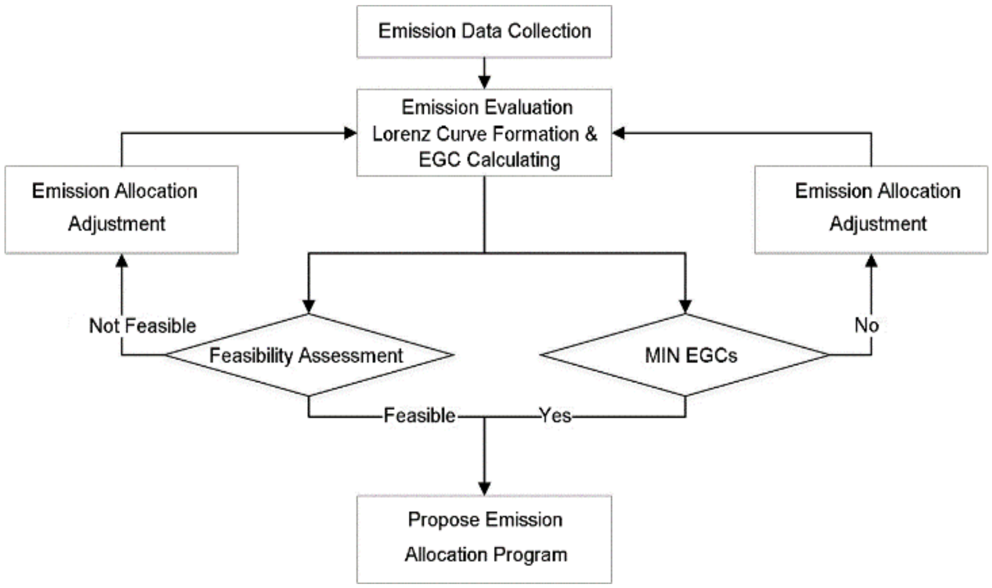

Figure 3. Flowchart of minimum EGC method.

In this study, we applied the EGC method to examine the impacts of pollution inequity on population and industry development. Firstly, the EGC value was calculated from the Lorenz curve based on population and industrial added values, respecttively, i.e., $EGC_{population}$ and EGC_{IAV}. We used the minimum EGC method to adjust the load allocation of point sources. Based on the results of first-level allocation, the reduction amount of point source was allocated to each administrative district in the Tangxun lake basin based on their areas. The schematic flowchart is shown in Figure 3.

The MIN ($EGC_{population}$) and MIN (EGC_{IAV}) refer to the conditions that once the most reasonable emission program is adapted, the distribution of emission amount is compatible with the distribution of population and industrial added value, respecttively. The target function can be defined as:

$$\begin{cases} MIN(EGC_{population}) \\ MIN(EGC_{IAV}) \end{cases} \tag{6}$$

where $EGC_{population}$ refers to the EGC calculated based on population, EGC_{IAV} refers to EGC calculated based on industrial added values.

(3) Third-level Allocation

For the goal of Third-level allocation is to maintain the water quality of inner-lake area better than level Ⅲ of the National Environmental Standard for Surface Water (Chinese Ministry of Environmental Protection, 2002), given the lake body being divided into nearshore area and inner-lake area firstly. Third-level allocation allocates the results of second-level allocation to each outlet within the emission segments based on a 2-D hydrodynamic and water quality model (Xiao et al., 2015). This model was applied for simulating the effects of emission of each outlet to the lake water body after calibration and validation. The governing equations of hydrodynamic processes are described as:

$$\begin{cases} \dfrac{\partial H}{\partial t}+\dfrac{\partial(uH)}{\partial x}+\dfrac{\partial(vH)}{\partial y}=q \\ \dfrac{\partial u}{\partial t}+u\dfrac{\partial u}{\partial x}+v\dfrac{\partial u}{\partial y}+g\dfrac{\partial z}{\partial x}-fv=\dfrac{\tau_{wx}}{\rho}-\dfrac{\tau_{bx}}{\rho} \\ \dfrac{\partial v}{\partial t}+u\dfrac{\partial v}{\partial x}+v\dfrac{\partial v}{\partial y}+g\dfrac{\partial z}{\partial y}+fu=\dfrac{\tau_{wy}}{\rho}-\dfrac{\tau_{by}}{\rho} \end{cases} \tag{7}$$

where h refers to water depth, m, q refers to inflow/outflow per square meter, positive stands for inflow and negative stands for outflow, $m^3/(s\bullet m^2)$, ρ refers to water density, $1g/cm^3$, f refers to Coriolis coefficient, $f=2\omega\sin\varphi$, where φ refers to local latitude, ω refers to rotational angular velocity of the earths (7.29 $\times 10^{-5}$ rad/s), τ_{wx} refers to x axis component of shearing stress on water surface, τ_{bx} refers to x axis component of shearing stress on water bottom.

The governing mass-balance equation for water quality indicators is expressed as

$$\frac{\partial(CH)}{\partial t}+\frac{\partial(uCH)}{\partial x}+\frac{\partial(vCH)}{\partial y}-\frac{\partial}{\partial x}\left(E_x\frac{\partial CH}{\partial x}\right)-\frac{\partial}{\partial y}\left(E_y\frac{\partial CH}{\partial y}\right)+H\sum S_i+F(C)=0 \tag{8}$$

where C refers to the concentration of pollutants, g/m^3 or mg/L, H refers to water depth, m, t refers to modeling time, hour, u, v refer to speed vectors at the direction of x, y axis, m/s, E_x, E_y refer to dispersion coefficients at the direction of x, y axis, m/s^2, S_i refers to source and sink term, $g/(m^2\bullet s)$, $F(C)$ refers to reac-

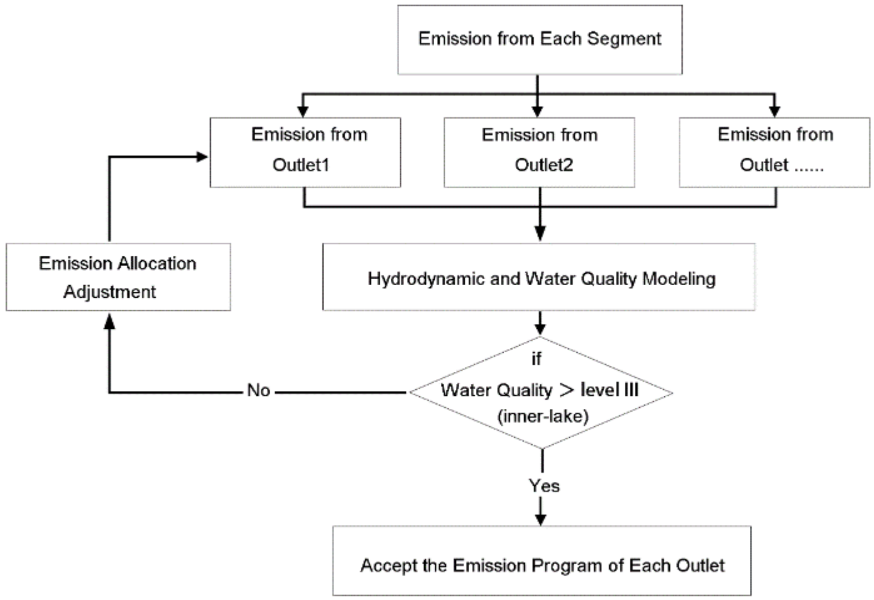

Figure 4. Optimization process of the third-level allocation.

tion term, for COD_{Mn}, $F(C) = -K_C \times C \times h$, $K_C = K_{20} \times 1.047^{T-20}$, where, K_C stands for the of COD_{Mn}, K_{20} refers to the of COD_{Mn} at the water temperature of 20℃.

For the inner lake body, the optimization process of the third-level allocation of outlets is shown in Figure 4. Given the amount of emission reduction of each segment, this level is to determine the reasonable emission reduction amount of each outlet within the segment. The COD_{Mn} concentration at the set of the optimized emission program is examined at the sampling points every four day from 1st June to 28th August (Figure 1). By comparing the results of hydrodynamic and water quality modeling to the level Ⅲ of the National Environmental Standard for Surface Water (Chinese Ministry of Environmental Protection, 2002), a necessary adjustment should be undertaken among the outlets to reach a final acceptable emission program of the outlets (Figure 4).

Table 1. Coordinates of Sampling Points at Inner-lake Region

Sampling Points	Longitude	Latitude
1	114.335	30.444
2	114.343	30.432
3	114.328	30.428
4	114.341	30.408
5	114.324	30.396
6	114.383	30.427
7	114.392	30.434
8	114.405	30.420
9	114.393	30.412
10	114.379	30.404

2.3. Sample Collection

In order to verify the hydrodynamic and water quality model, field sampling measurements were conducted in the Tangxun Lake water body. In the case study, the inner-lake water body was divided into 10 subareas firstly (Figure 1). Afterwards, the altitude and longitude of the sampling points were collected by GPS in each subarea in 2015 (Table 1). Water level and flow speed were selected as the variables for hydrodynamic calibration and validation, which were monitored monthly. COD_{Mn} were selected as the indicator of water quality index as the chemical pollutant emission contributed mostly to total pollutant loading of the Tangxun Lake water body (Wuhan Environment Protection Agency, 2011), which was investigated every two months since January, 2015.

3. Result and Discussion

3.1. Emission Reduction Program of Four Pollution Classes

Results showed that the total reduction amount of COD_{Mn} loading to the Tangxun Lake was 294.2 t/a. Four classes of pollutants divided this amount based on first-level allocation. The emission reduction of COD_{Mn} as point source was 201.1 t/a, which contributed the most of the total amount. This indicates that point source pollution, partially derives from the domestic sewage generated by the 500,000 people dwelling around the Tangxun Lake (Yang et al., 2009), still remains to be the major task for the pollution control. The emission reduction as non-point source, inner-source and tributary source were 24.1, 48.9, 20.1 t/a, respectively. Results of the proportion of each class of pollution loading as well as the emission reduction loading were shown in Table 2. Based on emission reduction program, the minimum marginal cost could be achieved based on the restraint function as:

$$PR_{PS} + PR_{NPS} = 225.18 \tag{9}$$

The marginal cost of reducing PS and NPS was 59.38 and 18.40 (1000 yuan/a), i.e., 8699.3 and 2695.2 United States Dollar/a (USD/a). Given the marginal cost of disposing the PS and NPS pollution, the first-level allocation could address the largest amount of pollution at the least price. It should be noted that the marginal costs for disposing wastewater from PS and NPS pollution largely rely on the key technologies and management of the wastewater treatment processes. In the study, we proposed a regression model to estimate the treatment costs. Further investigations on wastewater treatment plants and advances in technology and operation schemes, e.g., the usage and the arrangement of chemicals, energy and labor inputs, in the treatment processes are likely to shift the relationships between the amount of pollution loading to be treated and the costs generated during the processes (Thompson and Singleton, 1986; Dearmont et al., 1998). This might induce a lower marginal cost in disposing these industrial and domestic pollution loadings.

Table 2. Different Classes of COD_{Mn} Loading for Tangxun Lake

Class	Current COD_{Mn} Loading (t/a)	Proportion of Total Loading	Emission Reduction (t/a)	Marginal Cost (USD/a)
PS	983.76	68.35%	201.1	8699.3
NPS	117.9	8.19%	24.1	2695.2
IS	239.21	16.63%	48.9	-
TS	98.33	6.83%	20.1	-
Total	1439.2	100.00%	294.2	11394.5

3.2. Emission of Districts Based on Minimum EGC Method

Setting that the emission reduction of point source was 201.1 t/a, the goal of second-level is to allocate the emission reduction among the surrounding districts of the Tangxun Lake within the basin based on the minimum EGC method. The EGC values were calculated in terms of population and industrial added value. The results of EGC were shown in Table 3. Results show that the EGC based on population decreases from 0.29 to 0.22, while the EGC of industrial added value drops from 0.57 to 0.5 after allocation. By that level, the largest reduction amount (157.56 t/a) is set at Miaoshan Districts. Afterwards, the goals of Zhifang, Canglongdao and Daqiao District are to cut off 20.81, 13.05, 9.12 t/a, respectively. Besides, minor reduction (0.56 t/a) should be implemented at Hongshan District, while the Wulijie District deserves no adjustment. The emission reduction program of each district was shown in Figure 5. Based on the program, the reduced emission program has achieved the least EGC values.

The $EGC_{population}$ decreased for 24.14%, while EGC_{IAV} dropped for 12.28% by implementing this emission program. Nevertheless, the EGC_{IAV} is still relatively high (0.50) after allocation. This implies that the COD_{Mn} emission among the districts within the lake basin is more equally distributed by population than by industrial added value. Though previous studies have argued that the COD_{Mn} emission originated mostly from domestic sewage and industrial wastewater (Chu et al., 2009; Yang et al., 2009), our results indicate that industrial wastewater, rather than domestic sewage, has greater impacts on the inequality of pollution emission within the lake basin. This can be explained by the fact that the COD_{Mn} emission of Gaoxin High-tech districts accounts more than 95% of the total COD_{Mn} emission in the Tangxun Lake Basin. This inequality of emission in the Tangxun Lake Basin could lead to large EGC value, which deserves more adjustment in pollution control and regional development strategy. The results also indicate that the impacts of inequality of population on COD_{Mn} emission are more likely to be relieved than that of industrial development in the Tangxun Lake Basin, if the emission allocation program based on minimum EGC method were to be implemented. Similar results were also reported in a case study on the wastewater discharge permit allocation in Tianjin City, the third largest city in China, which suffers from large amount of pollution emission and the deterioration of water quality problems (Sun et al., 2010). These studies claimed the need for further campaigns on urban pollution emission control, particularly in the respects of industrial wastewater, either on the urban lake basin scale or metropolitan scale.

Table 3. EGC Results Based on Population and Industrial Added Value

Scenario	$EGC_{population}$	EGC_{IAV}
Before Allocation	0.29	0.57
After Allocation	0.22	0.50
Change Rate	24.14%	12.28%

3.3. Allocation of Outlets to Meet Water Quality Goals

Based on the TPLA method, the annual reduction amount of COD_{Mn} emission of each outlet was optimized to meet the water quality goal. Results showed that among the 26 sewage outlets investigated in the Tangxun Lake Basin, those 24 of them should be adjusted. The largest pollution emission reduction amount (142.21 t/a) was found at the Bee Jiaotou Plant outlet at Miaoshan District. Two outlets with second largest reduction amount of 10.41 t/a respectively were located at Zhifang District. Ten of the 26 outlets should cut their emissions by 1 to 10 t/a. Half of the outlets should reduce their emission under 1 t/a. The emission reduction program of each outlet was shown in Figure 5.

To validate the effects of this program, modelling results of COD_{Mn} concentration at the sampling points in the inner-lake region were tested. Results show that despite of the high values of COD_{Mn} concentration in part of the outlets, the peak value of the COD_{Mn} concentrations lies down under 6 mg/L, i.e., grade Ⅲ in the national water quality standard (Chinese Ministry of Environmental Protection, 2002), in the modeling period (Figure 6). This indicates that the water quality of the Tangxun Lake could meet the grade Ⅲ in terms of COD_{Mn} after the implementation of the emission allocation among the sewage outlets.

It should be noted that a couple of recent studies showed that the Tangxun Lake is experiencing a significant shrinking trend. The water surface area of Tangxun Lake shrinks more than 10% since the 1990s, reported by Yang and Ke (2015). Therefore, the environmental capacity of the lake may become

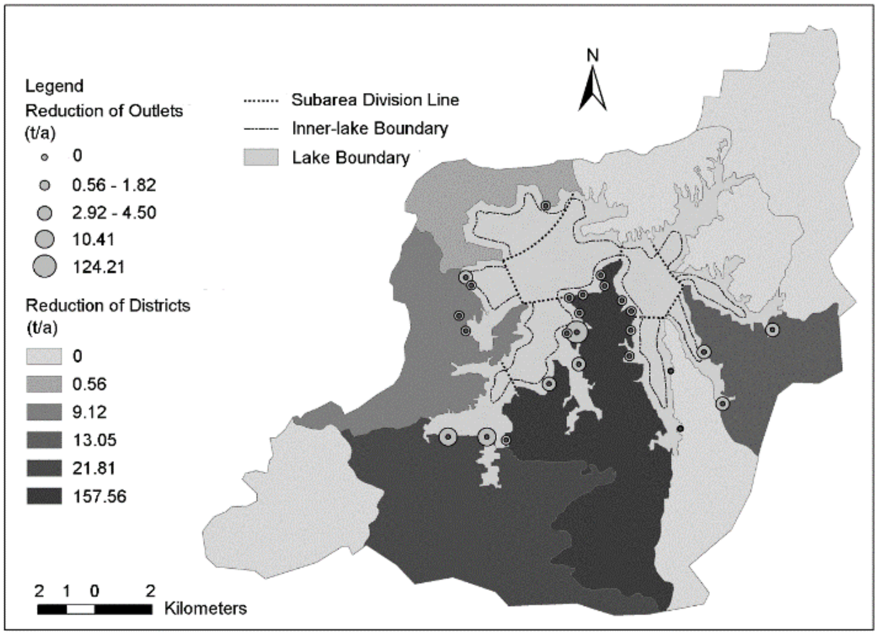

Figure 5. Emission reduction program of outlets and districts within the Tangxun Lake Basin.

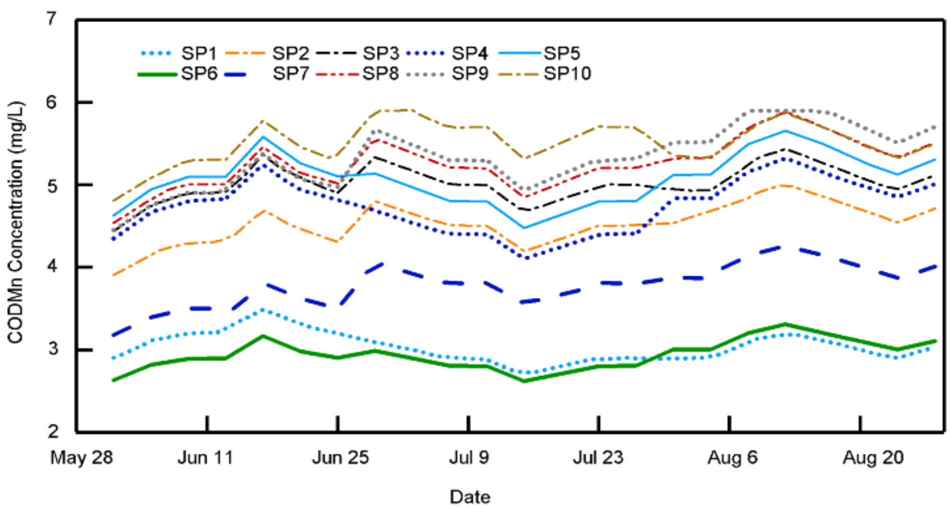

Figure 6. Modeling results of COD_{Mn} concentration of ten sampling points in the inner-lake region of the Tangxun Lake.

smaller and the lake ecosystem more vulnerable to the pollutants emitted into the lake body during the processes of fast urbanization. Consequently, the emission reduction among various sources, districts and outlets should be adjusted accordingly. In this respect, a dynamic pollution loading allocation strategy is urgently needed in future studies, considering the evolution of the lake and the land within the basin.

4. Conclusions

With the rapid population growth and economic development, pollutants from urban and agricultural lands in the nearshore of inland lake basin have become major stressor of this ecosystem. And the water quality deterioration has become one of the most threatening restraints that hindered the social and economic development within the lake basin. This drives the need to derive a cost-efficient solution for pollution loading control. However, the implementation of plan and the achievement of water quality goals of lake basin are still problematic, due to the difficulty in balancing the efficiency and fairness among various regions. In this study, a Tri-level Pollutant Loading Allocation (TPLA) model was estimated and integrated for inland lake basins management that could achieve three main goals, i.e., minimizing the economic costs, maintaining the social fairness and meeting the water quality goals of the lake water body. TPLA was applied to a typical inland lake basin, i.e., Tangxun

Lake Basin in the city of Wuhan, China. The TPLA method provides an optimal approach for waste-load allocation of lake basins, which is easy to implement and flexible to adjust for decision makers and stakeholders managing water resources in inland lake basins.

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