RESEARCH ARTICLE

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Study of ecological compensation in complex river networks based on a mathematical model

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Abstract

Transboundary water pollution has resulted in increasing conflicts between upstream and downstream administrative districts. Ecological compensation is an efficient means of restricting pollutant discharge and achieving sustainable utilization of water resources. The tri-provincial region of Taihu Basin is a typical river networks area. Pollutant flux across provincial boundaries in the Taihu Basin is hard to determine due to complex hydrologic and hydrodynamic conditions. In this study, ecological compensation estimation for the tri-provincial area based on a mathematical model is investigated for better environmental management. River discharge and water quality are predicted with the one-dimensional mathematical model and validated with field measurements. Different ecological compensation criteria are identified considering the notable regional discrepancy in sewage treatment costs. Finally, the total compensation payment is estimated. Our study indicates that Shanghai should be the receiver of payment from both Jiangsu and Zhenjiang in 2013, with 305 million and 300 million CNY, respectively. Zhejiang also contributes more pollutants to Jiangsu, and the compensation to Jiangsu is estimated as 9.3 million CNY. The proposed ecological compensation method provides an efficient way for solving the transboundary conflicts in a complex river networks area and is instructive for future policy-making.

Keywords Water pollution · Ecological compensation · Taihu Basin · River networks

Introduction

Administrative diversion brings split jurisdictions, resulting in an imbalance in regional development and management (Nikolaou et al. 2008; Zhuang 2016). The lack of cooperation for environmental management in different administrative regions creates ongoing competition and conflicts between the

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upstream and downstream with an emphasis in water resources (Zhao 2009; Qin et al. 2010). Taihu Basin, one of the largest basins in China, is currently faced with unclear and inefficient strategies in water resource management. Rapid economic development has led to severe deterioration of regional water quality. Water contamination is not limited to the local area; transportation of pollutants to neighboring administrative regions is noted (Wang et al. 2006; Shi et al. 2016). Transboundary water pollution events and corresponding conflicts occur frequently, particularly in the transboundary area of the Taihu Basin (Zhao et al. 2012; Wang et al. 2016). The Central Ministry of China has reported 12 large-scale transboundary pollution conflicts in the Taihu Basin, since the 1990s. In June 2005 (Jiang et al. 2006), the drinking water source area for Xinteng Town in Zhejiang province, a transboundary river segment of 6 km, was severely polluted by the industry wastes excessively discharged from the upstream reach of Jiangsu province. This transboundary pollution directly forced 30,000 residents in Xinteng Town to resort to drinking bottled water. The drinking water safety of approximately 800,000 residents in nearby Jiaxing City of Zhejiang province was also threatened. This pollution incident

ultimately led to a serious dispute between Zhejiang and Jiangsu provinces.

The concept of ecological compensation was motivated by transboundary pollution problems as well as the sustainability of water resources at the transboundary areas. It is an example of trade-off whereby loss of natural values is remedied or offset by a corresponding compensatory action. One-to-one commercial compensation between upstream and downstream could target pollutant discharge restriction and facilitate regional cooperation on water resource management between the upstream and downstream areas (Davies and Mazumder 2003; Zheng and Zhang 2010; Wang et al. 2017a, b). Ecological compensation has been proposed, and successfully applied, in many countries (Luo et al. 2011; Yin et al. 2017). Examples include the clean water transaction between New York City and its upstream area (Perrotmaître and Davis 2004) and the Dutch compensation principles for spatially protected areas (Cuperus et al. 2001). In China, ecological compensation was first introduced in 2008 through a major amendment to the Law of the People's Republic of China on the Prevention and Control of Water Pollution (Standing Committee of the National People's Congress 2008). This amendment was immediately applied in pilot research projects of the Taihu Basin for environmental management and protection (Zhang et al. 2007; Li et al. 2014; Su and Shang 2010; Lin and Li 2016). The People's Government of Jiangsu Province also announced the Environmental Water Resources Compensation Measurement for Taihu Basin in 2008 (Environmental Protection Department of Jiangsu Province 2008), in which the compensation calculation based on excessive pollutant flux was proposed. For the multi-districts of north Jiangsu province, Xie et al. (2013) estimated the criteria for excessive discharged chemical oxygen demand (COD) at 2000 CNY per ton and ammonia nitrogen (NH_3-N) and total phosphorus (TP) at 8000 and 80,000 CNY, respectively. However, this basic compensation method is still a long way from successful implementation, particularly for the river networks area of East China. This is primarily due to a lack of clarity in the estimation of regional transboundary flux due to complex hydrologic and hydrodynamic conditions. A good number of inter-provincial rivers intersect each other or converge. Tidal influence from the East China Sea as well as dry/wet seasonal patterns results in great variation of river flow and surface water levels. As a result, pollutant transport mechanisms across the boundaries show strong temporal and spatial variation. Flux estimation solely based on limited field measurements for a river networks area cannot precisely reflect the transboundary pollutant flux (Hao et al. 2012).

Mathematical modeling is an important tool for environmental management and decision making. Doulgeris et al. (2012) applied a one-dimensional model to investigate an ecosystem approach to the Strymonas River catchment with two different water-level management scenarios. Chau and Jiang

(2003) used a three-dimensional model to estimate pollutant transportation between Guangdong Province and Hong Kong. Limited field measurements along the tri-provincial boundaries cannot cover all the transboundary rivers and spatiotemporal pollutant flux across the boundaries cannot be accurately represented. A well-validated model based on available water sampling data is capable to simulate the variation of discharge and water quality in a high frequency, then effectively capture the transboundary flux. Considering the simplicity and density of rivers, a one-dimensional model is accurate and efficient enough in calculation for the study area. Hence, in this study, an ecological compensation calculation method based on a one-dimensional model is proposed for the river networks in the tri-provincial area of the Taihu Basin, China. The overall objective is to estimate the compensation payment between the three provinces for better water resource management. Specifically, the research focused on the following objectives: (1) validate the one-dimensional river networks model established for the study area; (2) calculate regional transboundary pollutant flux with the one-dimensional model; and (3) identify compensation criteria for different regions and finally estimate the total ecological compensation payment.

Materials and methods

Study area

The Taihu Basin is located on the southern coast of the Yangtze Delta between 30.06 N to 31.59 N and 119.04 E to 121.57 E (Fig. 1). According to administrative delineation, the Taihu Basin contains almost 400 km provincial boundary line which mainly composed of three parts: Jiangsu-Zhejiang boundary (137 km), Jiangsu-Shanghai boundary (115 km), and Zhejiang-Shanghai boundary (81 km). The tri-provincial area of the Taihu Basin contains the highest river density in China (approximately 3.5 km/km^2) and is the most typical river networks area. This area includes the major inter-provincial rivers such as the Grand Canal, the Taipu River, and the Wusong River (Fig. 1). These rivers flow across multiple districts and are administered by different departments. Billions of tons of water are transported across provincial boundaries through these rivers each day. Flow directions for these rivers vary notably because of the tidal influence and dry/wet season alternation.

This tri-provincial area, benefiting from advantageous geographic factors, has become the core economic region of East China and is experiencing rapid urbanization and industrialization. While the area has enjoyed continuous, dramatic economic growth since the 1980s, transboundary water pollution has, over time, become a serious problem. Environmental management of this study area has attracted increasing attention of both the basin agency and regional management.
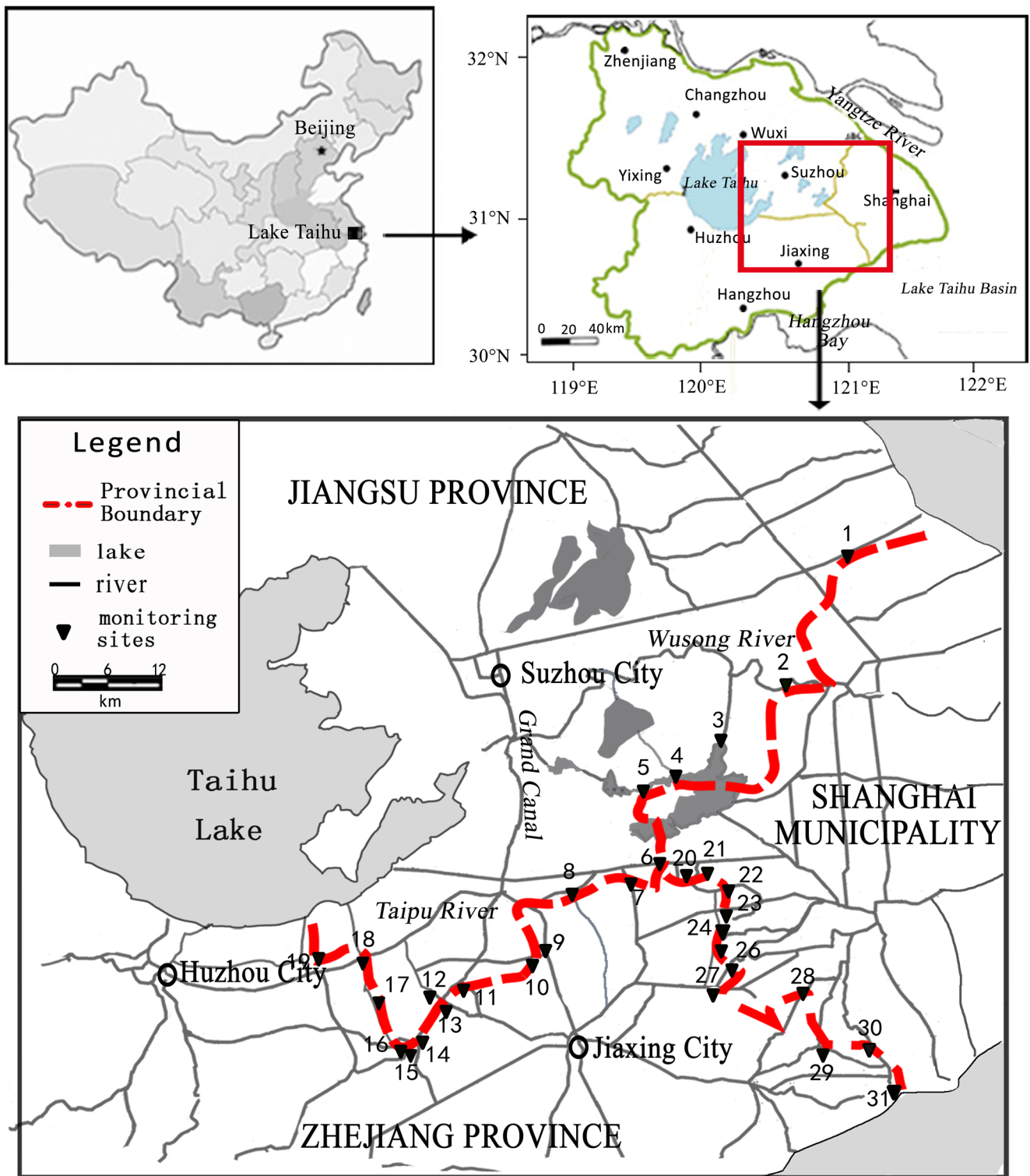
Fig. 1 River networks and measurement sites in the tri-provincial area of the Taihu Basin

Dataset

Taihu Basin Authority (TBA) of the Ministry of Water Resources has located 31 important transboundary cross sections in the study area, covering all major transboundary rivers

(Fig. 1). Five sites (no. 1 to no. 5) are at the Jiangsu-Shanghai boundary; site 6 is exactly at the tripoint; 13 sites (no. 7 to no. 19) are located at Jiangsu-Zhejiang boundary; and 12 sites (no. 20 to no. 31) are found along the Zhejiang-Shanghai boundary (Fig. 1). Field measurements for water quality and

hydrology conditions were carried out at these sites regularly. In the "Twelve-five" Comprehensive Research Program of Emission Reduction conducted by the government in the Taihu Basin (People's Government of Jiangsu 2012), COD and NH$_3$-N are listed as two key indicators for water quality evaluation. In our study area, harmful algal blooms are frequently recorded, along with increasing nitrogen and phosphorus loading for the past few years (Zhang et al. 2007). As a result, TP is listed as another water quality indicator. Hydrodynamic and water quality data at these 31 transboundary sites in 2013 were collected for this study to explore the temporal and spatial variation of pollutant flux between the different administrative regions.

The transboundary ecological compensation study includes three sections and data usage for each section is presented in Table 1. The regular monitoring data at all the main rivers are from 65 local hydrological and water quality stations managed by environmental monitoring centers. Field measurements in 2013 were also carried out monthly at all of the 31 transboundary cross sections. Meanwhile, pollutant sources including sewage treatment plants are obtained from the annual census data conducted by provincial environmental monitoring centers and the regional bureau of statistics. Water quality and hydrodynamic measurements along the transboundary are summarized in Fig. S1–S2.

One-dimensional river networks model

Given the complexity and uncertainty of pollutant transportation in the intertwined river networks area, MIKE 11 (DHI 2009), which has been successfully applied for the management of river networks (Wang et al. 2016; Hu et al. 2017), is used here to predict hydrodynamic and water quality conditions with high spatial and temporal resolution. The model (MIKE 11) for our study generally includes a hydrodynamic (HD) module and an advection-dispersion (AD) module (Havnø et al. 1995). The HD module adopts the Abbott-Ionescu 6 implicit finite difference scheme to solve the Saint-Venant equations. The AD module is implemented based on the HD module. A one-dimensional AD equation is adopted to simulate the water quality variation along the river:

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} = \frac{\partial}{\partial x}\left(E_x\frac{\partial C}{\partial x}\right) - K \tag{1}$$

where C represents the concentration (mg/L), u is the mean velocity along the river (m/s), and Ex and K denote the convective diffusion coefficient (m^2/s) and the first-order decay coefficient (mgL^{-1} s^{-1}), respectively.

The one-dimensional model has been successfully applied to investigate the regional emission control in the Taihu Basin (Wang et al. 2016). In this study, the one-dimensional model covers 198 river branches of the research area with a length from 0.2 to 2.0 km. Dimension for each segment is obtained from TBA and is implemented into the model as geometry data. The model consists of 958 points in total (Fig. S3) where surface elevation and water quality (e.g., COD and NH$_3$-N) parameters are predicted. Model time step is set as 120 s to consider the model stability and calculation efficiency. Measured river discharge and surface elevation at the boundary node are used as the boundary conditions. Point sources including sewage treatment plants and industry sources are added at the nearest node point as external nutrient loading.

Table 1 Details of data sources for the study area

Data usage	Time	Data type		Data sources
Mathematical simulation of pollutant transportation	2013	Hydrology	Water elevation (m) discharge (m^3/s)	Monitored daily at 65 hydrological stations located within the whole tri-provincial area
	2013	Water quality	COD, NH$_3$-N, TP (mg/L)	Monitored monthly at 65 water quality stations located within the whole tri-provincial area
	2013	Point sources	COD, NH$_3$-N, TP (t/a)	Annual census of pollutant discharge including 2151 industry sources, 193 sewage treatment plants, and 1070 centralized animal farms
	2013	Nonpoint sources	COD, NH$_3$-N, TP (t/a)	Annual census: pollutant discharge by urban people, rural people, farmland, and animal farms
Transboundary pollutant flux calculation	2013	Hydrology	Discharge (m^3/s)	Monthly field measurements at 31 important transboundary cross sections
	2013	Water quality	COD, NH$_3$-N, TP (mg/L)	Monthly field measurements at 31 important transboundary cross sections
Eco-compensation criterion and payment calculation	2013	Treatment capacity	COD, NH$_3$-N, TP (t/a)	Annual census of 193 sewage treatment plants in the research area
	2013	Operation costs	CNY	Annual census of 193 sewage treatment plants in the research area

Nonpoint sources such as rural and farming sewage are added along the rivers evenly. The model is calibrated throughout the year 2011 due to limited data sources and model validation is conducted with comparison between field measurement and model simulation in August 2014. Calibration and validation results including relative error (RE) and root mean square error (RMSE) are presented in Figs. 2 and 3. The one-dimensional model accurately reproduced the water elevations in both calibration and validation scenarios, with small RE values. Water quality simulation results including COD, NH₃-N, and TP agree well with the field measurements as well, with an average RE of 30% for calibration and 18% for validation. The bottom roughness of the river networks in study area is calibrated in a range of 0.023–0.032 while degradation coefficients for COD, NH₃-N, and TP are in a range of 0.09–0.15, 0.07–0.13, and 0.04–0.10 d^{-1}, respectively, all of which agree well with previous estimations in the study area (Han 2008; Wang et al. 2014).

Transboundary flux estimation

Pollutant flux is calculated as a product of model-predicted concentration and river discharge (Eq. 2).

$$W = \sum CQ \tag{2}$$

where W is the pollutant flux (g/s), C is the concentration (g/m^3), and Q is discharge (m^3/s). Specifically, the total transboundary flux between two adjacent districts is calculated using equations:

$$W = \sum_{k=1}^{p} \sum_{j=1}^{m} \sum_{i=1}^{n} C_{ijk} Q_{ijk} \tag{3}$$

$$W_e = \sum_{k=1}^{p} \sum_{j=1}^{m} \sum_{i=1}^{n} \left(C_{ijk} - C_{js} \right) Q_{ijk} \tag{4}$$

where W_e is the excessive flux and i, j, and k are the indices of total time steps (n) between two field measurements, total transboundary rivers (m), and total number of field measurements (p), respectively. C_{ijk} and Q_{ijk} are model-predicted concentration and discharge; C_{js} is the target water quality.

Ecological compensation criteria and payment calculation

The local ecological compensation criterion for different pollutant is set as the treatment cost in the sewage wastewater treatment plant, following the study of Xie et al. (2013), in north Jiangsu province, China. Meanwhile, treatment capacities and prices for the sewage treatment plants in the study area are easy to collect. To account for the variation of regional sewage treatment prices on different types of pollutant, the derivative equal standard method (Zhong and Zhang 2005) is applied here to estimate the compensation criteria. It compares the treatment cost of one specific type of pollutant with other pollutants based on their individual discharge standard regulated by the government. This is a comparably

Fig. 2 Model calibration for water elevation, COD, NH3-N, and TP (year 2011) at Grand Canal and Wusong River
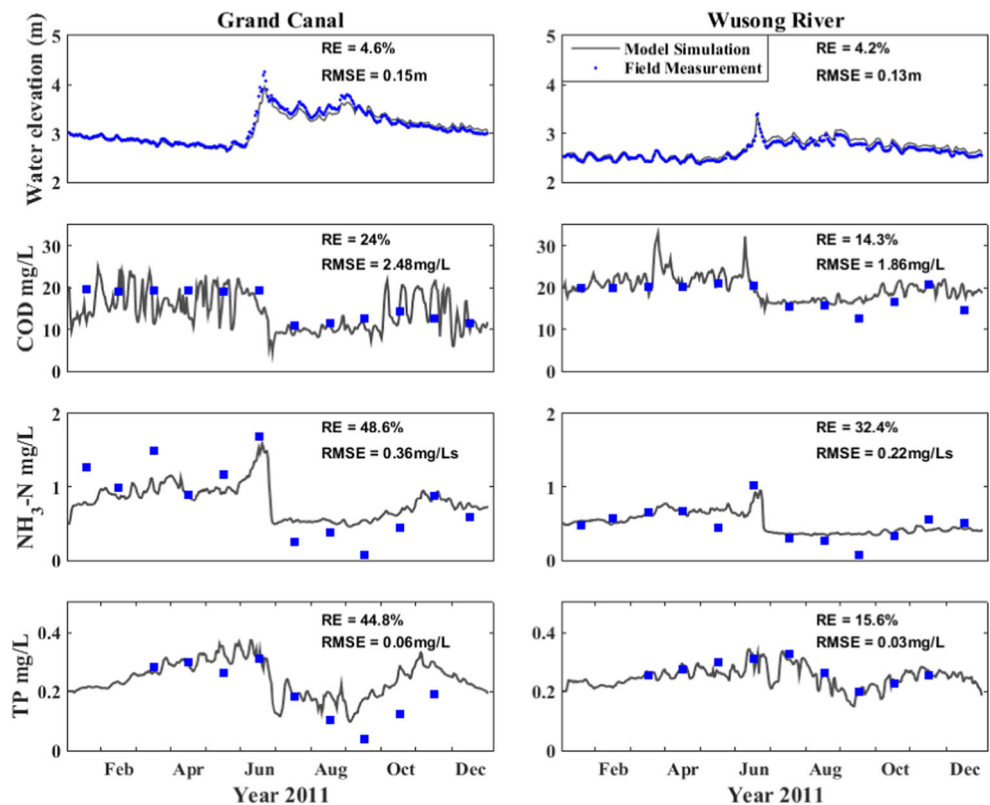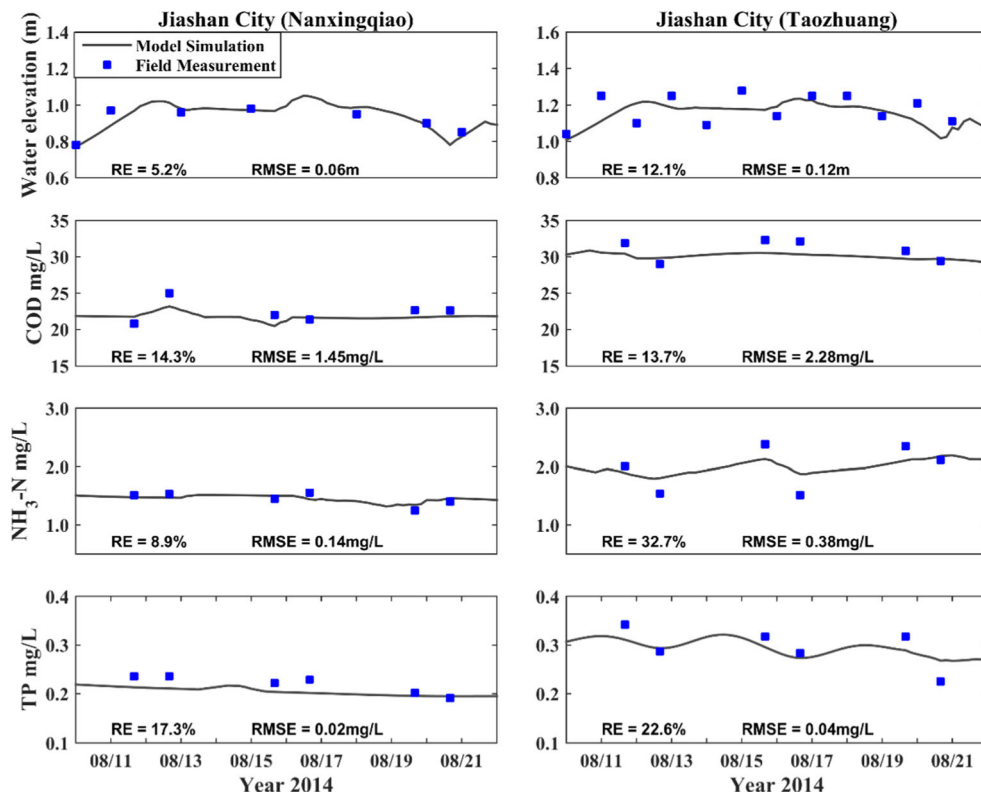
Fig. 3 Model validation for water elevation, COD, NH3-N, and TP (08/10/2014–08/22/2014) at Nanxinqiao, Jiashan City, and Taozhuang, Jiashan City

comprehensive method to consider both sewage treatment capacity and the proportions of different contaminants.

$$K_j = \sum_{i=1}^{a} k_{ij} \tag{5}$$

$$k_{ij} = \frac{m_i}{\sum_{i=1}^{a} m_i} \cdot \frac{S_i \cdot \gamma_{ij}}{w_{ij}} \tag{6}$$

$$\gamma_{ij} = \frac{\Delta c_{ij}/c_{sj}}{\sum_{j=1}^{b} \Delta c_{ij}/c_{sj}} \tag{7}$$

where i and j are the indices of total sewage treatment plants (a) and total types of pollutant (b); K_j is the compensation criteria of pollutant j; k_{ij} is the compensation criterion of pollutant j in sewage treatment plant i; m_i is the sewage treatment capacity; S_i is the total operation cost; w_{ij} is the total weight of pollutant j in sewage treatment plant i; γ_{ij} is the proportion of the equal standard pollutant load; Δc_{ij} is the concentration difference between efflux and criteria; and c_{sj} is the concentration criteria from Discharge Standard of Pollutant for a Municipal Wastewater Treatment Plant in China.

Total compensation payments are then estimated as a product of pollutant flux and compensation criteria for this area. Ecological compensation in the Taihu Basin could be determined as follows:

$$M = \sum_{j=1}^{b} W_{ej} K_j \tag{8}$$

where M is the eco-compensation payment between two administrative regions and W_{ej} is the regional excessive flux of pollutant j.

Results and discussion

Regional transboundary flux calculation

There are 12 county-level administrative districts identified along the provincial boundaries (Fig. 4). Among them, districts TC, KS, and WJ are situated in Jiangsu province; districts HZ, TX, JX, and JS are in Zhejiang province; and districts JD, QP, JS, and JinS are in Shanghai Municipality. To ensure the flux accuracy and account for the variation of treatment cost in different administrative regions, the segmental transboundary pollutant flux (e.g., flux between TC and JD) was calculated separately. Thus, the Jiangsu-Shanghai, Jiangsu-Zhejiang, and Zhejiang-Shanghai boundaries were divided into three segments (segments 1 to 3), four segments (segments 4 to 7), and three segments (segments 8 to 10), respectively (Fig. 4).

The monthly averaged flux ratio between field measurements and model simulations for the total 10 boundary segments was calculated and comparison results for 2013 are illustrated in Fig. 5. A ratio close to 1.0 suggests a good match and model predictions are supposed to be satisfactory for

Fig. 4 Distribution of administrative regions along the boundaries
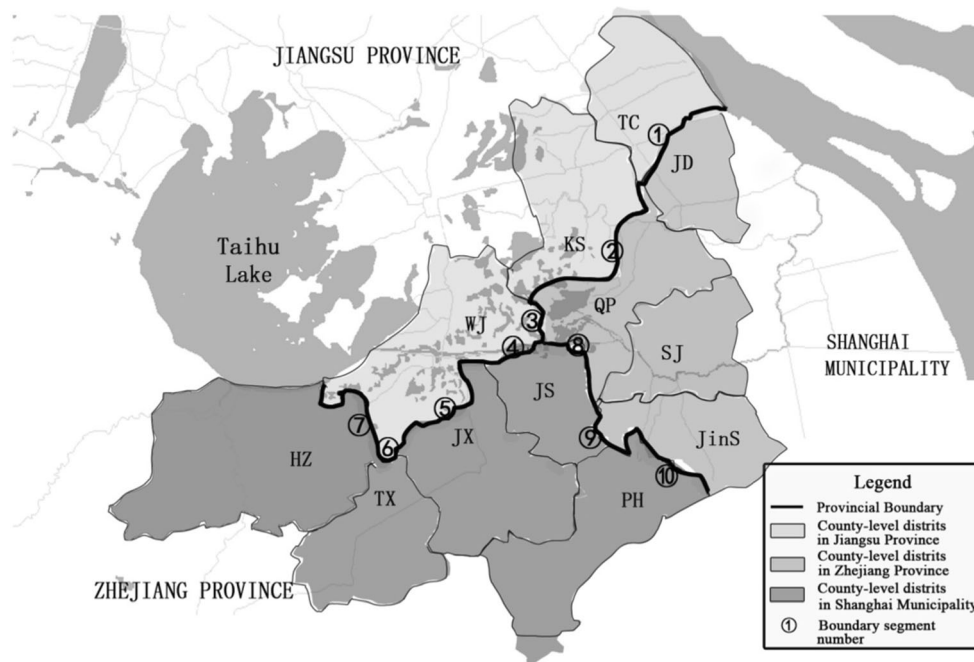
further ecological compensation. Our results indicate the one-dimensional river networks model can well predict the hydrodynamic and water quality condition in the study area, considering that the calculated annual average coefficients for the 10 segments distribute in a narrow range of 0.86–1.44 for

COD, 0.92–1.33 for NH$_3$-N, and 0.83–1.29 for TP. Spatial variation in model performance, however, still exists. At the Jiangsu-Shanghai and Zhejiang-Shanghai boundaries, flux ratios are overall in a narrow range with an average value close to 1.0, indicating a fair match between model simulation and

Fig. 5 Monthly averaged ratios between measured flux and predicted flux along the regional boundary. Boxplots represent temporal variations
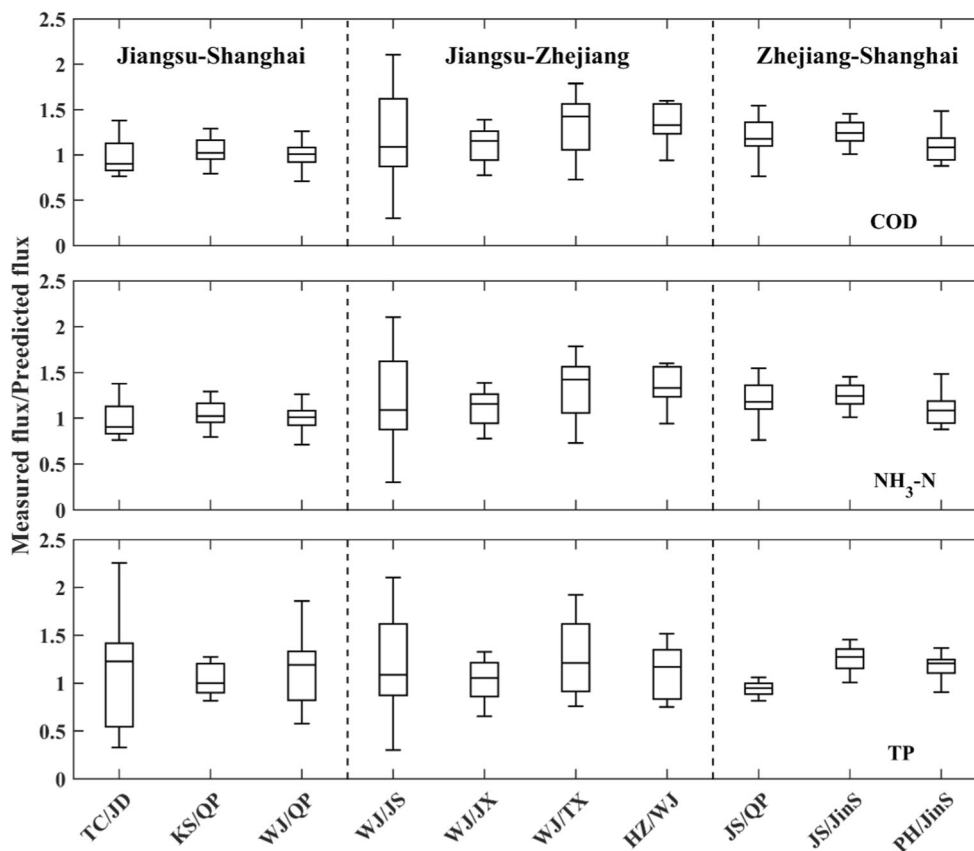
field measurements. Larger bias for all three indicators is observed at the Jiangsu-Zhejiang boundary, especially at segments 4 (WJ/JS) and 6 (WJ/TX). It should be noted that bathymetry elevation difference for these two provinces is little and flow direction is much more variable under tidal influence (Fig. S2). Additionally, the river discharges along the Jiangsu-Zhejiang boundary are comparably small. Both of these factors make it challenging for model prediction.

Annual total pollutant flux between different administrative districts at the transboundary area in 2013 was then determined based on the calculated correction coefficients. According to the Taihu Lake Basin Water Environmental Function Zoning promulgated by the State Council of China, water quality at provincial boundaries is required to reach grade III or better. Target water quality at transboundary rivers with excessive pollutant flux is set as 20 mg/L for COD, 1 mg/L for NH$_3$-N, and 0.2 mg/L for TP. These targets are set by the Environmental Quality Standard for Surface Water drafted by the Ministry of Environmental Protection of the People's Republic of China. Excessive transboundary flux in 2013 was calculated with Eq. 4 and detailed results are displayed in Fig. 6.

According to the calculation results, excessive transboundary pollutant flux between different segments varied significantly in 2013 with COD ranging from 2761 to 19,113 tons. NH$_3$-N varied from 140 to 1718 tons, and TP varied from 28 to 392 tons. Large amounts of excessive flux are clearly noted at the Jiangsu-Shanghai and Zhejiang-Shanghai boundaries because the river flow during most of the year is toward the Shanghai Municipality. Zhejiang is the main contributor to transboundary pollution toward Shanghai with 34,679 tons COD, 2992 tons NH$_3$-N, and 576 tons TP. The flux of excessive pollutant from Jiangsu to Shanghai is

also significant, with 45,079 tons of COD, 3073 tons of NH$_3$-N, and 575 tons of TP. The total flux across these two boundaries accounted for 91.37, 92.3, and 89.7% of the total COD, NH$_3$-N, and TP flux in this area. In contrast to the above two boundaries, bathymetry elevation between Jiangsu and Zhejiang does not differ too much, and the net flux at the Jiangsu-Zhejiang boundary is comparably small because of the opposite major transportation direction in the western (segments 6 and 7) and eastern (segments 4 and 5) sections of the boundary. This implies that Jiangsu and Zhejiang are equally accountable for the transboundary pollution occurring at their boundary.

Ecological compensation criteria and payment

The ecological compensation criteria are very different when the variable local proportion of treated pollutant composition and sewage treatment costs are considered. Sewage distribution and operating capacities in our study area are presented in Fig. 7 (left). Applying Eqs. 5 to 7, the criteria in each administrative area were calculated at county-level scale.

Clear spatial differences for the estimated criteria are noted in the study area (Fig. 7 (right)). The average compensation criterion in Shanghai is in a comparably lower value with 1047 CNY for COD, 9189 CNY for NH$_3$-N, and 92,083 CNY for TP, whereas Zhejiang had the highest criteria among the three provinces with 1698 CNY for COD, 16,153 CNY for NH$_3$-N, and 158,987 CNY TP.

With the revised regional compensation criterion and excessive pollutant flux calculations, payment among Jiangsu province, Zhejiang province, and Shanghai Municipality could be estimated. Calculated compensation payment for all the segments is summarized in Table 2.

Fig. 6 Annual regional excessive pollutant flux along the boundary (t/a)
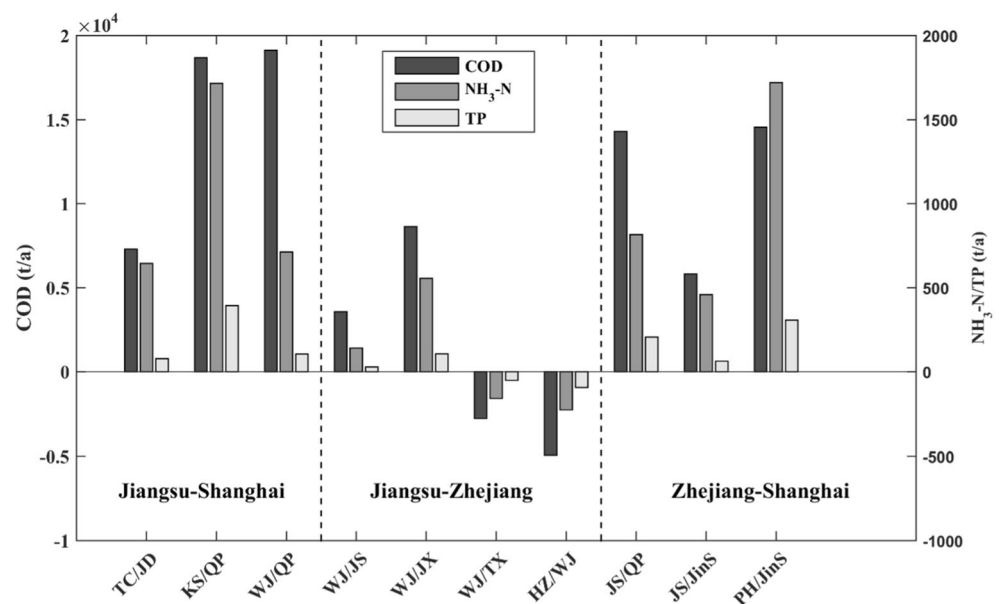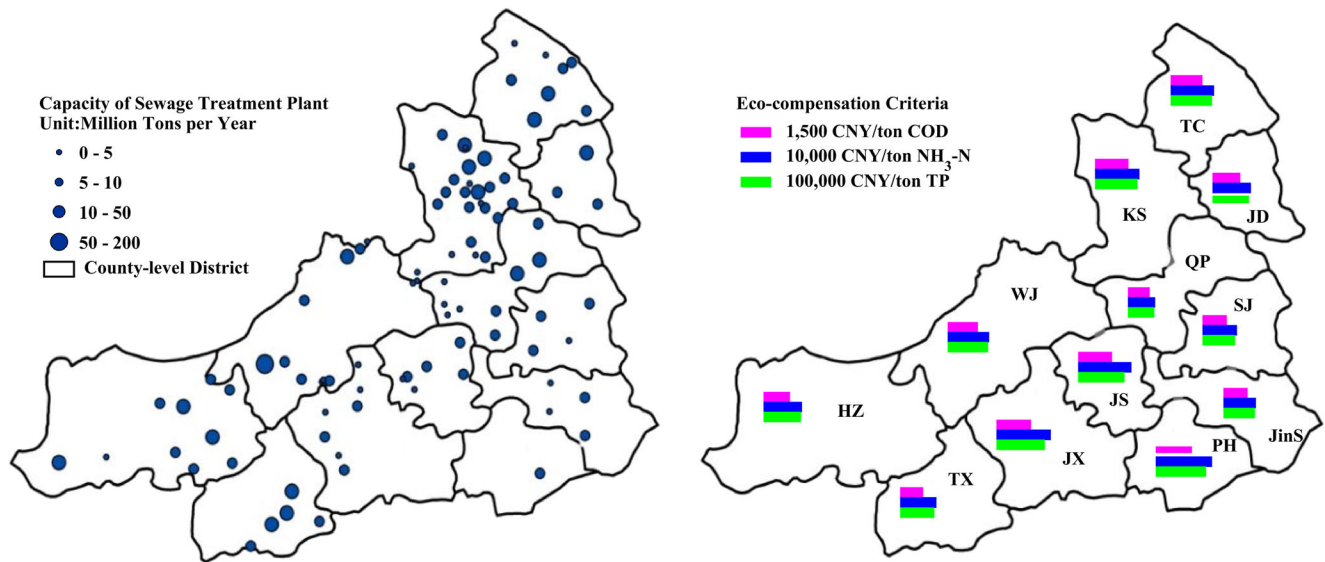
Fig. 7 Distribution and capacity of sewage (left) and criteria distribution in county level (right)

Similar to the excessive flux results, compensation payment for Jiangsu and Zhejiang is extremely high, reaching over 300 million CNY because a large amount of local pollutant is transported to Shanghai. COD compensation is comparably higher and accounted for 43 and 48% of total payment for Jiangsu and Zhejiang, respectively. This indicates that potential pollutant control of COD in the Taihu Basin might be preferable. Our results also suggest that QP county in Shanghai received the majority of the pollutant from the other two provinces. At the Jiangsu-Shanghai boundary, payment for QP could be up to 94% of the total payment. Thus, continuous water quality monitoring and water remediation in the QP area would be efficient for future environmental protection and management.

The calculated compensation is considered reasonable as the total payments represented less than 3% of local GDP, which is an appropriate proportion to be spent on environmental issues (Xie et al. 2013). The payment is affordable and sufficient to stimulate improvements in water environmental conservation.

Conclusion

The explosive pollutant load of inter-provincial rivers in the Taihu Basin is due to continuous excessive discharge from upstream administrative districts with a strong need of economic development. An ecological compensation method

Table 2 Estimation of compensation at boundary segments in 2013

Provincial boundary	Segment	Compensation payer	Compensation acceptor	Relevant eco-compensation payment (million CNY)			
				COD	NH$_3$	TP	Sum
Jiangsu-Shanghai boundary	1	Jiangsu	Shanghai	7.8	5.7	4.1	17.6
	2	Jiangsu	Shanghai	69.5	43.7	67.4	180.6
	3	Jiangsu	Shanghai	57.7	20.1	29.3	107.1
	Sum	Jiangsu	Shanghai	135.0	69.5	100.8	305.3
Jiangsu-Zhejiang boundary	4	Jiangsu	Zhejiang	7.5	2.2	2.5	12.2
	5	Jiangsu	Zhejiang	15.6	7.5	63.2	86.3
	6	Zhejiang	Jiangsu	8.6	7.3	28.0	43.9
	7	Zhejiang	Jiangsu	15.1	7.2	41.6	63.9
	Sum	Zhejiang	Jiangsu	0.6	4.8	3.9	9.3
Zhejiang-Shanghai boundary	8	Zhejiang	Shanghai	62.2	25.0	61.9	149.1
	9	Zhejiang	Shanghai	32.6	29.1	4.4	66.1
	10	Zhejiang	Shanghai	45.0	32.6	7.7	85.3
	Sum	Zhejiang	Shanghai	139.8	86.7	74.0	300.5

based on one-dimensional model was developed with the purpose of designing future effective environmental management for this tri-province area. The one-dimensional model was set up for the year 2013 and intensively "sampled" data (e.g., discharge, water quality) at the river networks area were predicted with this model. Simulated pollutant flux at the transboundary sections matches well with the field measurement, especially for the Zhejiang-Shanghai and Jiangsu-Shanghai boundaries. Regional flux ratios are close to 1.0, except for the Jiangsu-Zhejiang boundary where river flow direction is variable and river discharge is comparably small. Model results indicate that Jiangsu and Zhejiang contributed much more pollutant to Shanghai, especially to the QP district. Even though tidal influence is strong, over 90% of the annual flow direction is from Jiangsu to Shanghai and Zhejiang to Shanghai. Net pollutant flux between Jiangsu and Zhejiang is small as the major flow direction is from Zhejiang to Jiangsu at the western boundary while the direction is the opposite in eastern parts.

Ecological compensation criterion is determined with full consideration of regional differences in sewage treatment prices and pollutant proportion. Results show Shanghai has the lowest compensation criterion for all three indicators due to the low local treatment prices, while Zhejiang has the highest compensation criterion. Through the proposed compensation method, it is suggested that Shanghai is the major compensation receiver in 2013, with almost 610 M CNY from Jiangsu and Zhejiang. Conventional pattern of "treatment after pollution" in China has to be avoided. For the Taihu Basin, ecological compensation is an effective approach providing both economic and environmental benefits. The proposed compensation method in this study provides an efficient way for solving the transboundary conflicts in a complex river networks area and is instructive for future policy-making.

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