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Pollution Load Coordination and Eco-Compensation for Trans-Boundary Water Pollution Control: The Case of the Tri-Border Region of the Yangtze Delta

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Abstract: A partitioned governance mode, in the absence of multilateral cooperation, always culminates in recurring instances of trans-boundary conflicts and critical degradation of water bodies in border regions. Addressing the existing gaps in quantitative trans-boundary pollution control research in extensive river network, a new approach was designed to strategically guide water pollution control initiatives throughout the entire tri-border region of the Yangtze Delta (TBYD) via the following steps: (1) Building upon an analysis of the trans-boundary river hydrodynamics, the tri-border effective coordination scope (TECS), i.e., a strategic coordination scope for coordinated pollution control, was delineated, and 13 county-level administrative districts were identified as effective contributing regions for detailed coordination. (2) Considering water quality standard (WQS) attainment in the trans-boundary cross-sections, a one-dimensional mathematical model covering the complex river network was established. Then, the load capacities for all the contributing administrative regions were determined to facilitate coordinated pollution load reduction across the TECS. (3) Leveraging from the sewage treatment costs within the TECS, a standardized eco-compensation criterion was established to guide the coordinated compensation practices across the TECS. (4) By comparing the practical pollution discharging amount, the coordinated load reduction rates and eco-compensation payments of all 13 contributing administrative districts for trans-boundary pollution control were assessed. These assessments will guide policy promulgation and provide quantitative data support for harmonizing pollution control policymaking and addressing intricate trans-boundary pollution issues in complex river networks.

Keywords: trans-boundary water pollution; load coordination; river network; ecological compensation; Yangtze Delta

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1. Introduction

Partitioned governance mode, stemming from administrative division, inevitably leads to trans-boundary conflicts in water resource management happening between adjacent countries or other administrative division regions [1–3]. Given the global prevalence of river basins, namely, that there are more than 263 trans-boundary river basins encompassing the territorial claims of over 145 nations, which equates to over 61% of the total numbers of countries or regions in the word, pervasive apprehension has emerged regarding the amplification of trans-boundary environmental challenges [4,5]. Trans-boundary pollution issues have directly aggravated the overall surface water scarcity and threaten the drinking water safety of local residents, thereby instigating a cascade of deleterious consequences impacting both basin-wide harmony and economic development. Pervasive concerns about trans-boundary pollution have consequently driven a series of relevant research over the preceding four decades [4,6].

Abundant research results indicate that management agreements and policies should not be considered separately [2,7]. Consequently, scholarly research on trans-boundary pollution control based on regional cooperation has continuously progressed over the preceding three decades. Early in the 1990s, addressing trans-boundary conflicts within the Rhine River basin, Veeren [8] explored solutions for trans-boundary pollution control by proposing an allocation method for nutrient emission reduction strategies among border regions. More recently, a series of comprehensive analyses focusing on effective trans-boundary pollution control have emerged, employing diverse measures such as pollution discharge allocation, eco-compensation, and emission permits. Li and Guo [9] developed a dynamic model for transboundary watershed pollution, incorporating emission permits and pollution reduction strategies. Jie Zhang et al. [10] introduced a coordination decision-making model designed for the development of emissions reduction schemes and compensation standards within the Taihu Basin. Nan Li et al. [11] delved into the dynamics of pollution control behavior among various actors in the Heihe River water transfer project and utilized differential game theories to formulate an incentive coordination strategy.

In the current landscape of trans-boundary pollution control, predominant research efforts focused on emission reduction or eco-compensation were based explicitly on the objects and relevant responsibilities identified. This is always the basic prerequisite of applying decision-making models, e.g., typical Stackelberg games and stochastic differential games, which were frequently used in the research outlined above [2,12]. However, there is a noticeable research gap emerging in the context of trans-boundary pollution happening broadly in the large scale of river networks. This scenario often involves numerous administrative parties and trans-boundary rivers, exemplified by the tri-border region of the Yangtze River Delta (TBYD), which encompasses more than a dozen cities and over 30 interconnected trans-boundary rivers. The large number of participators without clear responsibility identification in trans-boundary pollution conflict have presented a formidable challenge that cannot be solved by the common decision-making models used in previous research. Furthermore, the inherent intricacy for detailed pollution responsibility identification is always exacerbated by the complex transportation characteristics of pollutants in an expansive river network and cannot be adequately addressed by the conventional decision-making models utilized in prior research [13,14].

In response to the aforementioned gaps, there is an imperative need to devise a systematic framework for trans-boundary pollution control specifically targeting and addressing the widespread trans-boundary pollution in an extensive river network. The key objective is to clarify the responsibility attribution and quantify the precise responsibility, i.e., load reduction and eco-compensation, of all the potentially contributing administrative regions. In this study, the tri-border region of Yangtze Delta (TBYD), characterized by a dense river network and the escalating challenge of trans-boundary pollution conflicts, has been selected as the study area. A new methodology was developed by simulating the complex pollutants' transportation in the river network to quantify the load reduction targets and eco-compensation payment of all the potential contributing regions. This methodology ensures a clear determination of the quantitative responsibilities for load coordination and eco-compensation, incorporating a comprehensive set of innovative solutions, as outlined below:

(1) The effective coordination areas for trans-boundary pollution control were proposed and delineated from the vague scope of the tri-border area in the Yangtze Delta. This facilitates the identification of administrative regions for the precise allocation of pollution discharge responsibilities.
(2) Considering the complex hydrodynamic and densely discharged pollution in the tri-border area of Yangtze Delta, a one-dimensional (1-D) mathematical model encompassing interconnected trans-boundary rivers was built to simulate the complex pollutant transportation and variation in water quality at the trans-boundary cross sections.

(3) Taking the water quality standard (WQS) achievement status of all the key trans-boundary cross-sections into consideration, the load reduction goals of all the contributing administrative regions were determined based on load capacity calculations.
(4) An eco-compensation calculation model was established with an objective compensation standard proposed based on the practical cost in TYBY, which enables the detailed compensation payment estimation of all the contributing regions for trans-boundary pollutant discharging.

2. Materials

2.1. Research Areas

The study region lies in the hinterland of the lower Yangtze Delta and is underlain by loose composite soil layers with low varying altitude ranging from −10 to 10 m [15,16]. As a typical plain river networks area, the area features notable high river density, expanding about 3.5 km per square kilometer [17,18]. The present state of the entire river network is undeniably complex, resulting from multifaceted factors of both human and natural origin, including intricate river topography, manual water diversion practices, and tidal influences [19,20].

The Ministry of Water Resources of the People's Republic of China has designated 33 pivotal trans-boundary cross-sections as provincial-level monitoring points (in Figure 1), encompassing all important trans-boundary rivers, such as the Taipu River and the Grand Canal. These cross-sections represent substantial conduits of water transport across provincial boundaries in eastern China [21]. In accordance with the National Environmental Standard of Surface Water (NESSW) [22], all these trans-boundary cross-sections are required to meet level III water quality standards (WQS); however, the rapid pace of development and urbanization within the study area has exacerbated the deterioration of surface water quality, which consistently fails to achieve the prescribed standards. An analysis of the water quality evaluations conducted by regional authorities underscores particular concern regarding key pollutants, namely, chemical oxygen demand (COD), ammonia nitrogen (NH_3-N), and total phosphorus (TP). Figure 1 illustrates the locations and current water quality level of the trans-boundary cross-sections.

2.2. Dataset

To coordinate the pollution load in the whole tri-border region, a comprehensive investigation into the hydrodynamics, water quality, and pollution sources within the study region was diligently conducted (Table 1). The monthly measurement data, including both hydrology and the water quality encompassing 33 trans-boundary cross-sections, were collected from 2010 to 2020. This effort aimed to elucidate the temporal variations in trans-boundary pollution. The field measurements encompassed a suite of water quality parameters, including the chemical oxygen demand (COD), ammonia nitrogen (NH_3-N), and total phosphorus (TP), along with hydrological metrics, i.e., the water level and discharge rates. Subsequently, routine monitoring data of 64 checkpoints monitored by regional authorities covering the entirety of the tri-border region were collected. These data compilations were instrumental in establishing an accurate depiction of the hydrodynamic and water quality states comprising the entire region. Furthermore, based on the pollution statistical census of 2018, the data of the primary contributors to pollution load emissions, including 200 key industrial facilities, 194 wastewater treatment plants, and centralized live-poultry farms, were collected.

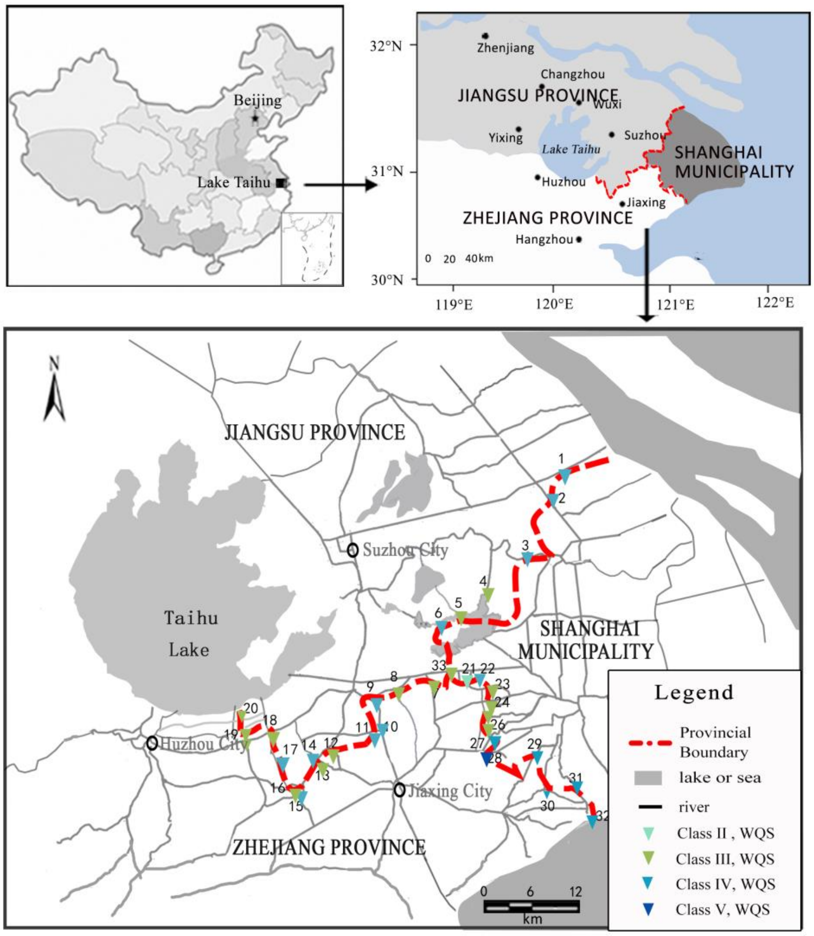

Figure 1. Distribution of locations and water quality classification results at 33 key trans-boundary cross-sections (site 1–site 33) designated by Ministry of Water Resources in tri-border area of Yangtze Delta (TBYD) in 2020.

Table 1. Dataset table collected in tri-border area of Yangtze Delta.

Data Type		Unit	Data Source
Water quality	Concentration of COD, NH_3-N, TP	mg/L	Monthly measurements at 33 boundary cross-sections
	Concentration of COD, NH_3-N, TP	mg/L	Monitoring data from 64 water quality stations
Hydrology	Water elevation, discharge	m, m^3/s	Monthly measurements at 33 boundary cross-sections
	Water elevation, discharge	m, m^3/s	Monitoring data from 64 hydrology stations
Point sources	Discharge amount of COD, NH_3-N, TP	t/n	Pollution census data of 202 sewage treatment plants
	Discharge amount of COD, NH_3-N, TP	t/n	Pollution census data of 200 key industry sources
	Discharge amount of COD, NH_3-N, TP	t/n	Pollution census data of 2070 centralized live-poultry farms
Non-point sources	Discharge amount of COD, NH_3-N, TP	kg/d	GIS analysis based on underlying distribution

3. Methodology

3.1. Tri-Border Effective Coordination Scope Delineation

Due to the vaguely defined management boundaries of TBYD, it is important to identify the tri-border effective coordination scope (TECS) for trans-boundary pollution control. Considering the inherent characteristics of the reciprocating flow in study area, attention should be paid to the bi-range of the bi-directional influence area of the trans-boundary section in the delineation work. Firstly, the effect weight model, evaluating the degree of influence of pollution sources on the water quality at the target section, could be established using a one-dimensional steady-state water quality equation, as Equations (1)–(3).

$$C_t = \exp\left(-K\frac{l}{86400v}\right)\frac{C_iQ_i + \sum m_l}{Q_i} \tag{1}$$

$$C_0 = \exp\left(-K\frac{l}{86400v}\right)\frac{C_iQ_i}{Q_i} \tag{2}$$

$$\alpha = \frac{C_t}{C_0 + C_t} \tag{3}$$

where C_t is the concentration of the trans-boundary cross-section under the influence of discharging pollution; C_0 is that without any discharging pollution effect; K is the comprehensive pollution degradation coefficient; v is the velocity of the trans-boundary river; l is the transportation distance along the river; C_i and Q_i are the inflow pollution concentration and discharge of the trans-boundary river; $\sum m_l$ is the total discharging amount covering all the pollution sources in the range of l length along the trans-boundary river; and α is the effect the weight of pollution on the water quality of the target trans-boundary section (%). Referring to previous research on effective control unit delineation in the study area [23], the empirical value of the effect weight α should be in the range of 60–70%.

The l_p and l_n, i.e., the length pertaining to positive flow and negative flow, of the trans-boundary cross-border section could be assessed, respectively, by the equations. Then, the effect ranges responding to bio-direction flow should be made as Equations (4) and (5).

$$L_p = l_p w_p \tag{4}$$

$$L_n = l_n w_n \tag{5}$$

where w_p and w_n are the frequency ratio of positive flow and negative flow (%); and L_p and L_n are the effective range of the target trans-boundary sections along different directions.

Finally, by superimposing the existing administrative boundaries and the calculated bi-directional effective ranges (L_p and L_n) for the 33 trans-boundary sections, the clear delineation of the TECS boundary is facilitated.

3.2. One-Dimensional Mathematical Model of River Network Establishment

3.2.1. One-Dimensional Mathematical Mode River Network Model Establishment

In this study, MIKE 11 model, which has been widely applied in the river network of the Yangtze Delta and has been proven to satisfy the simulation performance, was chosen to simulate the trans-boundary pollution transportation and the variation in the complex river network in the study area [19,24]. As a typical 1-dimensional mathematical model, it comprises two basic modules, i.e., the hydro-dynamic module and advection–dispersion module [25,26]. For the hydro-dynamic simulation, the Saint-Venant equation was used as the basic formula consisting of a mass conservation continuous equation (Equation (6)) and an energy conservation momentum equation (Equation (7)). The formulas are as follows:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{6}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial\left(a\frac{Q^2}{A}\right)}{\partial x} + gA\frac{\partial h}{\partial x} + \frac{gn^2Q|Q|}{AR^{\frac{2}{3}}} = 0 \tag{7}$$

where x and t denote the distance between the downstream direction (m) and time (s), respectively. h and A denote the water level (m) and cross-section area of the target cross-section (m^2), respectively; Q and q denote the discharge (m^3/s) and lateral inflow (m^2/s);

g and R donate the gravity acceleration and hydraulic radius; α denotes the momentum correction coefficient; and n denotes the Manning roughness factor.

In the advection–dispersion module, the convection–diffusion equation was implemented to simulate the pollution transportation in (Equation (8)), and it was calculated coupling the hydro-dynamic module.

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} = \frac{\partial}{\partial x}(E_x\frac{\partial C}{\partial x}) - KC \quad (8)$$

where C denotes the concentration of the target pollutant; u denotes the average velocity; Ex denotes the convection diffusion coefficient; and K is the attenuation coefficient.

In the process of river network establishment, 198 branches, including the 33 key trans-boundary rivers, were identified as the simulation targets. Based on the GIS data and survey data, including the river network topology, branches' lengths, and cross-section data, the river network data were imported to build the fundamental part of the mathematical model. On that basis, all the boundary data, including the (1) stream boundary data, including the water level data, discharging data, and water quality data collected from 54 hydrodynamic and water quality stations located in the boundary of streams as in Table 1 and (2) pollution discharging data containing over 300 point sources and non-point sources located in the study area, as in Table 1, were input as the boundary condition for model establishment.

Parameters play a crucial role in modeling. For hydrodynamic simulation, the Manning resistance coefficient (n) values, ranging from 0.025 to 0.035, have been determined by field measurements and experiments in previous research [27]. The AD parameters are mainly composed of diffusion coefficients (E_x) and attenuation coefficients (K). Generally, the diffusion coefficient was 10 m^2/s. The attenuation coefficient, reflecting the decay ability of the pollutants, is vital to guarantee the accuracy of the model. The attenuation coefficient K is in the range of 0.1–0.3/d varied with different pollutants, i.e., COD, NH_3-N, and TP, according to the field measurement in the TECS and experiments in previous research [28].

3.2.2. One-Dimensional Mathematical Model Calibration and Validation

The model was calibrated and validated by comparing it with the simulated values and measured values at the trans-boundary cross-sections. In the work, two typical model evaluation indicators, i.e., the Nash–Sutcliffe efficiency coefficient (*NSE*) and the root mean square error (*RMSE*), were used to assess the correlation between the simulated and measured data. *NSE* values between 0.0 and 1.0 were generally considered acceptable levels of performance, and *RSME* is a standardized version of the error index, which describes the error in the prediction. Lower RSME values indicate better model accuracy. In general, model simulation can be judged as satisfactory when $NSE > 0.5$ and $RMSE \leq 0.7$ [29,30].

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(O_t - S_t)^2} \quad (9)$$

$$NSE = 1 - \frac{\sum_{t=1}^{n}(O_t - S_t)^2}{\sum_{t=1}^{n}(O_t - \overline{S})^2} \quad (10)$$

where O_t is the observed value, S_t is the simulated value, $\overline{s}$ is the mean of the simulated value, and n is numbers of data.

The parameters of the model were calibrated via trial and error based on the hydrodynamic data, i.e., the water level and discharge, and the water quality data, i.e., concentration of COD, NH_3-N, and TP collected in the hydrodynamic stations and water quality stations located in TBYD. The calibration results showed the following: (1) the calibrated Manning roughness coefficient of the river network was in a range of 0.023–0.032; (2) the calibrated decay coefficient K was 0.15–0.33 d^{-1} for COD, 0.09–0.23 d^{-1} for NH_3-N, and 0.06–0.25 d^{-1} for TP, all of which agreed well with previous research in a relevant study [31].

On that basis, the data of 2018, including the water level and discharge and the water quality data, i.e., the concentration of COD, NH_3-N, and TP of the 33 trans-boundary cross-sections monitored, was applied for model validation using the calibrated parameter values. The modeled concentrations of the selected contaminants were compared graphically with the measured results using the monthly measured data from January to December 2018. In this paper, 3 main trans-boundary cross-sections (site 5, site 12, and site 29 shown in Figure 1) located, respectively, in the Jiangsu–Zhejiang boundary, Zhejiang–Shanghai boundary, and Jiangsu–Shanghai boundary, were selected as the key validation targets, and the comparison of the measured and simulated results are shown in Figure 2. The results show that the Nash–Sutcliffe efficiency (NSE) values are in the range of 0.639–0.943, and the RSR values are in the range of 0.026–0.271. The indicator values of the simulation satisfied the standard above, illustrating the reliability of the model predictions.

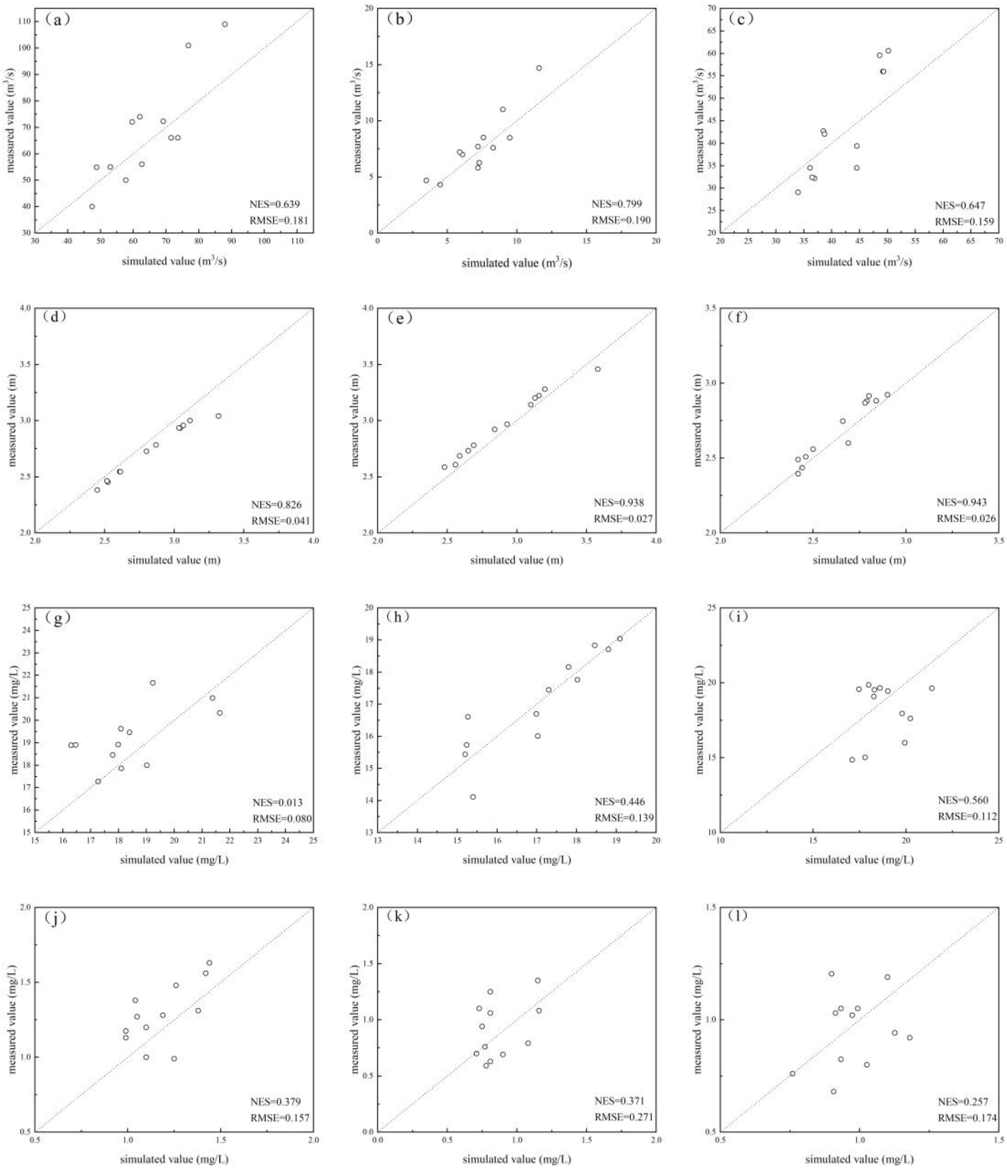

Figure 2. Comparison of measured and simulated results of established 1-D mathematical model. (**a**–**c**) refer to discharge at site 29, site 12, and Section 5, respectively; (**d**–**f**) refer to water level of site 29, site 12, and Section 5, respectively; (**g**–**i**) refer to the concentration of NH3-N at site 29, site 12, and Section 5, respectively; (**j**–**l**) refer to concentration of TP at site 29, site12 and site 5, respectively, in Figure 1.

3.3. Load Allocation Based on Water Pollution Load Carrying Capacity Calculation

The water pollution load carrying capacity was introduced as a pollution control goal for regional pollution control work [32,33]. By comparing the current load emission with the calculated load carrying capacity, it is possible to ascertain the exact rate of emissions that need to be reduced for the satisfaction of water quality reaching the target standards requirements. In this study, taking the corresponding requirements, i.e., water quality standard (WQS) attainment of the trans-boundary cross-sections, as the computing constraints, the final total allowable emission could be calculated on the basis of the established river network models for each contribution area. Detailed methods are presented in Figure 3.

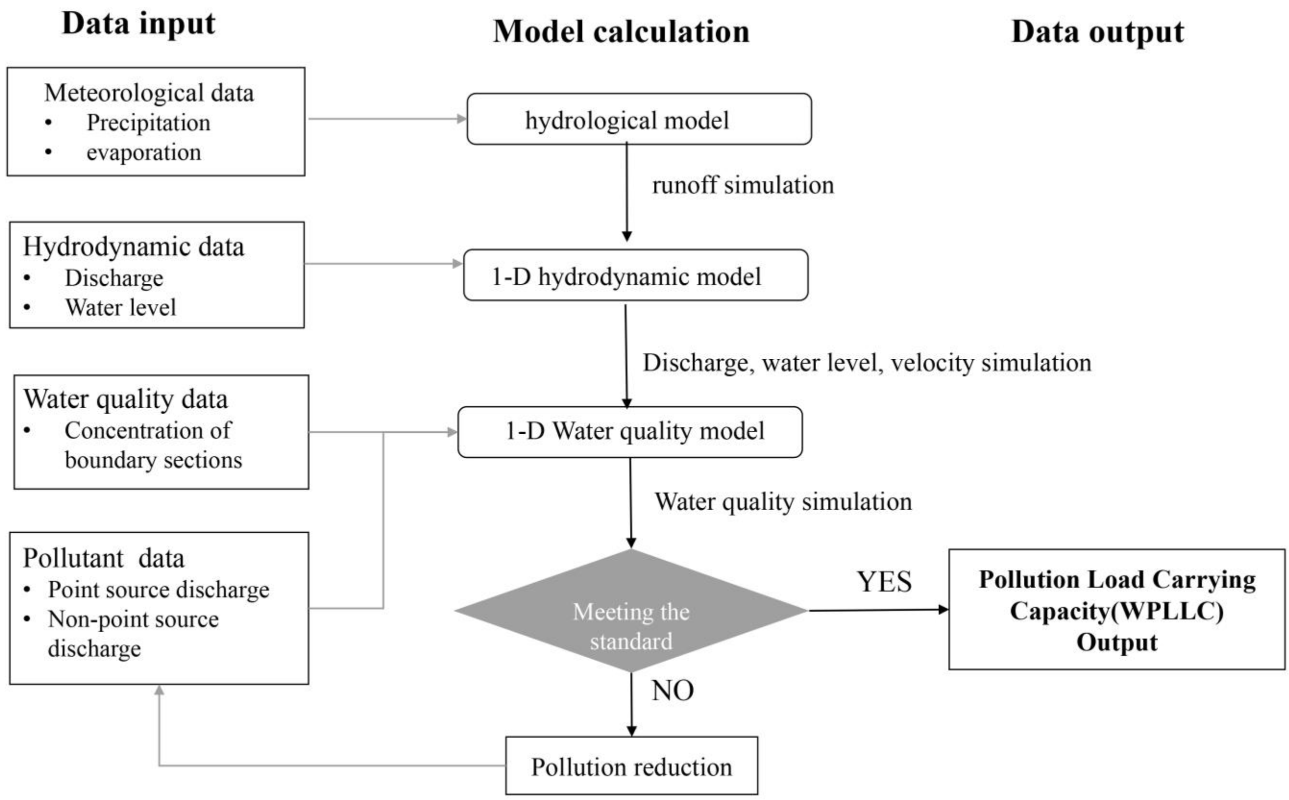

Figure 3. Framework of pollution load carrying capacity calculation by 1-D mathematical modeling simulation.

3.4. Eco-Compensation Calculation in Tri-Border Region

To bolster the execution of the pollution load coordination, an ecologically based compensation mechanism, recognized as a potent economic regulatory tool, was introduced in this study. In accordance with the "Technical Specification for the Supervision of Ecological Conservation Redline—Ecological Function Evaluation" [34], the recovering cost method (RCM) was selected as the basis for determining compensation payments, and the eco-compensation cost was determined by two key points: the pollutant overload amount leading to the pollution concentration WQS in the transboundary cross-section and the treating cost of the target pollutants. The formula is as follows:

$$M_j = \sum_{i=1}^{m} \left(P_{ji} - W_{ji}\right) k_i \tag{11}$$

where M_j is the total payment of eco-compensation in area j; P_{ji} is the discharging amount of pollutant i in area j; W_{ji} is the water environment capacity of pollutant i in area j; and k_i is the compensation criterion of pollutant i.

In this study, k_i is the unified criterion for the treatment cost and could be calculated based on the statistical treatment cost data from the sewage treatment plants. To account for the variation of sewage treatment costs for different typical pollutants, the derivative equal standard method [35] was used to calculate the unified eco-compensation criteria as follows.

$$k_j = \frac{\sum_{j=1}^{b} k_{ij} Q_i}{\sum_{i=1}^{a} Q_i} \tag{12}$$

$$k_{ij} = \frac{S_i \gamma_{ij}}{w_{ij}} \tag{13}$$

$$\gamma_{ij} = \frac{\left(c_{ij} - c_{sj}\right)/c_{sj}}{\sum_{j=1}^{b} \left(c_{ij} - c_{sj}\right)/c_{sj}} \tag{14}$$

where k_j is the compensation standard of pollutant j; S_i is the total operation cost of treatment i; k_{ij} is the compensation standard of pollutant j of treatment i; γ_{ij} is the treatment weight of pollutant j in sewage treatment plant i; Q_i is the capacity of treatment in sewage treatment plant i; w_{ij} is the total treatment amount of pollutant j in sewage treatment plant i; c_{ij} is the concentration of pollutant j in sewage treatment plant i; c_{sj} is the concentration criteria of pollutant j in the discharge standard of a pollutant for a municipal wastewater treatment plant in China.

In this study, the framework centers on the trans-boundary pollution control responsibilities of diagnosis and coordination among all the contributing administrative jurisdictions and has been concluded in a comprehensive set of research methodology as the flow chart below in Figure 4. The detailed methods used in this methodology are also detailed in the next section.

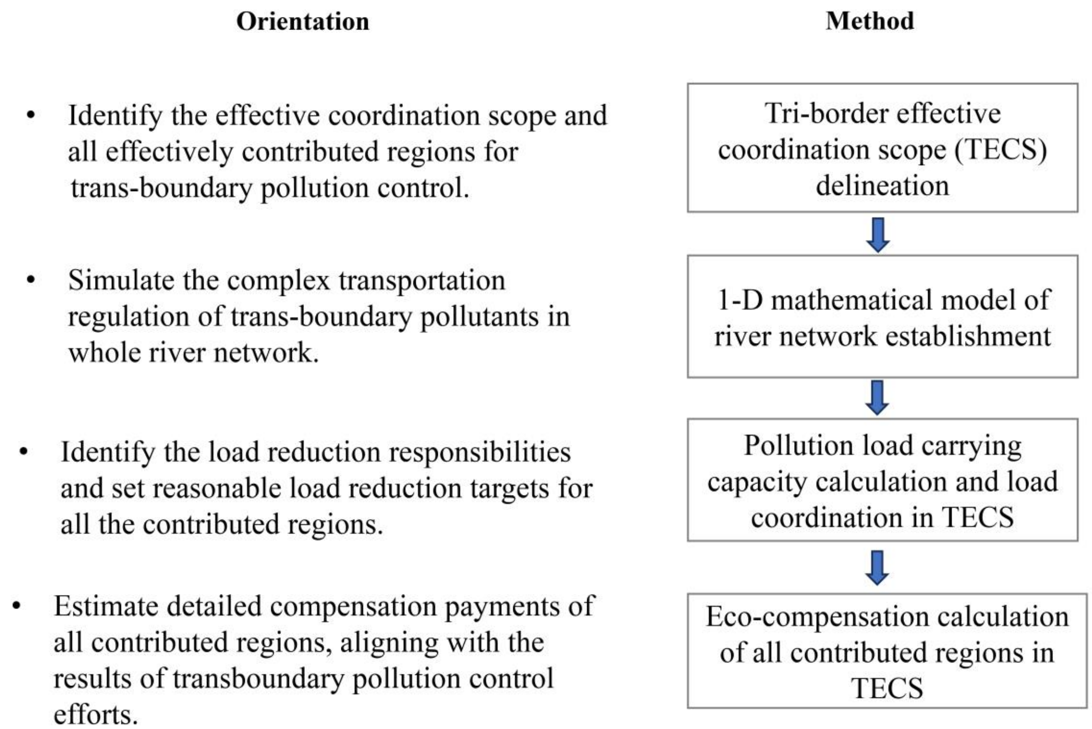

Figure 4. Flow chart of methodological framework for trans-boundary pollution control of complex river network.

4. Results and Discussion

4.1. Effective Coordination Scope of Tri-Border Region Delineation Based on Hydrodynamic Analysis

According to the monthly monitoring results of the target 33 trans-boundary rivers from 2009 to 2018, the dominate flow direction and frequency ratio of the flow directions were determined and are shown in Figure 5. The complex hydrodynamic characteristics in the whole river network of the tri-border region could be concluded as follows. In the Jiangsu–Shanghai boundary area, the main flow directions of the trans-boundary rivers consistently run from Jiangsu to Shanghai province, indicating a continuous transfer of water from Jiangsu to Shanghai. Notably, the largest reciprocating ratio is 33.3%, suggesting some degree of bi-directional water movement in the Jiangsu–Shanghai provincial area. Similarly, in the Zhejiang–Shanghai boundary, the results signify continuous water transfer from Zhejiang to Shanghai, with a reciprocating ratio of 2.6–35.8%, indicating some degree of bi-directional water movement. Along the Jiangsu–Zhejiang boundary area, complexity arises as the western part displays a dominate flow trend from Zhejiang to Jiangsu due to hilly terrain, while the middle and eastern sections experience a dominate flow trend from Jiangsu to Zhejiang, ultimately reaching the lower lying areas of Jiangsu and Shanghai. The reciprocating flow ratios ranging from 0% to 38.2% highlight a complex bi-directional flow phenomenon.

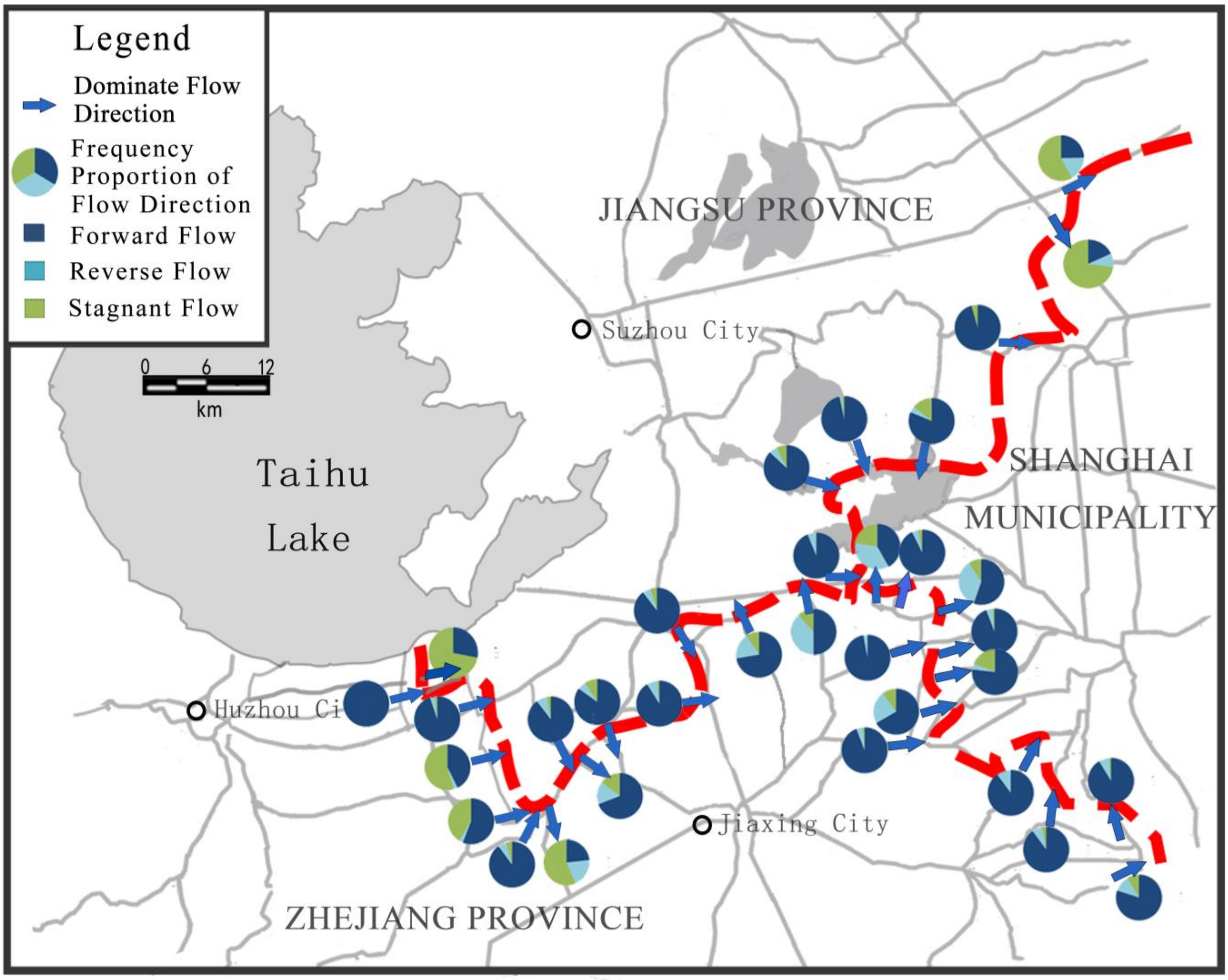

Figure 5. Distribution of trans-boundary flow direction frequency ratios at 33 trans-boundary cross-sections distributed in TBYD.

Overall, a comprehensive analysis of the complex hydrodynamic variations in the entire tri-border area of the Yangtze Delta was conducted by illustrating the main flow directions and reciprocating ratios in different border regions. The intricate flow variations reveal that the potential contributing regions are separately allocated on both sides of the trans-boundary cross-sections. This finding differs from the common understanding that upstream areas are always diagnosed as the sole contributors in trans-boundary conflicts.

Additionally, by combining statistical frequency ratios and the average velocities of 33 trans-boundary rivers, the bi-directional effect ranges of all the key cross-border sections responding to bio-directional flow were determined, as elaborated in the following paragraphs.

Based on the hydrodynamics analysis of the river network, including the frequency ratio w_p and w_n, each bi-direction effective range, i.e., L_p and L_n, of all 33 key trans-boundary cross-sections were determined with Equations (1)–(5). Finally, by superimposing all these effective ranges with the existing administrative boundaries, the tri-border effective coordination scope (TECS) was clearly delineated in Figure 6. As the delineation results show, the TECS lies along the boundaries in the shape of a triangle pattern and cover over 8425 km^2 composed of 35% of the area belonging to Jiangsu province, 50% of the area belonging to Zhejiang province, and 15% of the area belonging to Shanghai Municipality. In addition, according to the administrative delineation, 13 county-level administrative districts belonging to three provincial level groups in the TECS were diagnosed to be the effective coordination targets for trans-boundary pollution control.

Compared to previous research on trans-boundary pollution control in the Yangtze Delta, which implemented broad management plans covering entire areas of Jiangsu, Zhejiang, and Shanghai, this study introduces a novel method with clearer and refined responsibility identification. Through the delineation of the TECS, the efficacy of trans-boundary pollution control efforts can be enhanced, and the task volume of trans-boundary pollution control can be reduced by mainly focusing on effective control targets [10,36].

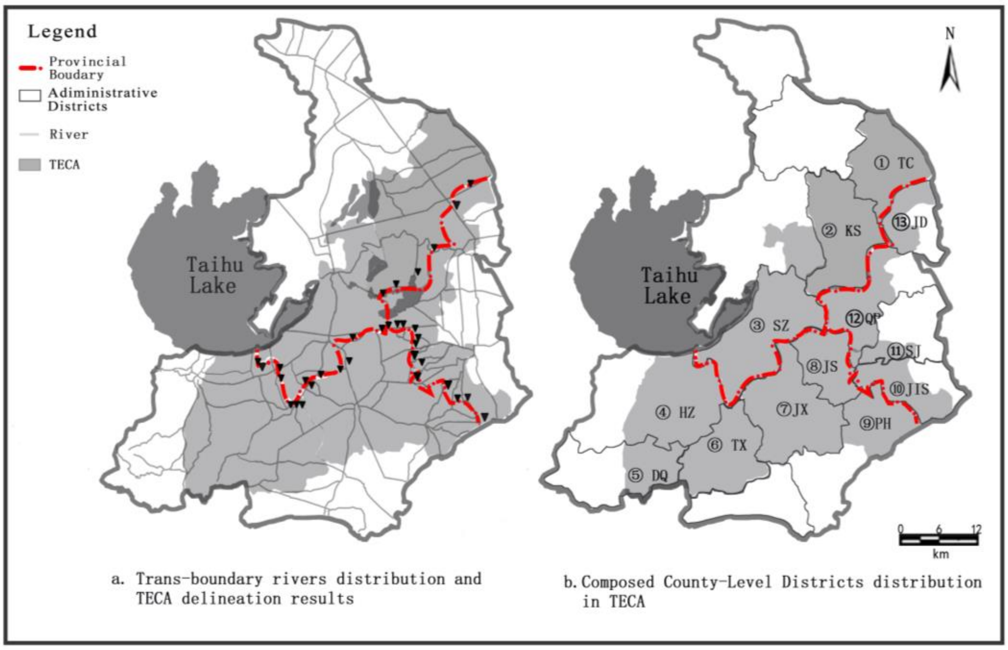

Figure 6. (**a**) Distribution of key trans-boundary rivers and the delineation results of tri-border effective coordination scope (TECS); (**b**) distribution of 13 county-level administrative districts in TECS delineated. (Note: ① TC: Taicang in Jiangsu Province, ② KS: Kushan in Jiangsu Province, ③ SZ: Suzhou in Jiangsu Province, ④ HZ: Hangzhou in Zhejiang Province, ⑤ DQ: Deqing in Zhejiang Province, ⑥ TX: Tongxiang in Zhejiang Province, ⑦ JX: Jiaxing in Zhejiang Province, ⑧ JS: Jiashan in Zhejiang Province, ⑨ PH: Pinghu in Zhejiang Province, ⑩ JIS: Jinshan in Shanghai Municipality, ⑪ SJ: Songjiang in Shanghai Municipality, ⑫ QP: Qingpu in Shanghai Municipality, ⑬ JD: Jiading in Shanghai Municipality).

4.2. Load Coordination Based on Pollution Load Capacity Calculation in TECS

4.2.1. Pollution Load Capacity Calculation of 13 Administrative Districts in TECS

By establishing a 1-D mathematical model coupling hydrodynamics and pollutant transportation, the quantitative simulation of water quality variation in all the trans-boundary rivers with a large number of load discharging in the delineated TECS could be achieved. By adjusting the input pollution boundary of the mathematical model, i.e., the load discharging amount in different administrative regions in the TECS, the load capacity of the 13 contributing county-level administrative districts could be determined by the trial calculation to maintain the WQS achievement in all the key trans-boundary cross-sections.

According to the calculation results, the spatial distributions of the load capacities in 13 contributing county-level administrative districts in the TECS were determined and are shown in Figure 7a–c and Table A1. The figure illustrates that the spatial distributions of the calculated load capacity in the TECS span from 2064 to 35,664 ton/year for COD, 153 to 2409 ton/year for NH_3-N, and 42 to 482 ton per year for TP. Among these 13 administrative districts, Suzhou (SZ), Kunshan (KS), and Taicang (TC) in Jiangsu Province and Huzhou (HZ) and Jiashan (JS) in Zhejiang Province demonstrate a higher load capacity, as featured by the relevant large area. Conversely, the regions located downstream of the water's main transportation, i.e., Songjiang (SJ), Jinshan (JS), and Jiading (JD) in Shanghai Municipality, always exhibit a comparatively low load capacity. The load capacity amounts, which could maintain the ability to achieve WQS in all the key trans-boundary cross-sections, could be set to be the upper limit value of the relevant administrative regions by the environment management policy formulation for trans-boundary pollution control of TBYD.

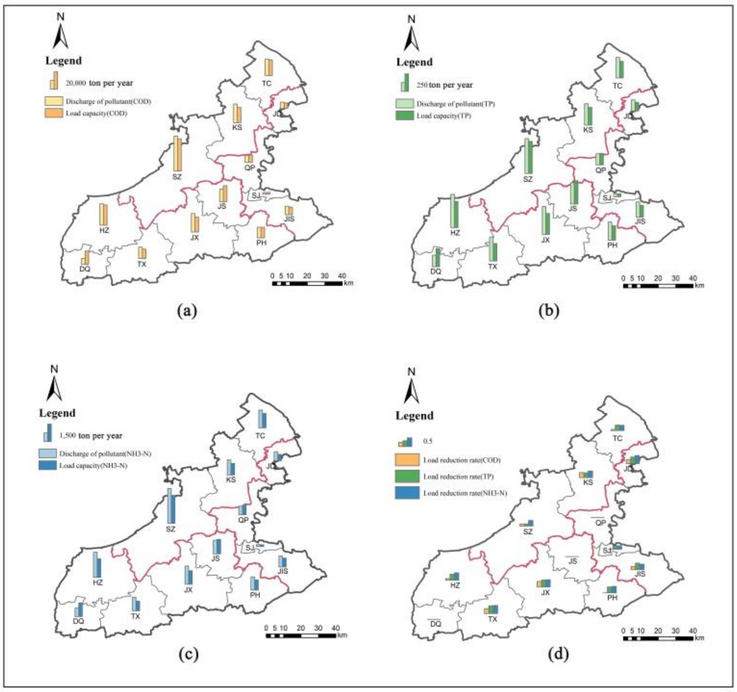

Figure 7. (**a**–**c**) Comparison of calculated load capacity and load discharging in 13 contributing administrative districts for COD (**a**), TP (**b**), and NH_3-N (**c**); (**d**) distribution of calculated load reduction rates for pollutants COD, TP, and NH_3-N in 13 contributing administrative districts.

By introducing the load capacity calculation into trans-boundary pollution control research, the complex pollution control responsibilities of the 13 contributing administrative districts could be quantitatively identified. Comparing the load reduction proposed by the decision model, the 1-D mathematical model reflecting the exact mechanism of pollution transportation in a large-scale river network could directly and objectively maintain the effect of trans-boundary pollution. The results could support the detailed load coordination work, as described below.

4.2.2. Pollution Load Cooperation in TECS

By comparing the load capacity calculation results of 13 administrative districts with the practical discharging amount of pollutants, which could be obtained from the discharging data of all the pollution sources in the database, as in Figure 7a–c, the spatial distribution of the pollution load reduction rates was determined and is shown in Figure 7d and Table A1. The results illustrate that the reduction rate varied among the different administrative regions, ranging from 0 to 24.2% for COD, 0 to 40.5% for NH_3-N, and 0 to 37.8% for TP. Among these 13 administrative districts, Jiashan (JS), Deqing (QP), and Qingpu (QP) all exhibited a reduction rate of 0%, indicating that these three regions are not accountable for pollution control. Conversely, the highest load reduction rates were observed in Jiaxing (JX) at 33.3%, Tongxiang (TX) at 30.8%, Jiading (JD) at 28.0%, and Kunshan (KS) at 24.5%. These regions feature a high population density and flourishing development. Additionally, across the entire TECS, the average reduction rate of NH_3-N (24.7%) and TP (20.9%) appears larger than COD (9.5%), which means that more attention should be paid to the pollutant control of NH_3-N and TP.

In summary, the load coordination could be implemented based on the precise load reduction allocation of 13 county-level administrative districts in the TECS. In contrast to setting a flat reduction rate to solve the transboundary pollution conflict in TBYD, as previous research has suggested [10,37], a more precise load reduction scheme for coordination among the different regions has been proposed. This scheme takes into account the diverse spatial distribution of pollution discharge and the complex transportation of pollutants across the entire tri-border area.

4.3. Eco-Compensation Standard and Payment Calculation in TECS

4.3.1. Eco-Compensation Standard Calculation in TECS

Based on the collected operation data, which include the sewage treatment capacity and the treatment cost of 98 treatment plants in the TECS, the treatment cost per unit for typical pollutants, namely, COD, NH_3-N, and TP, for all the treatment plants was calculated by Equations (12)–(14). The results presented in Figure 8a–c highlight obvious variations in the treatment cost per unit for different pollutants across different plants, ranging from CNY 102 to 4520 per ton for COD, CNY 4099 to 116,771 per ton for NH_3-N, and CNY 16,533 to 489,633 per ton for TP. Taking into account the calculation weight determined by the treatment capacity of all the sewage plants shown in Figure 8d, the uniform treatment cost per unit in the TECS, serving as the uniform eco-compensation standard for transboundary pollution based on the cost recovery method, is CNY 755 per ton for COD, CNY 18,150 per ton for NH_3-N, and CNY 141,402 per ton for TP.

Compared to the eco-compensation standards previously used in the Yangtze Delta, i.e., COD for CNY 15,000 per ton, NH_3-N for CNY 100,000 per ton, and TP for CNY 100,000 per ton, which were established through government consultation and decision making [10,38], a more objective and adapted ecological compensation standard has been derived from the analyzed results of practical pollution treatment costs in the study area.

4.3.2. Eco-Compensation Payment Calculation in TECS

Combined with the eco-compensation standard and prospective load reduction amounts obtained above, the exact eco-compensation payments of the 13 contributing administrative districts in the TECS could be estimated using Equation (9) and are shown in Figure 9 and Table A2. The results indicate that the total compensation payment for trans-boundary pollution in the TECS reached CNY 151.87 million. Among these 13 administrative districts, Deqing (DQ), Jiashan (JS), Qingpu (QP), and Songjiang (SJ) do not need to pay any compensation amount or only a negligible amount due to their existing discharging amount being below the calculated load capacity. In contrast, Huzhou (HZ), Tongxiang (TX), and Jiaxing (JX) are the largest contributors for compensation, with payments allocated at CNY 25,176,446, CNY 24,214,155, and CNY 20,841,180, respectively. The other regions, i.e., Suzhou (SZ), Taicang (TC), and Kunshan (KS), contribute similar amounts in the range of CNY 9,661,489 to 18,267,058. These eco-compensation results reflect the pollution control responsibility of all the regions in the TECS.

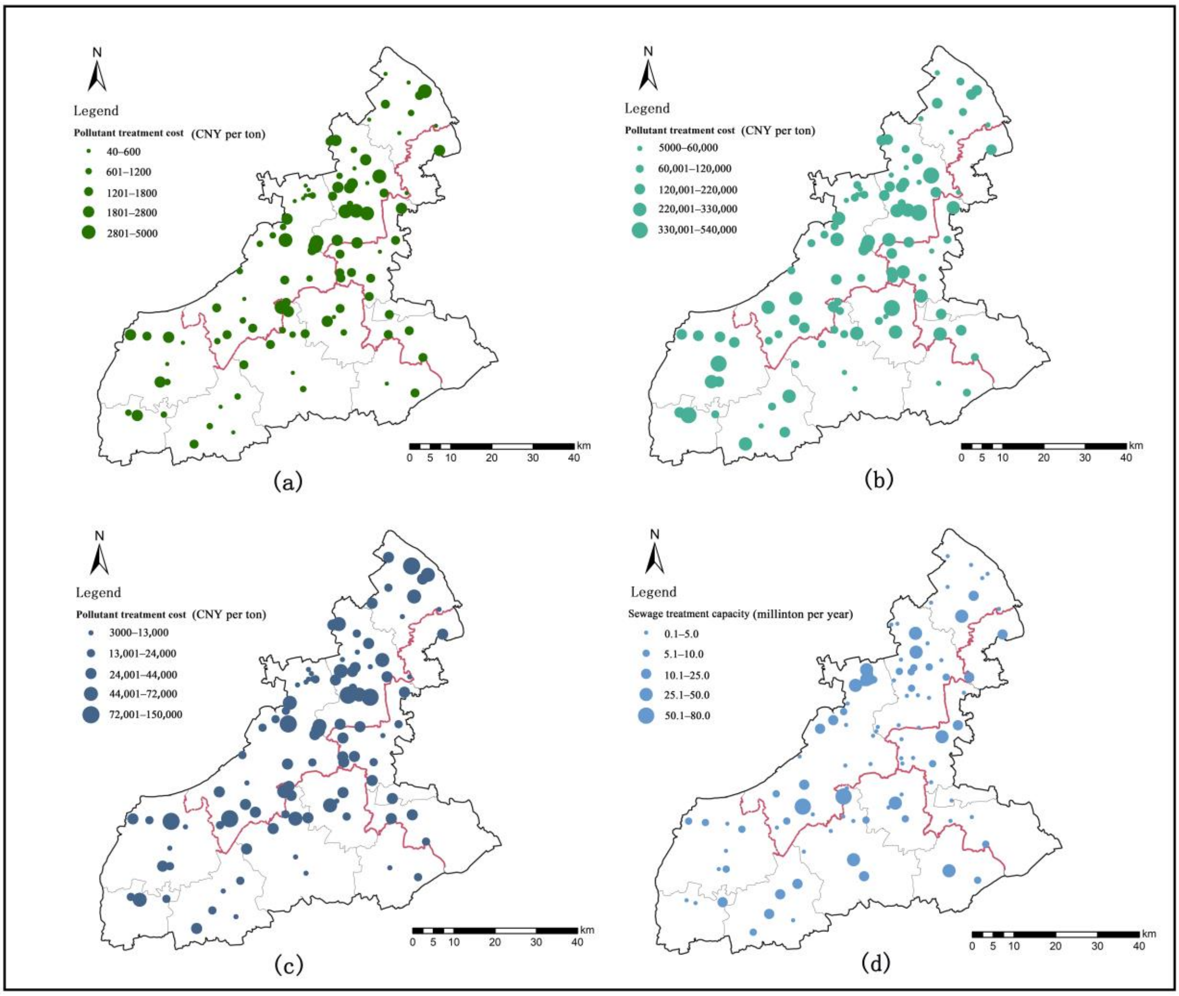

Figure 8. The treatment cost per unit for pollutants: (**a**) COD, (**b**) TP, (**c**) NH_3-N, and (**d**) treatment capacity of the 98 sewage plants in TECS.

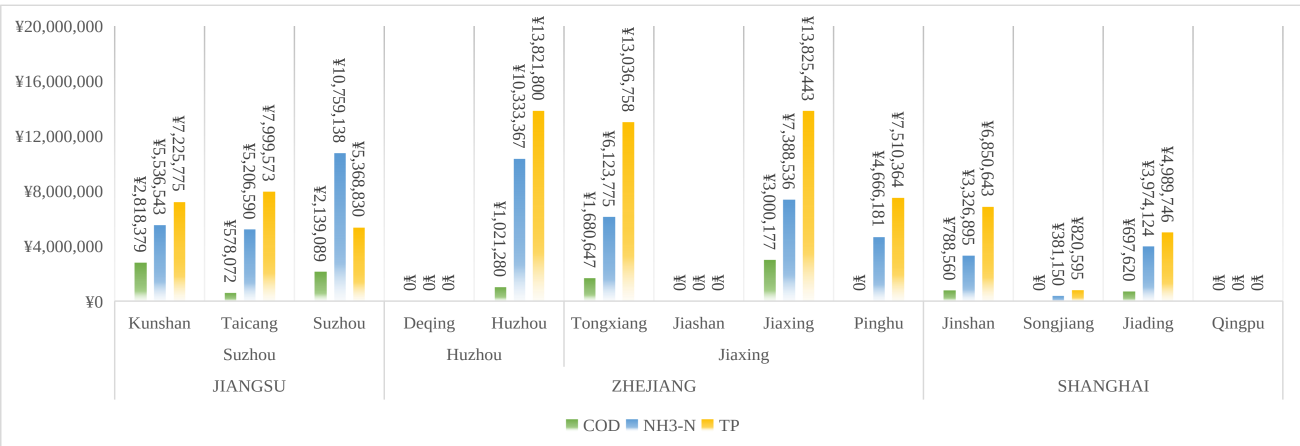

Figure 9. The calculation results of eco-compensation payment amount for different pollutants, namely, COD, NH_3-N, and TP, in the 13 contributing administrative districts of TECS.

In addition, the figure illustrates a prevalent phenomenon in which the payments for NH_3-N and TP occupy the majority, with an average occupation rate of 37.9% for NH_3-N and 53.6% for TP. This is attributed to the significant overload discharging of NH_3-N (24.7%) and TP (20.9%), along with the high eco-compensation standard for these two pollutant indicators. The results emphasize the importance of giving more attention to NH_3-N and TP in practical management for trans-boundary pollution control in the TECS.

Under the background of continuous urban infrastructure development in next 5 years [39], leading to a further decrease in load discharging in the future. It can be anticipated that both the reduction in load discharging and the amount of eco-compensation will decrease in the future. The trans-boundary pollution broadly occurring in the entire tri-border area of the Yangtze Delta will be mitigated in the future.

5. Implications and Limitation

5.1. Implications

The results and discussions presented above could provide important insights to promote trans-boundary pollution control coordination work in the tri-border area of the Yangtze Delta as the following policy recommendations:

Firstly, regional integration can effectively inhibit transboundary pollution by strengthening collaborative governance among governments [36]. Since the effective coordination scope of the tri-border area of the Yangtze Delta has been clearly delineated, a management authority could be set to coordinate the trans-boundary pollution control management in the 13 administrative regions in the TECS. This authority could be affiliated with the Yangtze Delta Commission of the Ministry of Water Resources, PRC. Hence, by establishing a uniform and systematical management structure, the cooperation between local governments in environmental governance could be strengthened.

Secondly, instead of implementing water pollution discharging load reduction tasks by Jiangsu, Zhejiang, and Shanghai respectively, as proposed in the Strictest Regulation for Water Resource Management issued by the General Office of the State Council, PRC since 2013 [40], a more coordinated regulation centering on trans-boundary pollution should be considered. Referring to the trans-boundary water convention signed by the United Nations Economic Commission for Europe (UNECE) [5], a coordinated convention in the TECS could also be issued and implemented under the guidance of a uniform and quantitative pollution load reduction. The load capacity amount calculated in this research could be taken into consideration for setting the upper limit value for pollution load discharge control in this convention.

Thirdly, this study represents a good attempt at aligning with the pilot scheme outlined in the "Ecological Comprehensive Compensation Pilot Scheme" [41], issued by China's National Development and Reform Commission in 2019. Since the compensation payment of all the contributing administrative regions have been determined in this study, the compensation could be centrally collected by the Management Authority of TECS to fund infrastructure construction investment and environment restoration costs in the entire tri-border area.

In total, the establishment of a management authority of the TECS, the implementation of the coordinated reduction convention, and the establishment of interlinked interests by eco-compensation would facilitate coordinated governance of trans-boundary pollution across the Yangtze River Basin. The adaptability of the management outline extends geographical boundaries, making it applicable for complex river network scenarios worldwide, especially in highly urbanized regions.

5.2. Limitation

This paper has proposed a new methodology that could identify and coordinate the trans-boundary pollution control responsibilities in a complex river network area. It is noteworthy that the coordination methodology for trans-boundary pollution control is primarily suitable for highly urbanized developed regions, e.g., the tri-border area of the Yangtze River Delta, where the urbanization rate in some administrative areas reaches as high as 89.3% [42], attributing to the limitations outlined below.

In the highly urbanized regions of TBYD, up to 90.7% of the sewage is collected for centralized treatment [43]. In the context of relatively stable pollution discharges from the sewage treatment plants in urbanized regions, the calculated load capacity in this methodological framework serves as a consistent and annual pollution reduction target, reasonably guiding regional trans-boundary pollution control and management. In contrast, in a basin characterized by a significant presence of rural areas, there is obvious temporal variation in the pollution discharges due to agricultural runoff [44]. Hence, significant deviations may exist in pollution control when relying on consistent values provided by the load capacity calculation results in this methodology.

In addition, considering the analysis above, it is reasonable to apply compensation standards based on the processing costs of sewage treatment plants only to well-urbanized areas. However, significant deviations also exist in the ecological compensation payment calculations provided by this methodology in rural areas. A more reasonable compensation standard suitable for a broad rural area should be explored based on a more comprehensive study of the multiple costs, encompassing rural sewage treatment and farmland runoff treatment, for ensuring reasonable and sustainable implementation of eco-compensation.

6. Conclusions

By examining the intricacies existing in practical trans-boundary pollution control work in an extensive river network, our research presents innovative solutions through multilateral pollution load coordination and eco-compensation mechanisms under a comprehensive framework. These proposals address the critical pollution issue broadly occurring in the tri-border region of the Yangtze Delta, and the key conclusions are as follows:

1. Delineation of tri-border effective coordination scope (TECS): Building upon the water hydrodynamic characteristics analysis of the whole river network in TBYD, the TECS, a strategic region where trans-boundary pollution control management could be uniformly implemented, has been divided considering the bio-influence range of key trans-boundary cross-sections. On that basis, 13 county-level administrative districts encompassed in the TECS have been identified as the coordination objects for trans-boundary pollution control.
2. Load coordination based on load capacity calculation: By constructing a large-scale river network mathematical model, the load capacity of each trans-boundary pollution-contributing region in the TECS has been determined and ranges from 2064 to 35,664 ton/year (cod), 153 to 2409 ton/year (ammonia nitrogen), and 42 to 482 ton/year (TP). Consequently, quantitative load reduction responsibilities of all the contributing regions were clarified and coordinated by comparing them to the current pollution load distribution.
3. Establishment of unified eco-compensation criterion: In analyzing the operational details of 94 treatment plants in the TECS, the standardized eco-compensation criterion has been calculated as follows: CNY 755 per ton for COD, CNY 18,150 per ton for NH_3-N, and CNY 141,402 per ton for TP. This guides equitable compensation practices across the contributing regions.
4. Trans-boundary pollution eco-compensation: Combined with the load coordination results, the detailed compensation payments of 13 administrative districts in the TECS for trans-boundary pollution control is in the range of CNY 0 to 25,176,446. In addition, the results illustrate that the NH_3-N and TP should receive more attention in the practical management for trans-boundary pollution control in the TECS.

Collaborative effort among the provinces or states is crucial for effective transboundary pollution control. The framework proposed in this study shows promise in resolving multi-party disputes in the river network area and implementation of effective strategies to mitigate trans-boundary water pollution. Its adaptability extends geographical boundaries, making it pertinent for complex river network scenarios worldwide, especially highly urbanized regions.

While our study marks a substantial step forward in addressing trans-boundary pollution, it is imperative to recognize specific constraints. Notably, the temporal variability in both the load capacity and the load discharging amount existing in broader scenarios highlights the need for further refined research. Future studies should aim to establish a more intricate load capacity framework that accounts for seasonal or daily variations, thereby enhancing the precision of load coordination management. Furthermore, the current eco-compensation calculation, centered on recovery cost, lacks consideration for potential ecological damages or wider impacts associated with trans-boundary pollution processes. Thus, a more comprehensive exploration of economic compensation strategies, encompassing detailed and holistic assessments of potential impacts, remains essential for ensuring reasonable and sustainable implementation of pollution management.

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Appendix A

Table A1. The results of calculated load capacity and expected reduction rate of 13 administrative districts in TECS.

Administrative Level			**Load Discharging Amount (Ton/Year)**			**Load Capacity (Ton/Year)**			**Reduction Rate (%)**		
Province	**City**	**County-Level District**	**COD**	**NH_3-N**	**TP**	**COD**	**NH_3-N**	**TP**	**COD**	**NH_3-N**	**TP**
Jiangsu Province	Suzhou	Kunshan	20,519	1296	319	16,787	991	265	18.2%	23.5%	17.1%
		Taicang	18,076	1534	309	17,310	1247	249	4.2%	18.7%	19.5%
		Suzhou	38,497	3002	523	35,664	2409	482	7.4%	19.7%	7.8%
Zhejiang Province	Huzhou	Deqing	6558	736	172	14,707	1182	272	0.0%	0.0%	0.0%
		Huzhou	23,640	2171	497	22,287	1602	393	5.7%	26.2%	21.0%
	Jiaxing	Tongxiang	12,588	1171	359	10,362	834	260	17.7%	28.8%	27.4%
		Jiashan	13,838	1178	318	17,650	1257	351	0.0%	0.0%	0.0%
		Jiaxing	20,397	1569	419	16,423	1162	315	19.5%	25.9%	24.9%
		Pinghu	11,677	1134	273	11,690	877	216	0.0%	22.7%	20.8%
Shanghai Municipality	Shanghai	Jinshan	9337	943	227	8293	760	175	11.2%	19.4%	22.8%
		Songjiang	1863	174	48	2065	153	42	0.0%	12.1%	12.9%
		Jiading	7009	776	165	6085	557	127	13.2%	28.2%	22.8%
		Qingpu	7869	728	166	8178	836	171	0.0%	0.0%	0.0%

Table A2. The results of calculated eco-compensation payment of 13 administrative districts in TECS.

Administrative Level			Eco-Compensation Payment			
Province	**City**	**County Level District**	**COD**	**NH_3-N**	**TP**	**SUM**
JIANGSU	Suzhou	Kunshan	¥2,818,379	¥5,536,543	¥7,225,775	¥15,580,698
		Taicang	¥578,072	¥5,206,590	¥7,999,573	¥13,784,235
		Suzhou	¥2,139,089	¥10,759,138	¥5,368,830	¥18,267,058
ZHEJIANG	Huzhou	Deqing	¥0	¥0	¥0	¥0
		Huzhou	¥1,021,280	¥10,333,367	¥13,821,800	¥25,176,446
	Jiaxing	Tongxiang	¥1,680,647	¥6,123,775	¥13,036,758	¥20,841,180
		Jiashan	¥0	¥0	¥0	¥0
		Jiaxing	¥3,000,177	¥7,388,536	¥13,825,443	¥24,214,156
		Pinghu	¥0	¥4,666,181	¥7,510,364	¥12,176,545
SHANGHAI		Jinshan	¥788,560	¥3,326,895	¥6,850,643	¥10,966,098
		Songjiang	¥0	¥381,150	¥820,595	¥1,201,745
		Jiading	¥697,620	¥3,974,124	¥4,989,746	¥9,661,490
		Qingpu	¥0	¥0	¥0	¥0

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