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A Developed Method of Water Pollution Control Based on Environmental Capacity and Environmental Flow in Luanhe River Basin

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Abstract: To solve increasingly serious water pollution problems, it is necessary to systematically manage water resources, water environment, and water ecology as elements of a watershed. Comprehensive watershed water pollution control should regard the basin as a whole, respect the natural laws of the river and lake system, and focus on the protection and restoration of its natural ecological environment so that the comprehensive ecological service functions of rivers and lakes can be fully realized. Based on the concepts of environmental capacity (EC) and environmental flow (EF), this study established watershed water pollution control scheme prediction and evaluation methods to explore the changes in the water environment and water ecology in the basin under different water pollution control schemes. The MIKE11 model was used to construct a hydrologic and water quality model of the study area, the one-dimensional water quality model was used to calculate the water environmental capacity, and the Tennant method was used to evaluate the environmental flow. In this study, the method was applied to the Luanhe River Basin of Chengde, Hebei Province, China. It simulated the concentration changes of four pollutants—namely, NH_3-N, COD, TN, and TP—under eight different water pollution control schemes, and the responses of EC and EF were compared and analyzed. Some conclusions are as follows: (1) Reducing point source pollution has the most obvious effect on water pollution prevention, especially on NH_3-N and COD, while reducing nonpoint source pollution is weaker and the effect of increasing upstream water is the weakest. (2) The increase in up-stream water inflow and reducing point source pollution can greatly increase the EC of NH_3-N and COD. The EC of TN can be greatly increased by reducing point source pollution, and the EC of TP can be greatly increased by reducing nonpoint source pollution. (3) The increase in upstream water inflow can improve the EF level to a certain extent. This method can also be applied to other similar river basins, providing valuable suggestions for rationally formulating water environmental management strategies and for promoting the sustainable development of the ecological environment and social economy in the river basin.

Keywords: watershed water pollution control; environmental capacity; environmental flow; MIKE11

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Citation: Li, X.; Li, C.; Wang, X.; Liu, Q.; Yi, Y.; Zhang, X. A Developed Method of Water Pollution Control Based on Environmental Capacity and Environmental Flow in Luanhe River Basin. *Water* **2022**, *14*, 730. https://doi.org/10.3390/w14050730

Academic Editors: Ian Prosser and José Gutiérrez-Pérez

Received: 12 January 2022
Accepted: 21 February 2022
Published: 25 February 2022

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1. Introduction

As a complete physical geographical unit, a watershed is a complex "natural–social–economic" system composed of natural factors such as water, soil, and gas; and human factors such as population, society, and economy, which are interrelated and interact with each other [1]. Water is the most important link between different geographical units and ecosystems in a watershed, and it is also a carrier for the migration of soil, nutrients, pollutants, and species within the watershed [2]. Watershed ecosystems provide related products and services to human society through hydrological, geochemical, and biological processes [3]. In the past, people usually managed watersheds as a single element through a single government agency, which makes it difficult to solve the complex problems of mutual influence and interweaving between the watershed water, ecological environment, and social economy [4]. With the popularization of sustainable development, it is generally recognized that the effective way to solve the increasingly serious problems of overpopulation, natural resource shortages, and environmental degradation in the process of development is to carry out the systematic and comprehensive management scheme of natural resources, ecological environment, and social economy in the basin as a unit. Comprehensive development and management of watersheds has been gradually accepted by governments and scholars [5].

Watershed water pollution control was first studied in European and North American countries. With rapid economic development after the Second World War, serious river water pollution problems appeared in Europe. Since then, many countries in the world have carried out various water environment management activities to prevent and control water pollution to solve the prominent problem of environmental degradation caused by economic development [6,7]. In Europe, famous rivers—such as the Seine River, the Thames River, and the Danube River—had all gone through the process of "pollution first and treatment later", which had caused them to pay a heavy price of ecological degradation. In the renovating process, scientific water pollution control planning played a leading role, and the theory and technology of water pollution control planning also developed [8]. After the 1960s, water pollution control entered the stage of comprehensive prevention and control, during which time countries attached more importance to the research of various technologies and methods for watershed water pollution control [9,10]. With the deepening of the research, scholars proposed new concepts of ecological water pollution control. They emphasized the natural laws of river and lake systems and paid attention to the restoration and protection of its natural ecology and natural environment so that the comprehensive ecological service functions of rivers and lakes could be realized. Increasingly, ideas and methods from the perspective of water ecology have been applied to comprehensive watershed water pollution control [11,12].

Water environmental capacity is an important basis for the total control of pollution sources and can provide an important reference for watershed pollution control. The water environmental capacity reflects the transformation, migration, and accumulation of pollutants in water and reflects the maximum limit of the pollutants that the water body can withstand under certain environmental target value constraints. At the same time, it is also the basis for formulating pollutant discharge standards and environmental standards [13,14]. In 1968, Japanese scholars took the lead in putting forward the concept of water environmental capacity and thus proposed a theoretical framework for total pollutant control [15]. This theory controlled the discharge of pollutants in the basin within a certain range by setting the maximum allowable limit of the total amount of pollutants entering the regional environment, which is environmental capacity, to improve the water quality of the region [16]. Since the 21st century, with the emergence of new calculation methods and tools, many excellent mathematical models of water quality and water quality modeling software have been applied [17]. For instance, the DO-BOD water quality model has developed into a comprehensive water quality model including BOD, ammonia nitrogen, DO, nitrate, and other linear systems [18]. In recent years, scholars have mostly adopted the concept of water environmental capacity, continuously optimized the research system by using mathematical water quality models, and applied the research results to the formulation of environmental standards [19]. For example, Feng et al. used the MIKE11 model to study the impact of the operation of gates on the river network in city of Wuxi and on the water environmental capacity of the basin, which provides basic data and information for the gate management and water quality improvement of the river network [20]. Zeng et al. used the SWAT model to quantitatively evaluate the impact of climate change on water environmental capacity in the middle and lower reaches of the Hanjiang River in China [21].

River environmental flow is an important basis to judge whether the reasonable flow of rivers is maintained, the basic ecological quality of water is guaranteed, and that the ecological function of water bodies is safeguarded. Its research results can provide important reference for water ecological protection in the process of watershed water pollution control. There are many concepts similar to environmental flow, such as ecological environmental water demand, ecological base flow, and minimum acceptable flow. At present, the interpretation of "Environmental Flow", described in the Brisbane Declaration in 2007, is the most widely accepted in the world. That is, "environmental flows" describe the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems [22]. The core idea of environmental flow is to put forward the recommended flow value for maintaining river ecological health from the perspective of maintaining the minimum flow requirements of aquatic organisms. The calculation methods mainly include the hydrologic method (Tennant method, 7Q10 method, flow duration curve method, etc.), the hydraulic method (wetted perimeter method, R2CROSS method, etc.), the habitat evaluation method (IFIM model, CASIMIR model, etc.), and the integral analysis method (BBM method, etc.) [23–25].

Based on the concepts of the EC and EF and the MIKE11 model, a watershed water pollution control plan prediction and evaluation method is established in this study. This method can be used to explore the changes in the water environment and water ecology under different water pollution control schemes. By combining EC and EF, this method can not only obtain the effect of water pollution reduction under different schemes, but also determine whether the reasonable environmental flow can be maintained under the scheme, so as to realize the combination of water pollution control and environmental flow maintenance. The utilization of this method can provide valuable suggestions for rationally formulating water environment management and pollution control countermeasures in the watershed and provide a theoretical basis for the rational layout of agricultural and industrial development in the watershed. This is beneficial for reducing water pollution and promoting ecological environmental protection and the sustainable development of the social economy in the basin.

2. Research Methods

2.1. Study Area

The Luanhe River is located in the northeastern North China Plain and originates from the north foot of Bayanguerrtu Mountain, Fengning County, city of Chengde, Hebei Province. It is one of the four major water systems in the Haihe River Basin. The Luanhe River Basin in Chengde is high in the north and low in the south, with complex terrain, winding mountains, and staggered rivers. The landform gradually transitions from the Bashang Plateau, to the middle and low mountains in the Yanshan Mountains, then to the hills at the south foot of the Yanshan Mountains, and on to the North China Plain. The Luanhe River has a total length of 888 km and a drainage area of 44,880 km^2. The catchment area of the Luanhe River Basin in Chengde, Hebei Province, is 28,616 km^2, accounting for 72% of the total area of the city and 64% of the total area of the whole Luanhe River Basin [26]. The water system distribution of the Luanhe River Basin is shown in Figure 1. The reach of the Luanhe River in Chengde plays an important role in the whole Luanhe River Basin.

The total amount of water resources is the total yield of surface water and groundwater formed by precipitation in the region. The multiyear average annual runoff of the Luanhe River Basin is 4.423 billion m^3, and the multiyear average total amount of water resources in Chengde is approximately 3.701 billion m^3, with a decreasing distribution from the southeast to the northwest. Since the Luanhe River Diversion Project was put into operation, the annual water transmission has reached 1 billion m^3, which has greatly alleviated the difficulty of water supply in Tianjin. The Luanhe River has become an important water source in Tianjin, bringing social, ecological, and environmental benefits to some areas of Hebei Province and Tianjin. As the Luanhe River forms an ecological barrier to Beijing and Tianjin and is an important source for agricultural products (including fruits and vegetables), research on the water pollution control scheme of the Luanhe River in Chengde is of great significance to the environmental management of Beijing, Tianjin, and Hebei.

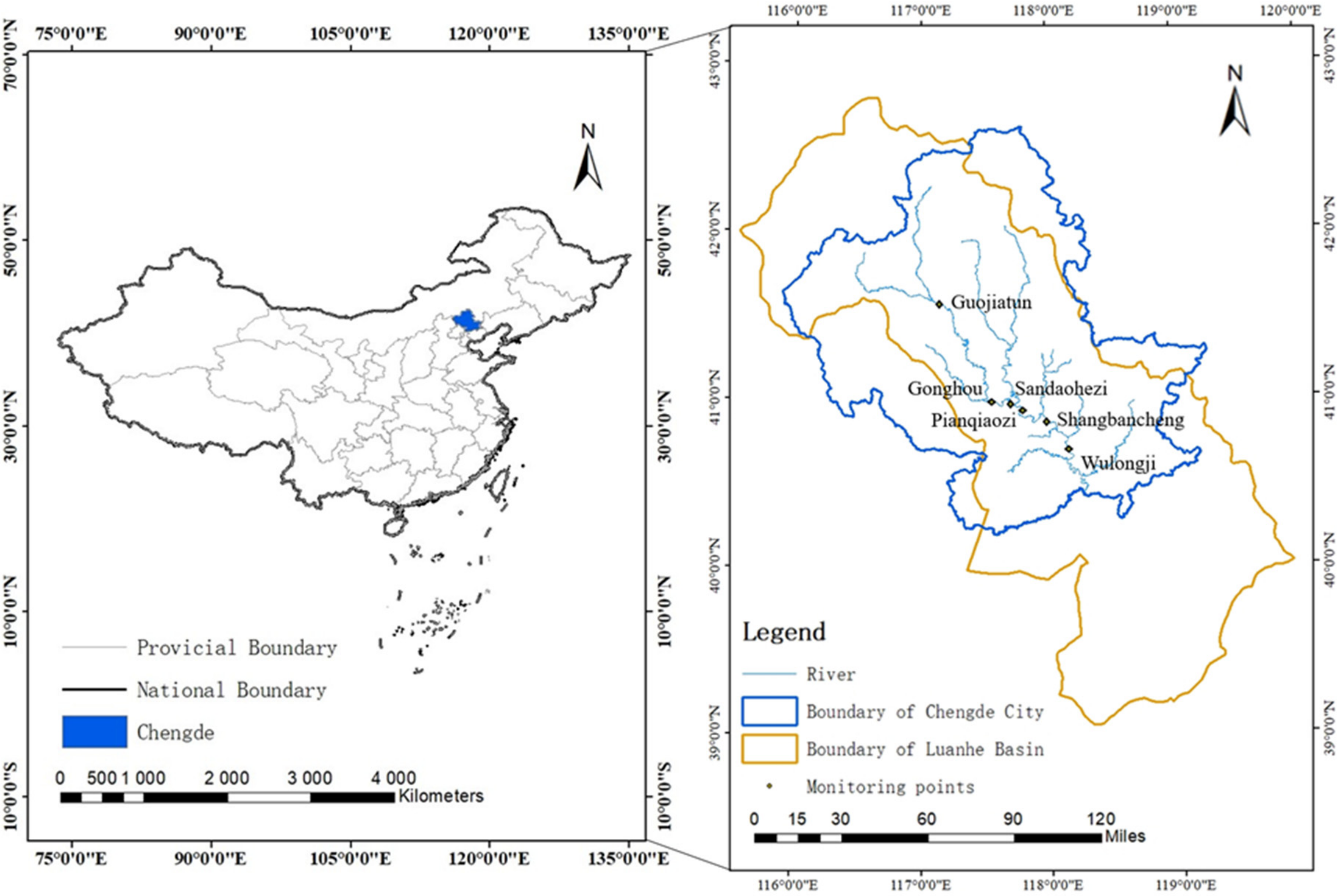


Figure 1. Distribution of Luanhe River System.

2.2. Methods

Based on the concepts of the EC and EF and the MIKE11 model, a simulation evaluation method of the basin water pollution control scheme is established to explore the changes in the water environment and water ecology under different water pollution control schemes. In this method, the MIKE11 model is used to construct the water quality model of the study area, the one-dimensional water quality model is used to calculate the water environmental capacity (EC), and the Tennant method is used to evaluate the environmental flow (EF). Different water pollution prevention and control schemes are set, and the concentration changes of NH_3-N, COD, TN, and TP under different water pollution prevention and control schemes in the study area are simulated by the method. The changes in EC and EF are compared and analyzed, which can provide valuable suggestions for reasonably formulating water pollution prevention and controlling countermeasures in the basin. The technical route is shown in Figure 2.

2.2.1. MIKE11 Model Construction and Calibration

MIKE11 is professional engineering software suitable for simulating one-dimensional hydrodynamics, water quality, and sediment transport in estuaries, rivers, irrigation channels, and other water bodies. At present, it is widely used and verified worldwide and has become a standard tool in many countries [27]. The MIKE11 model contains a variety of modules with different functions, which can easily and flexibly create personalized river simulation models. In this study, the hydrodynamic module (HD) and convection diffusion module (AD) were selected to model the hydrological and water quality of the main stream of the Luanhe River in Chengde.

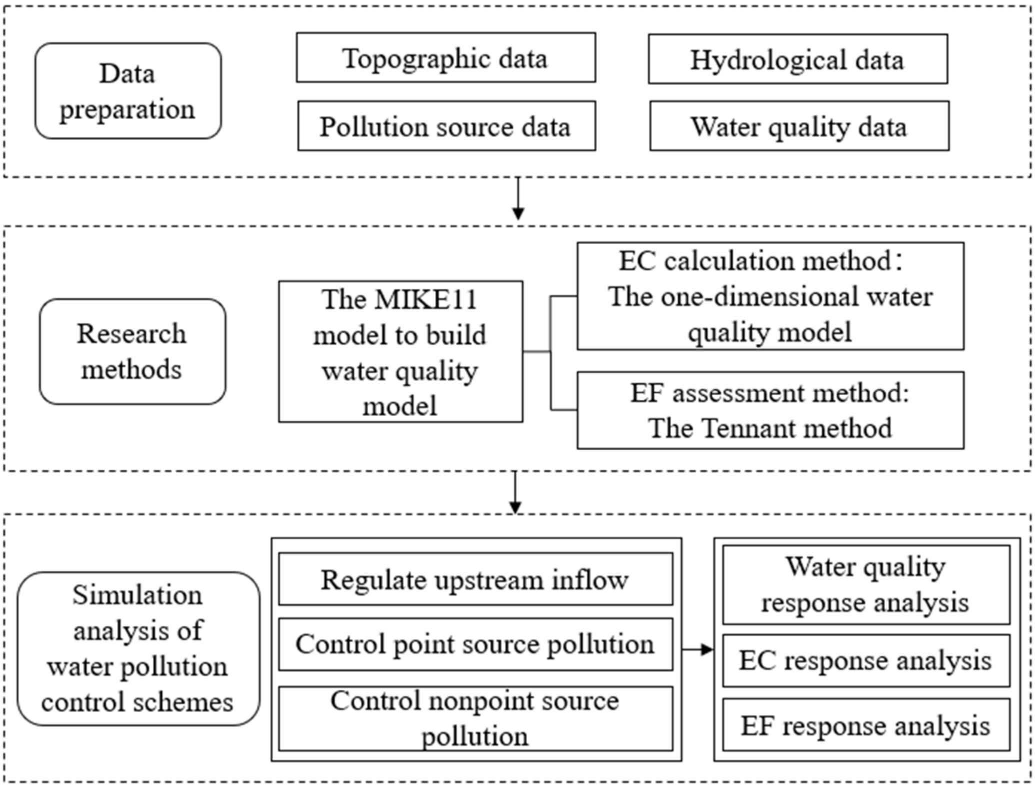


Figure 2. Technical roadmap.

The Mike11 HD hydrodynamic module is the main component of the MIKE11 software system and the basis and application premise of reasonable and scientific simulation research of other modules. It can carry out hydrodynamic simulation research on most one-dimensional water bodies. The basic principle of calculation is to solve the Saint-Venant system of equations by using a six-point Abbott–Lonescu finite difference scheme. The adaptive numerical calculation conditions of river flow on time and space scales are used to describe various flow environments of the river to simulate the hydrodynamic situation of the river. The formulas are

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial \left(\alpha \frac{Q^2}{A}\right)}{\partial x} + gA\frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2 AR} = 0 \tag{2}$$

where x is the position coordinate (m), t is the time coordinate (s), Q is the flow along the river section (m^3/s), q is the lateral inflow (m^3/s), A is the cross-sectional area of the river (m^2), h is the water level (m), R is the hydraulic radius (m), C is the Chézy formula, and α is the momentum correction coefficient [28].

The MIKE11 *AD* module can simulate the temporal and spatial distribution characteristics of pollutants in a water environment after transport and diffusion under hydrodynamic conditions. The change in substances in water described in MIKE11 can be expressed by the one-dimensional convection diffusion equation

$$\frac{\partial AC}{\partial t} + \frac{\partial QC}{\partial x} - \frac{\partial}{\partial}\left(AD\frac{\partial C}{\partial x}\right) = -AKC + C_2 q \tag{3}$$

where t is the time coordinate (s), x is the distance coordinate (m), C is the pollutant concentration (mg/L), q is the lateral inflow of the river (m^3/s), D is the longitudinal diffusion coefficient of the river (m/s), K is the degradation coefficient of the pollutant (1/d), A is the cross-sectional area of the river (m^2), and C_2 is the concentration of pollutant source/sink (mg/L) [29].

In this study, MIKE11 is used for water quality simulation. The simulated river section is mainly the Guojiatun–Wulongji section of the mainstream Luanhe River. There are four tributaries along the way—namely, the Xingzhou River, Yixun River, Wulie River and Laoniu River, from upstream to downstream. The main stream of the Luanhe River flows through five major sewage outlets, namely, the Luanping Sewage Treatment Plant, the Shuangluan Qingquan Water Company, and Phase I and Phase II of the Taipingzhuang Sewage Treatment Plant of Shuangqiao District and Chengde Qingcheng Water Company. The specific distribution is shown in Table 1. Nonpoint source pollution is mainly distributed in Longhua County, Luanping County, and Chengde County. The specific distribution is shown in Table 2. An overview of pollution source generalization is shown in Figure 3. The external boundary of the simulated reach includes the Guojiatun Hydrological Station on the main stream of the Luanhe River (at the upstream boundary), the Boluonuo Hydrological Station on the Xingzhou River, the Hanjiaying Hydrological Station on the Yixun River, the Chengde Hydrological Station on the Wulie River, the Xiabancheng Hydrological Station on the Laoniu River, and the Wulongji Hydrological Station (at the downstream boundary). The internal boundary includes five lateral inflow point sources of the main stream of the Luanhe River in Chengde and three lateral inflow nonpoint sources along the reach. The hydrological data at the inner and outer boundaries are time series values. In the time series file, the model period is from 9:00 on 1 June 2019, to 9:00 on 31 July 2019.

Table 1. Major sewage treatment plants discharged into the Luanhe River.

Point Source Pollution	Name	Distance from Upper Boundary (m)
①	Luanping Sewage Treatment Plant	127,868
②	Shuangluan Qingquan Water Company	170,949
③	Phase I of Taipingzhuang Sewage Treatment Plant	207,027
④	Phase II of Taipingzhuang Sewage Treatment Plant	207,067
⑤	Chengde Qingcheng Water Company	237,238

Table 2. Distribution of nonpoint sources flowing into the Luanhe River.

Nonpoint Source Pollution	Distribution Area	Distance from Upper Boundary (m)
①	Longhua County	0–84,010
②	Luanping County	84,010–16,060
③	Chengde County	188,040–216,060

The parameter file for the operation and calculation of the HD hydrodynamic module mainly defines the initial conditions of the simulation and riverbed roughness. According to the actual hydrodynamic conditions of the river section and considering the smooth start of the model, the initial water depth and velocity of the main stream of the Luanhe River are added. Riverbed roughness, which is assigned as n, is an important coefficient reflecting the influence of riverbed sidewall roughness on flow movement and the corresponding hydrological analysis. Its value is the key to river network hydrodynamic simulation. This model is calibrated from n = 0.03.

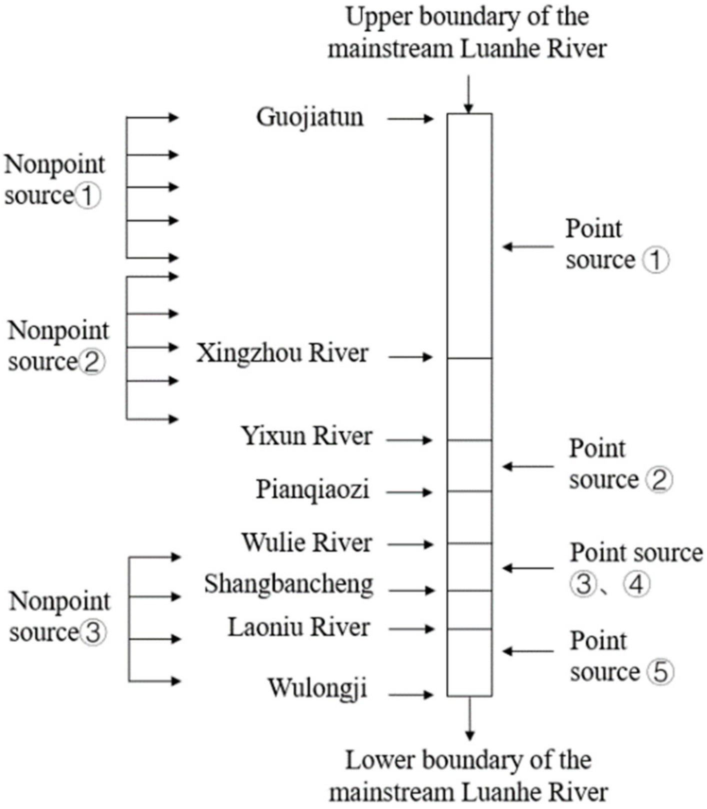


Figure 3. Schematic diagram of pollution source generalization.

The parameters of the AD water quality module mainly include the pollutant components to be simulated, the initial concentration of pollutants, the diffusion coefficient of pollutants in the channel, the attenuation coefficient of pollutants, etc. The pollutants to be simulated in this study are NH_3-N, COD, TN, and TP. The initial concentration is the water quality concentration of the whole basin at the beginning of the calculation. Since this simulation models a stable water quality state, the selection of the initial concentration has little impact on the simulation results. Therefore, in this model, the minimum value of each pollutant at each monitoring station is taken as the initial concentration. The diffusion coefficient in the model is a calibrating parameter. Generally, this value is 5–20 m^2/s. The attenuation coefficient of the pollutant indicates the degradation of the pollutant; that is, the pollutant is decomposed into other substances by microorganisms in the water body in the process of migration with the water flow, which reduces the concentration of the pollutant in the water body. In this study, degradation, adsorption of pollutants in water, and precipitation of pollutants in water are regarded as an overall attenuation. The attenuation coefficient is not uniform in different water bodies. Therefore, the attenuation coefficient should be calibrated by the model. Considering the stability of the calculation, the length of the calculation step is set to 30 s.

2.2.2. EC Calculation

In this paper, the main stream of the Luanhe River in the water system in Chengde is taken as the research object. Hydrological data, water quality data, sewage outlet data, water intake data, pollution source data, socioeconomic index data, research regional statistical yearbooks, etc. are investigated and evaluated. The data consistency is analyzed and a database is formed. The water area is generalized and the characteristics of the river water functional area are clarified. The Guojiatun–Wulongji section of the main stream of the Luanhe River is divided into three calculation units: the Guojiatun–Pianqiaozi section, the Pianqiaozi–Shangbancheng section and the Shangbancheng–Wulongji section. The following calculation model of water environmental capacity is selected.

- Calculation model of water environmental capacity

The one-dimensional water quality model of the river is used to calculate the water environmental capacity of three calculation units in the main stream of the Luanhe River in Chengde. The calculation model is:

$$\text{Total water environmental capacity}: \ E_T = E_D + E_S \tag{4}$$

$$\text{Self} - \text{purification capacity}: \ E_S \ = 86.4 \times (S - C_b) \times Q_r \tag{5}$$

where E_s is the self-purification capacity, kg/d; S is the water quality standard, mg/L; C_b is the river background concentration, mg/L; and Q_r is the river flow, m^3/s.

$$\text{Dilution capacity}: \ E_D = 86.4 \times SQ_t \left(1 - e^{-\frac{kl}{86{,}400u}}\right) \tag{6}$$

where E_D is the dilution capacity, kg/d; S is the water quality standard, mg/L; Q_t is "the river flow + wastewater flow", m^3/s; l is the length of river reach, m; k is the comprehensive attenuation coefficient, 1/d; and u is the river velocity, m/s.

- Water quality target value

The upper limit of the corresponding environmental quality standard category in the water environment functional area is taken as the water quality target value. According to the classification of the surface water environment functional area in Hebei Province, the river water functional area of the Luanhe River Basin in Chengde is mainly planned as class III. Among them, the Guojiatun–Pianqiaozi section is class III, and the Pianqiaozi–Shangbancheng section and the Shangbancheng–Wulongji section are class IV.

2.2.3. EF Assessment

The Tennant method is used to evaluate the environmental flow level in this study. Tennant et al. proposed the Tennant method in 1976 by measuring the physical parameters of river flow—such as the width, depth, and velocity—of 58 sections of the 3145 km reach many times from 1964 to 1974. The Tennant method uses the proportion of annual average flow to link the protection of fish, wildlife, entertainment, and related environmental resources with river flow. Based on the predetermined percentage of annual average flow, Tennant method divides the recommended value of river flow for protecting water ecological and environment into maximum, optimal range, excellent, very good, good, average or relatively poor, poor or minimum, and terrible value (Table 3). The EF level can be evaluated according to the proportion of monthly average flow to annual average flow. Macroscopically, it can guide basic water demand management in river ecological protection and can also reflect the local EF level to a certain extent.

Table 3. River flow conditions for protecting fish, wildlife, entertainment, and related environmental resources.

Narrative Description of the Flow	Percentage of Annual Average Flow	
	Dry Season (From October to March of the Next Year)	Wet Season (From April to September)
Maximum	200	200
Optimum range	60~100	60~100
Excellent	40	60
Very good	30	50
Good	20	40
Average or relatively poor	10	30
Poor or minimum	10	10
Terrible	<10	<10

According to this method, for most aquatic organisms, 10% of the annual average flow of the river is the minimum flow to maintain its short-term survival habitat. Thirty percent of that is the basic flow to maintain good living conditions for its general activities. When reaching 60%, an excellent habitat for their early growth and most activities is reached. In the Northern Hemisphere, the dry season is from October to March of the next year in most areas, and the river flow needs to meet general water use. The wet season is from April to September, which is the spawning and juvenile stage of most fish. The river flow needs to meet the reproduction and survival requirements of fish. Based on that, the Tennant method recommends 10% of the annual average flow for the ecological base flow from October to March of the next year in the dry season and 30% of the annual average flow for the ecological base flow from April to September in the wet season.

2.2.4. Setting of Water Pollution Prevention and Control Scheme

According to the water pollution discharge pattern and surface water resource reserves of Luanhe River Basin in Chengde, it is feasible to reduce point source pollution, reduce nonpoint source pollution, and increase upstream water inflow, which is also the main direction of water pollution prevention and control considered by Chengde Ecological Environment Bureau. Thus, these three measures—namely, reducing point source pollution, reducing nonpoint source pollution, and increasing upstream water—are selected to form eight water pollution control schemes, as shown in Table 4. The specific implementation methods of the three measures are determined by the emission of point and nonpoint source pollutants in the study area and the relevant plans of Chengde Ecological Environment Bureau, after consulting the officers of the government. Table 5 shows the details.

Table 4. Setting of water pollution control scheme.

	Reducing Point Source Pollution	**Reducing Nonpoint Source Pollution**	**Increasing Upstream Water**
Scenario 1			
Scenario 2	✓		
Scenario 3		✓	
Scenario 4	✓	✓	
Scenario 5			✓
Scenario 6	✓		✓
Scenario 7		✓	✓
Scenario 8	✓	✓	✓

Table 5. Setting of water pollution control measures.

Measures	**Specific Implementation Methods**
Reducing point source pollution	The total emission of point source ③ is reduced by 25%, the total emission of point source ① and point source ④ is reduced by 15%, and the total emission of point source ⑤ is reduced by 10%
Reducing nonpoint source pollution	The total amount of nonpoint sources ① and ③ entering the river is reduced by 20%, and the total amount of nonpoint sources ② entering the river is reduced by 25%,
Increasing upstream water	Water from upstream boundary increased by 10%

2.3. Data Sources

- Topographical data

The topographical data required in this study are basin digital elevation model (DEM) data, which are STRM 30 × 30 m data provided by the geospatial data cloud platform of the Chinese Academy of Sciences.

- Hydrological data

The hydrological data mainly include the river width (m), river depth (m), flow velocity (m/s), and flow volume (m^3) of the hydrological monitoring section of the mainstream

Luanhe River, which are provided by the local Water Resources Bureau and are mainly used for the basin hydrodynamic simulation in the HD hydrodynamic module of the MIKE11 model.

- Water quality data

The water quality data mainly include the pollution indicators and concentrations of the water quality monitoring section of the main stream of the Luanhe River, which is provided by the local Ecological and Environmental Protection Bureau and is mainly used for the calibration and verification in the AD water quality module of the MIKE11 model.

- Pollution source data

Pollution source data include point source pollution data and nonpoint source pollution data. Point source data refer to the concentration and flow of various indicators of wastewater discharged from sewage treatment plants and industrial enterprises, and nonpoint source data refer to the inflow of various pollutants caused by agricultural production, soil and water loss, and other factors. The data are provided by the local Ecological Environmental Protection Bureau and are mainly used for the construction of the AD water quality module of the MIKE11 model.

3. Results and Discussion

3.1. Model Calibration and Validation Results

Calibrated on the data of June 2019 and verified on the data of July 2019, the following results are obtained.

3.1.1. HD Hydrodynamic Module

After several commissioning calculations, the roughness value conforming to hydrodynamic conditions is determined. Taking the Guojiatun hydrological station as the starting point, the roughness values of 0–70 km, 70–126 km, and 126–242 km of the main stream of the Luanhe River are taken as 0.034, 0.030, and 0.024, respectively. The discharge data of the Sandaohezi hydrological station are used for verification. The results are shown in Figure 4. The calibration results are relatively accurate, and the water quality simulation can be carried out on the basis of these values.

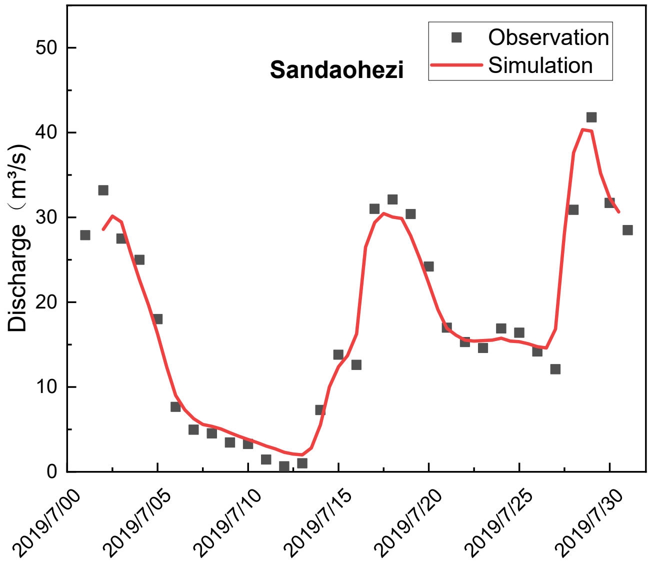


Figure 4. Comparison between simulated and measured discharge values of Sandaohezi hydrological station.

3.1.2. AD Water Quality Module

The longitudinal diffusion coefficient D of the river channel is estimated and simulated. Through continuous calibration and adjustment according to the actual concentration of pollutants in the monitoring section during simulation, the final value is determined to be 9. Taking the monitoring sections of Gonghou, Pianqiaozi, and Shangbancheng as calibration points, the measured values of pollutant monitoring indicators in July 2019 are selected to calibrate the model. By constantly adjusting the attenuation coefficient of various pollutants, comparing the simulated and actual values of pollutant concentration, and observing the multiple fitting results, the coefficients with the best fit are selected as the comprehensive attenuation coefficient values of pollutants in the river section. The calibration results are shown in Table A1.

Tables 6 and 7 show that the relative errors between the simulated and measured values of NH_3-N, COD, TN, and TP are controlled within ±8.00%, indicating that the water quality model has high simulation accuracy and that the selection of model parameters is reasonable.

Table 6. Error statistics of NH_3-N and COD simulation results of the MIKE11 water quality model.

Sections	**NH_3-N (mg/L)**			**COD (mg/L)**		
	MeasuredValue	**Simulated Value**	**Relative Error**	**Measured Value**	**Simulated Value**	**Relative Error**
Gonghou	0.10	0.10	0.00%	14.00	13.91	−0.65%
Pianqiaozi	0.13	0.14	6.15%	21.00	19.70	−6.18%
Shangbancheng	0.32	0.31	−3.13%	9.00	9.40	4.44%

Table 7. Error statistics of TN and TP simulation results of the MIKE11 water quality model.

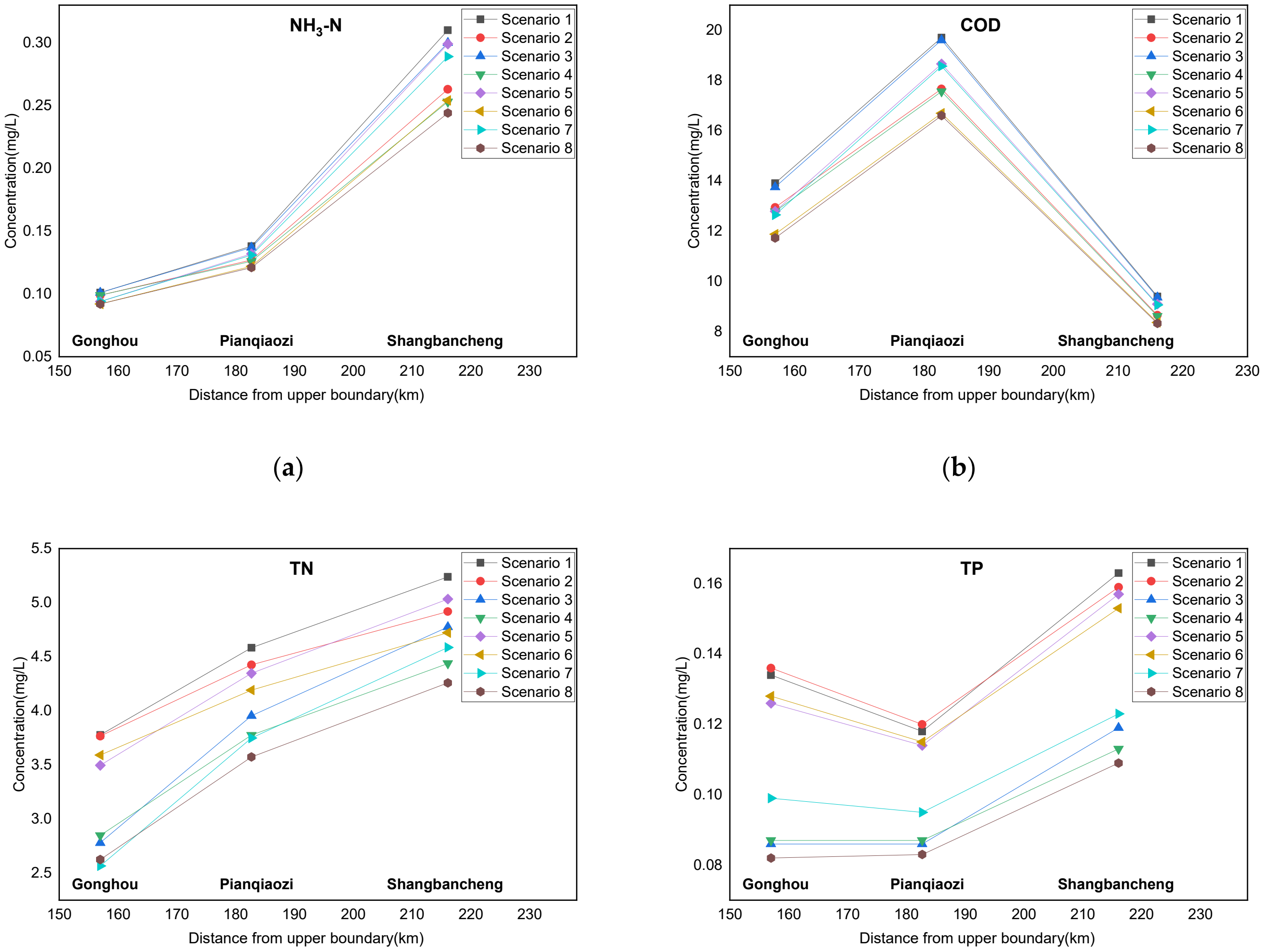
Sections	**TN (mg/L)**			**TP (mg/L)**		
	Measured Value	**Simulated Value**	**Relative Error**	**Measured Value**	**Simulated Value**	**Relative Error**
Gonghou	3.54	3.78	6.69%	0.14	0.13	−4.29%
Pianqiaozi	4.37	4.58	4.87%	0.11	0.12	7.27%
Shangbancheng	5.37	5.24	−2.46%	0.17	0.16	−4.12%

3.2. Analysis of Simulation Results of Different Water Pollution Control Schemes

3.2.1. Water Quality Response Analysis

Under the eight schemes, the changes in NH_3-N, COD, TN, and TP concentrations in the Gonghou, Pianqiaozi, and Shangbancheng monitoring sections are shown in Table A2.

As shown in Figure 5, on the whole, the reduction effects of reducing point source pollution on the concentrations of the four pollutants in each section are obvious, the reduction effects on NH_3-N and COD are significant, the reduction effect on TN is general, and the reduction effect on TP is weak. The reduction effects of reducing nonpoint source pollution on NH_3-N and COD in each section are not obvious, except for TN and especially TP. In the process of model building, the nitrogen nonpoint source pollutants are NH_3-N and TN, but the nonpoint source load reduction has little effect on the concentration of NH_3-N and has a great effect on the concentration of TN. It can be inferred that NH_3-N in nonpoint source pollutants may be transformed into nitrate nitrogen through chemical reactions, which increases the TN concentration. Increasing the upstream water also has a certain reduction effect on the concentration of pollutants, but the effect is often obvious near the upstream boundary. With a gradual increase in the distance from the upstream point, the reduction effect decreases gradually.



(**a**) (**b**)

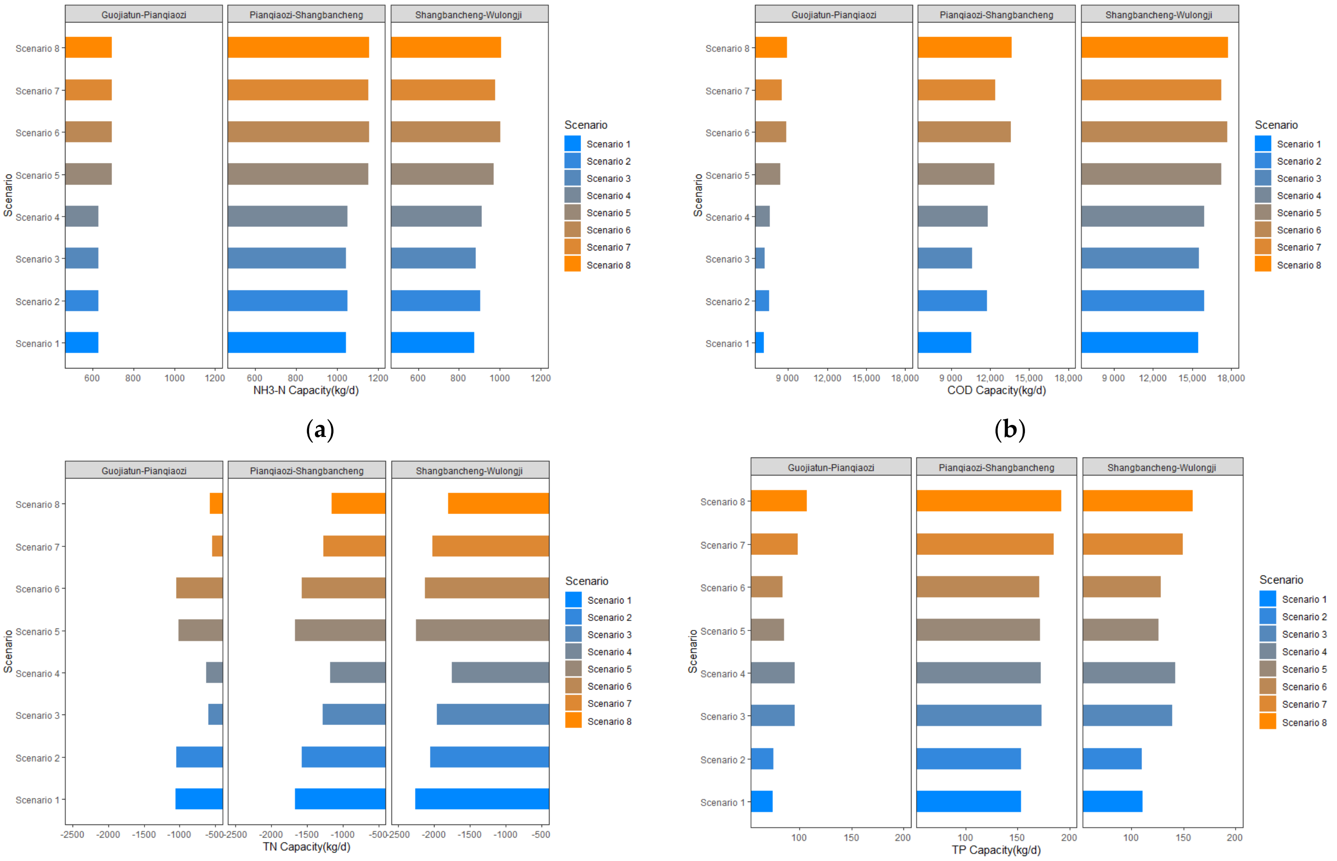
(**c**) (**d**)

Figure 5. Change in NH_3-N (**a**), COD (**b**), TN (**c**), and TP (**d**) concentration.

3.2.2. EC Response Analysis

According to the calculation model of the Luanhe River mainstream water environmental capacity, the NH_3-N, COD, TN, and TP capacities of the Luanhe River mainstream in the typical wet season under eight water pollution control schemes are calculated. The results are shown in Table A3.

The change patterns of NH_3-N and COD capacity are basically the same. Figure 6a shows that increasing upstream water has an obvious effect on increasing the NH_3-N capacity, reducing point source pollution can also expand the NH_3-N capacity to a certain extent, and reducing nonpoint source pollution has a weak impact on the change in NH_3-N capacity. Figure 6b shows that increasing upstream water has the most obvious effect on increasing the COD capacity. Reducing point source pollution can also expand the COD capacity to a certain extent. Reducing nonpoint source pollution has little effect on the COD capacity. Increasing the water from upstream and reducing point source pollution at the same time has an excellent capacity expansion effect on NH_3-N and COD.



(**a**) (**b**)

(**c**) (**d**)

Figure 6. Change in NH_3-N (**a**), COD (**b**), TN (**c**), and TP (**d**) capacity.

The TN capacity of the main stream of the Luanhe River in Chengde is negative, and the TN content is overloaded as a whole. Figure 6c shows that increasing upstream water has little impact on TN capacity, reducing point source pollution has a certain promoting effect on the increase in TN capacity, and reducing nonpoint source pollution can significantly increase TN capacity. As seen from Figure 6d, reducing point source pollution has little impact on TP capacity, increasing upstream water has a significant impact on TP capacity, and the effect of reducing nonpoint source pollution on TP capacity is slightly stronger than increasing upstream water. Reducing nonpoint source pollution and increasing upstream water at the same time can significantly expand TP capacity.

3.2.3. EF Response Analysis

The Tennant method is used to evaluate the ES status of the main stream of the Luanhe River under eight schemes, and the discharge data at Sandaohezi are taken for calculation. The results are shown in Table 8.

Table 8. Evaluation results of the Tennant method under different water pollution control schemes.

	Proportion in Annual Average Flow (100%)	**Narrative Description of the Flow**
Scenario 1	1.867	Out of optimal range, less than maximum
Scenario 2	1.849	Out of optimal range, less than maximum
Scenario 3	1.867	Out of optimal range, less than maximum
Scenario 4	1.849	Out of optimal range, less than maximum
Scenario 5	2.029	Maximum exceeded
Scenario 6	2.011	Maximum exceeded
Scenario 7	2.029	Maximum exceeded
Scenario 8	2.029	Maximum exceeded

The calculation results show that increasing upstream water can improve the level of ES to a certain extent and that reducing point source pollution and nonpoint source pollution has little effect on the change in ES. Generally, the main stream of the Luanhe River has sufficient flow in July, which can meet the demand under different simulation scenarios and can provide a good habitat and growth environment for aquatic animals and plants.

3.3. Discussion

According to the research results, the concentrations of NH_3-N and COD in the Luanhe River Basin of Chengde City are mainly affected by point source pollution, and the concentrations of TN and TP are mainly affected by nonpoint source pollution. The water environmental capacity of NH_3-N, COD, and TP is a surplus, but TN is obviously overloaded. The water in the study area is sufficient to meet the demand of the social economy and provide a good habitat and growth environment for aquatic animals and plants.

At present, the actual sewage treatment capacity of Chengde accounts for only 45% of the design treatment capacity, and some sewage treatment plants have problems, such as a lack of diversion of rainwater and sewage and the aging of pipe networks, resulting in sewage leakage and the pollution of surface and underground water resources. Therefore, Chengde can strengthen the diversion of rain and sewage, upgrade the sewage treatment plant, and speed up the improvement of the supporting pipe network and the management of sewage treatment systems to reduce the pollution load of sewage treatment plants in the water environment of the basin.

According to the survey, in addition to soil erosion and pollutants from sewage treatment plants, agricultural nonpoint source pollution has a great impact on the Luanhe River Basin. According to the analysis of the current situation of the Luanhe River Basin, agricultural nonpoint source pollution is still serious, and the proportion of total nitrogen and ammonia nitrogen flow to the environment due to agricultural pollution in 2019 is very high. At the same time, the low utilization rate of chemical fertilizers and pesticides in the basin is also one of the reasons for low amounts of agricultural nonpoint source pollution. Therefore, for the control of agricultural nonpoint sources, we should start with farmland, adopt different irrigation technologies according to local conditions, actively develop water-saving agriculture, continue to promote the mode of water fertilizer integration, and reduce farmland nutrient loss. At the same time, for some land types, the planting structure can also be adjusted appropriately to improve agricultural production efficiency.

4. Conclusions

Based on the concepts of the EC and EF and the MIKE11 model, a simulated evaluation method of the basin water pollution control scheme was established to explore the changes in the water environment and water ecology in the basin under different water pollution control schemes, and the method was applied to the Luanhe River Basin in Chengde, Hebei Province, China. Reducing point source pollution, reducing nonpoint source pollution, and increasing upstream water were selected to be combined into eight water pollution control schemes. The concentration changes of NH_3-N, COD, TN, and TP under eight different water pollution control schemes in the study area were simulated, and the responses of EC and EF were compared and analyzed. The results show that in the study area: (1) Overall, within the scope of model simulation, reducing point source pollution has the most obvious effect on water pollution prevention, reducing nonpoint source pollution is slightly inferior to reducing point source pollution, and the effect of increasing upstream water on water pollution prevention is the weakest. Reducing point source pollution has obvious reduction effects on NH_3-N, COD, and TN—especially on NH_3-N and COD—while the reduction effect on TP is weak. Reducing nonpoint source pollution has a very obvious effect on TP reduction and contributes to TN reduction. (2) The environmental capacity of the Luanhe River's main stream is still considerable, but TN overload is serious. The increase in upstream water inflow can greatly increase the water environmental capacity of NH_3-N and COD, and reducing point source pollution can also increase the water environmental capacity of NH_3-N and COD to a certain extent, but reducing nonpoint source pollution has no significant impact. The increase in upstream water inflow has little impact on TN and TP, but reducing point source pollution can reduce this impact. The water environmental capacity of TN can be greatly increased by reducing point source pollution, and the environmental capacity of TP can be greatly increased by reducing nonpoint source pollution. (3) The increase in upstream water inflow can improve the EF level to a certain extent. Generally, the main stream of the Luanhe River has sufficient flow in July, which can meet the demand under different simulation scenarios and can provide a good habitat and growth environment for aquatic animals and plants.

In summary, this method can be used to predict the changes in the water environment and water ecology in the basin under different water pollution prevention and control schemes and to provide a decision-making basis for the comprehensive prevention and control of water pollution in the basin to improve the effectiveness of water pollution prevention and control measures, highlight key points in the treatment process, promote the reduction of water pollutants, and improve the effectiveness of investment in water pollution control. At the same time, this method can also promote the completion of the total amount of control indicators of major water pollutants, and help solve the urgent problems faced by water pollution control and governance. It will be helpful to form a scientific management system for water environment protection and provide a scientific and reliable basis for water environmental capacity control and water ecological restoration in the basin.

Author Contributions: C.L. conceived and designed the research; X.L. wrote the paper; X.W. analyzed the data; Y.Y. performed the research; Q.L. and X.Z. contributed analysis tools. All authors have read and agreed to the published version of the manuscript.

Funding: This study is supported by Beijing Natural Science Foundation (JQ19034) and GEF Mainstreaming Integrated Water and Environment Management (P145897-3-03).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Restrictions apply to the availability of these data. Data are available from the authors with the permission of third party.

Acknowledgments: We would like to extend special thanks to the editor and reviewers for insightful advice and comments on the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Calibration results of the attenuation coefficient of the MIKE11 water quality model.

Index	**Index Attenuation Coefficient (d^{-1})**		
	Guojiatun–Gonghou	**Gonghou–Pianqiaozi**	**Pianqiaozi–Wulongji**
NH_3-N	0.14	0.12	0.09
COD	0.20	0.18	0.20
TN	0.14	0.10	0.11
TP	0.12	0.11	0.09

Table A2. Water quality simulation results under different water pollution control schemes.

	NH$_3$-N (mg/L)			COD (mg/L)		
	Guojiatun–Pianqiaozi	Pianqiaozi–Shangbancheng	Shangbancheng–Wulongji	Guojiatun–Pianqiaozi	Pianqiaozi–Shangbancheng	Shangbancheng–Wulongji
Scenario 1	0.10	0.14	0.31	13.91	19.70	9.40
Scenario 2	0.10	0.13	0.26	12.95	17.66	8.66
Scenario 3	0.10	0.14	0.30	13.75	19.61	9.36
Scenario 4	0.10	0.13	0.25	12.79	17.56	8.62
Scenario 5	0.09	0.13	0.30	12.79	18.66	9.10
Scenario 6	0.09	0.12	0.25	11.88	16.69	8.37
Scenario 7	0.09	0.13	0.29	12.65	18.57	9.06
Scenario 8	0.09	0.12	0.24	11.73	16.60	8.33
	TN (mg/L)			TP (mg/L)		
	Guojiatun–Pianqiaozi	Pianqiaozi–Shangbancheng	Shangbancheng–Wulongji	Guojiatun–Pianqiaozi	Pianqiaozi–Shangbancheng	Shangbancheng–Wulongji
Scenario 1	3.78	4.58	5.24	0.13	0.12	0.16
Scenario 2	3.89	4.43	4.92	0.14	0.12	0.16
Scenario 3	2.78	3.95	4.77	0.09	0.09	0.12
Scenario 4	2.85	3.78	4.44	0.09	0.09	0.11
Scenario 5	3.50	4.35	5.03	0.13	0.11	0.16
Scenario 6	3.59	4.19	4.72	0.13	0.12	0.15
Scenario 7	2.57	3.75	4.59	0.10	0.10	0.12
Scenario 8	2.63	3.57	4.26	0.08	0.08	0.11

Table A3. Water environmental capacity of NH3-N, COD, TN, and TP in the main stream of Luanhe River.

	NH$_3$-N (kg/d)			COD (kg/d)		
	Guojiatun–Pianqiaozi	Pianqiaozi–Shangbancheng	Shangbancheng–Wulongji	Guojiatun–Pianqiaozi	Pianqiaozi–Shangbancheng	Shangbancheng–Wulongji
Scenario 1	629.719	1044.326	875.980	7150.111	10,566.753	15,482.217
Scenario 2	628.375	1049.580	904.476	7546.266	11,787.000	15,930.188
Scenario 3	629.719	1044.925	882.244	7221.316	10,625.938	15,506.965
Scenario 4	628.375	1050.168	911.068	7620.370	11,848.053	15,955.604
Scenario 5	695.136	1152.398	970.887	8412.537	12,314.257	17,233.074
Scenario 6	693.869	1158.006	1001.273	8828.469	13,607.245	17,718.420
Scenario 7	695.136	1153.069	977.556	8485.712	12,376.311	17,259.481
Scenario 8	693.869	1158.676	1008.257	8904.421	13,671.142	17,745.585
	TN (kg/d)			TP (kg/d)		
	Guojiatun–Pianqiaozi	Pianqiaozi–Shangbancheng	Shangbancheng–Wulongji	Guojiatun–Pianqiaozi	Pianqiaozi–Shangbancheng	Shangbancheng–Wulongji
Scenario 1	−1052.491	−1663.054	−2257.688	73.920	153.540	111.063
Scenario 2	−1050.045	−1567.978	−2055.818	74.597	153.621	110.400
Scenario 3	−596.735	−1280.191	−1963.075	95.611	173.011	139.033
Scenario 4	−630.020	−1172.364	−1750.107	94.975	172.651	142.356
Scenario 5	−1017.201	−1664.750	−2250.534	85.011	172.032	125.970
Scenario 6	−1047.305	−1568.901	−2124.275	83.734	171.190	128.542
Scenario 7	−549.662	−1270.522	−2027.885	98.535	184.829	149.882
Scenario 8	−581.208	−1154.831	−1800.165	107.041	192.475	159.403

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