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Simulation of the Transboundary Water Quality Transfer Effect in the Mainstream of the Yellow River

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Abstract: In order to not only solve the technical problems of quantifying the degree and range of the effect that is caused by the water quality of upstream on that of downstream portions of a river, and of dividing the responsibility of transboundary water pollution, but also to tackle the difficulty in adapting to dynamic changes of the traditional water quality model in terms of practical application, pollutant discharge and water consumption were taken as the main influence factors to build the transboundary water quality transfer effect model. Supported by a comprehensive integration platform, the transboundary water quality transfer effect simulation system of the Yellow River mainstream was constructed. The simulation results show that the concentration decreases exponentially along the range. Gansu, Ningxia, and Inner Mongolia had a more significant effect of exceeding standard water consumption on pollution, while Ningxia, Inner Mongolia, Shaanxi, and Shanxi had a more distinct contribution to the over standard pollution discharge effect. The proposed model and simulation system can provide new methods and instruction for quantifying the degree and range of transboundary water pollution, as well as dividing the responsibility for water environment compensation.

Keywords: transboundary water pollution; water quality; comprehensive integration; the Yellow River mainstream

1. Introduction

The occurrence of transboundary water pollution events has not only resulted in adverse effects on surroundings, but also threatened the water ecology and human health in the whole basin. Moreover, it has resulted in disputes across the administrative regions [1]. A direct method to solve the disputes of transboundary water pollution is water environment compensation, but the demarcation of water pollution responsibility is a barrier to achieving this. The pollution transmission in a river basin is integral, and successive pollutant accumulation in upper reaches has a continuous impact on the overall area in the lower reaches. Therefore, clearly dividing the responsibility for transboundary water pollution has become a tough problem.

Current studies on transboundary water pollution mainly focus on the mechanism and regulations between relevant areas and departments in terms of coordination, as well as cooperation [2–4]. Meanwhile, they pay a great deal of attention to the strategies costs, along with the risk-related mitigation and adaptation measures [5]. Furthermore, cross boundary water quality monitoring is used to analyze or predict pollution changes [6–8]. Based on the water quantity and pollutant discharge change to construct the water environment input response model [9], a great mass of quantificational methods of transboundary water pollution are formed. They are widely used to predict the water quality in a certain area or several continuous sections of the downstream portions [10], determine the order of the effect caused by different pollution sources on the target section water quality [11], and so on. Diogo et al. [12] implemented total phosphorous quantification methodologies for urban, industrial, and diffuse (non-point) sources and used them as the input in the two-dimensional hydrodynamic and water quality model CE-QUAL-W2. Then, two scenarios were used to simulate the effect of pollution reduction on water quality of the Alqueva Dam. Ganoulis [13] explained the meaning of Integrated Water Resources Management (IWRM), and applied the mathematical modeling of water quality at the basin scale as a first step towards achieving environmental protection. Considering the uncertainty, Ganoulis proposed a risk-based methodology for IWRM at the basin scale with special reference to transboundary river basins. Based on a special algorithmic procedure, Batzias et al. [14] presented a methodology including 20 activity stages and 10 decision nodes to not only quantify the environmental impact, but to also formulate a necessary knowledge framework to maximize the joint benefit and create a suitable background for bilateral negotiations, so as to reach the ultimate goal, which is to come to an agreement of great satisfaction for both parts. Wang et al. [15], based on the water quality assessment requirements of the boundaries of the river basin, established the ecological compensation estimation model to determine the compensation amount in the adjacent administrative area, and constructed a method to calculate the pollutant flux in the provincial section. Ren et al. [16] established the water environment input response model, which predicts the pollution characteristics variation of the Yellow River Ningxia exit section caused by the change of water quality and quantity in the Yellow river mouth drainage channel. The model is used to predict the impact of sewage which discharged into the Yellow River on the water quality of the river basin. Zhang [17] established the transboundary pollution input response model of the Liaohe source region by using the linear superposition principle. The model quantifies the contribution to the water quality in the cross section among different pollutant sources, and it also determines the main pollutants in the river and the relationship between the pollutants and the cross section water quality. He [18] combined the main influence factors of the water quality, quantity of the upstream portion, and the pollutant discharge along the river, in order to build the input response model to study the river section water quality. After that, he explained the contribution degrees of the influence factors to the water quality, whilst also simulating and analyzing the sensitivity of the factors to the water quality changes. Based on the method of spatial regression, Yang et al. [19] evaluated and predicted the impacts of watershed characteristics on ambient total nitrogen (TN) concentration in a heavily polluted watershed. Regression results confirm that point and non-point pollution sources do have a substantial impact on TN concentration.

These studies provide a scientific basis for the prevention and solution in the research of transboundary water pollution. However, there are still some problems, such as the lack of quantifying methods for the transboundary pollution degree and scope, as well as unclear transboundary water pollution responsibility division. Thus, constructing a model to quantify the extent and scope of water pollution and divide the water pollution responsibilities is demanded. Furthermore, traditional methods and models with a large amount of calculation are unable to adapt to the dynamic changes and development, leading to a weak generality and applicability. Therefore, a simulation system relying on information technology should be established to make calculations among different demands, so as to adapt to dynamic changes and provide convenience in decision-making.

According to the evolution law of the water environment system, the influence factors of pollutant discharge and water consumption were considered, the transboundary water quality transfer effect model was set up, and the effect of scope and degree of water consumption and pollutant discharge on the water quality of the downstream sections were analyzed in this paper. Based on the comprehensive integration platform, the transboundary water quality transfer effect simulation system of the Yellow River mainstream was built. When demands were adjusted, the dynamic simulations of the transboundary water quality transfer effect in the Yellow River mainstream under different scenarios was realized. Therefore, the basis of decision-making was supplied. The model and system are beneficial to the exploration of the responsibility division in both cross-boundary water pollution and water environment compensation.

2. Study Area and Data

2.1. Study Area

The Yellow River is an important source of water in Northwest and North China. It has an important impact on the development of regional economy and society. The Yellow River originates from the Bayan Har mountains in the Qinghai province of China. It flows through nine provinces and regions of Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong, and finally injects into the Bohai Sea in the Shandong province.

Due to the rapid economic and societal development of the Yellow River basin in recent years, the provincial border Shizuishan of Ningxia and Inner Mongolia; the border Toudaoguai of Shanxi, Shaanxi, and Inner Mongolia; and the border Tongguan of Shanxi, Shaanxi, and Henan, do not reach their water quality goals. Cross-boundary water pollution problems still persist, severely restricting economic and social sustainable development. Therefore, there is an urgent need to solve the technical problems of dividing the responsibility of transboundary water pollution and carry out the research on the transboundary water quality transfer effect in the Yellow River mainstream.

Water shortage and pollution discharge have become major problems of the Yellow River and both of them affect the water quality of the mainstream. From the year 2003 to 2012, the consumptions of surface water in Shaanxi and Shanxi did not exceed the water distribution indexes of the Yellow River basin, and the other provinces and regions exhibited over index water consumption in varying degrees, among which the over index water use in Gansu, Ningxia, and Inner Mongolia was serious. In the period of 2003 to 2012, the highest excessive percentage in Gansu was 35.7%. Ningxia's highest percentage that exceeded the standard reached 87.4% in 2005. The percent of Inner Mongolia was up to 31.7%.

Since 1980s, the emission of waste water in the Yellow River Basin has increased due to human activities, and the pollution of surface water bodies is becoming more and more serious [20]. The Yellow River Basin Water Resources Protection Bureau adopted the monthly water quality data from 2010 to 2012, and the comprehensive pollution index method was used to evaluate the water quality of each provincial boundary in the Yellow River mainstream. The results were as follows: the six boundaries of Dahejia, Xiaheyan, Hequ, Huayuankou, Gaocun, and Lijin came up to the water quality standard, while the other three boundaries (Shizuishan, Toudaoguai, and Tongguan) failed.

In the substandard sections, Shizuishan section, an important section of Ningxia, was assessed as the fourth class standard in terms of water quality. The main unqualified indexes were the permanganate index, chemical oxygen demand (COD), ammonia nitrogen (NH_3-N), arsenic, BOD_5, and so on. In the years of 2011 and 2012, the water quality of Toudaoguai section—the Inner Mongolia's exit section—was measured as the fourth class standard. The unqualified indexes were COD and NH_3-N. Tongguan section, which is the junction of Shanxi, Shaanxi, and Henan provinces, was the fifth class standard for water quality in 2010, and the figure changed to the fourth class in 2011 and 2012. The main unqualified indexes were the permanganate index, COD, NH_3-N, and BOD_5.

The water quality evaluation results of the Yellow River mainstream showed that the main pollutants were aerobic organic compounds characterized by COD and NH_3-N. The two indexes are also control indexes of pollutant gross control, water quality assessment, and water function area assessment. Besides, according to the statistics of pollution discharge in key enterprises, the paper making industry, the printing and dyeing textile industry, and the food processing industry are considered as the key pollution industries. The main pollutants emitted by these three industries are COD and NH_3-N. According to the above considerations, this study took the COD and NH_3-N as calculation indexes to research the transboundary water quality transfer effect in the study area. It is worth mentioning that the research methods of other pollution indexes are similar.

2.2. Computing Units Division

The node division method was used to divide the calculation units. The reaches between provincial boundaries of the Yellow River mainstream were selected as the calculation units. When the interval was too long, such as the Toudaoguai-Tongguan reach, the calculation nodes were appropriately added. In addition, the sensitive points of important reservoirs and towns, such as Sanmenxia reservoir and Huayuankou, were also considered as nodes in the basin. In this study, Dahejia section, the boundary of Qinghai and Gansu provinces, was taken as the starting section, while Lijin section in Shandong was regarded as the termination section. Yellow River mainstream was divided into 12 computing units by 13 nodes in total (Figure 1). The river computing units and the lengths are listed in Table 1.

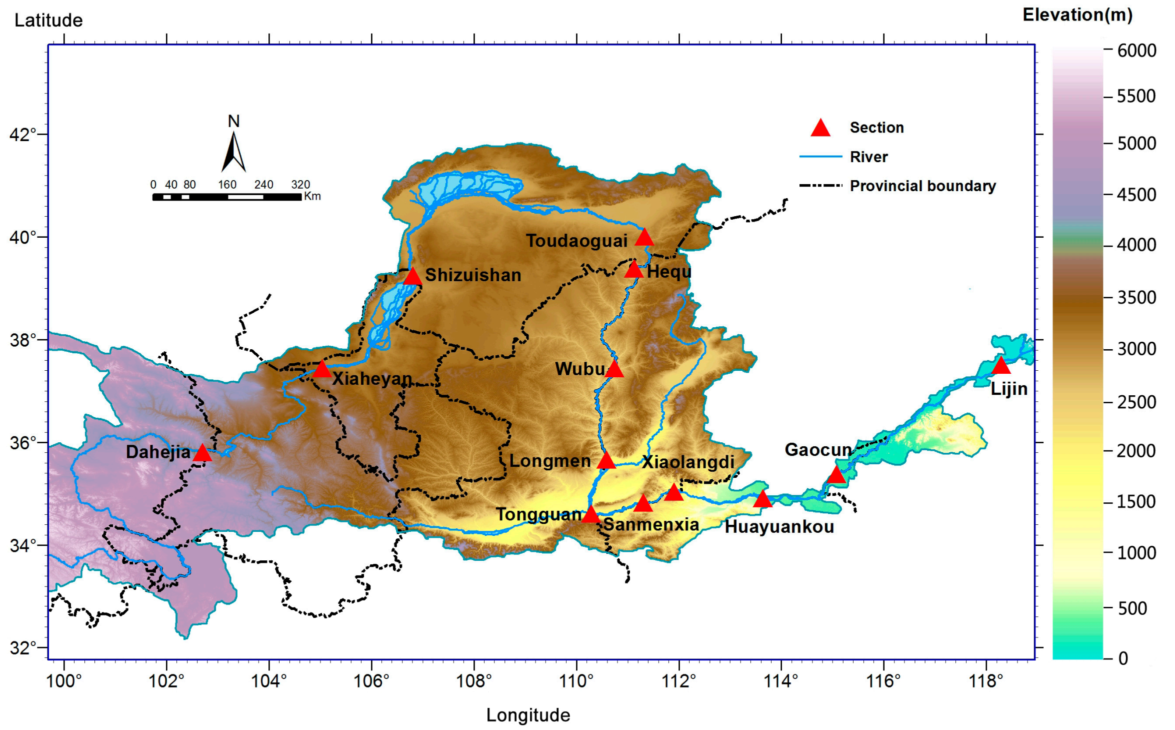


Figure 1. River computing units division.

Table 1. River computing units division list.

Number	Section	Computing Unit	Unit Length (km)	Number	Section	Computing Unit	Unit Length (km)
1	Xiaheyan	Dahejia-Xiaheyan	544	7	Tongguan	Longmen-Tongguan	129
2	Shizuishan	Xiaheyan-Shizuishan	337	8	Sanmenxia	Tongguan-Sanmenxia	111
3	Toudaoguai	Shizuishan-Toudaoguai	684	9	Xiaolangdi	Sanmenxia-Xiaolangdi	92
4	Hequ	Toudaoguai-Hequ	120	10	Huayuankou	Xiaolangdi-Huayuankou	167
5	Wubu	Hequ-Wubu	298	11	Gaocun	Huayuankou-Gaocun	189
6	Longmen	Wubu-Longmen	277	12	Lijin	Gaocun-Lijin	475

3. Transboundary Water Quality Transfer Effect Model

3.1. Model Description

The pollution in the upper reaches of the basin will affect the water quality of one or more areas in the downstream area, and the effect is continuous and transitive. Using the recursive calculation method to study the degree and scope of this effect from upstream to downstream is called the study of the water quality transfer effect. The purpose of this study is to explore the responsibility division method of the transboundary water pollution, and provide a quantitative basis for the related profit and loss accounting on water environment compensation.

To understand the transboundary water quality transfer effect intuitively, we can assume that there is a transboundary river that flows through n regions which is divided by $n+1$ sections (Figure 2), and two factors, water consumption and sewage discharge, affect the river water quality in each region. The flow of the initial section is Q_0 and the background concentration of it is C_0. The flow of the Section 1 is Q_1 and the concentration is C_1, the pollutant discharge flow of the region 1 is q_{p1}, and the water intake flow is q_{c1}, and the following indexes are named in the same way. C_1 is the superposition result of the attenuation and migration of C_0, as well as the water consumption and the pollutant discharge effect of region 1. Furthermore, this effect in the region 1 is regarded as ΔC_1, and the result of the attenuation and migration of C_0 in the region 1 is considered as $C_0{}'$. Therefore, C_1 could be expressed by the following equation:

$$C_1 = C_0{}' + \Delta C_1 \tag{1}$$

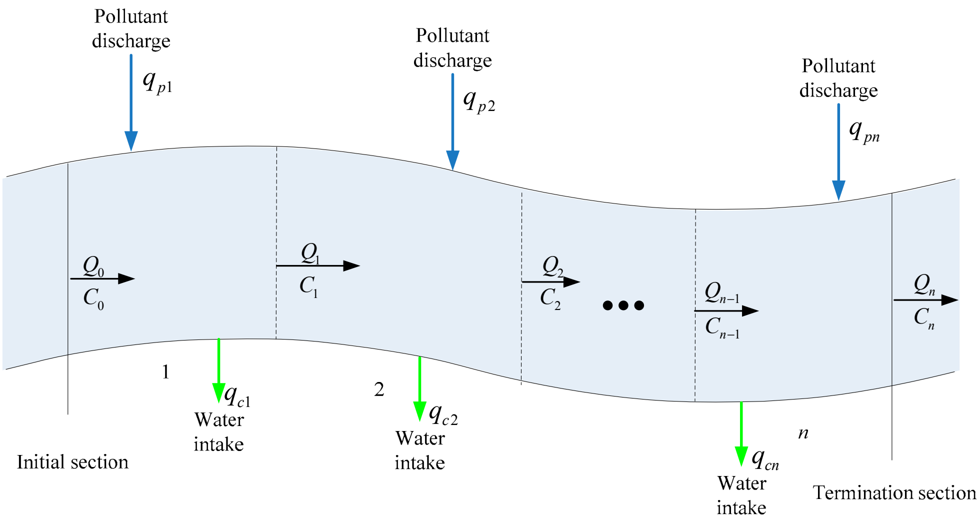


Figure 2. The schematic diagram of the transboundary water quality transfer effect model.

And we can deduce the rest from this:

$$C_2 = C_0{}'' + \Delta C_1{}' + \Delta C_2 \tag{2}$$

$$\vdots$$

$$C_n = C_0{}^{(n)} + \Delta C_1{}^{(n-1)} + \cdots + \Delta C_{n-1}{}' + \Delta C_n \tag{3}$$

To facilitate the study of the water quality transfer effect, two scenarios are proposed.

Scenario 1: The concentration transfer effect. It is assumed that whether the water quality of the section reaches the standard level or not will affect the downstream water quality. In this scenario, the water quality concentration, including the monthly measured value or annual mean value, is taken as the model variable to calculate the degree and scope of the concentration transfer effect on the downstream portion. The scenario does not take the situation of whether the pollutant concentration in the section is up to standard or not into account.

Scenario 2: The over standard concentration transfer effect. In practical application, in order to divide the pollution responsibility, define the loss of water pollution, and determine the compensation standard, the variation of the concentration caused by exceeding standard pollutant charge and exceeding index water consumption can also be used as the variable in the model. The calculation can reflect the impact of the compensation ratio in the upstream area on the downstream portion in terms of excessive sewage discharge and excessive water intake. The water consumption standard adopts the water distribution index of the Yellow River basin. The standard of pollutant discharge is judged according to the corresponding concentration of the water quality target level of the section, which refers to the national standard of Environmental Quality Standards for Surface Water (GB3838-2002), and the excess part is the over standard concentration. It is assumed that the water quality assessment of a certain section reached the standard, and the responsibility of the pollution discharge in this area should not be investigated; the water consumption in a certain area is up-to standard and the effect of water consumption on the downstream water quality should not be investigated. The model can calculate the transfer effect of two factors over standard discharge and over standard water consumption, both of which need to be converted into the concentration unit for calculating this effect. The scenario is mainly used in the situation where the section has the water quality assessment task and is only accountable for superscalar situations.

3.2. Model Construction

3.2.1. Concentration Transfer Effect

After entering the surface flow, the pollutant mixes with water and is then transported with the flow, on one hand. The concentration diffusion and dispersion will occur under the molecular motion, flow turbulence, and shear flow. On the other hand, the transformation and degradation will happen under chemical or biochemical conditions. The result of the comprehensive effects makes the concentration of pollutants in the surface water change along the path. Based on the existing water quality model, the transboundary water quality transfer effect was analyzed in this paper. The water quality calculation adopted the basic equation of the uniform flow water quality model, and assumed that the pollutant variation satisfied the first order attenuation reaction.

The general pollutants satisfied the first order kinetics degradation law, and the pollutant input response model can be simplified as follows, in which the dispersion effect is not considered:

$$C_x = f(C_0, k, u, x, \ldots) \tag{4}$$

where C_x is the pollutant concentration in the downstream area of the sewage outlet, mg·L^{-1}; C_0 is the concentration of pollutants at x = 0, mg·L^{-1}; x is the transport distance of pollutants, m; u is the average flow velocity of the river, m·s^{-1}; and k is the comprehensive attenuation coefficient, day^{-1}.

When calculating the concentration transfer effect, the C_0 in the beginning calculating unit could use the monthly measured concentration or mean annual concentration of pollutant in the section. The pollutant concentration C_x of the last computing unit will be used as the background water quality concentration C_0 for the next computing unit. The model is used to calculate the transfer effect, and the result can form the columns in the lower triangular matrix A.

$$A = \begin{bmatrix} \alpha_{11} & 0 & 0 & \cdots & 0 \\ \alpha_{21} & \alpha_{22} & 0 & \cdots & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & \cdots & 0 \\ \vdots & & & & \vdots \\ \alpha_{n1} & \alpha_{n2} & \alpha_{n3} & \cdots & \alpha_{nn} \end{bmatrix} \tag{5}$$

The items of the columns represent the degree and extent of the influence of one certain region on the downstream section(s). The items of a certain row indicate the effect on one section of each region from the upstream and the local areas.

In each row, the contribution rate of a region to one section can be expressed as:

$$b_{ij} = \frac{\alpha_{ij}}{\sum\limits_{j=0}^{n} \alpha_{ij}} \tag{6}$$

3.2.2. Over Standard Concentration Transfer Effect

In practical application, in order to divide pollution responsibility and define the loss of water pollution, the concentration change value caused by the exceeding index discharge or exceeding index water consumption can be used as a variable in the model, which is the over standard water quality transfer effect. Assuming that the pollutants in a boundary reached the standard level, the local area does not have responsibility for pollution discharge. In the model calculation, the initial concentration C_0 of pollution discharge in this area is set as 0 mg·L^{-1}. If the water consumption of an area is up to standard, the responsibility of water consumption on downstream water quality should not be investigated. The initial concentration of water quality affected by water consumption in this area is 0 mg·L^{-1}. Only the concentration caused by excessive water consumption or excessive sewage discharge is taken as a variable.

Taking the one-dimensional water quality model as an example, the river water quality one-dimensional model is shown in the following expression:

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} = E\frac{\partial^2 C}{\partial x^2} - kC \tag{7}$$

where C is the concentration of pollutant, mg·L^{-1}; t is the time, s; and E is the longitudinal dispersion coefficient, m^2·s^{-1}. The other symbols have the same meaning as above.

For inland rivers, which are not affected by the tide, the channel discrete action has little impact on convection. If the diffusion term is ignored, the analytic solution of Equation (7) under the condition of constant flow is:

$$C_x = C_0 \exp\left(-k\frac{x}{u}\right) \tag{8}$$

By incorporating $C_0 = \frac{1}{1000}\frac{M_0}{Q}$ into Equation (8), it can be obtained that

$$C_x = \frac{1}{1000}\frac{M_0}{Q}\exp\left(-k\frac{x}{u}\right) \tag{9}$$

where M_0 is the pollutant background flux of the section, mg·s^{-1}; and Q is the flow of the same section, m^3·s^{-1}.

In practical application, the frequency of water quality monitoring in the Yellow River mainstream provincial boundaries is monthly. At present, the frequency of water quality monitoring of the Yellow River main stream sections is 12 times per year. The monthly pollutant flux M is the result of the monthly measured concentration value C multiplied by the monthly average flow Q in the same section. Summarizing the monthly pollutant flux can reveal the flux value of the annual time period, and the annual flux is incorporated into Equation (9) after the unit conversion.

The difference value ΔC_0 between C_0 and the water quality target C_s can also be used as a variable, which is used to estimate the water quality effect of the superscalar ΔC_s on the downstream areas, and is shown in Equation (10):

$$\Delta C_s = (C_0 - C_s)\exp(-k\frac{x}{u}) = \Delta C_0 \exp(-k\frac{x}{u}) \tag{10}$$

At present, the frequency of water quality monitoring of the Yellow River main stream sections is 12 times per year. According to the document "the technical rules for evaluating the water quality in the important water function areas of the Yellow River Basin" issued by the Yellow River Conservancy

Commission in 2014, the standard water function area is that with over or equal to an 80% standard rate. However, it may be that the water quality assessment result of one certain water function area is substandard, but the mean annual concentration could reach the standard level, so the responsibility for the substandard of less than 80% months could not be investigated. In accordance with the requirements of the most stringent water resources management system, the average water quality flux M in the months with an over standard concentration (more than or equal to three months) should be divided by the flow Q, and the average concentration C can be obtained. Consider C as the annual concentration of accountability of water pollution. The average concentration of the months exceeding the standard can be inferred by Equation (11):

$$\Delta C_s = \left(\frac{\sum\limits_{i=3}^{n} Q_i \times C_i}{\sum\limits_{i=3}^{n} Q_i} - C_s \right) \exp\left(-k\frac{x}{u}\right) \ (i = 3, 4, \cdots, n \ 3 \leq n \leq 12) \tag{11}$$

Two kinds of factors can cause the change of the water pollutants concentration: one is the pollutant discharged into the water body, and the other is the change of water quantity in the water body, i.e., water consumption, water surface evaporation, river leakage, and so on. The Equations (9)–(11) are the pollutant input response model, which satisfies the superposition principle. Different parts of the pollution load can be superimposed. Compared to pollutant discharge and water consumption, the concentration change of water pollutants caused by evaporation and leakage is tiny. While, pollutant discharge and water consumption are caused by human factors. In order to evaluate and claim responsibility of water pollution in the boundaries, this study mainly considered the influence of the two factors of water consumption and sewage discharge on water quality.

According to the linear superposition principle, in the same hydrodynamic field, the equilibrium concentration field, which formed under the joint influence of several pollution sources, can be seen as the linear superposition of the various pollutant concentration fields. Therefore, different parts of the pollution load can be calculated separately, and then superimposed. Additionally, the changes of concentration caused by water consumption and discharge can be calculated separately. The effect of the concentration change on the downstream section is caused by the joint influence of the two factors.

$$\Delta C_s = \Delta W_0 \exp\left(-k\frac{x}{u}\right) + \Delta w_0 \exp\left(-k\frac{x}{u}\right) \tag{12}$$

where ΔW_0 is the concentration change caused by over standard discharge of the upper stream, $mg \cdot L^{-1}$; and Δw_0 is the difference between the concentration change caused by over standard water consumption of the upper stream and the water quality target, $mg \cdot L^{-1}$.

As the emission of pollutants is difficult to count, the effect of pollutant discharge is hard to measure. Theoretically, the concentration exceeding standard in the boundary detaches the influence of exceeding the standard discharge and water consumption in the upper reach areas, and then detaches the effect caused by the local area's over standard water consumption, and the impact of the exceeding standard pollution discharge in the local area is calculated.

Among them, the concentration change caused by over standard water consumption can be calculated by Equation (13):

$$\Delta w_0 = \frac{1}{1000}\left(\frac{M}{Q} - \frac{M}{Q+q}\right) \tag{13}$$

where q is excess standard water intake flow, $m^3 \cdot s^{-1}$. The rest of the symbolic meaning is the same as above.

Matrix A can be expressed by the sum of concentration changes caused by the two factors of sewage discharge and water consumption.

$$A = \begin{bmatrix} \alpha_{11} & 0 & 0 & \cdots & 0 \\ \alpha_{21} & \alpha_{22} & 0 & \cdots & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & \cdots & 0 \\ \vdots & & & & \vdots \\ \alpha_{n1} & \alpha_{n2} & \alpha_{n3} & \cdots & \alpha_{nn} \end{bmatrix}_{\text{water consumption}} + \begin{bmatrix} \alpha_{11} & 0 & 0 & \cdots & 0 \\ \alpha_{21} & \alpha_{22} & 0 & \cdots & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & \cdots & 0 \\ \vdots & & & & \vdots \\ \alpha_{n1} & \alpha_{n2} & \alpha_{n3} & \cdots & \alpha_{nn} \end{bmatrix}_{\text{pollutant discharge}} \quad (14)$$

The elements on each row of the matrix A should be summed and each element of the row should be divided by the sum to obtain the proportion of the concentration transfer effect of the water consumption or the pollutant discharge in the area.

$$b_{ij,\text{water consumption}} = \frac{\alpha_{ij}\big|_{\text{water consumption}}}{\sum\limits_{j=0}^{n} \alpha_{ij}} \quad (15)$$

$$b_{ij,\text{pollutant discharge}} = \frac{\alpha_{ij}\big|_{\text{pollutant discharge}}}{\sum\limits_{j=0}^{n} \alpha_{ij}} \quad (16)$$

In addition, look at the geographical distribution of various provinces and regions in the Yellow River basin. Qinghai, Gansu, Ningxia, and Inner Mongolia are located in the upper and lower reaches of the mainstream, taking the cross section of the river as the provincial boundary. Shanxi and Shaanxi (Hequ-Tongguan segment), and Shanxi and Henan (Tongguan-Xiaolangdi segment) are bounded by the left and right bank of the Yellow River. In this case, when the pollutant transfers through the upstream provinces and regions to the left and right banks of the downstream portion, the transferred pollutants can be distributed to two areas according to a certain proportion (such as the proportion of pollutant discharge).

3.3. Model Parameters

1. Average flow velocity u of river

The measured flow and flow velocity data of 2008 for the Yellow River mainstream representative hydrological monitoring section was gathered, and the flow-velocity relation curve was established, so the flow velocity could be determined by the corresponding design flow. The flow-velocity relation equation is $u = aQ^b$, where u is the average velocity of the section, m·s^{-1}; Q is the flow value, m^3·s^{-1}; and a and b are the undetermined coefficients.

Through the empirical equation of flow-velocity, we could obtain the main hydrologic section flow velocity of the Yellow River main stream under 90%, 75%, and 50% design flow. According to the flow, the design flow velocities of 12 watercourse computing units were determined, as presented in Table 2.

2. Parameters calibration of comprehensive degradation coefficient k

The comprehensive degradation coefficient of pollutants, which can directly reflect the speed of pollutant attenuation [21], is one of the most important parameters in water quality calculation. The comprehensive degradation coefficient is not the same in different pollutants, water bodies, and surroundings. In this paper, the comprehensive degradation coefficient k of the Yellow River mainstream was calculated by the two-point method [22] of measured data as follows:

$$k = \frac{u}{\Delta x} \ln \frac{C_1}{C_2} \quad (17)$$

where C_1 and C_2 are the pollutant mass concentrations in the upper and lower sections respectively, $mg \cdot L^{-1}$; and Δx is the distance between the upper and lower sections, m. Taking the integrity of data collected from hydrology, water quality, and pollutant discharge into account, this paper selected the year of 2011 as the calculation period. Combining the results of calibration as well as the recommendations and the experience of the Yellow River Basin Water Resources Protection Bureau, the final values of the comprehensive degradation coefficients of pollutants are listed in Table 3.

Table 2. The Yellow River mainstream computing units design flow velocity.

Number	Computing Unit	Design Flow Velocity ($m \cdot s^{-1}$)		
		90%	75%	50%
1	Dahejia-Xiaheyan	1.260	1.401	1.584
2	Xiaheyan-Shizuishan	0.889	1.060	1.234
3	Shizuishan-Toudaoguai	0.713	0.826	0.969
4	Toudaoguai-Hequ	0.700	0.810	0.936
5	Hequ-Wubu	1.021	1.142	1.273
6	Wubu-Longmen	1.311	1.428	1.569
7	Longmen-Tongguan	1.231	1.334	1.447
8	Tongguan-Sanmenxia	1.475	1.538	1.637
9	Sanmenxia-Xiaolangdi	0.100	0.100	0.100
10	Xiaolangdi-Huayuankou	0.978	1.073	1.205
11	Huayuankou-Gaocun	0.989	1.078	1.192
12	Gaocun-Lijin	0.926	1.128	1.351

Table 3. Pollutants' comprehensive degradation coefficients of river computing elements

Number	Computing Unit	k (Day^{-1})		Water Quality Target Level
		COD	NN_3-N	
1	Dahejia-Xiaheyan	0.23	0.19	II
2	Xiaheyan-Shizuishan	0.25	0.21	III
3	Shizuishan-Toudaoguai	0.20	0.17	III
4	Toudaoguai-Hequ	0.20	0.16	III
5	Hequ-Wubu	0.20	0.16	III
6	Wubu-Longmen	0.18	0.17	III
7	Longmen-Tongguan	0.25	0.22	III
8	Tongguan-Sanmenxia	0.29	0.27	III
9	Sanmenxia-Xiaolangdi	0.13	0.12	III
10	Xiaolangdi-Huayuankou	0.23	0.21	III
11	Huayuankou-Gaocun	0.16	0.14	III
12	Gaocun-Lijin	0.16	0.14	III

4. Transboundary Water Quality Transfer Effect Simulation System

The water environment compensation should take the social and economic factors into consideration. Additionally, the result of the transboundary water quality transfer effect model is only a reference for the quantification of water pollution and the definition of the pollution responsibility in the transboundary water environment compensation. It is not necessarily the final compensation result. In fact, when determining the amount of water environment compensation, it is usually essential for the relevant personnels and departments, such as the local, regional, national, and other authorities [23], to deliberate and modify the result according to actual demands. The calculation results are not the same in different conditions. For example, different water quality models, different design frequencies, different pollutant types, and different criteria will lead to entirely different calculation results. The large amount of data and complex calculation process in the practical application of the traditional water quality models and methods make their universality and operability absent, and it is difficult to adapt to dynamic changes and hard to popularize. Therefore, it is necessary to build a simulation system based on information technology, in order to simulate the transboundary water quality transfer effect in dynamic conditions.

4.1. System Construction

The knowledge visualization comprehensive integration platform [24], which is designed and constructed based on the water conservancy information processing platform technical specification (SL 538-2011) of the water conservancy industry standard, can provide an effective technical support and work platform for the application of the water quality model. This platform differs from the traditional ones due to the fact that it has no specific business function [25]. The framework of the platform is designed based on service oriented architecture (SOA), and all business applications are implemented by SOA and Web Service technology through knowledge maps and components. The use of the SOA system [26] can effectively improve the reuse rate and flexibility of the components. All that the users need to do is formulate relevant business components to organize business applications. Web Service is a collection [27] that implements SOA technology. It enables different systems to invoke each other and realizes the goal of seamless integration [28] based on the web.

The transboundary water quality transfer effect simulation system was supported by the integrated platform using a database as the basic information support and benefitted from a friendly human-computer interface to effectively realize the simulation function under two scenarios: the concentration transfer effect and over standard concentration transfer effect. The simulation system was rapidly constructed in the form of application themes, a knowledge map, and business components. Through the knowledge map, the relationship between the upstream and downstream areas of the Yellow River mainstream and the business process of the water quality transfer effect were visualized. All icons in the knowledge map were nodes, each node was connected by a directional connection line, and the direction of the link represented the data flow between nodes. The corresponding service components were added to each node for business application.

The transboundary water quality transfer effect simulation system was divided into two scenarios: concentration transfer and over standard concentration transfer. The system calculation process is demonstrated in Figure 3.

The main functions of the transboundary water quality transfer effect simulation system are as follows:

1. Concentration transfer effect simulation. The system can be used to calculate the pollutant concentration of the boundaries and the contribution rate of each area. The time scale, design frequency, type of pollutant, and calculation model can be modified by users as the demands change.
2. Over standard concentration transfer effect simulation. The system can adapt to the actual demand change and realize the concentration calculations of the up-to-standard water consumption and substandard water consumption, the pollutant concentration change caused by the excessive water diversion, and the pollution transfer effect of superscalar. The mode to calculate the concentration over standard is also selective, as are the time, pollutant type, design frequency, and model.

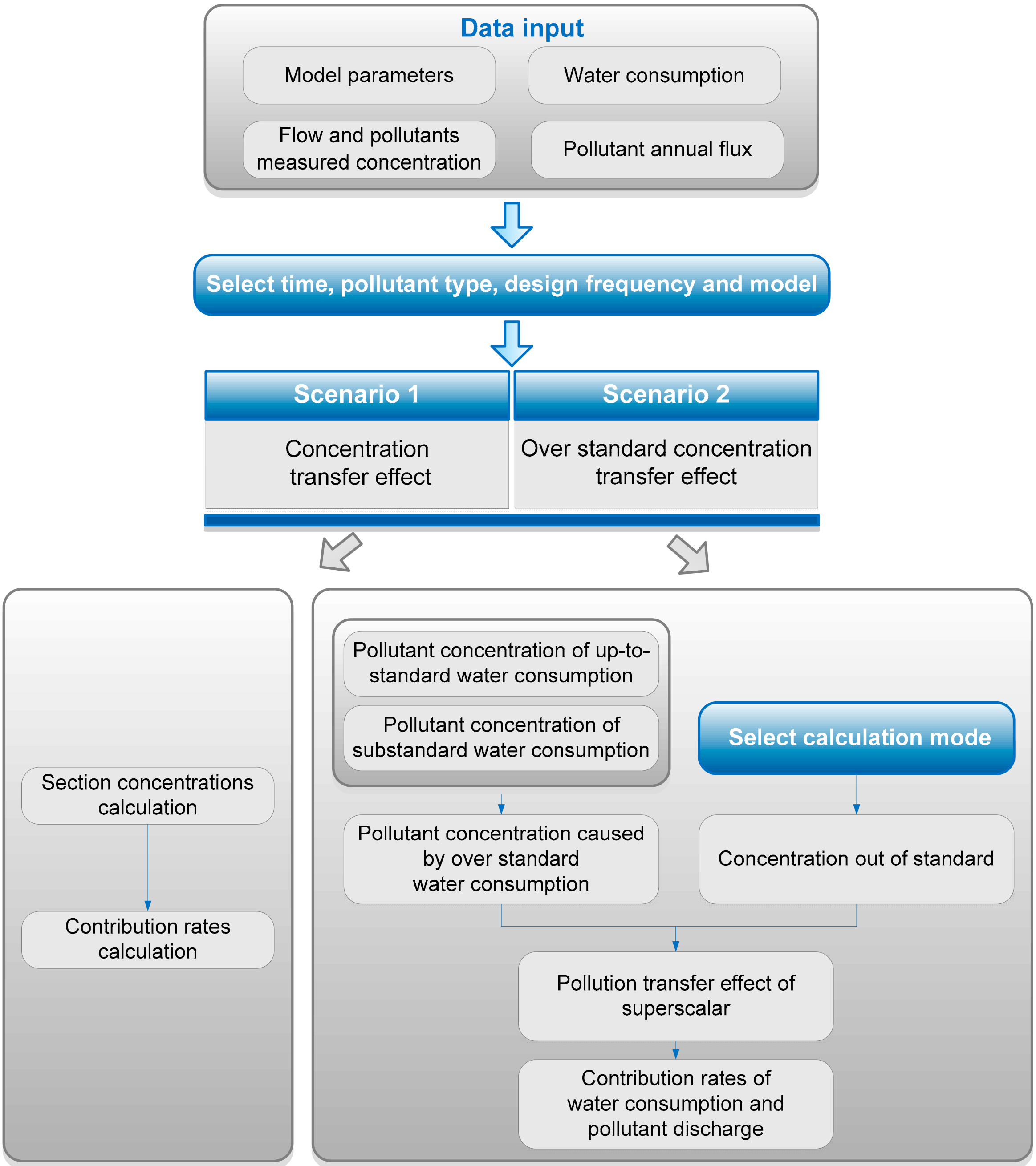


Figure 3. The calculation process of the simulation system.

4.2. System Application

The main interface of the transboundary water quality transfer effect simulation system is presented in Figure 4. Through clicking the clock icon, it will pop up a window to select the time, pollutant type, calculation model, and design frequency. The blue rectangle buttons are the statistic nodes of the boundaries' pollutant concentration under two scenarios. The red dots in the Yellow River generalization map represent the watercourse sections. Next to each dot, a blue tack icon is designed to adjust the parameters.

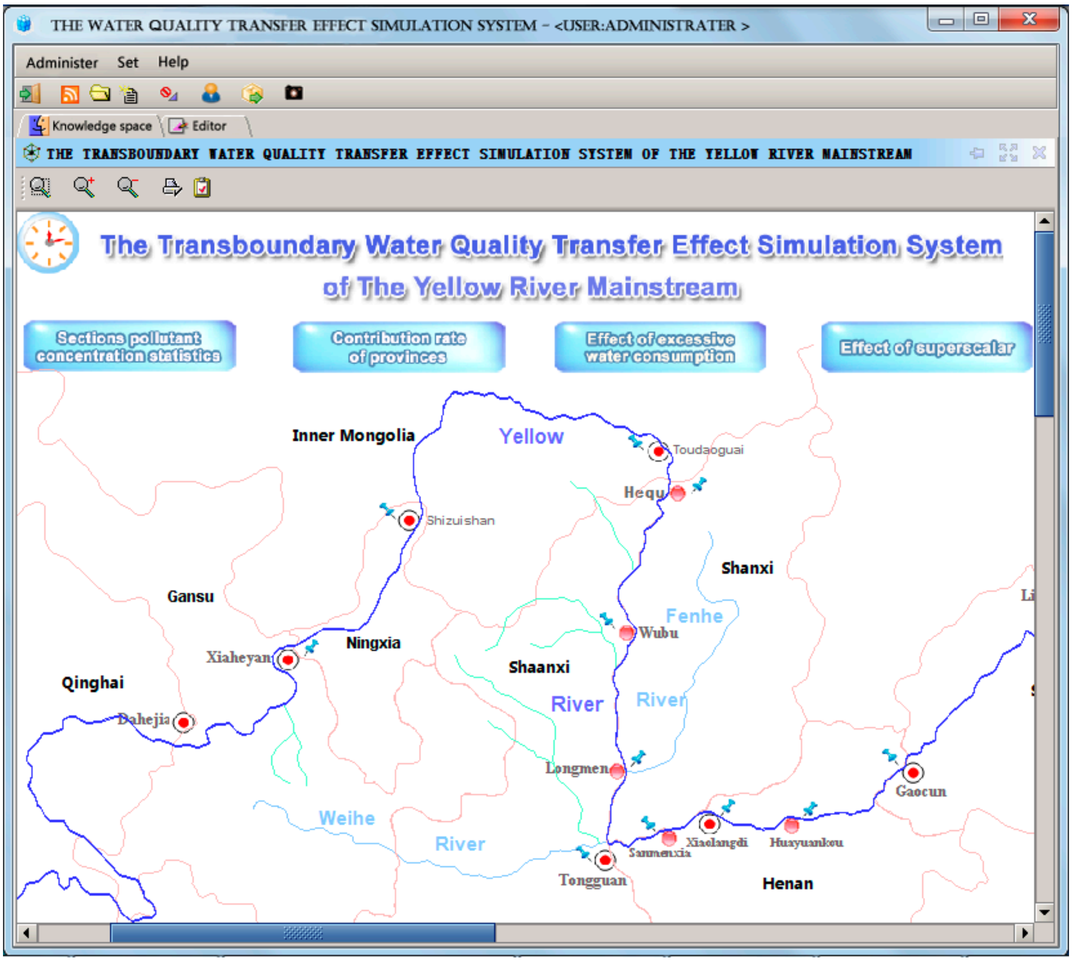


Figure 4. The main interface of the transboundary water quality transfer effect simulation system.

4.2.1. Scenario 1: Concentration Transfer Effect Simulation

The transboundary water quality transfer effect simulation system simulates the impact of upstream areas in terms of water consumption and sewage discharge on its downstream water quality. The input pollutant concentration of a certain section is the output of its upper section. Therefore, the function of the water quality transfer effect system is accomplished in series mode between the section concentration calculation components. The output value of pollutant concentration in the upstream area is the input value of that in the downstream area. Furthermore, the output results of the concentration calculation components for sections are the inputs of the statistical component. The data flow directions are all unidirectional. The system offers two kinds of time scale to users: an annual basis scale (e.g., "2011") and monthly basis scale (e.g., "April 2011"). Clicking on the drop-down menu of the pollutant selector, users could choose the pollutant type, such as COD or NH_3-N. The design frequency and calculation models are set in the same way. Clicking on the "sections pollutant concentration statistics" node, the result will be calculated and displayed immediately according to the set conditions. As is shown Figure 5, the table in the top left corner is the statistical result for the variation of pollutant concentration in the watercourse sections of the Yellow River main stream. The line graph in the bottom left corner shows the variation of pollutant concentration along the river. The table in the top right corner is the statistical result for the contribution rate of each province or region towards the study sections, and it could be drawn into a pie chart.

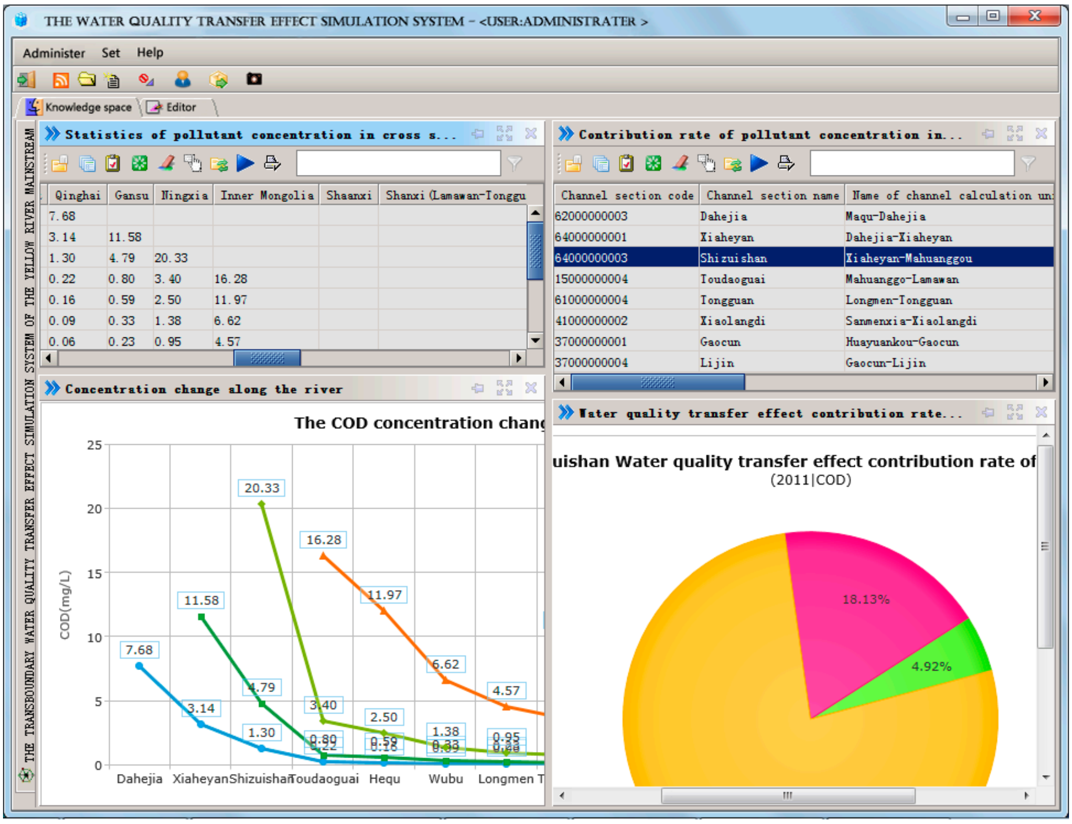


Figure 5. Water quality transfer effect results display of scenario 1.

4.2.2. Scenario 2: Over Standard Concentration Transfer Effect Simulation

1. The pollutant concentration change caused by the excessive water consumption

In the calculation of pollutant concentration change caused by the excessive water consumption, the difference value between pollutant concentration up-to-standard water consumption and substandard water consumption is considered as the pollutant concentration caused by the excessive water consumption, and is then calculated by substituting the value into the water quality transfer effect model. The data flow pattern between the components is similar to that of scenario 1. The system could calculate the pollutant concentrations up-to-standard water consumption and substandard water consumption. Furthermore, the variation of pollutant concentrations caused by excessive water consumption is the difference value between the two, as shown in Figure 6 down in the left corner. In addition, the system could also quantify and compare the pollutant concentrations caused by substandard water consumption of substandard water-consuming areas, and display the results in the form of a table and histogram, as shown on the right side of Figure 6.

2. The pollution transfer effect of superscalar

In the calculation of the pollution transfer effect of superscalar, the concentration change of a section caused by over standard water consumption and the total excess standard concentration of the section are taken as the input data, and the concentration caused by excess standard pollutant discharge can then be calculated. There are two ways to calculate the total excess standard concentration. One regards the difference value between the annual average concentration and the water quality target concentration of the substandard assessment section as the total excess standard concentration. The other takes the difference value between the monthly average concentration in the over standard months and the water quality target concentration as the exceeding standard concentration. By opening the time and pollutants type selection window and clicking the "calculation mode", the users could select the calculation modes of "Standard rate" or "Annual average" to calculate the total excess standard concentration (the left side of Figure 7). The time scale of the pollution transfer effect of the superscalar calculation could only be a yearly basis. The results are displayed in the form of a table, and the water consumption and pollutant discharge contribution rate of the related provinces and regions could be displayed in the form of a pie chart. The table and pie chart are shown on the right side of Figure 7.

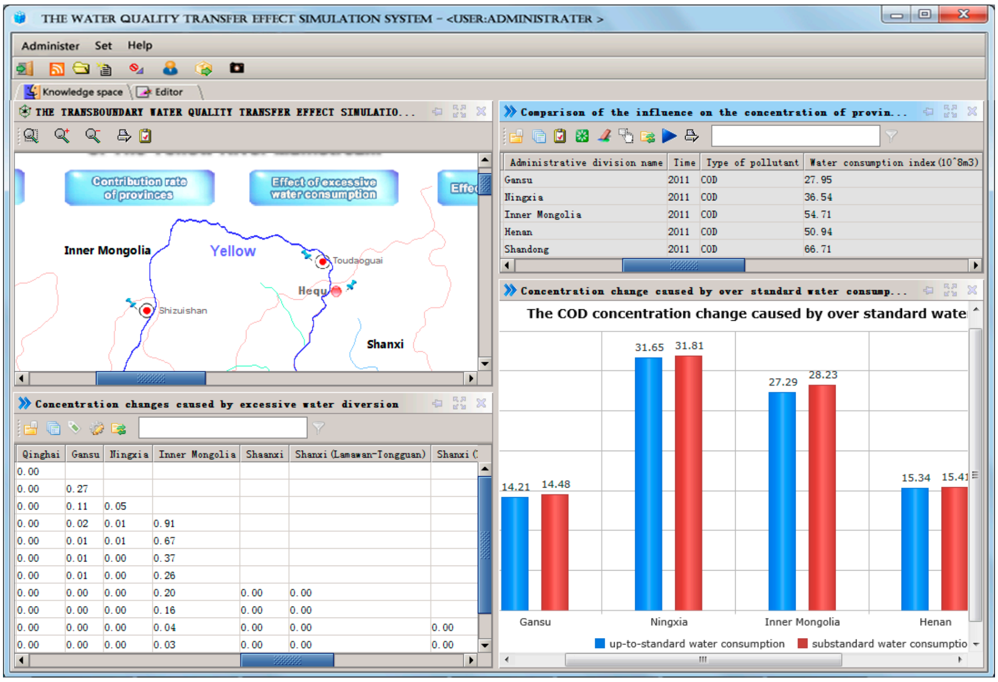


Figure 6. Comparison of effects on COD concentration of over standard water consumption areas.

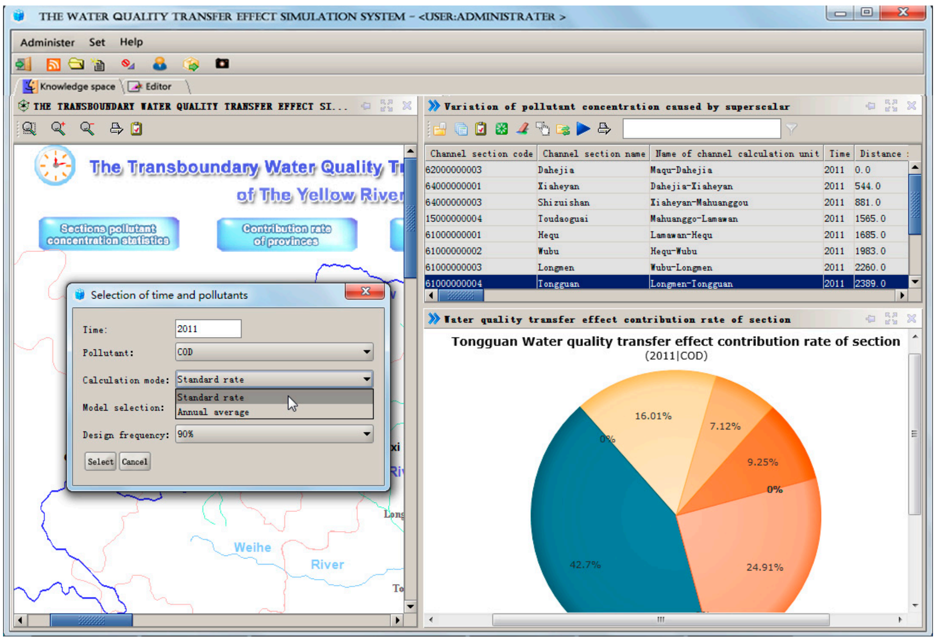


Figure 7. Water quality transfer effect results of scenario 2.

5. Results and Analysis

Due to the space limitation, this paper only listed the water quality transfer effect simulation results of COD and NH_3-N under the condition of 90% design frequency in these two scenarios—the concentration transfer effect and over standard concentration transfer effect. The water quality transfer effect of the two other design flows of 75% and 50% could also be calculated by the model and simulation system.

1. Scenario of the concentration transfer effect

The items of the columns in Tables 4 and 5 represent the degree and extent of the influence in a certain province or region on the downstream section(s). The items in a certain row indicate the effect of the pollutant which is produced by related province(s) or region(s) from the upstream and the local area, on the pollutant concentration in a certain section. It can be seen from the columns that the pollutants in the upstream areas may influence the water quality in the neighboring area of the lower reaches and even affect the water quality in the several following downstream areas. Additionally, it can be seen from the calculation results that each pollution level has a different effect on the degree and scope of pollutant concentration in the downstream area, and the provinces and regions with poor water quality have a greater influence on the pollutant concentration in its downstream area. The higher the concentration of pollutants is, the greater the range of the effect will be.

Comparing the final two columns of the measured pollutants' concentration and the water quality target concentration in Tables 4 and 5, it is shown that the concentration of COD in three sections of Shizuishan, Toudaoguai, and Tongguan, as well as the concentration of NH_3-N in two sections of Shizuishan and Tongguan, did not reach the water quality standard. The calculation results were consistent with the water quality evaluation results. Among them, the most serious COD pollution happened in the Shizuishan section of Ningxia, followed by the Toudaoguai section of Inner Mongolia. The most serious NH_3-N pollution was in the Tongguan section of Shaanxi and Shanxi junction, followed by the Toudaoguai section of Inner Mongolia, which were still in accordance with the results of the water quality evaluation.

According to each column in the calculation result tables, the line charts of pollutant concentration changing along the river could be drawn, as presented in Figures 8 and 9.

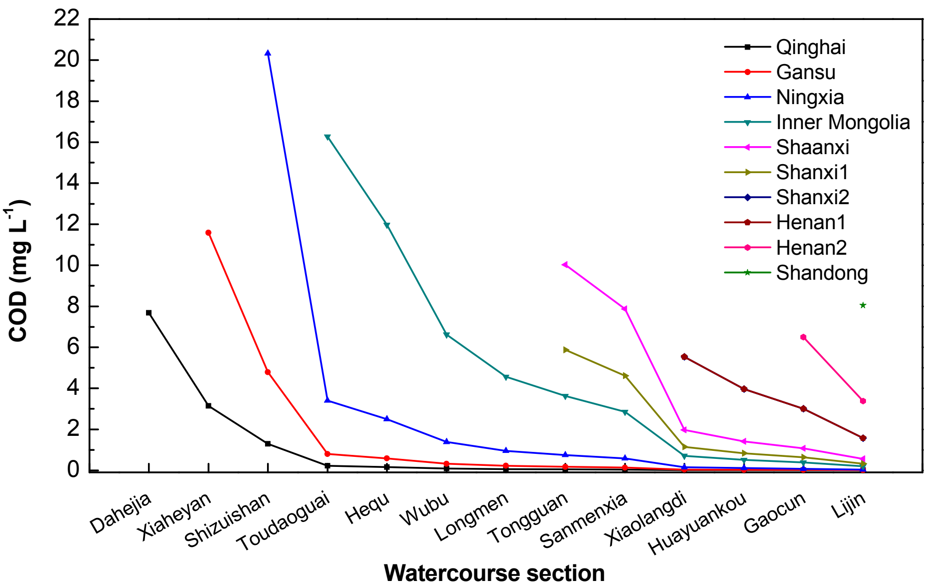


Figure 8. COD concentration change along the river of 2011 in scenario 1.

Table 4. Concentration transfer effect of COD in the Yellow River mainstream under 90% design frequency in 2011 (unit: mg·L^{-1}).

Section	Qinghai	Gansu	Ningxia	Inner Mongolia	Shaanxi	Shanxi [1]	Shanxi [2]	Henan [1]	Henan [2]	Shandong	Measured Pollutants Concentration	Water Quality Target Concentration
Dahejia	7.68										7.68	15
Xiaheyan	3.14	11.58									14.72	15
Shizuishan	1.3	4.79	20.33								26.42	20
Toudaoguai	0.22	0.8	3.4	16.28							20.7	20
Hequ	0.16	0.59	2.5	11.97								
Wubu	0.09	0.33	1.38	6.62								
Longmen	0.06	0.23	0.95	4.57								
Tongguan	0.05	0.18	0.75	3.63	10.03	5.87					20.52	20
Sanmenxia	0.04	0.14	0.59	2.85	7.87	4.61						
Xiaolangdi	0.01	0.04	0.15	0.71	1.97	1.15	5.54	5.54			15.1	20
Huayuankou	0.01	0.03	0.11	0.51	1.41	0.83	3.97	3.97				
Gaocun	0.01	0.02	0.08	0.39	1.07	0.63	3.01	3.01	6.5		14.73	20
Lijin	0.01	0.01	0.04	0.2	0.56	0.33	1.57	1.57	3.38	8.04	15.7	20

Shanxi [1] presents the Toudaoguai-Tongguan segment in Shanxi, and Shanxi [2] presents the Tongguan-Xiaolangdi segment in Shanxi. Henan [1] presents the Tongguan-Xiaolangdi segment in Henan, and Henan [2] presents the Xiaolangdi-Gaocun segment in Henan.

Table 5. Concentration transfer effect of NH_3-N in the Yellow River mainstream under 90% design frequency in 2011 (unit: $mg \cdot L^{-1}$).

Section	Qinghai	Gansu	Ningxia	Inner Mongolia	Shaanxi	Shanxi [1]	Shanxi [2]	Henan [1]	Henan [2]	Shandong	Measured Pollutants Concentration	Water Quality Target Concentration
Dahejia	0.1283										0.1283	0.5
Xiaheyan	0.0613	0.3253									0.3867	0.5
Shizuishan	0.0294	0.1558	1.1515								1.3367	1
Toudaoguai	0.0064	0.0338	0.2501	0.343							0.6333	1
Hequ	0.005	0.0264	0.1956	0.2682								
Wubu	0.0031	0.0164	0.1218	0.167								
Longmen	0.0022	0.0116	0.0859	0.1178								
Tongguan	0.0018	0.0095	0.0703	0.0964	0.6993	0.5352					1.4125	1
Sanmenxia	0.0014	0.0076	0.0559	0.0767	0.5565	0.4259						
Xiaolangdi	0.0004	0.0022	0.0161	0.0221	0.1606	0.1229	0	0			0.315	1
Huayuankou	0.0003	0.0016	0.0119	0.0163	0.1186	0.0908	0	0				
Gaocun	0.0002	0.0013	0.0093	0.0127	0.0927	0.0709	0	0	0.297		0.4842	1
Lijin	0.0001	0.0007	0.0052	0.0071	0.0517	0.0395	0	0	0.1655	0.0902	0.36	1

Shanxi [1] presents the Toudaoguai-Tongguan segment in Shanxi, and Shanxi [2] presents the Tongguan-Xiaolangdi segment in Shanxi. Henan [1] presents the Tongguan-Xiaolangdi segment in Henan, and Henan [2] presents the Xiaolangdi-Gaocun segment in Henan.

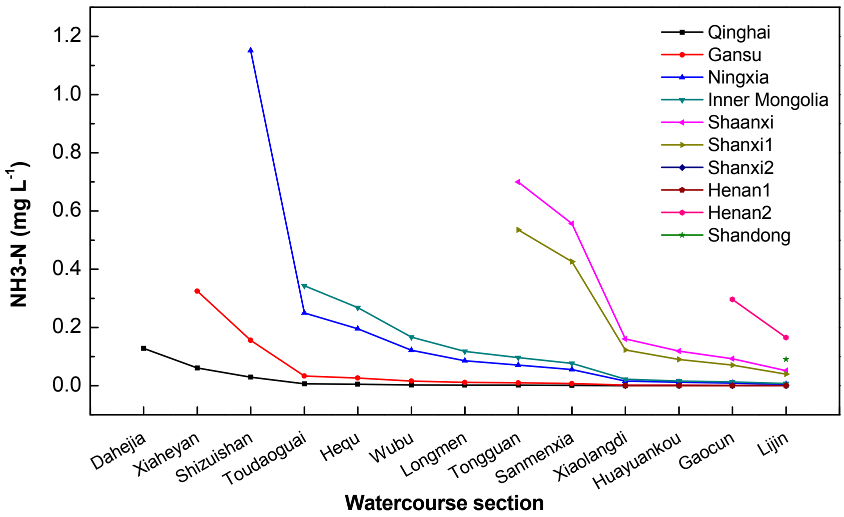
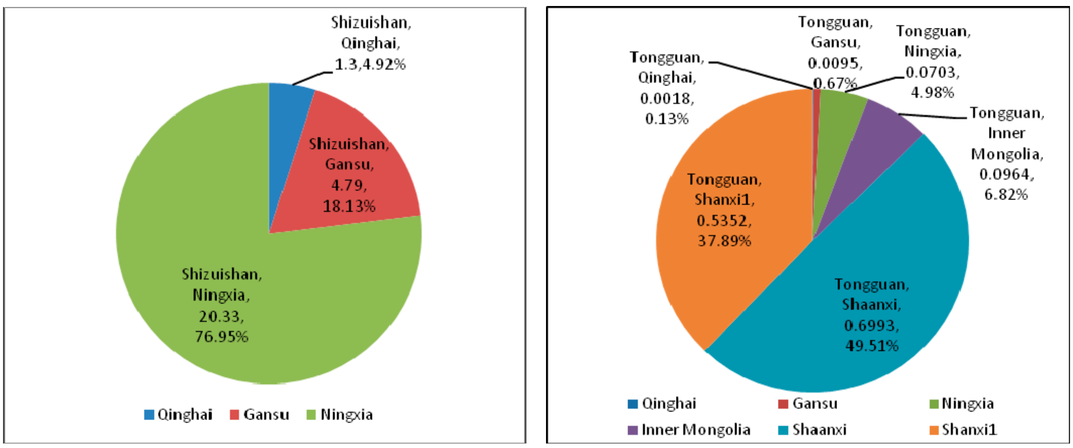


Figure 9. NH_3-N concentration change along the river of 2011 in scenario 1.

From the change of pollutants along the river, COD and NH_3-N pollution were mainly concentrated in the upper and middle reaches of the river basin. The concentrations of COD and NH_3-N decreased exponentially along the river and finally declined to a certain value and then remained stable. The attenuation rates of pollutants along the river could be seen from Figures 8 and 9. The fastest attenuation rate of COD appeared in the Xiaheyan-Toudaoguai segment, followed by the Sanmenxia-Xiaolangdi segment (Figure 8); for the calculation result of NH_3-N (Figure 9), the segment of the fastest attenuation rate was in the Shizuishan-Toudaoguai segment, and the attenuation speed in the Sanmenxia-Xiaolangdi segment was even lower.

After obtaining the degree and range of the water quality transfer effect in the main stream of the Yellow River, according to Equation (6), the pollution contribution rate of the sections in each province and region could be calculated. Taking the most serious COD polluted section, i.e., Shizuishan and the most serious NH_3-N polluted section, i.e., Tongguan as examples, the contribution rates of the pollutant concentration for the upper reaches of the two sections could be displayed in the form of pie charts, as displayed in Figure 10.



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

Figure 10. The contribution rates of provinces and regions in scenario 1: (**a**) The COD contribution rates of the Shizuishan section; (**b**) The NH_3-N contribution rates of the Tongguan section.

It could be seen from Figure 10a, for the Shizuishan section, that it was the Ningxia province which accounted for the highest contribution of pollution concentration, accounting for 77%, followed by

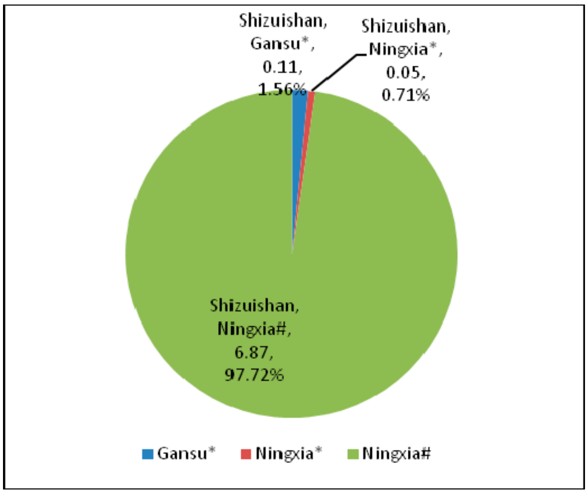
Gansu (18%), and Qinghai (5%). The most serious NH_3-N pollution was in the Tongguan section (Figure 10b), the highest contribution rate was occupied by Shaanxi province, which should take responsibility for about 50%, followed by Shanxi, accounting for 38%. It was Inner Mongolia that should occupy the responsibility proportion of 7%, while for Ningxia it was 5% and for Gansu it was 1%. The pollution contribution rates could provide a basis for the water pollution compensation proportions in the related areas.

2. Scenario of the over standard concentration transfer effect

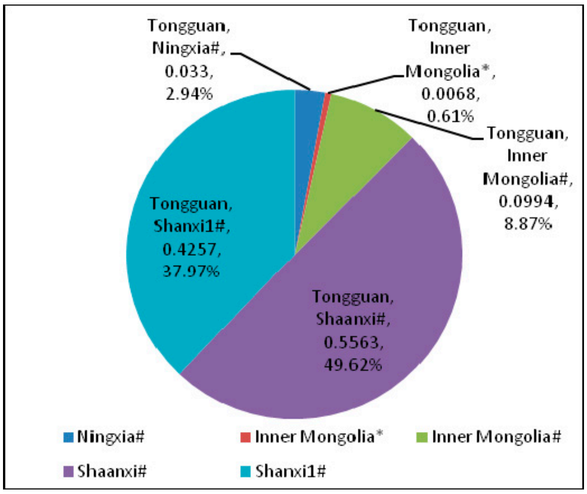
It could be seen from the calculation result of the water consumption effect of various provinces and regions in Tables 6 and 7 that the effect on water quality caused by exceeding standard water consumption in Gansu, Ningxia, and Inner Mongolia was more significant, while in other provinces and regions, there was rarely any effect of exceeding standard water consumption on water quality, or even no exceeding standard water consumption. The calculation results of the effect caused by excessive pollutant discharge showed that Ningxia, Inner Mongolia, Shaanxi, and Shanxi contributed much more to the effect of water quality, while other provinces and regions had little or no effect caused by exceeding standard pollution discharge.

It was observed from the second columns of Tables 6 and 7 that the substandard sections of COD and NH_3-N were mainly concentrated in the upstream and middle reaches under the condition of scenario 2. The reason for this was excessive pollution emission in Ningxia, Inner Mongolia, Shaanxi, and Shanxi. In scenario 1, it was Shizuishan, Toudaoguai, and Tongguan that failed to reach the standard of the COD concentration. However, in scenario 2, the sections whose COD concentration was substandard were four others besides these two. In scenario 1, Shizuishan and Tongguan were the only two sections that did not reach the standard of NH_3-N concentration. In addition, there were five more sections that did not reach the standard under the condition of scenario 2. The reason for this was that when the annual average concentration reached the standard, it might have failed to meet the annual target rate of 80% required by water quality assessment.

It could be well perceived from the calculation results that the most serious pollution of COD and NH_3-N still existed in the Shizuishan section and Tongguan section, respectively. The contribution rates of the pollutant concentration in the upstream provinces could be calculated according to Equations (15) and (16), and the pie charts of the contribution rates are shown as Figure 11.



(a)



(b)

Figure 11. The contribution rates of provinces and regions in scenario 2: (**a**) The COD contribution rates of the Shizuishan section; (**b**) The NH_3-N contribution rates of the Tongguan section.

Table 6. Over standard concentration transfer effect of over standard COD in the Yellow River mainstream under 90% design frequency in 2011 (unit: mg·L^{-1}).

Section	Average Concentration of Substandard Months	Qinghai *	Qinghai #	Gansu *	Gansu #	Ningxia *	Ningxia #	Inner Mongolia *	Inner Mongolia #	Shaanxi *	Shaanxi #	Shanxi ^{1,*}	Shanxi $^{1,\#}$	Shanxi ^{2,*}	Shanxi $^{2,\#}$	Henan ^{1,*}	Henan $^{1,\#}$	Henan ^{2,*}	Henan $^{2,\#}$	Shandong *	Shandong #
Dahejia		0	0																		
Xiaheyan		0	0	0.27	0																
Shizuishan	7.03	0	0	0.11	0	0.05	6.87														
Toudaoguai	4.14	0	0	0.02	0	0.01	1.16	0.91	2.04												
Hequ		0	0	0.01	0	0.01	0.85	0.67	1.5												
Wubu	5.42	0	0	0.01	0	0	0.47	0.37	0.83												
Longmen	4.52	0	0	0.01	0	0	0.32	0.26	0.57												
Tongguan	2.81	0	0	0	0	0	0.26	0.2	0.45	0	1.2	0	0.7								
Sanmenxia	1.92	0	0	0	0	0	0.2	0.16	0.36	0	0.94	0	0.55								
Xiaolangdi		0	0	0	0	0	0.05	0.04	0.09	0	0.24	0	0.14	0	0	0	0				
Huayuankou		0	0	0	0	0	0.04	0.03	0.06	0	0.17	0	0.1	0	0	0	0				
Gaocun		0	0	0	0	0	0.03	0.02	0.05	0	0.13	0	0.08	0	0	0	0	0.04	0		
Lijin	1.93	0	0	0	0	0	0.01	0.01	0.03	0	0.07	0	0.04	0	0	0	0	0.02	0	0.8	0.96

Shanxi ^{1} presents the Toudaoguai-Tongguan segment in Shanxi, and Shanxi ^{2} presents the Tongguan-Xiaolangdi segment in Shanxi. Henan ^{1} presents the Tongguan-Xiaolangdi segment in Henan, and Henan ^{2} presents Xiaolangdi-Gaocun segment in Henan. * presents the effect caused by water consumption, and # presents the effect caused by sewage discharge.

Table 7. Over standard concentration transfer effect of over standard NH_3-N in the Yellow River mainstream under 90% design frequency in 2011 (unit: $mg \cdot L^{-1}$).

Section	Average Concentration of Substandard Months	Qinghai *	Qinghai #	Gansu *	Gansu #	Ningxia *	Ningxia #	Inner Mongolia *	Inner Mongolia #	Shaanxi *	Shaanxi #	Shanxi [1],*	Shanxi [1],#	Shanxi [2],*	Shanxi [2],#	Henan [1],*	Henan [1],#	Henan [2],*	Henan [2],#	Shandong *	Shandong #
Dahejia		0	0																		
Xiaheyan		0	0	0.0068	0																
Shizuishan	0.5422	0	0	0.0032	0	0.0024	0.5366														
Toudaoguai	0.5	0	0	0.0007	0	0.0005	0.1183	0.0245	0.356												
Hequ	0.76	0	0	0.0006	0	0.0004	0.0924	0.0191	0.2781												
Wubu	0.56	0	0	0.0003	0	0.0003	0.0574	0.0119	0.1728												
Longmen	0.5517	0	0	0.0002	0	0.0002	0.0405	0.0084	0.1219												
Tongguan	1.1214	0	0	0.0002	0	0.0001	0.033	0.0068	0.0994	0	0.5563	0	0.4257								
Sanmenxia	0.4992	0	0	0.0002	0	0.0001	0.0264	0.0055	0.0793	0	0.4441	0	0.3398								
Xiaolangdi		0	0	0	0	0	0.0073	0.0015	0.0221	0	0.1237	0	0.0947	0	0	0	0				
Huayuankou		0	0	0	0	0	0.0054	0.0011	0.0163	0	0.0914	0	0.0699	0	0	0	0				
Gaocun		0	0	0	0	0	0.0043	0.0009	0.0128	0	0.0718	0	0.055	0	0	0	0	0.0013	0		
Lijin		0	0	0	0	0	0.0024	0.0005	0.0073	0	0.0406	0	0.0311	0	0	0	0	0.0007	0	0.0121	0

Shanxi [1] presents the Toudaoguai-Tongguan segment in Shanxi, and Shanxi [2] presents the Tongguan-Xiaolangdi segment in Shanxi. Henan [1] presents the Tongguan-Xiaolangdi segment in Henan, and Henan [2] presents the Xiaolangdi-Gaocun segment in Henan. * presents the effect caused by water consumption, and # presents the effect caused by sewage discharge.

In the calculation results of scenario 2, the most serious polluted sections of COD and NH_3-N were still the two sections of Shizuishan and Tongguan, respectively. Unlike in scenario 1, the responsibilities in scenario 2 could be specifically divided into two factors: the water consumption and pollutant discharge in each province and region. For the Shizuishan section, the largest pollution contribution rate was occupied by Ningxia, accounting for 97.7%; while Gansu and Ningxia should take responsibility proportions of water consumption for 1.56% and 0.7%, respectively. Thus, the total contribution rate of Ningxia was 98.4%. Besides, it was the Tongguan section that had the most content of NH_3-N pollution, and Shaanxi, Shanxi, Inner Mongolia, and Ningxia should account for responsibility proportions of sewage discharge for 49.6%, 37.9%, 8.9%, and 2.9%, respectively, as well as the responsibility proportion for 0.6% in the water consumption of Inner Mongolia. Therefore, the total responsibility proportion of Inner Mongolia was 9.5%. The contribution rate of each province and region to each section calculated under the condition of scenario 2 could not only divide the compensation proportion into per area, but also obtain the responsibility proportion under two effect factors: pollutant discharge and water consumption. Compared with previous studies which mostly focused on defining the contribution rates of different pollution sources [29,30], the transboundary water quality transfer effect model and simulation system can be easily adapted and developed for other regions, so that management authorities can easily use the tool in order to face the problem of transboundary pollution.

6. Conclusions

Based on the traditional water quality model, the transboundary water quality transfer effect model was established. Besides, on the basis of an integrated platform, the knowledge map and components were applied to build the transboundary water quality transfer effect simulation system. The quality of Yellow River mainstream was simulated under two scenarios: the concentration transfer effect and over standard concentration transfer effect. The main conclusions of this paper lie in the following two aspects:

1. Through the transboundary water quality transfer effect model, the contribution value and rate for pollutant discharges and water consumptions in a certain area can be calculated; besides, the quantitative relationship between the main pollution sources and boundaries can be determined. The results show that the overall concentration decreases exponentially along the watercourse. Areas with different degrees of pollution affect the range and extent of water quality concentration in the downstream area to varying degrees. It should be pointed out that the effect of exceeding standard water consumption on pollution in Gansu, Ningxia, and Inner Mongolia was more significant. Ningxia, Inner Mongolia, Shaanxi, and Shanxi had a more distinct contribution to the effect due to their over standard pollution discharge. The model offers a new idea and method for the division of transboundary water pollution responsibility and provides a quantitative basis for water environment compensation.
2. The system can be applied in different scenarios as the demand changes. The time, pollutant type, design frequency, and calculation model can be adjusted by the visualized man-machine interface, and the calculation results could be displayed in a variety of forms, such as a table, columnar chart, pie chart, and so on. The system provides a visualization tool for the transboundary water quality transfer effect model. More importantly, it could adapt to dynamic changes so as to offer decision-makers with technical support.

Author Contributions: All authors contributed to the conception and design of the study. X.Z. performed the model calculation, system programming, and original draft writing; J.L. and J.X. supervised the study; J.Z. performed the validation and reviewed the writing; L.Y. and Z.Y. led the collection and analysis of data, and improved the calculation method.

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