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Determination of River Ecological Base Flow Based on the Coupling Relationship of Sediment–Water Quality–Biodiversity in Water Shortage Area of Northwest China

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Abstract: Maintaining the integrity of ecosystem service functions of rivers has become the top issue in the water shortage area of Northwest China. By combining the coupling relationship of sediment, water quality, and biodiversity and the hydraulic relationship of the section, we established a quantitative calculation method for the river ecological base flow, which is mainly divided into the following three steps: first, we determined the reasonable ecological flow velocity range of rivers via water purification, maintaining the river geometry and biodiversity; second, we combined the hydraulic relationship between the river ecological velocity range and the river ecological base flow to determine the protection target of the river ecological base flow; finally, we combined the remaining water volume of rivers and ecological base flow protection target of rivers to determine their protection rate. Take the Baoji section of the Weihe River as an example: the results show that the ecological base flow in the Baoji section of the Weihe River is and $[32.94, 38.93 \text{ m}^3/\text{s}]$ from October of this year to May of next year and from June to September, respectively, and the protection rates of the ecological base flow for five typical years are 62.47%, 41.10%, 16.16%, 15.07%, and 10.68%. These coupling methods can also be used in the world's river basin, which has similar problems.



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Keywords: ecological service functions; sediment; water quality; biodiversity; ecological base flow; water shortage area

1. Introduction

Maintaining the integrity of watershed ecological service functions has become the research focus of watershed ecological health in Northwest China at this stage [1]. In recent years, climate change and human activities have had a negative impact on river runoff, resulting in a gradual decrease in the amount of water coming from the river [2–4]. In particular, the production of water in human activities is diverted from the river, resulting in a large reduction in river water resources [1,5,6], which makes the water demand of river ecological flow difficult to meet [7]. In order to prevent the continuous deterioration of the river ecological environment in the water shortage area of Northwest China, we first need to determine the appropriate water requirement for the ecological base flow of rivers [8]. Thus, it is imperative to study the water requirement of the river's ecological base flow to ensure the service functions of the river ecosystem [9].

At present, there are many reports about the determination of river ecological base flow based on the water requirement of ecosystem service functions of rivers, but most of the ecological indicators for the determination of river ecological flow are single service functions of rivers. Yang and co-workers (2016) developed a two-dimensional hydraulic and ecological model by investigating the impacts of flow alteration on ecosystems with different pollution rates and examining the underlying mechanisms, and applied this to 21 scenarios to understand ecosystem characteristics in response to various environmental

flow rates and water quality standards and determined reasonable environmental flow, to ensure that the water quality of the river meets the expected requirements [10]. Belmar et al. (2018) presented an analysis of the relationship between interannual flow regimes in the lower section of the Ebro River, defined using a set of daily and hourly hydrological indices and ecological quality based on a fish community to determine the proper environmental flow and to protect biodiversity in rivers [11]. Wang et al. (2020) described a new approach to evaluating the ecological flow regime that was a time series of discharge considering different life stages of the target species [12]. At the same time, there are reports of using double index and multi-index as a river ecological index to determine the river ecological flow. Zhao et al. (2018) proposed a new method to assess e-flows that aimed to satisfy the requirements of aquatic biota with regard to both the quantity and quality of the streamflow by linking fish tolerances to water quality criteria, specifically the allowable concentration of pollutants, thus promoting harmonious development of river water quality and biodiversity [8]. Song and Li (2004) used different calculation methods to determine different water demands for the ecological services of rivers, mainly including water purification, sediment transport, minimum habitat, etc. They then directly added the results to determine the ecological flow [13]. The calculation of river ecological base flow with single or double indexes has not met the requirements of the development of river ecological water demand at the present stage. Additionally, there will be some problems when it comes to determining the final river ecological flow if multiple ecological indexes are used to determine the river ecological flow based on simple comparison size and simple addition. For example, using fish as the water requirement of the ecological flow determined by the biodiversity index breaks the ecological model of water and sediment balance and causes river sediment impact or siltation, which will not only cause a change in the river geometry, downstream sedimentation, and the raising of the riverbed, but will also lead to river flood discharge, an increase in silt in the reservoir, and the raising of the normal pool level; this will cause major problems, such as personal and property safety [14,15].

Based on the above problems, we comprehensively consider the main ecological indicators of river sediment (especially river health indicators in the Loess basin of China), water quality, and biodiversity in the water shortage area of Northwest China, and establish a calculation method for the river base ecological flow through the coupling relationship of river sediment, water quality, and biodiversity. By doing this, we can effectively avoid the trend of single development of river ecological service functions of the ecological base flow of rivers and promote the coordinated development of the service function of rivers. Through this method, we can determine the ecological base flow in the Baoji section of the Weihe River and its protection rate after agricultural water diversion. The establishment of this method can provide a quantitative basis for the study of the functional integrity of watershed ecosystems and a scientific basis for water resource management.

2. Materials and Methods

2.1. Research Area

By selecting the Baoji section of the Weihe River as the case study, we tested our model by calculating the ecological base flow of rivers based on the coupling relationship of sediment–water quality–biodiversity in the water shortage area of Northwest China. The Weihe River, the largest tributary of China's second-largest river basin, is a typical water-scarce river in Northwest China. Due to excessive water diversion in the Baoji section of the Weihe River, ecological problems such as the decline of aquatic organisms, deterioration of water quality, and imbalance of water and sand being relatively prominent, this study takes the river as the case study. The Baoji section of the Weihe River is located in the middle of Shaanxi Province (Linjiacun Section–Weijiapu Section); the canal head of the Baojixia Diversion Project is next to the Linjiacun Section, which is mainly used to irrigate the Baojixia Yuanshang Irrigation District (see Figure 1).

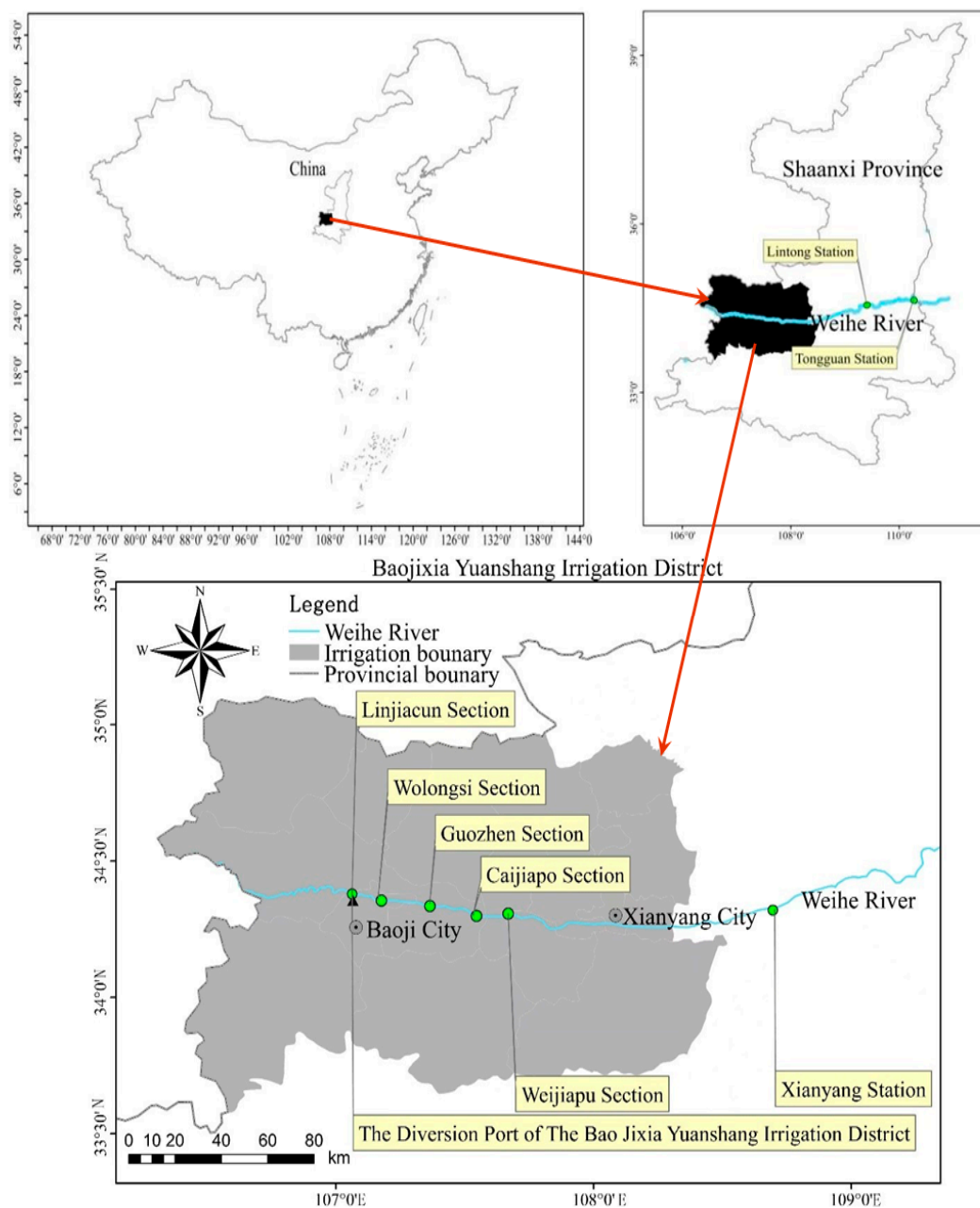


Figure 1. Location of the Baoji section of the Weihe River and Baojixia Yuanshang Irrigation District [5].

Before 2016, the sequence of water use in Baoji section of the Weihe River mostly aimed to meet the agricultural irrigation water use, first and foremost, followed by the water consumption of hydropower station, and finally the ecological water use of rivers (investigated by the Weihe River Administration Bureau of Shaanxi Province). Sometimes, agricultural irrigation water use accounts for more than 90% of dry years (the data come from the *People's Republic of China Hydrological Yearbook*), and large flood irrigation was adopted in the Baojixia Irrigation Area, with low water use efficiency and serious water resource waste [16]. A large amount of agricultural irrigation water diversion makes the water requirement of the river ecological base flow difficult to meet; sometimes, even the water purification function, which is the smallest water requirement, cannot be met [5], resulting in deterioration of the river water ecological environment [7]. According to a recent survey of aquatic organisms, with a sharp decrease in water quantity of the Weihe River, the number and species of fish are also sharply reduced [9]. At present, the main

fish species in the Weihe River include *Opsariichthys bidens*, *Carassius auratus*, *Pseudorasbora parva*, *Misgurnus anguillicaudatus* and *Cyprinus carpio*, etc. [8,9,17]. According to statistics, there are 85 sewage outlets along the Weihe River, with a total annual wastewater discharge of 555 million m³ [9]. In addition, the Weihe River Basin is mainly supplied by precipitation, which will introduce a lot of pollutants into the Weihe River in the process of precipitation confluence [18]. Because the Weihe River is located in the northwest loess plateau region, flow will carry a lot of sediment in the confluence process. In recent years, due to the large amount of water diversion, the water–sediment balance of the Weihe River has been damaged, and a lot of sediment has been deposited. As a result, it takes a lot of manpower and financial resources to remove sediment every year [19–21]. Therefore, in order to ensure the ecological healthy development of the Weihe River, we urgently need to analyze and calculate the overall water demand of ecological service function of the Weihe River.

The data used in this paper mainly come from the “People’s Republic of China Hydrological Yearbook”, “Shaanxi Statistical Yearbook”, and “Water Statistical Yearbook of Shaanxi”.

2.2. Methods

2.2.1. Ecological Velocity That Maintaining River Geometry

Rivers in water shortage areas of Northwest China are mostly the rivers with relatively high sediment content [9,21], which will cause frequent changes in river geometry, thus affecting river ecological safety and human safety and survival [22]. We must guarantee a safe flow velocity to protect the ecological geometry safety of rivers. And that flow velocity should not only not wash sediment, but should also not cause sediment deposition in the river channel when the flow velocity is too low. Therefore, the safe flow velocity is needed, which is referred to as the flow velocity of rivers without scouring and silting, also known as the safe flow velocity of the river’s ecological shape.

At this stage, the flow velocity of rivers without scouring and silting is mainly calculated using several methods, which mainly include the empirical formula method, the particle size grading method, and the sediment carrying capacity of the saturated flow [9,23–26]. Among these three methods, the particle size grading method and the empirical formula method were deeply discussed in the eighth volume of the Hydraulic Design Manual [23]. The detailed description and sources of three specific methods are shown in Table 1.

Table 1. Statistical table of quantitative calculation methods of river flow velocity. without scouring and silting.

Items	Detailed Description	Sources
Empirical formula method	Based on the analysis of the measured data in the study area, some scholars established the complex mathematical relationship between the flow velocity and sediment size, hydraulic radius, roughness of river channel, and soil composition, such as the formula of Shayuqing, the formula of the Institute of Water Science of the Yellow Committee, etc. Therefore, as long as the measured data of rivers have been collected, the flow velocity can be directly obtained.	[9,23,27]
Particle size grading method	The river course is composed of different soil types and gravel particle sizes, and they correspond to different flow velocities without scouring and silting. Some scholars have developed the non-scour tables of different soil and gravel particle sizes in river channels based on these conditions, which can further determine the water flow velocity of rivers without scouring and silting.	[23,26]

Table 1. Cont.

Items	Detailed Description	Sources
Sediment carrying capacity	The sediment-carrying capacity of the saturated flow can also be used to determine the water flow velocity of rivers without scouring and silting. The sediment-carrying capacity of saturated flow can be determined using the calculation formula. Firstly, when the sediment concentration in rivers is greater than the sediment-carrying capacity of the saturated flow, the sediment in rivers will be deposited, and the current flow velocity at this time is the critical flow velocity or the water flow velocity of rivers without scouring and silting.	[24,25,27,28]

When we obtain the flow velocity of rivers without scouring and silting, we can further obtain the ecological velocity required to ensure that the river geometry, which should be greater than or equal to the flow velocity of the sediment in rivers channels, will not accumulate and anything less than or equal to the velocity does not impinge on sediment, as shown in Equation (1).

$$V_{NSC} \leq V_{SAS} \leq V_{NSI} \quad (1)$$

where V_{SAS} refers to the flow velocity of rivers without scouring and silting, m/s; V_{NSC} refers to the flow velocity that will not deposit sediment, m/s; V_{NSI} refers to the flow velocity that does not impinge on sediment, m/s.

2.2.2. Ecological Velocity That Can Meet Water Requirement of Biodiversity

As the top community in the aquatic ecosystem of rivers, fishes have an important impact on the existence and abundance of other populations and are a more appropriate indicator species when it comes to calculating ecological water requirements [29,30]. Therefore, we take fish as the ecological index of biodiversity. Fish are relatively sensitive to the flow velocity and water quality of rivers (refer to Section 2.2.3 for the standard of safety water quality required by fishes). This paper mainly lists the flow velocity required by different fish species and takes the reasonable range of flow velocity required by different fish. The relationship between the ecological velocity meeting the biodiversity in rivers and the fish is shown in Equations (2) and (3).

$$\left\{ \begin{array}{l} V_{1,\min} \leq V_{BD1} \leq V_{1,\max} \\ \dots\dots\dots \\ V_{i,\min} \leq V_{BDi} \leq V_{i,\max} \\ \dots\dots\dots \\ V_{N,\min} \leq V_{BDN} \leq V_{N,\max} \end{array} \right. \quad (2)$$

$$\text{Max}(V_{1,\min}, \dots, V_{N,\min}) \leq V_{BD} \leq \text{Min}(V_{1,\max}, \dots, V_{N,\max}) \quad (3)$$

where V_{BD} refers to the ecological velocity that can meet biodiversity in the river, m/s; i refers to the i th fish species coming from all fish species in study rivers, which generally can be 1, 2, 3, ..., $N - 1$, N , dimensionless; $V_{i,\min}$ and $V_{i,\max}$ refer to the minimum and maximum flow velocity that is suitable for the i th fish species, respectively, m/s.

2.2.3. Ecological Velocity That Meeting Water Quality Standard

The river ecological velocity that meets the water quality standard required by biodiversity in rivers is the water quality standard required by different fish species [29], also known as the ecological purification flow velocity. We mainly consider the changes in pollutant transport along the river, so we use a one-dimensional water quality model [31], and a one-dimensional water quality model of rivers, as shown in Equation (4). Meanwhile, we mainly use a one-dimensional water quality model to analyze the relationship between the water quality of rivers and the ecological velocity of rivers that meets the water quality

purification standard under condition of a steady-state and non-tidal basin. The calculation process is as follows:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left(E_x \frac{\partial C}{\partial x} \right) - \frac{\partial}{\partial x} (uC) - kC \quad (4)$$

where C refers to the average concentration of pollutants in the section of the river, mg/L; u refers to the flow velocity of the river, m/s; E_x refers to the longitudinal dispersion coefficient, m²/s; x refers to the horizontal distance between the observation point and pollution sources, m; t refers to the time in the observation, s; k refers to the attenuation coefficient of pollutants, L/d.

For rivers with continuous sewage discharge and stable flow state, the steady-state model is generally adopted, i.e., $\partial C / \partial t = 0$. The basin is a general non-tidal basin in the water shortage area of Northwest China, and the pollutant migration effect of the push flow path is much greater than that of the dispersion effect [13]. Therefore, we can obtain the analytical solution of one-dimensional water quality model, as shown in Equation (5):

$$C = C_o \exp \left[-\frac{kx}{86400u} \right] \quad (5)$$

where C_o refers to the average concentration of pollutants in a cross-section of rivers when the distance between the observation point and pollution source is 0 m, mg/L.

Next, we can obtain the ecological velocity of rivers that can meet water quality standards; the quantitative calculation method is shown in Equation (6):

$$V_{WQ} = -\frac{kx}{86400 \times \ln \frac{C}{C_o}} = \frac{kx}{86400 \times \ln \frac{C_o}{C}} \quad (6)$$

where V_{WQ} refers to the ecological velocity of rivers that can meet water quality standards in study rivers, m/s.

2.2.4. Determination of the Ecological Base Flow of Rivers

River flow velocity is an important assessment element of river ecological health protection [7,8]. It can not only maintain the basic geometry of rivers and the living environment of fish, but also maintain the water quality standard of rivers. In general, there is a complex hydraulic relationship between flow velocity and flow in a certain hydrological section of rivers. Therefore, combining the complex hydraulic relationship of the ecological base flow protection target of rivers and the ecological flow velocity, we can determine the ecological base flow of rivers [8,9,17]. The quantitative calculation method based on the ecological base flow and ecological velocity of rivers is shown in Equations (7) and (8), respectively:

$$Q_{EBF} = A_O \times f(V_E) \quad (7)$$

$$\text{Max}(V_{SAS,LOW}, V_{BD,LOW}, V_{WQ,LOW}) \leq V_E \leq \text{Min}(V_{SAS,HIGH}, V_{BD,HIGH}, V_{WQ,HIGH}) \quad (8)$$

where Q_{EBF} refers to the water requirement of the ecological base flow of rivers in the study area, m³/s; V_E refers to the proper range of ecological velocity of rivers that can maintain the rivers basic health, m/s; A_O refers to a constant, which is dimensionless; f refers to the hydraulic relationship between the flow velocity and ecological base flow of rivers.

2.2.5. Protection Rate of Ecological Base Flow of Rivers

The protection rate of the ecological base flow is reflected by the degree of protection of the ecological base flow of the rivers in the water shortage area of Northwest China. The protection rate of the ecological base flow of rivers in this paper refers to the ratio of the days that can meet the water requirement of the ecological base flow of rivers and the

total number of days within a certain period of time, based on the protection rate of the ecological base flow, as shown in Equation (9).

$$P = D_{Q_R > Q_{EBF}} / D_T \times 100\% \quad (9)$$

where P refers to the protection rate of the ecological base flow of rivers in study rivers, %, which for the national standards or requirements of local government departments is 90%; D_T refers to the total number of days within a certain period of time, day; $D_{Q_R > Q_{EBF}}$ refers to the number of days that can meet the water requirement of the ecological base flow of rivers.

3. Results and Discussions

3.1. Determination of Ultimate Ecological Velocity of Rivers

3.1.1. Ecological Velocity That Maintains the River Geometry

The Weihe River Basin is located in the loess area of Northwest China, and the Weihe River's water is mainly supplied by precipitation, but the sediment content of the Weihe River is relatively high due to the annual rain erosion [13]. Therefore, in order to prevent the flow from further scouring the riverbed and the large amount of sediment carried by the rain wash depositing, we should put flow velocity between the non-scouring velocity and the non-silting velocity of rivers [9]. Due to the current theoretical level, there is considerable deviation when using theoretical formulas to estimate the sediment carrying capacity of natural rivers [32–34] and the particle size distribution method has a wide range of values and is suitable for general irrigation projects [23], and the error is larger than the former two methods [34]. In addition, empirical formula methods have been used in the Weihe River to determine the ecological velocity required to maintain the river geometry; therefore, in this paper, we use the empirical formula method to determine non-scouring and non-silting velocity of rivers, the specific calculation is shown below.

The main purpose of non-silting velocity is to prevent a large amount of sand from being deposited by the water flow, thus changing the riverbed shape and raising the riverbed, which can produce a series of negative effects. The non-silting velocity of rivers [9] is shown in Equation (10).

$$V_{NSI} = CH^{0.64} \quad (10)$$

where V_{NSI} refers to the non-silting velocity in the Weihe River, m/s; C refers to the coefficient of flow velocity determined by sediment properties in river flow, and the coefficient of sand grains with different particle sizes is different, generally, with regard to the fine sand, medium sand, coarse sand, C are 0.39~0.41, 0.54~0.57, 0.6~0.7 [9], respectively, and are dimensionless; H refers to the water depth, m.

Based on the *Hydrological Data of Yellow River Basin of Annual Hydrological Report*, released by P.R., China (Weihe River System), we can obtain the grain size distribution of the Baoji section of the Weihe River Basin. Its average value is 0.025, which is between 0.01 and 0.05; therefore, the riverbed in the Baoji section of the Weihe River Basin belongs to fine sand, and C is 0.39–0.41, so we can take the average value, which is $C = 0.40$.

The water depth in Linjiacun Hydrological Station of the Weihe River is uncertain, and there is a corresponding hydraulic relationship between discharge and water depth in the river. We combine these data with the flow measured in the *Hydrological Data of Yellow River Basin of Annual Hydrological Report* released, by P.R., China (Weihe River System). We use the Excel software (version number: 2021) to conduct regression analysis on the partially measured flow and water depth at the same time node from 2000 to 2015, and the regression results are shown in Figure 2 and Equation (11).

$$H = 0.1392 \times \ln(Q) + 0.2506 \quad (11)$$

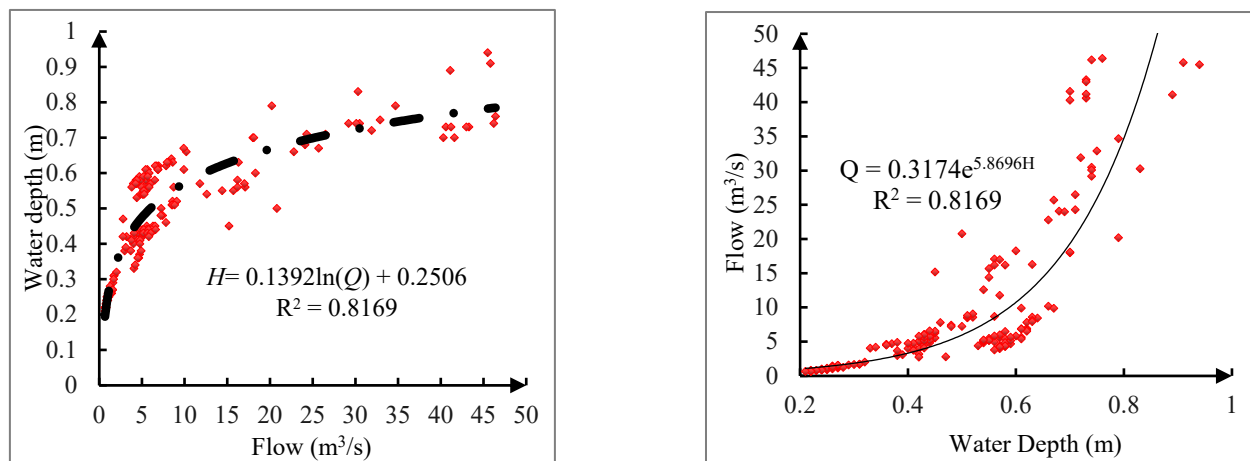


Figure 2. Regression analysis of the flow (water depth) and water depth (flow) at the same time node in the Linjiacun Section of the Weihe River.

Within the formula, the regression coefficient of measured flow and water depth in the Linjiacun Section of the Weihe River is 0.8169, and its accuracy is relatively high.

Based on the annual average runoff from 2000 to 2015, we use Equation (11) to obtain the average water depth in the Linjiacun Section of the Baoji section of the Weihe River. Its value is 0.74 m. Then, we can use Equation (10) to obtain the non-silting velocity in Baoji section of the Weihe River. The calculation result of the non-silting velocity is 0.33 m/s.

When the flow velocity of rivers is too high, it will cause flow erosion, which will affect the riverbed and the river embankment to a certain extent, and then change the geometry of the river channel. The non-flushing velocity of rivers is shown in Equation (12).

$$V_{NSC} = 0.1 \times \sqrt{\frac{\gamma_s - \gamma}{\gamma}} g \times \rho^{\frac{1}{3}} \times R^{0.2} \quad (12)$$

where V_{NSC} refers to the non-flushing velocity of rivers, m/s; γ_s refers to the volume weight of sand grains, the riverbed of the Baoji section of the main stream of the Weihe River is mainly composed of fine sand, and its selected value is $1.5 \times 10^3 \text{ kg/m}^3$; γ refers to the volume weight of water, and its constant value is $1.0 \times 10^3 \text{ kg/m}^3$; g refers to the gravitational acceleration, $9.8 \text{ m}^2/\text{s}$; ρ refers to the sediment concentration, and its value was 13.8 kg/m^3 in 2015 (according to the *Hydrological Data of Yellow River Basin of Annual Hydrological Report*, P.R., China (Weihe River System)), kg/m^3 ; R refers to the hydraulic radius of rivers, m.

The relationship between discharge and hydraulic radius is derived based on the Xiecai formula, as shown in Equation (13).

$$Q = \frac{1}{n} \times A^{\frac{5}{3}} \times P^{-\frac{2}{3}} \times S^{\frac{1}{2}} \quad (13)$$

Combined with the parameters of hydraulic gradient and the area of cross-section in Linjiacun section, Xu and his co-workers (2016) obtained the quantitative simulation formula between the discharge and hydraulic radius [9], as shown in Equation (14).

$$R = 0.0742 \times Q^{0.4787}, R^2 = 0.9919 \quad (14)$$

Combined with Equation (14), we used the average flow $36.19 \text{ m}^3/\text{s}$ from 2000 to 2015 to determine the hydraulic radius in the Linjiacun Section, and the average calculation result of the hydraulic radius was 0.42 m. Therefore, we can use Equation (12) to obtain the non-flushing velocity of rivers in the Baoji section of the Weihe River. And the non-flushing velocity of rivers in the Linjiacun section was 0.86 m/s.

Generally, the ecological velocity that maintains the river ecological geometry should be between the flow velocity of the non-flushing and non-silting. Therefore, the ecological velocity that maintains the river ecological geometry is shown in Equation (15).

$$0.33 \leq V_{SAS} \leq 0.86 \text{ (m/s)} \quad (15)$$

where V_{SAS} refers to the ecological velocity that maintains river geometry, m/s.

3.1.2. Ecological Velocity That Purifying Water Quality in Rivers

The Baoji section of the main stream of the Weihe River refers to the section from the Linjiacun Hydrological Station to the Weijiapu Hydrological Section of the Weihe River. The length of the river between the two hydrological sections is 65 km, and the river channel of this section is relatively straight [35]. Combined with the division of the national water quality monitoring section in the Baoji section of the main stream of the Weihe River [36], this section division method is also adopted in the process of determining the ecological velocity of water purification. In addition to the Linjiacun Section and Weijiapu Section, it also includes the Wolongsi Section, Guozhen Section and Caijiapo Section, and these four national water quality monitoring sections and the Weijiapu Section in the Baoji section of the Weihe River are shown in Figure 3.

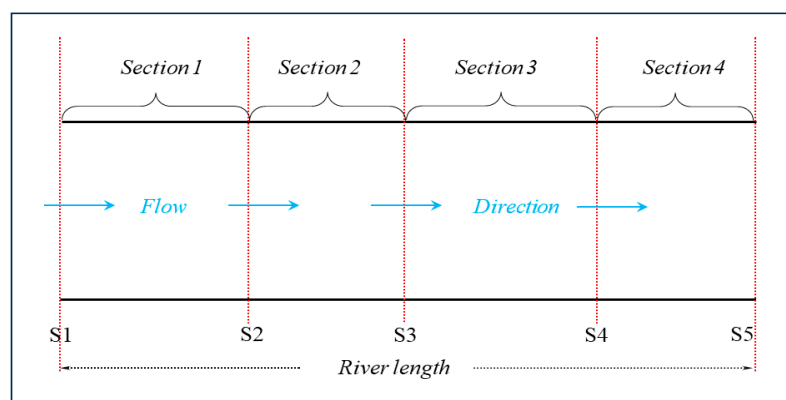


Figure 3. The 4 national water quality monitoring sections and the Weijiapu Section in the Baoji section of the Weihe River. These 5 water quality monitoring sections mainly include S1 (Linjiacun Section), S2 (Wolongsi Section), S3 (Guozhen Section), S4 (Caijiapo Section), and S5 (Weijiapu Section), respectively.

The main pollutants which enter the Baoji section of the Weihe River mainly include point source pollution and non-point source pollution [37]. According to the results reported with regard to the verification and distribution of sewage (water) outlets and water intakes in the main stream of the Weihe River, in work published by Shaanxi Water Environment Engineering Survey and Design Institute based on 33 sewage outlets in the Baoji section of the mainstream of the Weihe River, a lot of pollutants are discharged. Also, because the Weihe River Basin is mainly supplied by regional precipitation, and the Weihe River Basin is located in a loess area of Northwest China, the surface is mostly composed of bare soil and the soil is relatively loose [38], so the process of regional runoff and confluence will bring a lot of pollutants into the Baoji section of the main stream of the Weihe River [20].

The main pollutant emissions in the Baoji section of the main stream of the Weihe River are COD and $\text{NH}_3\text{-N}$ [39], so based on the pollutants of COD and $\text{NH}_3\text{-N}$, we determine the river ecological velocity needed for water quality purification in the Baoji section of the main stream of the Weihe River. In addition, according to the investigation results of the Survey Bureau of Hydrology and Water Resources of the Shaanxi Province, the pollutant degradation coefficient K of the chemical oxygen demand and ammonia nitrogen in the Baoji section of the Weihe River is 0.42~0.56/d and 0.17~0.51/d, respectively.

Due to the most serious stage of water pollution in the Baoji section of the mainstream of the Weihe River in 2000 and 2001, we can determine the threshold of ecological velocity according to the water quality purification of this period, and further determine the protection target value of ecological base flow, which can maintain the purification of river water quality. Combining our results with the environmental status report of the Shaanxi Province in 2000 and 2001, we can obtain the current concentration of pollutants in five river sections of the Baoji section of the mainstream of the Weihe River. The amount of concentration of pollutants in the Baoji section of the Weihe River is shown in Table 2. In addition, and combined with the published report of Xu et al. (2016) [9], we can obtain the distance between the four sections, including the Linjiacun, Wolongsi, Guozhen and Caijiapo sections, and the Weijiapu section; the distance is shown in Table 2.

Table 2. Total amount of water quality status and water quality standard of 5 national water quality monitoring and control sections in the Baoji section of the Weihe River.

Item	COD/(mg/L)		NH ₃ -N/(mg/L)		Distance (x) (Km)
	Current	Standard	Current	Standard	
Linjiacun	40	≤20	2.0	≤1.0	x = 65
Wolongsi	>40	≤20	>2.0	≤1.0	x = 45
Guozhen	>40	≤30	>2.0	≤1.5	x = 31
Caijiapo	>40	≤30	>2.0	≤1.5	x = 11
Weijiapu	>40	≤20	>2.0	≤1.0	x = 0

All data in this section come from the published report of the *Environmental Status Bulletin* of the Shaanxi Province (http://sthjt.shaanxi.gov.cn/newstype/hbyw/hjzl/hjzkgb/index_2.html (accessed on 4 June 2020)) and the *National Water Pollutant Control and Treatment Science and Technology Major Special Research Report*. Distance refers to the distance between the 4 national water quality monitoring and control sections and the Weijiapu Hydrological Section.

Based on the latest assessment index standard of surface water quality of the Weihe River recently issued by the Department of Ecological and Environment of the Shaanxi Province (*Technical guidelines for the development of water pollutant discharge standards in watersheds*, HJ945.3-2020, <http://bz.mee.gov.cn/bzwb/stzl/> (accessed on 1 March 2020)), we take this surface water quality standard as the water quality target requirement of the river ecological base flow protection in the Baoji section of the Weihe River. The total amount of the two standard pollutants of COD and NH₃-N is shown in Table 2.

We used Equation (6) to segmentally calculate the requirement of the ecological flow velocity of COD and NH₃-N of pollutants which can achieve the river water quality standard of designated four national water quality monitoring and control section in the Baoji section of the mainstream of the Weihe River, and two ecological flow velocities of COD and NH₃-N of pollutants can be obtained. We take its maximum value as the ecological flow velocity that purifying water quality. Therefore, the ecological flow velocity of the water purification requirement in the Baoji section of the mainstream of the Weihe River is shown in Equation (16).

$$0.394 \leq V_{WQ} \quad (16)$$

3.1.3. Ecological Velocity That Maintaining Biodiversity in Rivers

We take the existing fish species in the Weihe River Basin as the ecological index to calculate the ecological base flow protection target of rivers. The existing fish we selected in the middle and lower reaches (including the Baoji section of the Weihe River Basin) of the Weihe River mainly include the following five species: *Opsariichthys bidens*, *Carassius auratus*, *Pseudorasbora parva*, *Misgurnus anguillicaudatus* and *Cyprinus carpio* [8,9,17]. The preferred ecological velocities of these five fish in different periods are shown in Table 3.

Table 3. The suitable flow velocities of rivers that preferred by five fish species in the main stream of the Weihe River Basin.

Fish Species	<i>Opsariichthys bidens</i>	<i>Carassius auratus</i>	<i>Pseudorasbora parva</i>	<i>Misgurnus anguillicaudatus</i>	<i>Cyprinus carpio</i>
Spawning Season (Month)	6~9	4~6	5~6	4~5	4~7
Velocity (m/s)	≥ 0.8	No	No	No	No
V_{spaw} , V_{opt} , V_{max}	0.3~0.5 0.6	0.2~0.6 0.93	0~0.46 0.46	0.3~1.04 1.04	0.2~1.0 1.1

V_{spaw} , V_{opt} and V_{max} refer to the velocity required by a fish species, optimal velocity required by a fish species, and maximum velocity needed by a fish species, respectively.

Therefore, combined with the preference velocity of five fish species, we use Equations (2) and (3) to determine the common preference velocity of five fish species in the Baoji section of the Weihe River. The calculation results are shown in Equation (17).

$$\begin{cases} 0.8 \leq V_{BD}, 6 \sim 9 \text{ month} \\ 0.3 \leq V_{BD} \leq 0.46, 1 \sim 5 \text{ month}, 10 \sim 12 \text{ month} \end{cases} \quad (17)$$

3.1.4. Determination of the Ultimate Ecological Velocity in Rivers

At present, the water quality is deteriorating, destroying biodiversity and the geometry of the river course is changing dramatically in the Weihe River Basin, which will cause health problems for the rivers themselves and cause problems in relation to the safety and property of the surrounding residents [7,8]. Thus, we need to determine the coincident velocity that can purify the water quality and maintain the morphology and biodiversity of rivers. Combined with the ecological velocity that maintains the river geometry, purifies water quality in rivers, and maintains biodiversity in rivers, we used Equation (8) to determine the proper ecological velocity of rivers; the calculation result is shown in Equation (18).

$$\begin{cases} 0.80 \leq V_{BD} \leq 0.86, 6 \sim 9 \text{ month} \\ 0.39 \leq V_{BD} \leq 0.46, 1 \sim 5 \text{ month}, 10 \sim 12 \text{ month} \end{cases} \quad (18)$$

3.2. Determination of the Ecological Base Flow of Rivers and Rationality Analysis

We used the selected measured data (including the river flow and velocity) from the *Hydrological Data of the Yellow River Basin of the Annual Hydrological Report*, P.R., China (Weihe River System) to determine the hydraulic relationship between velocity and flow under different water surface widths in the Linjiacun Section from 2000 to 2015. And we used the Excel software to conduct a regression analysis on flow velocity and flow, and thus obtained the fitting relationship; the regression coefficient is 0.8363, and the accuracy of the fitting relationship is relatively high. The fitting results are shown in Figure 4 and Equation (19).

$$Q = 54.267 \times V^{2.2986} \quad R^2 = 0.8416 \quad (19)$$

where Q refers to the runoff coming from rivers, m^3/s ; V refers to the flow velocity, m/s .

We take the river geometry protection, biodiversity protection, and water quality purification in the Baoji section of the main stream of the Weihe River as the ecological indicators of river protection. Combined with the preferred flow velocity under different ecological protection objectives, we can further obtain the overall preferred flow velocity of rivers, and then we can obtain the protection target of the ecological base flow in the Baoji section of the mainstream of the Weihe River; that is to say, among them, the range of the protection target of the ecological base flow of rivers is $[6.26, 9.17 \text{ m}^3/\text{s}]$ from October of this year to May of next year, and $[32.94, 38.93 \text{ m}^3/\text{s}]$ from June to September, respectively. The calculation results in this paper are shown in Figure 5.

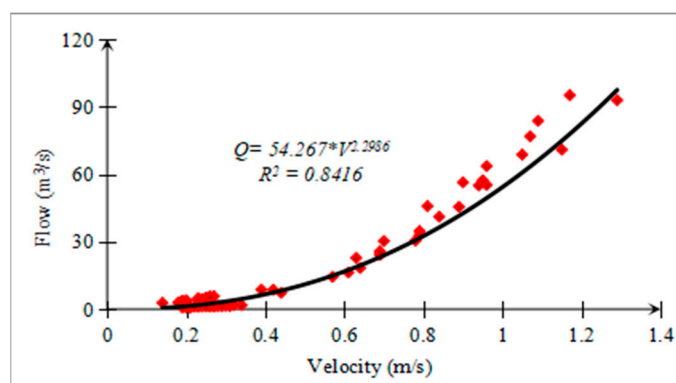


Figure 4. The fitting relationship between flow coming from rivers and flow velocity of rivers.

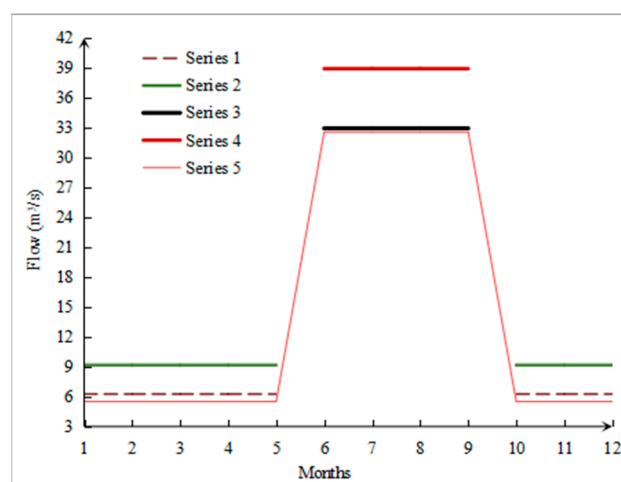


Figure 5. Comparison of the river ecological base flow and the calculation results using the Tennant method in the Baoji section of the Weihe River. Series 1 and 2 refer to the minimum and maximum ecological base flow from January to May and from October to December; Series 3 and 4 refer to the minimum and maximum ecological base flow from June to September; Series 5 refers to the calculation results achieved using the Tennant method.

Tennant's method [40] involves analyzing the impact of physical, chemical and biological information on cold water and warm water fisheries in 38 sections of 11 rivers in three states of the United States under different river flows [41,42]. The biggest advantages of the Tennant method are simple: it is very easy to perform, it does not require field measurements, and it is suitable for any rivers with any seasonal changes. It can be used to test the calculation results of other research methods [43,44].

Although the Tennant method is suitable for all rivers with seasonal changes, there are some differences between the Weihe River and American rivers, such as the climate conditions around the basin, the seasonal changes of rivers, and the spawning period of fish [45]. At the same time, there will be differences in the periodic selection of river ecological base flow [9]. Therefore, based on the report published by Tennant in 1976 [40], the seasonal changes, and fishes' survival in the Weihe River, we need to redivide the recommended base flow period. The result of redividing the recommended base flow period is from October of this year to May of next year and from June to September.

Combined with the redividing period of recombined recommended base flow, we use 10% and 40% of the average monthly runoff from 1953 to 2015 year as the basis for calculating the recommended ecological base flow in the Baoji section of the main stream of the Weihe River, and we take the calculation results of the recommended ecological base flow of rivers as the reference value for comparing its protection target. The totals of 10%

and 40% of the average monthly runoff in the Linjiacun Station of the Baoji section of the Weihe River from 1953 to 2015 year are 5.51 and 32.57 m³/s, respectively; the calculations results are shown in Figure 5.

By referring to the known protection target of the river ecological base flow in the Baoji section of the Weihe River and the revised recommended protection target of the ecological base flow, we conduct a comparative analysis of the two calculation results of the ecological base flow of rivers, as shown in Figure 5. Based on the comparison results, we can see that the calculation results are close to each other and protection of the ecological base flow of rivers, which is determined by the integrated method of river flow velocity, is relatively reasonable.

We recommend that the protection target of the ecological base flow of rivers should be [6.26, 9.17 m³/s] from October of this year to May of next year, and [32.94, 38.93 m³/s] from June to September, respectively. Of these, we take two values of 6.26 and 32.94 m³/s as the bottom line of river ecological base protection in non-flood season and flood season, respectively.

3.3. Assessment of Protection Status of the Ecological Base Flow of Rivers

By using frequency analysis software to analyze the frequency of runoff in Baoji section of the Weihe River from 1973 to 2018, we can obtain the wet year (2018, 25%), normal year (2012, 50%), partial dry year (2004, 75%), dry year (2000, 90%), and extremely dry year (2009, 95%). Based on the daily runoff of the above five typical years after the irrigation water diversion and the protection target of the river ecological base flow in the Baoji section of the Weihe River (6.26 and 32.94 m³/s in non-flood season and flood season are taken as the baseline of the ecological base flow of rivers), we analyze the protection rate of the ecological base flow, and we use Equation (9) to analyze and calculate the protection rate of the ecological base flow of the above five typical years in the Baoji section of the Weihe River; therefore, the calculation results of the protection rate of the ecological base flow are shown in Figure 6.

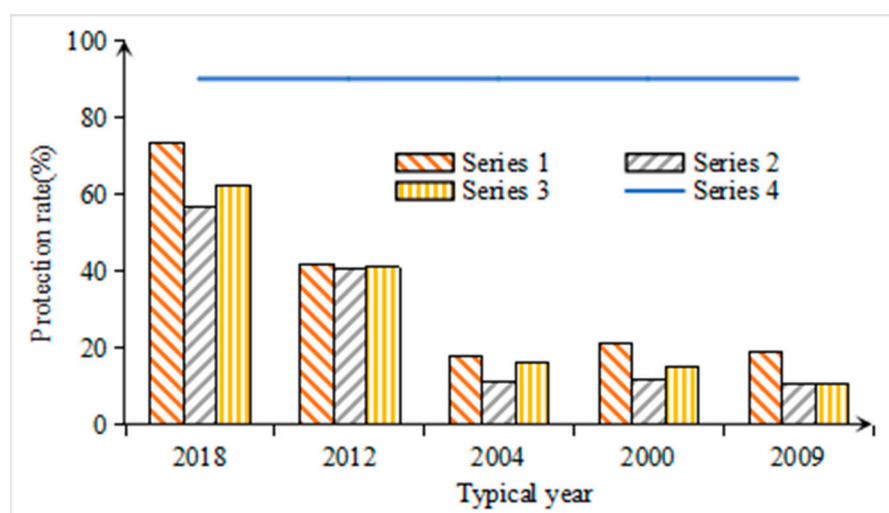


Figure 6. Analysis of the protection rate of the ecological base flow of different typical years in the Baoji section of the mainstream Weihe River. Series 1 refers to the protection rate of the ecological base flow in flood season; Series 2 refers to the protection rate of the ecological base flow in non-flood season; Series 3 refers to the protection rate of the ecological base flow in the whole year; Series 4 refers to the protection rate of the ecological base flow of national standards or requirements of local government departments (90%).

We can see from Figure 6 that the protection rate of the ecological base flow is relatively low in the Baoji section of the Weihe River. The protection rates of the ecological base flow of different five typical years in Baoji section of the Weihe River are 62.47%, 41.10%, 16.16%, 15.07%, and 10.68%, respectively, and each of them is far below 90%, which is the

evaluation criteria required as per the “ecological flow guarantee objectives of first batch key rivers and lakes” issued by the Ministry of Water Resources of the People’s Republic of China on April 17, 2020. In 2018, the protection scheme of the river ecological base flow was implemented, but the average protection rate of the ecological base flow of rivers is only 62.47%, and the average protection rates in non-flood season and flood season are only 66.79% and 73.77%, respectively. Therefore, we think that the related sector should strengthen the protection of the ecological base flow in the Baoji section of the Weihe River, so as to increase the protection rate above the standard range. At the same time, we can also see that with the strengthening of management by relevant departments, the protection rate of the river ecological base flow gradually starts to develop in a good direction.

In addition, in recent years, many scholars have proposed some assessment systems for the river ecological base flow to judge whether the residual flow after a large amount of water diversion has reached the required protection degree of the ecological base flow of rivers: the continuous non-compliance amounts to less than seven days; the flow is continuous month by month; and the monthly average runoff is all up to standard; the annual index evaluation needs at least three months to meet the protection target of the river ecological base flow.

Based on the measured daily runoff data of the Baoji section of the Weihe River from 2000 to 2018, we further verify the above four assessment systems. Firstly, the frequency of continuous substandard flow in the Baoji section of the Weihe River was often more than seven days; for example, the daily discharge of Baoji section from 2001 to 2002 reached a rare 221 days, which far exceeds seven days; this directly led to the drastic reduction of aquatic organisms. Secondly, the monthly average runoff cannot reach the goal of river ecological base flow, especially in non-flood season. Finally, the continuous monthly average runoff and at least three months met the protection goal value of river ecological base flow.

In view of the low protection rate of the river ecological base flow and failure to meet the given evaluation index, we put forward some corresponding suggestions. Firstly, in view of serious waste of agricultural water, related departments should establish effective water-saving measures as soon as possible to improve the utilization rate of water resources and reduce the waste of water resources [1,6]. Secondly, establishing an effective water resources management mode and defining the right to use water resources is very important, and should be followed by establishing an effective ecological compensation mechanism and water rights trading market to protect the ecological base flow of rivers. Thirdly, within available scope of groundwater utilization, irrigation authorities should appropriately enhance the use of groundwater. Finally, in order to strengthen people’s awareness of protecting river ecological base flow and river health, river authorities should vigorously publicize the importance of river ecological base flow protection to the river basin itself and the surrounding living population, and they should develop corresponding reward and punishment measures.

3.4. Analysis of Coupling Model for Determination of River Ecological Base Flow

The main purpose of this paper is to avoid using a single function to determine the ecological base flow of rivers and then affect other ecological functions of rivers. It seems reasonable to add up the water demand of various functions. In fact, the process of mutual influence between functions leads to the further loss of a certain ecological function of rivers. In other words, the purpose of this paper is to promote the determination of river ecological base flow based on the coupling relationship of overall ecological functions, and to avoid mutual influence between river ecological functions, and to maintain the trend of healthy river ecological development.

Northwest China’s water shortage area belongs to arid and semi-arid areas. The total amount of water resources in the region is very limited, and the contradiction between the supply and demand of water resources is extremely sharp. In particular, the agricultural water demand is large, the ecological water is seriously constricted, and the biodiversity

in rivers is sharply decreased [16]. And with the accelerated development of economy, sewage discharge and other phenomena have caused serious water pollution and bad water quality in this region [46]. At the same time, this region also belongs to the Loess Plateau area. The river water resources mainly rely on precipitation supply; the soft soil makes the precipitation water resources carry a lot of sediment, which makes the ecological geometry of the river section change, and the non-point source pollution is also very serious [20].

The problems of rivers in the water shortage areas of Northwest China include the main problems existing in most of the basins in other areas of China: the decline of aquatic biodiversity, serious deterioration of water quality, and problems of flow and sediment; for example, the deterioration of water quality and the decline of aquatic biodiversity in southern China. Similarly, rivers in many countries in the world have similar problems, such as water quality deterioration and biodiversity [47–49]. Therefore, this coupling method can also be used to determine the main problems of many world river basins.

However, the calculation method used to determine the ecological base flow of the river is based on various functions which should be selected according to the differences in the study areas. For some of these differences, such as the flow velocity of rivers without scouring and silting, the empirical formula method is selected in this paper; however, for other rivers, one of the above three methods should be selected. In addition, there will be some deviation in the water quality model. The steady-state one-dimensional water quality model is adopted in water quality model, but it may not be suitable for other rivers, so it is necessary to further improve the water quality model. Some rivers also take plants as ecological indicators, so it is necessary to consider the impact of water depth on plant ecological indicators, but the ecological base flow also can be determined through combination with hydraulic relationship. In summation, the research method can be applied to determine the ecological base flow in many rivers in order to ensure the integrity of river ecological functions.

4. Conclusions

We established the quantitative calculation model of the ecological base flow of rivers based on the coupling relationship of sediment transportation, water quality, and biodiversity in rivers. Taking the Baoji section of the Weihe River as an example, the main conclusions of the research results are as follows. The ecological flow velocities of water quality purification, biodiversity conservation, and protection of river geometry in Baoji section of the Weihe River from October to May and June to September are [0.39, 0.46 m/s] and [0.80, 0.86 m/s], respectively. The river ecological base flows are [6.26, 9.17 m³/s] and [32.94, 38.93 m³/s] from October of this year to May of next year and from June to September, respectively. The protection rates of the river ecological base flow of five typical years are 62.47%, 41.10%, 16.16%, 15.07% and 10.68% of the whole year and are far below 90%. Over the past 19 years, the residual water in Baoji section of the Weihe River basin after agricultural irrigation water diversion in Baojixia Yuanshang Irrigation District has been unable to meet the evaluation index standard of the river ecological base flow. This model can promote the determination of river ecological base flow based on the coupling relationship of overall ecological functions and avoid the mutual influence between river ecological functions to maintain the trend of healthy river ecological development.

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