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Compensation for Agricultural Economic Losses Caused by Restoration of Healthy Eco-Hydrological Sequences of Rivers

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Abstract: The rational allocation of ecological and economic water is a topic of high interest for water resource sciences. Taking into consideration the difficulties to maintain the basic ecologic functions of rivers, we propose a calculation model for compensation for agricultural economic losses by restoration of the healthy eco-hydrological sequences of rivers. Firstly, healthy eco-hydrological sequence of rivers was constructed by assessing the response relationship between hydrological processes and ecological functions of ecological base flow of rivers. Following, the ecological water shortage was analyzed qualitatively and quantitatively. Finally, the compensation for agricultural economic losses caused by restoration of healthy eco-hydrological sequence of rivers was calculated. Taking the Baoji section of the Weihe River as a case study, compensation for agricultural economic losses caused by the recovery of the healthy eco-hydrological sequence of rivers were calculated and further analyzed. The results show that the current water diversion in the area of study is excessive and the ecological water shortage is relatively obvious. The compensation for agricultural economic losses caused by the recovery of healthy eco-hydrological sequence of rivers mainly focus on the non-flood season, which is up to 218 million yuan for 2009 year.

Keywords: compensation; agricultural economics losses; ecological functions; the ecological base flow of rivers; healthy eco-hydrological sequences of rivers; Weihe River

1. Introduction

Conflicts that arise between agricultural water and ecological water usage represent an important environmental issue that has attracted international attention. Calzadilla and coworkers have reported that around 70% of the total water resources available from rivers are used for agricultural irrigation [1]. In 2008, agricultural irrigation in northern China was reported to consume 74.4% of the total available water resources [2], with the population and agricultural water consumption in this region continuing to increase gradually. This increase in demand for agricultural water has a serious impact on the amount of ecological water available to ensure a healthy river system is maintained. The ecological base flow [3,4] of a river corresponds to its relative volume of flow, which has also been described using the terms: Low flow; minimum acceptable flow; basic ecological water requirement; and ecologically acceptable flow regime [5–12]. The ecological base flow of a river is defined by the minimum rate of water flow required to ensure that atrophy, depletion, and loss of channel function does not occur [13]. However, many water owners believe that maintenance of a river's ecological base flow does not bring direct economic benefits, meaning that river ecological base flow rates are often not guaranteed, which can decrease the functions of rivers and result in the river environment being seriously damaged.



Therefore, the development of procedures and legislation to protect ecological base flow of rivers and equitably allocate agricultural water is a significant challenge for the water industry.

A number of quantitative studies have been carried out analyzing river ecological base flow of river systems [14–16], their economic value [17,18], and the ecological base flow of river protection procedures [19–21]. These studies have mainly focused on agricultural water-saving, regional water diversion strategies, and the development of policies for the rational control of water resources. However, relatively few studies have been carried out to quantify the economic losses caused by the introduction of river ecological base flow protection schemes. A quantitative study on the economic losses caused by transferring that the agricultural water to the ecological water in the Australian Murray basin has been reported by Qureshi et al. [22]. Jones [23] have constructed stochastic dynamic process models to determine influence of a number of factors on economic losses associated with diversion of agricultural irrigation water for ecological water usage. Malano and Davidson [24] used a balance analysis framework to determine the relationship between agricultural and ecological water use in the Krishna valley in India and the Murray-Darling valley in Australia. Pang [25] considered losses in crop production levels to calculate the amount of agricultural ecological compensation that should be awarded for ecological water use in the Yellow River. However, the economic impact of maintaining healthy eco-hydrological sequence of a river system, and an effective model for calculating the amount of compensation for agricultural losses caused by protection of the ecological base flow of rivers are lacking.

The main purpose of this study was to establish a calculation model to calculate compensation for the agricultural economic losses caused by the restoration of the eco-hydrological sequence of rivers that would enable agricultural economic losses to be compensated accordingly. This model was designed to consider changes in the ecological functions of the ecological base flow of rivers over time, with the aim of minimizing disruption to other water using sectors. We analyzed the compensation for the agricultural economic losses caused by restoration of healthy eco-hydrological sequences in the Baoji section of the Weihe River in China, thus enabling appropriate financial compensation amounts to be determined. These values enable a quantitative basis for the rational protection of river's ecological base flow that will allow the implementation of effective policies for managing water resources.

2. Materials and Methods

The healthy eco-hydrological sequence of rivers refers to the process of runoff change that can make the a river course in a healthy state, which is based on the response relationship between the hydrological process (runoff change) and the ecological function of the ecological base flow of rivers. Because of the contradiction between agricultural water use and healthy hydrological sequence of rivers, satisfying the hydrological sequences of rivers will inevitably reduce the economic losses of farmers, so the beneficiaries must compensate farmers. The calculation process of this paper is mainly divided into three parts: Firstly, the establishment of healthy eco-hydrological sequences of rivers based on runoff change and ecological function of river ecological base flow, and the healthy eco-hydrological sequences of rivers should follow the establishment principle; Secondly, the analysis of ecological water shortage of the healthy eco-hydrological sequences of rivers; and Finally, compensation for agricultural losses caused by healthy eco-hydrological sequence of river was calculated.

2.1. Establishment of Healthy Eco-Hydrological Sequences of Rivers

Based on the concepts of river ecological base flow and the ecosystem service functions [26,27], Li and Yue [18] reported the ecological base flow requirements for maintenance of ecological functions of rivers. The water requirements for different ecological functions of rivers greatly differed in the same section of a river and at the same period of time. Moreover, during the seasonal watershed, the hydrological sequences were also altered with time. These findings demonstrate that there is a direct relationship between the ecological functions and the effects of the hydrological sequences on water requirements for ecological base flow of rivers. Therefore, in this study we propose a healthy

eco-hydrological sequence of river systems by taking into account the response relationship between hydrological processes and the ecological functions of ecological base flow of rivers.

2.1.1. Quantitative Analysis of Ecological Functions of Rivers Ecological Base Flow

Based on the report published by Li and Yue [18], the service functions of ecological base flow of a river systems are divided into two types, including: The auxiliary ecological functions (as long as water resources exist) and the main ecological functions (must maintain a certain amount of water resources). The main ecological functions of the ecological base flow of rivers include: F1: Protection from drying-up rivers and flow required to maintain biological survival and growth, F2: Water purification (see Table 1).

Table 1. Maintaining the basic healthy ecological functions of rivers and their calculation method.

Service Functions	Protection Target	Research Methods		
F1: Protecting from drying-up rivers and the necessary water level required for normal growth and development of fishes and other aquatic organisms is guaranteed, and rare species are protected from extinction [28].	Protection of normal development and inhabiting reproduction of species	M1: Tennant [29], M2: Mean water depth method [30] M3: R2-CROSS [31] M4: Wetted perimeter method [32]		
F2: River ecological base flow enables rivers to purify a certain amount of pollutants, to maintain water self-purification capacity and improve river water quality [33].	Improving the water quality of rivers	M5: Water quality and water simulation method [30]		

2.1.2. Principle of Establishing Healthy Eco-Hydrological Sequences of Rivers

The establishment of the healthy eco-hydrological sequence of rivers was based on 4 main principles; coordinated economic development, main functional priority, functional completeness, and water content satisfiability.

Coordinated Economic Development. The objective of this study was mainly to establish a calculation model for calculating the amount of financial compensation for agricultural economic losses caused by the recovery of the healthy eco-hydrological sequences of rivers, and to satisfy all the functions required for their ecological base flow. Therefore, the minimum flow rates were selected as a healthy eco-hydrological sequence to ensure the applicability of the model for rational compensations and at the same time to meet water function requirements that would allow the economic development of other economic water use sectors. Based on these considerations we constructed the following model:

$$Q_{E} = Q_{Runoff} + Q_{1} + \dots + Q_{i} + \dots + Q_{n}$$

$$V_{L} = Min \sum_{i=0}^{N} (Q_{L,1} \times v_{1} + \dots + Q_{L,i} \times v_{i} \dots + Q_{L,n} \times v_{n})$$
(1)

where, Q_E refers to the volume of water requirements for the healthy eco-hydrological sequences of rivers within a certain period of time (unit: one hundred million m³); Q_i refers to the volume of water consumption of the *i*th water use sector (unit: one hundred million m³); V_L refers to the amount of economic losses of the different water sectors caused by the protection of river ecological base flow (unit: one hundred million yuan); Q_{Li} refers to the reduced intake volume of water of the *i*th water sector caused by the protection of river ecological base flow (unit: one hundred million yuan); Q_{Li} refers to the reduced intake volume of water of the *i*th water sector caused by the protection of river ecological base flow (unit: one hundred million m³); and V_i refers to the unilateral water benefit of the *i*th water use sector (unit: yuan/m³).

Main Function Priority. In order to ensure that there is no damage to the river and the sustainable use of water resources is guaranteed [34], the main water functions were first determined. Following, the leading function and function order of each water area were set up as follows:

$$Q_E = First\{Q_{E,1}, \dots, Q_{E,j}, \dots, Q_{E,m}\}$$
(2)

where, $Q_{E,J}$ refers to the *j*th water requirement of ecological functions of the river's ecological base flow (unit: one hundred million m³).

Functional Completeness. When water requirements of rivers can be satisfied, the ecological functions of rivers ecological base flow should be fully guaranteed. Therefore, we incorporated in our model the role of ecological functions of rivers, to ensure the balance between human development and nature conservation.

$$Q_E = Max \{Q_{E,1}, \dots, Q_{E,j}, \dots, Q_{E,m}\}$$

$$(3)$$

Water Content Satisfiability. In some cases, the amount of water available from rivers cannot meet the water requirements of service functions of river ecological base flow. In such cases, we calculated the warning values of the rapid deterioration for the river ecosystem. We used the flow duration curve (FDC) to determine the warning values [35].

$$Q_E = Q_{90\%0r95\%}, If(Q_{90\%0r95\%} > Q_E)$$
(4)

where, $Q_{90\% or 95\%}$ refers to the critical warning values of the rivers' flow (m³/s). In this study, we regard $Q_{90\%}$ as the warning value.

2.2. Ecological Water Shortage Analysis of the Healthy Eco-Hydrological Sequences of Rivers

The basic function of rivers requires a certain amount of water, however at the present because the diversion of water resource was fairly excessive, the water flow requirement for ecological functions was difficult to meet. Therefore, we calculated the functional water shortage, which refers to the difference between the water requirement for maintaining the basic ecological functions of rivers and the water resource available from the corresponding rivers. The ecological functional water shortage is expressed by Equation (5).

$$W_{WSEF} = W_{EFWD} - W_{RW} \tag{5}$$

where, W_{WSEF} refers to the volume of water shortage that can maintain the basic ecological functions of rivers (unit: one hundred million m³); W_{EFWD} refers to the amount of water required for sustaining the basic ecological functions of rivers (unit: one hundred million m³); and W_{RW} refers to the residual water of rivers after the implementation of the water diversion (unit: one hundred million m³).

The distribution coefficient of healthy water diversion was determined by the ratio of the amount of water diverted after maintaining the basic ecological health of rivers to the total volume of water available from rivers. The distribution coefficient of healthy water diversion was used to analyze the rationality of the water diversion and can be calculated by Equation (6).

$$D_{HHP} = \frac{W_T - W_{RW}}{W_T} \tag{6}$$

where, D_{HHP} refers to the distribution coefficient of healthy water diversion; W_T refers to the total available amount of water from rivers (unit: one hundred million m³); and W_{RW} refers to the amount of residual water in rivers after water diversion (unit: one hundred million m³).

The distribution coefficient of actual water diversion was determined by the ratio of the volume of residual water after different water use sectors diverted water from rivers to the amount of water coming from rivers. Equation (7) was used to determine the distribution coefficient.

$$D_{AWD} = \frac{W_T - W_{RW}}{W_T} \tag{7}$$

where, D_{AWD} refers to the distribution coefficient of the actual water diversion.

2.3. Compensation Calculation for Agricultural Economic Losses Caused by Restoration of Healthy Eco-Hydrological Sequence of Rivers

The crop water requirement coefficients were firstly introduced to calculate the typical crop water requirements, water content losses, and crop yield under different water supply conditions [36]. We developed the crop water requirement coefficient to calculate the crop yield losses caused by restoration of the healthy eco-hydrological sequence of rivers, and the compensation for agricultural economic losses was the product of grain yield losses and grain price [37], as shown in Equation (8).

$$Y = y \times p_c = \sum_{12}^{i=1} \frac{W_{AWSEFi}}{K_{ci}} \times p_c = \sum_{12}^{i=1} \frac{\eta \times W_{WSEFi} \times E_{oi}}{ET_i} \times p_c$$
(8)

where, *Y* refers to the amount of compensation for agricultural economic losses caused by restoration of the healthy eco-hydrological sequence of rivers (unit: one hundred million yuan); *y* refers to the amount of agricultural output losses by the implementation of the healthy eco-hydrological sequence of rivers (unit: one hundred million kg); P_C refers to the price of grain (unit: Yuan/kg); W_{AWSEFi} refers to the volume of water shortage caused by healthy eco-hydrological sequence of rivers in the period *i*th (unit: one hundred million m³); η refers to the irrigation water utilization coefficient in the irrigation area, dimensionless; K_C refers to the crop water requirement coefficient, (unit: m³/kg); E_{Ti} refers to the crop water requirement in *i*th time (unit: mm); and E_0 refers to the water surface evaporation of ET during the corresponding time period (unit: mm), typically, the evaporation values were obtained from a 80 cm caliber evaporator (unit: mm).

2.4. Case Study Analysis

A case study was used to calculate compensation for the agricultural economic losses caused by restoration of the healthy eco-hydrological sequence of rivers in the Baoji section of the Weihe River, which is the largest tributary of the Yellow River in China. The Guanzhong section of the Weihe River is located in the middle of the Shaanxi province, with the east longitude and north latitude coordinates for the Guanzhong section being 106°30′–110°30′ and 33°30′–35°40′, respectively. The Baoji section of the Weihe River (Linjiacun–Weijiabao) has a total length of 65 km and is located in the middle and lower reaches of the river (see Figure 1), and that is a seasonal basin and flood season and non-flood season are mainly concentrated in the June-September and October-May of each year. The Baojixia Irrigation District is located in the western Guanzhong region (latitude and longitude coordinates: 34.35° and 107.9°), covering an area of 2355 km². Two diversion hubs (Linjiacun and Weijiabao hydrological stations) are present in the Baojixia Yuanshang irrigation districts and Baojixia Yuanxia irrigation districts, respectively. The Baojixia Yuanshang Irrigation District mainly covers a part of Baoji and Xianyang city, such as Jintai, Qishan, Fengxiang, Qianyang, Chencang, Yongshou, and Qianxian districts (see Figure 1). This irrigation district obtains water from the Linjiacun hydrological station, covering an irrigation area of 128 thousand hm², which receives an annual average of 608 million m³ of diverted water, also some groundwater was used to irrigation. The main irrigation mode in Baojixia Yuanshang Irrigation District is flood irrigation, and a waste of water is more seriously, the irrigation water utilization coefficient in the Baojixia Yuanshang Irrigation Area is relatively low, and its actual investigation value is 0.49–0.52 (obtained from the "Water Statistical Yearbook of Shaanxi" in 2007–2012 years).

The data used in this paper mainly come from "People's Republic of China Hydrological Yearbook", "Shaanxi Statistical Yearbook", and "Water Statistical Yearbook of Shaanxi".



Figure 1. Location of the Weihe River and Baojixia Yuanshang Irrigation District [37].

3. Results and Discussion

3.1. Establishment of Healthy Eco-Hydrological Sequence of Rivers

Because of a large amount of water being diverted in the Baoji section of the Weihe River, the water requirements of the river's ecological base flow are difficult to meet, and as a consequence various water associated environmental problems have emerged. Therefore, this region has been extensively studied. Many scholars have calculated the water requirements for the river's ecological base flow functions [38–40]. Based on these reported water requirements [30,38], we set up the healthy eco-hydrological sequence for the Baoji section of the Weihe River (see Figure 2) by applying the principles of determining a healthy eco-hydrological sequence (see Figure 2). Our findings show that in January, the water requirements for different ecological functions are quite variable. The water requirement for the function of water purification (based on the water quantity and water simulation method) is minimum. And the requirement for growth and survival of fishes (obtained from the

average water depth method) is relatively large. However, the ecological security warning values obtained (obtained by the flow duration curve) indicate that only the water flow requirement for the water purification function, and not for fish survival and growth (obtained from the average water depth method), can be achieved. When function of protection of the living environment of fishes were selected, which cannot satisfy the principles of water content satisfaction, the research results show that the flow duration curve remains similar for the same time period, as well as for the rest of the months.



Figure 2. Establishment of the healthy eco-hydrological sequence of rivers based on response relationship of hydrological process and ecological functions of river ecological base flow. Notes: F1(M1) refers to the water requirement of the ecological function of protecting from drying-up rivers (F1) calculated by Tennant (M1), and also, F1(M2), F2(M3), F3(M4), F3(M5) are similar to F1(M1), F1, F2, F3, M1, M2, M3, M4, M5 as shown in Table 1. HEHS refers to the water requirement of the healthy eco-hydrological sequence of rivers.

From the results presented in Figure 2, it can be seen that the water flow in the dry period (from December to March) is not able to meet the requirements for ecological functions of the river's ecological base flow under the condition of water diversion. However, during the flood-season, the requirements for ecological functions can be satisfied in the absence of water diversion and under the condition of water diversion.

The establishment of a healthy eco-hydrological sequence of rivers should not only satisfy the ecological functions of the ecological base flow of rivers but should also minimize the impact on other water usage sectors. Therefore, we considered the healthy eco-hydrological sequence of rivers as the threshold for ecological flow to calculate the compensation for agricultural economic losses caused by restoration of the healthy eco-hydrological sequence of rivers. This integration approach is more accurate and more realistic than the single control value calculation approach that has been previously reported for ecological base flow of rivers [41] and can reflect the seasonal changes in the amount of compensation for the agricultural economic losses.

3.2. Analysis of Ecological Water Shortage Caused by the Healthy Eco-Hydrological Sequences of Rivers

In order to analyze the effects of the water diversion in the Baoji section of the Weihe River, the distribution coefficient of healthy water diversion and the actual diversion coefficient of water diversion were calculated (see Figure 3).

The actual diversion coefficient during the non-flood season (1–6 and 11–12 months) is far greater than the healthy diversion coefficient of rivers, which indicates that the actual amount of water diverted is far greater than the healthy water intake, leading to serious ecological water shortage problems. Additionally, the water requirement for the water purification function cannot be met, the water quality worsens and the environmental impact is greater, which can cause disconnection of rivers and irreversible damage. The actual diversion coefficient during the flood-season is obviously smaller than the healthy diversion coefficient, and the basic functions of the river's ecological base flow can be satisfied, which leads to an ecological surplus. Therefore, it is possible to timely dispatch water by ecological operation methods and solve the problems associated with the non-flood season to satisfy the demands of ecological functions of ecological base flow of rivers.



Figure 3. Comparison of distribution coefficient of the healthy water diversion and actual water diversion.

Through qualitative analysis, we calculated the volume of water shortage caused by restoration of the healthy eco-hydrological sequence of rivers by applying Equation (5) (see Table 2).

Items		Water Shortage/(10 ⁸ m ³)					
		2007	2008	2009	2010	2011	2012
F1	M1	3.16	3.52	4.41	2.94	2.12	1.46
	M2	0.80	0.78	1.06	0.89	0.87	0.48
	M3	1.64	1.54	2.21	1.69	1.67	1.12
	M4	2.01	1.90	2.68	2.02	2.00	1.44
F2	M5	0.15	0.20	0.17	0.18	0.22	0.08
HEHS		0.96	0.94	1.62	0.99	1.08	0.45

Table 2. Water shortage of restoration of healthy eco-hydrological sequence of rivers.

Our findings reveal that the greater the water flow requirement of a main ecological function is, the greater the water shortage caused by the restoration of the healthy eco-hydrological sequence. The water requirement for the water purification function is minimum, and its contribution to water shortage is the smallest, while the water requirement for the living environment of aquatic organisms (obtained by the wetted perimeter method) is relatively large and the amount of water shortage induced is the largest.

3.3. Compensation for Agricultural Losses Caused by Restoration of Healthy Eco-Hydrological Sequence of Rivers

In order to restore the ecological functions of rivers ecological base flow, it is necessary to establish healthy eco-hydrological sequence of rivers that would require a certain amount of water. However, this will inevitably lead to the reduction of available water for agricultural purposes and cause agricultural economic losses to local farmers in the Baojixia Yuanshang Irrigation District [41].

Therefore, it is necessary to compensate the farmers for restricting the use of agricultural water usage, and the amount of compensation should not only cover the expenses for maintaining the rights and interests of the owners and users of water resources but should also be aimed at restoring the healthy eco-hydrological sequence of rivers, to promote a harmonious development. The agricultural water shortage caused by the healthy eco-hydrological sequence of rivers was calculated by the product of water shortage of restoration of healthy eco-hydrological sequence of rivers (see Table 2) and irrigation water utilization coefficient in Baojixia Yuanshang Irrigation Areas (see case study analysis). The results of compensation for agricultural economic losses caused by the restoration of the healthy eco-hydrological sequence of rivers and effects of restoration on individual ecological functions are calculated by using Equation (8), which as shown in Table 3.

Items		Agricultural Economic Losses Compensation (10 ⁸ Yuan)						
		F1(M1)	F1(M2)	F1(M3)	F1(M4)	F2(M5)	HEHS	
	Corn	0.97	0	0	0	0	0	
2007	Wheat	1.42	0.68	1.39	1.71	0.13	0.82	
	Yearly	2.39	0.68	1.39	1.71	0.13	0.82	
2008	Corn	1.37	0	0	0	0	0.02	
	Wheat	1.22	0.60	1.17	1.44	0.15	0.69	
	Yearly	2.59	0.60	1.17	1.44	0.15	0.71	
2009	Corn	2.08	0.16	0.34	0.42	0.01	0.42	
	Wheat	1.79	0.86	1.77	2.14	0.16	1.09	
	Yearly	3.87	1.02	2.11	2.55	0.17	1.51	
2010	Corn	1.16	0	0	0	0	0	
	Wheat	1.47	0.84	1.59	1.90	0.17	0.93	
	Yearly	2.63	0.84	1.59	1.90	0.17	0.93	
2011	Corn	0.32	0	0	0	0	0	
	Wheat	2.49	1.20	2.32	2.77	0.30	1.49	
	Yearly	2.80	1.20	2.32	2.77	0.30	1.49	
2012	Corn	0.68	0	0	0	0	0	
	Wheat	0.98	0.59	1.37	1.77	0.09	0.55	
	Yearly	1.66	0.59	1.37	1.77	0.09	0.55	

Table 3. Compensation for agricultural economic losses caused by restoration of the healthy ecohydrological sequence of rivers.

The agricultural economic losses caused by the restoration of the healthy eco-hydrological sequence of rivers mainly occur during the non-flood period. The losses for winter wheat and summer corn production due to their output values, are small, and in some years there are no overall losses.

The financial compensation of agricultural economic losses cannot solve the water crisis [25], especially in areas with high water shortage. In addition, relatively low irrigation water efficiency can aggravate the water crisis situation in areas with water shortage, and the implementation or improvement of water-saving measures is necessary for the protection of the functions of ecological base flow of rivers [19]. At the same time, in order to promote the establishment of water-saving measures, to improve the efficiency of water resources utilization and to solve the problem of water crisis, compensation funds need to be provided. Therefore, diversified compensation modes can be applied to promote a harmoniously sustainable economic and environmental-friendly development of the agricultural irrigation system.

3.4. Variations in Water Requirements for Ecological Functions and Analysis of the Calculation Model

The amount of compensation due to the restoration of ecological functions of ecological base flow of rivers is greatly variable, and the amount of compensation required for the functional recovery of a

river (obtained by the Wetted perimeter method) is the largest, which is 13.42 times higher than the compensation for the recovery of the water purification function (2007), as shown in Figure 4.



Figure 4. Variations in the calculated compensations for agricultural economic losses caused by the healthy eco-hydrological sequence of rivers.

Moreover, there are great differences in the amounts of compensation estimated by different methods. The amount of compensation calculated by the Tennant method that was used to determine river ecological base flow by assessing the relationship between 21 catchment locations and number of fishes in the United States, is 3.55 times higher than that calculated by the average water depth method, which assesses the association between water requirements and number of fishes in the Weihe River (see Figure 4).

When we used wetted perimeter method to calculate the ecological functions of ecological base flow of rivers, the water requirements for ecological functions were fully satisfied, but the amount of water during the non-flood season is very low and therefore it was difficult to meet the demands for the ecological functions of ecological base flow of rivers. In fact, the degree of protection was so low that it greatly affected other water use departments, especially in the agricultural sector. At the same time, the differences in the amounts of agricultural economic losses caused by the water requirements for the protection of fishes (determined by the average water depth method) and by the restoration of the healthy eco-hydrological sequence of rivers are small, with the latter being slightly larger. Although the water requirement for fish protection (obtained by the average mean water depth method) is lower during the flood season, it cannot meet the water requirements for maintaining other aquatic creatures. The application of the healthy eco-hydrological sequence of rivers to determine the water demands for protecting fishes can eventually improve both ecological and economic functions.

Furthermore, the calculated compensation for the agricultural economic losses is practically applicable and can contribute to a harmonious economic development of the river's ecological system and the water use sectors surrounding the rivers.

3.5. Compensation Analysis Limitations and Prospective Development of the Model

The main irrigation mode applied in the Baojixia Yuanshang Irrigation District is flood irrigation, and the combined surface water and groundwater irrigation normally satisfies the water demands of the crops. However, the flood irrigation mode can change the process of the hydrological cycle. The evaporation and infiltration of water resources as well as the area precipitation can also be affected. In contrast, water diversion irrigation can potentially increase the groundwater levels, which could be used to increase the available groundwater resources for irrigation. Therefore, water diversion is required in this area of irrigation.

Precipitation is the main source of water supply for the Weihe River. With the influence of irrigation on local precipitation rates and on the amount of groundwater resources, the amount of

water in rivers and in irrigation areas needs to be adjusted by the mainly means of water diversion. However, there are no obvious rules to follow for implementing such changes and the model cannot predict the outcomes with certainty due to lack of defined characteristics.

Therefore, in the future, the analysis and the calculation procedure of the mutual conversion of groundwater and surface water into the process of water resources circulation, will be incorporated into our calculation model, which will potentially improve its predicting accuracy. These parameters were not included in our existing model due to lack of actual experimental data on the mutual exchange of surface water and groundwater and these are difficult to calculate from existing data. However, we speculate that the amounts of compensation for agricultural economic losses would be slightly lower than those reported in the current paper, but further studies are required to elaborate on this further.

3.6. Limitations of the Response Relationship Analysis between Hydrological Processes and the Ecological Functions of Ecological Base Flow Rivers

Understanding the interaction mechanism between the river ecosystem functions and the hydrological processes, and establishing a biological or ecological response model based on information from these internal relationships is crucial for establishing a calculation method for the ecological base flow of rivers. This also requires the knowledge of biology professionals to ensure more accurate results [42]. However, the current assessment method of the response relationship between hydrological processes and ecosystem functions has not considered the effect of biological factors, since most of the biological populations were considered to not undergo dynamic changes [43]. Also, the ecological feedback mechanism was not taken into consideration [44]. Therefore, the exclusion of these parameters might explain the variability in the calculation results of river ecological base flow, and in healthy eco-hydrological sequence of rivers.

At present, there are few studies that have implemented the periodic detection of the levels of aquatic organisms in developing countries. This might introduce a certain error when determining the healthy eco-hydrological sequence of rivers based on the response relationship between hydrological process and ecological functions of the ecological base flow of rivers [38]. In addition, in this study, the calculation of water demands for the survival of fishes is relatively simple, and the results might be biased.

Meanwhile, the hydrological processes and the living environment of other aquatic organisms have complex relations, and their relationship also affects hydrological changes. In this paper, this relationship between the living environment of other aquatic organisms and changes in hydrology and sediment motion were not considered in our model, hence it might have caused deviations in the calculation results.

4. Conclusions

In this study, in order to ensure that the water requirements for distinct ecological functions of rivers ecological base flow are satisfied and to reduce the economic impact on other water sectors, we established a healthy eco-hydrological sequence by incorporating the response relationships between the hydrological processes and the ecological functions of ecological base flow of rivers. On the basis of that sequence, a model for the calculation of the amount of compensations for agricultural economic losses caused by restoration of a healthy eco-hydrological sequence was established. Taking the Baoji section of the Weihe River as a case study, the model was applied to calculate compensation for the agricultural economic losses in the Baojixia Yuanshang Irrigation District caused by the restoration of the healthy eco-hydrological sequence in the Baoji section of the Weihe River. The main conclusions is that under the current situation in the Weihe River, the amount of water diverted is too large and it causes an ecological water shortage. The compensation for agricultural economic losses caused by restoration of the healthy eco-hydrological sequence of rivers is mainly required during the non-flood season, and the compensation reached up to 218 million yuan in 2009. However, compensation should not be limited to financial aid for agricultural economic losses, but it should be expanded to

compensation funds for the implementation of water-saving measures. The real time monitoring of mutual conversion of the surface water and ground-water in irrigation district is a necessary means to improve the accuracy of the calculation of the compensation for the agricultural economic losses. In China, we should monitor the dynamic changes of aquatic organisms and populations and the hydrological processes in rivers in real time, and intensively study the mutual complex relationships between hydrological processes and the living environment of other aquatic organisms, which can provide practical data to accurately calculate the water requirements for ecological functions of base flow of rivers.

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