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Value composition and quantitative calculation of economic value produced by river ecological base flow

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ABSTRACT

The definition of the economic value (EV) produced by river ecological base flow (REBF) is the role of REBF in avoiding river shrink or dry up and maintaining ecosystem health and natural process of river. Scientific and accurate establishment of quantitative method for calculating the EV produced by REBF is helpful for humans to understand the benefits of REBF protection directly and optimize the allocation of water resources by means of economics. Based on the characteristics of non-consumable and multi-values of REBF, we first identified its value composition by referring to the EV classification of river. Next, we established calculation methods for each sub-value using evaluation techniques of resources and environment economics. Finally, on the basis of calculation results of sub-values and the relationship of sub-values, we determined the maximum EV supported by each kind of water requirements of REBF, and summed up all independent parts to obtain the total EV. This method can remove repeated calculations in the process of assessing the EV produced by REBF. Our results indicated that the minimum total EV produced by REBF in the Shaanxi section of the Wei River was 4.54 billion yuan in 2017, which is close to previous studies. The new method developed here should provide a better theoretical support for quantitative research of the EV produced by REBF and scientific management of limited water resources coming from river.

Key words: economic value produced by river ecological base flow, remove repeated calculation, theory of resources and environment economics, Shaanxi section of the Wei River, value composition

HIGHLIGHTS

- Value composition of river ecological base flow based on its non-consumable and multi-values characteristics.
- A quantitative method of economic value produced by river ecological base flow to remove repeated calculation.
- The foundation for scientific management of limited river water resources by means of economics.

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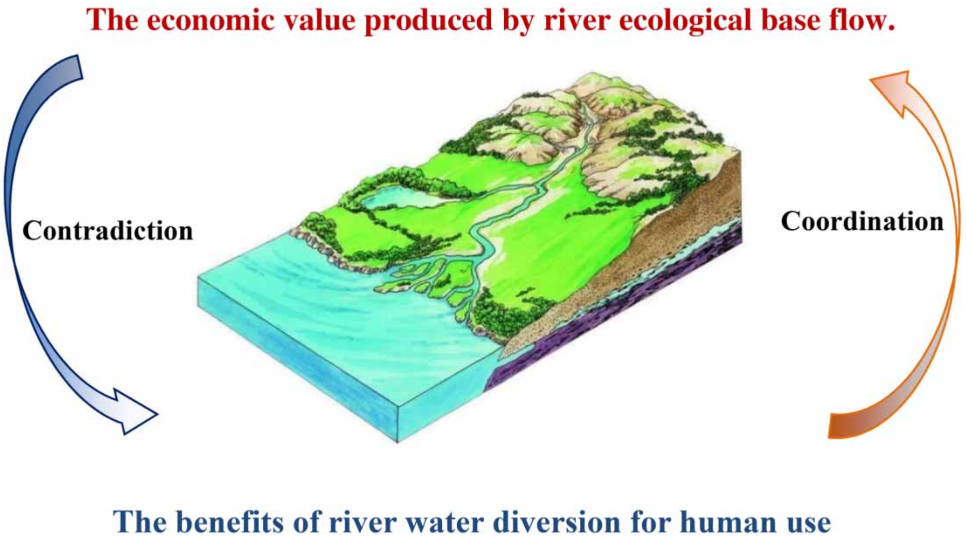
GRAPHICAL ABSTRACT



1. INTRODUCTION

For a perennial river, river ecological base flow (REBF) can maintain a stable water supply throughout the year. Its continuity is central for supporting the integrity of rivers and river ecosystems (Arthington *et al.* 2018). REBF is becoming a hot research topic in water resources management in recent years (Baghel *et al.* 2019). Although people are gradually understanding the significance of REBF, it remains difficult to reasonably determine the protection level of REBF (Zhang *et al.* 2020). In a water shortage area, natural flow in river is limited. The implementation of REBF protection will reduce the amount of water diversion from river and weaken the local economic development (Cheng & Li 2018; Kuriqi *et al.* 2021). What are the benefits of REBF protection? How to coordinate the contradiction between REBF protection and water diversion (for agricultural production purposes)? To address these questions, the development of scientific and accurate methods to calculate the economic value (EV) produced by REBF is important. It is also a basis for optimizing the allocation of river water resources by means of economics.

In this paper, the definition of the EV produced by REBF is the role of REBF in avoiding river shrink or dry up and maintaining ecosystem health and the natural process of a river. The study on the EV produced by REBF is now in the beginning stage. Most of the existing studies have been based on the models of water resources value or river ecosystem service value (Ojeda *et al.* 2008; Pang *et al.* 2013; Akter *et al.* 2014). These models emphasized the economic attribute or service attribute of a water resource (Young & Loomis 2014; Aznar-Sanchez *et al.* 2019), but ignored its natural attribute. However, the EV produced by REBF mainly includes the natural and ecological values (Yue *et al.* 2018). Ignoring the value composition properties of REBF would cause inaccurate results. Therefore, there is a need to establish an assessment system suitable for determining the EV produced by REBF.

The understanding of the EV of rivers is becoming mature (Costanza *et al.* 2014; Kaval 2019). Considering REBF as a part of river, we can propose the value composition of REBF by reference to the value classification of river and comprehensively assess the EV produced by REBF. However, we should pay attention to two characteristics of the EV produced by REBF over the course of study. The first characteristic is its non-consumable feature. Humans obtain the utility of REBF in a nonexpendable and nondestructive way. It differs from the value composition of a river. For example, provision service value of rivers (Hu *et al.* 2020) represents the conquest of humans over rivers. Nevertheless, if REBF is diverted from river channels for other uses (such as irrigation and power generation), its EV will be destroyed. The second characteristic is its multi-values. When a certain amount of REBF supports one sub-value, it simultaneously satisfies all or part of other sub-values. For instance, REBF purifies the pollutants in a river by transporting sediment and nutrients (Song & Li 2005). However, most of the previous ecological value assessments simply aggregated all sub-values to obtain a total value (Costanza *et al.* 1997; Wang *et al.*

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2019). In the process of determining the EV produced by REBF, a direct aggregation of sub-values might cause repeated calculations of total EV because of its multi-values characteristics.

According to these two characteristics of the EV produced by REBF, we put forward the value composition of REBF and discuss the relationship of the sub-values. Consequently, we established a calculation method for each sub-value using assessment techniques of resources and environment economics. On this basis, we determined the maximum EV supported by each kind of water requirement for the REBF and obtain its total EV by summing up the independent parts. This method can remove repeated calculations and accurately quantify the EV produced by REBF. To test this method, we used the Shaanxi section of the Wei River (SWR) as an example in this study.

2. METHODS

2.1. Value composition of REBF

By understanding the EV classification of rivers (Zhao *et al.* 2013), we put forward the value composition of the REBF (i.e., natural, eco-environmental, social values, Figure 1). Regarding the natural value, REBF maintains continuous runoff in a perennial river and plays a key role in the Earth and natural evolution. For example, REBF can realize four-dimensional connectivity of rivers (Kool & Nichol 2015) and sustain the normal transportation of water and sand. Regarding the eco-environmental value, REBF can produce ecological and environmental effects in a natural river, e.g., sustaining floodplain wetland ecosystems (Wallace *et al.* 2021), nutrient transport and water purification. Since REBF is beneficial for maintaining the health of river ecosystems, we classified these effects as the eco-environmental value of REBF. Regarding the social value, REBF can satisfy part of human demands without affecting its natural and eco-environmental values, such as fishery production, recreation and improving quality of human life. From above, it is obvious that the EV produced by REBF largely consists of indirect use values, which is different from the value composition of other natural resources.

2.2. Evaluation framework

A certain amount of REBF can satisfy all or part of other functions while supporting one function (Song & Li 2005). Therefore, it is not advisable to simply sum up all kinds of water requirement simply when determining the total amount of REBF. Typically, an appropriate approach is by analyzing the relationship of each kind of water requirement; calculating the maximum of repeated water requirement; and summing up the independent parts (Xia *et al.* 2002; Jia *et al.* 2011). We refer to this approach to put forward the evaluation framework of the total EV produced by REBF.

Based on connotation researches of REBF (Wang *et al.* 2003; Zhao *et al.* 2005), REBF includes four types of water requirement: evaporation water requirement, transport water requirement, self-purification water requirement and habitat water requirement. Evaporation water requirement is usually consumed because it participates in the hydrologic cycle. It hardly merges with other types of water requirement. As REBF transports sediment and nutrients when purifying pollutants in river, we combined transport water requirement and self-purification water requirement into one type, called transport and self-purification water requirement. Habitat water requirement mainly refers to the water required by floodplain wetland

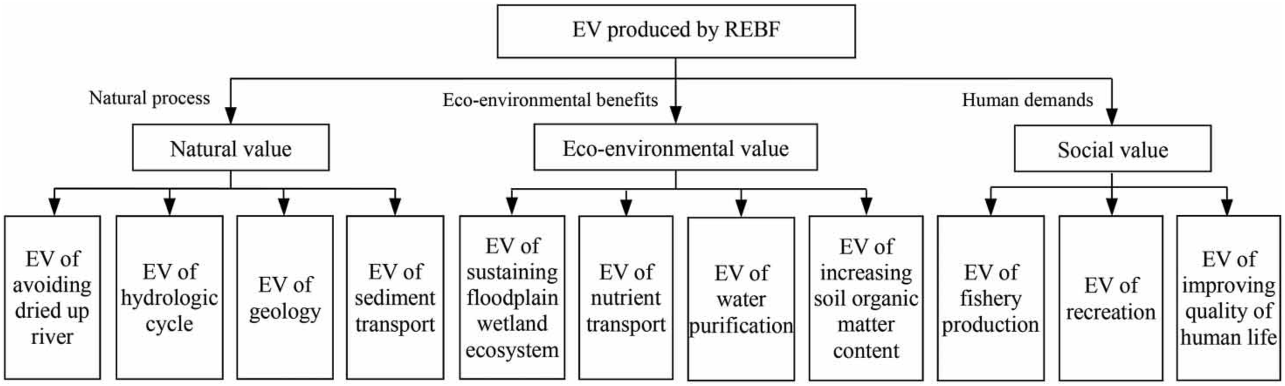

Figure 1 | Value composition of REBF.

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connected with river channel. Therefore, REBF consists of three independent types of water requirement: evaporation water requirement, transport and self-purification water requirement and habitat water requirement.

In view of multi-values characteristics, we established corresponding relationship between sub-values and water requirement types: the EV of avoiding dried up rivers is the foundation of other sub-values. It is supported by all types of water requirement. The EV of a hydrologic cycle is supported by evaporation water requirements. The EV of geology, EV of sediment transport, EV of nutrient transport, EV of water purification, EV of fishery production, EV of recreation and EV of improving quality of human life are supported by transport and self-purification water requirements. The EV of sustaining floodplain wetland ecosystems, EV of increasing soil organic matter content, EV of fishery production, EV of recreation and EV of improving quality of human life are supported by habitat water requirements. Social value is jointly supported by transport and self-purification water requirements and habitat water requirements.

According to calculation results of sub-values and their relationships, we obtained the maximum EV supported by transport and self-purification water requirement and the maximum EV supported by habitat water requirement; we combined them with the EV of the hydrologic cycle supported by evaporation water requirement, and obtained the total EV produced by REBF (Figure 2). This method can avoid repeated calculations in the assessment.

2.3. Quantitative methods

2.3.1. Sub-values produced by REBF

(a) *EV of avoiding dried up river* A dried up river brings irreversible impacts on a perennial river ecosystem (Datry *et al.* 2014). It causes the shrinkage of floodplain wetland connected with river channels; reduction in river buffer zone; and disappearance of other functions of REBF (Steward *et al.* 2018). If a river dries up, other sub-values produced by the

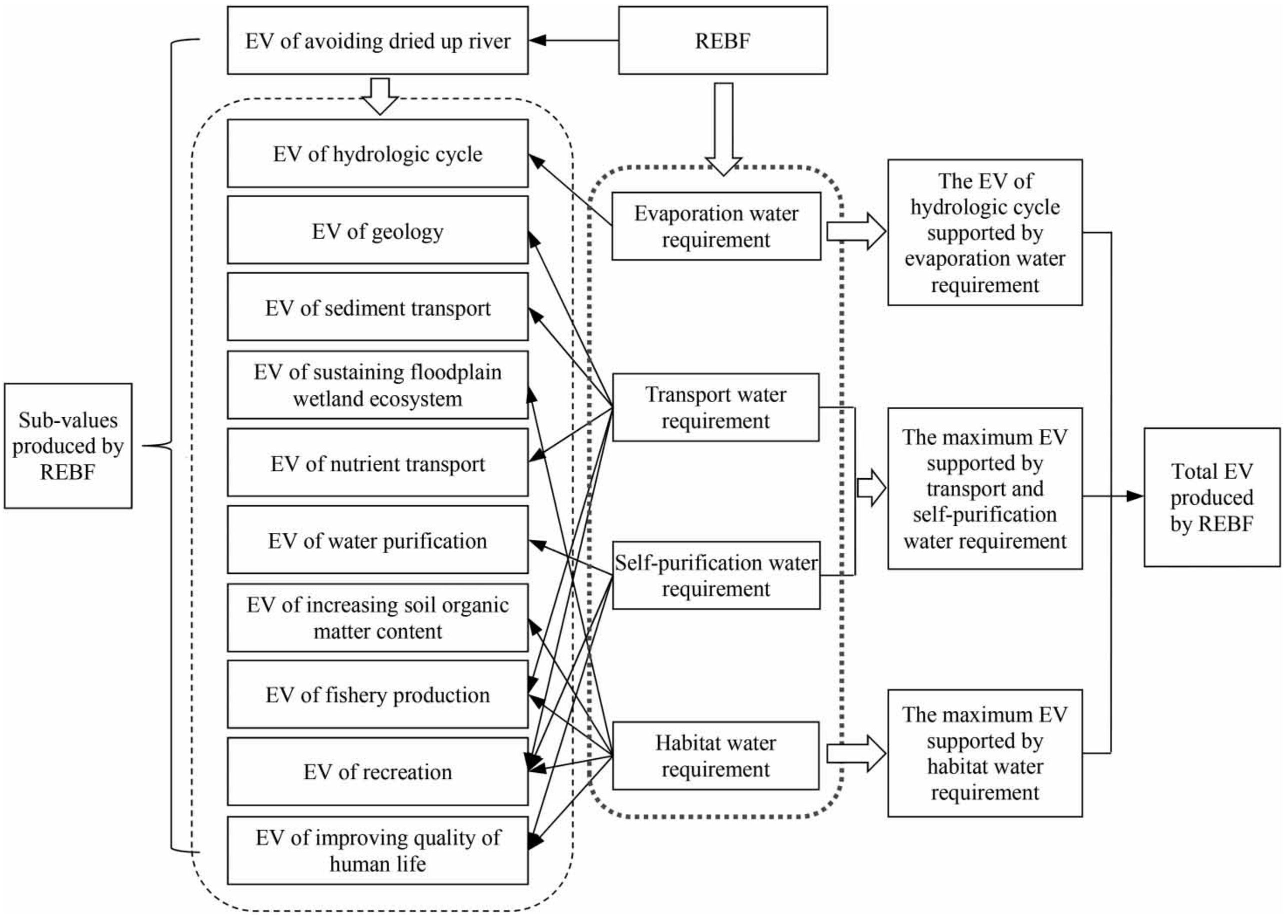

Figure 2 | Evaluation framework for the EV produced by REBF.

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REBF will be nonexistence. Hence, the EV of avoiding a dried up river is the foundation of the EV produced by REBF. It is already included in other sub-values, without the need for a separate calculation.

(b) *EV of hydrologic cycle* REBF plays an important role in regulating river runoff, recharging groundwater and maintaining regional water balance (Zeiringer *et al.* 2018). The EV of hydrologic cycle is supported by evaporation water requirements. When applying the market valuation method to determine the EV of hydrologic cycle, it needs to adopt the water amount of evaporation water requirement for assessment:

$$V_{HC} = W_E \times P_W \tag{1}$$

where V_{HC} is the EV of hydrologic cycle (yuan); W_E is the water amount of evaporation water requirement (m^3); P_W is the resident water price (yuan/m^3).

(c) *EV of geology* REBF has a scour and erosion effect on river channels. Limited by the existing assessment techniques of resources and environment economics, the EV of geology (V_{GV}) is difficult to evaluate. Hence, it is not estimated in this paper.

(d) *EV of sediment transport* REBF can increase the capacity of sediment transport in river and reduce sediment deposition (de Jalón *et al.* 2017). If sediment transport function drops due to a decline in REBF, the sediment needed to be removed by manpower. On basis of water amount of transport and self-purification water requirement, we can calculate the EV of sediment transport using the replacement cost method:

$$G_{ST} = c_{ST} \times W_T \tag{2}$$

where G_{ST} is the sediment transport quantity (t); c_{ST} is the sediment concentration (kg/m^3); W_T is the water amount of transport and self-purification water requirement (m^3):

$$V_{ST} = G_{ST} \times P_{ST} \tag{3}$$

where V_{ST} is the EV of sediment transport (yuan); P_{ST} is the cost of sediment removal by manpower (yuan/m^3).

(e) *EV of sustaining floodplain wetland ecosystem* Habitat water requirement is a key factor to sustain the normal operation of floodplain wetland ecosystem connected with river channel (Pander *et al.* 2019). If river dries up, floodplain wetland will be destroyed. There is a need to build artificial wetland to replace the original functions of floodplain wetland. Hence, we use the shadow project method to determine the EV of sustaining floodplain wetland ecosystem:

$$V_{FW} = V_{AW} \tag{4}$$

where V_{FW} is the EV of sustaining floodplain wetland ecosystem (yuan); V_{AW} is the construction cost of artificial wetland (yuan).

(f) *EV of nutrient transport* Nutrients in REBF are necessary for aquatic organisms, but overnutrition may cause eutrophication. Consequently we set a reasonable range of nutrients before evaluating the EV of nutrient transport.

Nutrients in REBF contain many elements. Restricted by data sources and water quality indicators in China, we selected ammonia-nitrogen (NH_3-N) as an indicator of nutrients in REBF. We chose the concentration limit of NH_3-N in the *Environmental Quality Standards for Surface Water in China* (GB 3838-2002) as the limit value of nutrients content in REBF. According to the water function zoning of river, if NH_3-N concentration in REBF is within the concentration limit of NH_3-N in the corresponding water function zoning, we consider that all NH_3-N in REBF belong to nutrients. If it exceeds the concentration limit, we consider that the excessive part does not belong to nutrients, and we only calculate the part within the limited value:

$$c_N = \begin{cases} c_{NH} & c_{NH} \le c_{LNH} \\ c_{LNH} & c_{NH} > c_{LNH} \end{cases} \tag{5}$$

where c_N is the nutrients concentration in REBF (mg/L); c_{NH} is the NH_3-N concentration in REBF (mg/L); c_{LNH} is the concentration limit of NH_3-N in the *Environmental Quality Standards for Surface Water in China* (mg/L).

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On basis of c_N and W_T, we adopt the replacement cost method to estimate the EV of nutrient transport:

$$V_{NT} = c_N \times W_T \times P_N \tag{6}$$

where V_{NT} is the EV of nutrient transport (yuan); P_N is the organic fertilizer price (yuan/t).

(g) *EV of water purification* River pollutants mainly come from point source and non-point source. Point sources are often sewage outlets in river. However, the locations and emissions of non-point source pollution are difficult to determine due to wide distribution. Thus we only estimate the purification value on point source pollutants.

Typically, pollutants concentrations at sewage outlets are high. After purification by REBF, they would reduce. River water can meet the requirement of eco-environmental function. As required by the Ministry of Ecology and Environment of China, the dominant pollutants of river in China are chemical oxygen demand (COD) and NH_3-N. We select them as inputs for estimating the EV of water purification. According to the concentrations of COD and NH_3-N at sewage outlets and in water body after purification, we combine W_T to assess the removal quantities of COD and NH_3-N from water body by REBF purification, respectively:

$$G_{COD} = (c_{SCOD} - c_{WCOD}) \times W_T \tag{7}$$

$$G_{NH} = (c_{SNH} - c_{WNH}) \times W_T \tag{8}$$

where G_{COD} and G_{NH} are the removal quantities of COD and NH_3-N by REBF purification, respectively (t); c_{SCOD} and c_{SNH} are the concentrations of COD and NH_3-N at sewage outlets, respectively (mg/L); c_{WCOD} and c_{WNH} are the concentrations of COD and NH_3-N in water body, respectively (mg/L).

If purification function of river is decreased because of declined REBF, it is required to replace it by increasing the quantity of sewage treatment. We calculated the EV of water purification using the replacement cost method:

$$V_{WP} = (G_{COD} \times P_{COD}) + (G_{NH} \times P_{NH}) \tag{9}$$

where V_{WP} is the EV of water purification (yuan); P_{COD} and P_{NH} are the treatment costs of COD and NH_3-N, respectively (yuan/kg).

(h) *EV of increasing soil organic matter content* REBF can keep soil in floodplain moist. When soil moisture is saturated, oxygen hardly diffuses. It is beneficial to form an anaerobic environment and increase soil organic matter content, which is an important source of essential nutrients for plants in river bank. We adopted the replacement cost method to estimate the EV of increasing soil organic matter content:

$$V_{SO} = G_{SO} \times P_N \tag{10}$$

where V_{SO} is the EV of increasing soil organic matter content (yuan); G_{SO} is the usage amount of organic fertilizer needed for increasing soil organic matter content (t).

(i) *EV of fishery production* In the dry season, REBF can support the reproduction and survival of organisms in rivers and maintain a certain amount of biomass. It is conducive to rapid growth of aquatic organisms in the wet season (Armasvargas *et al.* 2017). The fish price can be found in the market. Based on the market price method, we calculated its EV. Other aquatic organisms (e.g., microorganisms and algae) can be viewed as fish bait, and are included in the EV of fish:

$$V_{FP} = G_F \times P_F \tag{11}$$

where V_{FP} is the EV of fishery production (yuan); G_F is the fish weight in river (t); P_F is the fish price (yuan/t).

(j) *EV of recreation* In general, tourists who consider river as destination for recreation are mostly local individuals or families. Their tour period is normally within a day. When we applied the travel cost method for calculation, the expenses of tourists only cover transportation, dining and entertainment fees (excluding accommodation and ticket fees):

$$V_{RV} = Z_R \times P_R \tag{12}$$

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where V_{RV} is the EV of recreation (yuan); Z_{R} is the number of tourists who consider river as destination for recreation; P_{R} is the average traval expense per tourist (yuan).

(k) *EV of improving quality of human life* Residence price reflects the attributes of house itself (e.g., architecture structure, floor) and the quality of surrounding environmental landscape. If other attributes of a residence are basically same, the closer the residence is to a river view or wetland (Miao 2019), the more expensive it is. It reveals that people are willing to pay extra for a better landscape. This kind of influence range mainly exists within 1 km away from a river or wetland. We considered residence price as an indicator and applied the hedonic price method to indirectly estimate the EV of improving the quality of human life:

$$\mathrm{V_{LQ} = A_H \times \Delta P_H} \tag{13}$$

where V_{LQ} is the EV of improving quality of human life (yuan); A_{H} is the residence area within influence range (m^2); ΔP_{H} is the increased residence price within influence range (yuan/m^2).

2.3.2. Total EV produced by REBF

Due to the complexity of river, we divided a river into n sections based on cross-sections. According to above evaluation framework (Figure 2), the quantitive method of total EV produced by REBF in the ith section is:

$$\begin{cases} \mathrm{V_{E-i} = V_{HC-i}} \\ \mathrm{V_{T-i} = max(V_{GV-i}, V_{ST-i}, V_{NT-i}, V_{WP-i}, V_{FP-i}, V_{RV-i}, V_{LQ-i})} \\ \mathrm{V_{H-i} = max(V_{FW-i}, V_{SO-i}, V_{FP-i}, V_{RV-i}, V_{LQ-i})} \end{cases} \tag{14}$$
$$\text{and } \mathrm{V_{T-i} \neq V_{H-i}}$$

where $V_{\mathrm{E}-i}$ is the EV of hydrologic cycle supported by evaporation water requirement in the ith section (yuan); $V_{\mathrm{T}-i}$ is the maximum EV supported by transport and self-purification water requirement in the ith section (yuan); $V_{\mathrm{H}-i}$ is the maximum EV supported by habitat water requirement in the ith section (yuan); *max* is the maximum value.

Since V_{FP}, V_{RV} and V_{LQ} are jointly supported by transport and self-purification water requirement and habitat water requirement, $V_{\mathrm{T}-i}$ and $V_{\mathrm{H}-i}$ might be equal. In this case,

$$\text{if } \mathrm{second\_max(V_{GV-i}, V_{ST-i}, V_{NT-i}, V_{WP-i}, V_{FP-i}, V_{RV-i}, V_{LQ-i})} \\ \leq \mathrm{second\_max(V_{FW-i}, V_{SO-i}, V_{FP-i}, V_{RV-i}, V_{LQ-i})}$$

$$\begin{cases} \mathrm{V_{T-i} = max(V_{GV-i}, V_{ST-i}, V_{NT-i}, V_{WP-i}, V_{FP-i}, V_{RV-i}, V_{LQ-i})} \\ \mathrm{V_{H-i} = second\_max(V_{FW-i}, V_{SO-i}, V_{FP-i}, V_{RV-i}, V_{LQ-i})} \end{cases} \tag{15}$$

$$\text{if } \mathrm{second\_max(V_{GV-i}, V_{ST-i}, V_{NT-i}, V_{WP-i}, V_{FP-i}, V_{RV-i}, V_{LQ-i})} \\ > \mathrm{second\_max(V_{FW-i}, V_{SO-i}, V_{FP-i}, V_{RV-i}, V_{LQ-i})}$$

$$\begin{cases} \mathrm{V_{T-i} = second\_max(V_{GV-i}, V_{ST-i}, V_{NT-i}, V_{WP-i}, V_{FP-i}, V_{RV-i}, V_{LQ-i})} \\ \mathrm{V_{H-i} = max(V_{FW-i}, V_{SO-i}, V_{FP-i}, V_{RV-i}, V_{LQ-i})} \end{cases} \tag{16}$$

where *second_max* is the secondary maximum value.

The total EV produced by REBF in the ith section (V_i) is given by:

$$\mathrm{V_i = V_{E-i} + V_{T-i} + V_{H-i}} \tag{17}$$

We can get the total EV produced by REBF in the whole river (V) by summing up the total EV in each section of river, i.e.,

$$V = \sum \mathrm{V_i} \tag{18}$$

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3. STUDY AREA

3.1. Generalized river

The Wei River, located in the arid and semi-arid region of China, is the largest tributary of the Yellow River. Its river flow originates from the Niaoshu Mountain in Gansu Province, it flows through the Ningxia and Shaanxi Provinces, and runs into the Yellow River at Tongguan in Shaanxi Province (Yue *et al.* 2021). The SWR belongs to the middle and lower reaches of the Wei River, with a length of about 502 km. There are six hydrological stations in the SWR: Tuoshi, Linjiacun, Weijiabu, Xianyang, Lintong and Huaxian (Figure 3). By taking these hydrological stations as generalized points, we divided the SWR into five sections. Linjiacun station is the cross-section of Section 1 (Tuoshi–Linjiacun, 109 km). Weijiabu station is the cross-section of Section 2 (Linjiacun–Weijiabu, 65 km), and there it is nearby the urban area of Baoji city. Xianyang station is the cross-section of Section 3 (Weijiabu–Xianyang, 112 km), and it is nearby the urban area of Xianyang city. Lintong station is the cross-section of Section 4 (Xianyang–Lintong, 54 km), and it is close to the urban area of Xi'an city. Huaxian station is the cross-section of Section 5 (Lintong–Huaxian, 84 km), and it is close to the urban area of Weinan city.

3.2. REBF in the SWR

Many studies have calculated the REBFs in the cross-sections of the Wei River and recommended these ranges (Pang *et al.* 2012): Linjiacun was 4–8 m^3/s; Weijiabu was 6–10 m^3/s; Xianyang was 8–12 m^3/s; Lintong was 12–18 m^3/s; Huaxian was 16–20 m^3/s. Based on these recommendations, we set the baseline values of REBF in the cross-sections by considering the actual situation of the Wei River: 5 m^3/s in Linjiacun; 6 m^3/s in Weijiabu; 8 m^3/s in Xianyang; 12 m^3/s in Lintong; and 20 m^3/s in Huaxian (Yue *et al.* 2018). In this paper, the meaning of baseline value of REBF is that, if the actual river flow is greater than the baseline value in a cross-section, we assumed the requirement of REBF in the cross-section is satisfied. If the actual river flow is lower than the baseline value, we considered that it does not satisfy the requirement of REBF. Consequently, we put forward a simple method to separate REBF from river flow:

$$EF_j = \begin{cases} Q_j & Q_j < EF_B \\ EF_B & Q_j \geq EF_B \end{cases} \tag{19}$$

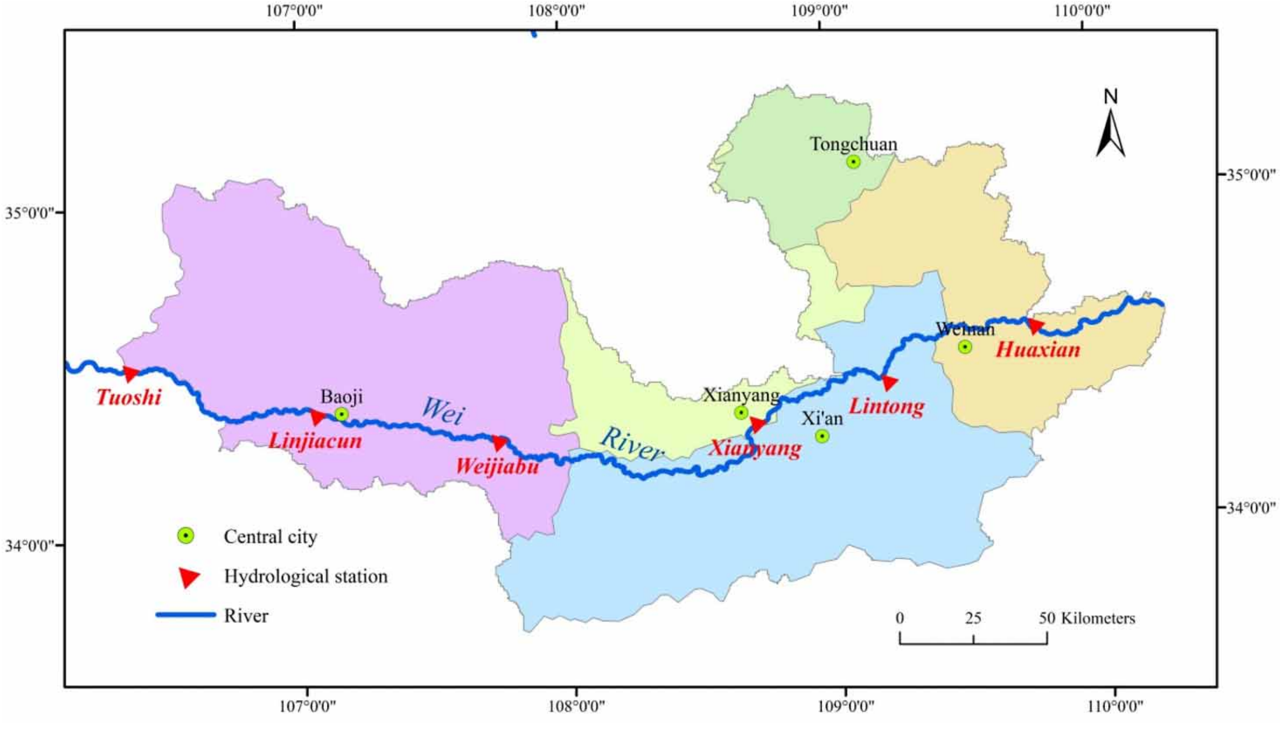

Figure 3 | Overview map of the SWR.

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where EF_j is the monthly average value of REBF in the jth period (m^3/s); Q_j is the measured flow in the jth period (m^3/s); EF_B is the baseline value of REBF (m^3/s).

Following the *Annual Hydrological Report of the Yellow River* compiled by the Ministry of Water Resources of China, we applied Equation (19) to process the measured flow data and obtain the multi-year monthly average of EF_j in the cross-sections of the SWR (1972–2017). As shown in Figure 4, the period of insufficient REBF in the SWR mainly appears in the dry season (December to March). Particularly, REBF in Linjiacun can hardly meet the 5 m^3/s baseline in all months because of water diversion used for large-scale irrigation in this cross-section (Wu *et al.* 2012). The SWR has been an area of dense population in Northwest China since ancient times due to its wide plain and fertile soil. The local people require plenty of water for life and economic development (Cheng *et al.* 2019). The Wei River has been the main water source. However, the natural flow in the Wei River varies quite significantly with seasons. This has increased the difficulty of REBF protection in the SWR, especially in the dry season. Therefore, accurate evaluation of the EV produced by REBF in the SWR is critical for establishing REBF compensation mechanisms.

4. RESULTS AND DISCUSSION

4.1. Corresponding water amount of REBF in the SWR

On the basis of the *Annual Hydrological Report of the Yellow River*, REBF in Linjiacun, Weijiabu, Xianyang, Lintong and Huaxian cross-sections all met EF_B in 2017. We applied Equation (19) to calculate EF_j in cross-sections and obtained the annual corresponding water amount of REBF (W_{EF}) in 2017.

We divided REBF into three independent types of water requirement: evaporation water requirement, transport and self-purification water requirement and habitat water requirement. Song & Li (2005) and Hao (2017) have studied different types of water requirement in cross-sections of the SWR. We took the component proportion of water requirements in these studies as the allocation basis and put forward the water amount allocation in the SWR (Table 1).

4.2. Sub-values produced by REBF in the SWR

4.2.1. V_{HC}

According to the Shaanxi Provincial Development and Reform Commission, resident water price in Baoji city, Xianyang city, Xi'an city and Weinan city in 2017 was 1.92 yuan/m^3, 1.97 yuan/m^3, 1.69 yuan/m^3 and 2.25 yuan/m^3, respectively. Since Section 1 and Section 2 belonged to Baoji city, both $P_{W\text{–}1}$ and $P_{W\text{–}2}$ were 1.92 yuan/m^3. Section 3 belonged to Xianyang city, $P_{W\text{–}3}$ was 1.97 yuan/m^3. Section 4 belonged to Xi'an city, $P_{W\text{–}4}$ was 1.69 yuan/m^3. Section 5 belonged to Weinan city, $P_{W\text{–}5}$ was 2.25 yuan/m^3. Combined with W_E in Table 1, we employed Equation (1) to assess V_{HC} in each section:

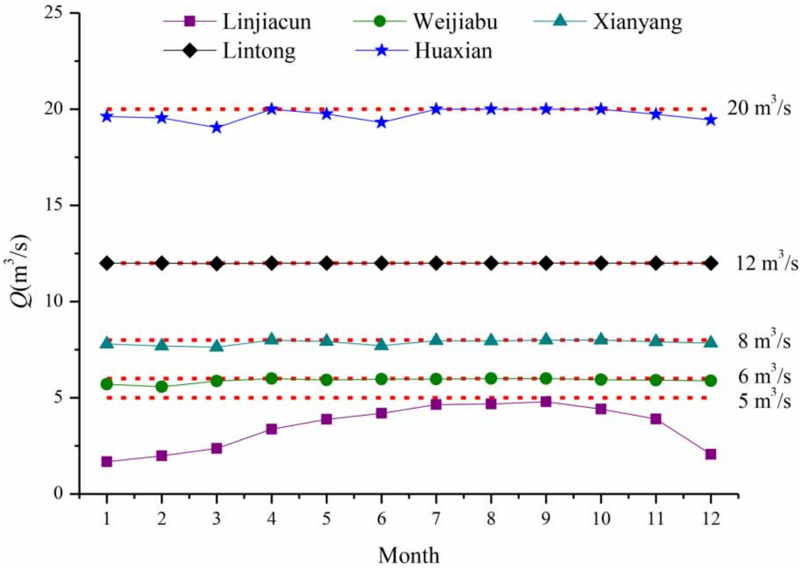

Figure 4 | Multi-year monthly variation of REBF in cross-sections of the Wei River (1972–2017).

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Table 1 | Water amount allocation of REBF in cross-sections of the Wei River in 2017

	Linjiacun		**Weijiabu**		**Xianyang**		**Lintong**		**Huaxian**	
Indicators	**Proportion %**	**Water amount million m^3**	**Proportion %**	**Water amount million m^3**	**Proportion %**	**Water amount million m^3**	**Proportion %**	**Water amount million m^3**	**Proportion %**	**Water amount million m^3**
W_{EF}	100	158	100	189	100	252	100	378	100	631
W_E	12	19	10	19	8	20	2	8	1	6
W_T	60	95	70	132	75	189	82	310	78	492
W_H	28	44	20	38	17	43	16	60	21	133

W_{EF} was annual corresponding water amount of REBF. W_E was annual water amount of evaporation water requirement. W_T was annual water amount of transport and self-purification water requirement. W_H was annual water amount of habitat water requirement.

V_{HC-1} was 36 million yuan; V_{HC-2} was 36 million yuan; V_{HC-3} was 39 million yuan; V_{HC-4} was 14 million yuan; V_{HC-5} was 14 million yuan.

4.2.2. V_{ST}

By referring to the *Annual Hydrological Report of the Yellow River*, the average sediment concentrations in cross-sections in 2017 demonstrated that c_{ST-1} was 6.59 kg/m^3; c_{ST-2} was 4.18 kg/m^3; c_{ST-3} was 1.80 kg/m^3; c_{ST-4} was 6.23 kg/m^3; c_{ST-5} was 8.95 kg/m^3. According to W_T in Table 1, we calculated G_{ST} in the sections using Equation (2). P_{ST} was 4 yuan/t. We assessed V_{ST} in each section using Equation (3): V_{ST-1} was 3 million yuan; V_{ST-2} was 2 million yuan; V_{ST-3} was 1 million yuan; V_{ST-4} was 8 million yuan; V_{ST-5} was 18 million yuan.

4.2.3. V_{FW}

The Wei River wetland is from the Baoji city boundary to the intersection of the Wei River and the Yellow River. It is an artificial wetland which includes river channel, river bank and flood plain. The investment cost from 2011 to 2015 was 21.5 billion yuan, while that from 2016 to 2020 was 18.9 billion yuan. Total investment cost in the recent decade was 40.4 billion yuan, and annual average investment cost was about 4 billion yuan. The length of the Wei River wetland was about 500 km, and annual unit investment cost was about 8 million yuan/km. We applied Equation (4) to evaluate V_{FW} according to the length of each section: V_{FW-1} was 872 million yuan; V_{FW-2} was 520 million yuan; V_{FW-3} was 896 million yuan; V_{FW-4} was 432 million yuan; V_{FW-5} was 672 million yuan.

4.2.4. V_{NT}

Based on water function zoning of the Wei River and the *Environmental Quality Standards for Surface Water in China*, we determined c_{LNH} in sections. From the *Environmental Statistics Bulletin of Shaanxi Province* compiled by the Department of Ecology and Environment of Shaanxi Province, we obtained c_{NH} in the sections in 2017. Based on Equation (5), we calculated c_N, as shown in Table 2.

P_N was 2,000 yuan/t based on the National Development and Reform Commission of China. By incorporating c_N and W_T, we assessed V_{NT} in each section using Equation (6): V_{NT-1} was 0.06 million yuan; V_{NT-2} was 0.2 million yuan; V_{NT-3} was 0.2 million yuan; V_{NT-4} was 0.9 million yuan; V_{NT-5} was 0.8 million yuan.

Table 2 | Nutrients concentration in REBF in sections of the Wei River

Indicators	**Section 1**	**Section 2**	**Section 3**	**Section 4**	**Section 5**
Water function zoning	III	III	IV	IV	IV
c_{LNH}	1.0	1.0	1.5	1.5	1.5
c_{NH}	0.30	0.73	0.61	1.43	0.86
c_N	0.30	0.73	0.61	1.43	0.86

The unit is mg/L. Water function zoning are from the *Water Function Zoning of Shaanxi Province* compiled by the Department of Ecology and Environment of Shaanxi Province.

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4.2.5. V_{WP}

The Wei River is the main receiving water of the surrounding city clusters. There are many sewage outlets along the SWR. We assumed that the concentrations of COD and NH_3-N in all sewage outlets are discharged following the *Wastewater Comprehensive Discharge Standard of the Wei River* (*Shaanxi Section*) compiled by the Department of Ecology and Environment of Shaanxi Province. We regarded COD and NH_3-N discharge limits in the standard as c_{SCOD} and c_{SNH}, respectively. Based on the *Environmental Statistics Bulletin of Shaanxi Province*, we consulted the average COD and NH_3-N concentrations in the sections in 2017, denoted by c_{WCOD} and c_{WNH}, respectively (Table 3).

We combined W_T to evaluate G_{COD} and G_{NH} using Equations (7) and (8), respectively. P_{COD} and P_{NH} were 4.5 yuan/kg and 2 yuan/kg, respectively. We adopted Equation (9) to estimate V_{WP} in each section: V_{WP-1} was 32 million yuan; V_{WP-2} was 41 million yuan; V_{WP-3} was 107 million yuan; V_{WP-4} was 174 million yuan; V_{WP-5} was 269 million yuan.

4.2.6. V_{SO}

The soil organic matter contents in the areas of 0–100 m and 100–500 m away from the Wei River were 13.2 g/kg and 11.9 g/kg, respectively (Zhang *et al.* 2017). The soil organic matter content in 0–100 m area was 1.3 g/kg higher than that in 100–500 m region. Hence, we took 0–100 m range as calculation region and used 1.3 g/kg (0.13%) as increased amount of soil organic matter content.

The thickness of organic horizon was taken as 20 cm (Zhang *et al.* 2014). The soil volume weight was 1.3 t/m^3. From this, we assessed that organic horizon weight was 2.6×10^5 t/km^2. Organic matter content of organic fertilize was set as 50% based on the standards compiled by the Ministry of Agriculture and Rural Affairs of China. Consequently, average increase of 0.13% organic matter in 1 km^2 soil required about 676 t/km^2 of organic fertilizer. According to the calculation region, we obtained G_{SO} in the sections. P_N was 2,000 yuan/t. Based on Equation (10), we calculated V_{SO} in each section: V_{SO-1} was 29 million yuan; V_{SO-2} was 18 million yuan; V_{SO-3} was 30 million yuan; V_{SO-4} was 15 million yuan; V_{SO-5} was 23 million yuan.

4.2.7. V_{FP}

Following Xu *et al.* (2016), the main fish species in the Wei River were Cyprinidae and Cobitidae, and we obtained G_F in the sections. P_F was 16 yuan/kg. We used Equation (11) to estimate V_{FP} in each section: V_{FP-1} was 2 million yuan; V_{FP-2} was 1 million yuan; V_{FP-3} was 4 million yuan; V_{FP-4} was 0.7 million yuan; V_{FP-5} was 3 million yuan.

4.2.8. V_{RV}

From the *Statistical Yearbook of Shaanxi Province* compiled by the Shaanxi Provincial Bureau of Statistics, we obtained the resident population in the sections in 2017 and used it as Z_R in Equation (12). Public transport was the main trip mode for nearby tourism. The dining and entertainment costs were excluded in the calculation. Therefore, P_R was the public transport charge of 4 yuan. We obtained V_{RV} in each section using Equation (12): V_{RV-1} was 2 million yuan; V_{RV-2} was 5 million yuan; V_{RV-3} was 7 million yuan; V_{RV-4} was 25 million yuan; V_{RV-5} was 5 million yuan.

4.2.9. V_{LQ}

The influence range of natural landscape on urban residence was generally within 1 km (Miao 2019). We used the residential communities within 1 km away from the Wei River wetland in our calculation. After investigation, there were no central city in Section 1; A_{H-1} was 0 m^2 and V_{LQ-1} was 0 yuan. A_{H-2} in Section 2 was 0.81 million m^2, ΔP_{H-2} was 200 yuan/m^2 and V_{LQ-2} was 162 million yuan using Equation (13). A_{H-3} in Section 3 was 0.88 million m^2, ΔP_{H-3} was 200 yuan/m^2 and V_{LQ-3} was 176

Table 3 | COD and NH_3-N concentrations in REBF in sections of the Wei River

Indicators	Section 1	Section 2	Section 3	Section 4	Section 5
c_{SCOD}	80	80	135	135	135
c_{SNH}	12	12	18	18	18
c_{WCOD}	11	16	17	18	21
c_{WNH}	0.30	0.73	0.61	1.43	0.86

The unit is mg/L. c_{SCOD} and c_{SNH} are from the Wastewater Comprehensive Discharge Standard of the Wei River (Shaanxi Section). c_{WCOD} and c_{WNH} are from the Environmental Statistics Bulletin of Shaanxi Province.

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million yuan. A_{H-4} in Section 4 was 0.73 million m^2, ΔP_{H-4} was 500 yuan/m^2 and V_{LQ-4} was 365 million yuan. The residential communities in Section 5 were far away from the Wei River wetland; A_{H-5} was 0 m^2 and V_{LQ-5} was 0 yuan.

4.3. Total EV produced by REBF in the SWR

Based on the calculation results of sub-values, we applied Equations (14)–(16) to quantify V_{E-i}, V_{T-i} and V_{H-i}. Then, we used Equation (17) to calculate V_i in each section; and obtained V in 2017 by applying Equation (18) (Table 4).

In 2017, V_1 (Tuoshi–Linjiacun, 109 km) was 0.94 billion yuan; V_2 (Linjiacun–Weijiabu, 65 km) was 0.72 billion yuan; V_3 (Weijiabu–Xianyang, 112 km) was 1.11 billion yuan; V_4 (Xianyang–Lintong, 54 km) was 0.81 billion yuan; V_5 (Lintong–Huaxian, 84 km) was 0.96 billion yuan. V in the SWR was 4.54 billion yuan. The results indicated that proportionality appeared between total EV and river section length. The longer river section was or the more water amount of REBF was, the higher the total EV was.

Sub-values mostly belonged to indirect use value. At present, quantitive calculation of indirect use value remains a challenge in resources and environment economics, and existing assessment techniques have some limitations (Turner *et al.* 2010). For example, when we adopted the hedonic price method to estimate the EV of improving quality of human life, we only utilized the residence price as an indicator and residential communities within 1 km away from the Wei River wetland as the calculation region. The assessed value should be less than its actual value. Due to the limitations of existing assessment techniques, some sub-values are difficult to quantify and monetize (e.g., the EV of geology). For the total EV, we learned from the method about total amount of REBF and assumed that the maximum EV supported by one type of water requirement already contained other values supported by the same type of water requirement. Based on above analysis, we calculated the maximum EV supported by each kind of water requirements, and summed up all independent parts to obtain the total EV. Therefore, the EV estimated using this method should be the minimum value, which means that the EV produced by REBF in the SWR was at least 4.54 billion yuan.

Our comparison showed that V_H is the highest among V_E, V_T and V_H. This is because REBF can ensure the four-dimensional connectivity of river and allow exchanges of matters and species between river and land-water ecotone. REBF also provides necessary environment and life cycle signal for aquatic organisms, and maintains abundant aquatic, terrestrial animals and plant resources in rivers. The significant role of REBF in eco-environmental function helps to explain that V_H is the highest.

4.4. Reasonable analysis of the results

Lin (2016) and Zhou & Zhou (2018) estimated the EV produced by REBF in the Baoji SWR with the Linjiacun cross-section. We directly compared the results of these two studies with our results of Section 1 (Tuoshi–Linjiacun). Furthermore, Yang *et al.* (2014) and Xu (2017) assessed the ecosystem service value of the SWR based on annual runoff. We calculated the

Table 4 | Total EV produced by REBF of the SWR in 2017

Categories	Sub-values	Section 1	Section 2	Section 3	Section 4	Section 5	SWR
Natural value	V_{HC}	36	36	39	14	14	139
	V_{ST}	3	2	1	8	18	32
Eco-environmental value	V_{FW}	872	520	896	432	672	3,392
	V_{NT}	0.06	0.2	0.2	0.9	0.8	2
	V_{WP}	32	41	107	174	269	623
	V_{SO}	29	18	30	15	23	115
Social value	V_{FP}	2	1	4	0.7	3	11
	V_{RV}	2	5	7	25	5	44
	V_{LQ}	0	162	176	365	0	703
V_{E-i}		36	36	39	14	14	/
V_{T-i}		32	162	176	365	269	/
V_{H-i}		872	520	896	432	672	/
V_i		940	718	1,111	811	955	4,535

The unit is million yuan.

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EV produced by REBF of the SWR on the basis of annual corresponding water amount of REBF. Because the EV produced by REBF is different from ecosystem service value, it prevents direct comparisons between them. The average annual runoff in Huaxian hydrological station is 190 m^3/s, and its baseline REBF is 20 m^3/s, which is about 10% of annual runoff. Therefore, we multiply the results from Yang *et al.* (2014) and Xu (2017) by 10% to make them more comparable with our results. The comparison results are shown in Table 5.

In Section 1, (1) V_{HC}, V_{NT} and V_{SO} are relatively close to the results of Lin (2016) or Zhou & Zhou (2018) (2) V_{ST} is below than the result of Lin (2016). Lin (2016) calculated V_{ST} according to annual average amount of sediment, and we obtained V_{ST} based on the amount of sediment carried by REBF. (3) V_{FW} is much larger than the results of Lin (2016) or Zhou & Zhou (2018). The reason for that is they only assessed the EV of biodiversity here with reference to other studies, and we calculated the EV of floodplain wetland. (4) V_{WP}, V_{FP}, V_{RV} and V_{LQ} are less than the results of Lin (2016) or Zhou & Zhou (2018). This is because that they adopted converted coefficient of sewage treatment cost, fishery production value or tourism value for evaluation, which was different from natural river. In the whole SWR, (1) V_{ST} is close to the results of Yang *et al.* (2014) and Xu (2017), and V_{FW}, V_{RV} and V_{LQ} are between these two results. (2) V_{HC} is less than the results of Yang *et al.* (2014) and Xu (2017). Because they calculated the EV of moisture regulation, which contained water storage function. REBF does not include this function. (3) V_{WP} is higher than the results of Yang *et al.* (2014) and Xu (2017). The reason is that their assessment was based on the data in 2008. (4) V_{FP} is lower than the results of Lin (2016) or Zhou & Zhou (2018). They adopted converted coefficient of fishery production value for evaluation. (5) There were not corresponding terms of V_{NT} and V_{SO} in the results of Yang *et al.* (2014) and Xu (2017). Overall, compared with similar studies, V_{HC}, V_{ST}, V_{FW}, V_{NT}, V_{SO}, V_{FP}, V_{RV} and V_{LQ} are within reasonable limits. V_{FP} is lower than the results of similar studies. This is because all the comparison results were obtained by converted coefficient of fishery production value, but we calculated this sub-value according to sample data of fish in the Wei River. The total EV of Section 1 and the SWR are all close to the results of similar studies. Therefore, it can be assumed that the calculation results in this paper are basically reasonable.

5. CONCLUSIONS

For perennial rivers, REBF keeps water in river channel all year round, maintains the continuity and integrity of rivers and maintains river ecosystem health. It is a hotspot of water resources management. Humans have gradually realized the importance of REBF, but it is often at a disadvantage in river water resources distribution, and hard to protect. The reason for this is that the EV produced by REBF is difficult to quantify. Therefore, there is an important basis to establish a quantitative calculation method for the EV produced by REBF for optimizing the allocation of water resources by means of economics. By taking the EV produced by REBF as a research object, we analyzed the value composition and established a method to quantify the EV produced by REBF. Then, we verified the new method by using the SWR as an example. The main conclusions are:

Table 5 | Comparisons of similar studies on the EV produced by REBF of the SWR

	Section 1			**SWR**		
Sub-values	**Our results**	**Lin (2016)**	**Zhou & Zhou (2018)**	**Our results**	**Yang *et al.* (2014)**	**Xu (2017)**
V_{HC}	36	/	53	139	4,147	2,490
V_{ST}	3	31	/	32	54	/
V_{FW}	872	12	2	3,392	3,742	1,706
V_{NT}	0.06	/	0.03	2	/	/
V_{WP}	32	112	203	623	30	11
V_{SO}	29	39	/	115	/	/
V_{FP}	2	35	/	11	40	50
V_{RV} and V_{LQ}	2	26	125	747	308	1,319
Total EV	940	200–900	383	4,535	8,320	5,750

The unit is million yuan.

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1. The EV produced by REBF consisted of the natural value, eco-environmental value and social value, and can be subdivided into 11 sub-values, which largely belonged to indirect use values. According to the assessment techniques of resources and environment economics, we established quantitative methods and equations for each sub-value.
2. Considering the characteristics of non-consumable and multi-values, we discussed the relationship of sub-values, and put forward the estimation method of the total EV produced by REBF. This method can remove repeated calculations in the assessment process.
3. The results of the case study implied that the minimum EV produced by REBF in the SWR was 4.54 billion yuan. These results are quite reasonable, thus this method is feasible. It also provided theoretical support for long-term protection mechanisms of REBF in the SWR.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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