

Article

The Value of Environmental Base Flow in Water-Scarce Basins: A Case Study of Wei River Basin, Northwest China

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Abstract: In the perennial river, environmental base flow, associated with environmental flow, is the base flow that should be maintained within the river channel throughout the year, especially in the dry season, to sustain basic ecosystem functions and prevent the shrinkage or discontinuity of a river. The functions of environmental base flow include eco-environmental functions, natural functions, and social functions. In this study, we provided a method based on these functions; this method estimated the function values per unit area, introduced the scarcity coefficient, multiplied by the corresponding water area, and summed over to quantify the value of environmental base flow from 1973 to 2015 in the Wei River Basin, the largest tributary of the Yellow River in Northwest China. We observed that there was a positive correlation between the total value of environmental base flow and its water yield, whereas this outcome was completely different in the benefit per unit discharge of environmental base flow, which was closely associated with the shortage of environmental base flow. This method can thus present the considerable value of environmental base flow in monetary terms in a simple and effective way and lay the foundation for further reasonable protection levels of environmental base flow.

Keywords: environmental base flow; function analysis; evaluation method; dry season; water scarce basin; Northwest China

1. Introduction

Water is the source of life. Humans have chosen to live near rivers, which are the main birthplaces of human civilization, since ancient times [1]. For example, China's civilization originated in the Yellow River Basin, and that of Egypt originated from the Nile River Basin. At that time, the riverine environment was largely pristine because the ability of humans to develop and utilize water resources was low, and the gross demand was also lower. Since the Industrial Revolution, with continuously burgeoning populations and rapid urbanization, flow extraction from rivers has been increasing in terms of feeding, drinking, irrigation, industry, hydropower, etc. [2], which has caused the remaining water in the river channel, known as environmental flow (e-flow) [3], which had been appropriated in the long term, to decrease in amount, followed by irreversible impacts on riverine ecosystems [4]. This phenomenon is particularly intensified in water-scarce basins.

The concept of e-flow has already been widely accepted [5] and was clearly described in the 2007 Brisbane Declaration as “the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems” [6].

Many researchers have explored a large number of studies in this area [7–10], and according to the statistics in 2003 [11], the record numbers of methods to calculate e-flow were more than 200, which can be broadly divided into three types. (1) Hydrological methods: the representative methods include Tennant [12], Texas [13], Q95, 7Q10, basic flow method (BFM) [14], flow duration curve (FDC) [15], and range of variability approach (RVA) [16] using the indicators of hydrologic alteration (IHAs) [17]. Due to lower requirements for data, the calculations are simple but the results are relatively rough, suitable for the rivers lacking in data; (2) Hydraulic habitat methods: this type of methods determines e-flow based on the hydraulic conditions needed for the indicator species [18], such as wetted perimeter [19] and instream flow incremental methodology (IFIM) [20]. However, because the indicator species is single, the entire status of riverine ecosystem is hard to reflect in general; (3) Comprehensive analysis methods: in this type of methods, the riverine ecosystem is viewed as a whole, and the link between hydrology and ecology is the emphasis [21], such as building block methodology (BBM) [22] and downstream response to imposed flow transformation (DRIFT) [23]. The disadvantage is the required data are complex, which present a difficult challenge for application.

The value of e-flow and the cost and related compensation of e-flow protection have been the new leading directions of e-flow research in recent years and are still at the exploration stage, but there have already been several researchers that have proposed their original viewpoints. Sisto [24] and Pang et al. [25] developed a production loss model to establish the relationship between production losses and agricultural water shortages caused by maintaining e-flow and estimated the appropriate economic compensation for different irrigation stakeholders. Perona et al. [26] proposed a simple economic model and the principle of equal marginal utility to obtain optimal water allocation rules between anthropic water use and e-flow. Akter et al. [27] presented a method for combining hydro-ecological response model outputs and nonmarket economic values of wetland inundation to estimate a unit price of e-flow. Yang et al. [28] quantified ecosystem service values by emergy analysis and used the results to design an e-flow regime for Baiyangdian Lake. It is observed that the study of e-flow value developed rapidly, but compared to the relatively complete calculation system of e-flow, it appeared late, with little research achievements, therefore further study would be needed to explore this area in depth.

Our team has long been engaged in research on e-flow value and the related compensation system [29,30] and has already adopted the fuzzy mathematics method, emergy analysis method, and opportunity cost method to estimate the value of e-flow, aiming to present the considerable value of e-flow in monetary terms and raise public awareness for e-flow protection. In this study, we focused on the e-flow within the river channel, which can be referred to as environmental base flow (EBF). In the perennial river, EBF can be defined as the base flow that should be maintained within the river channel throughout the year, especially in the dry season, to sustain basic ecosystem functions and prevent the shrinkage or discontinuity of the river; While base flow is that part of stream discharged from ground water seeping into the stream, belonged to hydrologic conception; They are distinct. Subsequently, we analyzed the functions of EBF and its difference between the dry season and non-dry season. Next, we developed a theoretical model to evaluate the EBF value based on its functions. Finally, a case study of the Wei River Basin in Northwest China was used to illustrate this method. The seasonal river is not considered in this article.

2. Materials and Methods

2.1. Study Area

The Wei River, the largest tributary of the Yellow River, originates from Niaoshu Mountain in Gansu Province, flows through Ningxia and Shaanxi Provinces, and joins the Yellow River at Tongguan. Wei River is a perennial river. The Wei River Basin (Figure 1), of which the northern region is the Loess Plateau and the southern region is the Qinling Mountains, has a length of 818 km and a drainage size of $1.35 \times 10^5 \text{ km}^2$ and is dominated by semi-arid hydrological characteristics; that

is, the climate is cold and dry, rain occurs mainly in summer and autumn, the mean air temperature is 7.8–13.5 °C, mean annual precipitation is between 400–800 mm (decreasing from south to north), mean potential evapotranspiration is 800–1100 mm (decreasing from east to west), and mean runoff is 195 m³/s [31]. The Wei River has two main tributaries on the north side: the Jing River is the largest tributary, which has a length of 455 km and a catchment area (4.54×10^4 km²) that represents 34% of the Wei River Basin, and Beiluo River is the second largest tributary, which has a length of 680 km and a catchment area (2.69×10^4 km²) that constitutes 20% of the Wei River Basin.

The Mainstream of the Wei River in Shaanxi Province (MSX, Figure 1b), due to its smooth terrain and fertile soil, has always been the industrial and agricultural production base. At present, MSX has become the most densely populated and most developed area in Northwest China. However, its water resources have always been limited: since ancient times, water in the Wei River has been extracted for human needs, such as irrigation, industry, and drinking water supply. The present water utilization rate is even up to 70% in the dry season and results in a shortage of EBF used by vegetation, wetlands, and aquatic organisms and significantly damages the healthy river basin ecosystem [32]. Therefore, we used MSX as an example for evaluating the value of EBF, which is the key to protecting EBF.

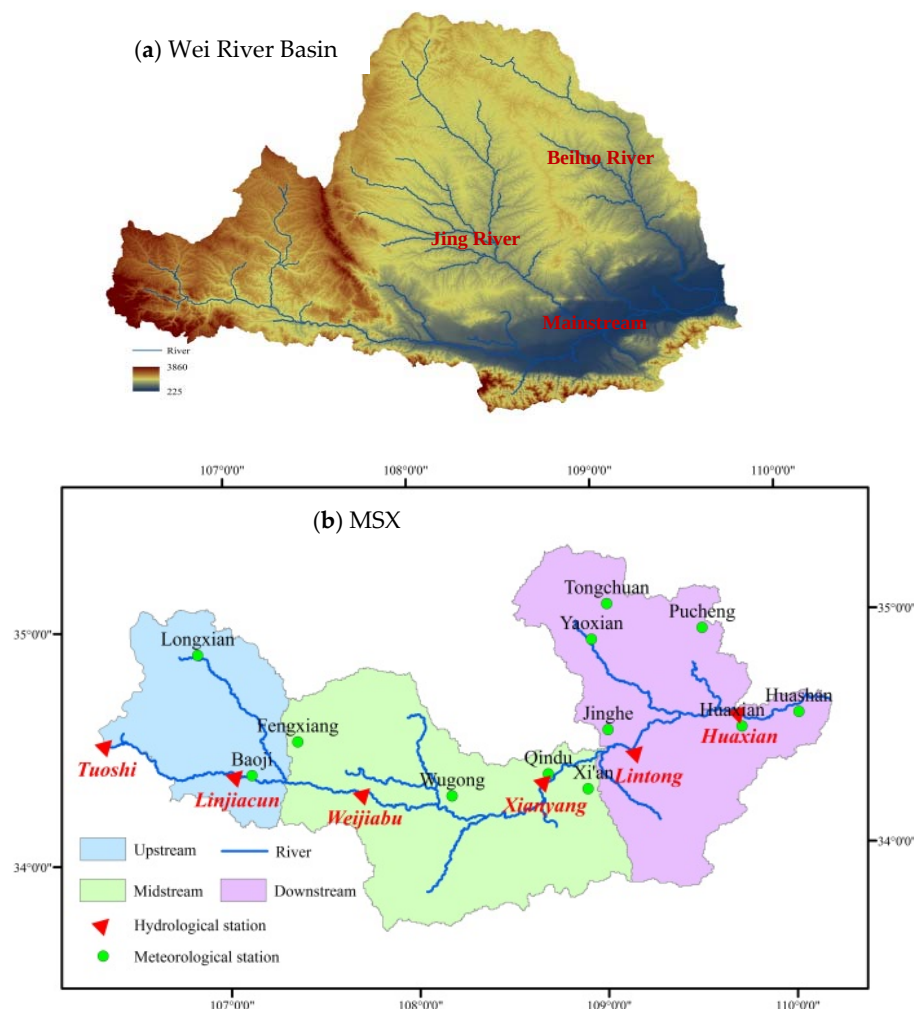


Figure 1. (a) The digital elevation map of Wei River Basin, which can be divided into the Mainstream, Jing River, and Beiluo River Basins; (b) Overview map of Mainstream of the Wei River in Shaanxi Province (MSX); Linjiacun is the hydrological control station at upstream, Xianyang is the hydrological control station at midstream, and Huaxian is the hydrological control station at downstream.

2.2. Functions of EBF

2.2.1. Function Analysis

First and foremost, as the most important and the most active factor in the ecosystem, water is the carrier of life and the media for substances cycling and energy exchange. In the perennial river, EBF, which ensures that the river channel always has water throughout the year, plays a key role in sustaining a healthy riverine ecosystem [4,33]. Therefore, the primary function of EBF is to maintain the basic ecological and environmental functions of a river (eco-environmental functions): (1) the most significant eco-environmental function is avoiding dried up rivers, which are directly related with water column depths that are critical parameters to many species, prevented the extinction of endangered species [34]; (2) EBF can maintain the normal functions of a wetland ecosystem connected to the natural river channel and guarantee its rich terrestrial–aquatic biological resources and unique climatic environment, such as localized humidity increases and air purification [35]; (3) EBF can increase the capacity for debugging pollutants in a river and improve a river's self-purification ability and water quality; (4) Rivers are the main passageways for nutrient transport in riverine ecosystems; EBF can maintain the continuity of rivers and promote the circulation and cycle of nutrients in a river; (5) Furthermore, with large EBF, the soil in flood plains can also be nourished, and their fertility can be improved.

Second, EBF has natural functions: (1) a certain amount of EBF within a river channel can meet the water demand for evaporation and seepage and maintain the flow conversion between surface water and groundwater; additionally, EBF plays an important role in recharging groundwater throughout the year in the funnel-shaped groundwater area; these characteristics are affiliated with the functioning of the hydrologic cycle [36]; (2) EBF also has the ability to scour the riverbed, carry sediment, maintain the integrity of a natural river channel, and sustain river geomorphology, which are geological functions.

Finally, EBF has a role in social functions [37]: (1) EBF contributes to the growth of fishes and other aquatic organisms in rivers, providing fishery products for humans; (2) EBF can improve the recreational experiences and landscape of a river basin; (3) Humans choose to live near rivers, and cities are built on river banks; EBF can revitalize a polluted/dry river, revive the surrounding areas of a river, and improve the quality of life for humans.

2.2.2. Different Functions between the Dry Season and Non-Dry Season

Generally, a river contains a wet season, a normal season, and a dry season. In the wet and normal seasons, also called the non-dry season, abundant water in the river can simultaneously meet the demands for anthropic water use and EBF, so the guarantee rate of EBF is high. In the dry season, reduced upstream inflow and lower water levels lead to sharp water contractions, coupled with the already high water utilization rates in water-scarce basins, which is why EBF often goes without protection [38]. Therefore, the dry season is the critical period for EBF protection in water-scarce basins and is also the emphasis of this study.

Compared to the non-dry season, EBF in the dry season is low; hence, differences exist in the functions between the two, as shown in Table 1.

2.3. Recommended EBF

The recommended EBF is the initial fundamental step to estimate its value, and its annual water yield is represented by “W” in this article. As mentioned earlier, a relatively complete system to calculate recommended EBF has already formed [11–23], and each method has advantages and disadvantages. How to choose the suitable methods and get the appropriate recommended EBF in the study area remains the challenge of EBF study. Because this is not the focus of this article, it is only covered briefly.

Table 1. Different functions of environmental base flow (EBF) between the dry season and non-dry season. “Y” represents the possession of this function; “N” represents the absence of this function.

Category	Functions	Non-Dry Season		Dry Season	
		Y or N	Reasons	Y or N	Reasons
Eco-environmental functions	Avoiding dried-up rivers	N	Plentiful river water is sufficient for anthropic use and EBF at the same time. Rivers rarely dry up.	Y	In the dry season, EBF can avoid dried riverbeds. 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.
	Sustaining wetland ecosystems	Y	EBF nourishes riparian vegetation, provides the environment in which riverine organisms live, sustains floodplain wetlands and improves local air quality.	Y	In the dry season, EBF can ease water shortages for wetlands, sustain normal growth and development of riverine organisms, adjust microclimates (such as temperature and humidity) and improve local air quality.
	Water purification	Y	EBF helps dilute, diffuse, transfer and purify pollutants, and increases the self-purification capacity of a river.	Y	In the dry season, EBF can increase river runoff, enhance the ability to dilute, diffuse, transfer and purify pollutants, and improve the self-purification capacity of a river.
	Nutrient transport	Y	EBF maintains the nutrient cycles of riverine ecosystems and nourishes riverine organisms.	Y	In the dry season, EBF can ensure the connectivity of a river, sustain the nutrient cycles of a riverine ecosystem, and nourish riverine organisms.
	Maintaining soil fertility	Y	In flood season, EBF moistens and fertilizes the soil of inundation areas, which are the essential nutrient sources for riparian vegetation.	N	In the dry season, EBF is low, almost within the river channel; thus, its effect on wetting the soil around a river can be diminished.
Natural functions	Hydrologic cycle	Y	EBF recharges groundwater, satisfies the water requirements of evaporation and seepage, and promotes regional hydrologic cycles.	Y	In the dry season, EBF can satisfy the water requirements of evaporation and seepage and promote regional hydrologic cycles.
	Geology	Y	When EBF is high, it has an effect on scouring the river bank.	N	In the dry season, EBF is low and the functions of brushing and scouring can be diminished.
	Sediment transport	Y	EBF can increase the capacity of a river to transport sediment and alleviate siltation.	N	Due to the low sediment concentration of a river in the dry season, this function of EBF can be reduced.
Social functions	Fishery production	Y	EBF contributes to the normal growth of fishes and other aquatic organisms in a river, which are aquatic products for humans.	Y	In the dry season, EBF can sustain the survival and multiplication of organisms in a river and guarantee a higher biomass, which is beneficial for the rapid growth of organisms in the wet season.
	Recreation and landscapes	Y	EBF maintains the river level and meets the water requirements for recreation and landscapes.	Y	In the dry season, the upstream inflow of a river decreases. EBF can raise the river water level and improve the river basin landscape.
	Improving quality of life	Y	EBF revitalizes the river, revives the areas surrounding the river, and improves human quality of life.	Y	In the dry season, EBF can improve pollution problems and river drought and provides a better life for humans.

2.4. Value Method of EBF

At present, the more popular method for calculating the value of an ecosystem is established by Costanza et al. [39]. On the basis of “willingness-to-pay” of individuals for ecosystem services, the unit value of ecosystem services was estimated, used either (1) the sum of consumer and producer surplus; (2) the net rent (or producer surplus); or (3) price times quantity as a proxy for the economic value of the service. Then the unit values were multiplied by the surface area of each ecosystem to arrive at global total. According to the results obtained by Costanza et al. [39], Xie et al. [40] established the value equivalent factor along with the responses of ecological questionnaires from specialists of China, which helped to get ecosystem services value unit area of Chinese terrestrial ecosystems, and then the ecological assets value of China was estimated.

Therefore, we can also estimate the value of EBF with this method, the following steps are (1) estimate the unit values of EBF in the study area by means of equivalent factors; (2) calculate the corresponding water areas of EBF; and (3) multiply the unit values times the corresponding water areas to gain the value of EBF.

2.4.1. Value Equivalent Factor of EBF

(1) Standardization equivalent

The standardization equivalent (1 standard unit value equivalent factor of ecosystem service), which is used for representing and quantifying the potential contribution of different ecosystems in ecosystem service functions, is the value of the average grain yield of 1 ha of farmland in the study area [41]. The value of the average grain yield in a farmland ecosystem is calculated based on the net profits of rice, wheat, and corn.

$$D = S_r \times F_r + S_w \times F_w + S_c \times F_c \quad (1)$$

where D is the standardization equivalent; S_r , S_w , and S_c are the ratios of sown areas of rice, wheat, and corn to the total area of these three crops in the study area, respectively. F_r , F_w , and F_c are the net profits of rice, wheat, and corn in a unit area of the study area, respectively.

(2) Estimation of the value equivalent factor

In order to simplify the evaluate methods of the functions shown in Table 1, we reviewed the research achievements that focused on the function value methods of ecosystem [42–45] and consulted various annual public statistic data of China, such as the *Chinese Statistical Yearbook*, the *Chinese Environmental Quality Bulletin*, and the *National Economy and Society Developed Statistical Bulletin*, etc. Based on this literature, we obtained the function capacity per unit area and the value per unit function (Table 2). Then, we can calculate the function value per unit area and compare it with the standardization equivalent, from which the value equivalent factor of EBF can be obtained [41].

2.4.2. Corresponding Water Area of EBF

The corresponding water area of EBF can be obtained used the simple hydraulic rating method or the more sophisticated hydraulic/habitat simulation methods. Due to few local ecological data in MSX, we applied the simple hydraulic rating method to estimate it roughly.

The river channel can be graded into several sections according to its geometrical features. We can collect the data at generalized point j and obtain the fitting curve of EBF and its corresponding water surface width.

$$B_j = f(Q_j) \quad (8)$$

where B_j is the water surface width at generalized point j ; Q_j is the flow at generalized point j .

By combining B_j and the length of each section L_j , we can calculate the corresponding water area S_j .

$$S_j = \frac{1}{2}(B_j + B_{j+1})L_j \quad (9)$$

Table 2. The function value of EBF in the dry season. The functions in the non-dry season were not included here.

Functions	Equation	Meaning	Equation No.
Avoiding dried-up rivers	Preventing the extinction of endangered species.	From the Ministry of Water Resources of the People's Republic of China: the judgement standard of the dried-up rivers in Yellow River Basin is if the flow is lower than $1 \text{ m}^3/\text{s}$. This is also the dried-up threshold of Wei River because Wei River is the tributary of Yellow River. EBF can ensure the flow in Wei River is more than $1 \text{ m}^3/\text{s}$, and avoid dried riverbeds.	
Sustaining wetland ecosystems	$V_1 = V_{w1}$	V_1 is the value of sustaining wetland ecosystem per unit area; A dried-up river may result in large-scale destruction of wetlands and degradation of related functions, and constructed wetland is necessary to build to replace its environmental functions, so V_{w1} is the cost per unit area of constructed wetland.	(2)
Water purification	$V_2 = (G_1 \times P_1) + (G_2 \times P_2)$	V_2 is the value of water purification per unit area; G_1 and G_2 are the reductions in COD and $\text{NH}_3\text{-N}$ caused by increased purification ability; P_1 and P_2 are the treatment costs of COD and $\text{NH}_3\text{-N}$.	(3)
Nutrient transport	$V_3 = \sum C_m \times W \times P_3$	V_3 is the value of nutrient transport per unit area; C_m is the nutrient quantity per unit area; W is the water yield of EBF; P_3 is the price for nutrients.	(4)
Hydrologic cycle	$V_4 = W \times P_4$	V_4 is the value of the hydrologic cycle per unit area; W is the water yield of EBF; P_4 is the water price.	(5)
Fishery production	$V_5 = \alpha \times \beta \times V_{fs}$	V_5 is the value of fishery production per unit area; α is the proportion of water resources in the whole fishery production; β is the conversion coefficient of the river; V_{fs} is the fishery value per unit area.	(6)
Recreation and landscapes	$V_6 = \gamma \times \omega \times V_{tr}$	V_6 is the value of recreation and landscapes per unit area; γ is the proportion of the river's tourism income out of the total tourism income; ω is the conversion coefficient of EBF; V_{tr} is the tourism income per unit area.	(7)
Improving quality of life	Improving the city's image.	EBF can revitalize a polluted/dry river, revive the surrounding areas, and improve the quality of life for humans.	

2.4.3. Scarcity Coefficient

The fewer the water resources, the more expensive the water value; conversely, the greater quantity of water, the cheaper the water value, and this also applies to EBF. When EBF is sufficiently abundant in one area, scarcity has little effect on its value, and with the increase in “EBF abundance”, the scarcity value will decline rapidly, even approaching zero. In contrast, with the aggravation of scarcity, the scarcity value of EBF will increase, which is not linear growth, but a type of exponential growth [46].

$$\mu = \left(\sum_{n=1}^3 \frac{\xi_n}{w_n} \right)^\theta \quad (10)$$

where μ is the scarcity coefficient; w_n is the scarcity equivalent factor of EBF, ξ_n is the weight of w_n and $\sum \xi_n = 1$, $0 \leq \xi_n \leq 1$, and θ is the regulatory factor of policy.

- (1) w_1 : the average per capita water availability

$$w_1 = \frac{w_{11}}{w_{12}} \quad (11)$$

where w_{11} and w_{12} are the average per capita water availability in the study area and the nation, respectively.

- (2) w_2 : EBF

$$w_2 = \frac{w_{21}}{w_{22}} \quad (12)$$

where w_{21} and w_{22} are the measured data and baseline of EBF, respectively.

- (3) w_3 : precipitation

$$w_3 = \frac{w_{31}}{w_{32}} \quad (13)$$

where w_{31} and w_{32} are the precipitation rates in the study area and the nation, respectively.

2.4.4. EBF Value

The EBF value can be expressed in two indicators: the total value of EBF and the benefit per unit discharge of EBF (or “unit benefit”), which is the unit benefit brought by EBF.

In consideration of all of the above, the total value of EBF is

$$V_{jk} = \mu_{jk} \sum e_{ijk} \times D_{jk} \times S_{jk} \quad (14)$$

where V_{jk} is the total value of EBF in the j th section at the k th period, μ_{jk} is the scarcity coefficient of EBF in the j th section at the k th period, e_{ijk} is the value equivalent factor of the i th function in the j th section at the k th period, D_{jk} is the standardization equivalent in the j th section at the k th period, and S_{jk} is the water area in the j th section at the k th period.

The benefit per unit discharge of EBF is

$$BD_{jk} = \frac{V_{jk}}{W_{jk}} \quad (15)$$

where BD_{jk} is the benefit per unit discharge of EBF in the j th section at the k th period; V_{jk} is the total value of EBF in the j th section at the k th period; W_{jk} is the water yield of EBF in the j th section at the k th period.

3. Results and Discussion

3.1. Recommended EBF in MSX

So far, several Chinese researchers have calculated the recommended EBF at Linjiacun, Weijiabu, Xianyang, Lintong and Huaxian station in MSX in various ways. There not only have classic methods, but also the methods developed by their own. The results are shown in Tables 3 and 4 [21,47]. Tuoshi station established in 2004, for lack of long series hydrologic data, just viewed as the starting point of MSX.

Table 3. The results of recommended EBF estimated by hydrological methods at Linjiacun station, cited from [21,47]. Owing to the space limitation, the results estimated by hydrological methods at Weijiabu, Xianyang, Lintong and Huaxian station are not mentioned here. DMAF: driest monthly average flow method, Q90: average flow method in the driest month with 90% frequency, NGPRP: northern great plains resource program. The unit is m^3/s .

Methods	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Mean
Tennant (10%)	2.99	3.38	4.68	6.40	7.99	6.20	13.35	12.59	18.81	14.32	7.47	3.96	8.51
Tennant (30%)	8.97	10.14	14.04	19.2	23.97	18.60	40.05	37.77	56.43	42.96	22.41	11.88	25.54
DMAF	7.52	8.43	11.83	15.80	20.77	21.36	36.61	39.08	42.28	30.96	16.48	8.73	21.65
Q90	3.88	4.65	6.1	8.42	10.72	11.38	18.89	20.83	22.53	15.97	8.78	4.50	11.39
FDC	5.39	6.03	6.24	9.86	8.68	7.16	23.73	18.71	30.59	16.41	10.02	5.22	12.34
NGPRP	2.15	2.49	2.77	3.72	2.09	5.42	8.10	7.85	11.03	10.47	7.80	3.50	5.62
Texas	24.42	28.71	38.14	49.24	59.18	50.70	119.50	130.33	165.90	114.96	62.50	32.69	73.02
7Q10	102.62	116.36	97.96	81.52	70.96	58.51	64.25	168.56	181.31	127.41	86.35	80.39	103.02
RVA	5.52	5.17	7.22	8.43	28.61	18.04	21.16	28.16	28.24	26.08	13.00	10.76	16.79

Disturbance from anthropogenic activity has seriously influenced the Wei River, which is in severe shortage of water resources. In the dry year (1996), there even had 255 days that EBF did not reach $1 \text{ m}^3/\text{s}$ in the upstream of Wei River. So contrasted with the reality, some calculation results are too high to satisfy, such as 7Q10, Texas, wetted perimeter, etc. Therefore, compared the results of three types of methods (10% Tennant, mean depth method, and water quantity/quality method) and took the actual situation of MSX into account, then the recommended range and the short-term baseline of EBF were obtained as shown in Table 4, which has been gained recognition by Chinese experts. The recommendation will also be constantly adjusted once the aim of recent river rehabilitate of the Wei River is achieved.

Considering the emphasis of this article is the evaluation of EBF value, we did not calculate the recommended EBF in MSX here anymore but used the short-term baseline of EBF directly.

Table 4. The comparisons of recommended EBF estimated by 3 types of method at 5 stations in MSX, cited from [21] The unit is m^3/s .

Types	Methods	Linjiacun	Weijiabu	Xianyang	Lintong	Huaxian
Hydrological methods	Tennant (10%)	2.99	3.12	5.20	6.93	6.59
Hydraulic methods	Wetted perimeter	10.60	16.70	23.20	38.80	52.60
	R2CROSS	12.40	17.20	23.30	25.50	30.10
	Mean depth	6.17	10.70	12.00	14.50	27.60
Comprehensive analysis	Water quantity/quality	2.00	3.40	4.33	8.80	22.97
Recommended range of EBF		4–8	6–10	8–12	12–18	16–20
Short-term baseline of EBF		5	6	8	12	16

3.2. EBF Value in MSX

The dry season (Dec.–Mar.) is the critical period for EBF protection in MSX, when the conflict between anthropic water use and EBF is much more acute, so we primarily focus on the EBF value of MSX in the dry season. Thus, “Year” in this article indicates “from Dec. of the previous year to Mar. of the following year”, marked by “the next year”. For example, 1973 represents the period “from Dec. 1972 to Mar. 1973”.

3.2.1. Value Equivalent Factor in MSX

With the abovementioned method, we can obtain the value equivalent factor of EBF in Wei River Basin. On this basis, combined with D_{2015} in MSX (3068 RMB/ha) (RMB: Ren Min Bi, the Chinese currency), the value per unit area for each of the EBF functions in MSX was estimated in Table 5. Notably, to eliminate the price change and make the evaluation results more comparable, we selected the price of RMB in 2015 as the constant price, written as 2015 RMB.

Table 5. The value equivalent factor of EBF in Wei River Basin. The equivalent factor is unitless; the unit of value per unit area is RMB/ha in 2015.

Items	Eco-Environmental Functions			Natural Functions		Social Functions		
	Avoiding Dried-up Rivers	Sustaining Wetland Ecosystems	Water Purification	Nutrient Transport	Hydrologic Cycle	Fishery Production	Recreation and Landscapes	Improving Quality of Life
Equivalent factor	Preventing the extinction of rare species.	48.84	2.70	0.09	16.06	0.33	2.44	Improving the city's image.
Value per unit area		149,825.80	7448.99	288.39	49,256.74	966.42	8292.80	

3.2.2. Corresponding Water Area of EBF in MSX

(1) Generalized river

MSX included 6 hydrological stations: Tuoshi, Linjiacun, Weijiabu, Xianyang, Lintong, and Huaxian (Figure 1b), which can be divided into 5 sections: Section I (Tuoshi–Linjiacun), Section II (Linjiacun–Weijiabu), Section III (Weijiabu–Xianyang), Section IV (Xianyang–Lintong), and Section V (Lintong–Huaxian). Section I is upstream (denoted by “U”); Sections II and III are midstream (denoted by “M”), and Sections IV and V are downstream (denoted by “D”).

(2) Fitting curve of EBF in MSX

In the *Annual Hydrological Report of the People's Republic of China (Yellow River Basin)*, we find a variety of measured data of Wei River, including measured flow and its corresponding water surface width at different times. To establish the fitting relationship between low flow (Q) and water surface width (B) as accurately as possible, we only chose the data in dry season (December–March), because at this time the measured flow in the river channel almost can be regarded as EBF. The results of fitting curve at 6 hydrological stations are shown in Figure 2.

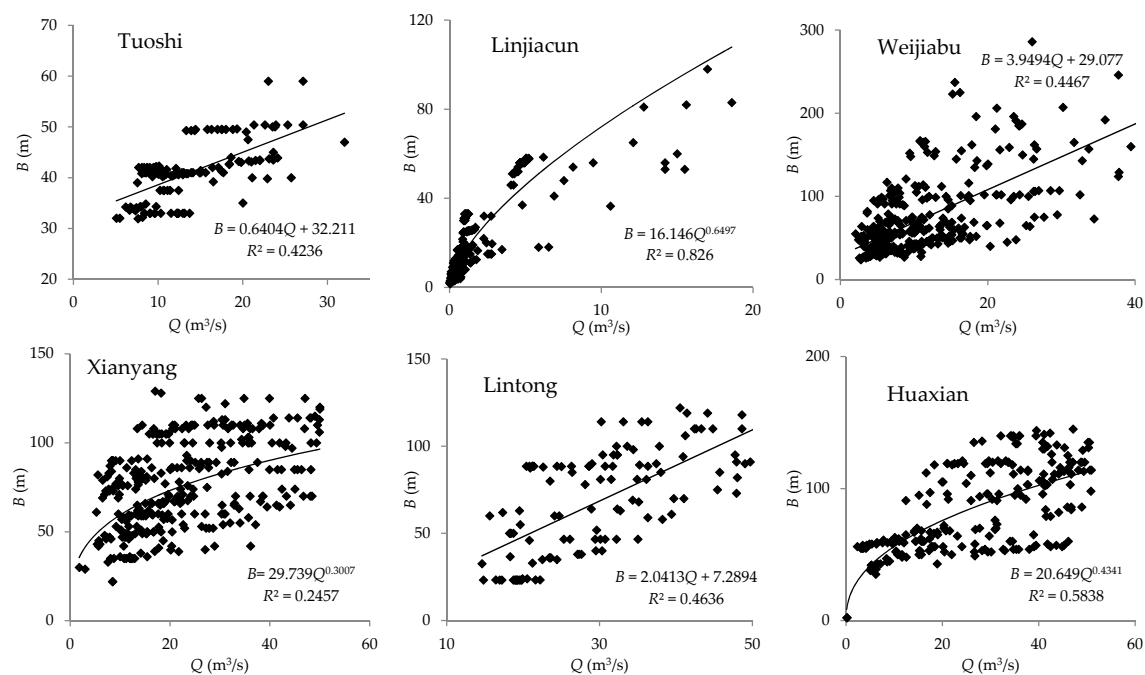


Figure 2. The fitting curve of low flow (Q) and water surface width (B) at 6 hydrological stations. Both Q and B were measured data provided by the *Annual Hydrological Report of the People's Republic of China (Yellow River Basin)*.

(3) Corresponding water area of EBF in MSX

Based on the data of EBF and the length of each section, we can calculate the corresponding water area S_j (Figure 3) in the dry season from 1973 to 2015 by means of Equation (9).

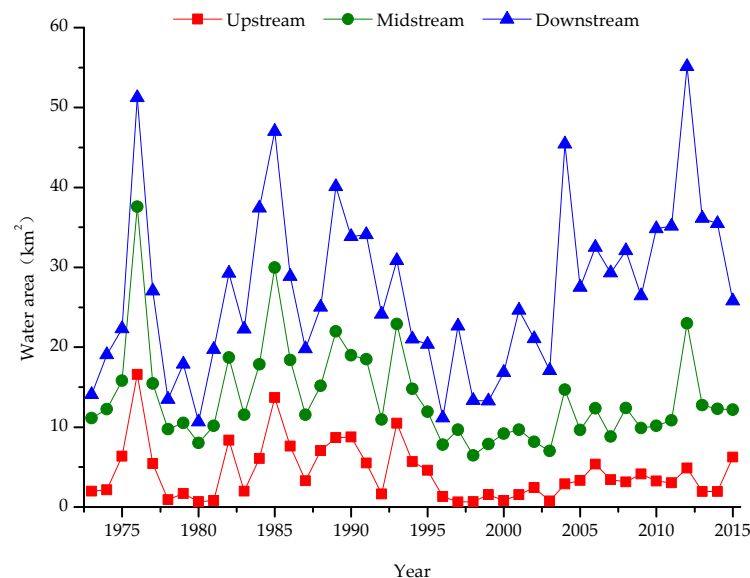


Figure 3. Corresponding water area of EBF in the dry season from 1973 to 2015.

3.2.3. Scarcity Coefficient in MSX

(1) w_1 : the average per capita water availability

The average per capita water availability in China is less than one quarter of the world average, approximately 2200 m³. Moreover, the average per capita water availability in MSX accounts for only 15% of China.

(2) w_2 : EBF

As can be viewed in Figure 4, the upstream EBF in most years cannot meet the baseline, whereas the relatively large midstream and downstream EBFs can satisfy the baseline, except for a few years.

(3) w_3 : precipitation

As shown in Figure 5, in the dry season from 1973 to 2015, almost all of the precipitation in MSX was lower than the national average data.

(4) ζ_n and θ

ζ_n : we set the same weight for w_n , $\zeta_n = 1/3$.

θ : Considering reasonability and residents' ability to afford the EBF value, we used the residential water price as the standard; that is, the annual mean EBF value should not rise too far beyond the residential water price, preparing for further EBF eco-compensation. According to the EBF situation in MSX, θ_U (θ for upstream) is 0.2 due to the severe scarcity of EBF, and θ_M (θ for midstream) and θ_D (θ for downstream) are 1.

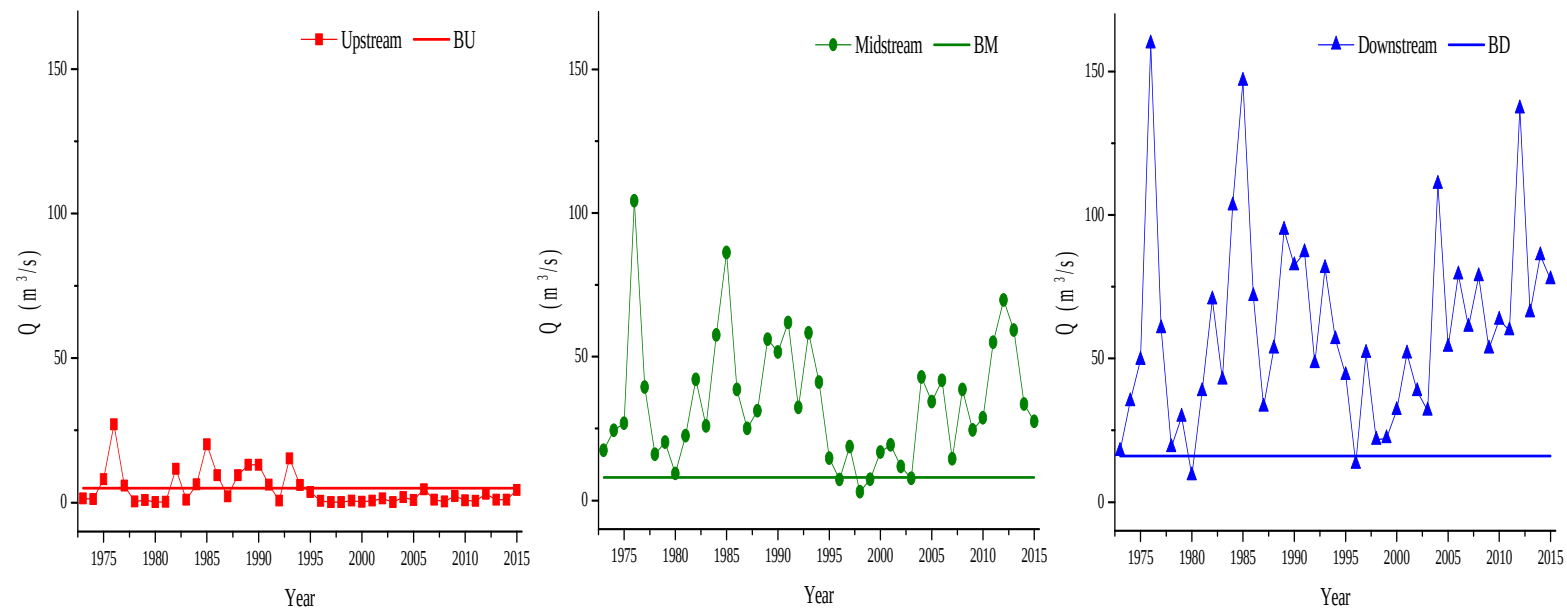


Figure 4. The measured data and baseline for EBF in the dry season at upstream, midstream and downstream sections of MSX from 1973 to 2015. “BU” represents the baseline of the upstream section ($5 \text{ m}^3/\text{s}$), “BM” represents the baseline of the midstream sections ($8 \text{ m}^3/\text{s}$), and “BD” represents the baseline of the downstream sections ($16 \text{ m}^3/\text{s}$). The measured data were provided by the *Annual Hydrological Report of the People’s Republic of China (Yellow River Basin)*, and the baseline data were from Table 4.

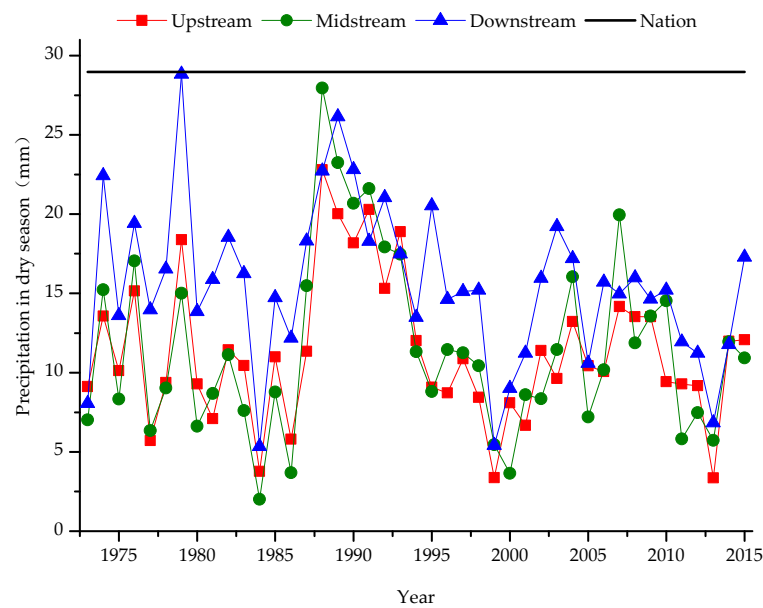


Figure 5. The precipitation in the dry season at upstream, midstream and downstream sections in MSX from 1973 to 2015. The upstream meteorological stations include Longxian and Baoji, the midstream include Fengxiang, Wugong, Qindu and Xi'an, and the downstream include Jinghe, Yaoxian, Tongchuan, Pucheng, Huaxian, and Huashan. The precipitation data from the upstream, midstream and downstream sections are the average values of the abovementioned stations over the same period. The national precipitation data are the long-time average annual values of China. All the precipitation data were provided by the National Meteorological Information Center of China.

3.2.4. EBF Value in MSX

We entered the above results into Equations (14) and (15) and obtained the total value and the unit benefit of EBF in MSX from 1973 to 2015 respectively (Figure 6).

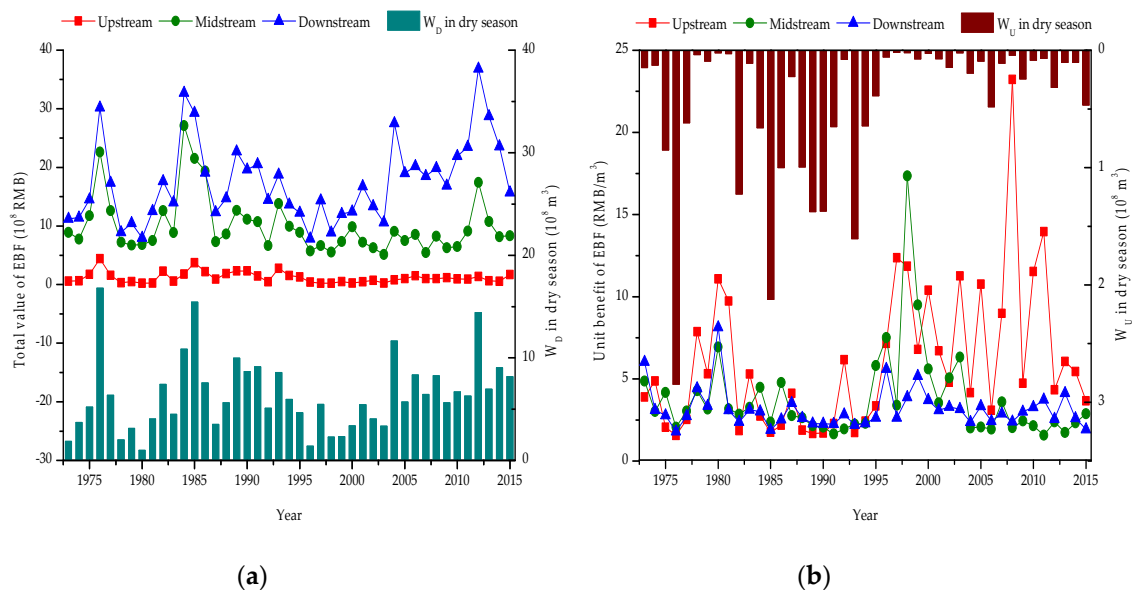


Figure 6. (a) The total value of EBF in MSX from 1973 to 2015; (b) The unit benefit of EBF in MSX from 1973 to 2015. “ W_U ” and “ W_D ” represents the water yields of EBF in the upstream and downstream sections in the dry season, respectively.

For one thing, as we can observe in Figure 6a, the total value in the downstream was higher than that in the midstream and upstream, ranging from 7.84×10^8 RMB to 36.82×10^8 RMB. The total value of EBF rose along with the water yield of EBF; this is because the EBF value is a functional value; the higher the EBF, the more service area, and the greater the total value of service function.

For another, with regard to Figure 6b, the unit benefit in the upstream was well above that in the midstream and downstream, and the difference between midstream and downstream was narrow. The unit benefit not only increased along with the reduction in EBF, but the lower the EBF, the higher the unit benefit, ranging from 1.56 RMB/m³ to 23.22 RMB/m³. The annual mean unit benefit in the upstream is 6.03 RMB/m³, slightly higher than the residential water price in MSX (5.64 RMB/m³). The reason for this is that a serious shortage of EBF in the upstream section led to a high unit benefit, and the strong security of EBF in the midstream and downstream reduced its unit benefit to approximately 3.70 RMB/m³.

3.3. Discussion

3.3.1. Comparison with Similar Studies

We compared our study with two classic articles: the first was *The Value of the World's Ecosystem Services and Natural Capital*, written by Costanza et al. in 1997 [39], who estimated the economic value of 17 ecosystem services for 16 biomes for the first time; the second was *Ecological Assets Valuation of the Tibetan Plateau*, written by Xie et al. [40] in Chinese, who established the ecosystem services value unit area for Chinese terrestrial ecosystems for the first time, according to partial global ecosystem services value evaluation results obtained by Costanza et al. [39] along with responses to ecological questionnaires from specialists in China.

There have been several differences in the research content between our study and the two articles; hence, to conduct contrastive analysis, we selected and processed their results, including the following: (1) EBF is part of a river, and its function is also part of a river's function. Thus, we only selected the functions of a river related to EBF for comparison; these functions are "water purification" to "waste treatment", "nutrient transport" to "nutrient cycling", "hydrologic cycle" to "water regulation", "recreation and landscapes" to "recreation" and "fishery production" to "food production"; (2) We believed EBF can maintain the normal functioning of wetland ecosystems connected with the natural river channel, so all functional values of a wetland could be included, that is, "sustaining wetland ecosystems" to "wetland"; (3) We converted all prices to 2015 RMB based on the exchange rate and discount rate for the sake of more comparable evaluation; (4) Qualitative analysis was not compared here.

Regarding the data comparison in Table 6, the values of "fishery production" and "recreation and landscapes" were slightly higher than the results in the other two articles. Both of them are associated with social function in the dry season of water scarce basins; EBF still provides for humans, supporting human recreation and fisheries, even if it is very costly for the ecosystem, and that is why the value of these two functions is high. In addition to these, the rest of the values are almost equal between the two. Overall, the values per unit area of our study are in a reasonable range. Therefore, it can be assumed that our estimated EBF value for MSX was reliable.

3.3.2. Typical Years

Due to the strong security of EBF in the midstream and downstream sections, we only analyzed the typical years in the upstream section. On the basis of the EBF in the dry season, combined with the annual inflow, we chose 1975 (25%), 2012 (50%), 2009 (75%), and 1997 (90%) for the typical years in the upstream.

As shown in Table 7, the average EBF in Dec.–Mar. cannot meet the baseline, except for in a wet year (25%). The total value dropped but the unit benefit increased along with the scarcity level of EBF.

Table 6. The comparisons of studies on the value per unit area. USD: United States Dollar; 1994 USD: the price of USD in 1994; 2003 RMB: the price of RMB in 2003. The exchange rate for USD was from 1994, and the discount rate over the years was sourced from the People’s Bank of China.

Data Sources	Units	Sustaining Wetland Ecosystems	Water Purification	Nutrient Transport	Hydrologic Cycle	Fishery Production	Recreation and Landscapes
		Wetland	Waste Treatment	Nutrient Cycling	Water Regulation	Food Production	Recreation
Our study	2015 RMB/ha	149,826	7489	288	49,257	966	8293
Costanza et al. [39]	1994 USD/ha	14,785	665	–	5445	41	230
	2015 RMB/ha	164,908	7418	–	60,727	455	2567
Xie et al. [40]	2003 RMB/ha	55,489	16,087	–	18,033	89	3840
	2015 RMB/ha	74,879	21,708	–	24,335	119	5182

Table 7. The total value and the unit benefit of EBF in typical years in the upstream. “BU” represents the baseline of the upstream section (5 m³/s).

Year	Typical Year	Frequency	BU m ³ /s	Average EBF in Dec.–Mar. m ³ /s	Total Value 10 ⁸ RMB	Unit Benefit RMB/m ³
1975	Wet year	25%	5	8.08	1.75	2.06
2012	Normal year	50%		3.01	1.37	4.34
2009	Dry year	75%		2.33	1.16	4.73
1997	Very dry year	90%		0.17	0.23	12.37

3.3.3. Limitations

In this study, we developed a relative simple method to evaluate the value of EBF, but there still exist some limitations in our study.

First, the equivalent factor method allows easily calculating the value of EBF. However, a typically encountered challenge in this method depends on the reliable value equivalent factor because different quantitative approaches and price bases lead to various evaluation results of equivalent factors [39]. The equivalent factor adopted in this study was calculated with Equations (2)–(7). The applicability of these equations to other areas may need to be further research.

Second, we estimated the corresponding water area of EBF in Wei River by means of a simple hydraulic rating method. Lower requirements for data in this method, the calculations are simple but the results are relatively rough. Actually, it has been replaced by the more sophisticated hydraulic/habitat simulation methods [18], which can get more accurate results. However, there exists little ecological data on the Wei River at present, which causes difficulties for hydraulic/habitat simulation. This is the future research orientation.

4. Conclusions

E-flow, which improves the human survival environment, is important for ecosystem protection, and this improvement is the value of e-flow. The estimation of e-flow values has been the new leading direction in e-flow research in recent years. It can scientifically measure the benefits accompanied by e-flow protection and is also the key to resolving conflict between anthropic water use and e-flow.

In this study, we focused on the e-flow within the river channel, referred to as EBF. The dry season is the critical period for EBF protection in water-scarce basins. During this period, the primary function of EBF is to maintain the basic ecological and environmental functions of rivers (eco-environmental functions), such as avoiding dried-up rivers in a perennial river, sustaining wetland ecosystems, water purification, and nutrient transport. Additionally, EBF also plays a role in the hydrologic cycle, fishery production, recreation and landscapes, and improving quality of life.

Using the Wei River Basin in Northwest China as a case study, we developed a method based on EBF functions to estimate the value of EBF in MSX from 1973 to 2015. The EBF value can be expressed in two indicators: the total value and the unit benefit. For the total value, we determined that the total value in the downstream was higher than the midstream and upstream, ranging from 7.84×10^8 RMB

to 36.82×10^8 RMB, and that the value increased along with the water yield of EBF. This is because the value of EBF is a functional value; the more EBF, the more service area, and the greater the total value of service function. For the unit benefit, the unit benefit in the upstream was well above that in the midstream and downstream, ranging from 1.56 RMB/m³ to 23.22 RMB/m³, and increased along with the reduction in EBF. The reason is that a serious shortage of EBF led to a high unit benefit, and strong security will reduce the unit benefit.

The results of our analysis provide a simple and effective way to present the considerable value of e-flow in monetary terms. Compared with similar studies, it can be assumed that our estimated EBF value of MSX is reliable, and this approach is achievable. However, additional work needs to be completed to advance our approach as a practical management tool. For example, it would be helpful to provide a decision-support tool that enables easier estimation of the reasonable protection levels of EBF with different water uses and hydrologic conditions. In addition, although there are still some functions of EBF that are difficult to evaluate with currency, such as avoiding dried-up rivers and improving quality of life, the values of these functions are irreplaceable in the areas of scientific research, aesthetic art and nurturing spirituality. Future research will attempt to address these problems.

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