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Adaptive ecological baseflow computation based on the ecological requirements: a case study in Weihe Basin, China

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ABSTRACT

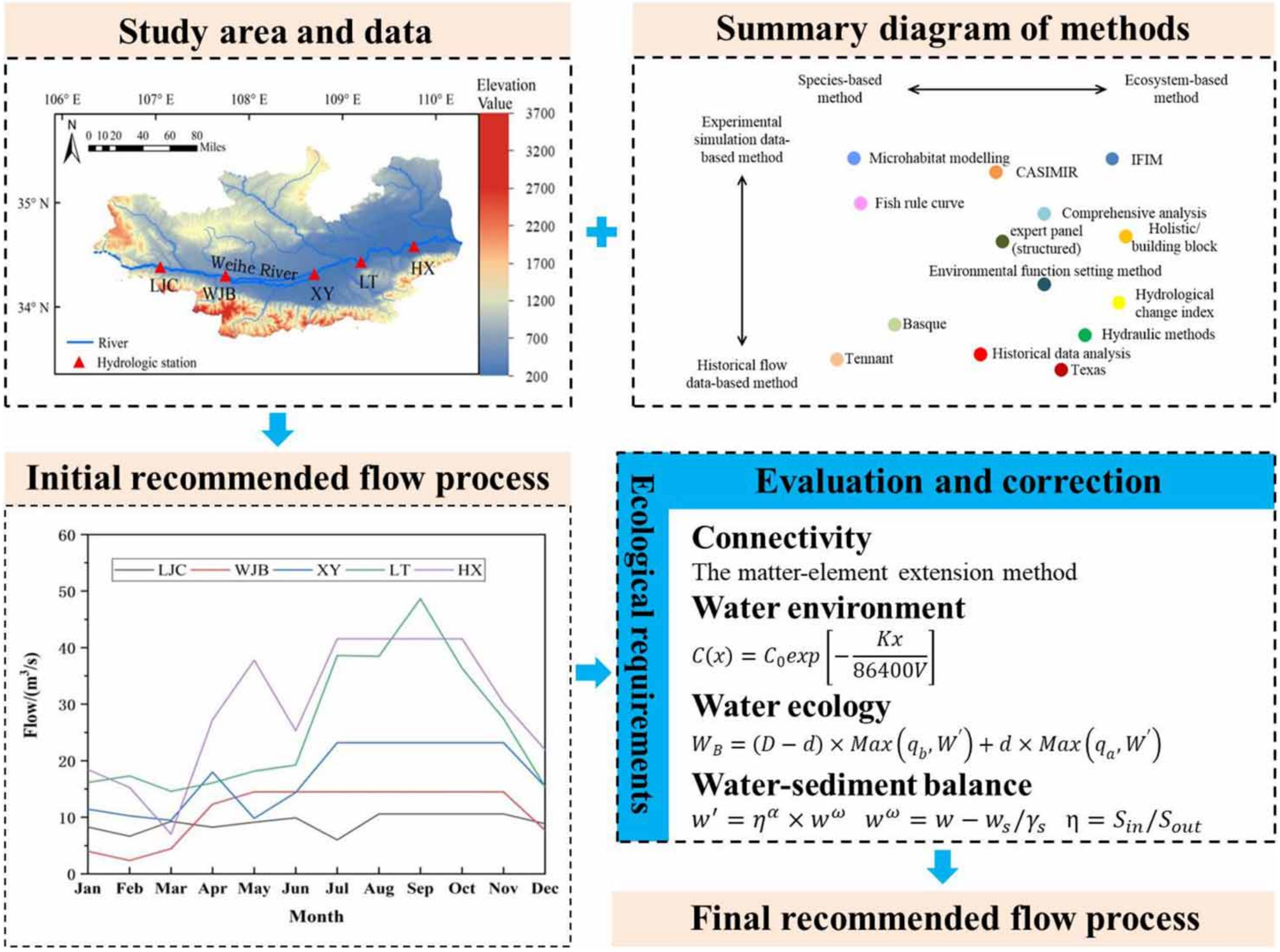
A certain flow plays a key role in preventing the shrinkage and drying of the river while maintaining good functionality. In recent years, ecological baseflow has become an important research issue in China with the emergence of ecological protection. Various ecological baseflow methods and their improvement methods were proposed and applied, but the reliability and applicability of the results are yet to be verified. This paper proposes an advanced ecological baseflow computation-dynamic thematic evaluation service model by considering the ecological protection objectives. The method was applied to five key cross-sections of the Weihe River, and a set of recommended ecological baseflow values was obtained considering the connectivity, water environment, and water-sediment balance, which is in line with the actual requirements. The analysis shows that the method has reliability and operability, which can provide support for management decisions.

Key words: application requirements, ecological baseflow, evaluation and correction, methodology summary

HIGHLIGHTS

- Preselection of methods is positively helpful to the results' reliability.
- Applying multi-method approach in flow processes is more convincing than single ones.
- The proposed correction can improve the simulation more close to practical requires.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Maintaining ecological baseflow plays a critical role in protecting rivers and their ecosystems. The ecological baseflow has been differently defined across different countries due to its different nature, origin, research scope, and focus (Horne *et al.* 2019): 'Instream Flow' in North America, 'Environment Flow' in Australia and South Africa (Van Niekerk *et al.* 2019), and 'Reserved Flow' in some European countries (Arthington *et al.* 2018). In this study, ecological baseflow is defined as the process that satisfies the environmental protection requirements, apart from the assurance of the constant flow in perennial rivers. According to Tharme's (2003) survey, there are 207 environmental flow methodologies (EFMs) from 44 countries into four distinct categories: hydrology, hydraulic, habitat simulation, and holistic methods.

The typical EFMs have been hydrological methods, which constitute the highest proportion of the overall methodologies recorded (30%). With 61 different hydrological indices or techniques applied to date (Tharme 2003). It relied on the recorded or estimated flow regime of the river, usually in the form of naturalized, historical monthly, or daily flow data (Cavendish & Duncan 1986; Tharme 2003). Tennant (1976) considered that 30% of the average flow would provide satisfactory stream width, depth, and velocity for a 'baseflow regime.' In addition, hydrological methods also include the Q95, 7Q10, Texas, etc. The simple hydrological methods are still widely used in current research, in the original and variant forms. However, the hydrological methods are more suitable in low controversial situations and are often applied at the planning level of water resource development.

Hydraulic rating methods, representing roughly 11% of the global total, were mainly applied in the United States, North America, Australia, and Europe (Gippel & Stewardson 1998). The most widely used hydraulic rating methodologies are the generic wetted perimeter and the R2-CROSS method. In this methodology, the minimum or preservation flows are determined by the relationship between wetted perimeter and discharge, usually applied for fish rearing or maximum production by benthic invertebrates (Stalnaker & Amette 1976). Because of field and analytical works, hydraulic rating methods are considered more difficult than historic flow methods (Mosely 1982). They are usually used to assess non-seasonal flow requirements (Jowett 1997).

Habitat simulation methodologies are the second most widely used (28% of the overall total), with approximately 58 recorded from countries throughout the world (Tharme 2003). These methods are a natural extension of hydraulic methods, which consider the special biological requirements in addition to hydraulic conditions (Tharme 2003; Sang *et al.* 2006). The instream flow increment method is the most used method to calculate environment flow for fish or invertebrates (Macura *et al.* 2017). Due to its more flexibility than historical flow and hydraulic methods, the habitat method can be used to examine the variation of the habitat utilized by many species and life stages throughout the year, selecting flows that provide this habitat. Therefore, the habitat method can provide a more reliable and convincing assessment in the United States than other methods (Jowett 1997).

Holistic methods focused on the entire riverine ecosystem instead of the outset. Although holistic EFMs represent only 7.7% of the global total, with 16 methodologies, they have contributed significantly to the field of environmental flow assessment in recent years (Tharme 2003). In a holistic method, critical flow events are identified based on the selection criteria that define flow variability for major components/attributes of the riverine ecosystem. The holistic methods are divided into the bottom-up method, top-down method, or a combination of them. The building block methodology (BBM) (King *et al.* 2008) is the most worldwide used holistic EFM.

Despite the fact that significantly different results can result from different methods to the same river (Xu *et al.* 2019), no comprehensive evaluation study has been conducted to guide the selection of a proper ecological baseflow calculation method (Olsen *et al.* 2013). In addition, in previous studies, various calculation indices and the definition of guarantee degree were inconsistently used. For instance, the used calculation indices were the characteristic value of historical flow data multiplied by the empirical ratio, the flow corresponding to a specific frequency or a period, and the flow corresponding to the hydraulic parameters of water demand for an ecological function (Caissie *et al.* 2014). As a guaranteed degree, minimum flow standard, habitat maintenance, and self-purification requirement were used.

Kawamoto *et al.* (1998) investigated the accuracy and applicability of the IFIM method in Yamaguchi Prefecture, Japan, showing significantly diverse results from the same method for different rivers. Yao *et al.* (2021) calculated the ecological baseflow of two cross-sections of the Luan River using seven hydrological methods; the results differed significantly during the wet season. Four of these methods provided a relatively smaller baseflow and were recommended for northern China. On the other hand, the Northern Great Plains Resource Program (NGPRP) method is more suitable for southern regions. Jin *et al.* (2014) calculated the environmental flow of two typical cross-sections of the Dadu River (the largest tributary of the Minjiang River in China). The results showed highly different minimum and maximum values calculated by the four methods, which is mainly due to the principles and assumptions of different methods. The significant differences between methods indicate the importance of research in rationality and the applicability of different methods to select the proper one for the target region (Chen *et al.* 2017).

The determination of river ecological baseflow in semi-humid and semi-arid regions of northern China is more complicated than in humid areas (Chen 2007). Affected by climate change and human activities, the region faces water scarcity, severe water pollution, and ecosystem degradation (Jing *et al.* 2017). Thus, it is important to ensure the required river ecological baseflow and the process during dry seasons (Widén *et al.* 2021), which is actively studied in China (Hao 2017). However, existing research lacks rationality and applicability analysis of the methods. Especially, two unsolved questions remained: (i) how to select the ecological baseflow calculation method in interested rivers; (ii) how to evaluate the rationality of calculated results from different methods. To answer these, the primary objectives of this study include: (i) to classify and analyze ecological baseflow calculation methods to guide researchers in method selection; and (ii) to correct the calculation results of multiple methods using the proposed dynamic thematic evaluation service model for ecological baseflow. We hope that our findings will not only improve the reliability and adaptability of ecological baseflow calculation results and better provide decision support for river managers in ecological baseflow calculation, assessment and evaluation.

2. METHODOLOGY

2.1. Study area

The study area, the Weihe River Basin in Shaanxi Province (Figure 1), is located between 104–110 °E and 34–37 °N, covering an area of 13.43×10^4 km^2. It belongs to the perennial river in northern China with an average annual runoff of 7.57 billion m^3 (Wang *et al.* 2019). The basin area is about 67,100 km^2, and the mainstream length is 502 km. The topography is high west and low east. Land utilization types are mainly arable land and forest. Most cities are in the middle and lower reaches of the Weihe River (Wu *et al.* 2020). Most of the flows are from the northwest to the southeast through the Loess Plateau, with a high sediment content and low river channel gradient (Wang *et al.* 2019).

In general, the water environment still needs further improvement. To prevent further deterioration of water ecology caused by insufficient flow, it is imperative to determine the ecological base flow in the middle and lower reaches of the Weihe River. Therefore, this study aims to determine the ecological baseflow of five key cross-sections of the Weihe River: Linjiacun (LJC), Weijiabu (WJB), Xianyang (XY), Lintong (LT), and Huaxian (HX). The catchment areas of these five hydrologic stations are 30661, 37012, 46827, 97299, and 106498 respectively, and the unit is km^2. The measured annual average runoffs of five hydrologic stations are 19.03, 27.66, 39.11, 40.36, and 65.57 respectively, and the unit is 100 million m^3 with variation coefficients ranging from 0.457 to 0.594. The calculation was based on 63 years of daily runoff data from 1956 to 2018 (from the Hydrological Yearbook). The calculation time scale was months.

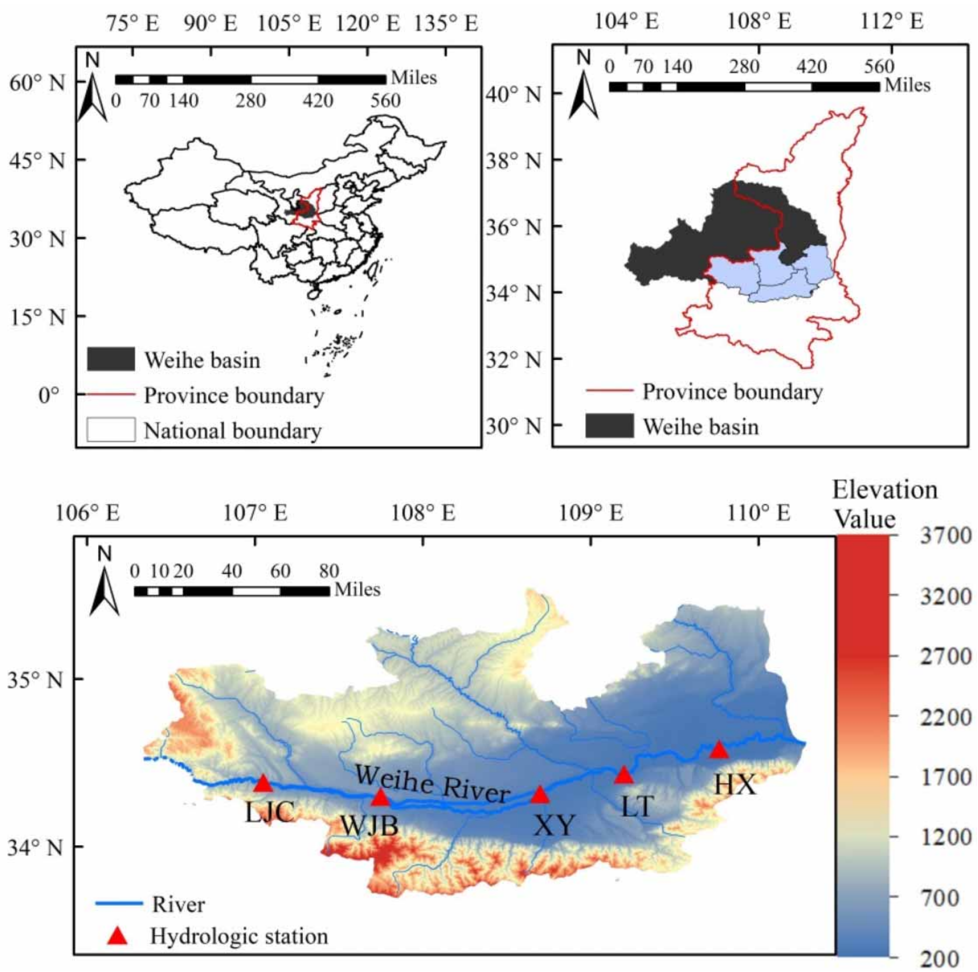


Figure 1 | Schematic diagram of five typical hydrological stations in the middle and lower reaches of the Weihe River in Shaanxi Province.

2.2. Method categorization and selection

This section conducts the categorization and analysis of the ecological baseflow calculation methods to guide for selecting a proper method for each application. The 29 hydrological methods, including four hydraulic methods, seven habitat methods, and nine comprehensive methods, according to their description, applicability, and data requirements, were divided into 14 categories and analyzed (Gao 2021). The summary of method selection was drawn in Figure 2. The horizontal axis represents the main research object (from left to right: the method with single species to the method with the whole ecosystem), and the vertical axis represents the basis of the method (from bottom to top: the historical flow data-based to experimental simulation data-based, the more bottom the more inclined to (routine monitoring data)-based). Note that, due to the restrictions and constraints in the practical application process, the calculation methods in the lower half tend to be selected.

Due to data and financial resource limits, a simple hydrologic or hydraulic method was commonly used in developing countries. This study investigates the method selection process focused on two categories. Method selection was performed by considering the data requirements and applicable conditions of the two types of methods. The required data were divided into two categories and the applicable conditions were divided into four categories (Figure 3). Combined with the

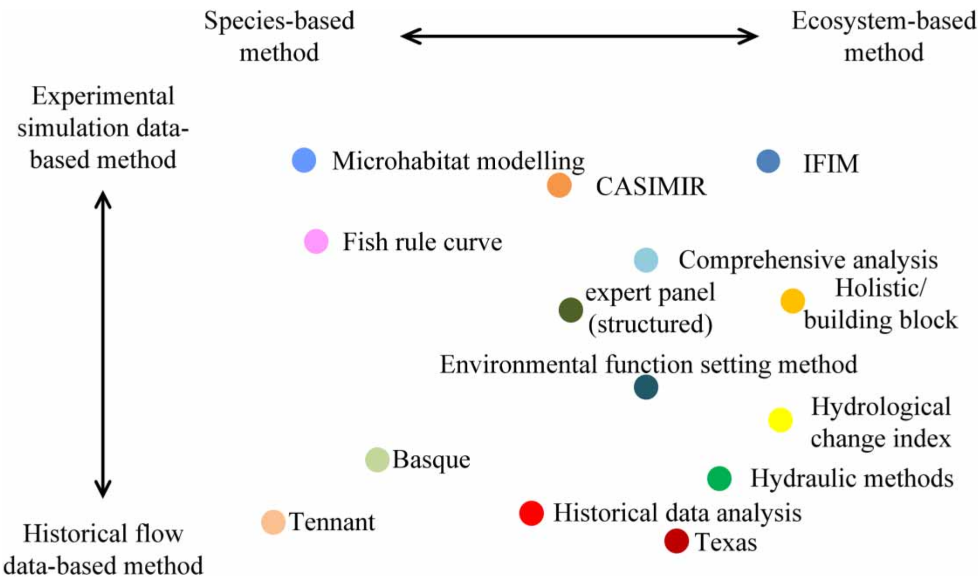


Figure 2 | Summary diagram of the selected 14 methods (six hydrological methods, one hydrodynamic method, four habitat simulation methods, and three holistic methods).

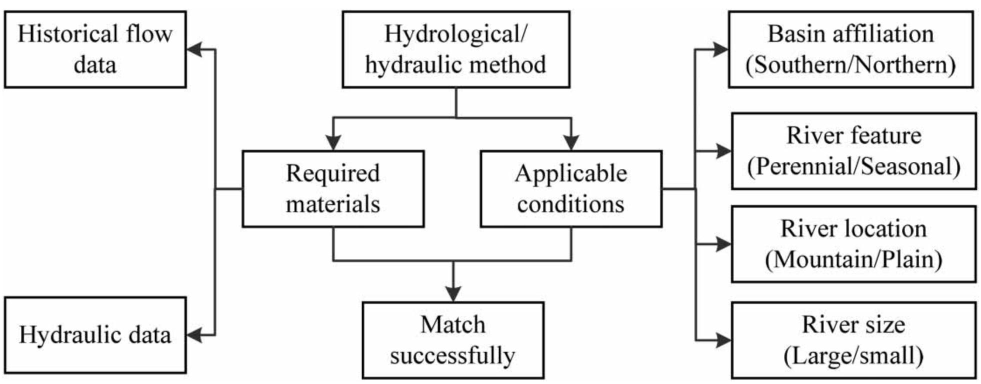


Figure 3 | The adaptive selection process of the ecological baseflow calculation method.

characteristics of specific reaches of the river, one or more ecological baseflow calculation methods can be selected corresponding to the target river.

Based on the summary diagram and the adaptive method selection process, we suggested 17 methods to compute the ecological baseflow for the five cross-sections. The description and indices of each method are summarized in Table 1.

2.3. Result evaluation and correction

According to the definition, the ecological baseflow should satisfy two types of environmental protection objectives: general and special application requirements (Liu 2021). The general requirement refers to the connectivity requirement that ensures the continuous flow of the river, and the special requirement consists of water environment, water ecology, and water–sand balance. The initial recommended values are evaluated and corrected to obtain the final recommended values (Gao 2021).

(1) Connectivity requirement evaluation

The connectivity requirement is evaluated by the matter-element extension method (Zhang & Liang 2005), solving the multi-factor evaluation problem with uncertainty, which is conducted as follows. (1) The matter element matrix R_0 is constructed, where the evaluation index is from January to December, and the target value is the ecological baseflow of each month. (2) Classic domain R_j and node domain matrix R_P are established according to the evaluation criteria of each evaluation index. In this study, the Tennant flow classification (Jiang *et al.* 2020) is used as the evaluation criterion. (3) The correlation function $K_j(X_i)$ is computed. (4) The comprehensive relevance $K_j(P_0)$ is computed and evaluated.

(2) Water environment requirement evaluation

When conducting the thematic evaluation of the water environment, the evaluation indicators are selected according to the main pollutant types of the river reach. In this study, the water environment theme evaluation was carried out on the XY cross-section, and the main pollutants in the XY cross-section are COD and ammonia nitrogen, thus these two evaluation

Table 1 | Description of the selected ecological baseflow computation method

Method	Description	Equation	Citation
Tennant	10% ~ 30% average flow	$Q_i = (0.1\tilde{0}.3) \times \frac{1}{12}\sum_{i=1}^{12}\overline{q_i}$	Huang *et al.* (2019)
Flow-duration curve	Number of flow events above 90th percentile		Lytle & Poff (2004)
Annual dynamic calculation	Average flow, 30 days mean, contemporaneous ratio	$Q_i = \overline{q_i} \times \frac{\bar{Q}_{min}}{\bar{Q}}$	Fan *et al.* (2017)
Minimum monthly average measured runoff	Average flow, 30 days mean, minimum month	$W_b = \frac{1}{n}\sum_{i=1}^{n}\tau Q_{min,i}$	Hou *et al.* (2019)
NGPRP	Number of flow events above 90th percentile		Dunbar *et al.* (1998)
Monthly (annual) guarantee rate setting	Average flow, a certain percentage	$Q_{i,j,k} = \begin{cases} R_{i,ave} \cdot W_k \ (R_{i,j} > R_{i,ave} \cdot W_k) \\ R_{i,j} \ (R_{i,j} \leq R_{i,ave} \cdot W_k) \end{cases}$	Ma *et al.* (2011)
Q90	Average flow, 30 days mean, number of flow events above 75th percentile		Armentrout & Wilson (1987)
Baseflow ratio	Average flow, baseflow ratio	$T_{i+1} = [1 + (Q_i/Q_{i+1} - 1) \times \mu] \times T_i$	Wu *et al.* (2011)
Average monthly flow in last decade	Average flow in last decade, 30 days mean	$\mathrm{W} = \frac{T}{n}\sum_{n-1}^{n}\min(Q_{ij}) \times 10^{-8}$	Yu *et al.* (2013)
Lyon	Medium flow, a certain percentage	$Q = \begin{cases} 0.4 \times Q_{mid} & Q_m \leq Q_a \\ 0.5 \times Q_{mid} & Q_m > 0.8 \times Q_a \end{cases}$	Opdyke *et al.* (2014)
Monthly minimum runoff	Minimum flow, 30 days mean	$Q_i = \min\{q_i\}$	Yu *et al.* (2004)
Monthly frequency calculation	Different frequency and duration		Li *et al.* (2007)
Wetted perimeter	Inflection point or 50% wetted perimeter rate		Gippel & Stewardson (1998)
Comprehensive analysis	Water quality simulation by MIKE11		Xu *et al.* (2019)

indicators were used to evaluate the water environment. The one-dimensional water quality (Shore *et al.* 2017) is adopted, which is defined as follows:

$$C(x) = C_0 \; exp\left[-\frac{Kx}{86400V}\right] \tag{1}$$

where C(x) and C_0 represents the downstream and initial pollutant concentrations [mg/L], respectively. K and x represent the degradation coefficient and the distance [km] from the sewage outlet to the downstream cross-section, respectively.

(3) Water ecology requirement evaluation

The biological water demand satisfaction degree was used to evaluate the water ecology. The water demand standard of the target organism was calculated by the habitat simulation method, which is used to determine the biological water demand satisfaction degree, computed as follows:

$$W_B = (D - d) \times Max(q_b, W') + d \times Max(q_a, W') \tag{2}$$

where W_B is the ecological water requirement of important aquatic organisms in the sensitive period. q_a and q_b are the suitable ecological flow and the ecological baseflow, respectively. D is the total days in the breeding period, and d is the days required to reach a suitable ecological flow. W′ is the water requirement for sediment transport [m^3].

(4) Water–sediment balance requirement evaluation

The water–sediment balance requirements were evaluated by the water demand satisfaction degree for sediment transport. Also, the sediment concentration method was used to calculate the water demand standard of the reaches. The water demand satisfaction degree for sediment transport was calculated by comparing the historical runoff with the water requirement standard to evaluate the initial recommended values (Yan & Hong 2004).

The evaluation and correction process of ecological baseflow is depicted in Figure 4 and conducted as follows.

Step 1: Input parameters: monthly ecological baseflow q_j, multi-year monthly average flow Q_{-j}, monthly flow weight α_j, Tennant flow interval boundary α_j, where j represents jth month;

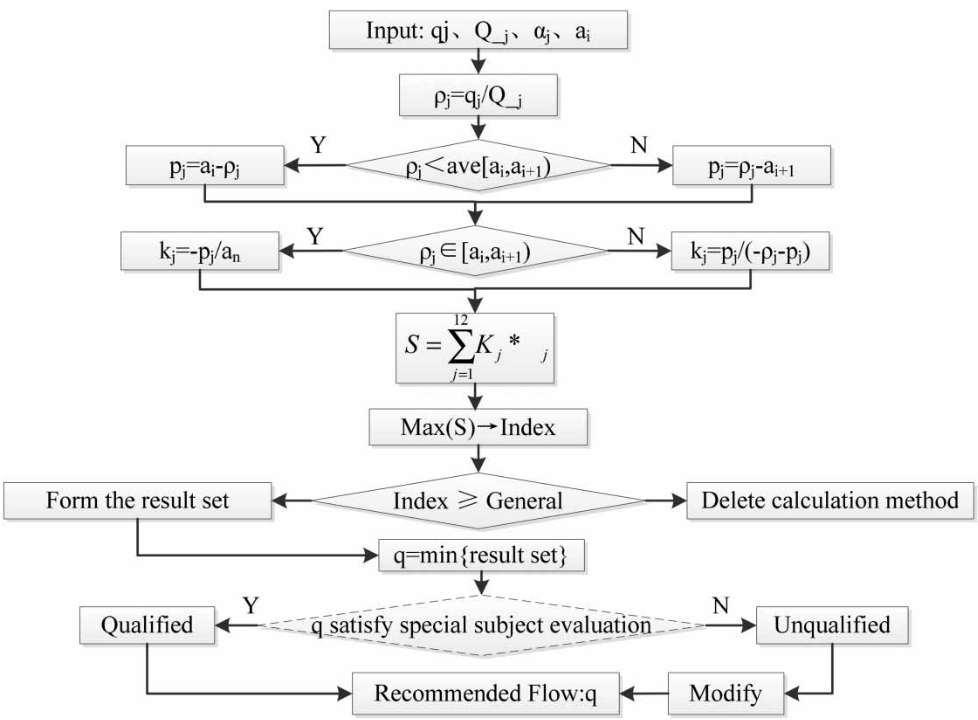


Figure 4 | Evaluation and correction process of ecological baseflow.

Step 2: The ratio ρ_j of the monthly ecological baseflow to the multi-year averaged monthly flow is calculated;

Step 3: The relationship between the ratio ρ_j and the average value of the flow interval $[a_i, a_{i+1}]$ is determined, obtaining the intermediate value ρ_j according to different determination results;

Step 4: Whether the ratio ρ_j belongs to the flow interval $[a_i, a_{i+1}]$ is determined, and the monthly ecological baseflow correlation k_j is calculated according to different judgment results;

Step 5: The annual ecological baseflow correlation degree is calculated through the weighted multiplication of the monthly baseflow correlation degree;

Step 6: The proper method is selected based on the correlation degree of ecological baseflow;

Step 7: The initial recommended ecological baseflow values are set as the lower limit of the ecological baseflow with the highest degree of correlation;

Step 8: Satisfaction of the initial recommended ecological baseflow to the application requirements is checked. The final recommended ecological baseflow values are improved by correction for unsatisfactory results.

3. RESULTS AND DISCUSSIONS

3.1. Ecological baseflow calculation

According to the analysis results, 14 hydrological, one hydraulic, and one habitat methods were selected for five key cross-sections of the Weihe River (Figure 5). A comparison of this research results was made to past research.

Comparing the multi-method calculation results with the study of Yu *et al.* (2013) (Figure 6). The bar graph represents the interval formed by taking the minimum and maximum values using six hydrological methods. It can be seen that the most ecological baseflow values obtain significant differences during the flood season but relatively small differences in the

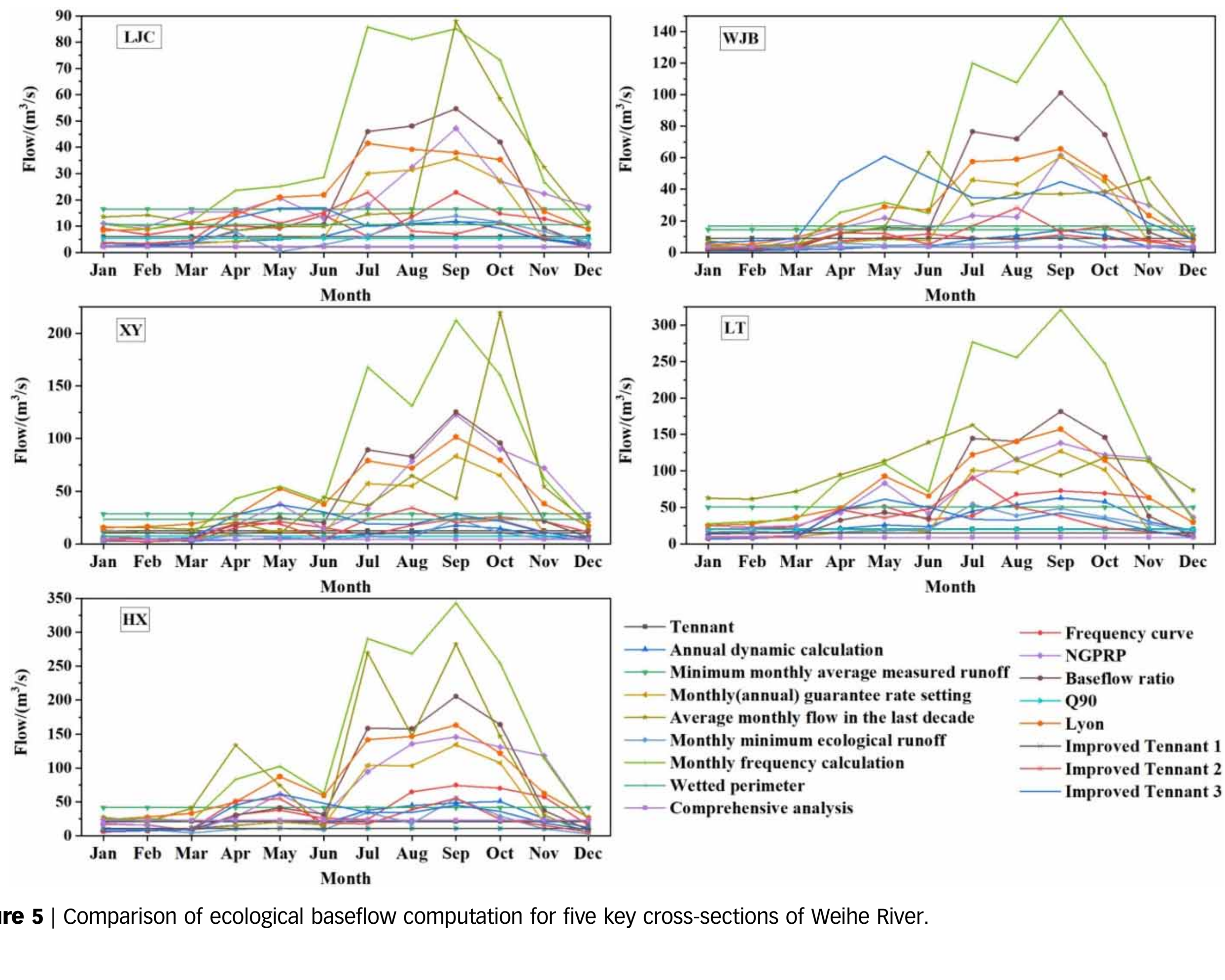


Figure 5 | Comparison of ecological baseflow computation for five key cross-sections of Weihe River.

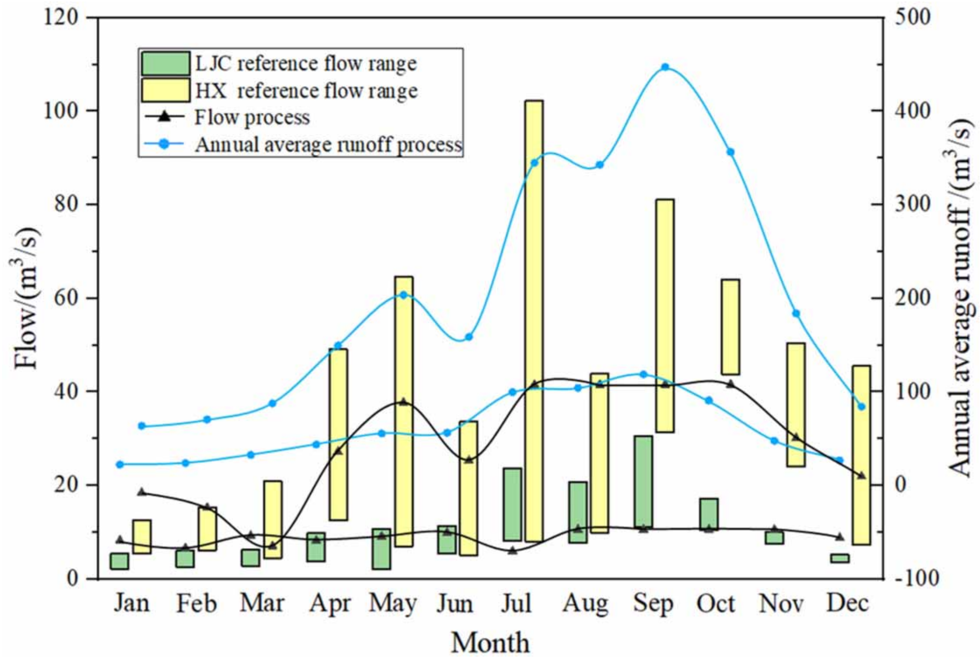


Figure 6 | Annual process of ecological baseflow in LJC and HX cross-sections.

non-flood season, and are much smaller than the annual average runoff. The ecological baseflow in HX cross-section is larger than that in LJC cross-section. According to the climatic characteristics of the middle and lower reaches of the Weihe River, its rainfall is mainly concentrated in July, August, and September, so the maximum flow also occurs in September, which is basically consistent with the flow process in Figure 5. In addition, the ecological baseflow process calculated by the Tennant method correlates with the annual runoff process, i.e., the ecological baseflow is more in wet years and less in dry years.

These consistencies verify the reasonability of our method adaptation process. It shows the necessity of adaptive selection from multiple methods since different methods work properly for different regions. However, despite this, there are still about 1/3 of the flow processes that are larger than the average flow calculated by the multi-method. Thus, the calculated results need to be corrected and further optimized to achieve the reliable recommended value of ecological baseflow.

3.2. Evaluation and revision of ecological baseflow

3.2.1. Initial recommended values

The examples of initial recommended ecological baseflows are shown in Table 2, where the LJC cross-section was used as an example. As shown in Table 2, six methods were evaluated as 'general,' which is better than the other methods. For those methods, the lower limit of the evaluation interval with the evaluation grade of 'General' equals 10% of the annual average flow. Accordingly, the minimum and maximum values calculated by the six methods are taken as the ecological base flow range, and the minimum value is taken as the initial recommended value. In the same way, the recommended initial ecological baseflow values for the other four key sections were determined, as shown in Figure 7.

Due to the confluence of main and tributaries, the ecological baseflow values of the five cross-sections continue to increase from upstream to downstream; the interval formed after the theme evaluation of connectivity is more specific than that of (Xu *et al.* 2019), as shown in Figure 8. It is more useful for river managers, which verifies the necessity of evaluation.

3.2.2. Final recommended values

Based on the initial computations, the final recommended ecological baseflows are obtained by evaluating special application requirements. No correction is conducted if the initial results satisfy the special application requirements; otherwise, it paths the revision process. Since the water pollution of the XY section is relatively severe, combined with the actual situation of the middle and lower reaches of the Weihe River, the theme of the water environment was evaluated. Also, since the LT and HX

Table 2 | Evaluation results for 17 suggested methods in the LJC cross-section

Method	Comprehensive correlation					Evaluation result
	Poor	General	Better	Good	Optimal	
Tennant	−0.022	−0.321	−0.583	−0.713	−0.774	Poor
Frequency curve method	−0.240	0.302	−0.197	−0.546	−0.667	General
Annual dynamic calculation	−0.045	−0.461	−0.757	−0.860	−0.897	Poor
Minimum monthly average measured runoff method	−0.203	0.028	−0.154	−0.494	−0.624	General
NGPRP	−0.246	0.005	−0.182	−0.554	−0.667	General
Monthly (year) guarantee rate setting method	−0.085	−0.667	−0.701	−0.762	−0.798	Poor
Q90	−0.026	−0.378	−0.611	−0.728	−0.784	Poor
Basic flow ratio method	−0.298	−0.542	−0.839	−0.745	−0.971	Poor
Average monthly flow method in the last decade	0.314	−0.120	−0.505	−0.598	−0.720	Poor
Lyon	−0.371	−0.176	−0.317	−0.663	−0.859	General
Monthly minimum ecological runoff computation method	−0.117	−0.510	−0.834	−0.911	−0.945	Poor
Monthly frequency calculation method	−0.427	−0.297	−0.337	−0.698	−0.629	General
Improved tennant method 1	−0.068	−0.780	−0.897	−0.945	−0.963	Poor
Improved tennant method 2	−0.201	−0.308	−0.604	−0.754	−0.798	Poor
Improved tennant method 3	−0.280	−0.370	−0.654	−0.776	−0.816	Poor
Wetted perimeter method	−0.038	0.003	−0.395	−0.617	−0.708	General
Comprehensive analysis	−0.071	−0.800	−0.907	−0.950	−0.967	Poor

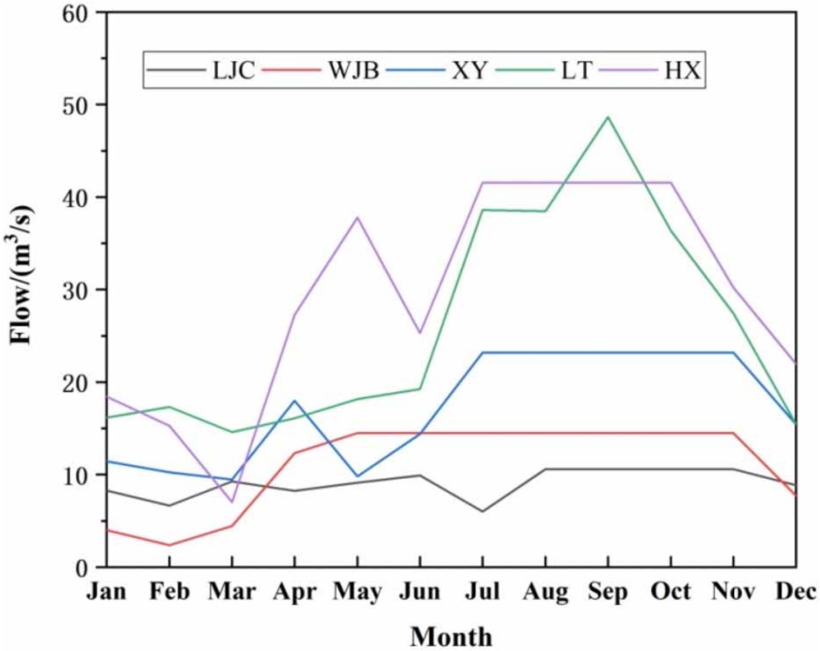


Figure 7 | Comparison of initial ecological baseflow of five cross-sections.

cross-sections demand sediment transport during the flood season (July–October), the theme of water and sediment balance was evaluated.

(1) Water environment requirement

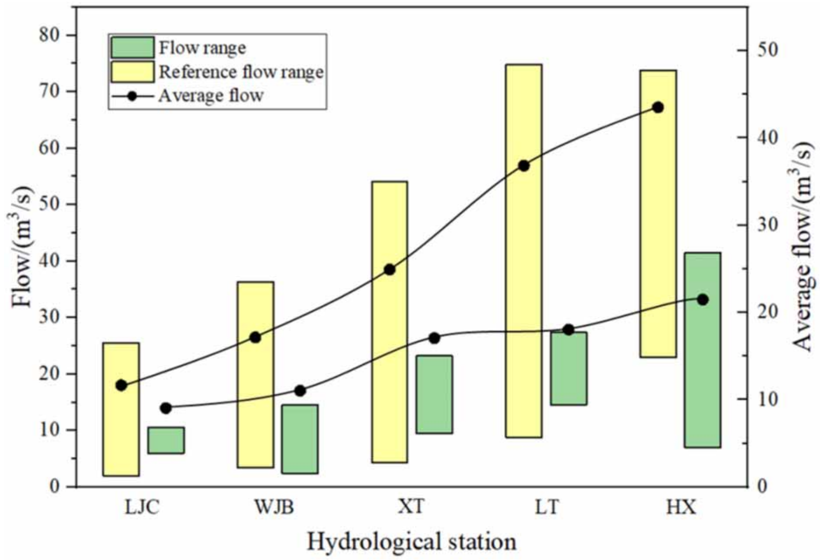


Figure 8 | Variation interval of ecological base flow of five cross-sections.

The one-dimensional water quality model (Yan *et al.* 2020) was used to verify the water environment requirement satisfaction of the initially recommended flows of XY cross-section. The monthly initial pollutant concentrations C_0 were calculated by averaging water quality monitoring data of WJB cross-section in recent years. The degradation coefficient was derived from (Wang 2017). The relationship between flow and velocity of XY cross-station is $V = 0.1736Q^{0.3328}$, and the length of the XY reaches in Weihe River for sewage control is 5.4 km. According to the monthly report of water environment quality in Shaanxi Province in December 2020, the COD and ammonia nitrogen assessment target values of XY cross-section are respectively 30 mg/L and 1.5 mg/L. The calculated results were all in line with the standard, indicating that the initial recommended ecological baseflows satisfied the water environment requirement. Thus, no further correction process was not conducted.

(2) Water-sediment balance requirement

The sediment transport requirement of the initially recommended flows in LT and HX cross-sections during the flood season is evaluated by the sediment concentration method. The results showed that the flow required for sediment transport during the flood season was much greater than the initial recommended flow values. By comparing the calculated flows with the measured flows from 2001 to 2011, the statistical results of LT and HX cross-sections were achieved. The proportion of sediment transport in line with the standard was 20% and 17.5%, respectively. The evaluation results were all poor; thus, it needs to be corrected.

The final recommended ecological baseflows were obtained by considering the general and special application requirements (Table 3); the bolded sections from July to October are the corrected ones.

Overall, the obtained results were comparable with other studies conducted in the same region. For example, Hou *et al.* (2019) calculated ecological baseflow in LJC by considering biological factors. The results for the LJC cross-section from

Table 3 | Final recommended ecological baseflow results (unit: m^3/s)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LJC	8.28	6.64	9.25	8.24	9.12	9.92	6.00	10.60	10.60	10.60	10.60	8.84
WJB	4.00	2.38	4.44	12.31	14.49	14.49	14.49	14.49	14.49	14.49	14.49	7.70
XY	11.43	10.23	9.47	18.00	9.81	14.38	23.20	23.20	23.20	23.20	23.20	15.43
LT	16.16	17.31	14.60	16.09	18.17	19.26	**294.45**	**353.82**	**545.14**	**513.49**	27.44	15.43
HX	18.44	15.27	7.03	27.27	41.57	10.06	**322.58**	**337.76**	**594.39**	**575.97**	30.20	21.95

The bold values represent the part of the change in ecological baseflow values before and after the correction.

April to June were 10 m^3/s (close to our result in Table 3). Xu *et al.* (2019) calculated ecological baseflow for the five key cross-sections but with different considerations. First, the habitat requirement, mainly for fish spawning and migration, was considered during calculating the ecological baseflow (the unit is m^3/s) from April to June. The recommended ecological baseflow values for five key cross-sections were 10.60, 16.70, 23.20, 38.80, and 52.60, which are higher than the current study. The results from Xu *et al.* (2019) can supplement our results. In contrast, a clear difference is found between Xu's study and ours that the maximum recommended ecological baseflow values in LT and HX cross-sections, respectively, were 74.79 m^3/s and 73.84 m^3/s. In comparison, the average values of ecological baseflow from July to October in the current study were 426.72 m^3/s and 457.68 m^3/s, which are about six times higher than those of Xu *et al.* (2019). That is because the water-sediment balance requirement is specifically considered here.

In summary, the peak ecological baseflow value mainly occurred in September in a year, which was consistent between studies. It is because of concentrated rainfall in July and August in the Weihe River. Also, the ecological baseflow increased from upstream to downstream in five cross-sections of Weihe River, which was theoretically reasonable. Our study can help decision-makers make an easy and reliable decision due to the consideration of the application requirements.

4. CONCLUSION

Existing methods for calculating ecological baseflow have different performances in different regions. This paper conducted a categorization analysis and proposed a novel correction method – dynamic thematic evaluation methods of ecological baseflow, enhancing the reliability of the ecological base flow calculation. According to different ecological protection objectives, the evaluation is divided into four themes – connectivity theme, water environment theme, water ecology theme, and water–sediment balance theme, and corresponds to the corresponding evaluation indicators and evaluation methods. The baseflow that does not satisfy the requirements of the environmental protection objectives after the evaluation is corrected to form a recommended ecological baseflow.

The case study on five key cross-sections in Weihe River shows the following: i) the proposed adaption process can provide a reasonable ecological baseflow estimation, ii) the calculated ecological baseflow of Weihe River becomes more reliable with the proposed correction method by considering the general and special application requirements, and iii) the final recommended ranges of ecological baseflow during non-flood seasons in Weihe River were LJC (6.64, 10.60), WJB (2.38, 14.49), XY (9.47, 23.20), LT (14.60, 27.44), and HX (7.03, 30.20), respectively, and the unit is m^3/s. The monthly ecological baseflow values generally increase along the river, which is reasonable. It should be noted that this method applies to the rivers in northern China represented by the Weihe River Basin, which lacks consideration of the water requirement of fish, and for other river basins, the themes and evaluation indicators need to be expanded. Furthermore, the calculation method of ecological baseflow still needs to be improved, especially in the study of habitat simulation methods and holistic methods for domestic rivers; the ecological baseflow dynamic thematic evaluation computation still needs to be optimized to make it more reliable and adaptable.

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COMPETING INTERESTS

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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