Research on the improvement of wetted perimeter method and application in seasonal rivers- Case study of Fenhe River, China

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Abstract: Environmental flow is vital for maintaining river ecosystem health and ensuring the normal growth of aquatic organisms. The wetted perimeter method is indeed very useful in the assessment of environmental flow due to consideration of stream forms and minimum flow for aquatic life habitat. In this study, a river with obvious seasonality and external water diversion was selected as the typical research object, taking Jingle, Lancun, Fenhe Reservoir and Yitang hydrological sections as control sections, we improved the existing wetted perimeter method in three aspects:(1) We improved the selection of hydrological data series. The selected hydrological data series should be of a certain length and can well reflect the hydrological changes of wet, normal and dry years. (2) Different from the traditional wetted perimeter method, which only gives one environmental flow value, the improved method calculates the environmental flow month by month. (3) The improved wetted perimeter method establishes the relationship between native fish survival and environmental flow. Results indicated that, the improved wetted perimeter took the survival of the main fishes into consideration, the ratio of the calculated results by the slope method to the multi year average flow was greater than 10%, which can ensure the fishes habitat not being destroyed, the results are more reasonable. Furthermore, the monthly environmental flow processes obtained was better than the annual unified environmental flow value determined by the

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existing method, and is consistent with the natural hydrological situation and water diversion situation of the river. This study shows that the improved wetted perimeter method is feasible for research of river environmental flow with strong seasonal and large variation of annual flow.

Keywords: Environmental flow；The improved wetted perimeter；Flow process；Seasonal rivers；Aquatic life habitat

1.INTRODUCTION

In recent years, the utilization of water resources greatly increased with the rapid development of the social economy (Wu et al. 2020; Pal and Singha 2022) and therefore resulted in a series of river ecological problems, such as the decrease of river runoff, destruction of vegetation near the river course, degeneration of river ecological structure and functioning, some rivers even dried up (Saha et al. 2022). All of these have led to a serious threat to river biodiversity and the development of cities around the river (Cheng and Li 2021), hence there is a general consensus among human beings about preserving the river ecological environment (Achieng et al. 2020; Almond et al. 2021; Ghorbani et al. 2021; Theodoropoulos et al. 2021), and environmental flow is of vital importance in river protection and is an important guarantee to ensure that the river ecological functions do not deteriorate (Forslund et al. 2009). With the background of more and more attention to river ecology, research on river environmental flow has become a hot topic at home and abroad (Abebe et al. 2020; Hairan et al. 2021; Hamidifar et al. 2022).

Research on environmental flow is divided into three stages: theoretical sprouting (1940s-1960s), popularization (1970s-1990s), and hydro-ecological research (after 2000 s) (Fu et al. 2021). At the theoretical sprouting stage, the river environmental flow was estimated mainly by practical experiences, and the systematic calculation method had not yet appeared (Dong et al. 2017). At the beginning of popularization stage, the minimum flow that rivers can maintain a healthy ecological function was mainly studied, and numerous calculation methods for environmental flow appeared (Stalnaker and Arnette 1976; Loar et al. 1986; Milhous et al. 1989; Gordon et al. 2004). However, subsequent researches showed that natural stream flow processes (such as flow, cycle, frequency and duration, as well as the variation process of flow and flood on the annual and interannual time scales) were the most important, rather than only reaching the minimum environmental flow (Poff et al. 1997; Richter and Richter 2000). As a result, the focus of the study transferred from the minimum flow to natural stream flow processes of the river. In the 21st century, the response relationship between hydrology and ecology has been emphasized, study of environmental flow needs not only the efforts of a single discipline but also the interdisciplinary research, including hydrology, biology, ecology, etc. (Poff and Zimmerman 2010; King and Brown 2010).

The calculation methods of environmental flow can be generally divided into 4 categories, including the hydrological method, hydraulic method, habitat method and comprehensive analysis method (Tharme 2003). The hydrological method usually uses long series (≥30 years) natural stream flow data, and takes the percentage of average annual natural flow as environmental flow. The hydraulic method mainly studies the relationship between hydraulic parameters, and takes the point of abrupt change of parameters as environmental flow. This method to some extent can compensate for the shortcomings of the hydrological method in considering topographic factors. Based on the hydraulic method, the habitat method needs hydraulic parameters and biological data to build species suitable habitat models, and environmental flow is determined by studying the hydraulic conditions of indicative species. The comprehensive analysis method takes the river ecosystem as a whole, and then analyzes the relationship between hydrological conditions and sediment transport, river bed shape, and river habitat, meanwhile, combining expert opinions to determine environmental flow under different scenarios.

In summary, the hydrological method is easy to collect data and is widely used, but it takes less account of the river topographic characteristics, which vary greatly in different rivers (Ramesh and Thampi 2023). The habitat method and comprehensive analysis method, which require a large amount of biological data, but also need to spend more time to process and analyze the data, are generally used to determine the environmental flow of small watersheds. Compared to the above three methods, the hydraulic method is easier to collect data and measured data from the hydrological station can be used directly, which to a certain extent can decrease the impact of human activities on stream flow, effectively. On the other hand, the hydraulic method mainly studies variations of hydraulic parameters, therefore, can consider the influence of river topography, adequately.

The wetted perimeter method is one of commonly used method of the hydraulic method (Sedighkia et al. 2017). By constructing the relationship between wetted perimeter and flow, the wetted perimeter method determines recommend environmental flow by the breakpoint on curve (Gao et al. 2022). Recently, research on the wetted method mainly included the following three aspects. On the other hand, it mainly focused on the curvature method and slope method calculation results selection. Gippel and Stewardson (1998) took the point with slope of 1 and the point with the maximum curvature on the relationship curve as the breakpoint, and calculated the environmental flow of two rivers in Australia. Men et al. (2012) thought that the point with a slope of 1 is not necessarily a real breakpoint point, so he selected the second highest slope as breakpoint to determine the environmental flow of South-to-North Water Diversion Project Phase I. Shang (2008) proposed a new breakpoint determination method, Ideal point methods, which considered the determination of environmental flow as a multi criteria decision-making problem containing two main contradictory objectives, and used different proportional coefficients to solve the wet perimeter and flow model. On the other hand, mainly focused on the curvature method and slope method calculation results selection. Liu (2006) used the slope method and the curvature method to determine the environmental flow of several rivers in the first phase of the West Line of the South-to-North Water Diversion Project. The results of the curvature method were mostly 10~30% of the annual average flow, and the slope method was 10~117%, so the curvature method was selected as the final result. Alireza Shokoohi's research on Safarood River showed that the curvature method is better than that of the slope method, because the result of curvature method was 62.5% of the annual average flow, while the slope method result was close to twice (Shokoohi and Hong 2011). However, Shang (2008) found that the curvature method result was less than 6% of the annual average flow, while the slope method and IPM1 was more than 21%, and finally recommended the slope method and IPM1 results for the ecological flow. Besides, some studies just took the wetted perimeter method as one of the methods to determine the environmental flow of rivers, and compared it with the results of hydrology method, etc., but without further study (Elhatip and Hinis 2015; Hao et al. 2016; Ye et al. 2013; Zhao et al. 2021; Berthot et al. 2021).

In general, compared with other methods, the hydraulic method is easier to collect data, can reduce the influence of human activities to a certain extent, and can fully consider the influence of river topography. So far, researches of the wetted perimeter method were mostly focused on the determination of breakpoint location and the selection of slope method and curvature method results (Ji and Jiang 2018). Whereas, there were different results due to different study rivers (some with the abundant flow and some with great variation throughout the year). More importantly, the results of the existing wetted perimeter method are mostly just one annual environmental flow value, which is reasonable for rivers with the abundant annual flow and little changes, but there may be some problems for rivers with strong seasonality and large variation of annual flow.

Therefore, this work aims at associating river wetted perimeter with the effectiveness of fish habitat, to improve the existing wetted perimeter method and examine the reasonableness of the improved method in analysis of environmental flow processes in rivers with strong seasonal and large annual flow variation.

2. MATERIALS AND METHODS

2.1 Study area

Fenhe River, which is the second-largest tributary of the Yellow River, was taken as a typical seasonal river for analysis. It is located in Shanxi province, northern China. Fenhe River basin belongs to the continental semi-arid monsoon climate, and covers 39721 km^2, with less precipitation, greater evaporation, more wind and sand. The topography is high in the north and low in the south. The local average annual temperature is 17.7~7℃. The annual precipitation is approximately 500 mm with a maximum of 700 mm and minimum of 300 mm, nearly 70% of the annual precipitation occurs from July to September.

In recent decades, water resources of Fenhe River have been highly utilized and the flow has decreased obviously. Therefore, water from Yellow River was supplied to Fenhe River in 2008 through the Wanjiazhai Yellow River Diversion Project. The water diversion time from October to July of next year.

Considering the existence of specific fish (Leuciscus waleckii) in upper reaches, the serious water shortages and ecological problems in middle reaches, four hydrological section (Jingle, Fenhe Reservoir, Lancun and Yitang), which are distributed on the upper and middle reaches of Fenhe River (Fig. 1), were selected to study the environmental flow, and basic information of four research hydrological sections is summarized in Table 1.

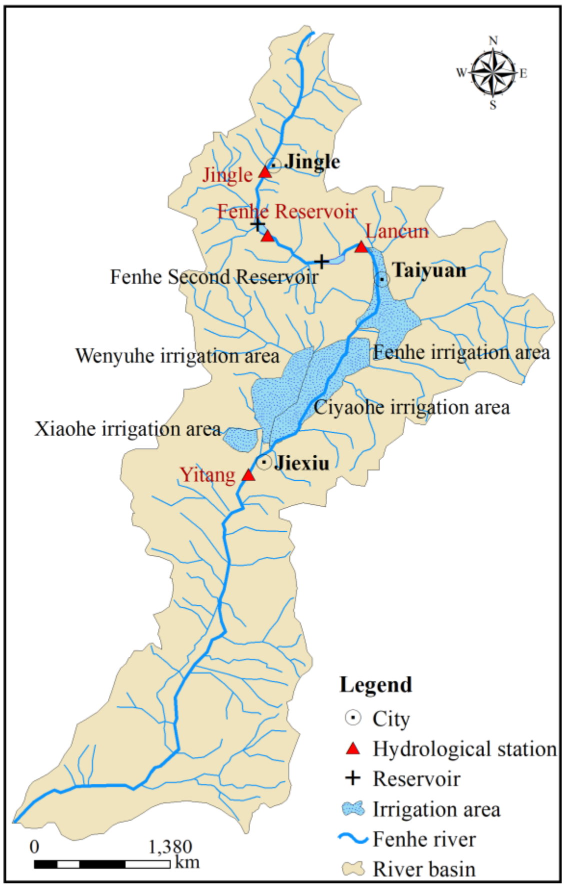


Figure 1 Study area

Table 1 Basic information of the research hydrological sections

Section Name	Section Location	Basic Situation
Jingle	E 111°55′ N 38°20′	The catchment area is 2796 km^2, the main river above the section is 83.9 km with an average gradient of 6.7 ‰.
Fenhe Reservoir	E 111°56′N 38°03′	The catchment area is 5268 km^2, the length of the main river above the section is 130.6 km, and the longitudinal slope of the main river is 4.58 ‰.
Lancun	E 112°26′ N 38°00′	The catchment area is 7705 km^2, the length of the main river above the section is 219.6 km, and the longitudinal slope of the main river is 3.35 ‰.
Yitang	E 111°50′ N 37°00′	The catchment area is 23945 km^2 and the river length is 262.7 km.

2.2 Data

The daily measured flow and water level data (2009-2018) and measured river cross-section shape data (river bed elevation, distance from initial point) in 2018 both came from four hydrological stations (Jingle, Fenhe Reservoir, Lancun, and Yitang), and the data series were basically complete. The basic information of hydrological station, basin water system map, water level and flow data all came from the General Station of Hydrological and Water Resources Survey in Shanxi Province. The figure of study area (Fig. 1) was obtained by ArcGIS based on basin water system map. Data related to fishes came from previous study findings (Shi et al. 2015; Jiang et al. 2019; Wang et al. 2020; Lyu et al. 2021).

Generally speaking, the data used to calculate environmental flow should be the natural flow. However, since the exploitation and utilization rate of water resources in the Fenhe River basin is as high as 80%, which is used for industrial, agricultural, living and ecological water, the natural flow of the river continues to decline in recent years, and the function of the river can no longer be maintained. Therefore, since 2003, water has been transferred from the Yellow River to replenish the Fenhe River. Certainly, the natural flow data provided by local Hydrology and Water Resources Survey Station was used to calculate the environmental flow of Fenhe River, the results were small and the values of most hydrology stations were less than 10% of the multi year average flow. Consequently, in order to solve the current practical problems of Fenhe River, this study finally adopts the measured flow to calculate the environmental flow, which is used to guide the river ecological restoration.

2.3 Methods

2.3.1 Basic theory of the wetted perimeter method

There is a close relationship between wetted perimeter and aquatic life habitat, so wetted perimeter has been used as an indicator of habitat quality (Bradford et al. 2014). Based on the relationship between changes in wetted perimeter and flow variability, the wetted perimeter method estimates environmental flow by the breakpoint of the curve.

Generally, the wetted perimeter is positively correlated with the river flow (Gholami et al. 2020). A breakpoint on the wetted perimeter-flow relation curve would be identified, and when the wetted perimeter reaches or exceeds this point, even a rapid increase of the river flow will only cause a small change of the wetted perimeter. However, the breakpoint is defined as a threshold to river habitat changes, below which the aquatic habitat conditions will rapidly decline (Prakasam et al. 2021).

Therefore, from the perspective of ensuring river ecosystem health, it is of great significance to maintain the flow corresponding to the breakpoint.

According to the research of Gippel and Stewardson (1998), the logarithmic function and power function can be used to fit the relationship of wetted perimeter and flow, which are defined in terms of Eq. (1):

$$q = \frac{Q}{Q_m} \qquad p = \frac{P}{P_m} \tag{1}$$

Where, q and p are relative environmental flow and relative wetted perimeter respectively (Q_m in this paper selects the maximum flow and P_m selects the maximum wetted perimeter). p and q are dimensionless in order to eliminate the influence of coordinate scale (Shang 2008). The relationship between *p* and *q* can be characterized in terms of Eq. (2) and (3):

$$p = a \ln q + 1 \quad (2),$$

$$p = q^d \quad (3),$$

Where, *a* and *d* are two parameters related to river section shape. The power function Eq. (3) can be used to represent triangular, U-shaped and parabolic sections, while the logarithmic function Eq. (2) can be used to represent rectangular and trapezoidal sections. For the actual river section, the power index *d* is generally less than 0.5.

This research used the maximum curvature (c) method and slope (s) method to estimate river environmental flow, *q*, which are distinguished as q_c and q_s, respectively. For the logarithmic function, q_c and q_s are calculated using Eq. (4) and (5), respectively, Yu et al. (2016).

$$q_s = a \quad (4),$$

$$q_c = a\sqrt{0.5} \quad (5).$$

For the power function, they are calculated using Eq. (6) and (7).

$$q_s = \left(\frac{1}{d}\right)^{\frac{1}{d-1}} \quad (6),$$

$$q_c = \left(\frac{d-2}{d^2(2d-1)}\right)^{\frac{1}{2(d-1)}} \quad (7),$$

At last, the actual environmental flow worked out using the two methods are:

$$Q_s = q_s \times Q_m \quad (8),$$

$$Q_c = q_c \times Q_m \quad (9),$$

Where, Q_m, the maximum flow is determined using the fitting curve, m^3/s.

2.3.2 The improvement of wetted perimeter method

To improve the estimation of the environmental flow for seasonal rivers, this research proposes a revision for the wetted perimeter method based on the following concepts:

Firstly, for rivers that are seasonal and have water diversion input, the relationship between flow and wetted perimeter is to be characterized on the recorded measurement data in the time up to 10 years. With the data in ten years, we can : ① refer to the 7Q10 method and the driest monthly average flow in the past 10 years method, two classic approaches in hydrological research. ② reflect as far as possible the changes of wet, normal and dry hydrological situations. For example, at Jingle Station, the record in the time from 1997 to 2016 (excluding the water diverted from the Yellow River) shows that 2013 was a wet year, 2014 was a normal year, and 2015 was a dry year. Fig. 2 gives out the hydrological situation percentages in the 20 years period, which is calculated based on anomaly percentage method (Sun et al. 2008).

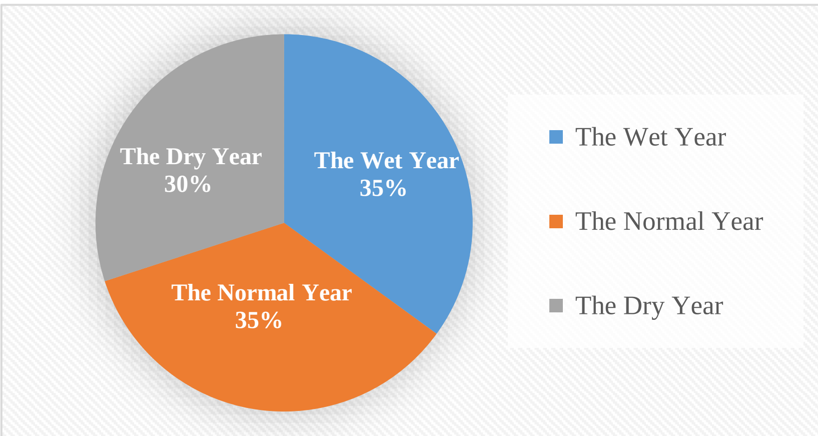


Figure 2 Results of hydrological year Division during 1997-2016

③ take account of the adaptability of aquatic organisms to the river environment and population restoration. For example, it generally takes 3-4 years and 4-5 years for Leuciscus waleckii and Four carps of Cyprinidae, respectively, to become sexually mature (Shi et al. 2015; Jiang et al. 2019). Within 10 years these species can reproduce 2-3 offspring generations. If the population can maintain stability within 10 years, it can adapt to the existing river environment.

Secondly, the annual environmental flow is analyzed by monthly calculation. For seasonal rivers, there are great differences between the discharge in the flood season and non-flood season. For example, at the Yitang hydrologic section, the average flow during flood season (June-September) is 33.625 m^3/s, whereas the flow during non-flood season (October-May of the next year) is 16.305 $m^{3/}s$, only half of that in floor season. Therefore, to estimate the annual environmental flow with monthly data is necessary for seasonal rivers to improve the perimeter method. The Tennant method (Tennant 1976), which uses the percentage of the monthly average flow, is adopted to calculate the current month's environmental flow.

Thirdly, this research also takes river functions and aquatic lives composition into consideration. So far, the wetted perimeter method has paid less attention to influence of aquatic life species. The main fish species in Fenhe River is Cyprinidae, which dominates in the upstream. Particularly, there is a unique fish species, Leuciscus waleckii, which lives above the Fenhe Reservoir Station. Its spawning period is between March and April (Shi et al. 2015) and growing period is May to October. In addition, there are blue carp, grass carp, silver carp and Bighead carp, primarily below the Fenhe Reservoir Station. Their spawning periods are between May and June (Jiang et al. 2019) and growing period is July to October. The details of fish species' hydraulic characteristics are shown in Table 2 (Wang et al. 2020; Lyu et al. 2021).

Because the growing period of fishes is basically located in the flood season of Fenhe River, it can basically meet the flow and nutrient needs for the normal growth of fishes. Therefore, in this study, we compared the flow for fishes spawning with the calculated environmental flow, and take their intersection to obtain the environmental flow that can simultaneously meet the needs of river ecological functions and fish survival and spawning.

Table 2 Hydraulic properties of fish

	Leuciscus waleckii (fry)	Leuciscus waleckii (parent fish)	Four carps of Cyprinidae
	Jingle Section		
Water depth(m)	0.2~1.5	0.5~1.25	0.4~2
Velocity(m/s)	0~0.15	0.1~0.7	0.2~1.2
Flow(m^3/s)	0~12.33	0.94~42.84	0.85~162.73
	Fenhe Reservoir Section		
Water depth(m)	0.2~1.5	0.5~1.25	0.4~2
Velocity(m/s)	0~0.15	0.1~0.7	0.2~1.2
Flow(m^3/s)	0~4.41	0.76~15.79	1.16~49.89
	Lancun Section		
Water depth(m)			0.4~0.28
Velocity(m/s)			0.2~1.2
Flow(m^3/s)			1.19~148.66
	Yitang Section		
Water depth(m)			0.40~2.00
Velocity(m/s)			0.2~1.2
Flow(m^3/s)			0.46~45.42

Notes: Leuciscus waleckii is mainly distributed near the upper reaches of the Fenhe River, so its hydraulic characteristics are only considered in Jingle and Fenhe Reservoir Section, and the hydraulic characteristics of the four carps of Cyprinidae are mainly considered in other sections.

3.Results and Discussion

3.1 Comparation of slope method and curvature method

According to the monitoring section images in 2018 (Fig. 3) and average water level from 2009 to 2018 of Jingle, Fenhe Reservoir, Lancun and Yitang hydrological sections, the monitoring cross-section shapes of Jingle, Fenhe Reservoir and Yitang are approximately regarded as triangular, and Lancun section is approximately trapezoidal. Ji et al. (2006)

suggested that the relationship between wetted perimeter and flow can be expressed by functions, and the functional form is related to cross section shape. That is, the triangular, U-shaped and parabolic cross section channels can be better fitted by the power function, and the logarithmic function is applicable to rectangular and trapezoidal cross section channels.

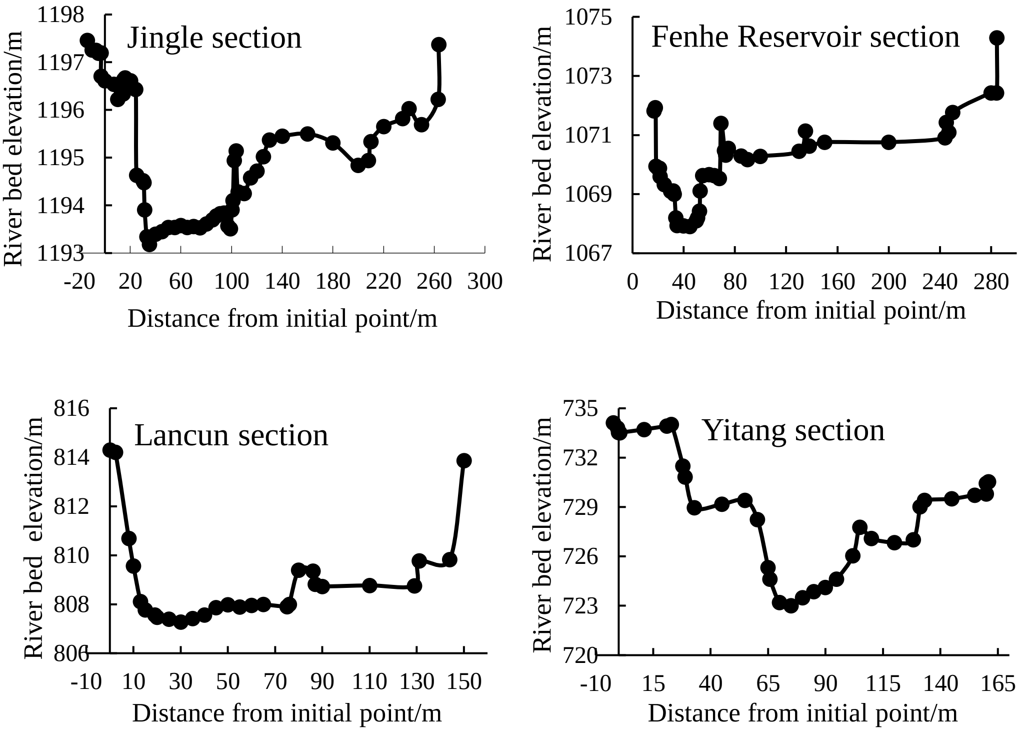
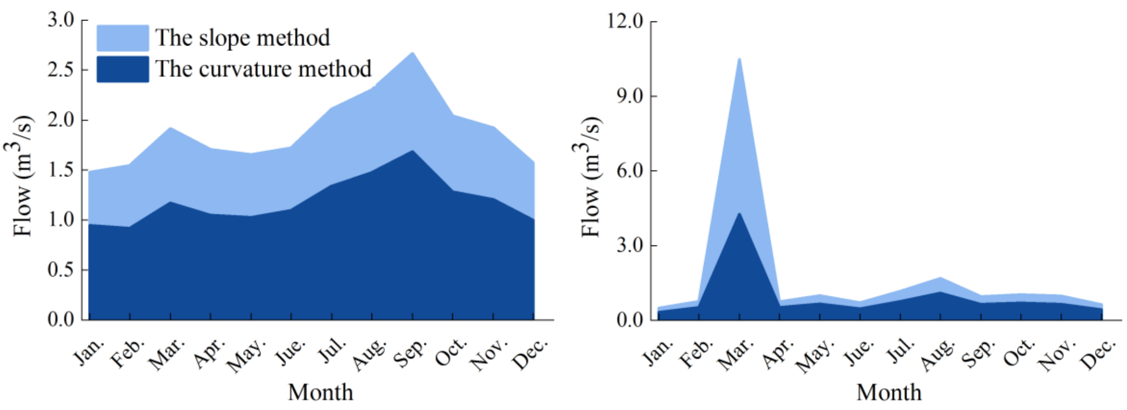


Figure 3 Cross-Sections of four sections

In this study, the relationship between wetted perimeter and flow month by month was built based on measured hydrological data from 2009 to 2018 (Fig. 4). Results showed that relationships in Jingle, Fenhe Reservoir and Yitang hydrological sections can be expressed using the power function, and Lancun section using the logarithmic function, with correlation coefficients R^2>0.90, indicating that there is a close relationship between wetted perimeter and flow of the four study hydrological sections, and the improved method is suitable for this type of river. Furtherly, according to the improved method mentioned above, monthly environmental flow determined by the slope method (*Qs*) and curvature method (Qc) of four hydrological sections were obtained, respectively, and meanwhile calculated the ratios of Qs and Qc to multi year average flow (Qav) (2009~2018) (shown in Fig. 5 and Fig. 6).

Results indicated that the values of Qs at four hydrological sections were higher than that of Qc (Fig. 4), which was consistent with previous researches (Liu et al. 2006; Shokoohi and Hong 2011). Qs and Qc are the point with slope of 1 and the point with maximum curvature on the relative wetted perimeter-flow relation curve, respectively. Generally, the former is greater than the later. In addition, the values of Qs/Qav at four hydrological sections were 12-22%, 5-32%, 15-53% and 14-30%, respectively, and those of Qc/Qav were 7-14%, 4-19%, 11-37% and 9-18% (Fig. 5). According to Tennant (1976), 10% of the average annual flow is the minimum value to maintain a healthy habitat, and there are 14 values calculated by the curvature method were less than 10%, whereas only 2 values by the slope method. Considering the protection of river channel structure function and aquatic habitat, this study suggested that the environmental flow determined by the slope method is better than that of the curvature method.



Jingle Section (a) Fenhe Reservior Station (b)

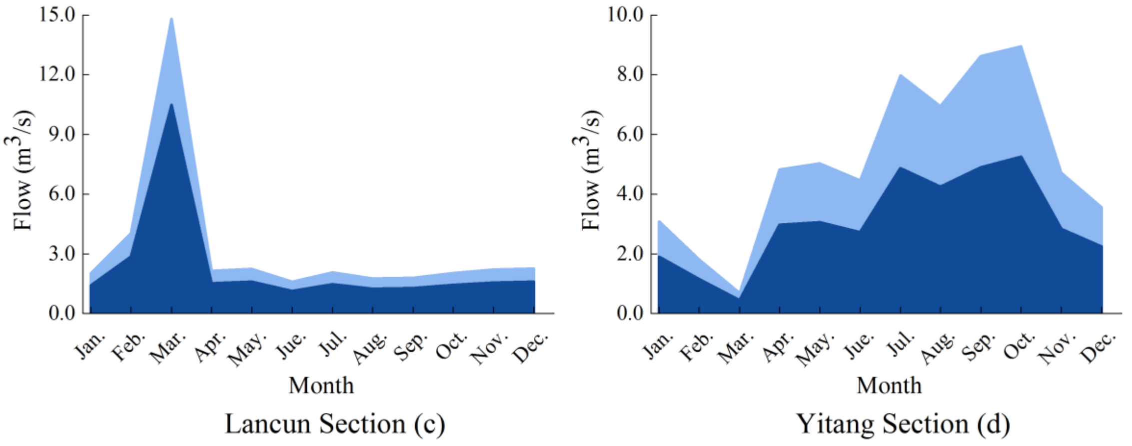


Figure 4 Environmental flow results determined by the slope method and curvature method

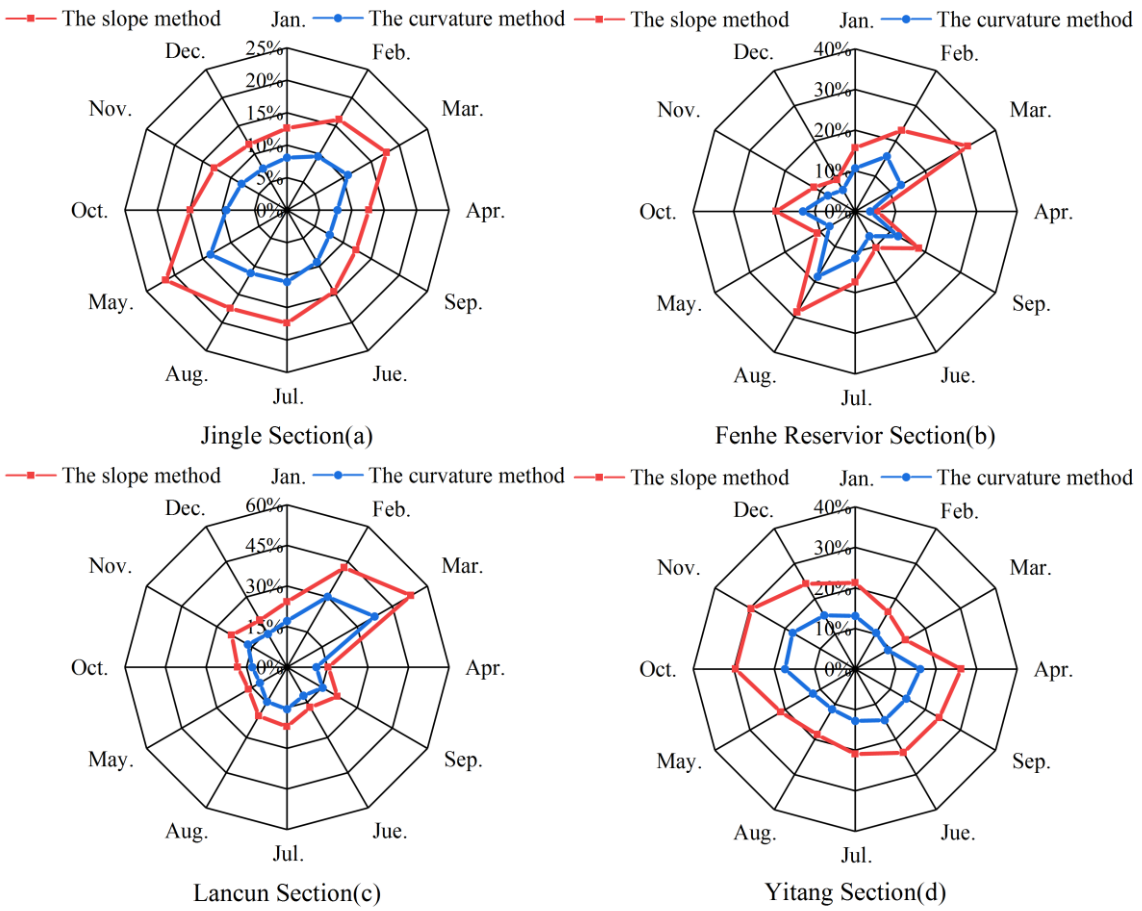


Figure 6 The ratio of the environmental flow and multi year average flow

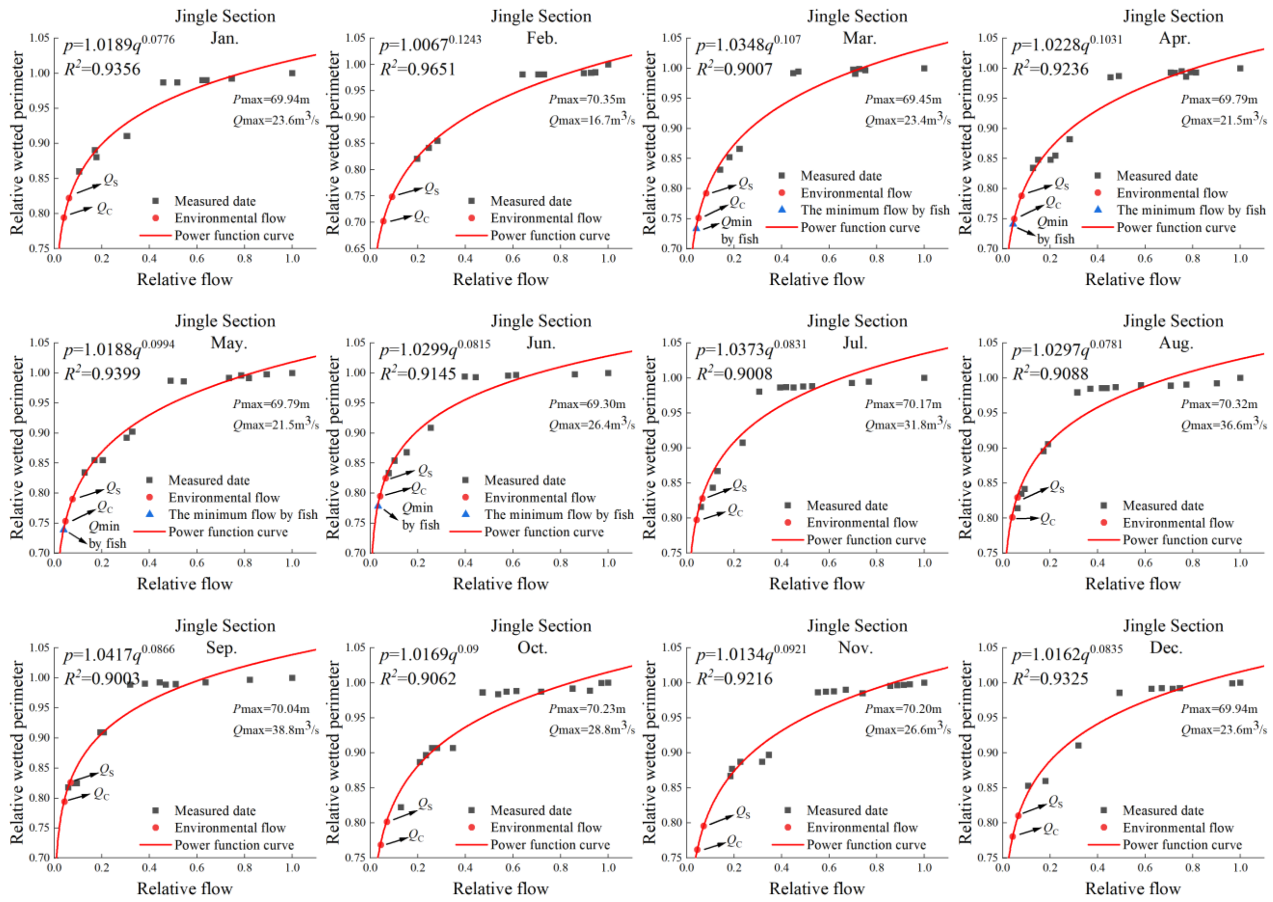
3.2 Environmental flow determination considering aquatic organisms

Combining the hydraulic properties of fish (Table 2), we analyzed the environmental flows *(Qs*) at four study hydrological sections estimated by the slope method, as shown in Fig. 4, except for Fenhe Reservoir, environmental flows at Jingle, Lancun and Yitang sections were all meet fish habitat availability.

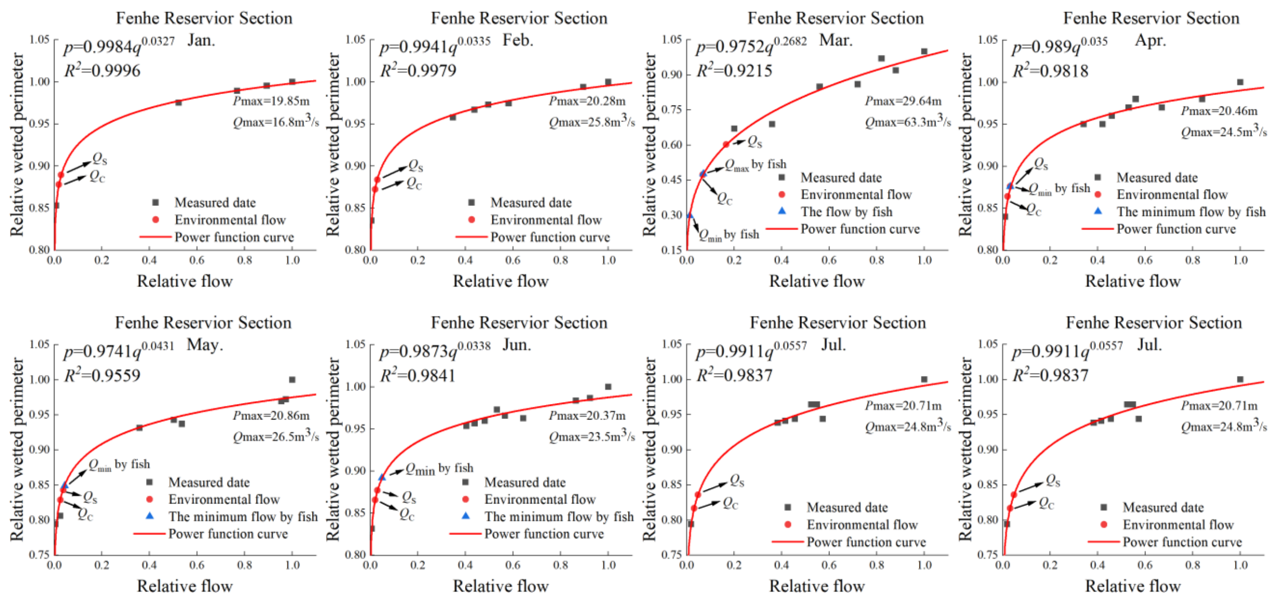
At the hydrological section of Fenhe Reservoir, on one hand, the environmental flow in March was so great that it exceeded the flow demand during spawning period of Leuciscus waleckii. Consequently, the results need to be modified, and the revised environmental flow was determined to be 4.41 m^3/s in March. There were mainly two reasons, firstly, according to Ngor et al. (2018), fishes need certain impulse flow stimulation during spawning. Thus, choosing the upper limit of spawning flow can ensure the flow in March is higher than that in February (0.77 m^3/s) and April (0.88 m^3/s), so as to constitute a complete flow fluctuation process, which ensures the impulse flow requirement of Leuciscus waleckii. Secondly, environmental flow of 4.41 m^3/s accounts for 14% (>10%) of the multi year average flow, which can ensure fishes habitat availability. On the other hand, the environmental flow in May and June were lower than the spawning flow of the four carps of Cyprinidae, so the revised value was determined to be 1.16 m^3/s. The main reason was that the May and June were not only the spawning period of the four carps of Cyprinidae, but also the growing period of the juvenile fish of Leuciscus waleckii, too high flow would have a negative effect on juvenile fish growth (such as foraging). The high flow was not conducive to the growth of the juvenile fish. At the same time, environmental flow of 1.16 m^3/s accounts for 21% and 17% of the muti-year average flow in May and June, respectively, which can completely ensure that fish habitat is not destroyed.

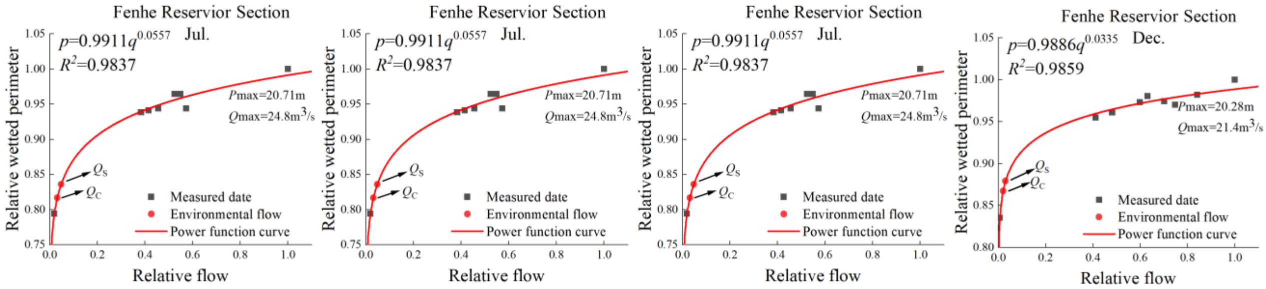
To sum up, by combining the slope method with the hydraulic properties of fish, we suggested the environmental flow (*Qe*) determined by the improved wetted perimeter method on the Fenhe River. In this study, based on the improvement of the existing wetted perimeter method and the flow required by the spawning period of native fishes, the environmental flow（Qe）with both hydraulic and biological significance was finally obtained.

According to Fig. 7, we can see that each hydrological section has environmental flow value month by month. This will certainly help the authorities better allocate water resources. In addition, the obtained environmental flow is critical to the reproduction and growth of native fishes. However, although the improvement of the wetted perimeter method has achieved a certain effectivity, there are still some shortcomings in this study. First of all, it is difficult to distinguish the influence of transferring water from Yellow River and reservoir operation. Secondly, the study of fishes in this paper is relatively simple, only involving the most important growth stage of spawning period, and there is no further research on the whole growth stage of fishes.

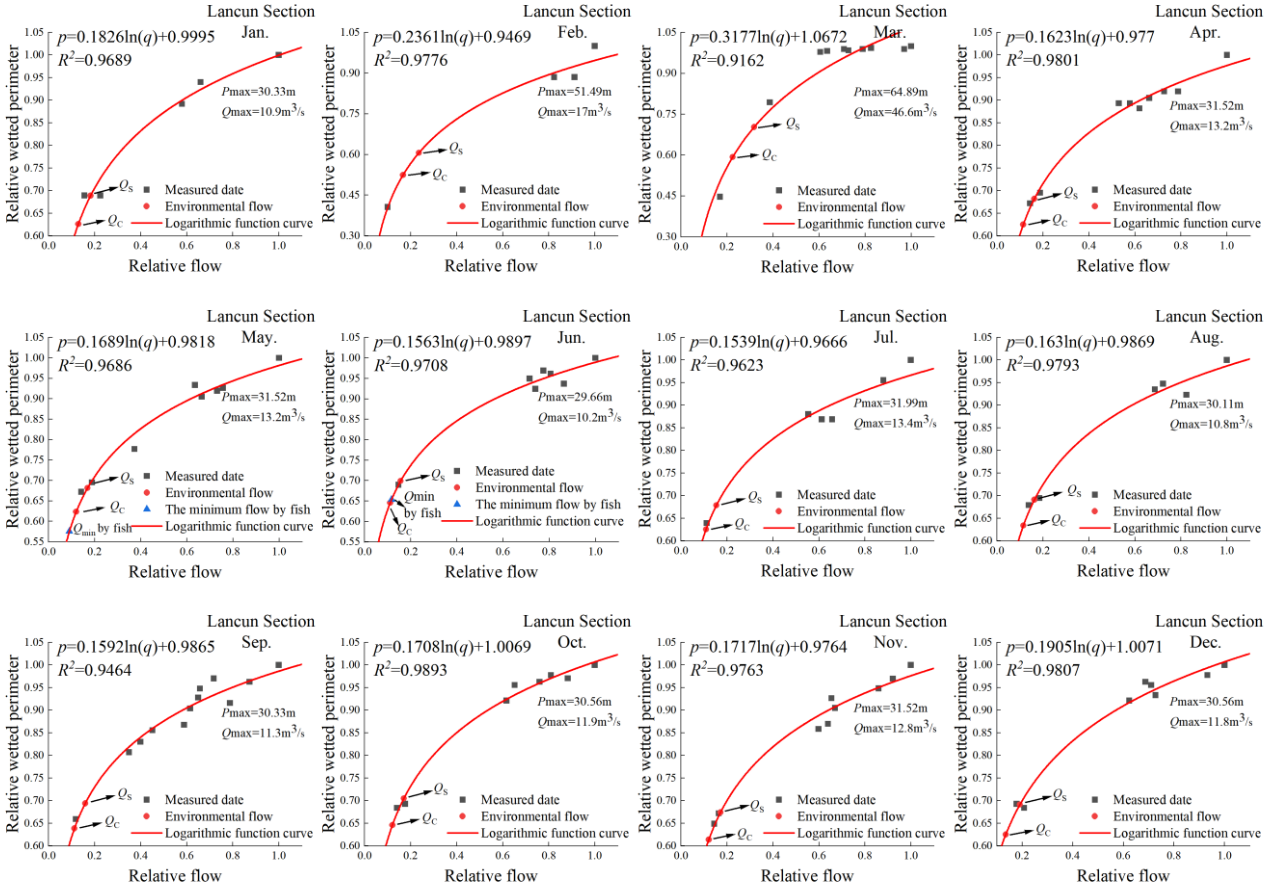


Jingle Section(a)

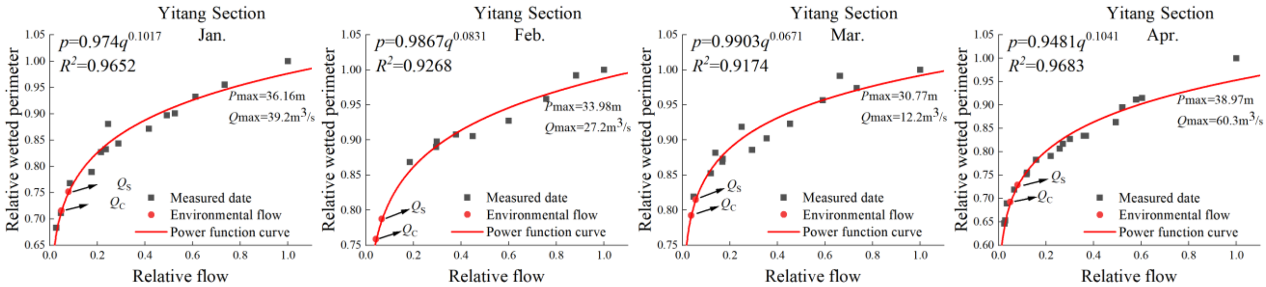


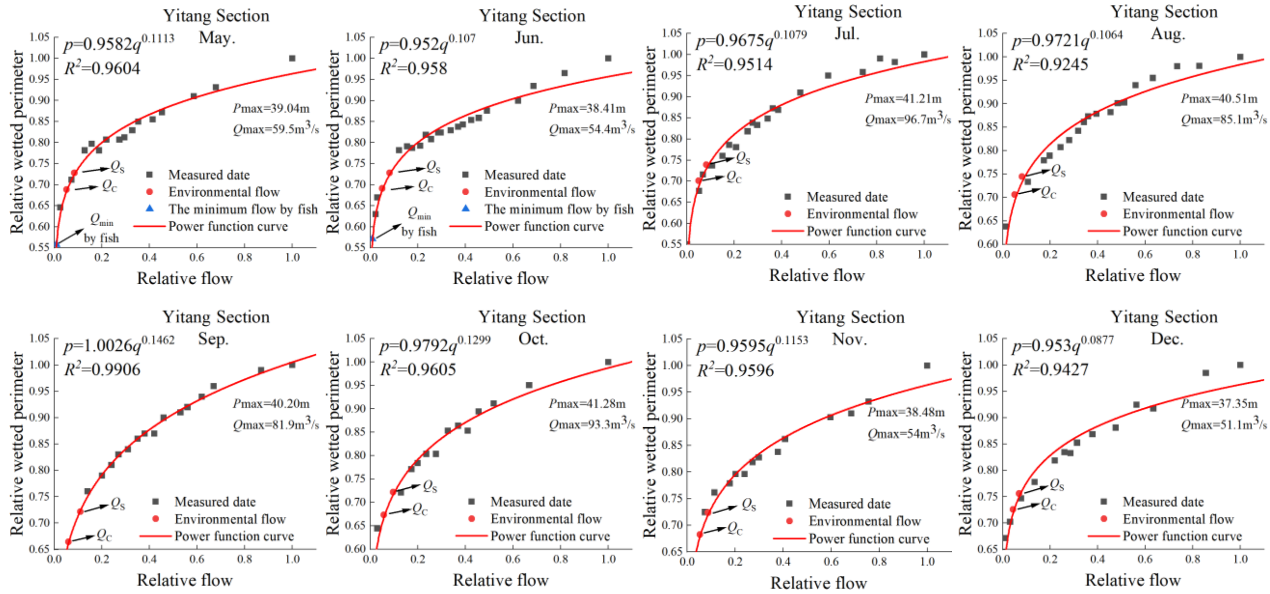


Fenhe Reservoir Section(b)



Lancun Section(c)





Yitang Section(d)

Figure 4 Environment flow at study hydrological sections

3.3 Rationality analysis of environmental flow results

In order to furtherly analyze the rationality of the determined environmental flow, the comparisons of environmental flow and multi year average flow were plotted in Fig. 7.

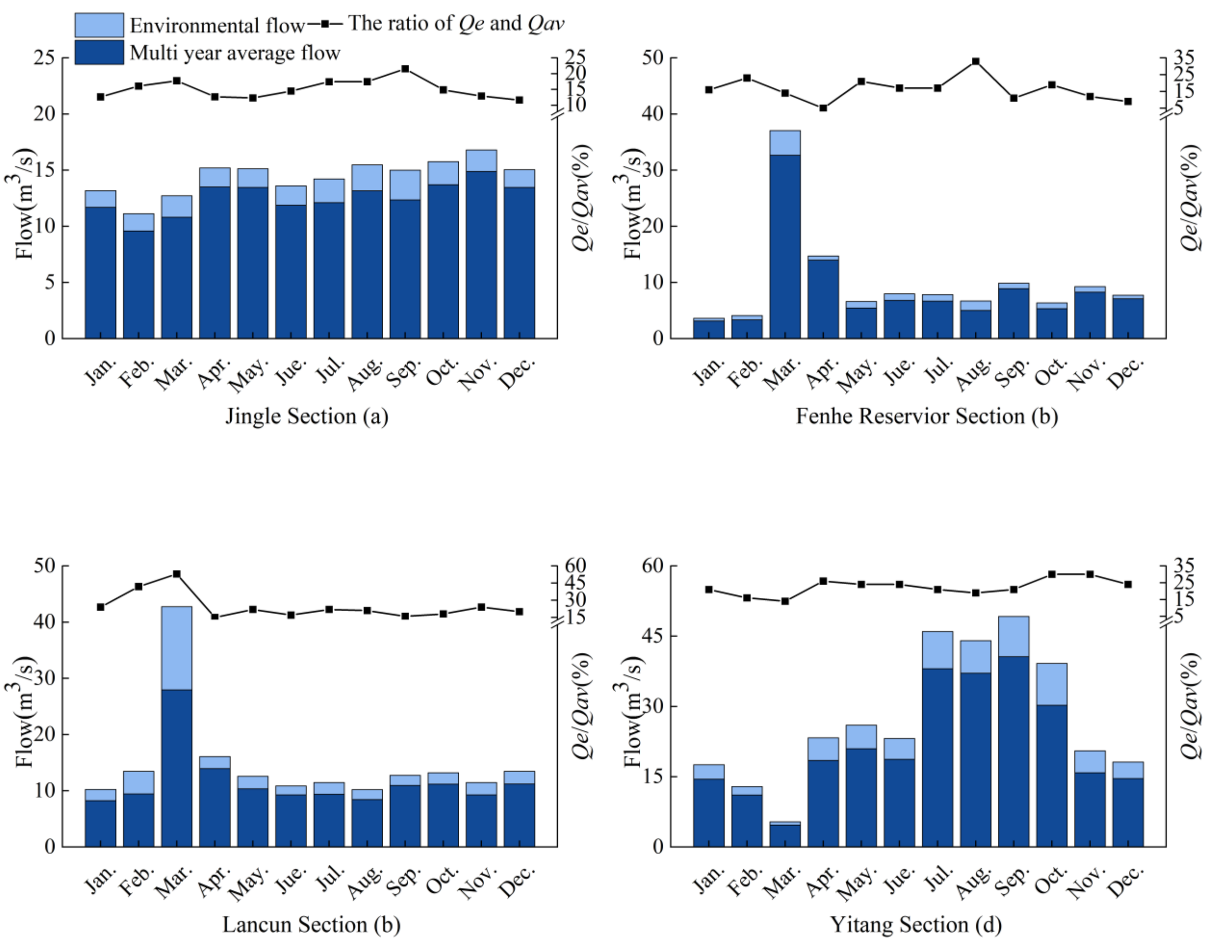


Figure 7 Comparison of environmental flow and multi year average flow

First of all, the environmental flow of four study hydrological sections presented 12-22%, 6-33%, 15-53%, and 14-30% of the multi year average flow, respectively. Except for Fenhe Reservoir section in April (5%) and December (9%), the environmental flows of other hydrological sections were all greater than 10%, which can meet the demands of fish growth and ensure that habitat does not deteriorate. From the point of protecting river ecosystem, the environmental flow determined in this study is reasonable.

Secondly, there was a sharp increase of measured flow and environment flow in March at both Fenhe Reservoir and Lancun hydrological sections, the reason is that they are exit sections of Fenhe Reservoir and Second Fenhe Reservoir of water conservancy project, respectively. And from the late February to the mid-April, the three large irrigation areas downstream (Fenhe Irrigation area, Wenyuhe Irrigation area, and Xiaohe irrigation area), many small and medium-sized irrigation areas (Shown in Fig. 1) need to be irrigated by concentrated discharge with large flow in early spring. However, the Yitang section is located in the lower reaches of the irrigated area, the measured and environmental flow decreases abruptly from late February to mid-April due to the early spring irrigation. From the actual situation of Fenhe River, the environmental flow determined in this study is reasonable.

Thirdly, the annual flow process is closely related to river ecological health and the growth of fishes. An increase process of flow from February to April at Jingle hydrological section will supply, an impulse flow, which is benefit for the successful spawning of Leuciscus waleckii. Another flow increase will also occur from May to July, which is conducive to the spawning of the four carps of Cyprinidae. Generally, the maximum environment flow occurs from June to October, a continuous medium-high flow and a certain level of the floodplain can ensure the exchange of nutrients between rivers and banks, which will bring abundant nutrients for the young fish to survive the growing period. Whereas, continuous low environmental flow occurs from November to February in next year, which can maintain the migration channel for fishes and help them overwinter. From the perspective of needed flow for native fish growth stage, the environmental flow determined in this study is reasonable.

Finally, referring to the research results of "Fenhe River Basin Ecological Landscape Planning (2020-2035)" in Shanxi province, the environmental flow of Jingle section is 1.97m^3/s in flood season and 0.40m^3/s in non-flood season by Tennant method. In this study, the values of Jingle section are 2.20m^3/s in flood season and 1.73 m^3/s in non-flood season, mainly considering the fishes spawning period in non-flood season. From the comparison of this study with the existing research results, the environmental flow determined in this study is reasonable.

In conclusion, the environmental flow determined using improved wetted perimeter method is consistent with river actual hydrology and water diversion, and simultaneously meets habitat requirements for main river fishes. Therefore, the results in this study are basically reasonable and the improved perimeter method can be used in seasonal rivers.

4. Conclusions

In this study, we mainly improved the wetted perimeter method from three aspects, on one hand, by establishing the relationship between multi year average flow and wetted perimeter to calculate monthly environmental flow, the environmental flow process (rather than a single value) within the year can be more consistent with the actual hydrological situation of seasonal rivers. On the other hand, the selection of data series can well reflect the hydrological changes of wet, normal, and dry years, so as to ensure the rationality of the calculation results. Moreover, taking into account the growth and development process of the most representative fishes, which can ensure the calculated results meet fish habitat demands and the basic structure and function of the river without degradation.

A river with obvious seasonality and external water diversion was selected as the typical research object, and the improved wetted perimeter method was used to calculate the annual environmental flow process. Results indicated that the environmental flow calculated by the slope method is greater than that by the curvature method. If the survival of main fishes is taken into consideration, the ratio of the calculated results by the slope method to the multi year average flow was all greater than 10% except for the section of Fenhe Reservoir in April and December, which can ensure the fishes habitat not being destroyed. In addition, the calculated results are consistent with the natural hydrological situation and water diversion situation of the river. Therefore, the improved wetted perimeter method has certain applicability for this type of river, and the research results can provide a scientific basis for river ecological restoration.

In this study, we used the "wetted perimeter" as medium to establish the connection of native fishes with environmental flow, which makes the environmental flow no longer is a simple concept of hydrology and hydraulics, but also has the connotation of native biological attributes. In next step, we should strengthen the study of the response relationship between natural hydrological regime, fishes and environmental flow, so as to provide scientific basis for accurate estimation of environmental flow.

Statements & Declarations

Ethics approval

Not applicable

Consent to participate

Not applicable

Consent for publication

All authors reviewed and approved the manuscript for publication.

Availability of data and materials

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Chen Tian, Xingtao Fu and Yu Wang. The first draft of the manuscript was written by Chen Tian. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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