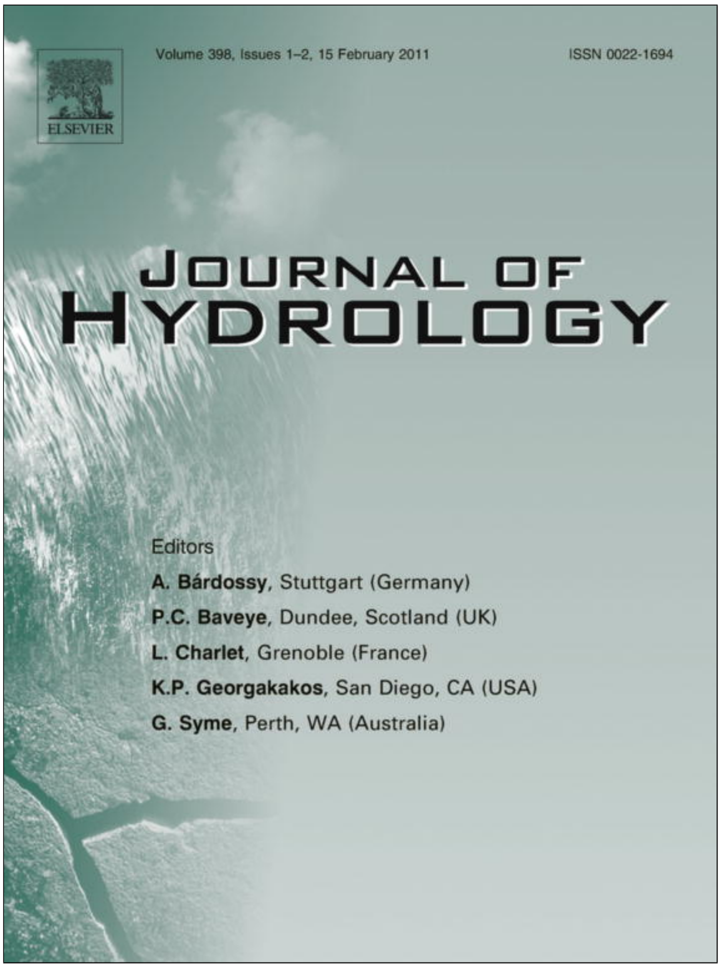
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An instream ecological flow method for data-scarce regulated rivers

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SUMMARY

Reliability of traditional methodologies is often challenged in determination of instream ecological flow (IEF) for a regulated river due to its non-natural condition. This paper deals with an IEF determination method for regulated rivers called the Adapted Ecological Hydraulic Radius Approach (AEHRA). It considers information of both instream ecosystem and river course, while it does not require any flow regime. Beside monthly IEF, it outputs monthly Instream Ecological Water-level (IEW) as well. The latter can greatly facilitate dam operation. Application of this method to the Huai River which is completely regulated by dams suggest: (1) AEHRA is especially predictive for rivers with limited ecological and hydrological data; (2) it can reflect the seasonal variation of IEF and IEW; (3) errors of AEHRA introduced by using a geometric shape generalized cross-section in an un-gauged site are generally acceptable; (4) comparison of the IEF values estimated by AEHRA with those by Tennant approach, Wetted Perimeter method and R2CROSS method showed fairly good agreement in terms of practical capability of the AEHRA. This method will be of great help for regionally sustainable water management in data-scarce regulated rivers

1. Introduction

To efficiently utilize limited water resources in China, 22,000 dams were built during the twentieth century, accounting for 46% of those worldwide (Tharme, 2003). More than half of them were built on the Huai River. Existence of the dams brought about a significant impact on the river ecology, and today deterioration in instream ecosystem of many river-sections is unprecedented. As such, the development of protocols to restore the instream ecosystem is of great significance. To achieve that, it is urgently necessary to operate these dams reasonably. However, reasonable dam operation must be based on the proper assessment of essential IEF and IEW of every river-section. Therefore, selection or establishment of a qualified ecological method is necessary.

Globally, there are over 200 ecological flow methods, which can be classified into hydrological, hydraulic rating, habitat simulation, and holistic methods, as well as combinatorial and other approaches (Tharme, 2003; Zhao, 2008).

In the Huai River, there is a dearth of riverine ecological data and it is impossible to collect hydrological data in every river-section. The scarceness of riverine ecological data makes it impossible to use such methods as habitat simulation methods (Milhous et al., 1989; Reiser et al., 1989), holistic methods (Arthington et al., 1992; King et al., 2000) and combined methods (Duel et al., 1996; Acreman et al., 2000). Hydrological methods, such as the Tennant method (Tennant, 1976), 7Q10 method (Boner and Furland, 1982; Caissie et al., 1998) and Texas method (Mathews and Bao, 1991) have the advantages of simple computation and easy handling. However, they not only often oversimplify the actual situation of a river, but fail to consider biological parameters and their interactions (Karim et al., 1995). In practice, they are more appropriate for natural rivers and are generally used as a rough verification of other approaches (Liu and Men, 2007). Traditional hydraulic rating methods, such as Wetted Perimeter method (Nelson, 1984; Leathe and Nelson, 1986; Ubertini et al., 1996; Christopher and Michael, 1998) and R2CROSS method (Kushner, 2008; Parker et al., 2004; Espegren, 1996, 1998; Mosely, 1982; Nehring, 1979) are readily applied due to a small data requirement, but they are unable to estimate the seasonal variations of ecological flows (Liu and Men, 2007). What should be noted is that all of these methodologies were developed according to characteristics of natural rivers, and they might fail to assess IEF of a non-natural/regulated river.

The objective of this research is to develop an instream ecological flow method that can be applied to regulated rivers like the Huai River. This method should adequately consider demand of instream ecosystem on flow velocity and water depth in different seasons and different river-sections, despite poor data availability.

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2. Methodology

Acquirement of detailed data on hydrology and water ecology is almost impossible on regulated rivers while their water ecological quality usually need improvement. Aimed to these characteristics, we developed a practical method – Adapted Ecological Hydraulic Radius Approach (AEHRA) to effectively assess instream ecological flows of such rivers.

2.1. Assumptions

AEHRA is based on hydraulic theories and therefore has two assumptions: (1) the fluid state of the study river-section is a uniform open channel flow; (2) velocity mentioned in AEHRA refers to the average velocity of a watercourse used to eliminate the impact of different velocity distributions on the watercourse wetted perimeter (Chow, 1959; Xue, 1995).

2.2. Input and output variables of AEHRA

AEHRA has five input variables (n, J, V_E, surveyed river cross-section, Z_{E2}) and three output variables (R_E, Q_E, Z_E). If the surveyed river cross-sectional data are absent or difficult to obtain, one can generalize the cross-section as a regular shape. For example, a cross-section similar to a natural shape can be generalized as a parabolic shape with Eqs. (6), (7) plus (2), as described by Liu and Men (2007).

2.3. Method

Fig. 1 demonstrates the full procedure of this method. It is worth noting that:

(1) Instream ecological velocity (V_E) is determined according to the actual situation of a river-section.

V_E is an integrated index accounting for velocity requirement of both river course and instream ecosystem. In detail, it refers to the minimum velocity to maintain river course and instream ecosystem components to keep their elementary functions, for example, velocity required by aquatic biota to live freely in their habitat and to incubate successively during their spawning season, that to keep a balance between watercourse erosion and sedimentation during sediment transportation, and that to prevent sea water from flowing back into river, and so on.

There may exist many V_E components in a river-section. We coupled them into one with the following equation:

$$V_E = \max(V_{E1}, V_{E2}, V_{E3}, \ldots, V_{Ek}) \quad (1)$$

where V_E is the integrated, month-averaged instream ecological velocity, in (m s^{-1}); V_{Ei} ($i = 1, \ldots, k$) are the month-averaged instream velocities required by the ith river course or ecosystem component, in (m s^{-1}); k is the number of components in a river-section.

(2) The minimum instream ecological hydraulic radius R_E is calculated using Eq. (2) based on V_E.

$$R_E = n^{\frac{3}{2}} V_E^{\frac{3}{2}} J^{-\frac{3}{4}} \quad \text{(Liu and Men, 2007)} \quad (2)$$

where R_E refers to the watercourse hydraulic radius (ratio between cross-sectional flow area and its wetted perimeter) corresponding to V_E (Liu and Men, 2007), in (m); n: roughness, dimensionless; J: hydraulic slope, in (%).

(3) AEHRA fits R–A and R–Z curves using the Least Square Method and traces all breakpoints in a river-section.

In a regulated river like the Huai River, most cross-sections do not have regular shape as a result of great impact by dams. To assess IEF more precisely in a river-section with a compound cross-section like Fig. 2, flow area (A), wetted perimeter (P) are firstly derived from easily surveyed cross-sectional data, under various presumed water level (Z with 0.1-m interval); hydraulic radius (R) is secondly calculated by Eq. (3); and finally, R–A and R–Z curves are fitted using the Least Square Method. Statistical F-test and T-test are conducted to ensure their robustness.

$$R = \frac{A}{P} \quad (3)$$

During computation of A and P, with a smaller Z-interval, all breakpoints in the cross-section are traced automatically to assure results are indicative of the actual situation.

What is worth noting is that, existence of three problems potentially affects the precision of regression model. Many methods were put forward during the last 50 years to test the presence of them, which were usually known as multicollinearity (Lin, 2008; Lazaridis, 2007; Wheeler and Tiefelsdorf, 2005; Marquardt, 1980), serial

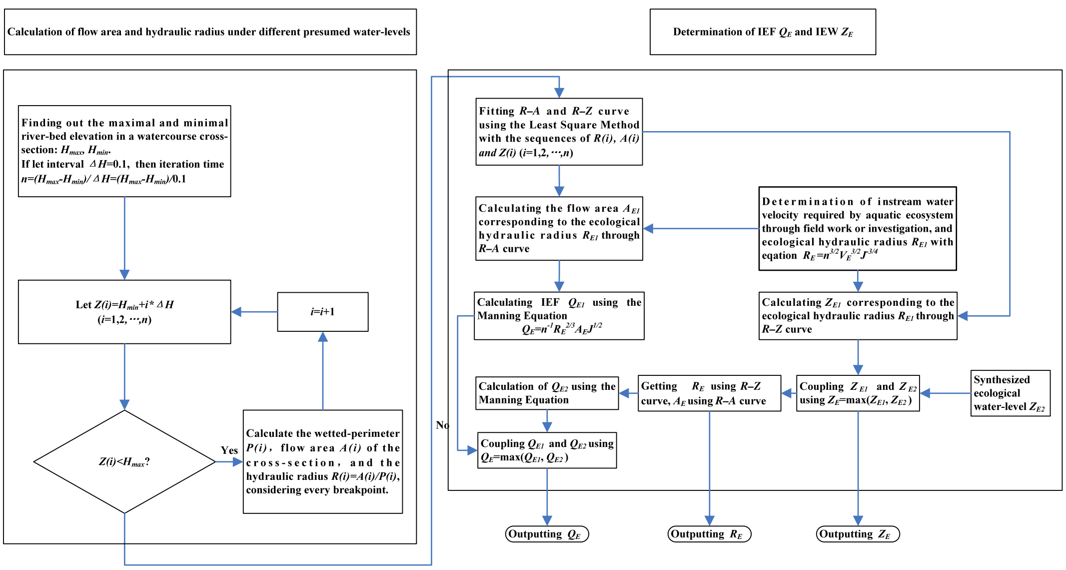


Fig. 1. AEHRA procedure.

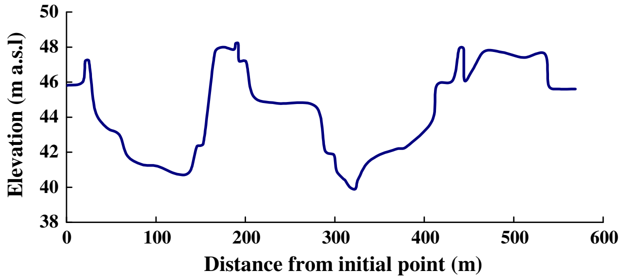


Fig. 2. Surveyed compound watercourse cross-section in the lower reach of the Xuanwu Sluice on the Huai River.

correlation (Wu and Liu, 2006; Liu et al., 2006; Li and Thanasis, 2003; Li and Hsiao, 1998; Reinsel, 1991; Chi and Reinsel, 1989; Box and Pierce, 1970), and heteroscedasticity (Liu, 2006; Zhu et al., 2001; You and Chen, 2005; Dette, 2002; Eubank and Thoms, 1993; Simonoff and Tsai, 1994; Cook and Weisberg, 1983; Bickel, 1978). In this paper, we employee the Variance Inflation Factors (VIF) to examine the presence of multicollinearity (Marquardt, 1980; Lin, 2008), use the empirical likelihood ratio (Wu and Liu, 2006) to test the magnitude of serial correlation and refer to the research of Liu (2006) to test the heteroscedasticity in our regression model. If test results show that a regression model is not robust, then attention should be paid to enlarge the size of dataset or re-construct the model.

(4) It computes IEW (Z_E) on the basis of R–Z curve.

Z_E refers to the instream water-level corresponding to IEF, usually is used to guide operation of a dam. In this case, it is even more significant than IEF (Q_E).

At the beginning, Z_{E1}, an initial value of IEW, is computed using the R–Z curve and R_E.

Then, Z_{E2}, a comprehensive water level required by the aquatic ecosystem, is determined by investigation for water-level requirement of ecosystem components, such as aquatic plants, fish, phytoplankton, zooplankton, and zoobenthos. Different biota has different requirement for water level. Taking fish as an example, the viscid egg of fish, which usually stick to pebbles or aquatic plants, generally perish after being out of water for a period of time. When determining Z_{E2} in practice, typical biological species, as many as one can get, should be taken into account.

Finally, Z_{E1} and Z_{E2} are coupled to Z_E with Eq. (4).

$$Z_E = \max(Z_{E1}, Z_{E2}) \quad (4)$$

where Z_E, Z_{E1} and Z_{E2} are all in (m).

(5) IEF (Q_E) is derived with the Manning Equation, R–A curve, R–Z curve and Z_E.

Firstly, AEHRA interpolates instream ecological cross-sectional area (A_E) from the R–A curve with R_E calculated from Eq. (2), and then computes an IEF Q_{E1} using the Manning Equation (Eq. (5)).

$$Q_E = \frac{1}{n} R_E^{\frac{2}{3}} A_E J^{\frac{1}{2}} \quad (5)$$

where Q_E, in ($m^3\,s^{-1}$); A_E, in (m^2).

Secondly, AEHRA computes another R_E from IEW (Z_E) by using the R–Z curve, and then determines a second IEF, Q_{E2} using Eq. (5).

Finally, Q_{E1} and Q_{E2} are coupled to determine Q_E using Eq. (6):

$$Q_E = \max(Q_{E1}, Q_{E2}) \quad (6)$$

(6) AEHRA generalizes the cross-section using mathematical formula when measurements are absent.

When the surveyed data are absent or hard to obtain in an un-gauged normal shape cross-section, the left part in Fig. 1 (calculation of flow area and hydraulic radius under different presumed water-level with the iteration method) can be replaced by another method as follows.

AEHRA firstly generalizes the cross-section as a parabola-shape, then computes flow area A with Eq. (7), wetted perimeter P with Eq. (8) and hydraulic radius R with Eq. (3) under various presumed water-level Z. Thereby, R–A and R–Z curves can be fitted.

According to the research of Liu and Men (2007), a parabola-shape cross-section has the relation of $B = b_1 h^{1/2}$, where B is the water surface width under a certain river flow. Therefore, the cross-sectional area corresponding to B can be calculated as:

$$A = \frac{2}{3} B \cdot h = \frac{2}{3} b_1 \cdot h^{\frac{3}{2}} \quad (7)$$

The corresponding wetted perimeter can be calculated as:

$$P = 2h^{1/2}\sqrt{h + \frac{b_1^2}{16}} + \frac{b_1^2}{8} \times \ln\left[\frac{4h^{1/2} + 4\sqrt{h + b_1^2/16}}{b_1}\right] \quad \text{Liu and Men, 2007} \quad (8)$$

where b_1, river water surface width in a river cross-section with a 1-m water depth (h_1), in (m); h, maximum water depth in a river cross-section under a certain river flow, it varies with Z and the form of a cross-section, in (m).

More details about Eqs. (7) and (8) can be found in Liu and Men (2007).

3. Application of AEHRA in the Huai River

We selected four typical dams in the upper, middle and lower reaches of the Huai River. They are: Baiguishan in the upstream, Zhoukou middle, Yingshang downstream, of the Shaying River which is the Huai River's largest tributary with its aquatic ecosystem being deteriorated; and Bengbu, a crucial control dam of the Huai River. The four typical dams are shown in Fig. 3. We are going to use AEHRA to assess IEF and IEW in the river-sections downstream the four typical dams.

Input variables:

- n in the four sections is the same value of 0.04.
- J: 0.0208% (Bengbu), 0.0261% (Yingshang), 0.0267% (Zhoukou), 0.1078% (Baiguishan).
- The surveyed cross-sections in the four sections are illustrated in Fig. 4.
- V_E and Z_{E2} will be determined in the following sections.

3.1. Determination of instream ecological velocity (V_E) in the Huai River

Determination of V_E at the four sections is mainly pertinent to such factors as aquatic ecosystem, instream habitat, sediment transportation, etc. Here, emphasis was laid on the aquatic ecosystem in the four river-sections. In an aquatic ecosystem, fishes are long-lived and are sensitive to a wide range of stresses; in comparison to macroinvertebrate, fish is easy to be identified, and relations between fish and stream health are better understood and valued by the public; in addition, stream flow adequate to maintain fisheries are usually sufficient to maintain macro-invertebrates and other aquatic life (Parker et al., 2004). Due to the lack of adequate instream ecosystem data, here we choose specific fish species as the instream ecological target species to assess IEF in the Huai River. Thus, the determination of V_E is simplified to determine the specific velocities required by fish to keep successive egg incubation and to sustain their daily life.

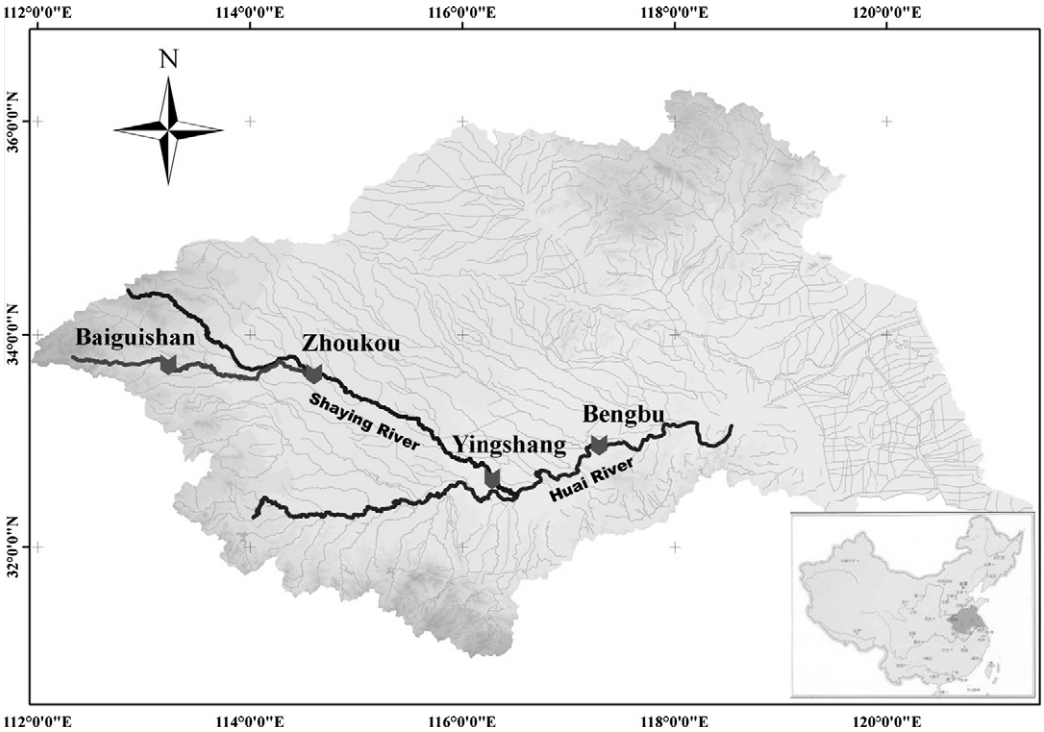


Fig. 3. The four typical dams: Baiguishan in the upper reach, Zhoukou in the middle reach, Yingshang in the lower reach of Shaying River, and Bengbu—a crucial control sluice on the Huai river.

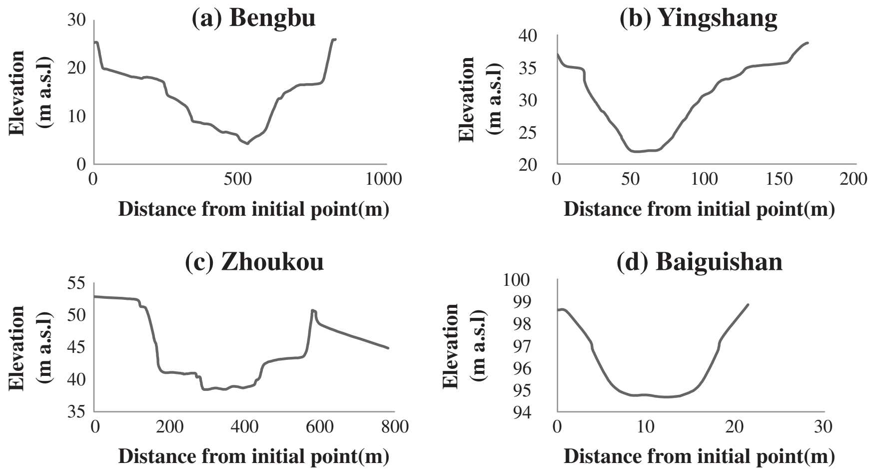


Fig. 4. Surveyed cross-sections downstream the four typical dams.

In this research, the spawning season in a typical river-section is comprehensively determined according to local fish types. For example, if there are *carassius auratus L.* (spawning season: April–July), *acanthodorama simoni Bleeker* (May–June), *siniperca chuatsi(Basilewsky)* (May–July), and *hemibarbus maculatus Bleeker* (April–May) in a river-section (Yang et al., 1994; Zhou, 2000; Yang, 2004; He and Li, 2006; Li et al., 2006; Zhou et al., 2006), the fish spawning season is determined as from April to July. Thus, the spawning season in the four river-sections is: from May to August at Bengbu, from May to June at Yingshang, from May to July at Zhoukou and from April to July at Baiguishan.

According to researches of Laboratory of Institute of Hydrobiology of Hubei Province (1976), He and Deng (1979), Yang et al. (1994), Liu (1999), Zhou (2000), Huang and Wei (2002), Wang and Wang (2004), Yang (2004), He and Li (2006), Zhou et al. (2006), Li et al. (2006, 2007) and websites No. 1, No. 2 and No. 3, instream ecological velocities (V_E) for fish in the Huai River can be determined as follows:

(1) During the spawning season, V_E for drifting-egg-type fish is 0.8 m s^{-1}, V_E for pelagic-egg-type fish is 0.3 m s^{-1}, and V_E for other egg-type fish is 0.3–0.4 m s^{-1}.
(2) During the non-spawning season, V_E for every species of fish is 0.3–0.4 m s^{-1}.

Determination of V_E in the Huai River is shown in Table 1.

3.2. Estimation of comprehensive water-level (Z_{E2}) in the Huai River

In view of data availability in the Huai River, fish was chosen as the target species. Therefore, the comprehensive water-level (Z_{E2}) is that required by fish. It is specially important for viscid fish

Table 1
Determination of V_E in the four typical river-sections.

River-section	Fish name in the river-section	January	February	March	April	May	June	July	August	September	October	November	December
Bengbu	*Pseudolaubuca engraulis (Nichols)*	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Carassius auratus L.	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Coilia ectenes Jordan et Seale[a]	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Acanthodorama simoni Bleeker	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Ctenogobius giurinus (Rutter)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Hemiculter bleekeri bleekeri Warpachowsky[b]	0.3	0.3	0.3	0.3	0.8	0.8	0.3	0.3	0.3	0.3	0.3	0.3
	Parabotia fasciata Dabry[b]	0.3	0.3	0.3	0.3	0.3	0.8	0.8	0.8	0.3	0.3	0.3	0.3
V_E at Bengbu		**0.3**	**0.3**	**0.3**	**0.3**	**0.8**	**0.8**	**0.8**	**0.8**	**0.3**	**0.3**	**0.3**	**0.3**
Yingshang	*Carassius auratus L.*	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Cyprinus carpio L.	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Parasilurus asotus (Linnaeus)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	Hemiculter bleekeri bleekeri Warpachowsky[b]	0.3	0.3	0.3	0.3	0.8	0.8	0.3	0.3	0.3	0.3	0.3	0.3
V_E at Yingshang		**0.4**	**0.4**	**0.4**	**0.4**	**0.8**	**0.8**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Zhoukou	*Ophiocephalus argus Cantor*[a]	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Parasilurus asotus (Linnaeus)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
	Pelteobagrus fulvidraco (Richardson)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Misgurnus anguillicaudatus (Cantor)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Carassius auratus L.	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
V_E at Zhoukou		**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Baiguishan	*Carassius auratus L.*	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Hypophthalmichthys molitrix(C.et V.)[b]	0.3	0.3	0.3	0.8	0.8	0.8	0.8	0.3	0.3	0.3	0.3	0.3
	Ophiocephalus argus Cantor[a]	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Rhodeus ocellatus ocellatus (Kner)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	Pelteobagrus fulvidraco (Richardson)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
V_E at Baiguishan		**0.3**	**0.3**	**0.3**	**0.8**	**0.8**	**0.8**	**0.8**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**

[a] Pelagic-egg-type fish, has the modest requirement for flow velocity.
[b] Drifting-egg-type fish, has the highest requirement for that; other fishes have no special requirement for that when eggs hatch.

egg in the spawning season. The four typical dams were built, in principle, for water supply purpose, and therefore, gates are fully open only during the main flood season (from June to September); most gates are closed during the dry season (the other nine months). Consequently, in the dry season the river water-level fluctuation, downstream of these dams, is neglectable, which has little impact on viscid fish egg.

Because of the lack of detailed in situ data about water-level requirement of fish in the Huai River, we take mean monthly water-level (1956–2000) during the fish spawning season in the four sections as Z_{E2} to assess IEF and IEW. They range from 9.56 to 10.22 m at Bengbu, 22.15–22.33 m at Yingshang, 39.16–39.82 m at Zhoukou, and 94.87–95.14 m at Baiguishan.

4. Results and discussion

If surveyed cross-sectional data in a river-section are available, AEHRA can be used directly, as exemplified in Section 4.1. However, cross-sectional data are hard to collect or measure sometime. On this case, AEHRA generalizes the cross-sectional shape before IEF and IEW assessment, as illustrated in Section 4.2. Reasonablity of AEHRA is finally checked by comparison with other widely used methods in Section 4.3.

4.1. IEF and IEW with surveyed cross-sectional data

Using inputted data encompassing the surveyed cross-sectional data as in Fig. 4, we employed AEHRA to compute IEF and IEW in the four typical sections, as listed in Table 2. Results are as follows.

4.1.1. IEF at the four sections

At Bengbu, during months from May to August, IEF should not be less than 543.38 $m^3\ s^{-1}$; in other months, it should not be less than 6.74 $m^3\ s^{-1}$. At Yingshang, during months from May to June, IEF should not be less than 48.82 $m^3\ s^{-1}$; it should not be less than 10.22 $m^3\ s^{-1}$ in other months. At Zhoukou, in every month of the year, IEF should not be less than 59.93 $m^3\ s^{-1}$. At Baiguishan, during months from April to July, IEF should not be less than 9.07 $m^3\ s^{-1}$; it should not be less than 0.63 $m^3\ s^{-1}$ in other months.

Naturally, ratios of maximum depth to maximum width of different cross-sections from downstream to upstream in an naturally alluvial river take on an increasing trend, which indicates that cross-sections change from a shallow-and-wide type downstream to a deep-and-narrow type upstream. However, it is not the case in the Huai River. The ratios of the four typical reaches are: 0.025 at Bengbu, 0.088 at Yingshang, 0.022 at Zhoukou and 0.182 at Baiguishan. Evidently, Zhoukou is an exception. Analysis on the ratios suggests the cross-section of Zhoukou should be a deep-and-narrow type since its hydraulic slope is greater than the other two sections. However, it is actually a shallow-and-wide type, and its ratio value is even less than that at Bengbu. This mainly contributes to excessive human interference during formation of the cross-section at Zhoukou, where the cross-section is constructed by man to meet his water demand, rather than formed by a natural alluvial process. This ultimately resulted in the exceptional IEF at Zhoukou.

On the whole, during the spawning season, the maximum IEF appears at Bengbu (543.38 $m^3\ s^{-1}$) while the minimum of 9.07 $m^3\ s^{-1}$ is at Baiguishan. Yingshang and Zhoukou rank middle (48.82 $m^3\ s^{-1}$ and 59.93 $m^3\ s^{-1}$). IEF takes on a decreasing trend from Bengbu (downstream) to Baiguishan (upstream), except for Zhoukou. This has an inverse trend with the above-discussed ratios, which implies that ratio of maximum depth to maximum width of a cross-section may be a potential parameter influencing IEF during the spawning season in the Huai river.

During the non-spawning season, IEF has a different pattern: IEF at Baiguishan (upstream) remains the minimum (0.63 $m^3\ s^{-1}$), but

Table 2
Calculation of AEHRA in the four typical river-sections.

Month		January	February	March	April	May	June	July	August	September	October	November	December
IEF Q_E ($m^3 s^{-1}$)	Bengbu	6.74	6.74	6.74	6.74	543.38	543.38	543.38	543.38	6.74	6.74	6.74	6.74
	Yingshang	10.22	10.22	10.22	10.22	48.82	48.82	10.22	10.22	10.22	10.22	10.22	10.22
	Zhoukou	59.93	59.93	59.93	59.93	59.93	59.93	59.93	59.93	59.93	59.93	59.93	59.93
	Baiguishan	0.63	0.63	0.63	9.07	9.07	9.07	9.07	0.63	0.63	0.63	0.63	0.63
IEW Z_E (m)	Bengbu	5.55	5.55	5.55	5.55	10.76	10.76	10.76	10.76	5.55	5.55	5.55	5.55
	Yingshang	23.21	23.21	23.21	23.21	25.87	25.87	23.21	23.21	23.21	23.21	23.21	23.21
	Zhoukou	39.95	39.95	39.95	39.95	39.95	39.95	39.95	39.95	39.95	39.95	39.95	39.95
	Baiguishan	95.02	95.02	95.02	95.95	95.95	95.95	95.95	95.02	95.02	95.02	95.02	95.02

that at Bengbu (downstream, 6.74 $m^3 s^{-1}$) is less than Yingshang (middle stream, 10.22 $m^3 s^{-1}$) and Zhoukou (middle stream, 59.93 $m^3 s^{-1}$). The different pattern results mainly from the lower velocity requirement (V_E) at Bengbu in non-spawning season (Table 1). If (V_E) at Bengbu increases from 0.3 to 0.4 m s^{-1}, IEF will increase to 71.09 $m^3 s^{-1}$ becoming the maximum among the four sections. Thus, the trend of IEF in this period will be the same as during the spawning season. This suggests that V_E is an important factor influencing IEF during the non-spawning season in the Huai River.

4.1.2. IEW at the four sections

As to water-level, IEW at Bengbu from May to August should not be less than 10.76 m; in other months it should not be less than 5.55 m. At Yingshang, IEW during May and June should not be less than 25.87 m; in other months it should not be less than 23.21 m. At Zhoukou, during every month of the year, IEW should not be less than 39.95 m. At Baiguishan, during the months from April to July, IEW should not be less than 95.95 m; in other months of the year, it should not be less than 95.02 m.

Overall, IEW during the spawning season has an increasing trend from 10.76 m in the downstream, Bengbu, to 95.95 m in the upstream, Baiguishan. It has the same trend during the non-spawning season as during the spawning season.

4.2. IEF and IEW without surveyed data in an un-gauged normal watercourse cross-section

An un-gauged normal cross-section can be generalized as a regular geometric cross-section. A manually structured cross-section may be of a circle shape, culvert shape, trapezoidal shape, or V shape. A naturally structured cross-section generally has a parabolic shape (Liu and Men, 2007). Among the four cross-sections, the shape of Yingshang is similar to a natural one, and as such, we used it as an example to illustrate errors introduced by generalization of a cross-section shape.

Let the greatest water depth equal to 1 m, the river water surface width (b_1) at Yingshang was measured as 25.36 m. According to the procedure described by Liu and Men (2007), the geometric parabola, $y = 0.009x^2$, was obtained. Next, sequences of flow area (A), wetted perimeter (P) and hydraulic radius (R) were computed from the initial value of presumed water level (Z) or h with Eqs. (7), (8), and (3), respectively. After that, AEHRA iterated the calculation until the maximum of Z or h was reached. Because IEF usually occupies the lower part of a cross-section, only the lower part at Yingshang (Z = 21.91–25.91 m) was analyzed.

When IEF was assessed at Yingshang with a parabola-shape generalized cross-section instead of an actual one, there may produce an error of 6% (2.93 $m^3 s^{-1}$) during the spawning season, and −15% (−1.53 $m^3 s^{-1}$) during the non-spawning season.

When assessing IEW under the same condition, there maybe exist an error of 7% (0.28 m) during the spawning season and −15% (−0.20 m) during the non-spawning .

In summary, AEHRA may produce an IEF error of −15–6% (−1.53–2.93 $m^3 s^{-1}$) and an IEW error of −15–7% (−0.20–0.28 m) when using generalized cross-section to assess IEF and IEW at Yingshang.

4.3. Comparison of outputted IEF with other approaches

Three widely used methods (Tennant approach, Wetted Perimeter method and R2CROSS method) (Tharme, 2003; Parker et al., 2004; Liu and Men, 2007; Kushner, 2008) were employed to verify the accuracy of AEHRA.

4.3.1. With the Tennant approach

We assessed IEF by Tennant approach with the Averaged Annual Natural Runoff (AANR) (1956–2000) in the four river-sections.

During the spawning season, IEF by AEHRA in all four river-sections is in the range from the Tennant-recommended "minimum" level (10% of AANR) to the "outstanding" level (60% of AANR). Details are as follows:

(1) Bengbu: between "very-good" level (50% of AANR) and "outstanding" level (60% of AANR).
(2) Yingshang: between "minimum" level (10% of AANR) and "fair" level (30% of AANR).
(3) Zhoukou: between "good" level (40% of AANR) and "very-good" level (50% of AANR).
(4) Baiguishan: between "fair" level (30% of AANR) and "good" level (40% of AANR).

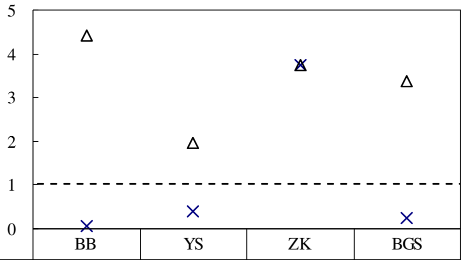
During the non-spawning season, IEF determined by AEHRA at Bengbu, Yingshang, Baiguishan is less than the Tennant-recommended "minimum" level. Zhoukou remains an outlier, as it lies between "outstanding" and "excellent". This mainly attributes to the unique cross-section of Zhoukou. It has been significantly changed from the natural condition. Undoubtly, the AANR in this river-section has been changed due to additional evaporation and seepage caused by the widened cross-section which are usually neglected when retrieving AANR. This may be indicative of the improperness of using Tennant here.

Overall, results from AEHRA are reasonable and more practical on a regulated river-section, compared with the Tennant approach.

4.3.2. With the Wetted Perimeter method (WP)

From relations between perimeter and river flow (P–Q curve) in the four sections, IEF can be determined as: Bengbu—123 $m^3 s^{-1}$; Yingshang—25 $m^3 s^{-1}$; Zhoukou—16 $m^3 s^{-1}$; Baiguishan—2.7 $m^3 s^{-1}$.

Usually, floodgates on a regulated river like the Huai River are kept closed in dry season and opened in flood season. AEHRA computes IEF on monthly basis with 12 values in a year, while WP has only one annual value. We took the sole value from WP as basis, to compare the minimum and maximum IEFs from AEHRA with it. Ratios of IEF by AEHRA to that by WP were calculated, ranging from 0.05 to 4.42 (Fig. 5). The minimum and maximum AEHRA



	BB	YS	ZK	BGS
× AEHRA_min / WP	0.05	0.41	3.75	0.23
△ AEHRA_max / WP	4.42	1.95	3.75	3.36

Fig. 5. Comparison of IEF from AEHRA with from WP in the four sections.

values have the least differences with WP IEF at Yingshang, because of its nearly natural cross-section there (Fig. 4). Most AEHRA IEFs fluctuate around the WP value except for Zhoukou. The same V_E during spawning and non-spawning seasons at Zhoukou results in the same AEHRA IEF in 12 months.

Application of WP in this river suggests:

(1) Because floodgates are closed in dry season and opened in flood season, one knows that in order to maintain the same perimeter, in dry season (flow velocity is relatively small), a lower discharge is needed; whereas in flood season, a higher discharge is necessary. Therefore, breakpoints in *P*–*Q* curve from annual or multi-annual data are difficult to exactly reflect the biota water requirement in a regulated river.

(2) When floodgates up- and down-stream a river-section are closed in dry season, a lower velocity or a lower discharge may result in a higher water-level. This suggests discharges derived from WP might make habitat be overly inundated, i.e., IEF by WP be over-estimated. Contrarily, WP IEF in high-flow season may be under-estimated.

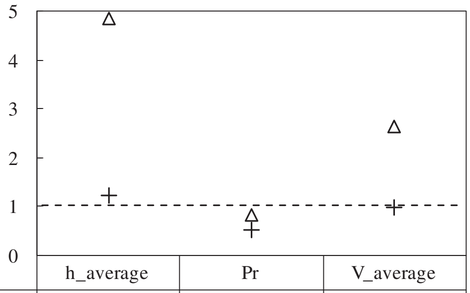
(3) Velocity requirement of some special habitat organisms and IEF variations among different months are not fully considered in WP. Therefore, IEF may be under-estimated, resulting in some types of organisms, for example, fish egg perishes in spawning season.

This is similar to the research of Parker et al. (2004), WP underestimates stream flow requirements when applied to sites in channels that run at higher flows. Moreover, Parker et al. stressed that WP should be applied only to cross-sections in riffle habitats, is best applied to rectangular or trapezoidal cross-sections within riffles on straight reaches; it is best applied in alluvial channels that can naturally adjust their depth and width—application of the method to disturbed channels (widened or narrowed) or channels with hardened stream banks (rip–rap or a stone wall) will likely increase the variability of stream flow requirements determined by the method. In the Huai River neither cross-sections are alluvial nor have they rectangular or trapezoidal form, which makes results from WP in the four sections uncertain.

Though IEF from AEHRA is greater than that from WP in spawning season, because of higher velocity requirement of certain types of fish egg, it is versa in non-spawning season. Overall, the man-controlled downstream flows in the Huai River result in greater WP IEF in flood season and smaller one in dry season, which may makes the mean annual WP IEF less than the actual situation. That demonstrates AEHRA is more reasonable and practical than WP in a regulated river.

4.3.3. With the R2CROSS method

The R2CROSS method is based on the assumption that a discharge chosen to maintain habitat in the riffle is sufficient to maintain habitat for fish in nearby pools and runs for most life stages of fish and aquatic invertebrates (Nehring, 1979; Parker et al., 2004).



	h_average	Pr	V_average
+ AEHRA_min / R2CROSS	1.21	0.52	0.98
△ AEHRA_max / R2CROSS	4.85	0.83	2.62

Fig. 6. Comparison of *h*_average (average depth), *Pr* (percent wetted perimeter) and *V*_average (average velocity) by AEHRA with the R2CROSS specified three criteria at Baiguishan.

This method specifies three criteria which must be met by the flow rate to be considered adequate (Kushner, 2008). They are average water depth (*h*_average), percent of wetted perimeter (*Pr*) and average velocity of the current (*V*_average). Because the maximum steam top width at bankfull discharge in R2CROSS is 30.48 m (100 feet) and only bankfull width of Baiguishan in the four typical sites is less than 30.48 m, we chose Baiguishan to compare AEHRA with the R2CROSS method. To compare IEF by AEHRA with that by R2CROSS, we calculated the three indices (*h*_average, *Pr* and *V*_average) with IEFs by AEHRA, then compared them with the R2CROSS specified criteria. Taking the latter as standard, ratios of the former to the latter are illustrated in Fig. 6.

From Fig. 6, one can see: ratios of *h*_average and *V*_average are mostly greater than 1.0, which means AEHRA derived IEFs generally fall in the range between R2CROSS 2 and R2CROSS 3 of three criteria derived ones (Parker et al., 2004), which implies the reasonability of AEHRA.

On the whole, comparison with the three globally wide-used methods indicates that AEHRA is more practical and robust when it is used in a regulated river. Plus its inner features of fewer and easy-accessible input data, successful reflection of the seasonal variation of IEF and IEW, considering component information of both river course and instream ecosystem make it especially feasible and promising in determination of IEF and IEW for regulated rivers under great impact from human activities.

5. Conclusions

We developed an instream ecological flow method for regulated river, termed the Adapted Ecological Hydraulic Radius Approach (AEHRA). Our study suggests:

(1) In addition to instream ecological flow (IEF), AEHRA also yields the corresponding minimum Instream Ecological Water-level (IEW), which is important for aquatic biota spawning and is of great help for dam operation.

(2) Ratio of maximum depth to maximum width of a cross-section may be a potential parameter influencing IEF during the spawning season; while V_E is significantly important during the non-spawning season in the Huai River.

(3) AEHRA is able to be applied to river-sections where is a dearth of detailed aquatic biological or hydrological data because of AEHRA's fewer input parameters and easy accessibility of the parameters. Besides, when the surveyed data of a cross-section are absent or difficult to obtain, normal

cross-sections can be generalized as regular geometric shapes. That makes it specially qualified for IEF assessment of regulated river-sections.

(4) Seasonal variation of instream ecological velocity V_E makes AEHRA reflect seasonal variation of IEF and IEW easily.
(5) Replacement of a surveyed cross-section by a generalized one may produce errors in IEF and IEW. However, they are usually acceptable and worthwhile in respect of the difficulty in obtaining data in un-gauged sites.
(6) Verification of AEHRA by the Tennant approach, Wetted Perimeter method and R2CROSS method shows a reasonable and promising AEHRA.

Though our results employing AEHRA are encouraging, the method itself still requires further improvement to make result more accurate. Besides, it is urgently necessary to make deep-going investigation and research on instream ecosystem components for the purpose of enlarging the target species range to more accurately assess IEF and IEW of the whole aquatic ecosystem by AEHRA. This is now underway in our research unit.

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