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Construction of habitat suitability models (HSMs) for benthic macroinvertebrate and their applications to instream environmental flows: A case study in Xiangxi River of Three Gorges Reservior region, China

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Abstract

Based on a long-term ecological monitoring, the present study chose the most dominant benthic macroinvertebrate (*Baetis* spp.) as target organisms in Xiangxi River, built the habitat suitability models (HSMs) for water depth, current velocity and substrate, respectively, which is the first aquatic organisms model for habitat suitability in the Chinese Mainland with a long-term consecutive *in situ* measurement. In order to protect the biointegrity and function of the river ecosystem, the theory system of instream environmental flow should be categorized into three hierarchies, namely minimum required instream flow (hydrological level), minimum instream environmental flow (bio-species level), and optimum instream environmental flow (ecosystem level). These three hierarchies of instream environmental flow models were then constructed with the hydrological and weighted usable area (WUA) method. The results show that the minimum required instream flow of Xiangxi River calculated by the Tennant method (10% of the mean annual flow) was 0.615 $m^3 s^{-1}$; the minimum instream environmental flow accounted for 19.22% of the mean annual flow (namely 1.182 $m^3 s^{-1}$), which was the damaged river channel flow in the dry season; and 42.91% of the mean annual flow (namely 2.639 $m^3 s^{-1}$) should be viewed as the optimum instream environmental flow in order to protect the health of the river ecosystem, maintain the instream biodiversity, and reduce the impact of small hydropower stations nearby the Xiangxi River. We recommend that the hydrological and biological methods can help establish better instream environmental flow models and design best management practices for use in the small hydropower station project.

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Keywords: Habitat suitability model; Weighted usable area; Instream environmental flow; Benthic macroinvertebrate; Xiangxi river; Three Gorges reservoir

1. Introduction

Water is essential to bring sustenance, which almost has connections with any part of the natural environment more or less, and is deeply intimate with all fields of human life [1]. Along with the rapid development of industrial civilization, humans excessively affect, occupy or control water resources at various spatial and temporal scales, resulting in a gradual lost of the ecological functions of water resources, and eventually leading to serious eco-environmental problems [2–4]. Therefore, water resources for protecting, repairing and rebuilding the ecosystem should be calculated and regulated scientifically, namely studies on environmental flow. Generally, the watershed environmental flow is divided into instream and outstream uses for further study, and this essay focuses mainly on the study of instream environmental flow.

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Instream environmental flow refers to the flow required by protecting structure integrity and biodiversity of the instream ecosystem [5]. Studies on it initiated in western countries. In the past decades, many work groups have been concerned with the development of methods, and there have been many famous methods available till now all over the world. These methods can be mainly classified into four categories: the hydrological method, the hydraulic method, the habitat method and the holistic method [5–7]. Among these methods, habitat method based on quantitative biological information integrates flow-related changes with the preferred hydraulic habitat conditions for target assemblages, so it becomes currently the most reliable evaluation method [5,8]. Instream flow incremental methodology (IFIM) is one of the most widespread and advocated habitat methods, which combines a large amount of hydrological *in situ* data and specific aquatic organisms (e.g. fish, benthic macroinvertebrate, and macrophyte) information to assess the effect of flow variation on biological habitat available over a possible range of flows [9,10]. This method is widely used in more than 20 countries, including America, France, Germany, Japan, the Czech Republic and the UK [5,11]. Most often, IFIM has addressed the responses of target fish, and to a less extent, aquatic benthic macroinvertebrate and macrophyte organisms. Historically, management decisions employing the IFIM have focused upon the prediction of the available habitat for fish due to its particular predominance. Related studies, however, show that benthic macroinvertebrates are abundant in most low-order streams, and that many small streams, which naturally support a diverse benthic macroinvertebrate fauna, only support a limited fish fauna [12,13]. The greatest application of benthic macroinvertebrates will be in low-order streams where a more immediate link to fish communities can be established [13–15]. The same studies linked to IFIM for benthic macroinvertebrates were also reported in use for limited countries, including America, Canada and New Zealand [5,13,16,17].

At the same time, much work related with the instream environmental flows has been carried out in China, which was normally assessed by means of hydrologic or hydraulic-based methodologies, but less explicitly referenced to biological information. Due to the quantitative research of instream environmental flow which started later in China, and the lack of a long-term series of *in situ* data about aquatic organisms, there is less study and application of IFIM in China. Xu et al. [18] based on the minimum space requirements of fish, calculated the minimum ecological instream environmental flow in Huai River, China; Yi et al. [19] adjusted the habitat suitability model from Edwards, and built the habitat suitability model of four major Chinese carp in the Yangtze River. Based on the literature materials, habitat suitability indices for the Chinese Sturgeon were proposed and calculated by Yi et al. [20]. However, most of their assessments for the suitability of environmental factors are derived from different periods, literature or estimation, so long-term consecutive *in situ* information should be improved to develop a more accurate model.

All the methods of instream environmental flow are established in a certain specific region, similarity of natural environmental and community composition in different regions plays a very important role for successful application of the method. Though two adjacent catchments having similar geologic condition and watershed area, their sensibility may differ greatly in the dry season [3,21,22]. Based on the above questions, development of a particular and veracious site-specific habitat suitability model (HSM) is necessary for further calculation of instream environmental flow. Long-term ecosystem monitoring in Xiangxi River is a good platform for developing HSM. Therefore, based on the long-term consecutive *in situ* monitoring data, the present study chose the most dominant benthic macroinvertebrate (*Baetis*) of Xiangxi River as target organisms [23], HSMs were attemptedly built for water depth, current velocity, and substrate, respectively, which is the first aquatic organisms model for habitat suitability in the Chinese Mainland within a long-term consecutive *in situ* measurement.

The objective of this study lies on constructing three hierarchies of instream environmental flow models, namely minimum required instream flow, minimum instream environmental flow and optimum instream environmental flow, with the hydrological and weighted usable area (WUA) method. Studies on instream environmental flow could be the scientific basis for implementing the optimized allocation of water resources in the Xiangxi River watershed. The results can be the basis of management decision-making for ecological, economic, and social sustainable development of the Xiangxi River watershed. The results can also be shared in other regions where hydropower will be exploited.

2. Methods

2.1. Study area and sites setting

Originating from the Shennongjia forest region, the Xiangxi River is a tributary of the Yangtze River, having a length of 94 km, a catchment area of 3099 km^2, and a natural fall of 1540 m. Gufu River, Gaolan River and Jiuchong River are the three main tributaries (Fig. 1) [24,25]. Studies on the long-term monitoring for the Xiangxi River ecosystem could be traced back to 1999. The seasonal routine monitoring began in June 2000, and our team carried out monthly routine monitoring since August 2001. Based on the natural environmental characteristics of the Xiangxi River watershed and the feasibility of sampling, 154 sites were settled down. Among these sites, there were 13 sites for monthly sampling. The study interests include hydrology, aquatic physical-chemical factors, and aquatic organisms (phytoplankton, epilithic algae, zooplankton, benthic macroinvertebrate, fish, etc.). In this study, we calculate instream environmental flow by taking full advantage of the monthly data and the whole watershed data, over 1400 matched sets of hydrological and biological data were

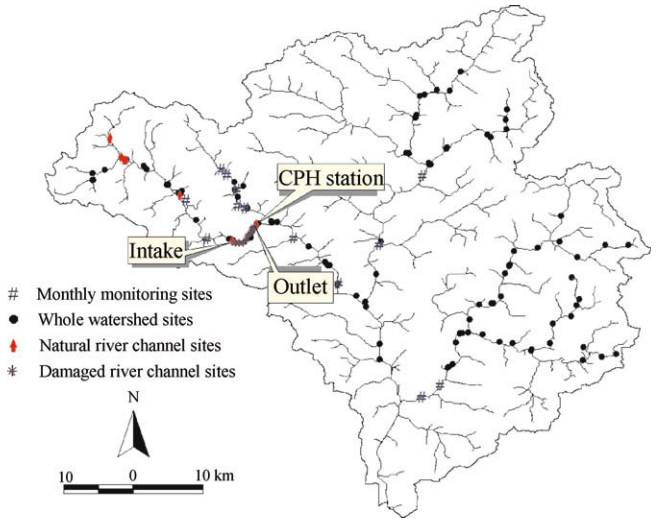

Fig. 1. Locations of sampling sites in the Xiangxi River watershed.

analyzed. Long-term studies show that benthic macroinvertebrates and epilithic algae were the main aquatic organisms in the Xiangxi River [23,26–29], and then plankton [30], the diversity of fish was much lower due to their unsuitabilities for mountainous lotic habitat [31].

In order to calculate the instream environmental flow of the natural river and damaged river which was influenced by the small hydropower station (mainly in the drought period), 10 cross sections on the main stream of the Xiangxi River were set to represent the natural river, and nine cross sections were set between the intake and outlet of a typical diversion hydropower station, Cangpinghe (CPH) hydropower station, to represent the damaged river (several sites are overlapped to the whole watershed sites).

2.2. Data collection

Data for analyses in this study were derived from the long-term monitoring information of the Xiangxi River ecosystem after 1999. Benthic macroinvertebrate samples were collected with a D-frame net (before June, 2004) and Surber sampler (after June, 2004). The river width was measured with measuring tape, and then according to the river width, there was a cross section at the intervals of 0.2–2 m. The water depth (metal ruler was used) and current velocity (LJD printer velocity instrument was used to measure at 0.6 times of the depth from the surface) were measured at each sampling point. Visual estimation of the substrate composition (%) was made for each location using the EPA particle size scale [12], bedrock (a whole rock), boulder (>256 mm), cobble (64–256 mm), pebble (16–64 mm), gravel (2–16 mm), sand (0.06–2 mm), silt (0.004–0.06 mm), clay (<0.004 mm). On the one hand, considering the habitat diversity of benthic macroinvertebrates, several kinds of substrate which attract some organisms to live are taken into account, such as vegetable and debris. On the other hand, the bedrock is too to take into account in this study.

2.3. Data analysis

2.3.1. The IFIM method

IFIM is a quantitative method to assess the effect of flow variation on the usable biological habitat [10], which predicts how physical habitat (e.g. water depth, current velocity, and substrate) changes with flow and combines this information with habitat suitability criteria to determine an index of the amount of habitat available (the so-called WUA) over a possible range of stream flows [9,10]. Benthic macroinvertebrate densities have been related to many complex environmental factors, such as water depth, current velocity, substrate, water quality, and water temperature. Currently, most studies paid more attention to the major factors, such as the water depth, current velocity, and substrate [13,32,33].

2.3.2. The habitat suitability model

The classical approach to quantifying habitat consists of estimating local habitat indices according to the available knowledge regarding the optimum range of abiotic conditions for the targeted aquatic organisms [34]. The habitat suitability index, as the most commonly used index of habitat, is an analytical tool used to represent preferences of aquatic organisms for various instream variables [35,36]. Currently, categories of information and data treatment used to generate the habitat suitability model include [6,10]: (1) professional opinion or the literature model, which is derived from professional opinion and literature, or from negotiated definitions. It can be developed relatively quickly and at a minimal cost. (2) The habitat utilization model, which represents the conditions that were being occupied by the target organisms when the observations were made, based on the frequency distributions of microhabitat attributes measured at locations used by the target organisms. (3) The habitat preference model, which is designed to reduce the bias associated with environmental availability, and resource selection refers to the utilization of resources disappropriate to their availability. Among these three models, the literature model is negotiable, obtaining consensus about the criteria may also prevent conflict over their subsequent use in WUA; the habitat preference model is too complex to apply in China. Based on the above analyses, in this study, we adopt the habitat utilization model to calculate the instream environmental flow, which has very good practicability and maneuverability, and is suitable for the practical situation of China.

2.3.3. The weighted usable area method

By combining the hydraulic model at different flow conditions and the habitat suitability of target organisms, WUA evaluates the impact of integrate flow-related changes on habitat, and then calculates the minimum instream environmental flow. HSMs are used to describe the adequacy of various combinations of water depth, current velocity, and substrate conditions in each habitat computational cell to produce an estimate of the quantity and quality of habitat in terms of surface area [6,10], WUA is computed within the reach at a specific flow from

$$WUA = \sum F[f(D_i), f(V_i), f(S_i)] \times A_i$$

where A_i is the surface area of cell i; $f(D_i)$, $f(V_i)$, and $f(S_i)$ are the suitabilities associated with the water depth, current velocity, and substrate in cell i, respectively; $F()$ is the combined suitability factor (CSF).

By repeated calculation of the WUA under all kinds of flows, the functional relation between WUA and flow can be obtained, and then the minimum instream environmental flow can be obtained according to the determinate threshold.

There are many methods for determining the threshold of minimum instream environmental flow, the slope method and the curvature method are the two main methods for estimating the breakpoint at present. These two methods define the breakpoint with a specified slope (the slope equals a critical value), usually (1) or a maximum curvature [37,38]. Below this breakpoint, WUA declines rapidly with the change of flow; but above it, WUA changes very slightly. The slope method (equals 1) was used in this study to determine the breakpoint.

2.3.4. Determination of weight attribution of environmental factor

The effect of different environmental factors on target organisms is different, so it is much better to determine the weight attribution to each factor, and then calculate the CSF. In this study, we choose the analytic hierarchy process (AHP), which is widely used in the theory of system engineering, to determine the weight attribution. According to the relative importance of each factor, the principle of level analysis is used to quantize the qualitative indicators, and then through the mathematic approach and qualitative analysis, the weight attribution of each factor is determined [39].

2.3.5. Simulation of mean annual flow

Because there is only one hydrological monitoring station, these monitoring data cannot meet the calculation of instream flow in the Xiangxi River nearby the CPH hydropower station. Fortunately, with the development of “three S” skill, it is likely to simulate the hydrological conditions at each sub-catchment. Based on the geographical information, climate information, land use information of the Xiangxi River watershed and the mean annual flow of this hydrological monitoring station, the soil and water assessment tool (SWAT) model can calculate the mean annual flow for each sub-catchment, and the instream flow nearby the CPH hydropower station is 6.15 $m^3 s^{-1}$ [40].

2.3.6. The hydrological method

Historical flow data are also used to calculate the instream environmental flow with the hydrological method, and the typical hydrological methods include the Tennant method [41], the mean flow in the driest month under 10 years [8,42], the mean flow in the driest month under 90% guaranteeing rate [8,42].

(1) Tennant method: this method is based on the multi-year hydrological data, which takes 10% of the mean annual flow as the minimum required instream flow.
(2) Mean flow in the driest month under 10 years: this method is derived from the 7Q10 method, which takes the mean flow in the driest month under 10 years as the minimum required instream flow.
(3) Mean flow in the driest month under 90% guaranteeing rate: this method arranges the frequency of the consecutive multi-year hydrological data in the driest month, and then takes the mean flow in the driest month under 90% guaranteeing rate as the minimum required instream flow.

2.3.7. The three hierarchy instream environmental flow models

In order to protect the integrity of structure and function of the Xiangxi River ecosystem, models of instream environmental flow should be categorized into three hierarchies, that is to say, the minimum required instream flow, the minimum instream environmental flow, and the optimum instream environmental flow:

(1) The first flow on the hydrological level can ensure that the river flow is constant from the source to the estuary, and we call it minimum required instream flow.
(2) The second flow on the bio-species level can maintain an integrated process of survival and reproduction of the important organisms, and we call it minimum instream environmental flow.
(3) The third flow on the ecosystem level can fulfill all the ecological services, and we call it optimum instream environmental flow.

3. Development of the habitat suitability model

The habitat suitability model was constructed by directly observing the usable habitat of target organisms – *Baetis*, and then according to the relations between microhabitat attributes (water depth, current velocity, and substrate) and *Baetis* relative abundance at locations, the frequency distribution method was used to simulate mono-factor suitability.

3.1. Water depth

The water depth ranged within 0–1 m in the studied reach. HSM of the water depth indicates that the suitable water depth of *Baetis* ranges within 0.1–0.3 m (it was also called riffle), and the optimum water depth is 0.2 m (Fig. 2(a)). The reach with water depth of over 0.9 m is almost located at the downstream reach, whereas more aquatic oligochaetes and chironomid larvae occurred. We have no observation of depths more than 1 m, but we assume that deep water was limited for *Baetis* in the stream [43,44], nearly no *Baetis* occurred in water depth more than 0.9 m as shown in Fig. 2(a).

3.2. Current velocity

The mean current velocity of sampling units ranged within 0–1.5 m s^{-1}. HSM of water current velocity indicates that the suitable current velocity of *Baetis* ranges within 0.3–0.7 m s^{-1}, which is located between torrent (more than 1.0 m s^{-1}) and subcritical flow (less than 0.3 m s^{-1}), and the optimum current velocity is 0.4 m s^{-1} (Fig. 2(b)). HSM of current velocity demonstrates the extreme influence of current velocity on *Baetis*, some species of *Baetis* still live in the pool, but it is very hard for *Baetis* to stand against the over-fall (more than 1.5 m s^{-1}).

3.3. Substrate

Nine kinds of substrates were analyzed in this study. HSM of substrate indicates that *Baetis* preferred coarser substrate, such as cobble, pebble, gravel and boulder, and among these categories, cobble is the best habitat for *Baetis* (Fig. 2(c)). The contents of clay, vegetable, debris, sand and silt were very low, so these fine substrates could not provide suitable habitat for *Baetis*. Jowett also confirmed this view that large substrate was generally more productive than the small one [16].

3.4. Determination of weight attribution

Many studies have shown that the substrate and current velocity are two major microhabitat factors, and benthic macroinvertebrate assemblages are most closely related to the substrate composition, followed by the current velocity, and the essentiality of water depth is the least associated [16,32,33,45,46]. According to the literature information about microhabitat factors, the relative importance of each factor was determined as follows: substrate > current velocity $\geqslant$ water depth. And then the judgment matrix

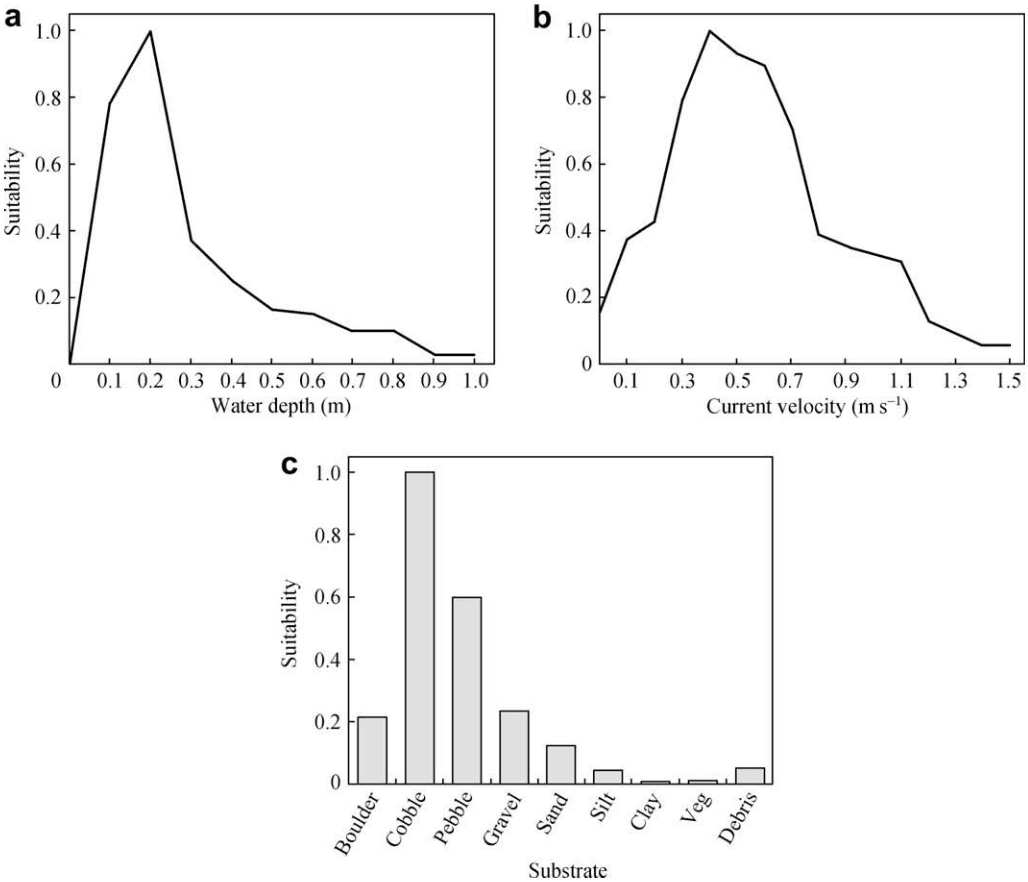

Fig. 2. Habitat suitability models of *Baetis* for (a) water depth, (b) current velocity, and (c) substrate in the Xiangxi River.

Table 1
Judgment matrix of environmental factors.

	Water depth	Current velocity	Substrate
Water depth	1	1	0.5
Current velocity	1	1	1
Substrate	2	1	1

built according to the environmental factors is given in Table 1.

With the principle of level analysis, the weight attributions of water depth, current velocity and substrate are 0.260, 0.327 and 0.413, respectively. The consistency test indicates that $\lambda_{\max} = 3.054$, $CR = 0.046 < 0.1$, so it is proved that the satisfying consistent exists in this matrix, and the result can meet further calculation. The equation of CSF with the weighted mean method is as follows:

$$\mathrm{CFS} = 0.260 \times f(D) + 0.327 \times f(V) + 0.413 \times f(S)$$

4. Calculation of instream environmental flow models

According to the method mentioned in Section 2.3.3, WUA versus flow (in the form of natural logarithm transformation) obtained from regression models is shown in Fig. 3. We calculated the first inflection point using the slope method (equals 1), whereas the minimum environmental flow was 1.182 $\mathrm{m^3\,s^{-1}}$ (accounting for 19.22% of the mean annual flow), and this flow referred to the minimum instream environmental flow for maintaining the most dominant benthic macroinvertebrate – *Baetis* in the damaged river. The same calculation was carried out in the natural river, whereas the minimum environmental flow was 2.639 $\mathrm{m^3\,s^{-1}}$ (accounting for 42.91% of the mean annual flow), and this flow referred to the minimum instream environmental flow for maintaining *Baetis* in the natural river.

Table 2
Environmental flow of the Xiangxi River with the hydrological method and the WUA method.

Method	Environmental flow ($\mathrm{m^3\,s^{-1}}$)	Environmental flow/mean annual flow (%)
Tennant method	0.615	10.00
Mean flow in the driest month under 10 years	0.912	14.83
Mean flow in the driest month under 90% guaranteeing rate	1.373	22.32
WUA method (minimum instream environmental flow)	1.182	19.22
WUA method (optimum instream environmental flow)	2.639	42.91

In order to build three hierarchy instream environmental flow models, besides the biological method, we also considered the hydrological method. According to the hydrological data from 1988 to 2005, we calculated the instream environmental flow of the Xiangxi River with the hydrological method, such as the Tennant method, mean flow in the driest month under 10 years and mean flow in the driest month under 90% guaranteeing rate (Table 2).

By comparing the results of each method, three hierarchy instream environmental flows of the Xiangxi River can be determined as follows:

1. Minimum required instream flow: we chose the lowest flow as the minimum required instream flow (0.615 $\mathrm{m^3\,s^{-1}}$), which was calculated by the Tennant method.
2. Minimum instream environmental flow: we chose the flow of damaged river in the dry season as the minimum instream environmental flow (1.182 $\mathrm{m^3\,s^{-1}}$), and this flow can reach the "common" condition of the Tennant method in the dry period.
3. Optimum instream environmental flow: we chose the flow of natural river in the dry season as the optimum instream environmental flow (2.639 $\mathrm{m^3\,s^{-1}}$), which accounts for 42.91% of the mean annual flow, and this flow can reach "very well" the condition of the Tennant method in the dry period.

5. Discussion

5.1. The applicability of HSM

HSM is the biological basis of habitat simulation, and the facticity and veracity of this simulation directly affect

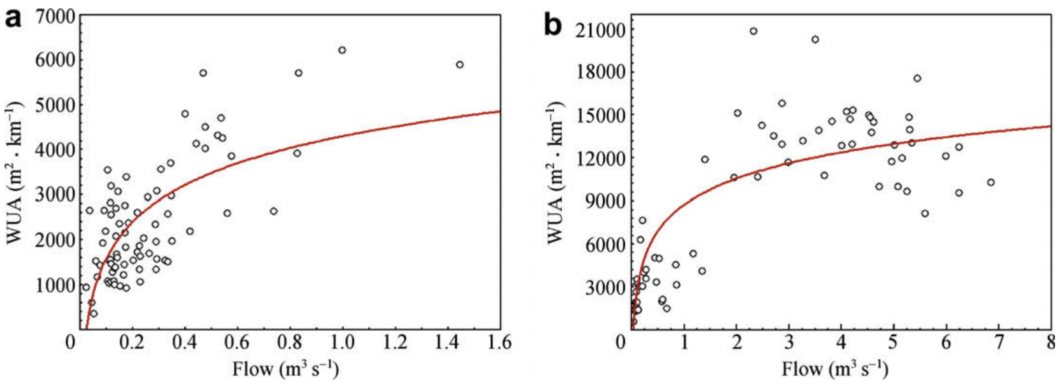

Fig. 3. Regression diagrams of relations between WUA and flow of *Baetis* in the Xiangxi River. (a) The damaged river and (b) the natural river.

the results of habitat and the further calculation of instream environmental flow. Benthic macroinvertebrate HSM of the Xiangxi River has the representative feature in this watershed, and this model can meet the further calculation of instream environmental flow in the Xiangxi River watershed. On the other hand, the instream water requirement of organisms is not a constant in a year, according to the rule of reproduction and development of biologic community. Being the same as the change of instream flow in a year, the instream water requirement of organisms is also various. And it is acceptable that the instream water requirement is quite dissimilar for different rivers and different organisms [5,10]. Therefore, later study should pay attention to all kinds of HSMs for different life stages. Because the HSMs in this study are built on the mountainous stream in the western Hubei Province, these models are applicable to the Xiangxi River and its flanking regions. However, maybe they are inapplicable to the stream of other regions, especially the large river, and this also should be improved.

5.2. Three hierarchy instream environmental flows

Instream environmental flow is mainly used to maintain the reproduction and development of target organisms, and provide optimum habitat area. In the Xiangxi River, we can choose 10% of the mean annual flow as the minimum required instream flow, and this flow is just the "poor" condition of the Tennant method in the dry period. Many studies considering the instream environmental flows have been carried out. Using the hydrological method, He [47] studied the instream environmental flow of the Huoxi River, and confirmed that 10% of the mean annual flow in the dry period could be thought as the minimum required instream flow. We can define the minimum required instream flow due to lack of information, for example, in France, the minimum required instream flow should be above 10% of the mean annual flow, even though rivers whose mean annual flow exceed 80 $m^3 s^{-1}$, the minimum required instream flow also should be more than 5% of the mean annual flow [48]. The minimum instream environmental flow was studied by using the biological method in the Adda River (the mean annual flow is 35 $m^3 s^{-1}$) of Italy, Vismara et al. [36] took 19% of the mean annual flow as the minimum environmental flow to maintain the habitat of brown trout. Similar observations have been made in the Surna River (the mean annual flow is 56 $m^3 s^{-1}$) of Norway. Halleraker et al. [7] took 27% of the mean annual flow as the minimum environmental flow to maintain the habitat of salmon. Results of this study indicate that the minimum required instream flow and the minimum instream environmental flow agree with most current studies, so these two hierarchy instream environmental flows can be applicable to our studied region.

Optimum instream environmental flow considers the hydrological feature requirements of the reproduction and development of target organisms. When the river flow declines constantly for a long time, it would cause the break of ecological chains, the obvious reduction of organisms, and then the decrease of biointegrity. Flows should protect the normal physiological activities of the target organisms, create optimum habitat area, and provide the amount of aquatic organisms to maintain the watercourse sight, physical morphology and cross-sectional area, etc. Therefore, 2.639 $m^3 s^{-1}$ should be viewed as the minimum flow of this studied area in order to protect the health of the river ecosystem, maintain the ecological sight of watercourse, and reduce the impact of the small hydropower station nearby the Xiangxi River. Most studies often emphasize the minimum environmental flow, while less emphasis was now put on optimum environmental flow. The concept of optimum instream environmental flow was put forward in this study, which aims to protect the river ecosystem, and the ecological functions can exert well. But because this theory is still in its initial stage, further perfection from theory to calculation method should be improved.

The natural conditions in China are very complicated: great changes happen between inter-annual and different seasons in the same region, and there are different emphasis points of instream environmental flow in different regions, and so different instream environmental flow methods should be taken into account in different regions. The habitat method may be more applicable for rivers with abundant water resources in south China, while the calculation methods of the north Chinese rivers still need to be further studied by combining with specific rivers.

6. Conclusions

(1) Three hierarchical instream environmental flows on the hydrological, bio-species, and ecosystem levels are applicable to the practical situation, and it could provide a very important decision-making basis for rational use and integrated management of water resources, and to make the water resources be utilized harmoniously among the production, life and ecology.

(2) Due to the moderate water depth, current velocity, sufficient light and abundant food, riffle becomes a good habitat for benthic macroinvertebrate assemblages. Therefore, from this point of view, the protection of the riffle is one of the most important measures to provide a better habitat for those aquatic organisms.

(3) With the implementation of many important projects, such as the international hydrological project, research objectives of the instream environmental flow have shifted from the bypast organisms and the channel's physical morphology to the research of how to maintain the river flow. And during this period, integrity of river ecology must be considered, so further research should be extended to the outstream ecosystem.

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