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Coupling habitat suitability and ecosystem health with AEHRA to estimate E-flows under intensive human activities

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ABSTRACT

Sustaining adequate environmental flows (e-flows) is a key principle for maintaining river biodiversity and ecosystem health, and for supporting sustainable water resource management in basins under intensive human activities. But few methods could correctly relate river health to e-flows assessment at the catchment scale when they are applied to rivers highly impacted by human activities. An effective method is presented in this study to closely link river health to e-flows assessment for rivers at the catchment scale. Key fish species, as indicators of ecosystem health, were selected by using the foodweb model. A multi-species-based habitat suitability model (MHSI) was improved, and coupled with dominance of the key fish species as well as the Index of Biological Integrity (IBI) to enhance its accuracy in determining the fish-preferred key hydrologic habitat variables related to ecosystem health. Taking 5964 fish samples and concurrent hydrological habitat variables as the basis, the combination of key variables of flow-velocity and water-depth were determined and used to drive the Adapted Ecological Hydraulic Radius Approach (AEHRA) to study e-flows in a Chinese urban river impacted by intensive human activities. Results showed that upstream urbanization resulted in abnormal river-course geomorphology and consequently abnormal e-flows under intensive human activities. Selection of key species based on the foodweb and trophic levels of aquatic ecosystems can reflect a comprehensive requirement on e-flows of the whole aquatic ecosystem, which greatly increases its potential to be used as a guidance tool for rehabilitation of degraded ecosystems at large spatial scales. These findings have significant ramifications for catchment e-flows assessment under intensive human activities and for river ecohealth restoration in such rivers globally.

1. Introduction

Freshwater ecosystems provide services for human life and terrestrial productivity; however, they are increasingly threatened by human activities, e.g., urban stormwater, water pollution, habitat fragmentation and degradation, etc. (Joniak and Kuczyńska-Kippen, 2010; Walsh et al., 2012; Sobczyński and Joniak, 2013; Bobbi et al., 2014). Rivers support not only complex and highly diverse freshwater ecosystems but also human requirements throughout the world (King et al., 2009). To sustain a healthy freshwater ecosystem, the concept of environmental flows (e-flows) was proposed, which is to retain natural flow regimes in rivers (Poff et al., 2010). This is a key principle for maintaining freshwater biodiversity and ecosystem processes, and for achieving environmentally sustainable water resource management goals (Acreman and Ferguson, 2010).

There are more than 200 methods for assessing e-flows (Liu et al., 2011), such as methodologies of Tennant, River2D, AEHRA and ELOHA. Amongst all e-flows methodologies, the River2D model (Steffler and Blackburn, 2002) stands out due to its use in studies to determine environmental flows (de Souza et al., 2016). Without compromising accuracy, River2D can reach a steady-state solution and also can embed a fish habitat module by using the Instream Flow Incremental Methodology (IFIM) (Zhou et al., 2014). Despite its widespread use, a larger degree of discrepancy for velocities than for depths was found when comparing the values measured in the field and the ones River2D yielded, and elimination of this discrepancy is unattainable (Smith et al., 2002; Katopodis and Ghamry, 2007; Gard, 2009; Waddle and Bovee, 2010;

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Boavida et al., 2013). However, the model was developed specifically for use in natural rivers with localized hydrodynamic analysis at the micro-habitat scale (Steffler and Waddle, 2002). It is unsuitable for application to large scale catchment studies and rivers with intensive human disturbance.

Most current e-flows methods need accurate long-term hydrological and/or ecological data (Poff et al., 2003 and Poff et al., 2010**)**, which are not yet broadly available for many rivers globally (Sanderson et al., 2012). The Adapted Ecological Hydraulic Radius Approach (AEHRA), requiring a few hydrological and/or ecological data, uses hydraulic radius as the surrogate for hydraulic habitat and has the potential to calculate e-flows in consideration of requirements of the river's dynamic balance, pollutant transport and dominant species in an aquatic ecosystem (Liu et al., 2011; Gopal, 2013). One of the few research needed for its application is the determination of preferred flow velocity of key aquatic species. Using velocity requirements from basins other than the study area based on published researches increases uncertainties in the e-flows assessment. To reduce the uncertainties determination of the preferred velocity for key species based on large-scale in-situ aquatic ecosystems samplings is highly necessitated. In addition, subjectively selecting key fish species in AEHRA unavoidably introduces uncertainties in e-flows assessment. In short, AEHRA is suitable for assessment of e-flows in large scale catchment with intensive human disturbance after objectively selecting key fish species and accurately determining preferred flow velocity for key aquatic species.

The preferred flow velocity is often determined using habitat suitability models, or the Habitat Suitability Index (HSI). It is assumed that aquatic organisms are distributed in suitable environments and a number of environmental factors must be considered in riverine environments (e.g., water depth, flow velocity etc.) (Nukazawa et al., 2011). HSI is widely used to indicate the degree of preference of a particular species to different habitats attributes on the assumption that a species would choose its optimal habitat (Schamberger and O'Neil, 1986; Vadas and Orth, 2001; Vismara et al., 2001; Leclerc et al., 2003; Ahmadi Nedushan et al., 2006; Paredes et al., 2014). Using HSI to determine the input variable preferred velocity for AEHRA is a practical way. However, most previous HSI model integrates only population attributes (presence/absence and number of individuals) with indices of physical factors that relate to the inhabited environments of the studied species. Biomass of the studied species was left out, despite the fact that it is an important attribute for the existence and health of any biotic community (Zhao et al., 2014 & Zhao et al., 2015a), which inevitably introduced great uncertainties to the preferred flow velocity and water depth.

Generally, there are three forms of the HSI, i.e., binary-, univariate- and multivariate-format where the univariate-format HSI is most widely used (Yi et al., 2013). Consideration of only a single species rather than multiple species precludes the univariate HSI from estimating the synthetic effect of a habitat factor on the whole ecosystem community. Hence, Zhao et al. (2015b) developed a multi-species-based HSI (MHSI) model which is able to estimate responses of multi-species to a habitat environmental factor. However, the omission of the relative frequency of available habitat (*A* in the research of Hampton (1988)) in MHSI brought uncertainties to findings.

Flow velocity and water depth greatly influence the habitat of aquatic ecosystems (Sempeski and Gaudin, 1995; Asaeda and Manatunge, 2007; Langerhans, 2008; Liu et al., 2011) and consequently the health of fish communities. A healthy habitat is the basis for fish survival and reproduction, which is usually assessed by using a health index, such as IBI (Index of Biological Integrity) (Karr, 1981). The IBI is an effective indicator for aquatic ecosystem health and has been widely applied across the world, e.g., Tejerina-Garro et al. (2006); Casatti et al. (2009); Qadir and Malik (2009); Wu et al. (2014). River health as well as its relationship with e-flows should therefore be fully considered in processes of e-flows assessment, especially in rivers that are highly impacted by human activities. To retain river health in these rivers, it is necessary to closely link river health to e-flows assessment.

Generally IBI includes F-IBI for fish and B-IBI for benthos. In aquatic ecosystems, fish occupying the top position of the food chain make appropriate ecosystem indicators and can provide an integrative view of the environment (Wu et al., 2014; Zhao et al., 2015a). Fish communities are thus considered effective indicators of ecosystem health (Oberdorff et al., 2002). Stream flows that are adequate to maintain fisheries are usually sufficient to maintain macro-invertebrate and other aquatic life (Parker et al., 2004; Liu et al., 2011). As such IBI for fish is more practical in assessment of river ecosystem health. It is noticeable that over the life span of fish, there are some specific crucial seasons for fish reproduction, e.g., spawning season. In these seasons, fish have special requirements on flow velocity and water level for the successful survival of their eggs/larvae, or to migrate from the ocean to the upstream freshwater reaches to spawn (Liu et al., 2011). Those special requirements for fish in spawning seasons should be fully considered.

The objective of this paper is to develop an effective method to closely link habitat suitability and river health (indicated by IBI for fish) to current e-flows assessment method AEHRA for rivers with intensive human activities, taking as the basis large-scale in-situ aquatic ecosystems sampling and determining the preferred habitat variable of key fish species. It is expected to fully consider population and biomass of key fish species as well as their special requirements in spawning seasons. Analysis on the responses of multiple fish to the preferred variables is based on the improvement of MHSI model accounting for the relative frequency of available habitat. Key fish in AEHRA are selected objectively based on the research of Zhang et al. (2017c). In such ways uncertainties in AEHRA are expected to be reduced remarkably. The method is then used to study e-flows in a river under intensive human activities, the Xiaoqing River, China, to provide scientific support for its river-ecological remediation.

2. Material and methods

2.1. Methodologies

With key fish species selected on the basis of the food web model (Zhang et al., 2017c), dominance of key fish species was coupled with HSI model to determine preferred flow-velocity and water-depth to overcome the weakness of only accounting for presence/absence, density of species individuals, and omitting biomass as in previous research (Wu, 2015). Subsequently, multi-species-based HSI (MHSI) in the research of Zhao et al. (2015b) was improved and used to evaluate responses of multiple species to their physical habitat attributes whereby flow-velocity and water-depth attributes along with consideration of habitat health were used as two of five input variables (ecological flow velocity, ecological water-level, roughness, hydraulic slope, and cross-section) for AEHRA (Liu et al., 2011) to estimate e-flows for river ecosystems.

The foodwebs were reconstructed by using the widely-used 'Ecopath' model which describes the feeding relationships between all species occurring in the food web (Colvin et al., 2015; Valls et al., 2015; Zhang et al., 2017c). The key fish species are actually the keystone species or a functional group which is defined as a group of species with similar effects on ecosystem processes, without redundancy among the other groups (Perry, 2010), or simply as the most abundant species within its functional group (Davic, 2003; Valls et al., 2015).

(1) Dominance of key fish species

The combination of density and biomass reflects the contribution of a species to its community. The dominance model (Eq. (1)) by Zhao et al., 2012, 2014, 2015a) was employed in this study to calculate the dominance of a key fish species in its community.

$$I_{mprotance,i} = \omega_1 P_{a,i} + \omega_2 P_{b,i} \quad (1)$$

where,$I_{mprotance}$ represents the dominance of a species; P_a and P_b respectively refer to the ratio of the species' density and biomass to the total for the communities considering the spatial presence/absence of the species, $P_{a,i} = \frac{N_i}{\sum N_i}, P_{b,i} = \frac{B_i}{\sum B_i}$; N_i is the density of the i-th species and B_i is the biomass of the species; ω_1 and ω_2 are the weightings of density and biomass, determined using the mass-center weighting determination method (Zhao et al., 2015b), $\omega_1 + \omega_2 = 1.0$.

(2) Determination of key-species-preferred flow velocity and water depth based on the Habitat Suitability Index

To effectively reduce the uncertainties in previous HSI model, the MHSI is improved in this study with the addition of the relative frequency of available habitat (A), as shown in Eq. (2).

$$MHSI_k = \sum_{i=1}^{I} \frac{p_{ki}}{I} \text{ with } p_{ki} = \frac{n_{ki}}{N_i A_k} \quad (2)$$

where$MHSI_k$ is the multi-species-based unnormalized index of preference, i.e., the suitable probability of all dominant species in the k-th gradient, varying between 0 and 1; k represents the k-th gradient of a certain habitat environmental factor, e.g., flow velocity, water-depth, $k = 1, \ldots,$ K, where K is the total number of habitat-factor gradients (the variation of habitat factor in space); i represents the i-th dominant species ($i = 1, \ldots,$ I) and I is the total number of the dominant species; n_{ki} is the abundance of the i-th species in the k-th gradient of the habitat factor; N_i is the abundance of the i-th species in all gradients of the habitat factor, $N_i = \sum_{k=1}^{K} n_{ki}$; p_{ki} is the suitable probability of the i-th species in the k-th gradient.

To analyze the preferred gradient of a habitat factor, the factor investigated in field campaigns for fish and their habitat needs to be initially classified into different gradients with the optimum interval (Eq. (3)).

$$IL = \frac{R}{K} \text{ with } K = 1 + 3.322 \log No \quad (3)$$

(Hampton, 1988) where IL is the optimum interval; R is the total range of observed values and No represents the number of observations taken, i.e., the number of sampling sites across the study area. By using Eq. (3) the total gradient number (K) in a habitat factor could also be determined.

Hereafter, $MHSI$ at every gradient of a factor such as flow velocity and water depth can be calculated. Results were then used to determine the most suitable gradients whereby to determine the ecological flow velocity and water depth preferred by key-species occurring in study rivers.

Spawning seasons were carefully assessed to satisfy the flow velocity and water depth/level requirements of the fish community. Since fish can stay in the lower-velocity riverbed or seek shelter in near-bank habitats (Boavida et al., 2013) when the flow-velocity in a mid-river is much higher than their critical velocities, only the minimal flow velocity, which is deemed the top priority in water resources management, was coupled and determined in the present study.

For maximum protection of the incubating eggs of all key fish species the spawning seasons of different fish were coupled together with the occurrence probability of key fish species. The maximum periods of their spawning seasons were determined as the spawning season of a river section.

(3) Complementation to key-species-preferred flow velocity and water depth by taking into account habitat health

In addition to the consideration of requirements of key species for the two habitat factors – flow velocity and water depth, the health of the fish community was also fully integrated into the e-flows assessment by correlating fish IBI into the two factors to reflect the requirement of ecosystem health on flow velocity and water depth, using the dataset from field sampling campaigns.

The IBIs at the sampling sites were classified and correlated with gradients of flow velocity and water depth. The gradients with the highest IBI values, implying the healthiest habitat, were then complemented with the key-species-preferred flow-velocity and water-depth which had been determined as described in the previous section.

To further reduce uncertainties from the omission of the relative frequency of available habitat (A), the relative frequency of healthy sites at every gradient is calculated by using Eq. (4).

$$RF_k = \frac{ph_k}{A_k} \text{ with } ph_k = \frac{m_k}{M} \quad (4)$$

where RF_krepresents the relative frequency of healthy sites at the k-th gradient; $ph_k$is the proportion of sampling sites with a healthy ecosystem (with IBI greater than 50) at the k-th gradient, in other words, the ratio of healthy-site number (m_k) at the k-th gradient to the total number of samplings (M) in the study area.

By using the optimum interval (IL) and the total gradient number (K) calculated with Eq. (3), the relative frequency of healthy sites at all gradients can be determined and related to flow velocity and water depth with healthy ecosystems.

(4) Assessment of e-flows using AEHRA

The Adapted Ecological Hydraulic Radius Approach (AEHRA) uses hydraulic radius as the surrogate for hydraulic habitat to estimate e-flows for a river system. The core of the AEHRA is the determination of flow velocity and water depth preferred by river ecosystems (Liu et al., 2011). Having obtained the two crucial variables, e-flows for the river by system can be estimated using Eq. (5).

$$Q_E = \frac{1}{n} R_E^{\frac{2}{3}} A_E J^{\frac{1}{2}} \quad with \quad R_E = n^{\frac{3}{2}} V_E^{\frac{3}{2}} J^{-\frac{3}{4}} \quad (5)$$

(Liu et al., 2011) where, Q_E is e-flow, in $m^3 \cdot s^{-1}$; R_E refers to the watercourse hydraulic radius (ratio between cross-sectional flow area and its wetted perimeter) corresponding to ecological flow velocity (V_E) in m; A_E, flow area for e-flows in m^2; n: roughness which is dimensionless; J: hydraulic slope in%.

Having determined the preferred flow velocity and water depth, fully considering the responses of the two variables to habitat suitability (MHSI) and health status (IBI) of the habitat in a river system, AEHRA estimates the e-flows to retain adequate water resources for a sustainable and healthy river system.

2.2. Case study

The methodologies were applied to the Xiaoqing River. Three large-scale *in-situ* aquatic ecosystem sampling and investigation (Jinan-Xiaoqing-River campaigns) were conducted covering the Jinan City catchment and the main stream of the Xiaoqing River.

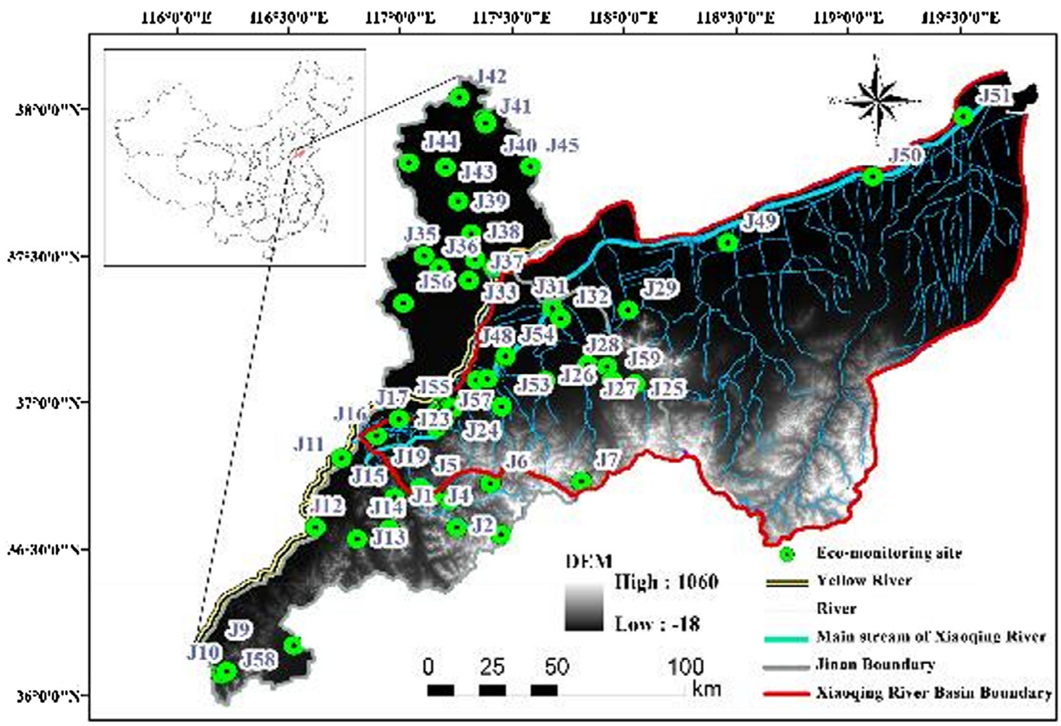

Fig. 1. Study area and fish monitoring stations in the three Jinan-Xiaoqing-River campaigns (from Zhang et al., 2017b).

Jinan City (the Spring City) (36.0°–37.5°N, 116.2°–117.7°E), a pilot city modeled as a civilized and ecological city in China, is bordered by Mount Tai to the south, is traversed by the Yellow River and has a steeper topography in the south than in the north (Fig. 1). Hilly areas, piedmont clinoplain and alluvial plains span the city from south to north. The altitude within the area ranges from −66 to 957 m above sea level, with highly contrasting relief. The semi-humid continental monsoon climate in the city area is characterized by cold, dry winters and hot, wet summers (Zhao et al., 2015b).

The Xiaoqing River is an urban-influenced river originating from the western suburb of Jinan City, flowing from southwest to north-east parallel to the Yellow River, and eventually flows into the Bohai Sea. Most of its tributaries begin in the southern mountains and flow north to the main stream of the river. The Xiaoqing River has a total length of 237 km and a catchment area of 10,572 k m^2, of which 70.3 km and 2824.1 km^2 are in the urban districts of Jinan City. Its catchment covers half of the whole urban area of Jinan City. Rainfall is the main source of the stream water (Cui et al., 2009). The uneven distribution of rainfall clearly defines the low-flow and high-flow periods over a year. During low-flow periods, scarce rainfall and on-going water resources development usually result in zero flow; while at high-flow periods, the sharp increases of flow rate, steep slope, and narrow cross sections all contribute to flood inundation (Yu and Wang, 2006; Cui et al., 2009). Healthy river ecosystems can provide for human abundant ecological services, such as fish production, irrigation, and stormwater drainage. The consequences of drought and flood impose unprecedented threats to aquatic ecosystem health and sustainable supply of ecological services. To sustain a healthy freshwater environment in the Xiaoqing River and to retain those sustainable ecological services, informed assessment and maintenance of its e-flows are required..

2.3. *Data*

Extensive field campaigns to monitor the fish community and concurrently their habitat attributes in the Xiaoqing River and rivers in the Jinan City catchment were conducted over three periods: May 1st-20th, August 2nd-21st and November 1st-20th, 2014 for purpose of aquatic ecosystems rehabilitation. In the three campaigns, 37 habitat parameters of hydrology and water quality (as listed in Table 1 of Zhao et al. (2015a)) were measured / sampled concurrently with the sampling of 38 fish species at 153 sites (Table 1). In total, 5084 (in Jinan rivers) and 880 (in the Xiaoqing River) fish were sampled and tested.

Hydrologic attributes (flow velocity, water depth, river width and river flow) were measured *in-situ* with portable equipment. Fish were collected for 30 min in three habitats (i.e., pools, riffles, and runs) along a fixed-length reach (between 200 and 300 m depending on the river-width) at a sampling site (river-section). Individuals caught from the three habitats were combined to represent a site. All individuals collected were identified *in situ* to species according to Zhao et al. (2015a) and then counted, weighed and recorded in field data sheets. All identified fish were then released. A few specimens that could not be identified in the field were preserved in a 10%-formalin solution and stored in labelled jars for subsequent identification. Detailed methods for habitat parameter measurements and fish sampling can be found in Zhao et al. (2015a). All these data were used to evaluate the habitat suitability and health status of the study river sections in the Xiaoqing River.

(Table 1 Fish species recorded in the three Jinan-Xiaoqing-River campaigns in 2014 (modified from Zhao et al. (2015a)).)

Generally, 14 fish species were found in the Xiaoqing River during the three campaigns (Table 2). Five species (*Carassius auratus, Rhodeus ocellatus, Gnathopogon imberbis, Misgurnus anguillicaudatus, Paramisgurnus dabryanus*) were found in the upper reach section (J49 in Fig. 1); seven species (*Carassius auratus, Channa argus, Huigolio chinssuensis, Hypseleotris swinhonis, Pseudorasbora fowleri, Hemiculter leucisculus, Oryzias latipes*) were recorded in the middle reach section (J50); and six species (*Carassius auratus, Hemiculter leucisculus, Oryzias latipes, Pseudorasbora parva, Ctenogobius giurinus, Ctenogobius cliffordpopei)* were recorded in the lower reach section (J51). Among all the species, *Carassius auratus* were

Table 1
Fish species recorded in the three Jinan-Xiaoqing-River campaigns in 2014 (modified from Zhao et al. (2015a)).

No.	Species	No.	Species
1	*Carassius auratus*	20	*Pelteobagrus fulvidraco*
2	*Hemiculter leucisculus*	21	*Spualiobarbus curriculus*
3	*Channa argus*	22	*Acheilognathus chankaensis Dybowski*
4	*Misgurnus anguillicaudatus*	23	*Sarcocheilichthys nigripinnis*
5	*Abbottina rivularis*	24	*Lateolabrax japonicus*
6	*Cyprinus carpio Linnaeus*	25	*Culter erythropterus Basilewsl*
7	*Pseudorasbora parva*	26	*Mylopharyngodon piceus*
8	*Rhodeus ocellatus*	27	*Mastacembelus aculeatus*
9	*Ctenopharyngodon idellus*	28	*Monopterus albus*
10	*Hypophthalmichehys molitrix*	29	*Oryzias latipes*
11	*Huigolio chinssuensis*	30	*Hypseleotris swinhonis*
12	*Ctenogobius giurinus (Rutter)*	31	*Botia superciliaris Günther*
13	*Opsariichthys bidens Günther*	32	*Macropodus chinensis (Bloch)*
14	*Gnathopogon imberbis*	33	*Perccottus glenii*
15	*Pseudorasbora fowleri*	34	*Silurus asotus Linnaeus*
16	*Ctenogobius brunneus*	35	*Lefua costata(Kessler)*
17	*Paramisgurnus dabryanus*	36	*Gobio rivuloides Nichols*
18	*Ctenogobius cliffordpopei*	37	*Clarias fuscus (Lacepede)*
19	*Rhodeus sinensis Günther*	38	*Misgurnus anguillicaudatus*

found across the whole river while *Hemiculter leucisculus* and *Oryzias latipes* were caught in both of the middle and lower reach sections Different spatial distribution of the fish species reflects different habitat quality across the whole river.

3. Results

3.1. Selection of key fish species for the Xiaoqing river

Fish communities were used as the indicators of aquatic ecosystems of the Xiaoqing River to calculate e-flows therein. In our previous research (Zhang et al., 2017c) the 14 fish species in the Xiaoqing River were further analyzed by using keystoneness index based on the food-web model – Ecopath (Christensen and Pauly, 1992; Essington, 2007; Colvin et al., 2015; Valls et al., 2015), in which four species (*Carassius auratus*, *Misgurnus anguillicaudatus*, *Hemiculter leucisculus, Oryzias latipes*) were selected as the key species of the Xiaoqing River, playing a critical role in maintaining the structure of the aquatic ecosystems of the study river. Among them *Carassius auratus* and *Misgurnus anguillicaudatus* were found in the upper reach section, and *Carassius auratus*, *Hemiculter leucisculus* and *Oryzias latipes* were recorded in the middle and lower reach sections (Table 2). They were then used as key species for the three river sections to calculate instream e-flows aiming to protect them on behalf of their aquatic ecosystems.

3.2. Determination of key-species-preferred flow velocity and water depth using the improved MHSI

The improved MHSI (Eq. (2)) with flow velocity was calculated based on the key species occurring at this section. Statistics of biomass, density and dominance were conducted taking as basis fish dataset from the three field campaigns. Prior to this determination, flow velocity monitored in the three campaigns was classified based on Eq. (3) with which the total gradient number (K) was calculated to be seven. Overall the flow velocity was classified into seven gradients from less than 0.19 m s^{-1} to greater than 1.14 m s^{-1} with an interval of 0.19 m s^{-1} (Table 3). Likely, water depth was classified into seven gradients from less than 0.40 m to greater than 2.40 m with an interval of 0.40 m (Table 3).

(Table 3 Gradient of flow velocity and water depth monitored in the three field campaigns for the fish investigation)

Based on the seven gradients of flow velocity, the flow velocity that concurred with the four key fish species across the whole Jinan-Xiaoqing-River area was categorized, along with their densities, biomass and dominance. Dominance was calculated based on density and biomass using Eq. (1). Subsequently, the proportions of density, biomass and dominance of the four key species in every gradient (Table 3) were calculated as the responses of the four key fish species, i.e. the multi-species-based HSI (MHSI) of density, biomass and dominance along the gradients of flow velocity using Eq. (2) (Figs. 2 & 3). Water depth was processed in the same way as that for flow velocity.

In the upper reach section of the river, all MHSIs for biomass, density and dominance of the two key species (*Carassius auratus* and *Misgurnus anguillicaudatus*) along flow velocity (Fig. 2: a-c) take on a similar pattern. MHSI for biomass (Fig. 2-a) had higher values at the 4th gradient while MHSI for density (Fig. 2-b) peaked at the 3rd gradient. MHSI for dominance reached the highest value at the 4th gradient (Fig. 2-c). As the density and biomass usually have different contributions for different species to their communities (Zhao et al., 2012 & Zhao et al., 2014), to derive a comprehensive effect of flow velocity on key species, the MHSI along dominance (Fig. 2-c) was finally adopted in this study to determine the preferred velocity gradients of the key species. In other words, the 4th gradient (0.57–0.76 m s^{-1}) was determined to be the preferred flow velocity range for the key species in the upper reach section of the river. As to the water depth MHSIs for biomass, density and dominance of the key species in the upper reach section peaked at the 1st gradient with that for density having a second highest value at the 7th gradient. Overall, the 1st gradient

Table 2
Fish species found in the field campaigns in the Xiaoqing River in 2014.

No.	Fish Species	Upper Reach	Middle Reach	Lower reach
1	*Carassius auratus*	●	●	●
2	*Rhodeus ocellatus*	●		
3	*Gnathopogon imberbis*	●		
4	*Misgurnus anguillicaudatus*	●		
5	*Paramisgurnus dabryanus*	●		
6	*Channa argus*		●	
7	*Huigolio chinssuensis*		●	
8	*Hypseleotris swinhonis*		●	
9	*Pseudorasbora fowleri*		●	
10	*Hemiculter leucisculus*		●	●
11	*Oryzias latipes*		●	●
12	*Pseudorasbora parva*			●
13	*Ctenogobius giurinus*			●
14	*Ctenogobius cliffordpopei*			●

Table 3
Gradient of flow velocity and water depth monitored in the three field campaigns for fish investigation.

Gradient	1	2	3	4	5	6	7
Flow velocity (m s^{-1})	0–0.19	0.19–0.38	0.38–0.57	0.57–0.76	0.76–0.95	0.95–1.14	>1.14
Median of flow velocity (m s^{-1})	0.06	0.30	0.48	0.64	0.83	0	1.20
Water depth (m)	<0.40	0.40–0.80	0.80–1.20	1.20–1.60	1.60–2.00	2.00–2.40	>2.40
Median of water depth (m)	0.21	0.55	1.05	1.40	1.75	2.10	2.45

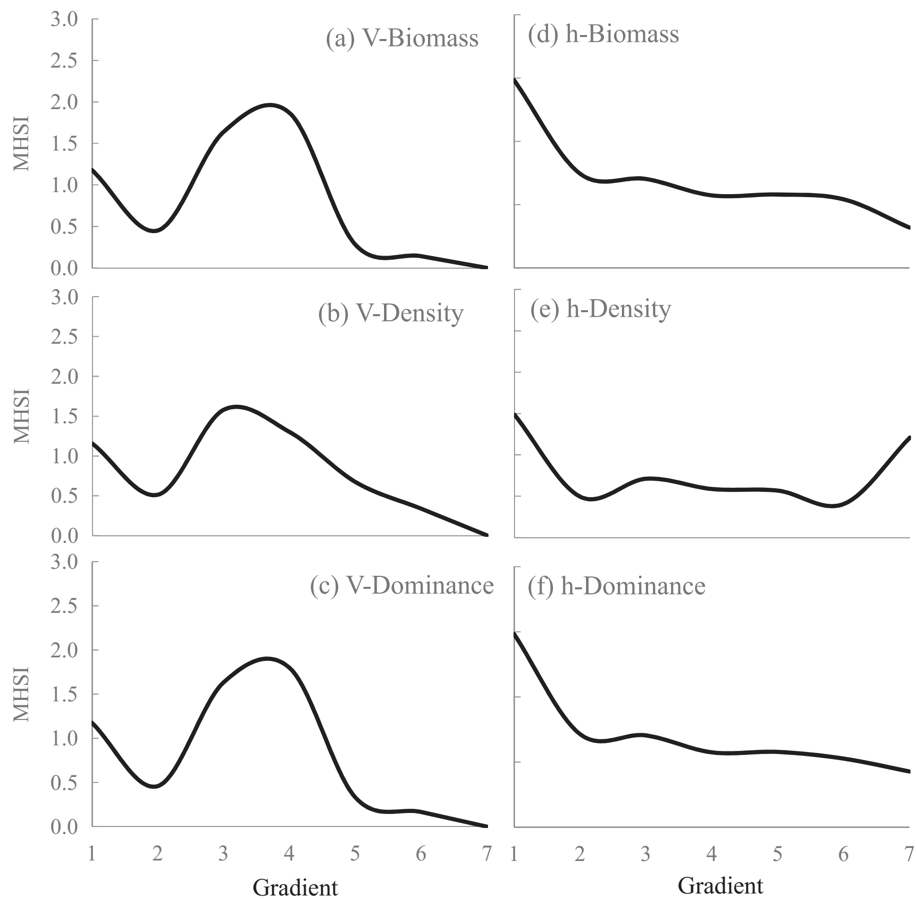

Fig. 2. Intergated multi-species-based HSI (MHSI) of biomass (a&d), density (b&e) and dominance (c&f) of the two upper-reach key-species (*Carassius auratus*, *Misgurnus anguillicaudatus*) occurring in the upper reach section along gradients of flow velocity *V* (a-c) and water depth *h* (d-f). The x-axis represents the gradient of flow velocity (or water depth) and the y-axis is the MHSI for each gradient.

(<0.40 m) is expected to be preferred by the key species in the upper reach section of the river.

Fig. 3 shows the ecological flow-velocity and water-depth preferred by the three key species (*Carassius auratus*, *Hemiculter leucisculus* and *Oryzias latipes*) inhabiting the middle and lower reach sections of the Xiaoqing River. In terms of the MHSIs for density and dominance (Fig. 3: b&c) along flow velocity, they were highest at the 2nd gradient while that for biomass peaked at the 1st gradient (Fig. 3: a). Overall, the 1st to 4th (0–0.76 m s^{-1}) gradients had higher values than that of the remaining gradients based on the key-species in the middle and lower reach sections. As to water depth, there was a similar trend in all MHSIs for biomass, density and dominance (Fig. 3: d-f). The 5th gradient with a water depth of 1.60–2.00 m is preferred by the key species in the middle and lower reach sections of the Xiaoqing River as indicated by the peaks of the MHSI attributes.

In brief, a flow-velocity of 0.57–0.76 m s^{-1} for the upper reach section and 0–0.76 m s^{-1} for the middle and lower reach sections, as well as a water-depth of <0.40 m for the upper reach section and 1.60–2.00 m for the middle and lower reach sections of the Xiaoqing River is suitable for the corresponding key fish species.

3.3. Reconsidering key-species-preferred flow velocity required in fish spawning seasons to determine the ecological flow velocity for AEHRA

According to the egg-type of the four key species – *Carassius auratus*, *Misgurnus anguillicaudatus*, *Hemiculter leucisculus*, and *Oryzias latipes*, two issues i.e., specific flow-velocity and water-level required by their eggs to maintain successful incubation over their spawning seasons were analyzed and listed in Table 4. Overall, all species' eggs can survive in zero-velocity water conditions during the spawning seasons except for *Oryzias latipes* since its eggs' specific gravity is a little but not much greater than that of water. Moreover, all key species other than *Oryzias latipes* have no special flow velocity requirements during their spawning seasons. *Oryzias latipes*, with pelagic eggs, have a flow velocity requirement of at least 0.30 m s^{-1} (Liu et al., 2011), as shown in Table 4.

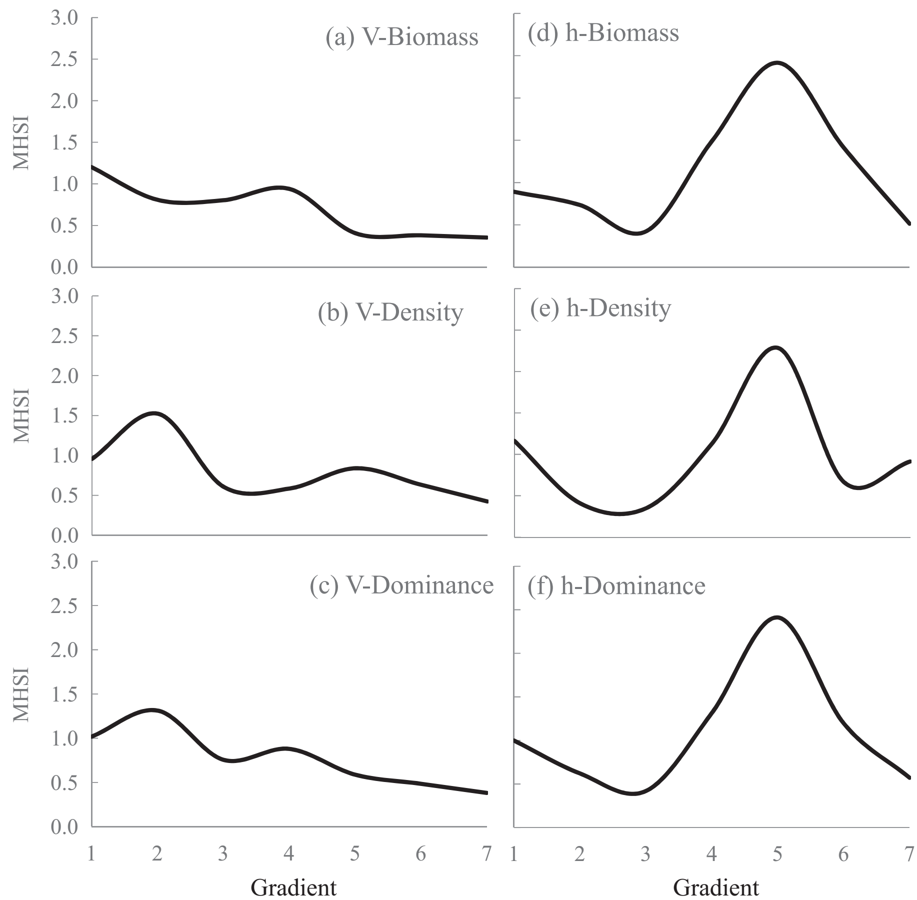

Fig. 3. Intergated multi-species-based HSI (MHSI) of biomass (a&d), density (b&e) and dominance (c&f) of the three key species (*Carassius auratus*, *Hemiculter leucisculus* and *Oryzias latipes*) occurring in the middle- and lower- reach sections along gradients of flow velocity *V* (a-c) and water depth *h* (d-f). The x-axis represents the gradient for flow velocity (or water depth) and the y-axis is the MHSI for each gradient.

Table 4
Spawning season, egg-type and flow velocity requirement of the key species.

Key species	Spawning season	Egg-type	Flow velocity required ($m\ s^{-1}$)
Carassius auratus	April, May	viscid	–
Misgurnus anguillicaudatus	April, May	viscid	–
Hemiculter leucisculus	April, May, June, July	viscid	–
Oryzias latipes	May, June	pelagic	Greater than 0.30

Table 5
Coupled flow velocity requirement in spawning seasons of the four key fish species ($m\ s^{-1}$).

Month	Upper reach	Middle reach	Lower reach
Jan	0.57–0.76	0.38–0.76	0.38–0.76
Feb	0.57–0.76	0.38–0.76	0.38–0.76
Mar	0.57–0.76	0.38–0.76	0.38–0.76
April	0.57–0.76*	0.38–0.76*	0.38–0.76*
May	0.57–0.76*	0.38–0.76*	0.38–0.76*
June	0.57–0.76	0.38–0.76*	0.38–0.76*
July	0.57–0.76	0.38–0.76*	0.38–0.76*
Aug	0.57–0.76	0.38–0.76	0.38–0.76
Sept	0.57–0.76	0.38–0.76	0.38–0.76
Oct	0.57–0.76	0.38–0.76	0.38–0.76
Nov	0.57–0.76	0.38–0.76	0.38–0.76
Dec	0.57–0.76	0.38–0.76	0.38–0.76

*: spawning season.

Three key species, of *Carassius auratus, Hemiculter leucisculus* and *Oryzias latipes* occurring in the lower reach section of the Xiaoqing River have spawning seasons of [April to May], [April to July] and [May to June], respectively (Table 4). Thus the spawning season for the lower reach section of the Xiaoqing River was determined to cover April to July. Similarly, the spawning seasons for the upper and middle reach sections were April to May and April to July, respectively, as marked by asterisks in Table 5.

Based on the flow velocity requirements of all key species in the spawning seasons of the different reach sections and the species-preferred flow velocity, a flow-velocity range required by fish communities in different reach sections of the whole river was determined by using Eq. (2) (Table 5). In general, it is recommended that flow velocity is maintained in the range of 0.57–0.76 $m\ s^{-1}$ for upper reach section and 0–0.76 $m\ s^{-1}$ for the middle and lower reach sections in the non-spawning seasons. In the spawning seasons (marked by asterisks in Table 5) there is no additional requirement for velocity in the upper reach section, while over two months (May to June) of spawning seasons in the middle and lower reach sections there is an extra requirement for velocity since eggs of *Oryzias latipes* need at least 0.3 $m\ s^{-1}$ to keep them floating at the water surface for successful incubation. The extra spawning-season flow-velocity requirement was then coupled with that in non-spawning seasons at the three reach sections, as shown in Table 5. The coupled range of flow-velocity was then used for assessment of e-flows by using AEHRA.

3.4. Re-thinking the ecological water-depth and flow velocity for AEHRA with habitat health

The ecosystem health status at sampling sites in the three field campaigns in this study was assessed by using the IBI. Relative frequency of healthy sites at every gradient was calculated by using Eq. (4) based on all data in the three Jinan-Xiaoqing-River campaigns and graphed in Fig. 4.

The 1st and 2nd gradients for water depth (0–0.80 m) had a higher proportion of healthy sites (with *RF* greater than 30%) across all sites over the three field campaigns (Fig. 4 dash line). Thus the water depth range of the two gradients (i.e., 0–0.80 m) was most likely beneficial to the aquatic ecosystems in the study river. Due to the lower relative frequency of healthy sites (30%) across the whole river basin for this water-depth range but with higher MHSI for depths greater than 2.0 (Fig. 2:d-f & Fig. 3:d-f), first priority was given to the latter when determining the ecological water-depths for AEHRA. In other words, water depth ranges of 0–0.4 m for the upper reach section and 1.6–2.0 m for the middle and lower reach sections were adopted as the ecological water-depths for AEHRA in the non-spawning seasons, as shown in Table 6.

For the viscid egg fish such as *Carassius auratus* and *Misgurnus anguillicaudatus*, a water depth at least 0.30 m is required for these eggs to be successfully laid and hatched (Wang and Li, 2010). This depth was then coupled with the ecological water depth in non-spawning seasons as the ecological water depth for AEHRA. In general, 0.3–0.4 m water depth was suitable for fish in the upper reach section during their spawning seasons between April and May while 1.6–2.0 m depth was required in the middle and lower reach sections in the spawning seasons from April to July, as values with asterisk shown in Table 6.

Similarly, the flow velocity at the 3rd and 4th gradients had a higher proportion of healthy sites (with *RF* greater than 50%) (Fig. 4 solid line), i.e., the flow velocity range of the two gradients (0.38–0.76 m s^{-1}) is expected to be helpful in maintaining the habitat health of the study river. After having been coupled with flow-velocity outcomes from Sections 3.2 and 3.3, ranges of 0.57–0.76 m s^{-1} for the upper reach section and 0.38–0.76 m s^{-1} for the middle and lower reach sections were respectively taken as the ecological flow-velocities for AEHRA, as listed in Table 5.

Overall, water depth ranges of 0–0.4 m (0.3–0.4 m in the spawning seasons) for the upper reach section and 1.6–2.0 m for the middle and lower reach sections were adopted as the ecological water-depths for AEHRA; flow velocity of 0.57–0.76 m s^{-1} for the upper reach section and 0.38–0.76 m s^{-1} for the middle and lower reach sections were taken as ecological flow-velocities for AEHRA.

Table 6
Ecological water-depth based on requirement on water-depth of the four key fish species (m).

Month	Upper reach	Middle reach	Lower reach
Jan	<0.40	1.60–2.00	1.60–2.00
Feb	<0.40	1.60–2.00	1.60–2.00
Mar	<0.40	1.60–2.00	1.60–2.00
April	0.30–0.40*	1.60–2.00*	1.60–2.00*
May	0.30–0.40*	1.60–2.00*	1.60–2.00*
June	<0.40	1.60–2.00*	1.60–2.00*
July	<0.40	1.60–2.00*	1.60–2.00*
Aug	<0.40	1.60–2.00	1.60–2.00
Sept	<0.40	1.60–2.00	1.60–2.00
Oct	<0.40	1.60–2.00	1.60–2.00
Nov	<0.40	1.60–2.00	1.60–2.00
Dec	<0.40	1.60–2.00	1.60–2.00

*: spawning season.

3.5. Assessment of e-flows and their supply rates for the Xiaoqing River using AEHRA

With ecological flow-velocity (Table 5) and water-depth (Table 6), monthly e-flows for the upper, middle and lower reach sections were calculated by using AEHRA (Eq. (3)), as shown in Fig. 5. Generally, the upper reach section had the highest e-flows requirement (170–429 $m^3\ s^{-1}$), the lower reach section ranked second (44–432 $m^3\ s^{-1}$) while the middle reach section had the lowest e-flows requirement (20–295 $m^3\ s^{-1}$). In detail, the greatest maximum e-flows requirement was recorded in the upper and lower reach sections; the minimum e-flows requirement was least in the middle reach section. Overall both the maximum and minimum e-flows occurred in the middle reach section.

Using the data of e-flows and actual monthly river flows for 2015, the e-flows supply rate (ratio of actual flow to e-flow) was calculated, as shown in Fig. 6. The e-flows supply rate was lowest in the upper reach section (Fig. 6: a) due to its highest e-flows requirement and lower actual river flows (Fig. 7: a). The lower river flows in the upper reach come from its relatively smaller

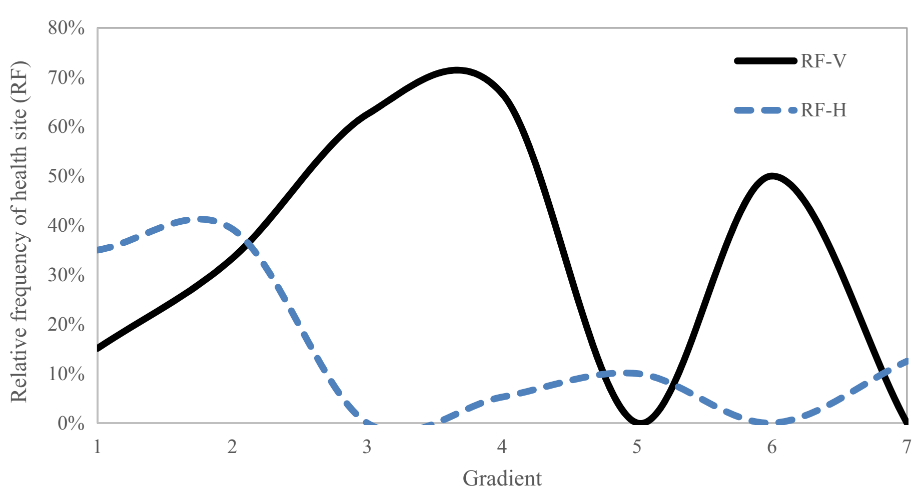

Fig. 4. Response of ecosystem health to flow velocity and water depth. Seven gradients of the two habitat indices are presented according to their range in the three Jinan-Xiaoqing-River field campaigns for fish and their habitats.

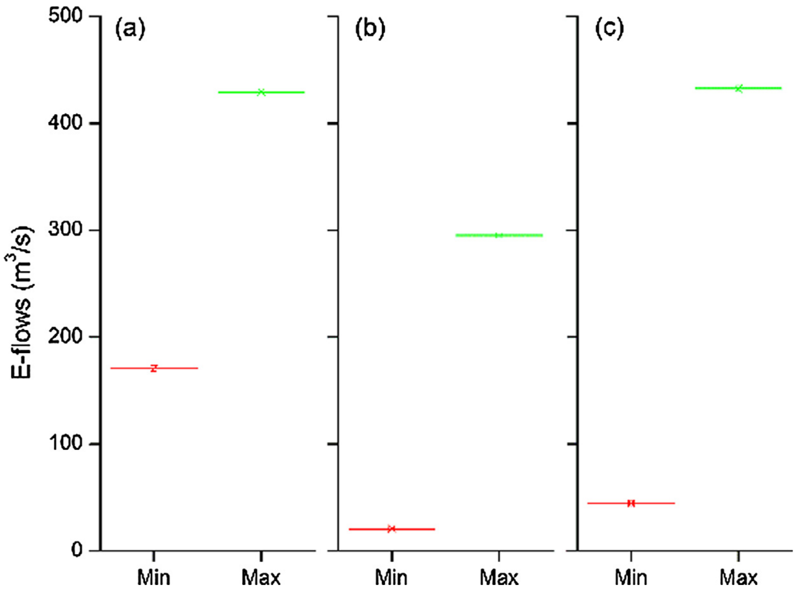

Fig. 5. Calculated e-flows for the upper (a), the middle (b) and the lower (c) reach sections.

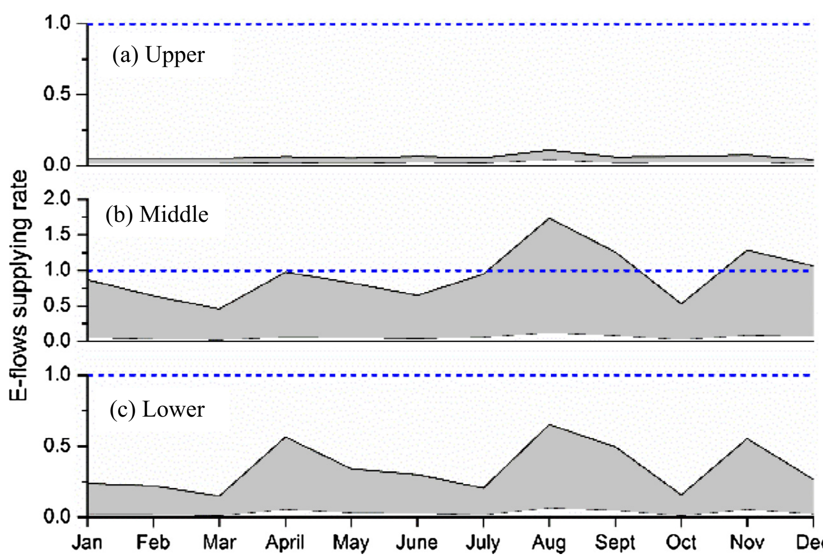

Fig. 6. E-flows supply rate in the dry year 2015. Dash line indicates rate of 1.0 below which e-flows requirements are not met. Gray area: e-flow requirement meeting range with bottom line being the meeting rate for the maximum e-flow requirement and top line being that for the minimum requirement.

catchment size compared with that of the middle and lower reach sections. In contrast, the e-flows supply rate was highest in the middle reach section attributing to its lowest e-flows requirement and highest actual river flows (Fig. 7: a).

In summary, the e-flows requirements across the year 2015 in the upper and lower reach sections were not met. E-flows requirement in the middle reach section was met for less than half a year (from July to December apart from October).

4. Discussion

4.1. Assessment of e-flows and their supply rate for the Xiaoqing River using AEHRA

Compared with natural rivers, the e-flows structure in the Xiaoqing River seemed abnormal. The upper reach section had the highest requirement while the middle reach section had the lowest requirement. This abnormality is attributed to the unique characteristics of this river. Urbanization in Jinan City increased the frequency of storms and floods (Huang and He, 2011). To deal with these disasters the upper reach section of Xiaoqing River was artificially widened and deepened to form a rectangular cross section (Fig. 8: a). This modified section captures rainfall and wastewater from Jinan City. The middle and lower reach sections, which have parabolic cross-sections and not artificially modified (Fig. 8: b&c) receive runoff from the catchment, point and non-point wastewater as well as backwater from farmlands. The rectangular cross section of the upper reach section has the capacity to receive larger flows than that of the parabola-shape cross-sections in the middle and lower reach sections even under conditions of the same ecological flow-velocity and water-depth. Besides, the upper reach section has almost the same depth as the middle and lower reach sections (the maximum water-depth: ∼ 10 m), contrary to the

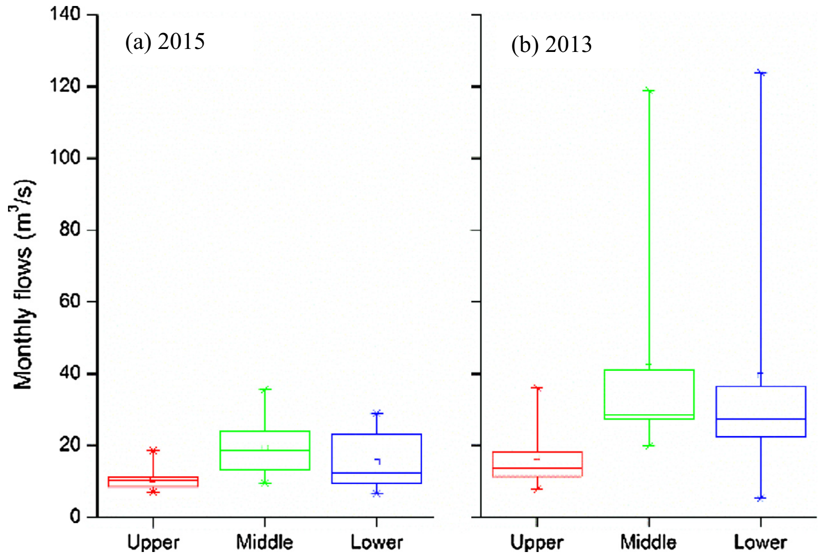

Fig. 7. Actual monthly river flows in the three reach section in 2015 (a) and 2013(b). Upper and lower crosses: 99% and 1% of flows; highest and lowest whiskers: maximum and minimum flows; upper and lower edges of the center box: 75% and 25% of flows; inner box: mean flow.

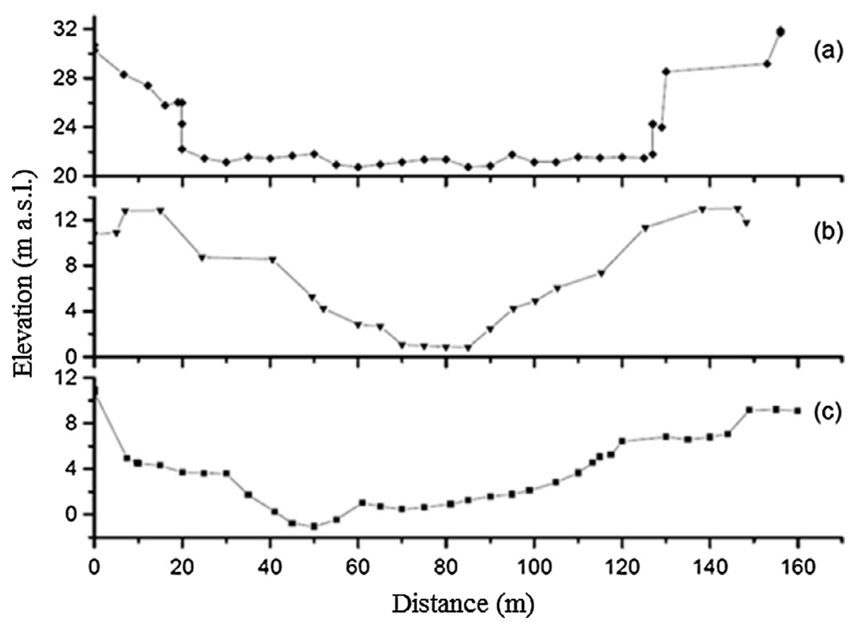

Fig. 8. Cross-sections of the upper (a), middle (b) and lower (c) reach sections.

traditional impression of a natural river –deeper in upper but shallower in lower reach section. This further aggravates the abnormality in the e-flows to maintain a healthy fish-community.

As to the e-flow supply rates, the upper reach section had the lowest rate while the middle reach section had the highest rate with the lowest reach section ranking second. There are two causes for this. In addition to the spatial difference in e-flows in the upper and middle reach sections, the actual river flow particularly the extreme maximum and minimum values contrasting to those of e-flows is a second critical cause. On average the middle reach had the highest river flows among the three reach sections, as shown in Fig. 7, both in the dry year 2015 (left) and wet year 2013 (right).

Though river flows on average for the Xiaoqing River Basin are relatively low due to periodic dry years such as in 2015 (Fig. 7: left), those in the wet years such as in 2013 (Fig. 7: right) are not improved to a large degree. Comparatively mean flows in the upper reach section in the wet year 2013 are at most 10 $m^3\ s^{-1}$ higher than that in the dry year 2015, and those in the middle and lower reach sections in 2013 are at most 20 $m^3\ s^{-1}$ higher than that in 2015. However, maximum values in the three reach sections in the wet year were substantially higher than that in the dry year, but are especially prominent in the middle and lower reach sections, as shown in Fig. 7.

To further illustrate this, the e-flows supply rate in the wet year 2013 was also calculated (Fig. 9). Increment in river flows in the wet year improved the e-flows supply rate, i.e. the meeting rate, compared with those in the dry year 2015 (Fig. 6). It is especially evident in the middle reach section (middle sub-figure in Fig. 9) where the minimum e-flows requirement (top line of gray area) can be met. In the lower reach section (low sub-figure in Fig. 9), the minimum e-flows requirement can be met in wet seasons from

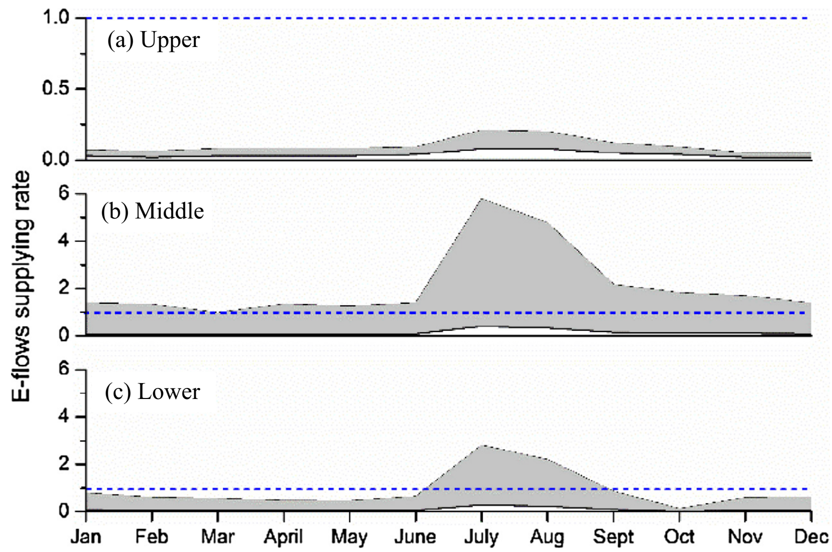

Fig. 9. E-flows supply rate in the wet year 2013. Dash line indicates rate of 1.0 under which e-flows were not met. Gray area: e-flows meeting range with the bottom line being the meeting rate for the maximum e-flows requirement and top line being that for the minimum requirement.

July to September. However, the situation for the upper reach section (top sub-figure in Fig. 9) remained unchanged because both maximum and minimum e-flows requirements were not met in 2013 despite it being a wet year.

Dash line indicates rate of 1.0 under which e-flows were not met. Gray area: e-flows meeting range with the bottom line being the meeting rate for the maximum e-flows requirement and top line being that for the minimum requirement.)

In general, upstream urbanization-induced discharge into rivers resulted in abnormalities in river-course geomorphology, remarkably different from natural rivers, which further led to abnormalities in e-flows structure in the Xiaoqing River. The consequence is that e-flows across the dry year 2015 in the upper and lower reach sections were not met. In contrast, e-flows in the wet year 2013 were met in the middle reach section and partly met in the lower reach section, but were not met in the upper reach section where the wide rectangular man-made cross-section ensured safe flood control but failed to protect the aquatic ecosystems.

4.2. Selection of key fish species

In contrast to the subjective way key fish species in previous studies were selected (Liu et al., 2011; Zhao et al., 2015a,b) key fish species in our study were objectively selected based on the actual foodweb of the studied aquatic ecosystems by considering all biota and their resources including fish, phytoplankton, zooplankton, zoobenthos as well as aquatic plants and detritus. In this way four species, *Carassius auratus*, *Misgurnus anguillicaudatus*, *Hemiculter leucisculus* and *Oryzias latipes*, were selected as representatives of functional groups related to fish communities. Similarly with our research, *Carassius auratus* and *Hemiculter leucisculus* were also identified as the most abundant fish species in the Xiaoqing River accounting for more than 70% of the total number of fish sampled in 2013 (Wu, 2015). *Misgurnus anguillicaudatus* was also detected but not as one of dominant species as its presence/absence and densities were recorded, but without biomass data in the research of Wu (2015). Both abundance and biomass are important attributes to assess the existence and health of any biotic community (Zhao et al., 2014 & Zhao et al., 2015a). In general, selection of key fish species in our study based on the foodweb and trophic levels of aquatic ecosystems is able to reflect both the biotic and abiotic processes in the ecosystems. Influences on habitat use through biotic and abiotic interactions occurring in ecosystems (Zhou et al., 2014) were considered. The selected key fish species can also represent functional groups related to fish communities. Stream flows adequate to maintain fisheries are usually sufficient to maintain other aquatic life (Parker et al., 2004; Liu et al., 2011). Therefore, the selected key species can be practically used as indicators of aquatic ecosystems of the study River.

4.3. Improvement on the HSI model when determining key input variables for AEHRA

Zhang et al. (2017b) recommended e-flows of 4.28–23.52 $m^3\ s^{-1}$, 0.74–8.65 $m^3\ s^{-1}$, 3.47–37.38 $m^3\ s^{-1}$ for the upper, middle and lower reach sections of the Xiaoqing River with AEHRA (Liu et al., 2011). However, their recommendations are much lower than ours although the same method was used. The reason for this difference is due to different way in determining key input variables for AEHRA. They used the univariate HSI model and the minimum-maximum method to determine the key variables, flow-velocity and water-depth instead of using MHSI with the addition of relative frequency of available habitat as was done in our study. Determination of the key variables is extremely crucial in correctly applying AEHRA.

Water-depth and flow-velocity constitute the key instream habitat descriptors (Brown and Pasternack, 2009; Melcher and Schmutz, 2010; Boavida et al., 2013). They were comprehensively determined in our study by considering the habitat preference (HSI) of key fish species as well as the ecosystem health (IBI) maintenance requirement on flow velocity. In other words, both requirements on flow-velocity water-depth of key species individuals and integral ecosystem health are comprehensively accounted for in our study.

As to HSI models the univariate ones have frequently been criticized on the basis that fish may select suitable combinations of all physical habitat variables, and functional habitats have been shown to be associated with distinct combinations of depth and velocity rather than with depth and velocity separately (Kemp et al., 1999; Boavida et al., 2013). To avoid this deficiency, a combination of flow velocity and water depth was adopted to assess e-flows in our study. Besides, in order to meet the comprehensive requirements of multiple key species on the two variables and their combinations, the multivariate HSI, or multi-species-based HSI (MHSI) (Zhao et al., 2015b) was improved and used in our study with the addition of the relative frequency of available habitats which effectively reduces the uncertainties when determining ecologically preferred flow-velocity and water-depth regimes.

Traditional HSI model integrates only population attributes (presence/ absence and number of individuals) with indices of physical factors that relate to the inhabited environments of the studied species. Biomass of the studied species was left out, despite the fact that it is an important attribute for the existence and health of any biotic community (Zhao et al., 2014 & Zhao et al., 2015a). To improve the performance of the HSI model the dominance of key species, an integrated variable of density and biomass, was integrated into this model in our study to comprehensively determine the preferred ecological flow-velocity and water-depth regimes as input variables of AEHRA.

Thus AEHRA potentially works better than traditional methodologies with these improvements, reflecting comprehensive requirements on e-flows of the whole aquatic ecosystems which are represented by key fish species determined by using the food-web model.

4.4. Comparison of AEHRA with other methodologies

To overcome the shortcomings of the River2D model, which is unsuitable for application to large scale catchment with intensive human disturbance, in this study the foodweb model Ecopath was initially used to select key fish species. The selected key fish species were then used to determine the ecological flow velocity and water-depth for AEHRA which was initially developed for large scale, anthropogenically modified rivers but has been successfully applied to natural rivers (Liu et al., 2011). This potentially allows the AEHRA to be applied to micro-habitat scale studies like the River2D model. It can also be applied to large scale studies. Moreover, presence/absence, biomass and dominance attributes of the key fish species were integrated into e-flows assessment with AEHRA, which differed from other micro-scale methodologies that used only presence/ absence and density attributes (Nukazawa et al., 2011). To determine flow-velocity and water-depth at large spatial scales, AEHRA can take into account the spatial links between habitats which have been ignored previously (Jorde et al., 2000; Mouton et al., 2007; Zhou et al., 2014).

To test the results of AEHRA, we compared them with those by Tennant (Zhang et al., 2017a). According to Tennant (1976), to maintain the health of aquatic ecosystems 10% annual-average natural river flows are the minimum threshold below which the health degrades severely, and 30% can support a better habitat for most river biota. Tennant recommended 9–16 $m^3\ s^{-1}$ for the upper reach section, 20–34 $m^3\ s^{-1}$ for the middle reach section, 18–31 $m^3\ s^{-1}$ for the lower reach section as optimum e-flows; and recommended 32 $m^3\ s^{-1}$, 67 $m^3\ s^{-1}$ and 61 $m^3\ s^{-1}$ as the maximum e-flows for the three reach sections, respectively (Zhang et al., 2017a). While AEHRA in our study recommends e-flows of 170–429 $m^3\ s^{-1,}$ 20–295 $m^3\ s^{-1}$ and 44–432 $m^3\ s^{-1}$ for the upper, middle and lower reach sections, respectively, the minimum value of e-flows in the upper reach section is much higher than that of Tennant's study (32 $m^3\ s^{-1}$) while those in the middle and lower reach sections are respectively within Tennant's range. As stated in Section 4.1, the artificially constructed rectangular-shaped cross-section in the upper reach section (Fig. 8: a) required much larger flows than the parabola-shape cross-sections in the middle and lower reach sections (Fig. 8: b&c) under the same ecological flow-velocity and water-depth regimes.

Zhang et al. (2014) took hydrological frequency of river flow in dry season as basis to calculate the minimum e-flows for the middle reach section of the Xiaoqing River. They recommended e-flows of 4.8 $m^3\ s^{-1}$ for January through March, 3.2 $m^3\ s^{-1}$ for April through June, 10.0 $m^3\ s^{-1}$ for July to September and 5.7 $m^3\ s^{-1}$ for October to December. The results are within the levels of "Poor" to "Good" (3.36–6.72/10.08 $m^3\ s^{-1}$) based on Tennant's classification in the research of Zhang et al. (2017a) and much lower than the minimum value of 20 $m^3\ s^{-1}$ in our study. As April to June is the fish spawning season their recommendation of 3.2 $m^3\ s^{-1}$ (Zhang et al., 2014), which is much lower than their recommendations of 4.8–10.0 $m^3\ s^{-1}$ in non-spawning seasons, can hardly be justified to maintain ecosystem health. In contrast AEHRA, like Tennant, recommend e-flows in spawning seasons that are larger than or at least equal to those in non-spawning seasons, which provide greater potential to rehabilitate degrading ecosystems.

In short, AEHRA in this study can be applied not only to large-scale rivers but micro-scale streams with or without intensive human disturbance, fully considering spatial links between habitats and requirements of fish over the spawning seasons, and provide greater potential to rehabilitate degrading ecosystems.

However, some other issues still have to be addressed in future when applying the HSI model which contribute to uncertainties to AEHRA to some degree: (a) habitat requirements of species depend on life stage and river type (Jungwirth et al., 2000; Zhou et al., 2014) and their preferences change between flow seasons (Santos and Ferreira, 2008); (b) many possible interactions between physical variables of the habitat are neglected (Jorde et al., 2000; Mouton et al., 2007; Zhou et al., 2014), such as sediment and erosion, water quality etc.; (c) the assumption that habitat use reflects habitat preference is rarely validated. Whether fish species are indeed selecting areas of previously determined higher preference is still in need of an answer (Boavida et al., 2013). Clearly, future studies should carefully address the above issues in an attempt to advance our knowledge about the mechanisms of ecosystems' performance and hence to understand more precisely e-flows requirements of aquatic ecosystems.

5. Conclusions

Fully accounting for river health during the e-flows assessment in rivers highly impacted by human activities is extremely important for effective ecosystem rehabilitation. This study primarily evaluated preferred key habitat variables based on the foodweb model, dominance model and habitat suitability model with both population and biomass of fish communities fully considered. Additionally, a multi-species-based HSI (MHSI) model was improved and used to further evaluate the fish-preferred key habitat variables. The key variables, flow-velocity and water-depth, were then adjusted by considering fish requirements during their spawning seasons. The two key variables with consideration of habitat health were finally used to drive AEHRA to estimate e-flows for the study river.

Results showed that the upper reach section had the highest requirement of e-flows while the middle reach section had the lowest requirement. The e-flows supply rate was lowest in the upper reach section while the highest was in the middle reach section. The e-flows requirement in the upper and lower reach sections was far from being met across the dry year. Further analysis indicates that upstream urbanization-induced large discharge into rivers resulted in abnormal river-course geomorphology and hence in e-flows requirement in the anthropogenically impacted Xiaoqing River, which is substantially different from natural rivers.

Comparison of the AEHRA results with that of other methodologies implies that the AEHRA-based e-flow-method in this study, which reflects comprehensive requirement on the critical hydrological attributes of the whole aquatic ecosystems, can be applied to both large-scale river and micro-scale stream systems with or without intensive human disturbance. Selection of key species based on the foodweb and trophic levels of aquatic ecosystems can reflect both the biotic and abiotic processes in the ecosystem. This greatly increases its potential to be used as a guidance tool to rehabilitate degrading ecosystems at large spatial scales all over the world. Uncertainties in the method can be effectively reduced by judiciously accounting for life stage, river type and flow seasons as well as further studying interactions between physical habitat variables.

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References

Acreman, M.C., Ferguson, A.J.D., 2010. Environmental flows and the European water framework directive. Freshw. Biol. 55 (1), 32–48.
Ahmadi Nedushan, B., St Hilaire, A., Bérubé, M., Robichaud, É., Thiémonge, N., Bobée, B., 2006. A review of statistical methods for the evaluation of aquatic habitat suitability for instream flow assessment. River Res. Appl. 22 (5), 503–523.
Asaeda, T., Manatunge, J., 2007. Physiological responses of topmouth gudgeon, Pseudorasbora parva, to predator cues and variation of current velocity. Aquat. Ecol. 41 (1), 111–118.
Boavida, I., Santos, J.M., Katopodis, C., Ferreira, M.T., Pinheiro, A., 2013. Uncertainty in predicting the fish-response to two-dimensional habitat modeling using field data. River Res. Appl. 29 (9), 1164–1174.
Bobbi, C.J., Warfe, D.M., Hardie, S.A., 2014. Implementing environmental flows in semi regulated and unregulated rivers using a flexible framework: case studies from tasmania, Australia. River Res. Appl. 30 (30), 578–592.
Brown, R.A., Pasternack, G.B., 2009. Comparison of methods for analysing salmon habitat rehabilitation designs for regulated rivers. River Res. Appl. 25 (6), 745–772.
Casatti, L., Ferreira, C.P., Langeani, F., 2009. A fish-based biotic integrity index for assessment of lowland streams in southeastern Brazil. Hydrobiologia 623 (1), 173–189.
Christensen, V., Pauly, D., 1992. ECOPATH II—a software for balancing steady-state ecosystem models and calculating network characteristics. Ecol. Model. 61 (3–4), 169–185.
Colvin, M.E., Pierce, C.L., Stewart, T.W., 2015. A food web modeling analysis of a midwestern, usa eutrophic lake dominated by non-native common carp and zebra mussels. Ecol. Model. 312, 26–40.
Cui, B., Wang, C., Tao, W., You, Z., 2009. River channel network design for drought and flood control: a case study of Xiaoqinghe River basin, Jinan City, China. J. Environ. Manage. 90 (11), 3675–3686.
Davic, R.D., 2003. Linking keystone species and functional groups: a new operational definition of the keystone species concept. Ecol. Society 7 (1).
Essington, T.E., 2007. Evaluating the sensitivity of a trophic mass-balance model (ecopath) t. Can. J. Fish. Aquat. Sci. 64 (4), 628–637.
Gard, Mark., 2009. Comparison of spawning habitat predictions of phabsim and river2d models. Int. J. River Basin Manage. 7 (1), 55–71.
Gopal, B., 2013. Environmental Flow – an Introduction for Water Resource Managers. National Institute of Ecology, New Delhi.
Hampton, M., 1988. Development of Habitat Preference Criteria for Anadromous Salmonids of the Trinity River. US Fish & Wildlife Service, Division of Ecological Services.
Huang, G.R., He, H.J., 2011. Impact of urbanization on features of rainfall during flood period in Jinan City [J]. Journal of Natural Disasters 3, 002 (in Chinese).
Joniak, T., Kuczyńska-Kippen, N., 2010. The chemistry of water and bottom sediments in relation to zooplankton biocenosis in small agricultural ponds. Oceanol. Hydrobiol. Studies 39 (2), 85–96.
Jorde, K., Schneider, M., Zöllner, F., 2000. Analysis of instream habitat quality–preference functions and fuzzy models. Stoch. Hydraul., 671–680
Jungwirth, M., Muhar, S., & Schmutz, S. (2000). Fundamentals of fish ecological integrity and their relation to the extended serial discontinuity concept. In Assessing the Ecological Integrity of Running Waters (pp. 85–97). Springer, Netherlands.
Karr, J.R., 1981. Assessment of biotic integrity using fish communities. Fisheries 6 (6), 21–27.
Katopodis, C., Ghamry, H.K., 2007. Hydrodynamic and physical assessment of ice-covered conditions for three reaches of the Athabasca River, Alberta, Canada. Can. J. Civ. Eng. 34 (6), 717–730.
Kemp, J.L., Harper, D.M., Crosa, G.A., 1999. Use of 'functional habitats' to link ecology with morphology and hydrology in river rehabilitation. Aquat. Conserv. 9 (1), 159–178.
King, A.J., Tonkin, Z., Mahoney, J., 2009. Environmental flow enhances native fish spawning and recruitment in the Murray River, Australia. River Res. Appl. 25 (10), 1205–1218.
Langerhans, R.B., 2008. Predictability of phenotypic differentiation across flow regimes in fishes. Integr. Comp. Biol. 48 (6), 750–768.
Leclerc, M., Saint-Hilaire, A., Bechara, J., 2003. State-of-the-art and perspectives of habitat modelling for determining conservation flows. Can. Water Resour. J. 28 (2), 135–151.
Liu, C., Zhao, C., Xia, J., Sun, C., Wang, R., Liu, T., 2011. An instream ecological flow method for data-scarce regulated rivers. J. Hydrol. 398 (1), 17–25.
Melcher, A. H., & Schmutz, S. (2010). The importance of structural features for spawning habitat of nase Chondrostoma nasus (L.) and barbel Barbus barbus (L.) in a pre-Alpine river. River Systems, 19(1), 33–42.
Mouton, A.M., Schneider, M., Depestele, J., Goethals, P.L., De Pauw, N., 2007. Fish habitat modelling as a tool for river management. Ecol. Eng. 29 (3), 305–315.
Nukazawa, K., Shiraiwa, J.I., Kazama, S., 2011. Evaluations of seasonal habitat variations of freshwater fishes, fireflies, and frogs using a habitat suitability index model that includes river water temperature. Ecol. Model. 222 (20), 3718–3726.
Oberdorff, T., Pont, D., Hugueny, B., Porcher, J.P., 2002. Development and validation of a fish-based index for the assessment of 'river health'in France. Freshw. Biol. 47 (9), 1720–1734.
Paredes, J., Solera, A., Martinez-Capel, F., Momblanch, A., Andreu, J., 2014. Integrating water management, habitat modelling and water quality at the basin scale and environmental flow assessment: case study of the Tormes River, Spain. Hydrol. Sci. J. 59 (3–4), 878–889.
Parker, G.W., Armstrong, D.S., Richards, T.A., 2004. Comparison of Methods for Determining Streamflow Requirements for Aquatic Habitat Protection at Selected Sites on the Assabet and Charles Rivers, Eastern Massachusetts, 2000–02. US Department of the Interior, US Geological Survey.
Perry, N., 2010. The ecological importance of species and the Noah's Ark problem. Ecol. Econ. 69 (3), 478–485.
Poff, N.L., Allan, J.D., Palmer, M.A., Hart, D.D., Richter, B.D., Arthington, A.H., Stanford, J.A., 2003. River flows and water wars: emerging science for environmental decision making. Front. Ecol. Environ. 1 (6), 298–306.
Poff, N.L., Richter, B.D., Arthington, A.H., Bunn, S.E., Naiman, R.J., Kendy, E., Ellipsis & Henriksen, J., 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshw. Biol. 55 (1), 147–170.
Qadir, A., Malik, R.N., 2009. Assessment of an index of biological integrity (IBI) to quantify the quality of two tributaries of river Chenab, Sialkot, Pakistan. Hydrobiologia 621 (1), 127–153.
de Souza, Rodrigues., Castro, E.R.R., Moreira, M.C., da Silva, D.D., 2016. Environmental flow in the River Ondas basin in Bahia, Brazilian Cerrado. Environ. Monitor. Assessment 188 (1), 68.
Sanderson, J.S., Rowan, N., Wilding, T., Bledsoe, B.P., Miller, W.J., Poff, N.L., 2012. Getting to scale with environmental flow assessment: the watershed flow evaluation tool. River Res. Appl. 28 (9), 1369–1377.
Santos, J.M., Ferreira, M.T., 2008. Microhabitat use by endangered Iberian cyprinids nase Iberochondrostoma almacai and chub Squalius aradensis. Aquat. Sci. 70 (3), 272–281.
Schamberger, M. L., & O'Neil, L. J., (1986). Concepts and Constraints of Habitat-model Testing. Wildlife 2000: Modeling Habitat Relationships of Terrestrial Vertebrates, Madison, Wisconsin. USA: University of Wisconsin Press: 5–10.
Sempeski, P., Gaudin, P., 1995. Habitat selection by grayling—I. Spawning habitats. J. Fish Biol. 47 (2), 256–265.
Smith, A., Katopodis, C., & Steffler, P. (2002). Assessment of flow characteristics of fish habitat structures in a constructed tundra channel using the River2D finite element model. In Proceedings of 4th ecohydraulics symposium and conference on environmental flows for river systems. Cape Town, South Africa.
Sobczyński, T., Joniak, T., 2013. The variability and stability of water chemistry in a deep temperate lake: results of long-term study of eutrophication. Polut. J. Environ. Stud. 22 (1), 227–237.
Steffler, P., Waddle, T., 2002. Mesh Generation Program for River2D Two Dimensional Depth Averaged Finite Element: Introduction to Mesh Generation and User's Manual. University of Albert, Edmomton, p. 31.
Steffler, P., & Blackburn, J. (2002). Two-dimensional depth averaged model of river hydrodynamics and fish habitat. River2D user's manual, University of Alberta, Canada.
Tejerina-Garro, F.L., de Mérona, B., Oberdorff, T., Hugueny, B., 2006. A fish-based index of large river quality for French Guiana (South America): method and preliminary results. Aquat. Living Resour. 19 (1), 31–46.
Tennant, D.L., 1976. Instream flow regimens for fish, wildlife, recreation, and related environmental resources. In: Orsborn, J.F., Allman, C.H. (Eds.), Proceedings of

Symposium and Specility Conference on Instream Flow Needs II. American Fisheries Society, Maryland, Bethesda, pp. 359–373.
Vadas Jr, R.L., Orth, D.J., 2001. Formulation of habitat suitability models for stream fish guilds: do the standard methods work? Trans. Am. Fish. Soc. 130 (2), 217–235.
Valls, A., Coll, M., Christensen, V., 2015. Keystone species: toward an operational concept for marine biodiversity conservation. Ecol. Monogr. 85 (1), 29–47.
Vismara, R., Azzellino, A., Bosi, R., Crosa, G., Gentili, G., 2001. Habitat suitability curves for brown trout (Salmo trutta fario L.) in the River Adda, Northern Italy: comparing univariate and multivariate approaches. Regul. Rivers Res. Manage. 17 (1), 37–50.
Waddle, T. J., & Bovee, K. D. (2010). Environmental flow studies of the Fort Collins Science Center, US Geological Survey-Cherry Creek, Arizona (No. 2009–1272). US Geological Survey.
Walsh, C.J., Fletcher, T.D., Burns, M.J., 2012. Urban stormwater runoff: a new class of environmental flow problem. PLoS ONE 7 (9), e45814.
Wang, R., Li, J., 2010. Influence of water-depth, flow-velocity and water-temperature variation at hydroelectric station on fish spawning. Sichuan Water Power 2010 (2), 76–79 (in Chinese).
Wu, J. (2015). The ecological health assessment of Xiaoqing Rvier based on biotic integrity index of fish. Dissertation of Shandong University. (in Chinese).
Wu, W., Xu, Z., Yin, X., Zuo, D., 2014. Assessment of ecosystem health based on fish assemblages in the Wei River basin. China. *Environmental monitoring and assessment* 186 (6), 3701–3716.
Yi, Y.J., Cheng, X., Zhou, J., 2013. Research progress in habitat suitability assessment methods. Ecol. Environ. Sci. 22 (5), 887–893.
Yu, C.S., Wang, Y.L., 2006. Problems and their countermeasures of flood control in the basin of Xiaoqinghe River. Water Resour. Dev. Res. 2, 39–41 (in Chinese).
Zhang, T., Li, G.J., Ran, L.H., 2014. Minimum ecological flow calculation of river channel based on frequency method. Yellow River 3, 32–34 (in Chinese).
Zhang, Y., Zhao, C.S., et al. (2017a). A method to calculate e-flows by coupling multi-species' flow velocity requirement. Journal of Beijing Normal University (Natural Sciences), in press. (in Chinese).
Zhang, Y., Zhao, C.S., et al. (2017b). Calculating e-flows based on key functional group. South-to-North Water-Transfers and Water Science & Technology, in press. (in Chinese).
Zhang, Y., et al. (2017c). A method to build key functional group based on ecological model Ecopath. South-to-North Water-Transfers and Water Science & Technology, in press. (in Chinese).
Zhao, C.S., Yang, S.T., Liu, C.M., Dou, T.W., Yang, Z.L., Yang, Z.Y., Mitrovic, S.M., 2015a. Linking hydrologic, physical and chemical habitat environments for the potential assessment of fish community rehabilitation in a developing city. J. Hydrol. 523, 384–397.
Zhao, C.S., Yang, S.T., Xiang, H., Liu, C.M., Zhang, H.T., Yang, Z.L., Ellipsis & Lim, R.P., 2015b. Hydrologic and water-quality rehabilitation of environments for suitable fish habitat. J. Hydrol. 530, 799–814.
Zhao, C., Liu, C., Xia, J., Zhang, Y., Yu, Q., Eamus, D., 2012. Recognition of key regions for restoration of phytoplankton communities in the Huai River basin, China. J. Hydrol. 420, 292–300.
Zhao, C., Sun, C., Liu, C., Xia, J., Yang, G., Liu, X., Sobkowiak, L., 2014. Analysis of regional zoobenthos status in the Huai River Basin, China, using two new ecological niche clustering approaches. Ecohydrology 7 (1), 91–101.
Zhou, J., Zhao, Y., Song, L., Bi, S., Zhang, H., 2014. Assessing the effect of the Three Gorges reservoir impoundment on spawning habitat suitability of Chinese sturgeon (Acipenser sinensis) in Yangtze River, China. Ecol. Informatics 20, 33–46.