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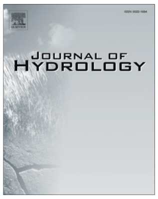

Hydrologic and water-quality rehabilitation of environments for suitable fish habitat

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SUMMARY

Aquatic ecological rehabilitation is attracting increasing public and research attention, but without knowledge of the responses of aquatic species to their habitats the success of habitat restoration is uncertain. Thus efficient study of species response to habitat, through which to prioritize the habitat factors influencing aquatic ecosystems, is highly important. However many current models have too high requirement for assemblage information and have great bias in results due to consideration of only the species' attribute of presence/absence, abundance or biomass, thus hindering the wider utility of these models. This paper, using fish as a case, presents a framework for identification of high-priority habitat factors based on the responses of aquatic species to their habitats, using presence/absence, abundance and biomass data. This framework consists of four newly developed sub-models aiming to determine weightings for the evaluation of species' contributions to their communities, to quantitatively calculate an integrated habitat suitability index for multi-species based on habitat factors, to assess the suitable probability of habitat factors and to assess the rehabilitation priority of habitat factors. The framework closely links hydrologic, physical and chemical habitat factors to fish assemblage attributes drawn from monitoring datasets on hydrology, water quality and fish assemblages at a total of 144 sites, where 5084 fish were sampled and tested. Breakpoint identification techniques based on curvature in cumulated dominance along with a newly developed weighting calculation model based on theory of mass systems were used to help identify the dominant fish, based on which the presence and abundance of multiple fish were normalized to estimate the integrated habitat suitability index along gradients of various factors, based on their variation with principal habitat factors. Then, the appropriate probability of every principal habitat factor was estimated and graded, and the priority of habitat factors for rehabilitation was determined. Application of the model to Jinan City, a pilot city for the construction of a civilized and ecological city in China, proved effective, revealing that carbonate is the poorest habitat factor and has the highest priority for ecological rehabilitation. This was tested using two methods: alternative priority models and a dataset of all habitat factors in place of only the principal habitat factors. We also found that hydrological factors have higher priority than the water quality factors at the levels of both the whole city and its subordinate eco-regions and therefore that hydrological factors deserve special attention in the future ecosystem rehabilitation. Further, the current habitat state makes nearly half of the habitats in Jinan City undesirable for fish communities, largely due to long-term agricultural practices. Spatially, rivers in the mountainous region south of Jinan city and adjacent to the urban area and rivers in the agricultural region north of the city should be emphasized in future habitat rehabilitation. All of these findings have substantial ramifications for the rehabilitation of aquatic ecosystems in Jinan City as a reference for river ecological remediation in rivers with scarce ecological data worldwide.

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1. Introduction

Globally, climate change and human activities have strongly influenced the world in terms of land use, soil characteristics, hydrological regime, water quality, and biota in aquatic ecosystems (Xu, 2015). In particular, intensive human activities have been changing riverine environments in terms of their hydrology, pollutant loads and habitat attributes (Walters et al., 2009). Environmental variation can exert direct or indirect effects on species arranged along a gradient from proximal to distal attributes (Austin, 2002; Guisan and Thuiller, 2005). In aquatic ecosystems, species that are intolerant of these changes can decline or disappear and are replaced by organisms that are more tolerant (Fraker et al., 2002; Helms et al., 2005; Morgan and Cushman, 2005; Kemp, 2014). Biodiversity in aquatic ecosystems is thus negatively influenced, and degradation of aquatic ecosystems is therefore unavoidable (Svirčev et al., 2014).

Over the past several decades, water habitat restoration has been utilized as a strategy for recovering and conserving threatened and endangered species (Bernhardt et al., 2005) by which to recover the biodiversity and even the aquatic ecosystem health. However, the success of habitat restoration without knowledge of the response of aquatic species to their habitats is uncertain (Wissmar and Bisson, 2003; Bellmore et al., 2012). Hydrology and water quality are two principal attributes of aquatic habitats. Suitable habitats are very important for species survival and diversity in aquatic ecosystems. Improvement or at least maintenance of habitats is therefore necessary for the recovery of aquatic ecosystems (Bellmore et al., 2012). River restoration thus requires the identification of environmental and pressure gradients that affect river systems, especially in terms of hydrology and water quality, as well as the selection of suitable indicators to assess habitat quality before, during and after restoration (Hughes et al., 2010).

Many models, e.g., the most popular Maxent (VanDerWal et al., 2009) and ENFA (Vaclavik and Meentemeyer, 2012), link the response of species to the environmental habitat factors based on ecological niche. However, most are based only on either the presence/absence or biomass of species (Schroeder and Vangilder, 1997; VanDerWal et al., 2009), with a few based on the combination of presence and abundance (Ehrlén and Morris, 2015). These models have contributed greatly to the prediction of geographical spatial distribution of a few certain species. They can be generally classified into two categories inclusive of correlative and mechanistic models. Species distribution models, or SDMs, a set of correlative models also known as climate envelope models, habitat suitability models, niche models and resource selection functions (Elith and Leathwick, 2009; Elith et al., 2011; Araujo and Peterson, 2012), typically combine information about known locations where a species occurs with data about abiotic variables to predict the probability of occurrence of that species. The recently proposed dynamic range model (DRM), a set of mechanistic models simultaneously estimating population dynamics and dispersal, yields better niche estimates than state-of-the-art correlative SDMs (Schurr et al., 2012). However, the DRM has not yet been applied to real data, and its data requirements may be quite high (Ehrlén and Morris, 2015). Data collection and model construction require substantial knowledge about the biology of the study organism, and their parameterization for specific environments is typically labor-intensive (Holt, 2009; Schurr et al., 2012). The considerable effort required for the direct measurement of demographic responses and for the development of mechanistic niche models thus currently precludes the application of DRMs to large numbers of species (Schurr et al., 2012). Moreover, while very appealing at the species level, DRMs often require too much data to be of general use in nature management and biodiversity assessment (Guisan and Thuiller, 2005). More importantly, most previous models emphasized prediction of species-level indices instead of selecting the highest-priority habitat factors for rehabilitation.

By comparison, SDMs are easy to implement and are therefore more suitable for prioritizing habitat environmental factors and gradients for the sake of better maintenance or restoration of biodiversity and river ecosystems. “Distribution from place to place and abundance at different times are two aspects of the one fundamental problem.” (Birch, 1953; Ehrlén and Morris, 2015). Abundance is a far better measure of the effects of a species on its local ecosystem than simply whether it is present (Ehrlén and Morris, 2015). Moreover, abundance reflects the number of individuals of a species, while biomass reflects the size of a species. The demands of a large species on the local ecosystem are markedly different from those of a small species. Both of them are important for the existence and health of any biological community (Zhao et al., 2012, 2014, 2015). SDMs provide the likelihood of occurrence of the species by associating occurrence records with a suite of environmental variables. If these factors also influence abundance, it follows that sites with high environmental suitability will support populations at high abundance. In fact, abundance is often highly variable among sites within the distribution of a species. To our knowledge, the relationship between local abundance and environmental suitability predicted from presence-only data has not been properly investigated (VanDerWal et al., 2009). It is also worth noting that consideration of only abundance or biomass in estimation of species response to the abiotic habitat environment inevitably biases the results and that therefore consideration of both factors is urgently required.

Among all SDMs, the habitat suitability index (*HSI*) is widely used to indicate the degree of preference of species to different habitats (Leclerc et al., 2003; Ahmadi-Nedushan et al., 2006). It is often used to quantify the response of a species to a set of habitat factors on the assumption that a species would choose its optimal habitat (Schamberger and O’Neil, 1986). Habitat suitability is defined as the preference of an aquatic organism for a particular set of habitat attributes (Vadas and Orth, 2001; Vismara et al., 2001). However, its estimation of the preference of an aquatic organism usually target a single species (Wakeley, 1988; Tikkanen et al., 2007; Gong et al., 2012; Zohmann et al., 2013) rather than multiple species, which precludes the extension of the traditional *HSI* to multiple species or a community. It is therefore difficult to estimate the synthetic effect of a habitat factor on the ecosystem community. Consideration of multiple species’ responses to their abiotic habitat in the *HSI* is therefore crucial for the synthetic effect estimation of a habitat factor.

Among all of the communities in aquatic ecosystems, fish communities are effective ecosystem indicators as they are relatively easy to identify, and their position at the top of the food chain helps provide an integrative view of the environment (Wu et al., 2014). Habitat type and complexity, or habitat heterogeneity, influence resource use by many fish species (Okun and Mehner, 2005; Visintainer et al., 2006), along with biological interactions such as competition and predation (Coen et al., 1981; Danielson, 1991; Whitley and Bollens, 2014). Therefore, understanding the response of fish to habitat variation in terms of hydrology and water quality is important for habitat rehabilitation.

The objectives of this paper are to develop an effective framework for identifying the highest-priority habitat factors influencing the aquatic ecosystems based on the multiple fish responses in terms of presence/absence, abundance and biomass to their habitat environment. This framework is expected to require only basic information and expertise (fish assemblage: only the abundance and biomass of dominant fish species; fish names are unnecessary). These easily recorded fish attributes are then linked to habitat environmental gradients of hydrologic, physical and chemical parameters to determine the dominant species, estimate the probability of suitability and evaluate the rehabilitation priority of habitat factors for aquatic ecological rehabilitation.

2. Study area

The Spring City Jinan City (36.0–37.5°N, 116.2–117.7°E), a pilot city for the construction of a civilized and ecological city in China, is bordered by Mount Tai to the south and traversed by the Yellow River, and it 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. The average annual precipitation is 636 mm 75% of which falling during the high-flow periods. The average annual temperature is 14.3 °C. The average monthly temperature is highest in July, ranging from 26.8 to 27.4 °C, and lowest in January, ranging from −3.2 to −1.4 °C (Cui et al., 2009; Zhang et al., 2010). The city represents a typical developing city in China, with an area of 8227 km^2 and a population of 5.69 million (Zhang et al., 2007). With rapid industrial development and urbanization in recent decades, the water resources in Jinan are severely polluted and reduced in quantity through extraction. As a result, drinking water, human health and well-being are being increasingly threatened (Hong et al., 2010), as is the fish community. Policy-makers and stakeholders are aware of the need to rehabilitate the aquatic ecosystems in Jinan City. To facilitate research programs on rehabilitating these aquatic ecosystems, 48 routine monitoring stations distributed evenly on typical rivers were established (Fig. 1). At these monitoring stations, 37 parameters are concurrently measured, including hydrologic, physical and chemical environmental factors (Table 1). To ensure successful aquatic ecosystem restoration over all river sections, river administrators urgently require a practical method for identifying the highest-priority habitat factors and the highest-priority regions for rehabilitation.

3. Data

For rehabilitating aquatic ecosystems, three extensive field campaigns to concurrently monitor the fish community and their habitat attributes were conducted in 2014. In these campaigns, 37 parameters were measured, as shown in Table 1. The three types of habitat factors in Table 1 were measured or sampled concurrently with the fish sampling during three periods: May 1st–20th, August 2nd–21st and November 1st–20th, 2014.

Hydrologic and physical factors were measured in situ with portable equipment. Water samples for chemical analysis were collected at the monitoring sites and tested in the laboratory within 24 h. A spectrophotometer (DR5000) was used to measure ammonia nitrogen, total phosphorus, total nitrogen and hexavalent chromium; an atomic absorption spectrophotometer (Thermo M6) was used for tests of copper, zinc, cadmium, lead, and other heavy metals; and an ion chromatograph (DIONEX-600) was employed to measure sulfate, fluoride, chloride and nitrate concentrations. Of the 27 chemicals measured, the concentrations of many of them were at or below the limits of detection for more than 80% of the sampling sites and are thus not listed in Table 1.

Concurrently, fish were collected during 30 min in three habitat types (i.e., pools, riffles, and runs) within 500 m along river at each sampling site. Individuals caught from the three habitats were combined to represent a site. In wadeable streams, fish collection was performed by a two-person team (Barbour et al., 1999). In unwadeable streams, seine nets (mesh sizes of 30 and 40 mm) were used to collect fish from a boat. In addition, electrofishing was conducted to ensure that a good representation of fish species was collected at each site. All individuals collected were identified in situ to species according to Chen et al. (1987) and then counted, weighed and recorded in field data sheets. After that, all identified fish were released. A few specimens that could not be identified in the field were preserved in 10% formalin solution and stored in labeled jars for subsequent laboratory identification. Details can be found in Wu et al. (2014). In total, 37 fish species were recorded, and their abundance and biomass are listed in Table 2.

4. Methodologies

A newly developed methodology to detect the highest-priority hydrologic and water-quality indices for regional ecosystems rehabilitation was constructed based on the response of fish to their habitat. Four new methods are presented (a) to determine weightings for two-variable equations, (b) to quantitatively calculate the multi-species-based habitat suitable index for a habitat factor, (c) to assess the probability of suitability for a habitat factor, and (d) to determine the rehabilitation priority of a habitat factor. All of these methods have been integrated into the EcoHAT (the Ecohydrological Assessment Tool) (Liu et al., 2009; Dong et al., 2013), which was used for spatial interpolation of data sequences of habitat indices.

Weightings for the abundance and biomass of aquatic species in a community of, for example, fish, were first determined to select dominant species using the dominance index from the studies of Zhao et al. (2014, 2015), i.e., to identify the representative species in the community. Next, the habitat suitability index of every hydrology and water-quality index in the study community was determined quantitatively; afterwards, the probability of suitability was calculated and graded for every habitat factor. Using those calculations, the rehabilitation priority was determined for all habitat indices, thus allowing the mapping and analysis of the spatial distribution of the highest-priority habitat factors.

4.1. Determination of weightings using center of mass

Both abundance and biomass are important for the existence and health of any biological community (Zhao et al., 2014, 2015). A new method determining the weightings (Eq. (2)) for the dominant model (Eq. (1)) by Zhao et al. (2014, 2015) is presented, using the theory of center of mass (Fig. 2).

$$I_{importance,i} = \omega_1 P_{a,i} + \omega_2 P_{b,i} \tag{1}$$

where $I_{importance}$ stands for the dominance of a species; P_a and P_b refer, respectively, to the ratios of the species' abundance 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 abundance of the i-th species and B_i is the biomass of the species; ω_1 and ω_2 are the weightings of abundance and biomass, $\omega_1 + \omega_2 = 1.0$.

In Fig. 2, the ratios of P_a and P_b consist of a mass system. P_a and P_b stand for the coordinates of a particle which moves/distributes around the centroid. Then, the weightings in Eq. (1) can be determined using the following equation:

$$\begin{cases} \frac{\omega_1}{\omega_2} = \frac{a}{b} \\ \omega_1 + \omega_2 = 1.0 \end{cases} \tag{2}$$

where a and b stand for the position of the centroid in the one-dimensional coordinates P_a and P_b. a and b can be determined by

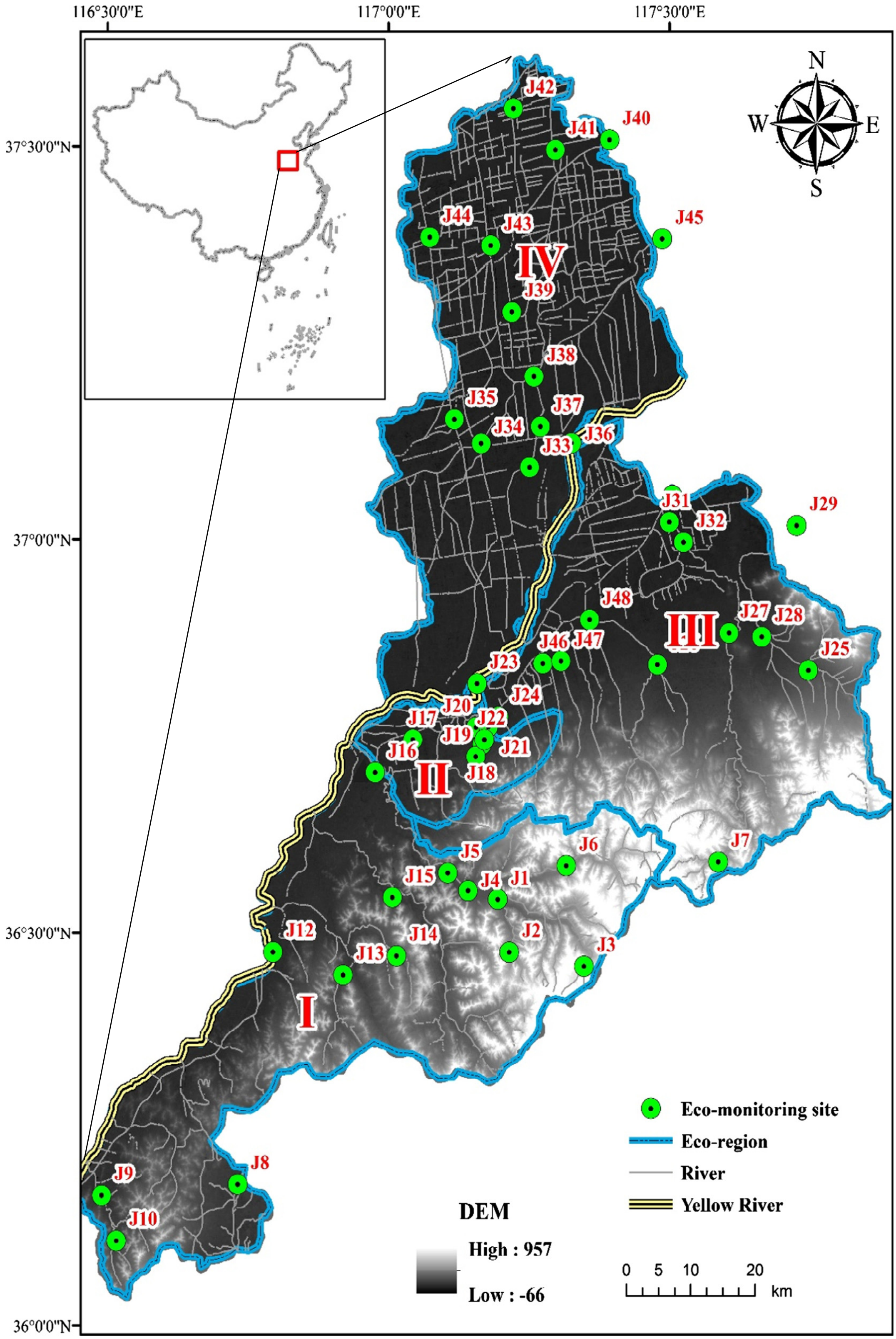

Fig. 1. Study area with routine hydrology-water quality-aquatic ecosystem monitoring stations.

Table 1
Monitored habitat factors in the Jinan City monitoring program (Zhao et al., 2015).

Habitat environment	Abbreviation	Name	Unit	Range (SD)
Hydrologic	FV	Flow velocity	m/s	0–1.50 (0.32)
	RW	River width	m	2.10–200 (45.30)
	FL	Flow	m^3	0–674 (158.88)
	WD	Water depth	m	0.01–3.50 (0.94)
Physical	AT	Air temperature	°C	15–33.10 (4.60)
	WT	Water temperature	°C	16.70–30.60 (2.85)
	pH			7.26–8.60 (0.35)
	Cond	Conductivity	mS/m	326–4130 (913.81)
	Trans	Transparency	cm	0–600 (111.32)
	Turb	Turbidity	degree	0.52–924 (139.53)
Chemical	Ca	Calcium	mg/l	17.63–315.83 (58.39)
	Cl	Chlorine		11.85–786.15 (176.39)
	SO_4	Sulfate		43.47–932.22 (179.28)
	CO_3	Carbonate		0–12.50 (2.83)
	HCO_3	Bicarbonate		50.05–845.32 (132.11)
	TA	Total alkalinity		51.48–693.35 (107.60)
	TH	Total hardness		141.12–989.89 (198.71)
	DO	Dissolved oxygen		1.17–9.92 (2.41)
	TN	Total nitrogen		0.25–21.84 (4.18)
	NH_4–N	Ammonia nitrogen		0.07–9.42 (2.63)
	NO_2–N	Nitrite		0–1.41 (0.30)
	NO_3–N	Nitrate		0.05–18.85 (2.90)
	COD_Cr	Chemical oxygen demand		6.32–130.61 (20.84)
	COD_Mn	Permanganate index		0.57–16.36 (3.34)
	BOD	Biochemical oxygen demand		0–35.80 (7.39)
	TP	Total phosphorus		0–3.64 (0.78)
	Fluoride			0.18–2.30 (0.49)

The other 10 heavy metal ions, e.g., copper, zinc and lead, were below detection and they are therefore omitted in the above table. All units of the chemical attributes are in mg/l.

using the density function of the mass systems, which can be rewritten in the present study as follows:

$$\begin{cases} a = \frac{\sum P_{a,i} N_i}{\sum N_i} \\ b = \frac{\sum P_{b,i} B_i}{\sum B_i} \end{cases} \tag{3}$$

Eqs. (2) and (3), the newly developed weighting determination method, are used for determination of weightings in the Eq. (1) in this paper.

4.2. Identification of breakpoint based on curvature of cumulative dominance

The curvature (κ, Eq. (4)) is the rate at which a curve turns. The maximum curvature suggests where the breakpoint of the curve appears and hence proves effective in selecting the breakpoint in the curve (Gippel and Stewardson, 1998; Liu et al., 2006).

$$\kappa = \frac{\frac{d^2y}{dx^2}}{\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{3/2}} \tag{4}$$

As for the cumulative dominance curve, the dominance increment after the breakpoint, i.e., the maximum curvature point, is rather small compared with that before the breakpoint. In other words, species showing dominance before the breakpoint contribute the most to the whole communities compared with those showing dominance after the breakpoint. Therefore, the maximum curvature is used to identify the breakpoint, thus allowing the selection of the dominant species within the fish communities in the study area.

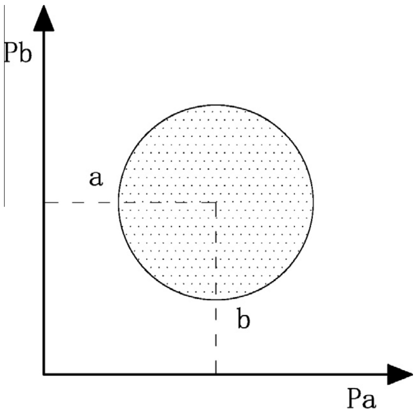

Fig. 2. Conception of weighting determination based on center-of-mass-system.

4.3. Calculation of multi-species-based habitat suitability index (MHSI)

Habitat suitability index (*HSI*), varying between 0 and 1, is an effective indicator for quantifying the response of a species to a particular set of habitat attributes (Ban et al., 2009; Vadas and Orth, 2001; Vismara et al., 2001). It is widely used to indicate the degree of preference of species to various habitats (Li et al., 2008). Highly preferred habitats usually have high *HSI* values. But consideration of only a single species rather than multiple species precludes the traditional *HSI* to estimate the synthetic effect of a habitat factor on the whole ecosystem community. For this purpose, a new multi-species-based *HSI* (*MHSI*) to estimate responses of multi-species to a habitat environmental factor is developed in this section (Fig. 3).

Contrary to the concept of a traditional *HSI*, in which the degree of suitability at a gradient of one habitat factor is calculated from the preference of only one species, the cumulative probability of

Table 2
Fish species recorded in Jinan City during the three field campaigns in 2014 (Zhao et al., 2015).

No.	Species	Abundance (individual)	Biomass (g)	No.	Species	Abundance (individual)	Biomass (g)
1	*Carassius auratus*	1211	16,710	20	*Pelteobagrus fulvidraco*	7	455
2	*Hemiculter leucisculus*	923	2415	21	*Spualiobarbus curriculus*	43	178
3	*Channa argus*	19	6453	22	*Acheilognathus chankaensis* Dybowski	38	163
4	*Misgurnus anguillicaudatus*	342	2356	23	*Sarcocheilichthys nigripinnis*	38	126
5	*Abbottina rivularis*	428	1165	24	*Lateolabrax japonicus*	3	318
6	*Cyprinus carpio* Linnaeus	12	3580	25	*Culter erythropterus* Basilewsl	12	221
7	*Pseudorasbora parva*	357	1080	26	*Mylopharyngodon piceus*	7	158
8	*Rhodeus ocellatus*	395	462	27	*Mastacembelus aculeatus*	15	83
9	*Ctenopharyngodon idellus*	45	1616	28	*Monopterus albus*	14	82
10	*Hypophthalmichthys molitrix*	3	1780	29	*Oryzias latipes*	23	8.3
11	*Huigolio chinssuensis*	239	97.7	30	*Hypseleotris swinhonis*	17	17.1
12	*Ctenogobius giurinus* (Rutter)	198	275	31	*Botia superciliaris* Günther	17	16
13	*Opsariichthys bidens* Günther	68	718	32	*Macropodus chinensis* (Bloch)	9	55
14	*Gnathopogon imberbis*	129	221	33	*Perccottus glenii*	14	14
15	*Pseudorasbora fowleri* Nichols	123	108.8	34	*Silurus asotus* Linnaeus	3	62
16	*Ctenogobius brunneus*	121	115	35	*Lefua costata* (Kessler)	4	19
17	*Paramisgurnus dabryanus* Sauvage	40	447	36	*Gobio rivuloides* Nichols	1	22
18	*Ctenogobius cliffordpopei*	88	103.5	37	*Clarias fuscus* (Lacepede)	1	4
19	*Rhodeus sinensis* Günther	77	156				

suitability at a gradient based on the preference of multiple dominant species (Eq. (5)) is adopted to stand for the effect of habitat factor on the community at the gradient.

$$MHSI_k = \sum_{i=1}^{I} \frac{p_{ki}}{I} \quad \text{with} \quad p_{ki} = \frac{n_{ki}}{N_i} \tag{5}$$

where k stands for the k-th gradient of a certain habitat environmental factor of hydrologic, physical and chemical parameters such as flow velocity (FV), dissolved oxygen (DO), transparency (Trans), chemical oxygen demand (COD), $k = 1,\ldots,K$, where K is the total number of gradients along the habitat factor; i stands for the i-th dominant species ($i = 1,\ldots,I$) and I is the total abundance 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; and $MHSI_k$ is the multi-species based HSI, i.e., the suitable probability of all dominant species in the k-th gradient, varying between 0 and 1.

4.4. Assessment and gradation of suitable probability of habitat factors

In an aquatic ecosystem with high quality, e.g., in the upstream segment of a river with high biodiversity and little human activity, species are abundant and can distribute evenly at every grade of a habitat factor. Meanwhile, in the downstream segment of a river, under the intensive impact of human activity, biodiversity is relatively low, and species are often absent from certain grades of the habitat factor. To take into account both of the above cases, two models were developed to estimate the probability of suitability of a habitat factor (*MHSIF*).

$$MHSIF = \sum_{k=1}^{K} \left(MHSI_k | p_{ki} \geqslant \frac{1}{K},\ \forall i \in (1, I) \right) \tag{6-1}$$

OR

$$MHSIF = \sum_{k=1}^{K} \left(MHSI_k | MHSI_k \geqslant \frac{1}{K} \right) \tag{6-2}$$

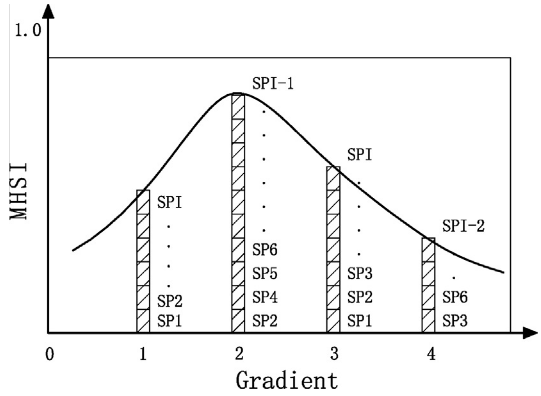

Fig. 3. Multi-species-based *HSI* to estimate the integrated effect of a habitat factor on a community represented by dominant species.

Eq. (6-1) has much higher requirement for the ecosystem quality because it demands that the suitable probability (p) of any dominant species in the k-th gradient is greater than the mean value at all gradients ($1/K$). Meanwhile, Eq. (6-2) is suitable for most regions due to its lower requirement for the species distribution along a habitat factor.

With the suitable probability (*MHSIF*) of various habitat factors, one can easily identify the factor with the lowest probability of suitability based on which river administrators or stakeholders could take timely measurements to remedy the damaged habitat. The habitat factor with the lowest probability of suitability should receive much more attention in the future rehabilitation of aquatic ecosystems.

4.5. Determination of the relative rehabilitation priority of habitat factors

Undoubtedly, the habitat factor with the lowest F has the highest rehabilitation priority. To make the selection process easier, we derived a set of formulae to objectively calculate the priority degree of a given habitat factor.

$$PD = \frac{MHSIF_b - MHSIF}{MHSIF_b} \tag{7-1}$$

OR

$$PD = \frac{MHSIF_{\max} - MHSIF}{MHSIF_{\max}} \tag{7-2}$$

Here, PD stands for the degree of rehabilitation priority of a habitat factor; $MHSIF_b$ is the suitable probability of a habitat factor at a baseline sampling site where all habitat factors are suitable for the dominant species (at least with $MHSIF$ greater than 0.6); $MHSIF_{\max}$ is the maximum suitable probability of a habitat factor at all sites in a catchment or region. Eq. (7-1) is recommended when the study area has a higher quality of habitat and where the baseline site is easy to determine; otherwise, Eq. (7-2) is recommended. For a region or catchment with a very poor quality habitat, Eq. (7-2) is used at the beginning rehabilitation stage, and Eq. (7-1) is employed at the second stage, when the habitat quality has recovered to a certain degree and a second rehabilitation is forthcoming.

5. Results

Using weightings determined via the center-of-mass system and the curvature-breakpoint identification method, the dominant fish in the community of the study area were selected. Those data were then used to calculate the multi-species based habitat suitability index (*MHSI*). Then, the probability of suitability of every principal habitat factor was estimated and graded for determining the rehabilitation priority of the habitat factors.

5.1. Selection of dominant species with the center-of-mass weighting determination method and curvature-breakpoint identification techniques

Based on equations derived from the center-of-mass system (Eqs. (2) and (3)), weightings in the whole fish communities of Jinan City were determined as 0.41 for abundance and 0.59 for biomass, which are similar to the results (0.43 and 0.57) from the Entropy method (Zhao et al., 2015). Subsequently, Eq. (1) was used to calculate the dominance values ($I_{importance}$) for every fish species in the studied communities. The cumulative $I_{importance}$ (Fig. 4) was then used to select the dominant species for the whole fish communities by using the curvature-breakpoint identification techniques.

The breakpoint (B) in Fig. 4 was identified using Eq. (4), showing that the incremental velocity of cumulated dominance slows down after the breakpoint. This means that the dominant species after the breakpoint contributed little (13%) compared with that before the breakpoint (87%) to the whole fish communities. Thus, 10 fish species, Nos. 1–8, 10 and 12 in Table 2, were selected as the dominant species in the fish communities. The number of selected dominant species (10) in the present study is smaller than that in the research of Zhao et al. (2015) (16). It is worth noting that the first 10 species in Zhao et al. (2015) are the dominant species identified in the present research. The former has a cumulative dominance value of 92.33% (Table 3 in the research), which is 5% higher than in the present study but must include 60% more species than the current study. This clearly demonstrates the efficiency of the curvature-breakpoint techniques. In fact, both groups of dominant species in the two studies can well represent the fish communities, but the dominant species group determined using the curvature-breakpoint techniques appears more objective and efficient.

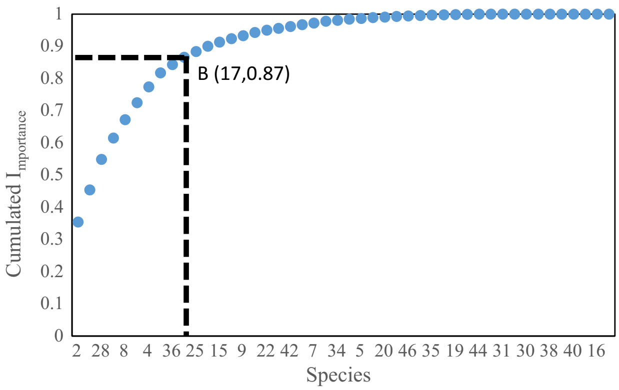

Fig. 4. Cumulative dominance values for all sampled fish species. B is the breakpoint, 17 is the species order and 0.87 is the cumulative dominance value before the breakpoint.

5.2. Calculation of multi-species based habitat suitability index (MHSI)

According to the research of Zhao et al. (2015), seven habitat factors, RW in the hydrologic group, Trans in the physical group, and COD_Mn, SO_4, TN, CO_3 and BOD in the chemical group, were selected as the principal habitat factors that influence the composition and spatial variation of fish species in the study area. To facilitate automatic computation of *MHSI*, the gradients of the seven principal factors were determined (Table 3) with equal interval distribution. The gradients of the seven key habitat factors formed the basis for the calculation of the probability of suitability and rehabilitation priority.

Based on the gradients in Table 3, the *MHSI* values for every gradient of the seven individual habitat factors were calculated by using Eq. (5), as shown in Fig. 5(a–g). The *MHSI* curves indicate the actual ecological niches of the 10 dominant species along the seven principal habitat factors instead of the fundamental ecological niches (Ehrlén and Morris, 2015). Most fish survive within the first five gradients. In particular, the favorite habitat for the fish community is that with river width less than 80.6 m, water transparency less than 3444 cm, sulfate concentration less than 562 mg/l, carbonate less than 6.29 mg/l, total nitrogen less than 8.89 mg/l, permanganate index less than 8.48 mg/l and biochemical oxygen demand less than 11.1 mg/l. The highest *MHSI* occurred at the first gradient of transparency, leading to the highest abundance within the dominant fish species. In brief, lower river width, higher water transparency and lower concentrations of sulfate, carbonate, total nitrogen, permanganate index and biochemical oxygen demand are favored by fish communities in Jinan City.

5.3. Probability of suitability and rehabilitation priority of habitat factors

Probability of suitability of the seven principal habitat factors can be estimated by using Eqs. (6-1) and (6-2). Results from Eq. (6-1) show that the *MHSIF* is zero for all seven principal habitat factors because the study area has undergone rapid industrial development and urbanization in recent decades (Hong et al., 2010), and the dominant species are therefore difficult to find simultaneously at the same site. This means that the 10 dominant species failed to occur at the same time at any grade of the seven habitat factors. Thus, we use Eq. (6-2) to continue to estimate *MHSIF*. Five of the seven habitat factors (Trans, SO_4, TN, COD_Mn and BOD) show *MHSIF* values greater than 0.6 (Fig. 5h), while the other two factors (RW and CO_3) have *MHSIF* values less than 0.6. Trans has the largest *MHSIF* value (0.91) and is the most suitable habitat factor, while CO_3 is the poorest habitat factor for fish in Jinan City, with the lowest *MHSI* value of the seven principal habitat factors (Fig. 5d and h). Consequently, CO_3 deserves further attention in future ecosystem rehabilitation.

Table 3
Gradients of the seven principle habitat factors.

Gradient	1	2	3	4	5	6	7	8	9	10
RW (m)	<20.9	20.9–40.8	40.8–60.7	60.7–80.6	80.6–100.5	100.5–120.4	120.4–140.3	140.3–160.2	160.2–180.1	$\geqslant$200
Trans (cm)	<861.31	861.312–1722.1	1722.1–2582.9	2582.9–3443.69	3443.69–4304.48	4304.48–5165.27	5165.27–6026.06	6026.06–6886.86	6886.86–7747.65	$\geqslant$8608.44
SO_4 (mg/l)	<97.27	97.273–190.046	190.046–282.819	282.819–375.592	375.592–468.365	468.365–561.138	561.138–653.911	653.911–746.684	746.684–839.457	$\geqslant$932.23
CO_3 (mg/l)	<4.18	4.181–5.232	5.232–6.283	6.283–7.334	7.334–8.385	8.385–9.436	9.436–10.487	10.487–11.538	11.538–12.589	$\geqslant$13.64
TN (mg/l)	<2.4	2.409–4.568	4.568–6.727	6.727–8.886	8.886–11.045	11.045–13.204	13.204–15.363	15.363–17.522	17.522–19.681	$\geqslant$21.84
COD_Mn (mg/l)	<2.15	2.15–3.73	3.73–5.31	5.31–6.89	6.89–8.47	8.47–10.05	10.05–11.63	11.63–13.21	13.21–14.79	$\geqslant$16.37
BOD (mg/l)	<3.94	3.94–7.48	7.48–11.02	11.02–14.56	14.56–18.1	18.1–21.64	21.64–25.18	25.18–28.72	28.72–32.26	$\geqslant$35.8

Decreases in the habitat quality produce increasing threats to the fish community as well as to drinking water, human health and well-being in Jinan City (Hong et al., 2010; Zhao et al., 2015). Therefore, Eq. (7-2) was selected to estimate the relative rehabilitation priority of the principal habitat factors (Fig. 6). Similar to the results of the probability of suitability, CO_3 has the highest rehabilitation priority, while Trans has the lowest priority and does not require rehabilitation.

6. Discussion

A new framework for rehabilitation priority assessment of habitat factors was developed based on fish responses to the factors, with few requirements for ecological information and expertise. Its application to Jinan City reveals that CO_3 has the highest rehabilitation priority and thus deserves special attention in future ecological habitat rehabilitation.

6.1. Applicability of rehabilitation priority models and testing for the relative rehabilitation priority of hydrologic, physical and chemical habitat factors

To further compare the two models for rehabilitation priority (Eqs. (7-1) and (7-2)) and test their applicability in practice, we selected substitute baseline sites by combining ecosystem health score with frequency of dominant species occurrence at a site. The reason for the selection of substitute baseline sites replacing the true baseline sites is because we failed to choose the true baseline sampling sites with all habitat factors suitable for the dominant species due to degeneration of ecosystem quality in Jinan City. To begin with, we assessed the ecosystem health status using the method in the research of Wu et al. (2014). Meanwhile, the frequency of occurrence of the 10 dominant fish species was calculated. Then, the sites with health scores greater than 60/100 as well as with occurrence frequencies greater than 0.6 were selected as J1, J9, J16, J18, J25, J34, J40, J44 and J48 in Fig. 1. Finally, the data monitored at these sites were used to estimate $MHSIF_b$ in Eq. (7-1), as listed in Table 4. As with the results from Eq. (7-2) CO_3 has the highest rehabilitation priority. However, Trans no longer has the lowest priority, replaced by BOD. Notably, the rehabilitation priority degree using Eq. (7-1) is not zero, unlike the result of using Eq. (7-2). A non-zero rehabilitation priority degree means that the habitat factor with the lowest priority (BOD in Table 4) still requires rehabilitation, though it is not urgent. However, using Eq. (7-2) inevitably produces zero-priority habitat factors, which deviates from the standard practices. At this point, Eq. (7-2) is suggested for use in identifying the highest-priority habitat factor for rehabilitation when the ecosystem quality is low and it is difficult to select baseline sampling sites. That is, Eq. (7-2) can be used to determine the highest-priority habitat factor at the first stages of rehabilitation, and Eq. (7-1) should be employed at the later stage when the habitat quality has recovered to a certain degree and a second rehabilitation is forthcoming.

Based on the seven principal habitat factors, CO_3 has the highest rehabilitation priority, while Trans has the lowest priority and does not require rehabilitation, as stated in Section 5.3. To verify this conclusion and further clarify the rehabilitation priority order of all hydrologic, physical and chemical habitat factors in Jinan City, we calculated their multi-species-based *HSI* and relative rehabilitation priority by linking them to the response of the dominant species (Fig. 7), although some responses are weaker. As in Fig. 6, the relative order of the seven principal habitat factors remains unchanged, with CO_3 ranking first and Trans last. On the whole, the hydrological factors, e.g., flow velocity (FV), river depth (RD),

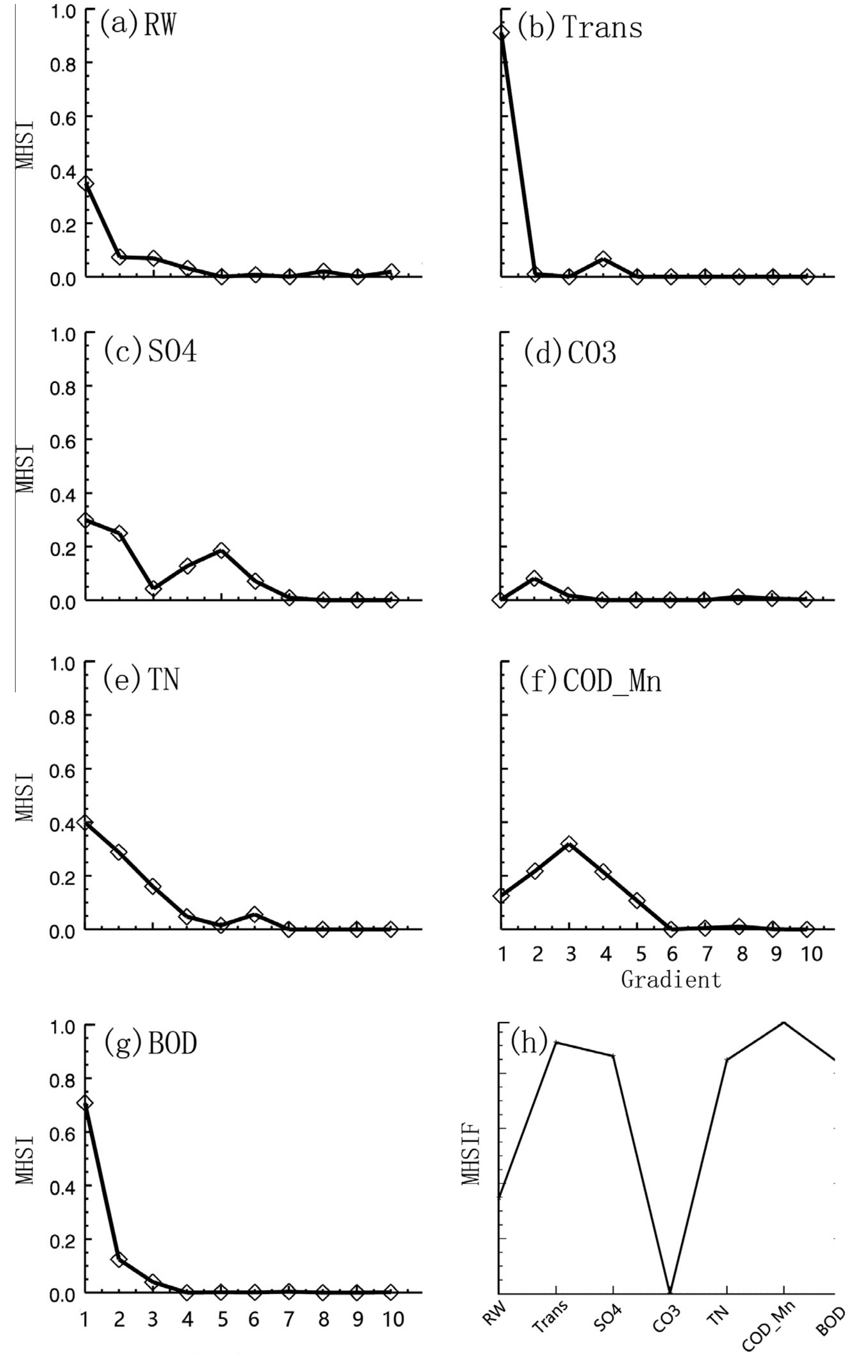

Fig. 5. Multi-species-based habitat suitability index (*MHSI*, a–g) and *MHSI* for principal habitat factors (*MHSIF*, h). In (a–g), the *X*-axis is the gradient of a factor, and the *Y*-axis is the *MHSI* of a factor gradient.

flow (FL) and river width (RW), have higher priority than the physical or chemical water-quality factors.

6.2. Sources of carbonate and bicarbonate

Carbonates (CO_3) and bicarbonates (HCO_3) are the most common and most important components of total alkalinity (TA), which is known as the buffer capacity to resist changes in pH upon the addition of acid. Conversion between CO_3 and HCO_3 can be indicated by pH: When pH is in the range of 4.3–8.3, the dissolved carbon dioxide begins to convert to HCO_3, with only HCO_3 present at a pH of 8.3; when pH is in the range of 8.3–10.2, the HCO_3 starts converting to CO_3, with almost all HCO_3 being converted to CO_3 at a pH of approximately 10.2 (Wurts and Durborow, 1992; McDonald, 2006). Water in Jinan City is dominated by HCO_3, with little CO_3. The pH value ranges between 7.3 and 9.1, which allows for the coexistence of a mixture of HCO_3 and CO_3 ions. Under normal circumstances, fish and other vertebrates have an average blood pH of 7.4. High concentrations of CO_2 lower the pH (acidification) and limit the capacity of fish blood to carry oxygen by lowering the blood pH at the gills. Fish will become stressed and die at $pH < 5$ or $pH > 10$, and high pH increases the ammonia toxicity. Therefore, a pH range of 6.5–9.0 is recommended for fish communities. A desirable range for pH should be close to that of fish blood (7.0–8.0) (Wurts and Durborow, 1992). Statistics for pH in the waters of Jinan City show that 99% of sites have pH values within

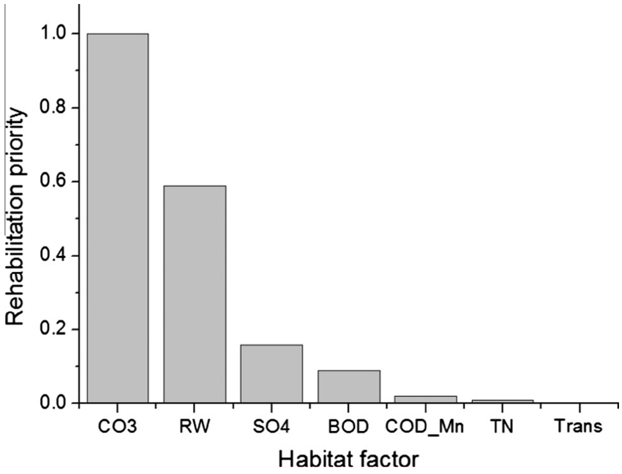

Fig. 6. Relative rehabilitation priority of the seven principal habitat factors in Jinan City.

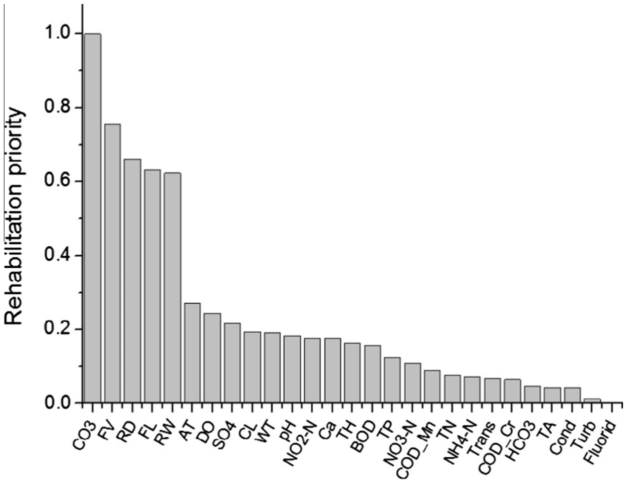

Fig. 7. Rehabilitation priority (*PD*) of all habitat factors in Table 1.

Table 4
Suitable probability (*MHSIF*), grade of the suitable probability, rehabilitation priority degree (*PD*) of the principle habitat factors at substitute baseline sampling sites.

	$MHSIF_b$	*MHSIF*	*PD* with Eq. (7-1)
CO_3	0.26	0.00	1.00
RW	0.50	0.35	0.30
COD_Mn	0.77	0.55	0.28
SO_4	0.82	0.64	0.22
BOD	0.77	0.66	0.14
Trans	0.83	0.69	0.17
TN	0.85	0.69	0.19

the range 6.5–9.0, and 46% of sites show pH in the range 7.0–8.0. This indicates that fish can survive in almost all of these waters, but 54% of habitats are not desirable for fish and require further rehabilitation. The conversion of HCO_3 to CO_3 is followed by increases in pH and TA. TA is based on carbonate chemistry and is expressed as calcium carbonate ($CaCO_3$). A desirable range of TA for fish is 75–200 mg/L $CaCO_3$ (Wurts and Durborow, 1992), which is the case for 56% of the sampling sites in Jinan City (Fig. 8b). This means that the other 44% of waters in Jinan City are not desirable habitats for fish and that further rehabilitation is necessitated. In brief, the current mixture of CO_3 and HCO_3 makes nearly half of the habitats in Jinan City undesirable for fish communities, and future rehabilitation is urgently necessitated. Similarly, in the spatial distribution of CO_3 (Fig. 8a) nearly half of the sampled habitats require future rehabilitation. The difference between Fig. 8a and b can mainly be attributed to the addition of HCO_3 into TA.

Most ions contributing to TA (CO_3 and HCO_3) in freshwater habitats are exported from terrestrial soil due to chemical weathering. In addition, Raymond and Cole (2003) reported a strong negative correlation between stream TA and land cover consisting of forest and a positive correlation between stream TA and land cover consisting of cropland. In general, agricultural practices increase the surface area of soil minerals and alter the hydrology of surficial soils, both of which may increase the rate of contact between water and minerals and therefore increase the production of CO_2 (Raymond and Cole, 2003). Consequently, converting non-croplands to croplands will inevitably result in an increase in amount of alkalinity exported from terrestrial ecosystems to aquatic ecosystems. Moreover, excessively intense human disturbances inevitably result in fish elimination (Vila-Gispert et al., 2002; Adams et al., 2005; Cheimonopoulou et al., 2011; Zhang et al., 2011). In the area of Jinan City, agricultural land accounts for nearly half of the region (Wen, 2013). Agricultural land predominates the northern regions of the area, especially the Eco-region IV (Li, 2010; Liu and Zheng, 2012). Though dramatically less than in the Eco-region IV, agricultural land is also the primary component of the northeast plain area of Ecoregion I, while a mixture of construction and agricultural lands forms the middle and northwest of Eco-region I (Wei, 2014). Accordingly, the agricultural practices in these areas contributed greatly to the presence of ions of TA (CO_3 and HCO_3) in the waters of Jinan City. This largely concurs with the distribution of CO_3 (Fig. 8a), except for the lack of sampling sites in the agricultural areas.

6.3. Spatial pattern of rehabilitation priority in Jinan City

To explore the spatial pattern of rehabilitation priority for the highest-priority habitat factor-CO_3, we analyzed the spatial distribution of the CO_3 concentration (Fig. 8a). On the whole, rivers in the south mountainous region adjacent to the urban area and especially in the northern agricultural region have the highest CO_3 concentrations (Ellipse in Fig. 8a), which undoubtedly have the highest priority for future habitat rehabilitation.

To further explore the spatial pattern of rehabilitation priority for all seven principal habitat factors, we calculated the multi-species-based *HSI* and relative rehabilitation priority with the responses of the 10 dominant species to the principal factors based on the eco-regions in the research of Yu et al. (2014). We counted the numbers of sampling sites within the eco-regions (Table 5), showing that the highest number of sampling sites within the 3rd grade eco-regions is less than five. In general, the use of too few sampling sites is expected to produce high levels of uncertainty in the results. To avoid this, we only used two levels of eco-regions (1st grade and 2nd grade) to study the spatial distribution of the rehabilitation priority for habitat factors (Fig. 10). The order of the rehabilitation priority among the seven factors varies between eco-regions. However, overwhelmingly in all analyzed eco-regions, CO_3 has the highest priority. The habitat factor with the lowest priority differs between locations (Table 5, Fig. 9). From the perspective of the 1st grade eco-regions, the southern mountainous region (Eco-region I) and the urban area (Eco-region II) have COD_Mn as the rehabilitation factor with the lowest priority, while the lowest priority in the northern agricultural area (Eco-region IV) is TN. For the 2nd grade eco-regions, the lowest-priority factors vary by location, including almost all of the factors except CO_3, which has the highest priority.

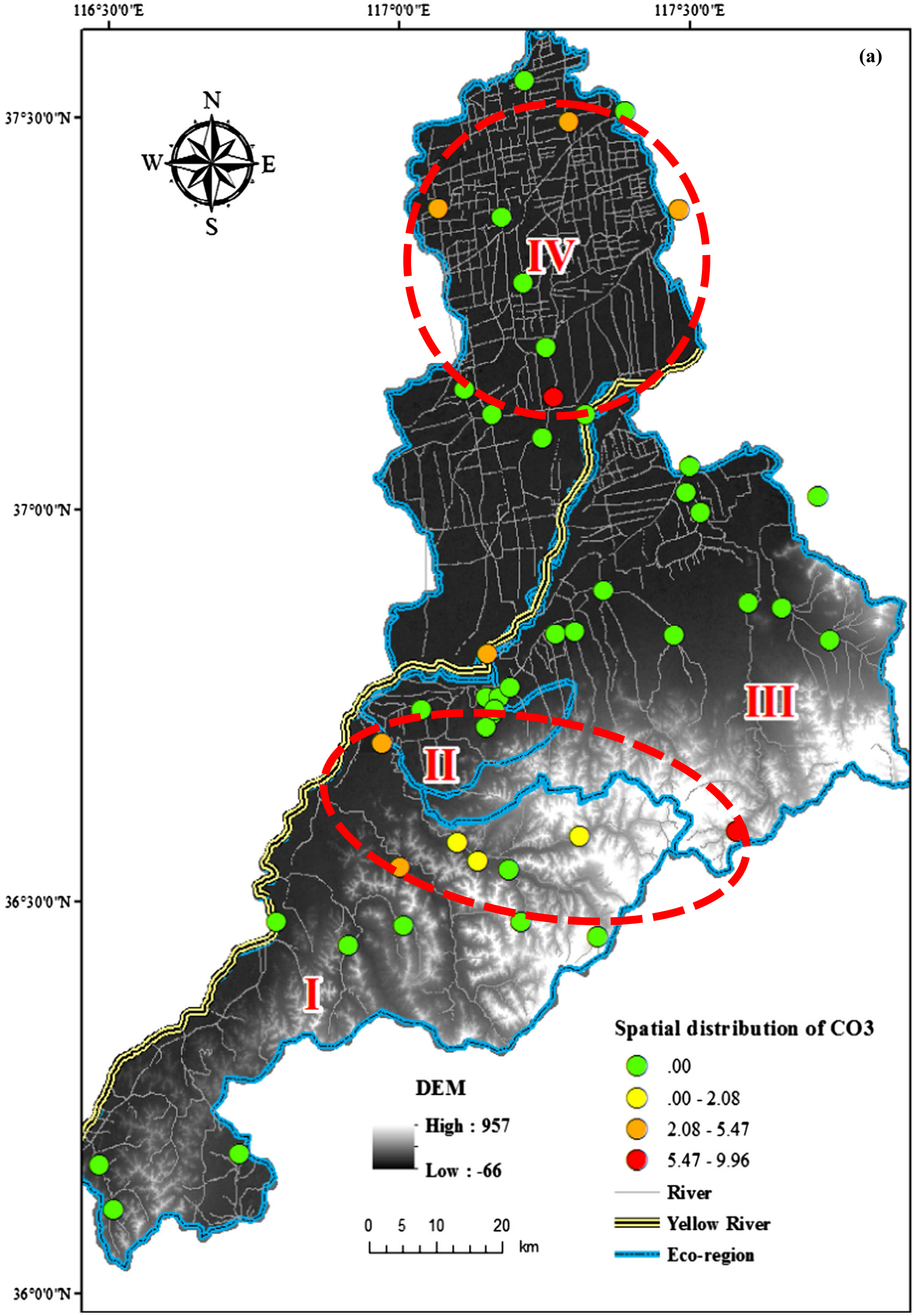

Fig. 8. Spatial pattern of (a) the highest-priority habitat factor, CO_3, and (b) fish-favored TA (75–200 mg/l).

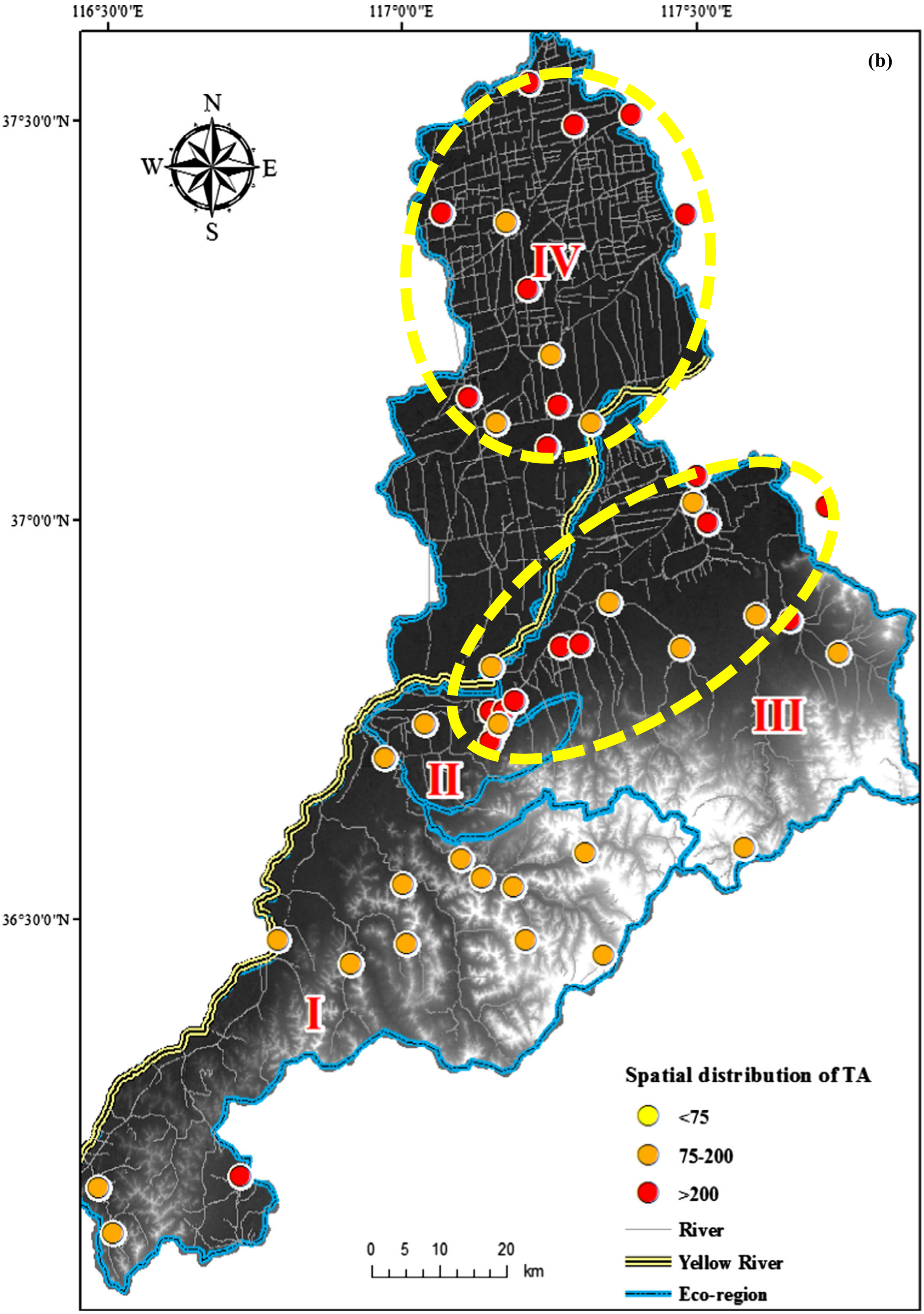

Fig. 8 (*continued*)

Table 5
Rehabilitation prior degree of the seven principle habitat factors in the eco-regions of the Jinan City.

Eco-region			Sampling number	CO_3	RW	SO_4	BOD	COD_Mn	TN	Trans
1st grade	2nd grade	3rd grade								
I			**16**	**0.82↑**	**0.77**	**0.01**	**0.13**	**0↓**	**0.15**	**0.09**
	I-1		4	1.00↑	0.60	0.41	0↓	0.20	0.73	0.09
	I-2		1	–	–	–	–	–	–	–
	I-3		11	1.00↑	0.80	0↓	0.13	0.04	0.08	0.11
		I-3-1	*2*							
		I-3-2	*3*							
		I-3-3	*6*							
II			**6**	**1.00↑**	**0.53**	**0.06**	**0.56**	**0↓**	**0.09**	**0.29**
III			**12**	**1.00↑**	**0.53**	**0.13**	**0.08**	**0.33**	**0.14**	**0↓**
	III-1		1.00	0.48↑	0↓	0.12	0.04	0.07	0.02	0.12
		III-1-1	*5*							
		III-1-2	*3*							
	III-2		4	1.00↑	0.63	0.18	0.26	0.36	0.01	0↓
		III-2-1	*1*							
		III-2-2	*3*							
IV			**10**	**0.79↑**	**0.11**	**0.10**	**0.14**	**0.14**	**0↓**	**0.35**
	IV-1		4	0.65↑	0.02	0.32	0.31	0.06	0.23	0↓
		IV-1-1	*0*							
		IV-1-2	*1*							
		IV-1-3	*3*							
	IV-2		6	1.00↑	0↓	0.07	0.03	0.33	0.05	0.41
		IV-2-1	*2*							
		IV-2-2	*4*							

Bold font stands for the 1st grade ecoregion; normal font for 2nd grade ecoregion; italic font is for 3rd grade ecoregion. "↑" means MAX and "↓" means MIN.

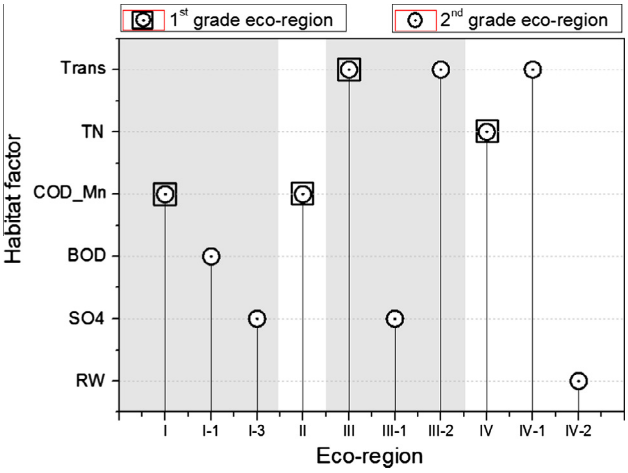

Fig. 9. Spatial variation of the lowest-priority habitat factor in the four eco-regions.

6.4. Requirement of rapid assessment of river habitat rehabilitation in developing countries/regions regarding the response of aquatic species to their habitats

The framework presented in this paper can be used to detect the rehabilitation priority of various habitat indices related to hydrologic, physical and chemical aspects of the habitat. This framework can be used to identify the highest-priority habitat indices in aquatic ecosystems of an area either independently or coupled with the method of Zhao et al. (2015). For example, after prioritized regions in an aquatic ecosystem have been detected based on Zhao et al. (2015), the method in the present study can be employed to identify the highest-priority habitat indices in the regions for future ecosystem rehabilitation. The framework is based on the response of aquatic species to their habitats, successfully linking the variation in their presence/absence, abundance and biomass to the geographical distribution of habitat factors. Similarly, correlative and mechanistic models (Araujo and Peterson, 2012; Schurr et al., 2012; Ehrlén and Morris, 2015), such as species distribution models (SDMs) and dynamic range models (DRMs) also link species responses to habitat factors. However, most such models are based only on either the presence/absence or biomass of species (Schroeder and Vangilder, 1997; VanDerWal et al., 2009), with a few models based on the combination of presence and abundance (Ehrlén and Morris, 2015). Despite the great appeal of DRMs at the species level, DRMs require too much data, which necessitates substantial effort for the direct measurement of demographic responses, and substantial effort is also required for the development of mechanistic niche models (Schurr et al., 2012). Those drawbacks currently preclude the application of DRMs for general use in ecosystem management and biodiversity assessment (Guisan and Thuiller, 2005). As to correlative SDMs, e.g., the popular Maxent (VanDerWal et al., 2009) and ENFA (Vaclavik and Meentemeyer, 2012), they are easy to be put into practice and therefore more suitable for identification of the prior habitat environmental factors. However, most of them emphasize the prediction of species-level indices instead of the selection of the highest-priority habitat factors for rehabilitation. More importantly, compared with DRMs, correlative models of environmental suitability ignore factors such as dispersal capabilities, biotic interactions, microenvironment suitability, and stochastic effects that could result in the species being absent or uncommon at sites that otherwise have high environmental suitability (VanDerWal et al., 2009), although they also have high requirements for ecosystem and habitat data.

Generally, river ecological restoration requires the identification of suitable indicators or of the relative priority of habitat factors, especially in terms of hydrology and water quality, to assess habitat quality before, during and after restoration (Hughes et al., 2010). Shortages of economic investment as well as expertise of hydrology, ecology and geography in many counties, especially in developing countries, hinder their organization of wide aquatic ecosystem monitoring and therefore make it difficult for them to use SDMs or DRMs to identify the high-priority habitat factors for rehabilitation. For many rivers the information they required

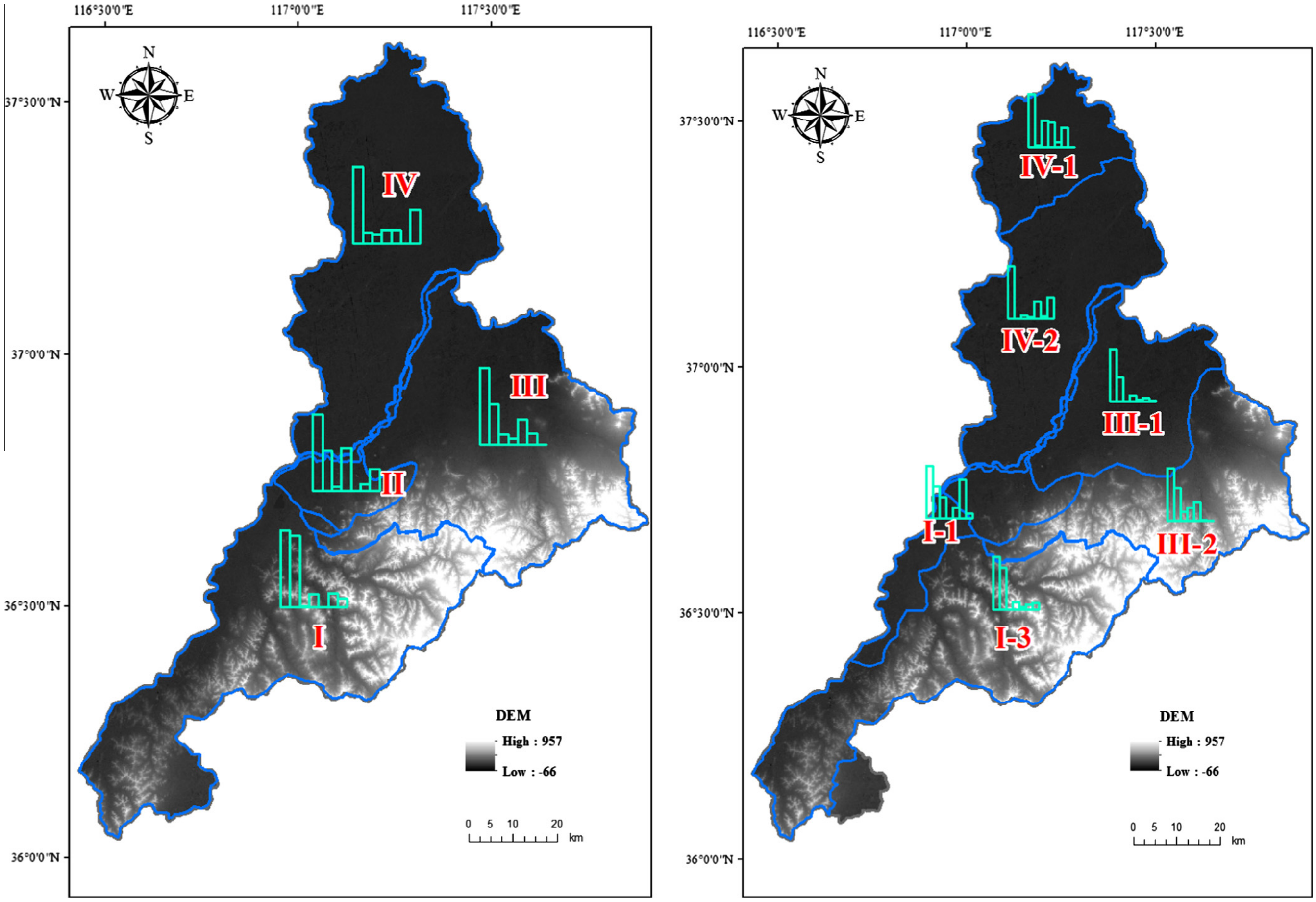

Fig. 10. Spatial variation of the rehabilitation priority of the seven principal habitat factors in the 1st grade eco-regions (Left) and in the 2nd grade eco-regions (Right).

is not available (Osmundson, 2011). An effective method that requires less data and expertise but accurately describes the response of aquatic species to their habitats would be of great help for those countries. Our framework therefore has great possibility to be widely used in the conservation of biodiversity and the ecological rehabilitation of rivers in those countries because it is based on fish but does not require knowing their exact names, which makes our framework easy to use without any expertise in ecology or biology. Importantly, fish are relatively easy to identify, and their position at the top of the food chain helps provide an integrative view of the aquatic ecosystems (Wu et al., 2014). Despite the ease of use and the full consideration of presence/absence, abundance and biomass, some uncertainties may also be introduced from field sampling and observations of fish and habitat factors, for example, insufficient care of influences of other factors like the spawning season, age, gender, of some fish species. Methods for handling uncertainties should be introduced in the future to improve the accuracy of the results, with relative lower requirement for assemblage information and expertise.

7. Conclusions

We present a framework that can be used to identify the high-priority habitat factors influencing the aquatic ecosystems based on the presence, abundance and biomass of the fish community to provide a practical method for improving successful aquatic ecosystem restoration. This framework has few requirements regarding assemblage information and scientific expertise and was demonstrated to be effective and practical in an application in Jinan City. In this framework, the theory of mass systems in the physical subject were used to develop a new method for determining weighting, with which the dominance of all species or the contribution of those species to the whole fish community in Jinan City was calculated. This method objectively selected the 10 dominant fish species with the help of curvature-breakpoint identification techniques. Then, the dominant species, along with the seven principal habitat factors detected in the research of Zhao et al. (2015), were used to calculate the multi-species-based habitat suitability index along gradients of all principal factors. Based on those results, the probability of suitability of every principal habitat factor was estimated and analyzed. Then, the relative rehabilitation priority of the seven habitat factors was studied.

Lower river width, higher water transparency and lower concentrations of sulfate, carbonate, total nitrogen, permanganate index and biochemical oxygen demand are favored by fish communities in Jinan City, and carbonate is the poorest habitat factor for fish in Jinan City. Thus, CO_3 deserves further attention in future ecosystem rehabilitation. Assessment of all habitat factors in Jinan City, including the seven principal factors, suggests that hydrological factors of flow velocity, river depth, flow and river width have higher priority than the physical and chemical water-quality factors. Analysis of the spatial pattern of carbonate in Jinan City reveals that rivers in the southern mountainous region adjacent to the urban area and especially in the northern agricultural region have the highest CO_3 concentrations and should be the emphasis for future habitat environment rehabilitation.

Because of its easily understandable theories and modest requirements for assemblage information and scientific expertise, we expect that this model will be applied to help identify the high-priority habitat factors for aquatic ecological restoration of those rivers lacking systematic monitoring in aquatic ecosystems all over the world and therefore to provide a scientific basis for decisions made by river administrators and stake-holders. Uncertainties in this model can be effectively reduced by judiciously selecting environmental attributes as well as by applying the new method for handling model uncertainties after the monitoring dataset of the habitat environment and fish assemblages has been strengthened.

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