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Linking hydrologic, physical and chemical habitat environments for the potential assessment of fish community rehabilitation in a developing city

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SUMMARY

Aquatic ecological rehabilitation is increasingly attracting considerable public and research attention. An effective method that requires less data and expertise would help in the assessment of rehabilitation potential and in the monitoring of rehabilitation activities as complicated theories and excessive data requirements on assemblage information make many current assessment models expensive and limit their wide use. This paper presents an assessment model for restoration potential which successfully 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. In this model three newly developed sub-models, integrated habitat index (*IHSI*), integrated ecological niche breadth (*INB*) and integrated ecological niche overlap (*INO*), are established to study spatial heterogeneity of the restoration potential of fish assemblages based on gradient methods of habitat suitability index and ecological niche models. To reduce uncertainties in the model, as many fish species as possible, including important native fish, were selected as dominant species with monitoring occurring over several seasons to comprehensively select key habitat factors. Furthermore, a detrended correspondence analysis (DCA) was employed prior to a canonical correspondence analysis (CCA) of the data to avoid the "arc effect" in the selection of key habitat factors. Application of the model to data collected at Jinan City, China proved effective reveals that three lower potential regions that should be targeted in future aquatic ecosystem rehabilitation programs. They were well validated by the distribution of two habitat parameters: river width and transparency. River width positively influenced and transparency negatively influenced fish assemblages. The model can be applied for monitoring the effects of fish assemblage restoration. This has large ramifications for the restoration of aquatic ecosystems and spatial heterogeneity of fish assemblages all over the world.

1. Introduction

Globally, intensive human activities have been changing riverine environments in terms of their hydrology, pollutant loads and habitat attributes (Walters et al., 2009). Species in aquatic ecosystems 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). For instance, in a large area of shifting riparian, marsh and estuarine ecosystems, the remnants of these aquatic ecosystems are largely fixed in place and cut off from each other by water management structures (Zamora et al., 2005; Glenn et al., 2013). This has been repeated around the world and in the USA the construction of 75,000 dams has contributed to declines of native fish populations (Osmundson, 2011). Many stressed

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rivers are resilient and can recover from degraded conditions after restoration activities as habitats are often naturally dynamic and frequently experience large-scale natural disturbances such as floods (Kauffman et al., 1995; Moerke et al., 2004; Hansen and Budy, 2011). Suitable habitats are very important for the 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). As a result, river restoration requires the identification of environmental and pressure gradients that affect river systems and the selection of suitable indicators to assess habitat quality before, during and after restoration (Hughes et al., 2010).

Over several decades river habitat restoration has been utilized as a strategy to recover and conserve threatened and endangered species (Bernhardt et al., 2005). However, the success of habitat restoration is often uncertain (Wissmar and Bisson, 2003), for example, the successful restoration of only the physical habitat does not guarantee success. Information about the response of aquatic species to hydrologic, physical and chemical environments is therefore needed to better understand the potential for habitat restoration (Bellmore et al., 2012). Further, periodical assessment of the rehabilitation potential is required to measure success.

Current potential assessment methods are often too difficult to use in practice by river administrators and stakeholders because of a need for multidisciplinary knowledge, e.g., biology, hydrology and ecology. Generally, previous assessment approaches focus on specific species (e.g., endangered, threatened or native species) (Palmer et al., 2005; Bain and Meixler, 2008), bioindicators (Hughes, 2005; Feld and Hering, 2007; Vaughn et al., 2007; Hughes et al., 2010), recruitment index (Armstrong and Hightower, 2002; Fox, 2004) or detection of impaired habitat and/or processes (Bellmore et al., 2012). Successful implementation of these methods depends critically on connecting the underrepresented taxa with the mechanisms responsible for their reduction/elimination but often requires substantial scientific expertise. Although many previous studies have related human activities to resident species assemblages, few have confirmed or determined mechanisms (Peoples et al., 2011; Kemp, 2014). Common bioindicators often include benthic macroinvertebrates, fish, benthic diatoms, macrophytes and birds (Feld and Hering, 2007; Vaughn et al., 2007; Hughes et al., 2010). An effective bioindicator should exhibit detectable and measurable changes in relation to specific environmental or pressure gradients, ideally starting from reference conditions (Johnson et al., 2006; Karr and Chu, 2000; Paavola et al., 2006; Hughes et al., 2010). In addition, some methods require the selection of specific restoration sites based on the outcome of watershed-level assessments (Roni et al., 2002; Pess et al., 2003; Bellmore et al., 2012). However, for many rivers the information required was not available (Osmundson, 2011). An effective method that requires less data and expertise would help in the assessment of rehabilitation potential and in the monitoring of rehabilitation activities.

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). Some habitat restoration programs have taken fish as representative of ecosystems health to evaluate aquatic ecosystem restoration potential, e.g., the use of the Endangered Species Act – listed anadromous Pacific salmon and steelhead populations in the United States (Bernhardt et al., 2005; Bellmore et al., 2012). 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 is important for monitoring their rehabilitation potential.

The objective of this paper is to develop an effective method for assessment of rehabilitation potential based on the responses of dominant fish species to their habitat environment. It has relatively simple theory (habitat gradient theory: habitat suitability and ecological niche), requiring only basic information and expertise (fish assemblage: only the number and biomass of fish species; fish names are unnecessary). These easily recorded fish attributes are linked to habitat environmental gradients of hydrologic, physical and chemical parameters to determine dominant species, select key habitat factors and assess the rehabilitation potential of fish communities.

2. Study area

Jinan City (36.0–37.5°N, 116.2–117.7°E) is bordered by Mount Tai to the south and 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. 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 is 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 well as the fish community. Policymakers and stakeholders are aware of the need to rehabilitate the aquatic ecosystems in Jinan City. To facilitate research program on rehabilitating these aquatic ecosystems, the entire city was divided into four eco-regions (Yu et al., 2014) and 48 routine monitoring stations distributed evenly on typical rivers were set up (Fig. 1). At these monitoring stations 37 parameters including hydrologic, physical and chemical environmental factors are concurrently measured (Table 1). To ensure successful aquatic ecosystem restoration over all river sections, river administrators and stakeholders urgently require an easy-to-use method to periodically assess their rehabilitation success.

In the research of Yu et al. (2014) three-level eco-regions were classified with geographic information system (ArcGIS) and spatial autocorrelation analysis. Meanwhile the first-level eco-region mainly take as basis the characteristics of the city administrative divisions and river watersheds. It is mainly composed of three watersheds of the Yellow, Xiaoqing and Tuhaimajia rivers as well as the city urban area. The classification of the second-level eco-region mainly considers spatial pattern of land use. Based on the second-level eco-region the classification of the third-level eco-region was conducted, where the clustering analysis was conducted with water quality indices at sampling sites. In the present study we take the first-level eco-region as basis to assess fish rehabilitation potential.

3. Data

To explore the response of fish species to habitat factors, we conducted three extensive field campaigns to monitor the fish community and concurrently their habitat attributes. These attributes were primarily classified into hydrologic, physical and

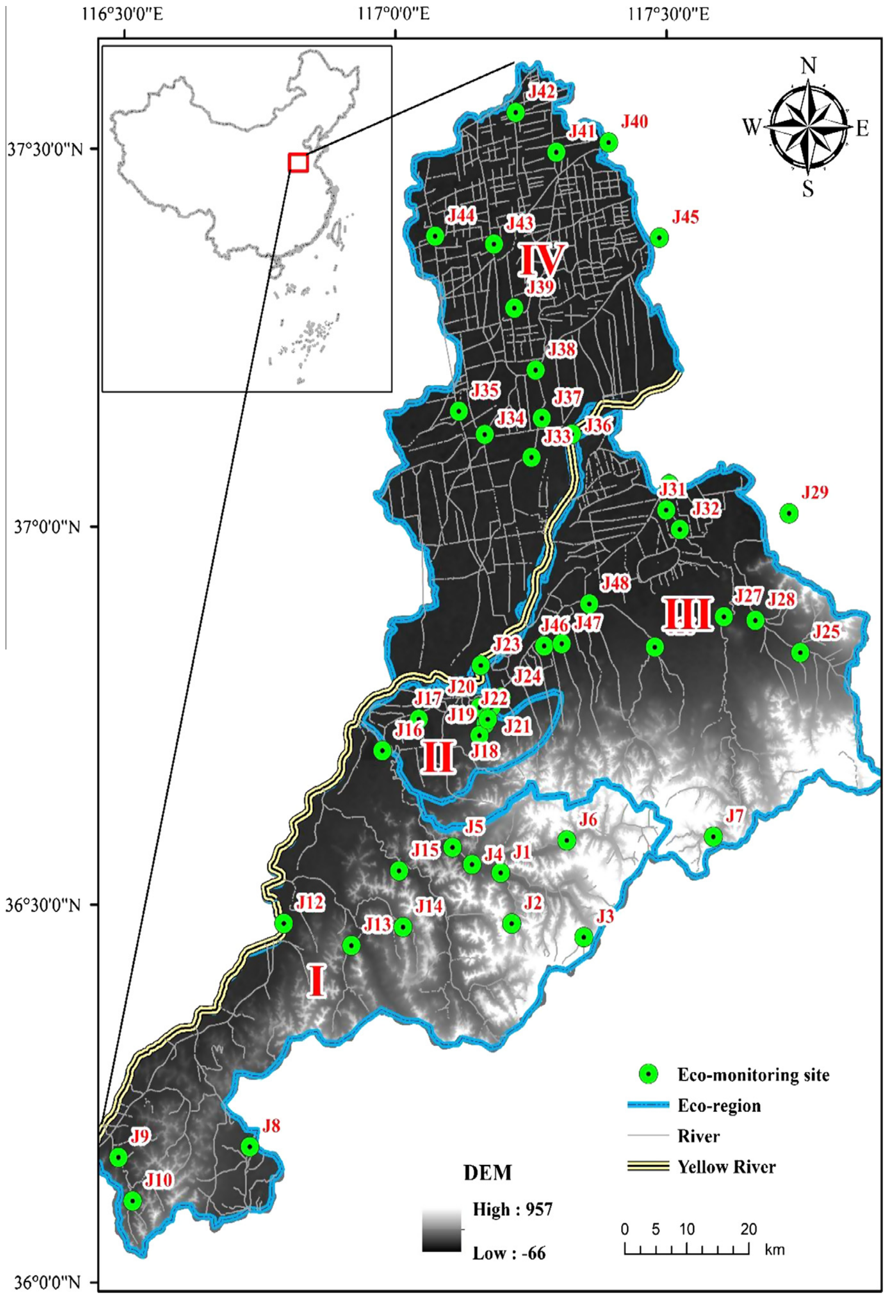

Fig. 1. Study area with routine hydrology-water quality-aquatic ecosystem monitoring stations.

chemical components in which 37 parameters were measured, as shown in Table 1. Pebble and mud were the only river bed sediment categories measured in the study area. These were insufficient to allow for key habitat factor selection and were therefore excluded in this study. The remaining three types of habitat factors in Table 1 were measured/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, etc., 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 for 30 min in three habitats (i.e., pools, riffles, and runs) along 200–300 m reach of a 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, seines nets (mesh sizes of 30 and 40 mm) were used to collect fish from 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

Table 1
Selected habitat factors in the Jinan City monitoring program.

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	deg	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. All units of the chemical attributes are in mg/l.

Table 2
Fish species recorded in Jinan City during the three field campaigns in 2014.

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	*Hypophthalmichehys 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				

were preserved in a 10%-formalin solution and stored in labelled 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. Methods

A rehabilitation potential model for the fish community was constructed based on the response of fish species to their habitat. In addition, three newly-developed sub-models – the integrated habitat index (*IHSI*), integrated ecological niche breadth (*INB*) and integrated ecological niche overlap (*INO*), were also developed. The rehabilitation potential model and its sub-models have been integrated into the EcoHAT (the Ecohydrological Assessment Tool) (Liu et al., 2009; Dong et al., 2013). Then the rehabilitation potential model can run smoothly, even in data-scarce rivers, with hydrological and water quality simulations by using the EcoHAT. Flow chart of the method for potential assessment is shown in Fig. 2.

4.1. Integrated habitat suitability index (IHSI)

Habitat suitability is defined as the preference of an aquatic organism to a particular set of habitat attributes (Vadas and

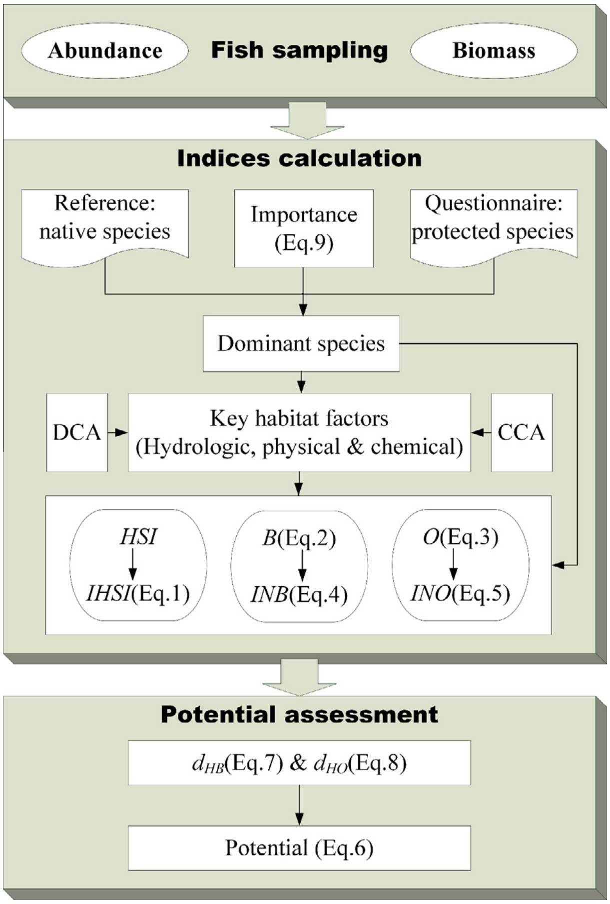

Fig. 2. Flow chart of potential assessment with all weights are estimated by using the entropy method. CCA: canonical correspondence analysis; DCA: detrended correspondence analysis.

Orth, 2001; Vismara et al., 2001). 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; Li et al., 2008). It varies between 0 and 1, and a higher *HSI* value indicates a habitat that is more suitable for species to live in (FWS, 1982; Bovee et al., 1998). 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; Ban et al., 2009). This study used the data set of hydrology-water quality-aquatic ecosystem to construct an integrated habitat suitability index (*IHSI*, Eq. (1)), to help study the rehabilitation potential of the river for the fish community.

$$IHSI_i = \sum_{n=1}^{N} \omega_n HSI_{in} \tag{1}$$

where $IHSI_i$ represents the integrated habitat suitability index of the ith species along all habitat factors ($i = 1, \ldots, I$), HSI_{in} is the habitat suitability index of the ith species along the nth habitat factor ($n = 1, \ldots, N$), which varies with habitat factors, e.g., river width (RW), transparency (Trans), and total nitrogen (TN), $HSI_{in} = \omega_m HSI_{ink}$ ($k = 1, \ldots, K$), HSI_{ink} is the habitat suitability index of the ith species along the kth gradient of the nth habitat factor, and ω_n and ω_m are weights determined using an entropy method.

IHSI makes the principal gradient of the main habitat factors that influence fish communities more prominent. It is a simple index that reflects the adaptability of a species to the habitat environment in a watershed and is easy for river administrators to use. For this reason, it is also easy to incorporate with geographical analysis tools to study spatial patterns of habitat suitability for fish communities in a watershed.

4.2. Ecological models: INB and INO

There are many models to calculate niche breadth and overlap (Levins, 1968; Pianka, 1974; Hurlbert, 1978; Smith, 1982). In this paper, we employed the widely used Levins Breadth Model (Eq. (2), Levins, 1968) and Pianka Overlap Model (Eq. (3), Pianka, 1974) to determine niche breadth and niche overlap, respectively.

The Levins' Breadth Model is $$B_i = 1 \Big/ \sum_{j=1}^{R} (P_{ij})^2 \tag{2}$$

where B_i is the niche breadth of the ith species along the axis of a resource, or habitat parameter, P_{ij} is the ratio of the number of individuals of the ith species in state j of the habitat parameter to the total number of individuals of the ith species, and R is the total number of habitat-parameter states. Habitat-parameter states are defined according to the national water quality criteria, with reference to the maximum and minimum values. They are gradients along one available resource, e.g., total nitrogen, dissolved oxygen, transparency, and river flow.

Pianka Overlap Model : $$O_{ik} = \sum_{j=1}^{R} P_{ij} P_{kj} \Big/ \sqrt{\sum_{j=1}^{R} P_{ij}^2 \sum_{j=1}^{R} P_{kj}^2} \tag{3}$$

where O_{ik} is the niche overlap of the ith species on species k, P_{ij} and P_{kj} are the ratios of numbers of individuals of the ith species and species k in resource state j to the total number of individuals of the ith species and k, respectively, and $O_{ik} \neq O_{ki}$. The calculations of niche breadth and niche overlap were conducted using the "Data Processing System (DPS)" software (Tang and Zhang, 2013).

After having obtained niche breadth along every resource, the integrated niche breadth (*INB*) along all available resources was calculated using Eq. (4). The *INB* for a fish species along all habitat resources in one watershed or region has been nearly unchanged during a given period, e.g., five years, due to the species' long-term (for instance, several decades) evolution and adaptation to the habitat. Therefore, the *INB* can be regarded as the innate characteristic of a fish species within the study period:

$$INB_i = \sum_{n=1}^{N} \omega_n B_{in} \tag{4}$$

where INB_i stands for integrated niche breadth of the ith species along all habitat resources, B_{in} is niche breadth of the ith species along the nth habitat parameter ($n = 1, \ldots, N$), and ω_n is the weight of B_{in}, which is determined using the entropy method.

The integrated niche overlap (*INO*) along all resources or habitat parameters can be calculated using Eq. (5). The *INO* also can be regarded as the innate characteristic of fish in a certain watershed or region:

$$INO_i = \sum_{n=1}^{N} \omega_n O_{in} \tag{5}$$

where INO_i stands for integrated niche overlap of the ith species along all habitat resources, and O_{in} is the niche overlap of the ith species along the nth habitat parameter.

4.3. Rehabilitation potential of the fish community

The habitat suitability index and ecological niche are two important indicators of species–habitat interactions and reveal the responses of a species to habitat variation. In the present study, we developed a model based on the habitat suitability index, ecological niche breadth and overlap models to assess the potential of fish community rehabilitation at different sites in a watershed:

$$Potential = \frac{(1.0 - d_{HB}) + (1.0 - d_{HO})}{2} = 1.0 - \frac{d_{HB} + d_{HO}}{2} \quad (6)$$

$$d_{HB} = [w_1^r(1.0 - IHSI)^r + w_2^r(1.0 - INB)^r]^{\frac{1}{r}} \quad \text{with} \quad r \geqslant 1 \quad (7)$$

$$d_{HO} = [w_1^r(1.0 - IHSI)^r + w_2^r INO^r]^{\frac{1}{r}} \quad \text{with} \quad r \geqslant 1 \quad (8)$$

The ultimate goal of these functions is a harmonious and healthy fish community: every fish has the greatest adaptability (or the widest niche breadth) but the least competition (or the smallest niche overlap) in an optimum habitat (or the largest *IHSI*). The set of a harmonous fish community is (*IHSI*, *INB*, *INO*) = (1.0, 1.0, 0.0). In Eqs. (6)–(8), *Potential* is the potential of fish community rehabilitation at a site; *IHSI* is the mean value of normalized *IHSI* of all fish species occurring at a site; *INB* is the normalized mean integrated niche breadth and *INO* is the normalized mean integrated niche overlap of all fish at a site; *IHSI*, *INB* and *INO* are in the range (0, 1); d_{HB} and d_{HO} are the distances of an actual fish community from the healthy fish community based on relationships of *IHSI*–*INB* and *IHSI*–*INO*, and the goals are nearer as the distance decreases; w_1 and w_2 are weights, which can be determined using weight determination methods, such as the entropy method, and $w_1 + w_2 = 1.0$; r is a scale-related coefficient, and d_{HB} and d_{HO} are the Hamming distances when r is 1.0 and Euclidean distances (Rajeswari et al., 2007; Hao and Shang, 2008; Zhao et al., 2013) when r is 2.0.

4.4. Dominance index to determine dominant species

Abundance and biomass of biota are fundamental indices for biological monitoring. Abundance reflects the individual number of a species, while biomass reflects the size of a species. The demands of a large species on the habitat gradient are greatly different from those of a small species. Both abundance and biomass are important for the existence and health of any biota community. In this study, they were combined to determine the dominant fish species using Eq. (9) (Zhao et al., 2014):

$$I_{importance} = \omega_1 PCT_{abundance} + \omega_2 PCT_{biomass} \quad (9)$$

where $I_{importance}$ stands for the dominance of a species, $PCT_{abundance}$ and $PCT_{biomass}$ refer to the ratio of the species' abundance and biomass to the total for the communities, respectively, and ω_1 and ω_2 are the weightings of abundance and biomass, which were determined using the entropy method.

4.5. Entropy method to determine weights

In the above-presented (sub-) models, the weighting of each indicator is of great significance. It determines the efficiency and precision of the assessment results. The entropy method has been proven to be appropriate for objectively deriving the weight assigned to each indicator (Dong and Liu, 2011). Information entropy represents uncertainties; it can measure effective information from the data provided. The entropy and entropy weighting decrease with the reduction of the amount of information, and vice versa (Hao et al., in press).

4.6. Key habitat factors determination

Habitat factors encompass hydrologic, physical and water chemical parameters, as shown in Table 1. Methods using unconstrained ordination (detrended correspondence analysis: DCA) and unimodal ordination (canonical correspondence analysis: CCA) with a Monte Carlo permutation test were used to select key factors (p less than 0.05) from the above three types of parameters that underpinning the spatial heterogeneity of the fish community.

Canonical correspondence analysis (CCA) is a multivariate gradient analysis method that is designed to elucidate relationships between biological assemblages of species and environmental factors. It develops a coordinate system that is optimal for correlation analysis, and the eigenvectors define this coordinate system. Eigenvectors of environmental variables permit the identification of those variables with higher loadings and, thereby, that have more important relationships with biological data. CCA creates orthogonal components and a set of scores for each item. Therefore, it has been widely used to predict interactions between community structure and environmental variables (Godoy et al., 2002; Martino and Able, 2003; Mansor et al., 2012; Barrella et al., 2014; Biswas et al., 2014).

5. Results and discussion

Dominant fish and key habitat factors were determined based on the dominance index as well as the detrended correspondence analysis (DCA) and canonical correspondence analysis (CCA). Subsequently, the *IHSI*, *INB* and *INO* were calculated based on the dominant fish species occurring at a site.

5.1. Determination of dominant fish species

Eq. (9) was used to select fish species that contribute the most to the fish community in the study area. Weightings of abundance ($PCT_{abundance}$, $\omega_1 = 0.43$) and biomass ($PCT_{biomass}$, $\omega_2 = 0.57$) were determined using the entropy method based on 144 fish samples in Jinan City. The dominance index (Table 3) suggests that 16 of a total 37 fish species ($I_{importance}$ greater than 1.0) contributed 92.33% to the whole community. Therefore, the 16 species were selected as the dominant fish species for the study area, which formed the basis for the calculation of the habitat suitability index and the ecological niche of the entire fish community.

In addition to the fish species in Table 3, *Mylopharyngodon piceus* and *Silurus asotus* Linnaeus are two native fish species recorded in previous studies (Zhang, 1959; Zhong, 1993). Long-term intensive human activities have greatly reduced the suitability of their habitat. Although their dominance index was very low (0.27% and 0.11%), they are very important to the local fish communities. Thus, they were listed as dominant species together with the other

Table 3
Dominance index of dominant fish species.

No.	Fish name	$I_{importance}$ (%)
1	*Carassius auratus*	33.03
2	*Hemiculter leucisculus*	11.07
3	*Channa argus*	8.98
4	*Misgurnus anguillicaudatus*	6.10
5	*Abbottina rivularis*	5.19
6	*Cyprinus carpio* Linnaeus	4.99
7	*Pseudorasbora parva*	4.48
8	*Rhodeus ocellatus*	3.96
9	*Ctenopharyngodon idellus*	2.59
10	*Hypophthalmichehys molitrix*	2.46
11	*Huigolio chinssuensis*	2.14
12	*Ctenogobius giurinus* (Rutter)	2.04
13	*Opsariichthys bidens* Günther	1.55
14	*Gnathopogon imberbis*	1.39
15	*Pseudorasbora fowleri* Nichols	1.18
16	*Ctenogobius brunneus*	1.18
Sum		92.33

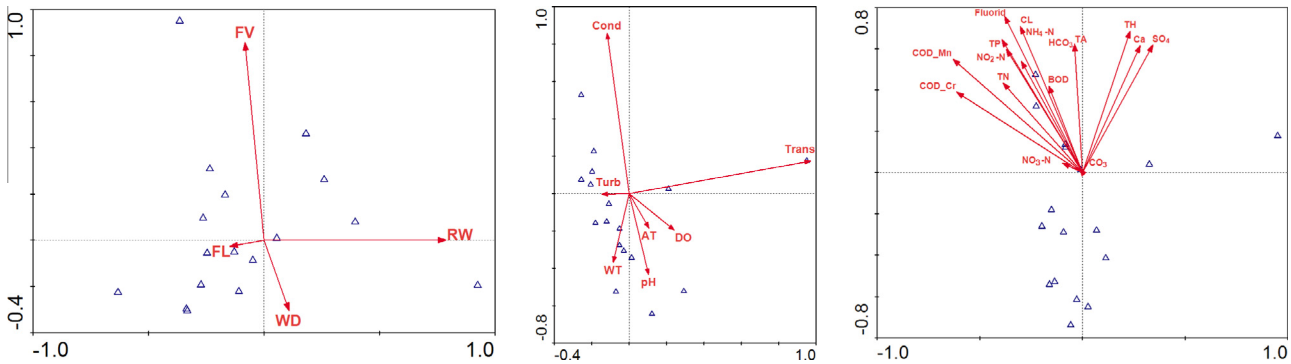

Fig. 3. Selection of key habitat factors from hydrologic (left), physical (middle) and chemical (right) habitat environments using the CCA method.

Table 4
Gradients of key habitat factors.

Gradient	1	2	3	4	5	6	7
RW	<30.37	30.37–58.64	58.64–86.91	86.91–115.18	115.18–143.45	143.45–171.72	⩾171.72
Trans	<1230.22	1230.22–2459.92	2459.92–3689.62	3689.62–4919.33	4919.33–6149.03	6149.03–7378.74	⩾7378.74
SO_4	<170.44	170.44–297.40	297.40–424.36	424.36–551.33	551.33–678.29	678.29–805.26	⩾805.26
CO_3	<1.78	1.78–3.57	3.57–5.35	5.35–7.14	7.14–8.93	8.93–10.71	⩾10.71
TN	<0.20	0.20–0.50	0.50–0.75	0.75–1.00	1.00–1.50	1.50–2.00	⩾2.00
COD_Mn	<2.00	2.00–4.00	4.00–6.00	6.00–8.00	8.00–10.00	10.00–15.00	⩾15.00
BOD	<3.00	3.00–4.00	4.00–5.00	5.00–6.00	6.00–8.00	8.00–10.00	⩾0.00

16 species; therefore, a total of 18 species were used to study the potential of fish community rehabilitation in the study area.

5.2. Selection of key habitat factors

In the first step, we calculated the unconstrained ordination with DCA, which provides a basic overview of the compositional gradients in the species data. The first gradient, which has a value of 4.190, is by far the largest and explains 15.6% of the total species variability, while the second and higher axes explain less (3.2–10.0%). This suggests that the use of unimodal ordination methods is appropriate here. Therefore, the unimodal ordination method CCA was selected to study the relationships between species and environment, to determine the principal environmental factors that influence the fish composition in the study area. The selection of key habitat factors are shown in Fig. 3.

Regarding the *hydrologic* factors (the left sub-figure in Fig. 3), the Monte Carlo test revealed that the first canonical axis was significant (P-value = 0.048 < 0.05). The CCA calculation showed that the cumulative percentage variance of the species data (6.5%) on the first canonical axis was much higher than that on the remaining three canonical axes (2.5%, 2.3% and 0.7%). Furthermore, the species–environment correlation of the first canonical axis (0.717) was much higher than the remaining axes (0.496, 0.619, 0.298). The marginal effect of RW (Lambda1 = 0.21) was greater than Flow velocity (FV), Flow (FL) and Water depth (WD) (Lambda1 was 0.1, 0.1 and 0.06, respectively). Additionally, RW had the highest biplot scores (0.79) on the first canonical axis among the four hydrologic predictors. Thus, RW was selected as the principal hydrologic factor influencing the spatial variation of fish species.

CCA analysis on the *physical* factors (the middle in Fig. 3) showed that the cumulative percentage variance of species data (10.3%) on the first canonical axis was much higher than that on the remaining three canonical axes (6.4%, 4.7% and 2.5%). Furthermore, the species–environment correlation on the first canonical axis (0.894) was much higher than that on the remaining axes

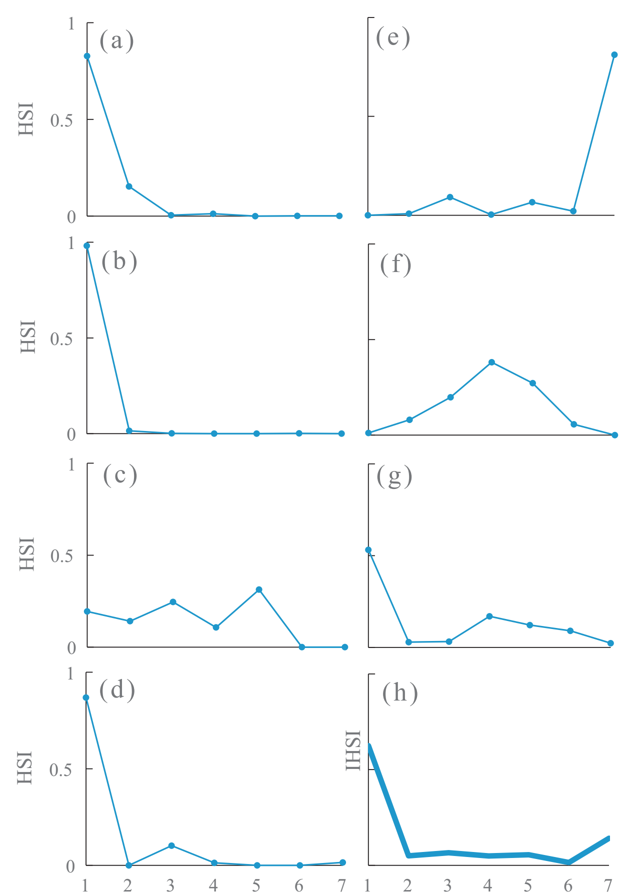

Fig. 4. Habitat suitability index (*HSI*) of *Carassius auratus* (SP1) along the seven key habitat factors (a–g) and the integrated *HSI* of SP1 (h). (a) RW; (b) Trans; (c) COD_Mn; (d) SO_4; (e) TN; (f) CO_3; (g) BOD.

Table 5
Weighted Mean *HSI* and *IHSI* of 18 representative species along the gradients of seven key habitat factors.

No.	Species	Weighted Mean *HSI* of species along							Weighted Mean *IHSI*
		RW	Trans	SO_4	CO_3	TN	COD_Mn	BOD	
1	*Carassius auratus*	0.04	0.02	0.21	0.04	0.03	0.15	0.09	0.05
2	*Hemiculter leuciscus*	0.06	0.03	0.17	0.03	0.03	0.09	0.05	0.05
3	*Channa argus*	0.02	0.01	0.20	0.03	0.02	0.06	0.05	0.03
4	*Misgurnus anguillicaudatus*	0.08	0.05	0.09	0.08	0.05	0.08	0.09	0.07
5	*Abbottina rivularis*	0.09	0.05	0.17	0.02	0.04	0.09	0.02	0.05
6	*Cyprinus carpio* Linnaeus	0.08	0.01	0.12	0.04	0.02	0.06	0.04	0.04
7	*Pseudorasbora parva*	0.10	0.02	0.07	0.01	0.05	0.09	0.02	0.04
8	*Rhodeus ocellatus*	0.04	0.26	0.21	0.03	0.08	0.17	0.04	0.13
9	*Ctenopharyngodon idellus*	0.02	0.30	0.06	0.01	0.02	0.06	0.02	0.11
10	*Hypophthalmichehys molitrix*	0.13	0.01	0.10	0.01	0.01	0.07	0.16	0.05
11	*Huigolio chinssuensis*	0.17	0.03	0.14	0.17	0.10	0.09	0.05	0.10
12	*Ctenogobius giurinus* (Rutter)	0.07	0.10	0.19	0.06	0.07	0.11	0.06	0.08
13	*Opsariichthys bidens* Günther	0.02	0.15	0.07	0.09	0.12	0.07	0.06	0.10
14	*Gnathopogon imberbis*	0.08	0.11	0.18	0.01	0.02	0.11	0.02	0.07
15	*Pseudorasbora fowleri* Nichols	0.06	0.02	0.21	0.03	0.04	0.17	0.17	0.06
16	*Ctenogobius brunneus*	0.10	0.03	0.15	0.01	0.06	0.07	0.03	0.04
17	*Mylopharyngodon piceus*	0.25	0.01	0.11	0.17	0.01	0.13	0.08	0.09
18	*Silurus asotus* Linnaeus	0.02	0.01	0.06	0.07	0.06	0.06	0.06	0.04

Table 6
Niche breadth of 18 representative species along the gradients of seven key habitat factors.

No.	Species	Niche breadth of species along							*INB*	Rank
		RW	Trans	SO_4	CO_3	TN	COD_Mn	BOD		
1	*Carassius auratus*	1.412	1.038	4.405	1.306	1.488	3.724	2.962	2.792	1
2	*Hemiculter leucisculus*	1.719	1.135	3.739	1.185	1.557	3.400	1.839	2.397	4
3	*Channa argus*	1.000	1.000	2.579	1.153	1.324	2.000	1.849	1.762	10
4	*Misgurnus anguillicaudatus*	2.193	1.232	1.838	1.976	2.190	2.933	3.870	2.463	3
5	*Abbottina rivularis*	2.464	1.246	3.012	1.129	1.776	2.688	1.166	2.101	8
6	*Cyprinus carpio* Linnaeus	2.000	1.000	1.690	1.324	1.324	1.815	1.324	1.552	12
7	*Pseudorasbora parva*	2.208	1.042	1.223	1.021	2.052	1.894	1.064	1.485	15
8	*Rhodeus ocellatus*	1.280	2.165	2.342	1.298	2.121	2.595	1.599	1.978	9
9	*Ctenopharyngodon idellus*	1.000	1.354	1.000	1.000	1.125	1.347	1.061	1.110	18
10	*Hypophthalmichehys molitrix*	1.000	1.000	2.000	1.000	1.000	1.000	1.000	1.248	17
11	*Huigolio chinssuensis*	1.662	1.090	1.750	1.468	1.762	1.513	1.632	1.602	11
12	*Ctenogobius giurinus* (Rutter)	1.943	1.651	3.931	1.583	3.034	3.224	2.216	2.754	2
13	*Opsariichthys bidens* Günther	1.000	2.015	1.169	1.800	2.036	1.226	1.800	1.492	14
14	*Gnathopogon imberbis*	1.808	1.843	3.296	1.048	1.221	3.570	1.064	2.185	6
15	*Pseudorasbora fowleri* Nichols	1.665	1.017	2.469	1.187	1.728	3.027	3.319	2.331	5
16	*Ctenogobius brunneus*	2.760	1.143	2.786	1.034	2.463	2.397	1.222	2.111	7
17	*Mylopharyngodon piceus*	1.000	1.000	1.800	1.800	1.000	1.800	1.800	1.534	13
18	*Silurus asotus* Linnaeus	1	1	1	1.8	1.8	1.8	1.8	1.421	16

Table 7
Niche overlap of 18 representative species along the gradients of seven key habitat factors.

No.	Species	Niche overlap sum of one species with the others along							*INO*	Rank
		RW	Trans	SO_4	CO3	TN	COD_Mn	BOD		
1	*Carassius auratus*	14.3747	16.3946	10.6501	16.5572	15.787	8.7765	15.0058	14.083	8
2	*Hemiculter leucisculus*	14.4062	16.4805	12.7092	16.4876	16.0289	13.775	15.2157	15.026	1
3	*Channa argus*	14.0347	16.3836	8.7802	16.4613	15.8442	13.0681	14.3784	14.434	3
4	*Misgurnus anguillicaudatus*	14.4361	16.5354	12.8754	16.5317	16.0575	13.8996	13.9384	14.952	2
5	*Abbottina rivularis*	13.7756	16.5425	11.6578	16.4639	15.8744	11.5283	15.1083	14.409	4
6	*Cyprinus carpio* Linnaeus	12.0364	16.3836	10.3663	16.2102	15.8442	12.3217	15.1212	13.857	9
7	*Pseudorasbora parva*	10.998	16.3889	11.5912	16.3927	15.5095	11.8304	15.0258	13.522	12
8	*Rhodeus ocellatus*	14.239	10.2971	7.4513	16.5257	9.2431	6.7693	15.1667	11.916	15
9	*Ctenopharyngodon idellus*	14.0347	3.9062	11.1849	16.38	15.6495	11.4241	15.0403	12.426	14
10	*Hypophthalmichehys molitrix*	2.9874	16.3836	12.6402	16.38	15.5025	8.0893	2.1801	9.278	17
11	*Huigolio chinssuensis*	5.898	16.4667	9.5901	6.1048	6.284	9.3001	15.0703	9.289	16
12	*Ctenogobius giurinus* (Rutter)	14.3246	16.2063	11.807	16.4666	13.5946	11.2573	15.278	14.274	5
13	*Opsariichthys bidens* Günther	14.0347	14.9625	11.6211	15.4062	14.0937	10.5233	14.3614	13.701	11
14	*Gnathopogon imberbis*	13.4268	15.9029	11.1493	16.4155	15.7805	11.9079	14.9915	14.200	6
15	*Pseudorasbora fowleri* Nichols	14.3418	16.3926	8.36	16.5195	15.9235	7.4946	6.1038	12.845	13
16	*Ctenogobius brunneus*	11.4568	16.3714	12.2642	16.4065	14.3061	13.2332	15.1161	13.799	10
17	*Mylopharyngodon piceus*	1.386	16.384	10.986	8.836	15.503	9.701	9.079	8.722	18
18	*Silurus asotus* Linnaeus	14.0347	16.3836	11.1849	15.6425	14.3581	11.8825	13.9067	14.110	7

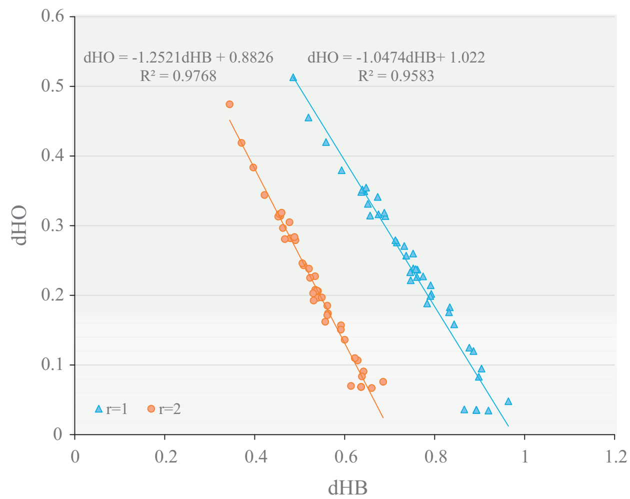

Fig. 5. Relationship of habitat suitability index – ecological niche breadth (d_{HB}) and habitat suitability index – ecological niche overlap (d_{HO}) with different scale related coefficients of $r = 1.0$ and $r = 2.0$.

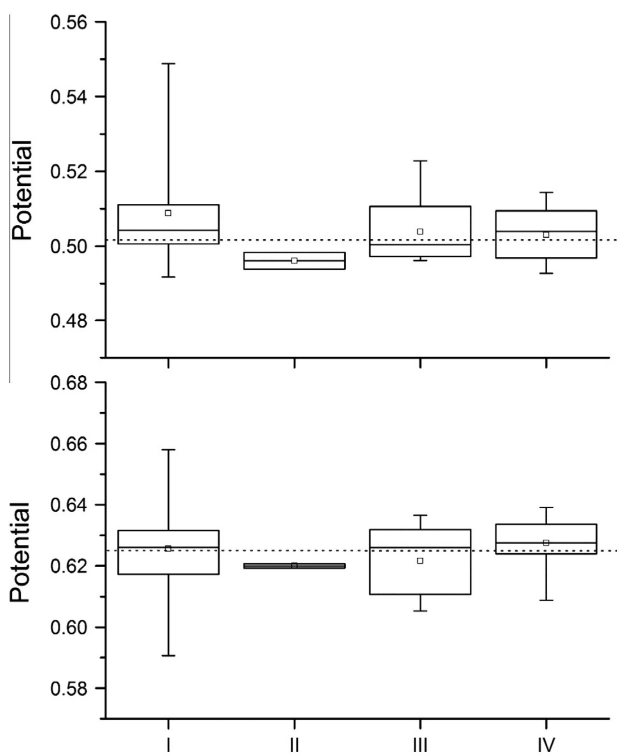

Fig. 6. Rehabilitation potential of fish community in the four eco-regions (ERs: I–IV), with different scale related coefficients, $r = 1.0$ (Hamming distance, above) and $r = 2.0$ (Euclidean distance, below). From top to bottom, the error bars in turn indicate values of the maximum, 75%, mean (small inner rectangle), 25% and minimum of the data set in every eco-region.

(0.702, 0.694, 0.508). The marginal effect of Transparency (Trans) (Lambda1 = 0.43) was much greater than those of the remaining six physical predictors, the maximum of which was 0.23 (Cond). Additionally, Trans had the highest biplot scores (0.9694) on the first canonical axis while the remainder of the physical predictors peaked at 0.2415 (DO: Dissolved oxygen). Therefore, Trans was the main physical factor influencing the variation of fish species.

With regards to the *chemical* factors (the right in Fig. 3) cumulative percentage variance of the species data (9.6%) on the first canonical axis was higher than that on the remaining three canonical axes (8.0%, 5.1% and 4.8%). Furthermore, the species–environment correlation on the first canonical axis (0.861) was higher than that of the remaining axes (0.798, 0.670, 0.671). Permanganate index (COD_Mn), Chemical oxygen demand (COD_Cr), Ammonia nitrogen (NH_4-N), Total nitrogen (TN), Total phosphorus (TP), and Fluoride had the highest biplot scores (0.7304, 0.6936, 0.5533, 0.5461, 0.5288, 0.4971) on the first canonical axis among the measured chemical factors. Among all factors, COD_Mn was highly correlated with COD_Cr, Fluoride, NH3-N, TP and CL ($r > 0.51$); Fluoride was highly correlated with Chlorine (CL), COD_Mn, Total alkalinity (TA), Bicarbonate (HCO_3), NH_4-N, TP, Total hardness (TH) ($r > 0.50$); Sulfate (SO_4) was correlated with Calcium (Ca) and TH ($r > 0.52$), and Total nitrogen (TN) was highly correlated with Calcium (Ca), CL, NH_4-N, Nitrite (NO_2-N), Nitrate (NO_3-N) and TP ($r > 0.65$). Taking into account the marginal effect and *p*-value in the conditional effect of these chemical factors, COD_Mn, SO_4, TN, Carbonate (CO_3) and Biochemical oxygen demand (BOD) were finally selected as the principal chemical factors that influence the variation of fish species in the waters of the study area.

In brief, 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 spatial variation of fish species in the study area.

The gradients of the seven key factors were determined (Table 4) with their maximum and minimum values, taking into account the national water quality standard of China (EPAC, 2002). The gradients of the seven key habitat factors formed the basis of the *HSI* and ecological niche calculations.

5.3. Habitat suitability index (HSI) for the fish community

Every fish species responds differently to different habitat factors. In this study, 18 representative fish species with the seven key habitat factors produce $18 * 7 = 126$ response curves. For example, *Carassius auratus* (SP1) has seven different forms of response curves (*HSI* – habitat factor) (a–g in Fig. 4). Generally, lower gradients (Table 4) of river width (RW), transparency, sulfate (SO_4) and biological oxygen demand (BOD) are more suitable for *C. auratus* (a, b, d, g in Fig. 4), while relatively higher total nitrogen (TN) is favoured by this species (e in Fig. 4). Regarding carbonate (CO_3) (f in Fig. 4), the middle gradient in Table 4 of CO_3 is favoured by *C. auratus*. Different gradients and different habitat factors were assigned different weights using the entropy method, whereby an integrated response curve was derived, as shown in Fig. 4h, which embodies an innate characteristic of *C. auratus* after long-term adaptation to the study area.Habitat suitability indices (HSI_{in} in Eq. (1), 'Weighted Mean *HSI*' in Table 5) of the 18 representative fish species along the seven key habitat factors were calculated, based on which the integrated habitat suitability indices ($IHSI_i$ in Eq. (1), 'Weighted Mean *IHSI*' in Table 5) of the 18 species along all habitat factors were obtained. With the *IHSI* of species that occur at a sampling site, which varies with geographical parameters, the spatial pattern of habitat suitability of Jinan City is easy to study.

5.4. Ecological niche of the fish community

We computed the ecological niche breadth (Table 6) and overlap (Table 7) of the 18 representative species along the seven key habitat factors using Eqs. (2) and (3). Integrated niche breadth (*INB*) and integrated niche overlap (*INO*) were calculated using Eqs. (4) and (5).

Generally, a species with a wider niche breadth has greater adaptability, while one with a narrower niche breadth is sensitive

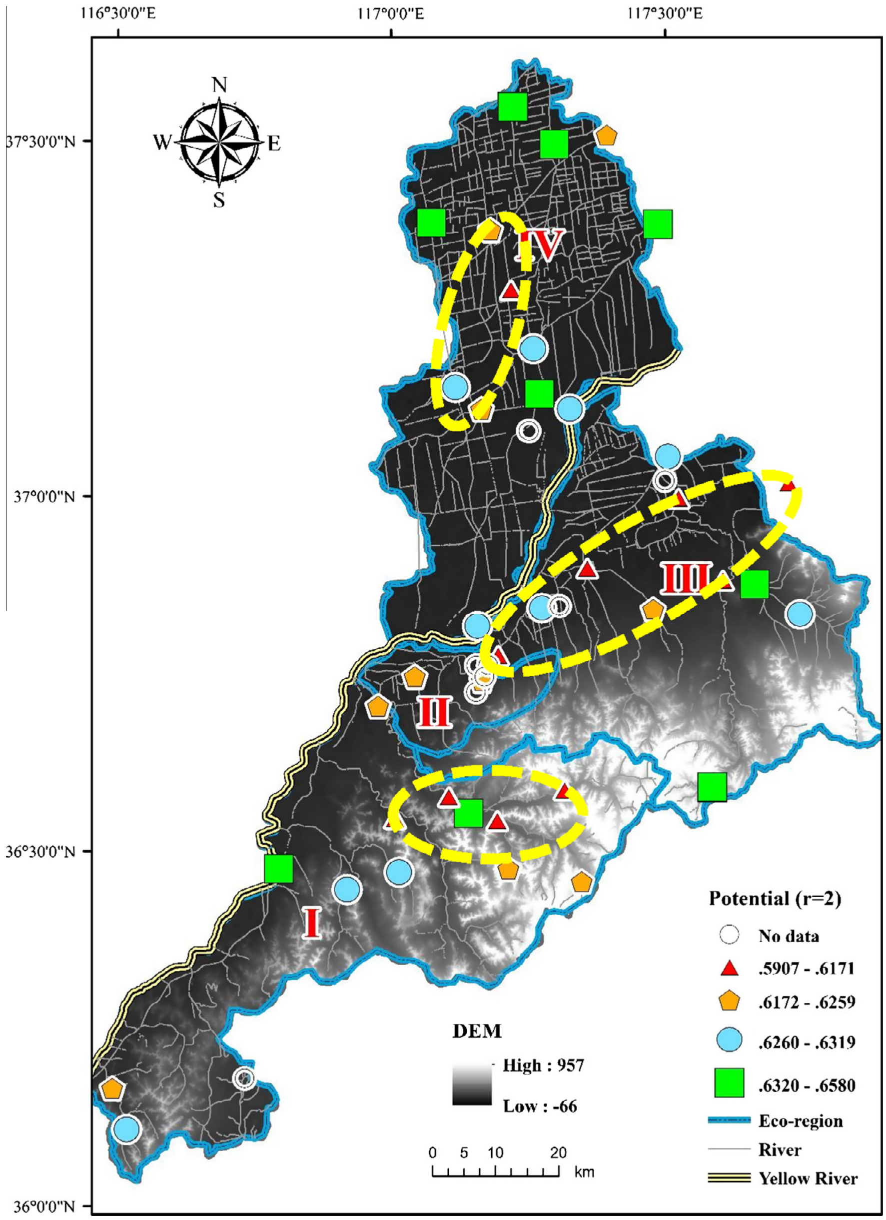

Fig. 7. Rehabilitation potential of the fish communities in Jinan City with the Euclidean distance (r = 2.0), "No data" means that no representative fish species occur there.

to habitat change. If two species have a large niche overlap, this suggests that they have similar behavior in the utilization of habitat factors, which might result in strong competition with each other under certain conditions (Zhao et al., 2012). Therefore, a wider niche breadth of a species along a habitat factor suggests, to some degree, a higher survival chance of the species when the factor varies greatly. Similarly, a wider integrated niche breadth (*INB*) of a species along all key habitat factors suggests a higher survival chance of the species in the study area (Table 6). Furthermore, a greater niche overlap sum of a species with the others along a factor could indicate a higher risk of survival along the factor gradient. A greater integrated niche overlap (*INO*) of a species with the others along all key factors indicates a higher survival risk of the species in the study area (Table 7).

In detail, among the 18 representative species, *C. auratus* has the highest survival chance in the study area (*INB* = 2.792, ranking the first), while *Hypophthalmichehys molitrix* has the least survival chance (*INB* = 1.0). When the habitat factors changed substantially, such as after some ecological rehabilitation measures were implemented, *H. molitrix* would face the greatest threat (Table 6).

Additionally, *Hemiculter* has the greatest survival risk in the study area (*INO* = 15.338, ranked first), while *Mylopharyngodon* has the lowest survival risk (*INO* = 8.736). When the habitat factors were substantially altered, *Hemiculter* would face the greatest threat of extinction (Table 7).

INB and *INO* (Tables 6 and 7) in Eqs. (6)–(8) were designed to calculate the potential of fish community rehabilitation.

5.5. Rehabilitation potential of fish community

With the *IHSI* (Table 5), *INB* (Table 6) and *INO* (Table 7) we assessed the rehabilitation potential of the fish community across the whole study area using Eqs. (6)–(8). The Hamming (r = 1) and Euclidean (r = 2) distances of the actual fish community to the goal of an ideal fish community were calculated (Fig. 5). With the adoption of either the Hamming distance or Euclidean distance, the

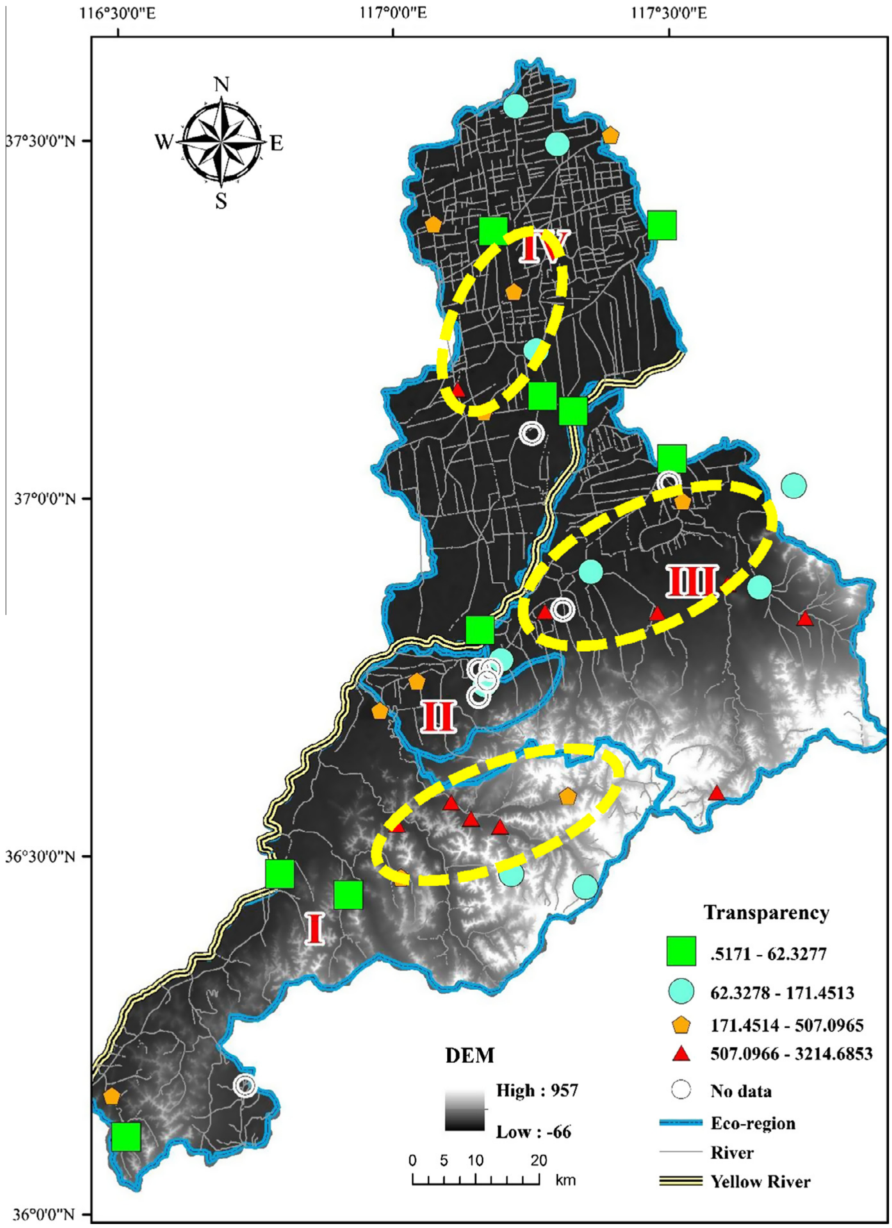

Fig. 8. Distribution of the key physical environmental factor, Transparency. "No data" means that no representative fish species occur there.

relationship between d_{HB} and d_{HO} remained almost unchanged with a highly negative correlation ($R^2 > 0.90$) i.e., a change of scale coefficient (r) has little effect on the d_{HB}–d_{HO} relationship.

Potential values of the fish communities in the four eco-regions using the Euclidean distance are all larger than those using the Hamming distance (Fig. 6). The mean potential values in the four eco-regions using the Hamming distance (Fig. 6, above) fluctuate around 0.50, while those using the Euclidean distance (Fig. 6, below) fluctuate around 0.62. The maximum value of the former is less than 0.55, while that of the latter is up to 0.66. Based on the research of Rajeswari et al. (2007), the Euclidean distance generally outperforms the Hamming distance. Therefore, in the following sections rehabilitation potential using the Euclidean distance ($r = 2.0$) was selected to study the spatial heterogeneity of fish communities in the study area.

Of the four eco-regions (ERs), the rehabilitation potential using the Euclidean distance ($r = 2.0$, Fig. 6 below) spatially varies. An analysis of the differences between the maximum and the minimum values suggests that the ER I has the greatest spatial heterogeneity, which is greater than ERs II, III & IV. ER IV has the greatest mean value among the four ERs and is slightly greater than ER I. ER II has the smallest value. It has the lowest spatial heterogeneity, with the mean, 25% and 75% values differing little (Fig. 6).

In ER II, a rural area, very intensive human activities has caused the deterioration of the environment (Zhang et al., 2007; Hong et al., 2010), to the extent that all 18 representative fish species were absent at most sites (67%) ("No data" in Fig. 7) while this was less so for the remaining ERs with few "no data" sites presented. On average, the rural area (ER II) has the lowest potential (Fig. 7).

Over the study area, three lower potential regions are distinguished (Fig. 7): the middle-west of ER IV, the north of ER III and the north of the ER I, as shown by the dashed elliptical areas in Fig. 7. These regions should be prioritized in future aquatic ecosystem rehabilitation.

For successful aquatic ecosystem rehabilitation, periodical assessment of rehabilitation potential to monitor the rehabilitation effect is required (Wissmar and Bisson, 2003; Bellmore et al., 2012). Current methods depend on too much information and expertise as well as too-complicated theories (Fox, 2004; Bain and Meixler, 2008; Hughes et al., 2010; Bellmore et al., 2012), which makes it difficult for them to be widely applied in routine assessments of rehabilitation potential. To fill this gap, this paper presents an effective method with easy-to-understand theories (habitat suitability and ecological niche theories), based on the dominant and native fish species extracted from routine monitoring data. It requires limited information and expertise: only the abundance and biomass of fish species; accurate fish names are unnecessary. The two easily recorded fish attributes can then be linked to habitat gradients of hydrologic, physical and chemical parameters to assess the rehabilitation potential across a study area. Application of this method in Jinan City suggests three lower potential regions (the dashed elliptical area in Fig. 7) would require active protection and improvement of habitats to ensure successful rehabilitation.

An optimized fish assemblage structure is the basis of high rehabilitation potential. Rodríguez and Lewis (1997) indicated that the fish assemblage structure in lakes was predictably related to, but not restricted to, transparency and surface area. Surface area can be simplified as the width of the water surface in a river, i.e., the river width (RW) in our study. Fish assemblages were not limited by a single factor but an interaction among many variables (Rahel, 1984). In the present study, a partial correlation with bootstrap indicates that the potential heterogeneity is positively correlated with river width (RW, p-value = 0.054 < 0.10) and negatively correlated with transparency (Trans, p-value = 0.087 < 0.10), which concur with the findings of Rodríguez and Lewis (1997). The mean values of measured RW within the three elliptical areas (Fig. 7) were 23.75, 13.73, 22.10 m (from top to low), respectively. They were much lower than the city-averaged value 41.45 m. The spatial pattern of transparency shows three high-transparency regions (dashed elliptical area in Fig. 8), which correspond to the three lower potential regions (dashed elliptical area in Fig. 7). This concordance indicates the rehabilitation potential assessment is promising based on the fish assemblages.

In addition, the three elliptical areas – the middle-west of ER IV, the north of ER III and the north of the ER I are densely populated with large area of farm land. The former two areas fall into categories of plain agricultural area (even DEM in Fig. 7) and the last one belongs to mountainous agricultural area. In these areas inadequate riparian cover allowed for increased runoff to enter into river unimpededly and unassimilatedly (Saalfeld et al., 2012). Non-point sources of pollutants from agricultural and domestic activities by the poorly planned settlers nearby the river were flushed into river along with runoff. These have been implicated to be causative to the poor quality of the river and its aquatic life (Kolawole et al., 2011). This resulted in increased periphyton biomass which negatively influenced the fish community health (Saalfeld et al., 2012). These areas should be prioritized in the fish community restoration.

What is worth noticing is that in ER II, the high-populated city urban area, many representative species were absent (blank circle in Fig. 7). Many scholars agreed that fish elimination might occur when human disturbances were excessively intense (Vila-Gispert et al., 2002; Adams et al., 2005; Cheimonopoulou et al., 2011; Zhang et al., 2011). Therefore impact intensity of socio-economic development on aquatic ecosystems should be substantially reduced. It is imperative to improve the rate of wastewater treatment before flowing into rivers.

Although our method is based on easy-to-understand theories with few requirements on fish assemblage information and science expertise and, as demonstrated in our study in Jinan City, it has some unavoidable uncertainties in the results. One source of uncertainty is the determination of dominant fish species, which can be influenced by selection of a species subjectivity. To reduce this uncertainty we selected as many of the fish species as possible (16 of 37), which represented 92.33% of the entire fish community in the study area (Table 3). The other source of uncertainty is the selection of key habitat factors. Key habitat factors are subject to many environmental parameters, e.g., solar radiation intensity, sunshine period, wind, riparian vegetation, and agricultural activities. Therefore, the key factors are disposed to vary with season. To reduce this type of uncertainty, we integrated monitoring datasets for three time periods (May, August and November), to more comprehensively select key habitat factors. Further, we used detrended correspondence analysis (DCA) before the canonical correspondence analysis (CCA) to avoid the "arc effect" in the gradient method of the CCA (Lepš and Šmilauer, 2003), which can produce uncertainty in the selection results.

Overall, few requirements on assemblage information and scientific expertise as well as an easily understandable theory and process make our method a practical tool for use to periodically assess the effect of rehabilitation that ensures successful restoration of aquatic ecosystems. This has great ramifications for restoration of aquatic ecosystems and fish communities all over the world.

6. Conclusions

To provide a practical model for assessing rehabilitation potential to improve successful aquatic ecosystems restoration, this paper presented an assessment method which successfully links hydrologic, physical and chemical habitat environments to fish assemblage attributes. It has easy-to-understand theories and few requirements on assemblage information and scientific expertise and was demonstrated to be effective and practical in an application in Jinan City.

In the present study, the development of the model was based on Hamming and Euclidean distances as well as three newly developed sub-models: integrated habitat index (*IHSI*), integrated ecological niche breadth (*INB*) and integrated ecological niche overlap (*INO*). The derivation of the three sub-models were based on relationships between environmental gradients of hydrologic, physical and chemical parameters and fish assemblages. They were specially designed to study spatial heterogeneity of the restoration potential of fish assemblages.

To reduce uncertainties in the model, the dominant fish species were selected (in this paper 92.33% contribution to the whole fish community across the study area). Moreover, monitoring datasets for three times (May, August and November 2014) were integrated to comprehensively select key habitat factors, to reduce uncertainty arising from seasonal variations of environment. Detrended correspondence analysis (DCA) was applied to the data to avoid the "arc effect" in the canonical correspondence analysis (CCA) in the present study.

Application of the model in Jinan City, China, revealed three lower potential regions that should be focused on for future aquatic ecosystem rehabilitation through protection, regulation and improvement of key habitat factors in the three regions. Through this modeling exercise we demonstrated that the hydrologic habitat parameter – river width positively influenced and the physical habitat parameter – transparency negatively influenced fish assemblage. In the three lower potential regions strict control on the excessive use of fertilizer and pesticide as well as on the domestic pollutant effluent is substantially necessary. Establishment of wide enough riparian forest buffers is an effective way to reduce the amount of pollutants into waters.

Because of its easily understandable theories and few requirements on assemblage information and scientific expertise, we expect that the model will be applied to monitor the effects of aquatic ecological restoration and to study the spatial heterogeneity of fish assemblages all over the world. Uncertainties in the model can be effectively reduced by judiciously selecting environmental attributes and optimizing the selection of dominant and native fish species, as well as by applying the new method after the monitoring dataset of the habitat environment and fish assemblages has been strengthened. There is potential to apply the model to the other assemblages (e.g., macroinvertebrates and benthic algae) in the future.

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