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Identifying the principal driving factors of water ecosystem dependence and the corresponding indicator species in a pilot City, China

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ABSTRACT

The world's aquatic ecosystems yield numerous vital services, which are essential to human existence but have deteriorated seriously in recent years. By studying the mechanisms of interaction between ecosystems and habitat processes, the constraining factors can be identified, and this knowledge can be used to improve the success rate of ecological restoration initiatives. At present, there is insufficient data on the link between hydrological, water quality factors and the changes in the structure of aquatic communities to allow any meaningful study of driving factors of aquatic ecosystems. In this study, the typical monitoring stations were selected by fuzzy clustering analysis based on the spatial and temporal distribution characteristics of water ecology in Jinan City, the first pilot city for the construction of civilized aquatic ecosystems in China. The dominant species identification model was used to identify the dominant species of the aquatic community. The driving effect of hydrological and water quality factors on dominant species was analyzed by Canonical Correspondence Analysis. Then, the principal factors of aquatic ecosystem dependence were selected. The results showed that there were 10 typical monitoring stations out of 59 monitoring sites, which were representative of aquatic ecosystems, 9 dominant fish species, and 20 dominant invertebrate species. The selection of factors for aquatic ecosystem dependence in Jinan were highly influenced by its regional conditions. Chemical environmental parameters influence the temporal and spatial variation of invertebrate much more than that of fish in Jinan City. However, the methodologies coupling typical monitoring stations selection, dominant species determination and driving factors identification were certified to be a cost-effective way, which can provide in-deep theoretical and technical directions for the restoration of aquatic ecosystems elsewhere.

1. Introduction

The world's ecosystems are important capital assets, yielding numerous vital services that are essential to human existence (Zhao et al., 2012). Unfortunately, escalating impacts of human activities on ecosystems imperil their delivery. Ecosystems are undergoing rapid degradation and depletion (Daily, 1999; Daily et al., 2000) and are increasingly threatened by human-induced habitat loss (Kagalou et al., 2010). Moreover, large quantities of pollutants have been discharged into rivers, resulting in water quality degradation and damaging aquatic ecosystems (Zhao et al., 2012).

In aquatic ecosystems, fish species are the most important ecological groups, playing an important role in the material recycling and energy flow through the system (Mansor et al., 2012). Fish communities are effective indicators of ecosystem health as they are relatively easy to identify, and their position at the top of the food chain means that they reflect the overall health of the environment (Wu et al., 2014). Some habitat restoration programs have taken fish as representative of ecosystems' health and used them to evaluate aquatic ecosystem restoration potential, e.g., the use of the Endangered Species Act to list the anadromous Pacific salmon and steelhead populations in the United States (Bernhardt et al.,

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2005; Bellmore et al., 2012). Habitat type and complexity, or habitat heterogeneity, influences the resource usage 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). Fish on the top of the food chain are more sensitive to chemical pollution than other species and their changes reflect changes of other organisms. Therefore, the status of the fish can reflect the environmental status of the entire ecosystems. Average age, oviposition capacity, and conditional factors are applied as monitoring indicators to track fish population responses to environmental changes, and thereby to assess the health of aquatic ecosystems (Norris and Thoms, 1999; Huo et al., 2012).

In addition to fish, invertebrate species also play a very important role in aquatic ecosystems (Schröder et al., 2013). They are an important nutritional link between microbial, algae, fish, and birds (Keast, 1985; McQueen et al., 1986; Xie et al., 2007a). By accelerating mineralization of the nutrients and facilitating the interchange of materials between the water and bottom sediment, invertebrate species can accelerate the self-purification of a water body (Ingham, 1985; Lindegaard, 1995, Benke, 1993; Kennedy, 1994; Wolfram, 1996; Xie et al., 2007a). Furthermore, invertebrate species are sensitive to environmental change and are therefore important indicator species for water pollution (Xie et al., 2007b). These factors have led to the widespread use of invertebrate species in the evaluation of the health of aquatic ecosystems, and having a guiding role in the protection, utilization, and management of freshwater habitats.

In recent years, a number of ecological restoration projects in Europe and the United States have been carried out, and an assessment of 78 large-scale projects has shown that only a few have achieved their aims (Palmer et al., 2010) due to the inadequacy in the researches on the response of species to environmental factors, which can make clear the relations between environmental factors and biological metrics and further identify the principal limiting factors in freshwater ecosystems (Gieswein et al., 2017; Statzner and Dolédec, 2011). Study on the interaction between ecosystem biological processes, hydrological and water quality processes of aquatic habitats, as well as identification of restricting factors can improve the success rate of ecological restoration projects (Palmer et al., 2005). Therefore, research is urgently necessitated to identify the principal factors driving ecosystem development across the world especially in the areas with ecological restoration projects.

At present, most researches on the ecosystem driving factors are based on the large-scale sampling of the river basin and analyze the impact of social factors and water quality factors on ecosystems caused by human activities (Liu et al., 2016; Wu et al., 2014). There is insufficient research on the spatiotemporal variation of the aquatic ecology of the river basin and its relationship with hydrology and water quality, with the existing studies based mostly on integrated index analyses of all biological factors in aquatic ecosystems (Liu et al., 2016; Xu et al., 2016; He et al., 2014). A failure to consider the change in the aquatic community structure obscured the behavior of the principal aquatic organisms resulting in the uncertainty of the research results. Research is urgently needed to identify typical sites that reflect the characteristics of the different temporal and spatial distribution of watershed habitats and the principal organisms that can reflect the changes of aquatic community structure.

Through analyses of hydrological and water quality coupled with observations of principal indicator species in typical sites, it should be a cost-effective way to identify the principal factors driving the dependence of aquatic ecosystems. Due to the critical role of fish and invertebrates in aquatic ecosystems, improving our understanding of their tempo-spatial heterogeneity is key to the maintenance and remediation of aquatic ecosystems, in terms of controlling the amount of pollutants put into rivers, which in turns sustains the development of society and economy. This is especially important for the Jinan City, a pilot for the construction of a civilized and ecological city in China.

Due to rapid industrial development and urbanization in recent decades, the water resources in Jinan are severely polluted and depleted through extraction (Hong et al., 2010). As a result, river ecosystems are being increasingly threatened and degraded. Policy makers and stakeholders are aware of the need to rehabilitate the river ecosystems in Jinan City. To ensure successful ecosystem restoration in all rivers, river administrators need a practical understanding of the temporal and spatial heterogeneity of river ecosystems, which, up to now, has received little attention outside the research community.

The objectives of this study are to explore the methodologies to improve our understanding of the tempo-spatial heterogeneity of aquatic ecosystems and their change in the community structure based on variation of fish and invertebrate as well as their habitat factors, taking the pilot city Jinan as a case, to improve the success rate of ecosystem restoration project all over the world.

2. Study area

Jinan City (36.0–37.5°N, 116.2–117.7°E), or the Spring City, is a pilot city for the construction of a civilized and ecological city in China. It is bordered by Mount Tai to the south and traversed by the Yellow River, with a steeper topography in the south than in the north (Fig. 1). Hilly areas, piedmont clinoplain, and alluvial plains span the city from north to south. The altitude within the area ranges from −30 to 937 m ASL, 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 with 75% 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). Jinan 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, and human health and well-being, are becoming increasingly threatened (Hong et al., 2010), as is the fish community. sixty routine monitoring stations distributed evenly on typical rivers were established (Fig. 1), In the spring, summer and autumn of the year 2014, 2015 and 2016, nine large-scale field investigations measured 37 hydrologic, water quality physical, and water quality chemical factors (Table 1).

3. Materials and methods

3.1. Data

Based on the comprehensive analysis of the characteristics of the watershed and administrative regions of Jinan City, and the consideration of the spatial differentiation of hydrological water quality, the hydrology/water quality/aquatic ecosystem monitoring stations were identified, located counties (cities) and districts of Jinan City. In spring, summer and autumn of 2014, 2015, and 2016, nine large-scale field investigations recorded a large quantity of hydrological, water quality and water biological synchronization data to analyze the principal driving factors of aquatic ecosystem changes in Jinan City. The monitoring seasons make inter-annual

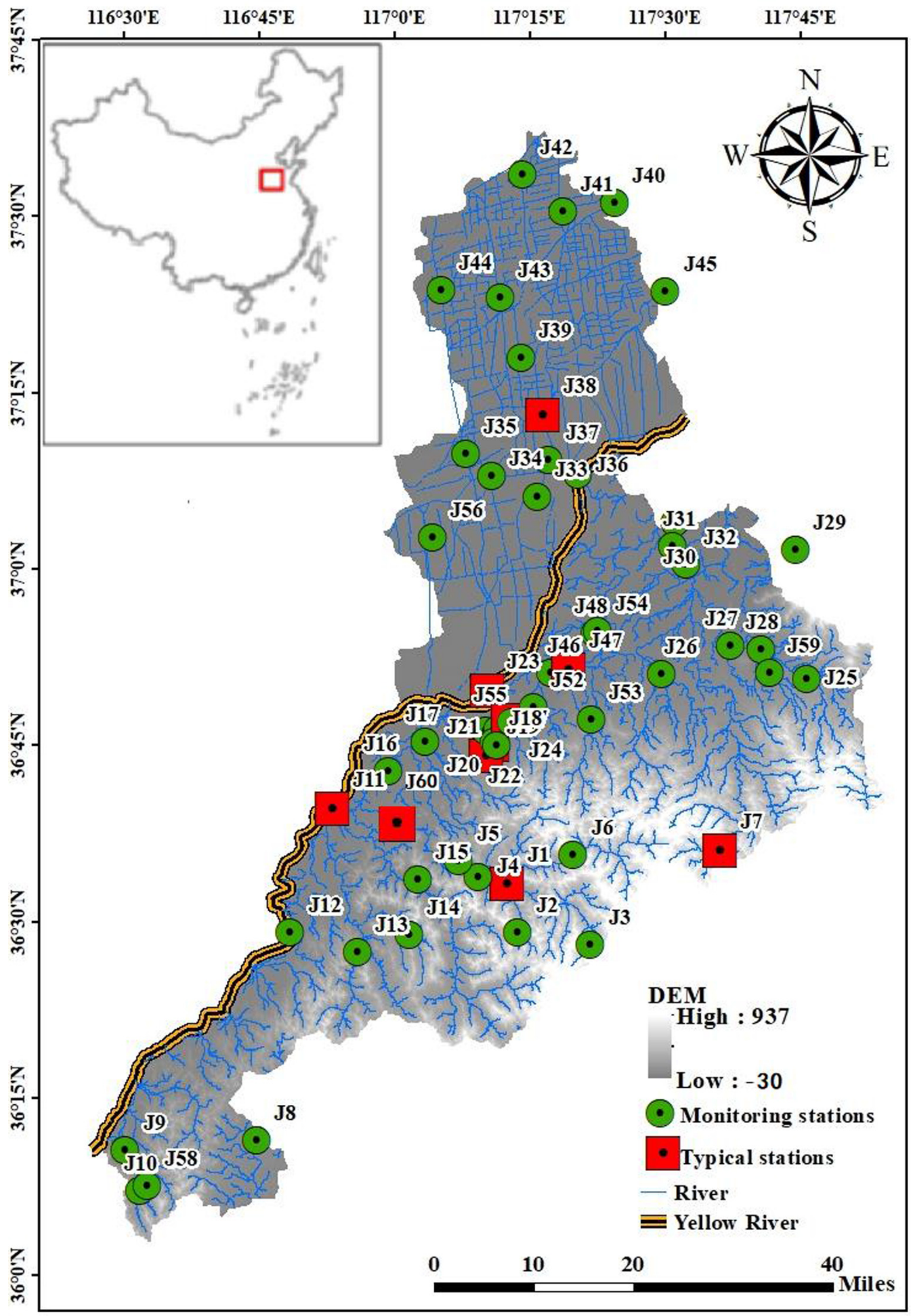

Fig. 1. Study area covering Jinan City and suburban areas with location of hydrology, water quality and aquatic ecosystem monitoring stations.

observations fully comparable and intra-annual observations well representative of variability of the synchronization data.

Data from the nine field investigations for each monitoring station were averaged to reduce influence of the temporal variation on the spatial site-clustering whereby to make prominent the spatial heterogeneity of the hydrology, water quality and biological factors. With the help of spatial site-clustering, typical monitoring stations were determined. All data from the nine field investigations for each typical monitoring station were then used for driving factors identification.

3.1.1. Fish and invertebrate monitoring

3.1.1.1. Fish species. Fish were collected over 30 min in three habitat types, i.e., pools, riffles, and runs, within a 500 m section of 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 according to the method described by 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 complete representation of fish species was collected at each

Table 1
Hydrologic, physical, and chemical environmental parameters in the Jinan City monitoring program (Zhao et al., 2015a).

Parameter	Abbreviation	Name	Unit	Range (SD)
Hydrologic	FV	Flow velocity	m/s	0–1.50 (0.32)
	RW	River width	m	2.1–200.0 (45.3)
	FL	Flow	m^3	0–674 (158.88)
	WD	Water depth	m	0.01–3.50 (0.94)
Physical	AT	Air temperature	°C	15.0–33.1 (4.6)
	WT	Water temperature	°C	16.70–30.60 (2.85)
	pH	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	Ammonia		0.07–9.42 (2.63)
	NO_2	Nitrite		0–1.41 (0.30)
	NO_3	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	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.

site. All individuals collected were identified in situ using the method described by Chen et al. (1987) and their numbers and masses were recorded in field data sheets. All identified fish were then released. A few specimens that could not be identified in the field were preserved in 10% formalin solution and stored in labeled jars for subsequent laboratory identification (Zhao et al., 2015a).

3.1.1.2. Invertebrate species. An oyster bucket harvester with a mouth area of 29 cm × 29 cm was used to dig substrate sludge, which was then washed with a 60-mesh filter. Finally, invertebrate was isolated, and 75% alcohol solution was added to preserve it (Zhao et al., 2010). As invertebrate species are larger than plankton, protoctists, and bacteria, they can be counted and classified by eye. The masses of all aquatic organisms were recorded in the laboratory using a torque balance or a pharmaceutical scale depending on size, and then classified using an aquatic organism atlas (Zhao et al., 2010; Wang and Yang, 2003).

3.1.2. Water quality parameters monitoring

In the nine field investigations, 480 water samples were collected. The physical parameters in Table 1 were measured in situ with portable equipment and the chemical parameters in Table 1were obtained by testing water samples in the laboratory within 24 h which were collected at monitoring sites. A spectrophotometer (DR5000) was used to measure ammonia nitrogen, total phosphorus, total nitrogen, and hexavalent chromium; an atomic absorption spectrophotometer (Thermo M6) was used to measure copper, zinc, cadmium, lead, etc. and an ion chromatograph (DIONEX-600) was used to measure sulfate, fluoride, chloride, and nitrate concentrations. Details of the techniques employed are described by Zhao et al. (2015b).

3.1.3. Hydrological parameters monitoring

The hydrological parameters were shown in Table 1. Other indicators such as substrate were also monitored in the part of habitat health assessment. In the study area, there were only 6/60 stations where substrate consisted of pebble or gravel. The rest were all of sludge. These were insufficient to allow for key habitat factor selection and were therefore excluded in this study.

In the monitoring stations, water depth and flow velocity were routinely monitored. The flow velocity was measured by radio flow meter (Stalker II SVR V1.0) and traditional flow meter (LS25-1) to ensure the accuracy of the results. Water depth and river width were measured with a tape gauge, and flow was calculated from the flow velocity, water depth and cross sectional area. Unmanned aerial vehicle (UAV) was used to retrieve river-course cross-sections with high-resolution stereoscopic images (Zhao et al., 2017).

3.2. Method

3.2.1. Fuzzy clustering method based on biological indices and habitat parameters

Clustering is important for pattern recognition, classification, model reduction, and optimization. Clustering analysis can be performed using the traditional hard clustering method or the fuzzy clustering method (FCM). The hard clustering method is more suitable for clustering conditions with clear boundaries, whereas for problems with unclear boundaries, an FCM is usually adopted (Pan, 2010; Zhao et al., 2013a). In this study monitoring stations distribute randomly covering the whole study area and it is hard to find clear boundaries. Therefore, clustering with FCM is the best choice. The advantage of this algorithm is that it can effectively avoid setting thresholds, and can solve the difficult problem of multiple branches in threshold segmentation (Li et al., 2007; Pan, 2010; Shafi et al., 2010). To facilitate calculation, data in a (n * m) matrix was pre-processed using the model $x'_{ij} = \frac{(x_{ij} - \bar{x_j})}{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_{ij} - \bar{x_j})}}$ ($I = 1,\ldots,n$; $j = 1,\ldots,m$) with the average value $\bar{x_j} = \sum_{i=1}^{n}\frac{x_{ij}}{n}$. During the establishment of a similar matrix, the widely used Euclidean distance $\left(r_{ij} = 1 - \frac{\sqrt{\sum_{k=1}^{m}(x_{ik} - x_{jk})^2}}{\max(\sqrt{\sum_{k=1}^{m}(x_{ik} - x_{jk})^2})}\right)$ was adopted (Zhao et al., 2013a). The maximum Euclidean distance between clusters were calculated during Fuzzy clustering which was conducted in the software "Data Processing System (DPS)" (Tang and Zhang, 2012).

In this study FCM was used to cluster monitoring stations based on biological indices and habitat parameters, which were dealt with the normalized formula $x = \frac{X - X_{min}}{X_{max} - X_{min}}$ before calculation. The habitat parameters include monitored water quality and hydrological variables. Three biological indices were used. The biodiversity index was calculated by Shannon–Weaver (Weaver and Shannon, 1949), and evenness was calculated by Pielou (Lloyd et al., 1968). IBI is one of the principal indices for ecosystem health assessment (Wang et al., 2005). In the process of fish IBI calculation we used three parameters as core parameters including the number of fish species, the number of dominant fish species and the biodiversity index of fish. Five core parameters of invertebrate were selected inclusive of EPT taxa (Mathers et al., 2017), the aquatic insects taxa, the percentage of the individual population, the chironomidae taxa and Shannon–Weaver biodiversity index. Based on the 17 factors listed in Table 2, the stations with similar indices were divided into one class. In the results of FCM the large difference between two station indices usually results in far distance between the stations. To keep as far distance among clusters as one can, the middle station in a cluster was selected to represent all stations in the cluster.

3.2.2. Dominant species identification with dominance breakpoints

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. In this study, they were combined to determine the dominant fish and invertebrate species using Eq. (1) (Zhao et al., 2014).

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

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, $P_{a,i} = \frac{N_i}{\sum_i^N}$, $P_{b,i} = \frac{B_i}{\sum_i^B}$; N_i is the abundance of the i-th species and B_i is the biomass of the species; and ω_1 and ω_2 are the weightings of abundance and biomass, $\omega_1 + \omega_2 = 1.0$. They are determined by using center of mass (Zhao et al., 2015b) as shown in Eqs. (2) and (3).

$$\begin{cases} \frac{\omega_1}{\omega_2} = \frac{a}{b} \\ \omega_1 + \omega_{2=1} \end{cases} \tag{2}$$

$$\begin{cases} a = \frac{\sum_{a,i}^{P} N_i}{\sum_i^N} \\ b = \frac{\sum_{b,i}^{P} B_i}{\sum_i^B} \end{cases} \tag{3}$$

After the dominance index of all species was calculated, the dominant species of the biological community were identified by the breakpoint, i.e., the point on the dominance curve where the curvature is significantly smaller after that point than the curvature before, was determined based on curvature of cumulative dominance using Eq. (4) (Gippel and Stewardson, 1998; Liu et al., 2006; Zhao et al., 2015b).

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

κ represents the curvature of the dominance curve. On the dominance curve, the curvature after a certain point is significantly smaller than the curvature before that point, which is called breakpoint. It is more objective to choose the dominant species in the aquatic population in this way.

3.2.3. Canonical Correspondence Analysis with the Monte Carlo permutation test

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

CCA is based on the corresponding analysis of the development of a sorting method, where the corresponding analysis and multiple regression analysis of the combination of each step are calculated with environmental factors regression, also known as multiple direct gradient analysis. During the iterative process of the corresponding analysis, the quadratic coordinate values obtained each time are subjected to multiple linear regression with the environmental factors. It requires two data matrices which were the species data matrix and the environmental data matrix in this study. A set of quadratic ordering values and sorting values (corresponding to the corresponding analysis) were calculated, and then the quadratic ordering values were combined with the environmental factors by regression analysis. The weighted average of the sorted values was then ranked (Mansor et al., 2012; Barrella et al., 2014).

Habitat factors influencing fish and invertebrate communities include hydrologic, physical, and water chemical parameters. Methods using unimodal ordination with a Monte Carlo permutation test were used to select principal factors ($p < .05$) from the above three types of parameters that underpinned the spatial heterogeneity of the fish and invertebrate communities. The figures of CCA were drawn by using Canoco (Lepš and Šmilauer, 2003).

4. Results

4.1. Typical monitoring stations selection

Hydrological factors (flow velocity, flow, river width, etc.), biological factors (biodiversity, evenness, index of biotic integrity [IBI]) and water quality factors (turbidity, total phosphorus, COD_Mn, etc.) were included in the classification (Table 2). Factors were excluded which were below detection level or similar across the stations.

In Fig. 2, it can be seen that J12, J23, and J36 have a high degree of similarity, belonging to the same cluster; and likewise, J7 and

Table 2
The factors involved in the fuzzy clustering method.

Number	Biology	Water quality	Hydrology
1	Biodiversity of fish	Turbidity	Flow velocity
2	Evenness of fish	K	River width
3	Index of biotic integrity (IBI) of fish	NH_4	Flow
4	Biodiversity of benthos	TP	Water depth
5	Evenness of benthos	NO_2	
6	IBI of benthos	NO_3	
7		COD_Mn	

J14 have a high degree of similarity, so belonging to the same cluster. The cluster containing J12, J23, and J36 is far away from the cluster containing J7 and J14, indicating significant differences. The reason is that as J12, J23, are J36 are all located in the mainstream of the Yellow River. J7 and J14 are both in reservoirs, though the spatial locations are different, the similarities in river landscape means that there will be similarities also in hydrology, water quality, and water ecology. Overall, the 59 monitoring stations can be divided into three clusters:

- Cluster 1: J14, J7, J56, J26, J9, J27, J15, J42, J32, J41, J39, J34, J48, J40, J43, J25, J17, J11, J38, J45, J37
- Cluster 2: J33, J8, J28, J55, J47, J30, J24, J46, J10, J58, J19, J18, J57, J22, J16, J44, J35, J21, J31, J20, J13, J54
- Cluster 3: J23, J12, J36

Clusters 1, 2, and 3 have 21, 22, and 3 monitoring stations, respectively. Cluster 1 and Cluster 2 belong to the same high-level cluster, which contains most of the monitoring stations. Most stations in Cluster 1 locate in lakes or reservoirs; those in Cluster 2 locate in rivers and those in Cluster 3 locate in the mainstream of the Yellow River which is the second largest river in China. Stations in Cluster 1 have deep water depth and low flow velocity while those in Cluster 3 have great flow and river width opposing to

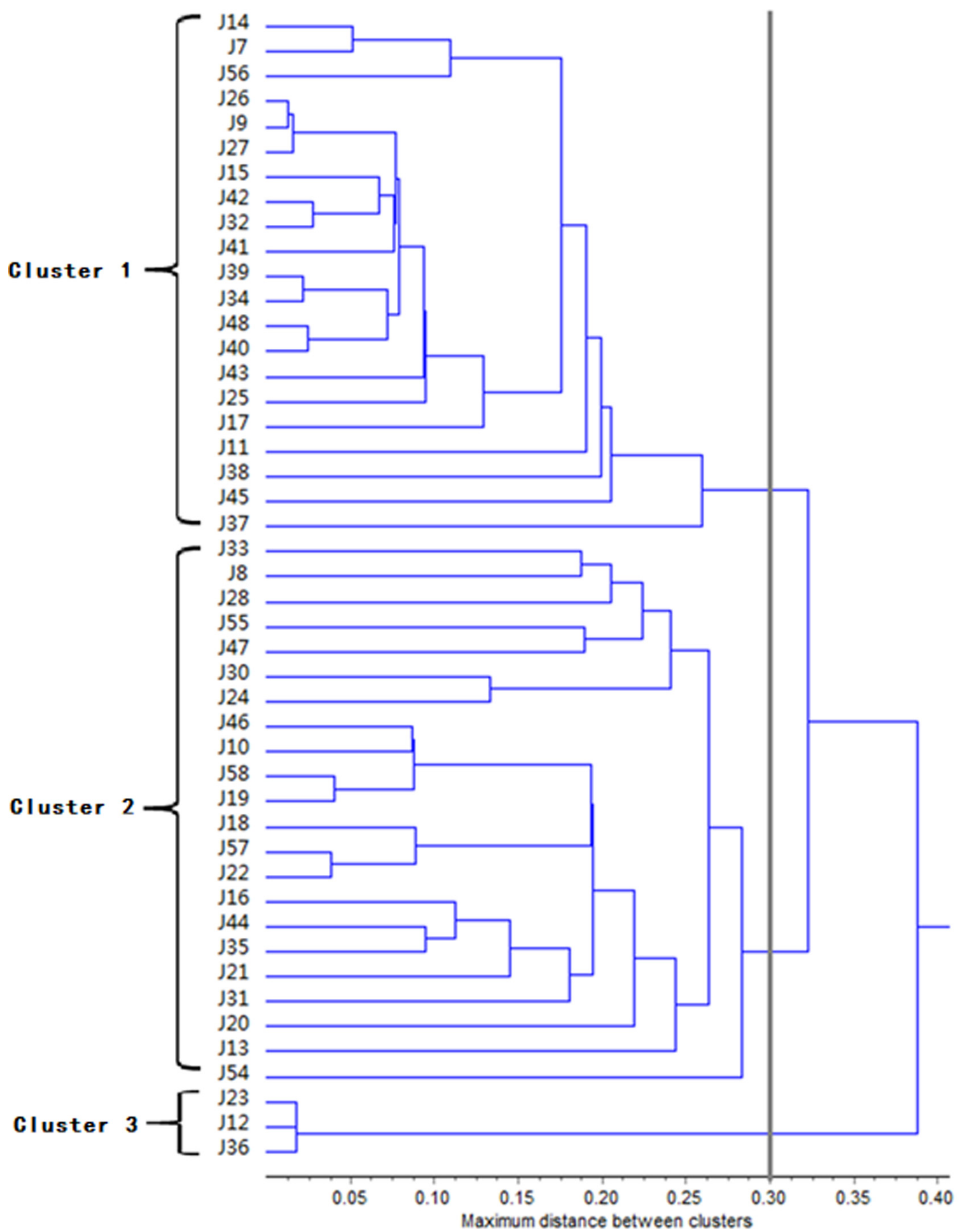

Fig. 2. The result of the fuzzy cluster method (Ji (i = 1,2,...) represents the water ecological monitoring stations in Jinan) ; x-axis represents Euclidean distance. A threshold value of 0.30 was used for identifying the clusters, which is a threshold to avoid that a single station represents one cluster.

the stations in Cluster 2. The difference of hydrological conditions among the clusters resulted in great variation in water quality. The results of FCM conform to the actual situation. To a certain extent, the results reflect that monitoring stations located in the mainstream of the Yellow River are different from others. The ecological status of the Yellow River has a special status in all the watersheds of Jinan City.

From the results of FCM analysis, the middle stations of each subordinate cluster was selected as the typical stations for that cluster. For example, J7 was selected as the typical station from the cluster containing J7, J14, and J56. According to this principle, 10 typical stations were selected. In order to ensure the representativeness of each selected station, the water quality level and flow of the monitoring stations were used to check that each monitoring station can represent a gradient range. The final typical monitoring stations are shown in Fig. 1.

4.2. Dominant species of fish and invertebrate species in typical stations

In the nine field investigations from 2014 to 2016, 58 species of bony fish were identified, belonging to 7 orders, 19 families, and 50 genera. The proportion of the abundance and biomass of each fish relative to the whole community was calculated. ω_1 (0.33) and ω_2 (0.67) were brought into equation (1) to calculate species dominance$I_{mportance}$, sorting the dominance from large to small and calculating the degree of accumulation to plot the dominance curve. The breakpoint was then calculated from the dominance curve (Fig. 3) as (9, 0.838), which corresponds to the species which were then selected as the dominant species in the fish population: *Carassiusauratus* (FSP1), *Channa argus* (FSP2), *Misgurnus anguillicaudatus* (FSP3), *Hemiculter leucisculus* (FSP4), *Pseudorasbora parva* (FSP5), *Abbottina rivularis* (FSP6), *Ctenogobius brunneus* (FSP7), *Cyprinus carpio Linnaeus* (FSP8), and *Rhodeus ocellatus* (FSP9).

Seventy-three invertebrate species were identified, belonging to 3 phyla, 6 classes, 12 orders, 26 families, and 31 genera, and the ratio of the abundance and biomass of the benthic fauna relative to the whole community was calculated. The weights of the abundance weights and biomass were calculated using the same method, with ω_1 equal to 0.625 and ω_2 equal to 0.375. The dominance curve was plotted in the same way as with the fish data to identify the dominant species in the benthic fauna population, as shown in Fig. 3. The breakpoint in Fig. 3 is (20, 0.873), corresponding to the dominant invertebrate species of *Limnodrilus hoffmeisteri* (ISP1), *B. fuchsiana* (ISP2), *Chironomus salinarius* Kieffer (ISP3), *Chironomus riparius* Meigen (ISP4), *B. aeruginosa* (ISP5), *C. fluminea* (ISP6), *Chironomus* (ISP7), *Barbronia weberi* (ISP8), *Turritella* .sp (ISP9), *Radix ovata* (ISP10), Assimineidae. sp (ISP11), *B. aeruginosa* (ISP12), *B. quadrata* (ISP13), *L. claparedianus* (ISP14), *Orthocladius thienemanni* Kieffer (ISP15), *Hydropsyche* sp. (ISP16), *Chironomus yoshimatusi* Martin (ISP17), *R. auricularia* (ISP18), *R. tagotis* (ISP19), and *E. modestus* (ISP20).

4.3. Driving factors of fish and invertebrate species

Based on the dominant species of the fish and invertebrate in typical monitoring stations, the response to the changes in aquatic parameters of fish and invertebrate species was studied using CCA wherein the principal driving factors were selected. The hydrological driving factors were identified solely based on monitoring data from rivers, while the water quality driving factors were identified with monitoring data from both rivers and lakes/reservoirs.

For fish species from 2014 to 2016 in Jinan, results of CCA showed that the principal hydrological factors affecting the distribution of fish in Jinan were river flow and river width; the principal water quality physical factors were the conductivity, turbidity, and temperature of the water; and the principal water quality chemical factors were carbonate and chloride levels (Fig. 4).

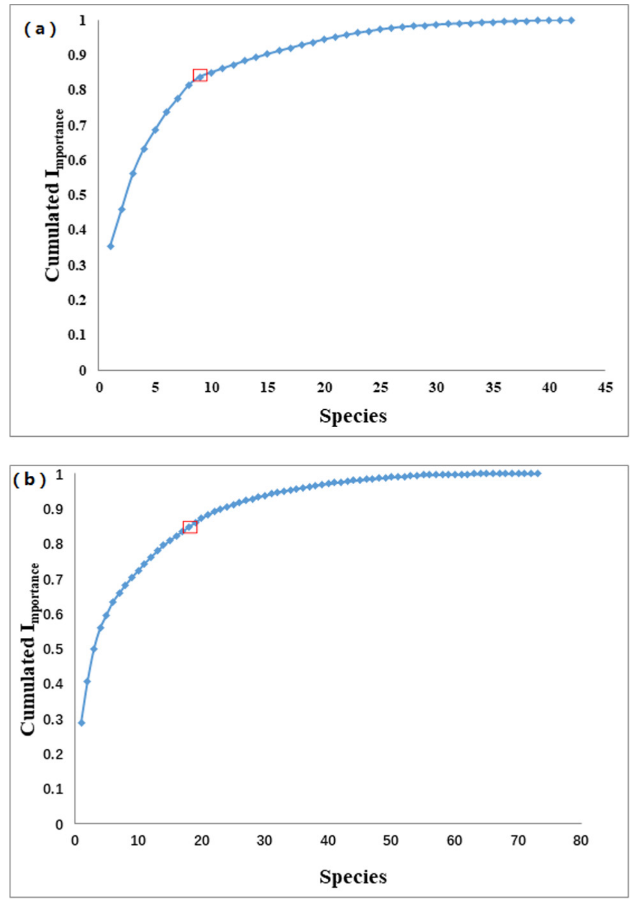

Fig. 3. The dominance index gradient curve for all fish (a) and invertebrate (b) of typical monitoring stations in 2014–2016. The x-axis is the species ID sorted with descending dominance index, the y-axis is the sum of dominance index before the corresponding species ID, so the dominance curve represent the accumulation of dominance index before the species ID in the x-axis. Cumulated $I_{mportance}$ represents the dominant degree of accumulation. Species represents the corresponding number of species. The red hollow box indicates where a breakpoint appears. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

For invertebrate species in Jinan from 2014 to 2016, results of CCA showed that the principal hydrological factors affecting the distribution of invertebrate species in Jinan were water depth and flow velocity; the principal water quality physical factors were water temperature and pH; and the principal water quality chemical factors were total phosphorus, bicarbonate, ammonia nitrogen, and dissolved oxygen (Fig. 4).

The hydrological factor that had the greatest impact on both fish and invertebrate species was water depth. In addition, the dependence of fish communities was mainly driven by flow and river width, and the dependence of invertebrate species was mainly driven by flow velocity. The water quality physical factor that had the greatest impact on both fish and invertebrate species was water temperature. In addition, the dependence of the fish community was driven by water conductivity and turbidity, and the dependence of invertebrate species was driven by pH. The principal water quality chemical factors for the dependence of fish communities was carbonate and chloride, and the principal water quality chemical factors for the dependence of invertebrate species was total phosphorus, bicarbonate, ammonia nitrogen, dissolved oxygen.

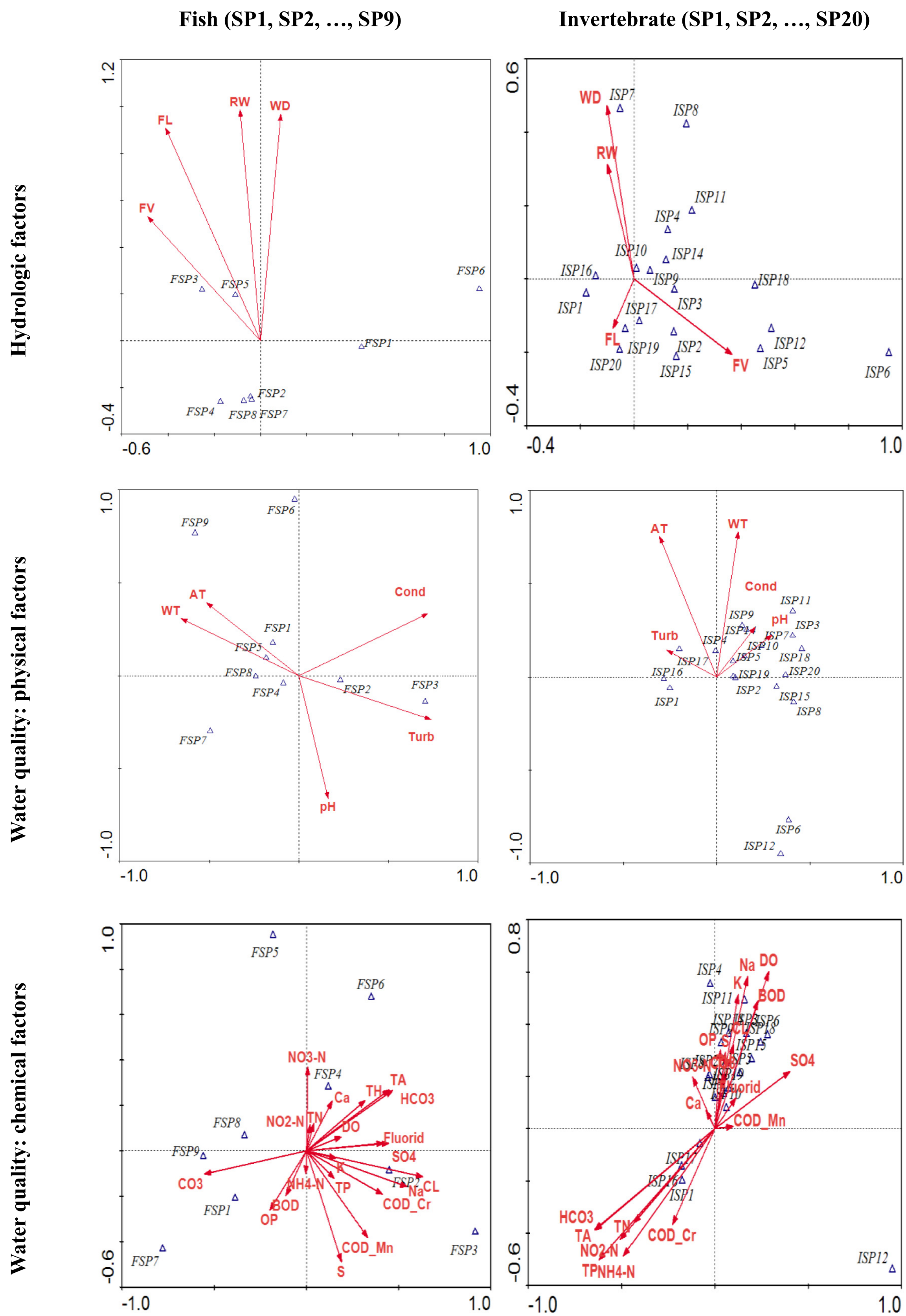

Fig. 4. Canonical correspondence analysis of biological and environmental factors of typical monitoring stations in 2014–2016 (the abbreviations of parameters are listed in Table 1).

5. Discussion

5.1. Similarities and differences in driving factors of fish and invertebrate species

Hydrological factors have a great impact on the health of aquatic ecosystems. Hydrological conditions are the principal influence on fish community structure, and the flow velocity, water depth, and flow play an important role in the reproduction and survival of fish and invertebrate species (Duan et al., 2008; Marchetti and Moyle, 2001; Wu et al., 2014). The four major hydrological factors are included in the principal driving factors of the aquatic ecosystem identified in this study, which again demonstrates the importance of hydrological factors in aquatic ecosystem health. Studies have shown that water temperature, pH, turbidity, total phosphorus, total nitrogen, ammonia nitrogen, and dissolved oxygen all have a strong effect on the dependence of aquatic ecosystems (Liu et al., 2016; Yang et al., 2007); and with the exception of TN, our findings are consistent with this. Total nitrogen has much more influence on phytoplankton than on fish and invertebrates, and therefore, it did not appear in our research results.

In brief, more hydrological and physical environmental parameters than chemical environmental ones were identified as principal driving factors for fish, while more chemical environmental parameters were selected for invertebrate. In other words, chemical environmental parameters drive the temporal and spatial distribution of invertebrate much more than that of fish in our study area.

5.2. Rationality analysis of the driving factors

Pollutant concentration is the most important variable affecting the chance of successful fish spawning (Nelson and Lieberman, 2002; Liu et al., 2011), and further affects the structure and behavior of the aquatic ecosystem communities. Our study indicates that when taking fish and invertebrates as representatives of aquatic ecosystems, the principal factors driving aquatic ecosystem, such as TP and NH_3-N, closely match the temporal and spatial patterns of these water quality factors exceeding water-quality standard limits. This can be used to reflect the patterns of water-quality in the Jinan City, which in turns suggests that the identification of these principal driving factors in this study can be of practical use in guiding policy-making for ecological and water-quality remediation in the study area.

Zhao et al. (2015b) identified principal habitat factors influencing the spatial variation of fish species in the Jinan City. Their results, as well as the results in the research of Rodríguez and Lewis (1997), suggested that fish assemblage structure in freshwater areas was related to, but not restricted to, transparency and surface area (or river width). Transparency can be transformed into turbidity (driving factors for fish in Table 3 in the present study) based on the research of Zhang et al. (2009) where the two factors were found negatively correlated ($p < .01$). In other words, the fish-driving factors of river width and turbidity identified in our study are acceptable. Wang et al. (2017) identified the principal limiting water quality factors for invertebrate in Jinan city, which suggested that total phosphorus, dissolved oxygen and pH were the principal factors. The three factors were also identified as principal factors in our study. Moreover our results keep consistent with the research of Hering et al. (2006), which showed that nutrient enrichment had more effect on aquatic organism groups.

Analysis on the geophysical conditions of the study area indicated that the cross sectional shape of the river was altered significantly. The cross-sectional shape includes orthogonal, trapezoidal, parabolic and compound types. The immense changes in the cross sectional shape make water depth a constraining factor. Besides, water temperature is the factor influencing both fish and invertebrates due to the spatial heterogeneity of the types and the height of plants below or above/covering water surface. Some waters are shaded by leaves (e.g., J34 in Fig. 1) while the others are barely exposed to the sun (e.g., J23 locating in the Yellow River) which resulted in great spatial variation of the water temperature.

Aquatic biota assemblages are not limited by a single factor but an interaction among many variables (Rahel, 1984) which may change with the geographical location, regional characteristics of study area. The Jinan City is dominated by farmland and downtown areas where non-point-source pollutants are from agricultural and domestic activities with poorly planned settlers nearby the river. These pollutants are flushed into river along with runoff. The variant degree of disturbances on freshwater increases the spatial heterogeneity of cross-section, water temperature, dissolved oxygen, carbonate etc. These have been implicated to be causative to the variant degree of poor quality of the river and its aquatic life (Kolawole et al., 2011).

5.3. Indicator species of the principal driving factor

At present, the study of indicator species is only on the community scale, such as fish, invertebrate species, phytoplankton, and zooplankton (Wu et al., 2014; Liu et al., 2016; Findlay and Shearer, 1992). Even if there is a study of a single species, but also to study the degree of dirt tolerance, such as α-polysaprobic, β-polysaprobic, α-mesosaprobic, β-mesosaprobic, oligosaprobic, clear water (Zhao et al., 2013b; Peng and Li, 2016). Only few studies have been conducted on specific indicator species for specific water quality factors. Water quality factors have a great impact on the survival, distribution, and community dependence of aquatic organisms. To provide a ready method for stakeholders to estimate water quality, we have summarized the indicator species of the principal driving water quality factors of Jinan in Table 4. The indicator species was selected according to Fig. 3 where the more the absolute value of the cosine of the angle between a species and an environmental factor is closer to 1, the closer the relationship between the species and the environmental factor is. This will allow a determination of the status of water quality factors and the health of the aquatic ecosystem, which can then provide a reference for long-term monitoring and control of aquatic ecosystem health in Jinan. Our results for the species dependencies are in line with studies based on the database "http://www.freshwaterecology.info" (Schmidt-Kloiber and Hering, 2012; Schröder et al., 2013) which mean the relationships between species and factors in our study are not only useful to study area but applicable elsewhere.

Table 4 shows that *H. leucisculus* and *Chironomus* spp. are indicative for water environmental index; *H. leucisculus* can indicate the regime of conductivity, turbidity, water temperature, pH

Table 3
The driving factors of fish and invertebrate species.

Species	Principal driving factor		
	Hydrologic factors	Water quality: physical factors	Water quality: chemical factors
Fish	Flow River width Water depth	Conductivity Turbidity Water temperature	Carbonate Chloride
Invertebrates	Water depth Flow velocity	Water temperature pH	Total phosphorus Bicarbonate Ammonia nitrogen Dissolved oxygen

Table 4
Indicator species of the principal water quality driving factors based on typical stations.

Water quality factor		Fish species	Invertebrate species
Conductivity	↑	*H. leucisculus*	*Assimineidae* spp.
	↓	*C. brunneus*	*Chironomus* spp.
Turbidity	↑	*H. leucisculus*	*C. riparius Meigen*
	↓	*C. argus*	*L. claparedianus*
Water temperature	↑	*C. argus*	*B. quadrata*
	↓	*H. leucisculus*	*C. yoshimatusi Martin*
pH	↑	*H. leucisculus*	*Assimineidae* spp.
	↓	*R. ocellatus*	*Chironomus* spp.
Carbonate	↑	*C. carpio Linnaeus*	*B. quadrata*
	↓	*P. parva*	*Chironomus* spp.
Chloride	↑	*P. parva*	*Assimineidae* spp.
	↓	*C. argus*	*Chironomus* spp.
Total phosphorus*	↑	*H. leucisculus*	*Chironomus* spp.
	↓	*M. anguillicaudatus*	*Hydropsyche* spp.
Bicarbonate	↑	*R. ocellatus*	*Chironomus* spp.
	↓	*C. brunneus*	*Hydropsyche* spp.
Ammonia nitrogen*	↑	*C. brunneus*	*Chironomus* spp.
	↓	*M. anguillicaudatus*	*Hydropsyche* spp.
Dissolved oxygen	↑	*R. ocellatus*	*Assimineidae* spp.
	↓	*C. carpio Linnaeus*	*Chironomus* spp.

* Represents a serious water quality issue in Jinan City, ↑ indicates species numbers increase with improved water quality, ↓ indicates species numbers decrease with improving water quality.

and total phosphorus; and *Chironomus* spp. can indicate the situations of conductivity, pH, carbonate, chloride, total phosphorus, bicarbonate, ammonia nitrogen and dissolved oxygen.

Overall the research methods in this paper have great potential to make clear the factors driving spatiotemporal variation and community structure of the aquatic ecology, by coupling typical monitoring stations selection, dominant species determination and driving factors identification. Though some results were highly influenced by its regional conditions in Jinan. The methodologies can help policy-makers and stakeholders to manage freshwater habitat by reducing discharge quantity of pollutant, e.g. with chemical factors influencing dominant species, and laying emphasis in ecological restoration on the dominant species, principle driving factors and typical stations or river sections selected through our methods. This will significantly improve the cost-effectiveness and success rate of restoration projects.

6. Conclusions

Based on hydrological, water quality, and aquatic organism data obtained from nine large-scale field surveys at 59 water ecological monitoring sites in Jinan City from 2014 to 2016, we selected 10 typical stations by fuzzy clustering method. The dominant species of fish and invertebrate species were obtained by using the identification model of aquatic dominant species. Combined with the canonical correspondence analysis, the principal driving factors of aquatic ecosystem dependence were identified, and the indicator species of the principal driving factors were selected. The main conclusions are as follows:

(1) The 59 monitoring stations for hydrological, water quality, and water ecological data in Jinan were divided into three clusters. The stations of the middle of each cluster was selected as the typical stations.
(2) In the nine field investigations, 58 species of bony fish were identified, belonging to 7 orders, 19 families, and 50 genera. Seventy-three invertebrate species were identified, belonging to 3 phyla, 6 classes, 12 orders, 26 families, and 31 genera. There are nine dominant species in the fish population of Jinan City with a cumulative dominance of 0.838 and 20 dominant species in the invertebrate population with a cumulative dominance of 0.873. The common driving factors for fish and invertebrate communities are water depth and water temperature. In addition, the principal driving factors of fish communities also include flow, river width, conductivity, turbidity, carbonate, chloride; and the principal driving factors of invertebrate species communities also include flow velocity, pH, total phosphorus, bicarbonate, ammonia nitrogen, and dissolved oxygen.
(3) The principal factors driving aquatic ecosystem, e.g., total phosphorus and ammonia nitrogen, closely match the temporal and spatial pattern of water quality factors exceeding the maximum levels for water quality standards, and can well reflect the patterns of water quality in the Jinan City, which in turn suggests those principal driving factors can inform the development of practical policies for ecological and water-quality remediation in the study area.
(4) The indicator species for the principal factors driving the aquatic ecosystem dependence in Jinan was selected. *Ctenogobius brunneus* and *Chironomus* spp. were more likely to appear in an environment with a high ammonia nitrogen content, but *M. anguillicaudatus* and *Hydropsyche* spp. were more likely to appear in an environment with low ammonia nitrogen content. *Hemiculter leucisculus* and *Chironomus* spp. were more likely to appear in locations with high total phosphorus content, but *M. anguillicaudatus* and *Hydropsyche* spp. were more likely to appear in locations with low total phosphorus content.

This study selected the typical monitoring stations based on the characteristics of temporal and spatial distribution of aquatic ecology, and the factors that drive the dependence of aquatic ecosystems were analyzed in typical monitoring stations. These driving factors therefore are able to accurately reflect the status and health of aquatic ecosystems. For the first time, we have applied these research methods to identify the driving factors of aquatic ecosystem based on aquatic organisms, to China's first water ecological civilization construction pilot city. This provides the route to a successful restoration of the aquatic ecosystem in Jinan City and provides the scientific basis for the restoration of aquatic ecosystems in other such cities. The specific results obtained in this study are valid for the investigated region only, but the methodologies can provide in-deep theoretical and technical directions for the restoration of aquatic ecosystems elsewhere.

Due to the complexity of aquatic ecosystems, the study of the driving factors in this paper needs to further investigate the ecosystem natural characteristics in order to better preserve and promote the health of the aquatic ecosystems. Some results in this paper were preliminarily qualitative and therefore quantitative research with the accumulation of long-term monitoring data is needed in future.

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References

Barrella, W., Martins, A.G., Petrere, M., Ramires, M., 2014. Fishes of the south eastern Brazil Atlantic Forest. Environ. Biol. Fishes 97 (12), 1367–1376.

Barbour, M.T., Gerritsen, J., Snyder, B., Stribling, J.B., 1999. Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macro invertebrates, and Fish. USEPA, Washington.

Bellmore, J.R., Baxter, C.V., Ray, A.M., Denny, L., Tardy, K., Galloway, E., 2012. Assessing the potential for salmon recovery via floodplain restoration: a multitrophic level comparison of dredge-mined to reference segments. Environ. Manage. 49 (3), 734–750.

Benke, A.C., 1993. Concepts and patterns of invertebrate production in running waters. Verh. Int. Ver. Limnol. 25, 15–38.

Bernhardt, E.S., Palmer, M.A., Allan, J.D., Alexander, G., Barnas, K., Brooks, S., Carr, J., Clayton, S., Dahm, C., Follstad-Shah, J., Galat, D., Gloss, S., Goodwin, P., Hart, D., Hassett, B., Jenkinson, R., Katz, S., Kondolf, G.M., Lake, P.S., Lave, R., Meyer, J.L., O'Donnel, T.K., Pagano, L., Powell, B., Sudduth, E., 2005. Synthesizing U.S. river restoration efforts. Science 308, 636–637.

Biswas, S., Hussain, K.J., Das, N.P.I., Russell, B.C., Satpathy, K.K., Mishra, S.S., 2014. Imprint of monsoonal patterns on the fish assemblage in coastal waters of south-east India: a case study. J. Fish Biol. 85 (3), 773–799.

Chen, J., Xu, T., Fang, S., Song, S., Wang, X., 1987. Fishes in Qingling Mountain area. Science Press, Beijing (in Chinese).

Coen, L., Heck Jr., K.L., Abel, L.G., 1981. Experiments on competition and predation among shrimps of seagrass meadows. Ecology 62, 1484–1493.

Cui, B.S., Wang, C.F., Tao, W.D., You, Z.Y., 2009. River channel network design for drought and flood control: a case study of Xiaoqinghe River basin, Jinan City China. J. Environ. Manage. 90 (11), 3675–3686.

Daily, G.C., 1999. Developing a scientific basis for managing Earth's life support systems [online] URL: Conserv. Ecol. 3 (2), 14.

Daily, G.C., Söderqvist, T., Arrow, K., Dasgupta, P., Ehrlich, P.R., Folke, C., Jansson, A. M., Jansson, B.O., Levin, S., Lubchenco, J., Mäler, K.G., Starrett, D., Tilman, D., Walker, B., 2000. The value of nature and the nature of value. Science 289, 395–396.

Danielson, B.J., 1991. Communities in a landscape: the influence of habitat heterogeneity on the interactions between species. Am. Nat. 138, 1105–1120.

Duan, X.B., Chen, D.Q., Li, Z.H., Wang, K., Huang, M.G., Liu, S.P., 2008. Current status of spawning grounds of fishes with pelagic eggs in the middle reaches of the Yangtze River after impoundment of the Three Gorges Reservoir. J. Fishery Sci. China. 15 (4), 523–532.

Findlay, D.L., Shearer, J.A., 1992. Relationships between sedimentary diatom assemblages and lake water pH values in the experimental lakes area. J. Paleolimnol. 7, 145–156.

Gieswein, A., Hering, D., Feld, C.K., 2017. Additive effects prevail: The response of biota to multiple stressors in an intensively monitored watershed. Sci. Total Environ. 593, 27–35.

Gippel, G.J., Stewardson, M.J., 1998. Use of wetted perimeter in defining minimum environmental flows. Regul. Rivers: Res. Manage. 14 (1), 53–67.

Godoy, E.A.S., Almeida, T.C.M., Zalmon, I.R., 2002. Fish assemblages and environmental variables on an artificial reef north of Rio de Janeiro Brazil. ICES J. Mar. Sci. 59, S138–S143.

He, Z., Gui, J.Z., Yu, N., Wu, D., Liu, S., Liu, Q., 2014. Integrated assessment of the aquatic ecosystem function and main driving factors based on principal component analysis, entropy methods and correlation analysis. Chin. Agric. Sci. Bull. 30 (26), 178–183.

Hering, D., Johnson, R.K., Kramm, S., Schmutz, S., Szoszkiewicz, K., Verdonschot, P.F. M., 2006. Assessment of Europe-an streams with diatoms, macrophytes, macroinvertebrates and fish, a comparative metric-based analysis of organism response to stress. Freshwater Biol. 51 (1757), 1785.

Hong, Q.A., Meng, Q.B., Wang, P., Wang, H., Lui, R., 2010. Regional aquatic ecological security assessment in Jinan China. Aquat. Ecosyst. Health Manage. 13 (3), 319–327.

Huo, T.B., Jiang, Z.F., Karjan, A., Wang, Z.C., Tang, F.J., Yu, H.X., 2012. Length–weight relationships of 16 fish species from the Tarim River China. J. Appl. Ichthyol. 28 (1), 152–153.

Ingham, R.E., 1985. Interactions of bacteria, fungi and their nematode grazers: effects on nutrient cycling and plant growth. Ecol. Monogr. 55, 119–140.

Kagalou, I.I., Kosiori, A., Leonardos, I.D., 2010. Assessing the zooplankton community and environmental factors in a Mediterranean wetland. Environ. Monit. Assess. 170 (1–4), 445–455.

Keast, A., 1985. Planktivory in a littoral-dwelling lake fish association: prey selection and seasonality. Can. J. Zool. 62, 1289–1303.

Kennedy, A.D., 1994. Carbon partitioning within meiobenthic nematode communities in the Exe Estuary UK. Mar. Ecol. Prog. Ser. 105, 71–78.

Kolawole, O.M., Ajayi, K.T., Olayemi, A.B., Okoh, A.I., 2011. Assessment of water quality in Asa River (Nigeria) and its indigenous Clarias gariepinus fish. Int. J. Environ. Res. Publ. Health 8 (11), 4332–4352.

Lepš, J., Šmilauer, P., 2003. Multivariate Analysis of Ecological Data using CANOCO. Cambridge University Press.

Li, Y., Shi, Z., Li, F., Li, H.Y., 2007. Delineation of site-specific management zones using fuzzy clustering analysis in a coastal saline land. Comput. Electron. Agric. 56 (2), 174–186.

Lindegaard, C., 1995. Classification of water-bodies and pollution. In: Armitage, P., Cranston, P.S., Pinder, L.C.V. (Eds.), The Chironomidae: The Biology and Ecology of Nonbiting Midges. Chapman & Hall, London, pp. 385–404.

Liu, C.M., Zhao, C.S., Xia, J., Sun, C.L., Wang, R., Liu, T., 2011. An instream ecological flow method for data-scarce regulated rivers. J. Hydrol. 398, 17–25.

Liu, S.X., Mo, X., Xia, J., Ji, L., 2006. Uncertainty analysis in estimating the minimum ecological instream flow requirements via wetted perimeter method: curvature technique or slope technique. Acta Geogr. Sin. 61 (3), 273–281 (in Chinese).

Liu, X., Chen, K., Chen, Q.W., Wang, M., Wang, L., 2016a. The community structure of macroinvertebrate and its relationship to the environmental factors in summer and autumn within typical reaches of Huai River Basin. Acta Sci. Circumstantiae 36 (6), 1928–1938.

Liu, W., Zhang, Y., Gao, X., Jia, X., Ma, S., Liu, S., 2016b. Fish community structure and its relationship with environmental variables in Hun River basin of Liaoning province. J. Environ. Eng. Technol. 6 (3), 266–274.

Lloyd, M., Inger, R.F., King, F.W., 1968. On the diversity of reptile and amphibian species in a Bornean rain forest. Am. Nat. 102 (928), 497–515.

Mansor, M.I., Mohammad-Zafrizal, M.Z., Nur-Fadhilah, M.A., Khairun, Y., Wan-Maznah, W.O., 2012. Temporal and spatial variations in fish assemblage structures in relation to the physicochemical parameters of the Merbok estuary Kedah. J. Nat. Sci. Res. 2 (7), 110–127.

Marchetti, M.P., Moyle, P.B., 2001. Effects of flow regime on fish assemblages in a regulated California stream. Ecol. Appl. 11 (2), 530–539.

Martino, E.J., Able, K.W., 2003. Fish assemblages across the marine to low salinity transition zone of a temperate estuary. Estuar. Coast. Shelf Sci. 56, 969–987.

Mathers, K.L., Rice, S.P., Wood, P.J., 2017. Temporal effects of enhanced fine sediment loading on macroinvertebrate community structure and functional traits. Sci. Total Environ. 599, 513–522.

McQueen, D., Post, J., Mills, E., 1986. Trophic relations in freshwater pelagic ecosystem. Can. J. Fish. Aquat. Sci. 43 (8), 1571–1581.

Nelson, S.M., Lieberman, D.M., 2002. The influence of flow and other environmental factors on benthic invertebrates in the Sacramento River USA. Hydrobiologia 489 (1), 117–129.

Okun, N., Mehner, T., 2005. Interactions between juvenile roach or perch and their invertebrate prey in littoral reed versus open water enclosures. Ecol. Freshwater Fish 14, 150–160.

Norris, R.H., Thoms, M.C., 1999. What is river health. Freshwater Biol. 41 (2), 197–209.

Palmer, M.A., Menninger, H.L., Bernhardt, E., 2010. River restoration, habitat heterogeneity and biodiversity: a failure of theory or practice? Freshwater Biol. 55 (s1), 205–222.

Palmer, M.A., Bernhardt, E.S., Allan, J.D., Lake, P.S., Alexander, G., Brooks, S., Carr, J., Clayton, S., Dahm, C.N., Shah, J.F., Galat, D.L., Loss, S.G., Goodwin, P., Hart, D.D., Hassett, B., Jenkinson, R., Kondolf, G., Lave, R., Meyer, J.L., O'Donnell, T.K., Pagano, L., Sudduth, E., 2005. Standards for ecologically successful river restoration. J. Appl. Ecol. 42, 208–217.

Pan, W.T., 2010. Combining fuzzy sammon mapping and fuzzy clustering approach to perform clustering effect analysis: take the banking service satisfaction as an example. Expert Syst. Appl. 37 (6), 4139–4145.

Peng, T., Li, J., 2016. Advances in metal pollution assessment by diatom-based indicators. J. Hydroecol. 1, 1–8.

Rahel, F.J., 1984. Factors structuring fish assemblages along a bog lake successional gradient. Ecology 65 (4), 1276–1289.

Rodríguez, M.A., Lewis Jr., W.M., 1997. Structure of fish assemblages along environmental gradients in floodplain lakes of the Orinoco River. Ecol. Monogr. 67 (1), 109–128.

Schmidt-Kloiber, A., Hering, D. (Eds.), 2012. http://www.freshwaterecology.info – The Taxa and Autecology Database for Freshwater Organisms, Version 6.0 (accessed on 14.08.2015).

Schröder, M., Kiesel, J., Schattmann, A., Jähnig, S.C., Lorenz, A.W., Kramm, S., Keizer-Vlek, H., Rolauffs, P., Graf, W., Leitner, P., Hering, D., 2013. Substratum associations of benthic invertebrates in lowland and mountain streams. Ecol. Indicators 30, 178–189.

Shafi, I., Ahmad, J., Shah, S.I., Ikram, A.A., Khan, A.A., Bashir, S., 2010. Validity-Guided Fuzzy Clustering Evaluation for Neural Network-Based Time-Frequency Reassignment. EURASIP J. Adv. Sig. Process. 2010, 1–14.

Statzner, B., Dolédec, S., 2011. Phylogenetic, spatial, and species-trait patterns across environmental gradients: the case of Hydropsyche (Trichoptera) along the Loire River[J]. Int. Rev. Hydrobiol. 96 (2), 121–140.

Tang, Q.Y., Zhang, C.X., 2012b. Data processing system (DPS) software with experimental design, statistical analysis and data mining developed for use in entomological research. Insect Sci. https://doi.org/10.1111/j. 1744-7917, 2012.01519.x.

Visintainer, T.A., Bollens, S.M., Simenstad, C., 2006. Community composition and diet of fishes as a function of tidal channel geomorphology. Mar. Ecol. Prog. Ser. 321, 227–243.

Wang, B.H., Wu, D., Zhang, J., Yin, X.W., Zhao, C.S., Dou, T.W., 2017. Diversity and temporal-spatial dynamics of macroinvertebrate functional feeding groups in the rivers of the Jinan Region. Acta Ecol. Sin. 37 (21).

Wang, B.X., Yang, L.F., 2003. A study on tolerance values of benthic macroinvertebrate taxa in eastern China. Acta Ecol. Sin. 24 (12), 2768–2775.

Wang, B.X., Yang, L.F., Hu, B.J., Shan, L.N., 2005. A preliminary study on the assessment of stream ecosystem health in south of Anhui Province using Benthic-Index of Biotic Integrity. Acta Ecol. Sin. 25 (6), 1481–1490.

Weaver, W., Shannon, C.E., 1949. The Mathematical Theory of Communication University of Illinois. Urbana.

Whitley, S.N., Bollens, S.M., 2014. Fish assemblages across a vegetation gradient in a restoring tidal freshwater wetland: diets and potential for resource competition. Environ. Biol. Fishes. 97 (6), 659–674.

Wolfram, G., 1996. Distribution and production of chironomids (Diptera: Chironomidae) in a shallow, alkaline lake (Neusiedler See, Austria). Hydrobiologia 318, 34–46.

Wu, W., Xu, Z., Yin, X., Zuo, D., 2014. Assessment of ecosystem health based on fish assemblages in the Wei River basin China. Environ. Monit. Assess. 186 (6), 3701–3716.

Xie, Z.C., Ma, K., Ye, L., Chen, J., Cai, Q.H., 2007a. Structure and spatial distributional pattern of macroinvertebrate species in Bao'an Lake. Acta Hydrobiol. Sin. 31, 174–183 (in Chinese).

Xie, Z.C., Zhang, J.Q., Chen, J., Ma, K., Liu, R.Q., Qang, Y.P., Cai, Q.H., 2007b. Spatial distributional pattern of macroinvertebrate species and pollution evaluation in East Lake Dongting Reserve. J. Lake Sci. 19, 289–298.

Xu, Z.X., Wu, W., Yin, X.W., 2016. Health assessment by using a benthic-index of biotic integrity in the Huntai river basin. Adv. Sci. Technol. Water Resour. 1, 23–30.

Yang, M.S., Xiong, B.X., Yang, X.F., 2007. Temporal and spatial distribution and evaluation of nitrogen and phosphorus of Macroinvertebrate species in Lake Nanhu, Wuhan China. J. Lake Sci. 19 (6), 658–663.

Zhang, W., Zhang, X.L., Li, L., Zhang, Z., 2007. Urban forest in Jinan City: distribution, classification and ecological significance. Catena 69 (1), 44–50.

Zhang, X.J., Li, C.Y., Jia, K.L., Wu, T.M., Li, W.P., 2009. Spatial-temporal changes in water transparency and its impact factors in Lake Wuliangsuhai. J. Lake Sci. 21 (6), 879.

Zhang, Z.G., Shao, Y.S., Xu, Z.X., 2010. Prediction of urban water demand on the basis of Engel's coefficient and Hoffmann index: case studies in Beijing and Jinan China. Water Sci. Technol. 62 (2), 410–418.

Zhao, C.S., Sun, C.L., Xia, J., Hao, X.P., Li, G.F., Rebensburg, K., Liu, C.M., 2010. An impact assessment method of dam/sluice on instream ecosystem and its application to the Bengbu Sluice of China. Water Resour. Manage. 24 (15), 4551–4565.

Zhao, C., Liu, C., Xia, J., Zhang, Y., Qiang, Y., Eamus, D., 2012. Recognition of key regions for restoration of phytoplankton communities in the Huai River basin China. J. Hydrol 420, 292–300.

Zhao, C.S., Liu, C.M., Zhao, J.H., Xia, J., Yu, Q., Eamus, D., 2013a. Zooplankton in highly regulated rivers: changing with water environment. Ecol. Eng. 58, 323–334.

Zhao, C.S., Liu, C.M., Sun, Y., Yang, G., Mitrovic, S.M., Wang, H., 2013b. Heterogeneity of water quality in Huai River, China by using bio-monitoring data. Water Sci. Technol. Water Supply 13 (6), 1524–1533.

Zhao, C., Sun, C., Liu, C., Xia, J., Yang, G., Liu, X., Zhang, D., Dong, B., Sobkowiak, L., 2014. Analysis of regional invertebrate species status in the Huai River Basin, China using two new ecological niche clustering approaches. Ecohydrology 7, 91–101.

Zhao, C.S., Yang, S.T., Xiang, H., Liu, C.M., Zhang, H.T., Yang, Z.L., Yang, Y., Zhang, Y., Sund, Y., Mitrovic, S.M., Yue, Q., Lime, R.P., 2015a. Hydrologic and water-quality rehabilitation of environments for suitable fish habitat. J. Hydrol. 530, 799–814.

Zhao, C.S., Yang, S.T., Liu, C.M., Dou, T.W., Yang, Z.L., Yang, Z.Y., Liu, X.L., Xiang, H., Nie, S.Y., Zhang, J.L., Mitrovic, S.M., Yu, Q., Lim, R.P., 2015b. Linking hydrologic, physical and chemical habitat environments for the potential assessment of fish community rehabilitation in a developing city. J. Hydrol. 523, 384–397.

Zhao, C.S., Zhang, C.B., Yang, S.T., Liu, C.M., Xiang, H., Sun, Y., Yang, Z.L., Zhang, Y., Yu, X.Y., Shao, N.F., Yu, Q., 2017. Calculating e-flow using UAV and ground monitoring. J. Hydrol.