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Linking fish tolerance to water quality criteria for the assessment of environmental flows: A practical method for streamflow regulation and pollution control

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ABSTRACT

The survival of aquatic biota in stream ecosystems depends on both water quantity and quality, and is particularly susceptible to degraded water quality in regulated rivers. Maintenance of environmental flows (e-flows) for aquatic biota with optimum water quantity and quality is essential for sustainable ecosystem services, especially in developing regions with insufficient stream monitoring of hydrology, water quality and aquatic biota. Few e-flow methods are available that closely link aquatic biota tolerances to pollutant concentrations in a simple and practical manner. In this paper a new method was proposed to assess e-flows that aimed to satisfy the requirements of aquatic biota for both the quantity and quality of the streamflow by linking fish tolerances to water quality criteria, or the allowable concentration of pollutants. For better operation of water projects and control of pollutants discharged into streams, this paper presented two coefficients for streamflow adjustment and pollutant control. Assessment of e-flows in the Wei River, the largest tributary of the Yellow River, shows that streamflow in dry seasons failed to meet e-flow requirements. Pollutant influx exerted a large pressure on the aquatic ecosystem, with pollutant concentrations much higher than that of the fish tolerance thresholds. We found that both flow velocity and water temperature exerted great influences on the pollutant degradation rate. Flow velocity had a much greater influence on pollutant degradation than did the standard deviation of flow velocity. This study provides new methods to closely link the tolerance of aquatic biota to water quality criteria for e-flow assessment. The recommended coefficients for streamflow adjustment and pollutant control, to dynamically regulate streamflow and control pollutant discharge, are helpful for river management and ecosystems rehabilitation. The relatively low data requirement also makes the method easy to use efficiently in developing regions, and thus this study has significant implications for managing flows in polluted and regulated rivers worldwide.

1. Introduction

Freshwater ecosystems provide services for human life and terrestrial productivity. However, they are increasingly threatened by human-engineered "gray infrastructure", e.g., dam building, flow diversion and barrier construction (Palmer et al., 2015). Instream gray infrastructure exerts substantial negative effects on the biophysical processes necessary to sustain freshwater ecosystems and habitats (Palmer et al., 2015), resulting in serious

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consequences such as water pollution, habitat loss, and decreased fish diversity. (Palmer, 2010; Walsh et al., 2012; Sobczyński and Joniak, 2013; Bobbi et al., 2014). Rivers support not only complex and highly diverse ecosystems but also human needs throughout the world (King et al., 2009). Efforts targeting restoration of hydrological processes and prevention of pollutants from entering rivers appear to offer the most promise (Palmer et al., 2014). To sustain a healthy freshwater environment, the concept of environmental flows (e-flows) – the quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems as well as human livelihood and well-being that depend on these ecosystems – was proposed to retain natural streamflow (or discharge, Q) regimes in rivers (Poff et al., 2010). This is a key principle for maintaining freshwater biodiversity and ecosystem processes and for achieving environmentally sustainable water resource management goals (Acreman and Ferguson, 2010).

There are more than 200 methods for e-flow assessment (Liu et al., 2011), but most methods require accurate and long-term hydrological and/or ecological data, which are not yet broadly available for many rivers globally (Sanderson et al., 2012). More importantly, most e-flow methods have focused principally on the quantity and delivery pattern of water, while fewer methods are available for the assessment of water quality (Scherman et al., 2003; Pinilla-Agudelo et al., 2014). The Adapted Ecological Hydraulic Radius Approach (AEHRA), requiring few hydrological and/or ecological data, uses the hydraulic radius (one of properties of a channel that controls water discharge) as a surrogate for hydraulic habitat and has the potential to calculate e-flows in consideration of the requirements of a river's dynamic balance, pollutant transport and dominant species in an aquatic ecosystem (Liu et al., 2011; Gopal, 2013). However, only fish responses to the variance in hydrological habitat (e.g., flow velocity and water level) are considered, while fish responses (or tolerance) to the variance in water quality habitat have not yet been included. Scientists have recognized that water quantity is important because the structure and function of a riverine ecosystem as well as many adaptations of its biota are jointly determined by water quantity and quality (Nilsson and Renofalt, 2008). The most common approach to water quality protection is the use of water quality criteria, allowing for the selection of levels of appropriate resource protection. However, these are not often linked to environmental flows (Palmer et al., 2007; Wepener and Chapman, 2012; Pinilla-Agudelo et al., 2014). Far fewer studies link the river biota's responses or tolerances to pollutant concentration variations for the assessment of e-flows (Pinilla-Agudelo et al., 2014), which are urgently needed to retain or rehabilitate healthy aquatic ecosystems from the point of the aquatic biota, especially in regulated rivers of developing countries.

Fish are long-lived and sensitive to a wide range of stresses. In terms of the aquatic ecosystem, one of the most obvious and unacceptable effects of anthropogenic activities is the collapse of the riverine fish community due to uninformed river regulation strategies, e.g., reduction in streamflow with attendant decrease in water quality. Stream flows that are adequate to maintain fisheries are usually sufficient to maintain macro-invertebrates and other aquatic life. Fish communities are thus considered effective indicators of ecosystem health. As successful spawning and survival during the early life stages of fish often dictate the strength of subsequent cohorts, understanding the influence of natural flow regimes on the early life of fishes is vital to protecting fish populations in flow-altered rivers (Balcombe et al., 2006). Streamflow alteration also plays important roles in fish body shape changes, periodic life-history strategy, and fish community structure and patterns (Meyers and Belk, 2014; Doledec et al., 2015; Lamouroux and Olivier, 2015; Pool and Olden, 2015).

In a river, streamflow or discharge (Q) changes linearly and positively with flow velocity (u) under a constant cross-sectional flow area (A), i.e., $Q = A^{*}u$. Flow velocity is therefore at the core of discharge. Besides, flow velocity and the associated physical forces collectively represent the most important environmental factors affecting the organisms of running waters (Ahmadi-Nedushan et al., 2006). Fish habitat conditions are generally believed to be of major evolutionary significance, and they vary greatly in the intensity of flow velocity and predation stress (Langerhans, 2009). Increased flow velocity can increase the metabolic rate of fish within a certain velocity range (Asaeda and Manatunge, 2007). Flow velocity can provide important cues for spawning at particular times of the year, and eggs and larvae have distinct flow velocity requirements (Liu et al., 2011). In the non-spawning season, there is usually no special requirement for velocity provided it is under the maximum velocity that a fish can tolerate (Fu et al., 2012). As one of important communities sustaining fish, algae are often influenced by the concentration of nutrient pollutants. Heavily nutrient polluted waters often accelerates the rampant growth of toxic cyanobacteria, e.g., *M. aeruginosa,* which can have strong adverse effects on *Daphnia*, a key species in freshwater pelagic food webs and a major food for fish larva (Zhang et al., 2009). In addition, toxic pollutants impose direct threats to fish survival. Hence, excessive pollutant concentrations in water exceeding the fish tolerance values ultimately decrease the number of fish species. In general, flow velocities and pollutant concentrations are the most important variables explaining opportunities for successful fish spawning (Liu et al., 2011). Additionally, because streamflow greatly influences the concentration of a pollutant (Kumpanenko et al., 2012; Morales-Hernandez et al., 2013), flow velocity as the core of streamflow is deemed one of the most highlighted variables in terms of river pollution control.

Water quality criteria are often used to calculate the water environmental capacity (WEC), a measure of the water's maximum capacity to accommodate a pollutant within a unit of time, which can be classified into attenuation capacity and assimilation capacity (CAEP, 2003). Attenuation and assimilation processes govern the concentration of a pollutant in streams and influence the speed of pollutant removal (Gomes and Wai, 2014). The former refers to the processes of pollutant concentration reduction through dilution, mixing and/or dispersion, while the latter is the association of pollutants with photosynthetic and heterotrophic organisms (e.g., algae, vegetation, microbes) as well as pollutant sorption to sediments (Craig et al., 2008; Ranalli and Macalady, 2010; Stamati et al., 2010). The speed of pollutant degradation in streams can be indicated using the integrated degradation coefficient (CAEP, 2003; Dang et al., 2009). The most critical factors among all hydrological variables influencing pollutant degradation processes (or the integrated degradation coefficient) are flow velocity and stream flow (Gomes and Wai, 2014). For pollutant control strategies, one can set the maximum allowable pollution levels (water quality criteria) for a river-section to ensure the maximum level measured is less than the one set at the pollutant input point at the uppermost reach of the river-section (defined as the head-control) or downstream of the input at the lowermost reach of the river-section (defined as the end-control) under study. End-control can only serve to control pollutants, while head-control is helpful for water ecological remediation (Zhou et al., 1999; Dang et al., 2009) due to its lower pollutant input allowances. Therefore, head-control will be adopted in this paper for better water quality delivery in the e-flow assessment.

The objective of this paper is to present a practical e-flow assessment method, with fish tolerance closely linked to water quality criteria, for streamflow regulation and pollutant control in data-scarce rivers. In this method water quality criteria were adjusted in relation to fish tolerance thresholds and employed to calculate water environmental capacity (WEC). The variation in WEC was dynamically fed back to the quantity of environmental flows whereby streamflows could be ecologically regulated and pollutants discharged into rivers could be reasonably controlled. Based on dynamical streamflow regulation and pollutant discharge control both quantity and quality of environmental flows were optimized.

2. Methodology

2.1. Study area

The Wei River is the largest tributary of the Yellow River, China. The Wei River basin, lying between 103.5 and 110.5°E and 33.5–37.5°N, is located in a continental monsoon climatic zone. The daily mean temperature ranges from 6 to 14 C, with annual mean rainfall from 450 to 700 mm and annual mean evaporation ranging from 1000 to 2000 mm (Li et al., 2014). In recent decades, the whole basin has witnessed many serious high-severity drought episodes with prolonged drought durations (Huang et al., 2014).

The Wei River basin plays an important role in the development of West China. It is the major region for agriculture, industry, and commerce in Northwestern China (Song et al., 2007). Over the past decades, intensive human activities have had a substantial negative impact on the Wei River, characterized by decreasing annual runoff and heavy pollution through increased extraction and unsustainable use of water (Zuo et al., 2014). As a consequence, 69.2% of the water quality observations exceeded the national water protection standards in 2009 and resulted in serious degradation of ecosystem function, including reduced fish species richness, contracted wetlands, and decreased forest vegetation (Wu et al., 2014b). The main pollution issues in this region are chemical oxygen demand (COD), ammonia nitrogen (NH_3-N) levels, biological oxygen demand (BOD_5), volatile phenols and petroleum (Zhang et al., 2012). Among these, COD as an indicator of organic pollutants in surface waters had the highest concentration over all sampling events in both wet and dry situations with values much greater than the other three indicators, which severely threated fish assemblages and resulted in ecosystem function degradation (Li et al., 2011; Wu et al., 2014b) and is therefore worth special attention in future ecological rehabilitation studies. Therefore, in this paper COD is used as a surrogate for water quality in the Wei River study to protect the fish assemblages therein.

Linjiacun (LJC) and Xianyang (XY) are two important hydrological and water quality stations along the river. The catchment of the river section from LJC to XY (Fig. 1) encompasses important cities and a large agricultural area. Frequent drought spells plus high levels of water abstraction has impacted normal ecosystem functions. Additionally, agricultural return water as well as industrial wastewater discharge and domestic sewage (Guo et al., 2013) seriously affected the health of riverine ecosystems, substantially restricting the sustainable development of the region. To sustain local socio-economic development, the health of riverine ecosystems must be given the highest priority with the aim of protecting and rehabilitating their ecosystem functions. To achieve this goal, the assessment of streamflows for the environment (e-flows) that considers both pollutant reduction and the tolerance of aquatic organisms to pollutant levelin riverine ecosystems is urgently needed.

2.2. Data

Data requirements for the method in the present study, that do not need long-term hydrological and water-quality monitoring programs, are considerably lower than traditional methods for e-flow assessment. The essential dataset includes dominant fish species and their tolerance to pollutants, as well as some hydrological and water quality observations. The dominant fish species is accessible by way of on-site catch or fishery investigation while their tolerance values are available in published literature or online datasets.

2.2.1. Water quality indicators and streamflows

Water quality indicators (COD) and streamflows at the water-quality stations LJC and XY and at sewage outlets, water-use canal and tributaries from Jan. 2007 to Dec. 2009 were provided by the Yellow River Conservancy Commission of the Ministry of Water Resources (MWR), China. All sewage outlets, water-use canals and tributaries were generalized as one virtual sewage outlet into the river (GSO in Fig. 2) to facilitate the calculation of e-flows.

The mainstream section of the Wei River between the two water quality stations (LJC and XY) was selected to study its e-flows. There are nine sewage outlets, nine tributaries and two water abstraction canals along the 197-km length of this section of the river (Fig. 1). All raw data were subjected to quality control before use with the quality-control methods of Smirnov et al. (2000).

2.2.2. Fish species and their tolerances

The study of Wu et al. (2014a) on the fish community of the Wei River reveals that five fish species, *Misgurnus anguillicaudatus*, *Opsariichthys bidens*, *Pseudorasbora parva*, *Abbottina rivularis* and *Carassius auratus,* dominate the fish community. Under intensive anthropogenic disturbances e.g., channelization and dam construction many native fish species are absent (Han et al., 2008a, b; Garcia et al., 2011; Gomes and Wai, 2014; Chu et al., 2015; Gibson et al., 2015) increasing the risk that there exists no target species for e-flows calculation. To reduce the absence risk, dominant fish species instead of native fish species, were selected as instream ecological target species to assess e-flows. Requirements of the five fish species for flow velocity and COD were obtained from two sources, one of which was the selected records from the integrated dataset of three extensive field campaigns in Jinan City (Zhao et al., 2015a). Jinan City is in the lower reach of the Yellow River basin, whereas the Wei River is in the upper reach. The other source was published literature. The requirements are summarized in Tables 1 and 2. In the three extensive field campaigns in Jinan City, attributes inclusive of 37 hydrologic, physical and chemical parameters were measured concurrently with the fish sampling during three periods: May 1st-20th, August 2nd-21st and November 1st-20th, 2014. The three periods cover the most variable possibilities of the attributes. Meanwhile, 5084 fish were sampled and tested, concurring with hydrological and water quality parameters measured at a total of 144 sites.

2.3. Methods for e-flows assessment with streamflow regulation and pollutant control

The method presented in this paper considers fish requirements for streamflow and water quality (Fig. 3). The two output coefficients for streamflow regulation and water pollutant control are of use to river administrators and stakeholders for reducing negative impacts of streamflow regulation and pollutant discharge due to unreasonable urbanization, agriculture, mining and water extraction. They can be of great help to maintain or rehabilitate the health of river ecosystems.

The determination of the ecological velocity (V_E), or the flow velocity required to maintain the elementary functions of instream ecosystem components (Liu et al., 2011; Gopal, 2013), is the core of the method from which environmental flow (Q_E) is determined via the Adapted Ecological Hydraulic Radius Approach (AEHRA) (Liu

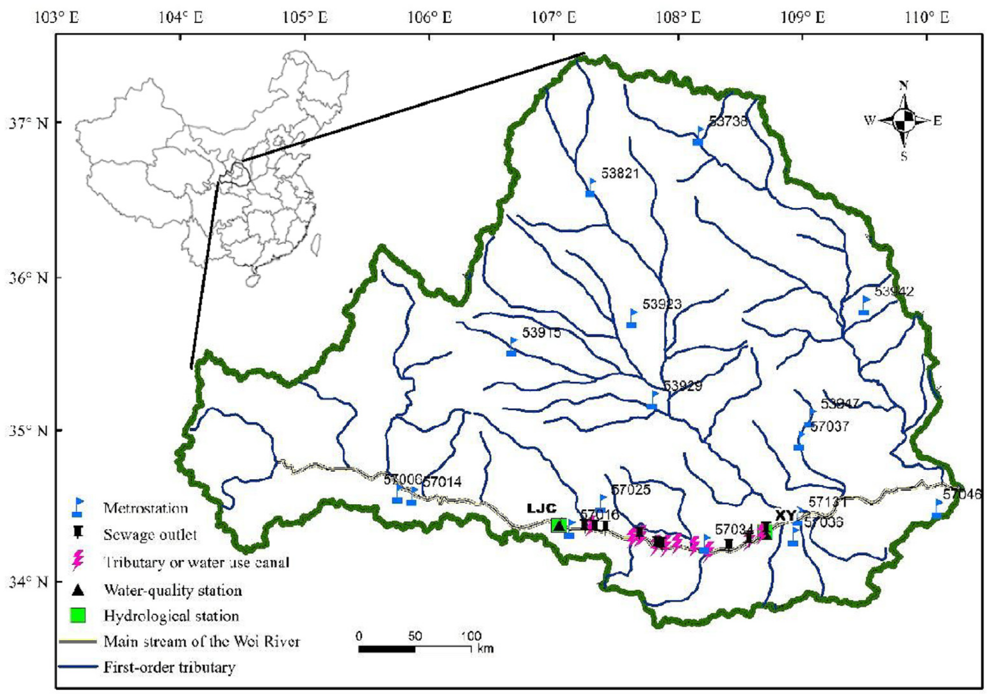

Fig. 1. The Wei River basin and the location of its meteorological, hydrological and water quality monitoring/sampling stations. "Metrostation" stands for meteorological station with the number representing the code assigned by the China Meteorological Administration (CMA); LJC and XY are water quality and hydrological stations named by the Yellow River Conservancy Commission of the Ministry of Water Resources (MWR), China.

et al., 2011). River sections need to be generalized for the convenience of e-flow calculation. In the generalized river section, e-flows (Q_E) considering only water quantity were initially estimated using AEHRA. Subsequently, based on the range of both V_E and Q_E, the water environmental capacity (W) range is then calculated and recommended using the WECA method presented in this paper. The recommended W range can be slightly adjusted by river administrators and stakeholders in special situations, e.g., under a severe drought. The adjustment of W is fed back to V_E and then Q_E. After several iterations of dynamic adjustments of W, V_E and Q_E, a set of three variables is determined with which streamflow in the UCC reach (Fig. 2a) could be regulated using the streamflow regulation coefficient (α, the ratio of Q_E to river discharge through UCC), and pollutants discharged into the river could be controlled by the pollutant control coefficient (β, the ratio of actual pollutant discharge to WEC at GSO).

2.3.1. River-section generalization

In the present study the river is assumed to be one-dimensional, with point source pollutant and non-point source pollutant discharges, tributaries and water-use canals defined as a single, generalized sewage outlet (GSO). The GSO position can be calculated by the concentration of the studied pollutant. A river section between two control cross-sections is then generalized as in Fig. 2a.

The position of the generalized sewage outlet (GSO) (Fig. 2a) can be determined by Eq. (1) derived from EPAC (2002).

$$X_2 = \frac{\sum_{i=1}^{n} q_i C_i e^{-x_i} x_i}{\sum_{i=1}^{n} q_i C_i e^{-x_i}}. \tag{1}$$

i stands for the number of actual sewage outlets or tributaries, $i = 1, \ldots, n$; n is the number of sewage outlets; x_i refers to the distance from the outlet to the DCC; q_i refers to the pollutant discharge rate at the i-th outlet, in $m^3\ s^{-1}$; C_i is the concentration of a specific pollutant corresponding to q_i at the i-th outlet, in mg l^{-1}.

2.3.2. E-flows assessment (Q_E) using the AEHRA

The core of the AEHRA is the determination of ecological velocity (V_E in m•s^{-1}). The velocity requirements for fish species vary with season, which can be determined by $V_E \in [V_{low}, V_{\mathrm{high}}]$. V_{low} is the lowest threshold of velocity for the dominant fish species, while V_{high} is the highest threshold. Both V_{low} and V_{high} can be determined from the attributes given in Table 1. Having obtained the V_E, e-flows Q_E in the river section can be estimated using the AEHRA (Eq. (2)). When cross-sectional data were absent in a data-scarce river, they were obtained via the cross-section generalization method in the AEHRA (Liu et al., 2011).

$$Q_E = \frac{1}{n} R_E^{\frac{2}{3}} A_E J^{\frac{1}{2}} \text{ with } R_E = n^{\frac{3}{2}} V_E^{\frac{3}{2}} J^{-\frac{3}{4}} \tag{2}$$

Q_E is e-flow in m^3•s^{-1}; R_E refers to the watercourse hydraulic radius (ratio between cross-sectional flow area and its wetted perimeter) corresponding to V_E in m; A_E, flow area for e-flows in m^2; n: roughness or Manning's n, which is dimensionless; J: hydraulic slope in %.

With Q_E, river administrators can regulate streamflows through the UCC (Q_0) by using the streamflow regulation coefficient ($\alpha = Q_E/Q_0$) for the purpose of pollutant dilution and the rehabilitation of its ecology. Then, a recommended range of ($[\alpha_{low}, \alpha_{\mathrm{high}}]$) was suggested to river administrators or stakeholders for streamflow regulation after iterations of adjustment on W (Fig. 3).

2.3.3. Water environmental capacity calculation with streamflow regulation and pollutant control by linking fish tolerance to water quality criteria

Herein we put forward a new method for Water Environmental Capacity Assessment (WECA) with streamflow regulation and

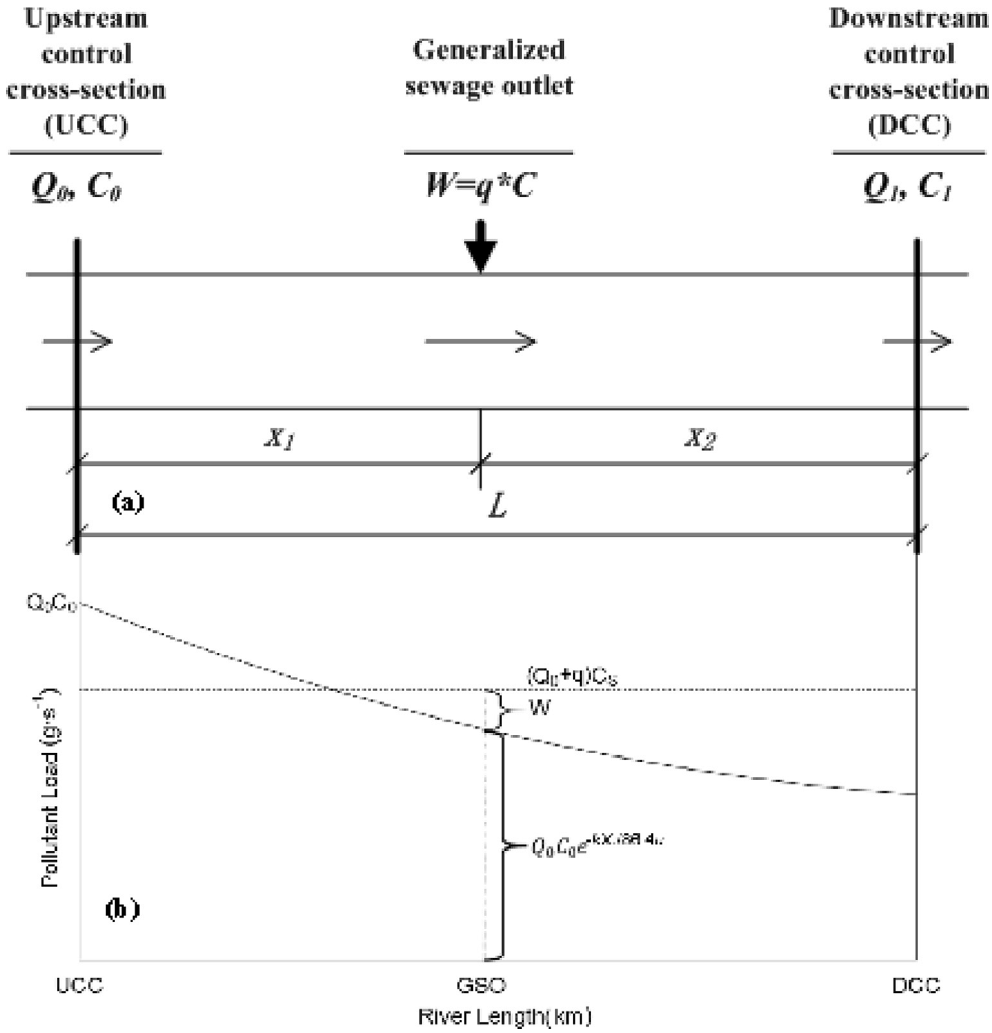

Fig. 2. River-section with a generalized sewage outlet (GSO) (a) and its pollutant degradation process (b). q refers to the pollutant water discharge in $m^3\ s^{-1}$; Q_0, Q_1 are river discharges through the upstream and downstream control cross-sections (UCC and DCC), respectively, in $m^3\ s^{-1}$; Assuming $Q_1 = Q_0 + q$; C_0 and C_1 are concentrations of a specific pollutant at the UCC and DCC, C is the concentration of a specific pollutant corresponding to q at the GSO, and C_s stands for water quality criteria, all in mg l^{-1}. W is the water environmental capacity at the GSO in g s^{-1}; X_1 and X_2 are the distances from the GSO to the UCC and DCC, respectively, in km. L is the length of the studied river section, $L = X_1 + X_2$, in km. Multiple sewage outlets within a river-section can be generalized as one outlet (GSO) as illustrated in (a). A pollutant from the upstream of the study river-section, sometimes with a load (Q_0C_0) much higher than that in the downstream due to excessive pollutant discharge in the upstream reach, flows in and continuously degenerates to the load of $Q_0C_0e^{-kX_1/86.4u}$ (u: the mean flow velocity between the UCC and GSO). The difference between the above load and the load $(Q_0 + q)C_s$ is the water environmental capacity (W), i.e., the total load of the pollutant allowed to be discharged into the river-section, as illustrated in (b).

Table 1
Flow velocity requirements of the five fish species in the lower reach of the Yellow River (Zhao et al., 2010, 2015a; Liu et al., 2011; Fu et al., 2012; Yan, 2012).

Fish species	*Opsariichthys bidens*	*Carassius auratus*	*Pseudorasbora parva*	*Misgurnus anguillicaudatus*	*Abbottina rivularis*
Spawning season	June–August	April–May	May–June	April–May	April–May
Roe type	Drifting on water surface	Attached to waterweed or pebble	Attached to waterweed or pebble	Attached to waterweed or pebble	Attached to waterweed or pebble
V_{spaw} (m s^{-1})	>0.80	–	–	–	–
V_{opt} (m s^{-1})	0.30–0.50	0.20–0.60	0–0.46	0.30–1.04	0.08–0.34
V_{crit} (m s^{-1})	0.60	0.93	0.46	1.04	0.34

V_{spaw}: velocity required by a fish species.
V_{opt}: optimal velocity for a fish species.
V_{crit}: critical velocity, i.e., the maximum velocity that a fish species can tolerate.
"–": no requirement on V_{spaw}

pollutant control in a river section. WEC, as a measure of the water's maximum capacity to accommodate a pollutant within a unit of time in a river section, is mainly subjected to rate of streamflows which can be regulated based on the coefficient $\alpha = Q_E/Q_0$. The coefficient will also induce the regulation of mean flow velocity (u in m•s^{-1}). The magnitude of the flow velocity positively influences the value of the integrated degradation coefficient of a pollutant, which determines the rate of dilution and the degradation

Table 2
COD range where the five fish species live, monitored in the integrated bio-monitoring project in Jinan City (Zhao et al., 2015a, b).

Fish species		*Opsariichthys bidens*	*Carassius auratus*	*Pseudorasbora parva*	*Misgurnus anguillicaudatus*	*Abbottina rivularis*	Integrated threshold
COD (mg l^{-1})	Min	8.94	6.3	6.3	6.3	8.94	**6.3**
	Max	19.2	130.6	64.5	28.3	64.5	**19.2**
	Best	18.8	37.8	64.5	25.7	8.94	

"min" and "max" represent the lowest and the highest values where fishes were collected.
"best" represents the value where there is the most number of fish.
"Integrated threshold" (bold value) indicates the synthesized items in which all of the five fish species can survive optimally.

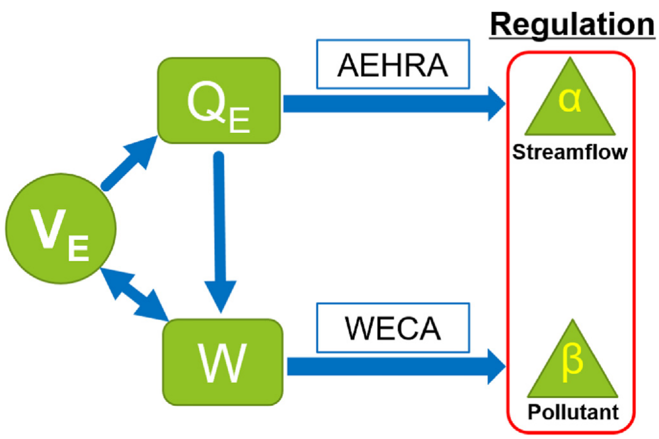

Fig. 3. Framework of the new method presented in this paper. V_E: ecological velocity, or the flow velocity required to maintain the elementary river functions, in m•s^{-1}; Q_E: e-flows, or environmental flows, calculated with V_E, in m^3•s^{-1}; W: water environmental capacity, in g•s^{-1}; α: streamflow regulation coefficient that guides the operation of water projects such as dams and sluices to satisfy e-flows, calculated based on AEHRA; β: pollutant control coefficient that guides controlling pollutants discharged into rivers to protect aquatic organisms, calculated based on WECA; AEHRA stands for the Adapted Ecological Hydraulic Radius Approach for the calculation of instream e-flows developed by Liu et al. (2011); WECA is the model for water environment capacity assessment, presented in this paper; Q_E coupled V_E is used for W assessment; regulation on W through β which dynamically impacts V_E and then Q_E.

efficiency of the pollutant and in turn influences WEC in the river section (Fig. 2a). If the pollutant concentration in the cross-section of a generalized sewage outlet (GSO) in Fig. 2a equals the water quality criteria, i.e., $C{=}C_s$ (Fig. 2b), we can express the total mass of the pollutant in a river section as Eq. (3), based on the mass conservation law and the first-order kinetics formula $C = C_0 e^{-kt}$ (Kadlec and Knight, 1996).

$$Q_0 C_0 + W = (Q_0 + q) C_s + Q_0 C_0 \left(1 - e^{\frac{-kX_1}{86.4u}}\right) \tag{3}$$

where the left side is the total mass of the pollutant in a river section, and the right side is the total pollutant capacity for dilution and degradation. Under conditions of pollutant control, the total mass of the pollutant is assumed to never exceed the total pollutant capacity in the river. W stands for WEC, in g•s^{-1}; k is the integrated degradation coefficient measuring the rate at which the environment can remove a pollutant, in d^{-1}; u is the average flow velocity in a river-section, in m•s^{-1}; X_1 is the distance of the generalized sewage outlet from the UCC, in km (Fig. 2).

Accordingly, WEC (W) can be solved as

$$W = (Q_0 + q) C_s - Q_0 C_0 e^{\frac{-kX_1}{86.4u}} \tag{4}$$

wherein the fish tolerance to pollutant concentration ("Integrated threshold" in Table 2) is embodied in the water quality criteria C_s which is achieved by satisfying both requirements of fish species and river functions to pollutant concentration. The previous value of C_s for a pollutant is modified to a level tolerated by the dominant fish species. The previous C_s value is the minimum of all *Css* for river functions, e.g., water use for agriculture, industry, swimming etc. The criteria *Css* are drawn from water quality standards, e.g., the Chinese national environmental quality standards for surface water "GB 3838-2002" (EPAC, 2002) whereby the previous C_s value for COD is 30 mg l^{-1} for the section LJC-XY with a river function for agricultural and industrial water supply.

When pollutant discharge into rivers exceeds the water environmental capacity W, pollutant control is the most appropriate way to maintain the pollutant concentration within that of the fish tolerance threshold values. u in Eq. (4) is initialized by $V_E \in [V_{low}, V_{high}]$ in Table 1 and accordingly $W \in [W_{low}, W_{high}]$ are calculated based on Eq. (4) with W_{low} the WEC calculated using the lower u value and W_{high} the WEC using the higher u value. In the next iteration of calculation, the value of u is expected to be dynamically adjusted with W which is regulated by river administrators or stakeholders based on a pollutant control coefficient. Here the COD-measured pollutant control coefficient is defined as $\beta = Wa/W$ with $\beta \in [\beta_{low}, \beta_{high}]$ in accordance with the range $[W_{low}, W_{high}]$. W_a (in g•s^{-1}) is the actual pollutant discharge at the GSO, which can be calculated using Eq. (5) that we derived from the generalized river model (Fig. 2) and mass conservation law. With any pollutant control coefficient β selected by river administrators the value of u can be calculated iteratively with Eq. (4). The recalculated u is fed back to the calculation of the streamflow regulation coefficient α as Fig. 2 shows.

$$W_a = \sum_{i=1}^{n} q_i C_i e^{\frac{-k(x_i - x)}{86.4 u_a}} \tag{5}$$

where x is the distance of the GSO from the DCC, and x_i is the distance of the i-th sewage outlet from the DCC. W_a includes those pollutant discharges from point and non-point sources and tributaries. Water abstraction can be regarded as the opposite of tributaries, data of which come from field observations or model simulations. A non-point source pollutant is estimated with the storm-runoff based mean concentration method (Li et al., 2011). u_a is the actual mean flow velocity in the studied river-section and can be calculated as the average of the flow velocity observed at the UCC and DCC.

The above-mentioned COD-measured pollutant control coefficient (β) can greatly facilitate the practical operation of pollutant discharge control. If necessary the coefficient β measured by other indicators, e.g., NH_3-N, BOD_5, can also be calculated to facilitate the control of pollutant discharged into rivers. In the present study, a recommended range of ($[\beta_{low}, \beta_{high}]$) would be highly acceptable to river administrators and stakeholders.

3. Results

3.1. River-section generalization and water quality criteria modification

According to the conceptual model in Fig. 2, all outlets into/from the river section LJC-XY were generalized as one virtual outlet (GSO) 3.06 km upstream from station XY. The river-section between stations LJC and XY (Fig. 1) is the water source for both industry and agriculture. Hence, the C_s (COD) for river function is 30 mg l^{-1}, according to the national environmental quality standards for surface water "GB 3838-2002" (EPAC, 2002). While the maximum COD levels that the five fish species (*Opsariichthys bidens*, *Carassius auratus, Pseudorasbora parva*, *Misgurnus anguillicaudatus* and *Abbottina rivularis*) can tolerate were, respectively 19.2, 130.6, 64.5, 28.3 and 64.5 mg l^{-1}, the minimum of maximum values (the above five values) was 19.2 mg l^{-1}. Most likely, the maximum of minimum values of COD levels that the five fish species can tolerate is 8.94 mg l^{-1} as listed in Table 2. Thus, the range for fish species ranged between 8.94 and 19.2 mg l^{-1}. Therefore, the C_s of 30 mg l^{-1} for the studied river section was modified to range between 8.94 and 19.2 mg l^{-1} after the fish tolerance to COD level was integrated.

3.2. E-flows assessment and streamflow regulation

In the river section LJC-XY, drifting fish roe of *Opsariichthys bidens* (Table 1) will sink onto the riverbed and perish when the flow velocity is lower than 0.8 m s^{-1} (Zhao et al., 2010). Therefore, in the fish spawning season from June to August, flow velocity must be kept higher than 0.8 m s^{-1} for the roe of *O. bidens* to survive, even though the velocity of 0.8 m s^{-1} is higher than the critical velocity of adult *O. bidens*, they could seek shelter in the lower-velocity deep water habitat or near the river bank. Accordingly, the following ecological velocity for fish in the Wei River is recommended: higher than 0.8 m s^{-1} from June to August and between 0.30 and 0.34 m s^{-1} in the other months (Table 1). The ecological velocity ranges of (0.30, 0.34) m s^{-1} were determined by the coupling of optimal velocity (V_{opt}) and critical velocity (V_{crit}). The minimum optimal velocity, which can satisfy all the five fish species is 0.30 m s^{-1} and the maximum optimal value is 0.34 m s^{-1}. The critical velocity for the fish *Abbottina rivularis* is 0.34 m s^{-1} a higher velocity than which would pose a higher survival risk to the species and its larvae. On integrating the COD level requirements for the five fish species with the standard COD level (30 mg l^{-1}) as shown in Table 2, e-flows and the corresponding streamflow regulation coefficients were calculated using Eq. (2) for AEHRA (Fig. 4).

The e-flow magnitude varied by month and remained high during the period from July through September (Fig. 4). To satisfy e-flows, streamflows must be regulated with the coefficient ranging between low and high α values. Generally, streamflow necessitates higher regulation in dry seasons than in wet seasons. In detail, higher streamflows (Q_0) in most of the wet season from July through September necessitated a lower streamflow regulation, while lower streamflows in the other season (Oct–June) required higher regulation. Moreover, the difference between α_{low} and α_{high} in the wet season was small, whereas the difference in the dry season was large due to the lower streamflow Q_0 plus the higher e-flow Q_E.

3.3. WEC calculation and COD-measured pollutant control

The WEC process for COD was similar to that of the e-flows (Fig. 4) and was heavily affected by streamflow Q_0 (Fig. 5). The process remained high when the streamflow was high during the wet season, while in the dry season it remained low most of the time. To keep the COD level within the tolerance range of the five fish species, the COD discharged into rivers had to be reduced greatly with the coefficients β_{low} and β_{high}. The two coefficients were heavily affected by streamflow. They remained lower (with little reduction) in wet seasons than in dry seasons. The difference between β_{low} and β_{high} was small during most years from 2007 to 2009.

3.4. The integrated degradation coefficient and its influencing factors

Water temperature, flow velocities and river length for pollutants to mix, dilute and degrade are important sources of uncertainties in the estimation of the integrated degradation coefficient k (Su, 2006; Liu et al., 2007; Wang et al., 2012). Our calculations show that the value of k for COD decreased with river length. In detail, k decreased abruptly in the initial 3 km of the flow path, while the decreasing trend slowed down and k plateaued within a river length of 4–10 km. In other words, the minimum river length threshold must be a priority to obtain a steady k value. Therefore, the minimum mixing length (CAEP, 2003) to ensure that pollutants mixed uniformly in the study river was ~10 km. To explore the role of water temperature and flow velocity in the

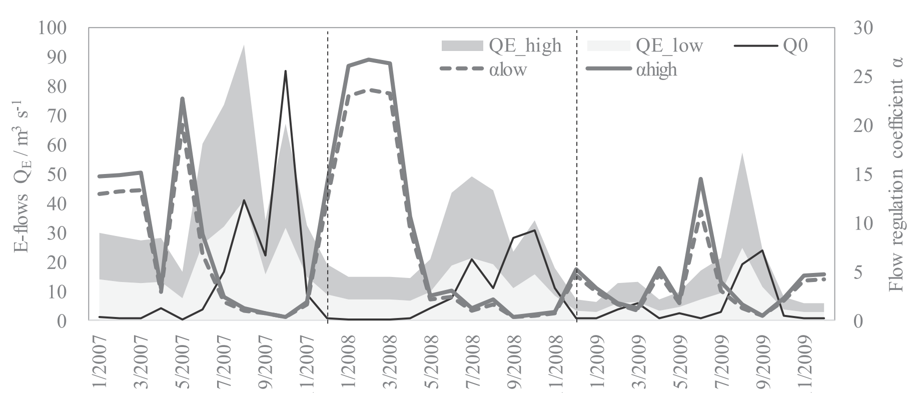

Fig. 4. E-flows (Q_E) and streamflow regulation coefficients (α). The dark gray area is the highest e-flow, while the light gray the lowest. The dark, thick solid line represents the high streamflow regulation coefficient to satisfy the highest e-flows, while the dark, thick dotted line represents the lowest coefficient. The black, thin line represents streamflow through the upstream cross-section (UCC).

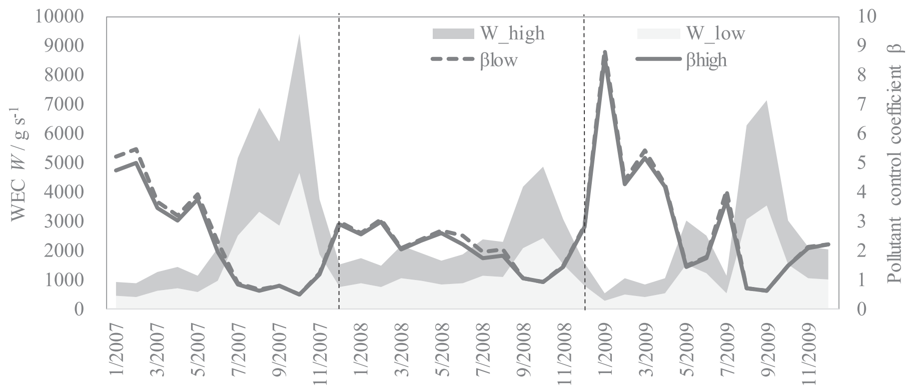

Fig. 5. Variations in the water environment capacity (WEC) and the pollutant control coefficient (β) between 2007 and 2009. The dark gray area is the highest WEC while the light gray area is the lowest. Likewise, the dark, thick solid line represents the pollutant control coefficient to meet the highest WEC, while dark, thick dotted-line represents the lowest. Coefficients less than 1.0 indicate that the pollutant concentration was less than the highest tolerance level for the five fish species, while coefficients higher than 1.0 indicate that the concentration required reductions.

variation of k, the two factors' variation processes and relationships with k are illustrated in Fig. 6.

The river sections LJC-XY and downstream of XY (XY-HX) were studied to demonstrate the influences of T_w and u on k. Taking into account the influences of the above two factors on k, Liu et al. (2007) suggested that the optimized k value in July 2006 for COD near station XY was 1.03 d^{-1}, which was similar to our results in July (2007–2009), where the k values for COD were 0.38–0.83 d^{-1} upstream of station XY and 0.70–1.27 d^{-1} downstream of this station (Fig. 8g). Likewise, Su (2006) studied the COD degradation process near station XY based on a water-quality dataset from 1992 to 2001 and derived the highest k value for COD of 1.43 d^{-1}, which was similar to the highest value of 1.36 d^{-1} in Aug. 2007 in the present study (Fig. 6c). Variations in water temperature and flow velocity explained the above differences. Water temperature near station XY in July 2006 was 26.03 C with a flow velocity of 0.46 m s^{-1} (Liu et al., 2007), while the water temperature in July 2007 was 22.11 C with a flow velocity of 0.97 m s^{-1}, which led to a higher k value for COD (1.27 d^{-1}) as shown in Fig. 6d and e. Water temperature and flow velocity had the closest relationships with k (Fig. 6a and b). In both sections, k exponentially increased with water temperature, while the upstream section (LJC-XY) had a slower k increase than that in the downstream section (XY-HX) (Fig. 6a). Contrary to water temperature, flow velocity drove k to increase logarithmically (Fig. 6b). Flow velocity in the upstream section had smaller influences on k compared with that in the downstream section. In brief, the influences of water temperature and flow velocity on the integrated degradation coefficient were remarkably substantial, and influences on the downstream section were even greater than that in the upstream section.

Both flow velocity and its standard deviation are important in explaining water quality variation (Gomes and Wai, 2014). The speed of pollutant degradation (or the integrated degradation coefficient) is critically influenced by attenuation and assimilation processes. Our analyses of the relationships between the degradation coefficient of COD and flow velocity, as well as their derivatives, revealed that flow velocity itself (u) had a much greater influence on the degradation coefficient (k) than the standard deviation of flow velocity (u_SD) based on temporal variations (Fig. 6b *vs* Fig. 7a) in both the upstream section (LJC-XY) and downstream section (XY-HX). The correlations of k-u (Fig. 6b) had higher correlation coefficients (R^2) than the k-u_SD (Fig. 7a). Variations in u_SD had greater influences on the degradation coefficient (k_mean) (Fig. 7a) than its standard deviation (k_SD) (Fig. 7b) with higher trend slopes in both the up- and downstream river sections. To summarize, the mean flow velocity had a much greater influence on the attenuation and assimilation processes of water quality than did the standard deviation of the flow velocity.

4. Discussion

The method presented in this paper successfully integrates the requirements of fish species and pollution control into the e-flow assessment. The presence of streamflow adjustments and pollutant control coefficients in the method makes it easy to use and substantially helpful to river administrators and stake-holders in many aspects, e.g., reduction of noxious odors and sulfide problems (Rauch and Kleidorfer, 2014), decrease of higher pollutant-tolerant species and increase of lower pollutant-tolerant species (Zhao et al., 2010), gradually increasing biodiversity and rehabilitating aquatic ecosystems.

4.1. Rationale for the selection of the key water quality indicator

Agriculture and industry occupy predominant positions in the development of the Wei River basin (Song et al., 2007), which resulted in heavy pollution that seriously degraded its ecosystem function (Wu et al., 2014b). For instance, large nitrogen sources are typically associated with agricultural activities in most regions (Craig et al., 2008). Of all water quality indicators, chemical oxygen demand (COD), ammonia nitrogen (NH_3-N), biological oxygen demand (BOD_5), volatile phenols and petroleum are five principal indicators in this basin (Zhang et al., 2012). Intensive human disturbance of the soil through agricultural tilling resulted in high COD levels in both water and sediment samples from the Wei River (Chen et al., 2003; Li et al., 2011). Because COD is used to indicate organic pollutants in surface waters, its sources consist of soil particles, agricultural chemicals, fertilizer and natural organic substances from disturbed surface soils in the Wei River basin (Li et al., 2011). It should be noted that COD, with the highest concentration of all of the main water quality indicators (Li et al., 2011), exerted the most stress on fish communities in the Wei River and contributed greatly to ecosystem function degradation, negatively influencing fish communities, wetlands and forest vegetation (Wu et al., 2014a&b). In addition, we studied the influences of hydrological, physical and chemical habitat factors on fish species in Jinan City downstream of our study area, showing that both forms of COD (COD_{Mn} & COD_{Cr}, or Permanganate index & Chemical oxygen

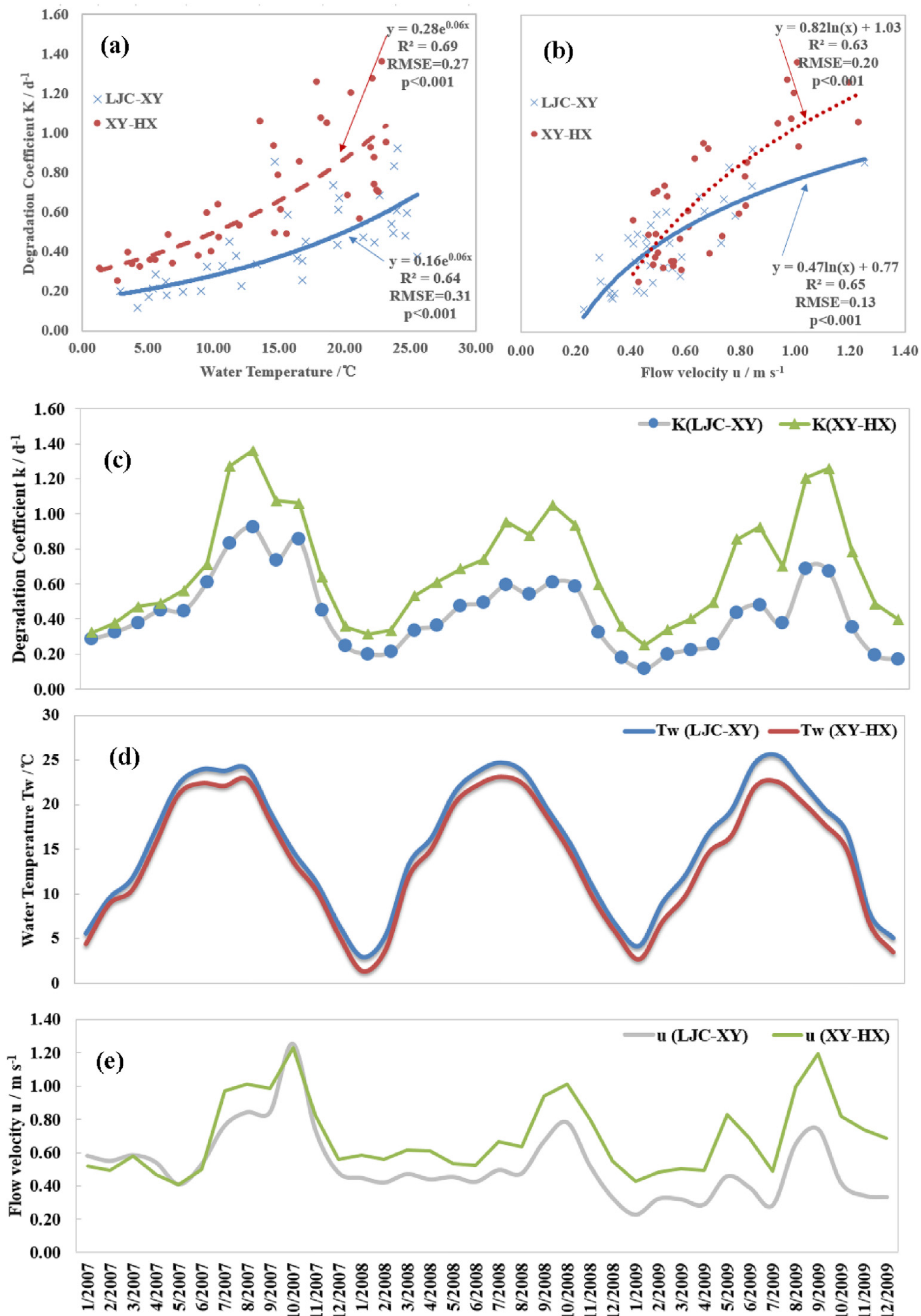

Fig. 6. Variation of the integrated degradation coefficient (k) for COD in the river upstream (LJC-XY) and downstream (XY-HX) (c) and their influencing factors inclusive of water temperature (Tw, a&d) and flow velocity (u, b&e). RMSE: root mean square error.

demand, see Fig. 2 in Zhao et al. (2015a)) had the highest biplot scores in the canonical correspondence analysis (CCA) of the chemical habitat factors. Moreover, COD_{Mn} was highly correlated with COD_{Cr} and NH_3-N with correlation coefficients greater than 0.51. Therefore, COD_{Mn} was selected to be one of the seven key habitat factors determining fish communities. Thus COD should be given the highest priority in future ecological rehabilitation programs and deserves a role as a surrogate of water quality for e-flows studies in the Wei River.

Similarly, water quality indicators were also studied by Gomes and Wai (2014) where eight indicators were selected as surrogates of water quality. They were unable to nominate one or two principal water quality indicators as surrogates because in their research land use in the mountainous area was devoid of medium- to large-scale industries, which differed greatly from the agriculture- and industry-dominated Wei River basin. Additionally the total catchment area of 4.21 km^2 in their research was far less than 135,000 km^2 of the Wei River basin (Li et al., 2011), which differed

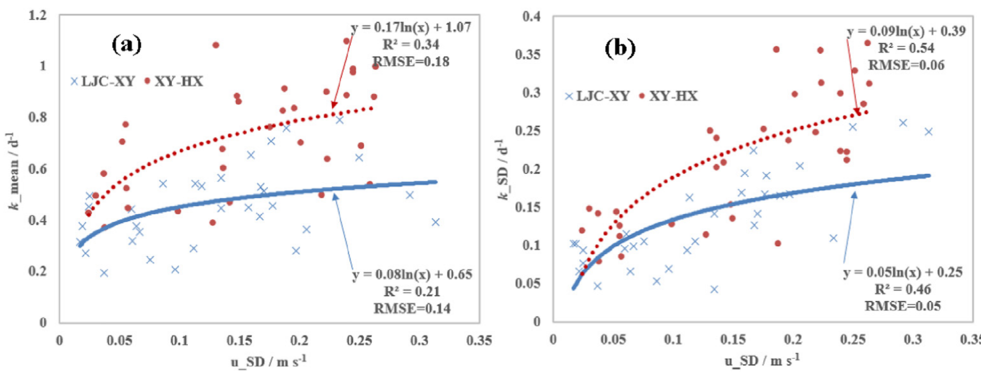

Fig. 7. Further exploration on the relationship between the integrated degradation coefficient (*k*) and flow velocity (*u*). *k*_mean: the mean value of integrated degradation coefficient; *k*_SD: the standard deviation of *k*; u_SD: the standard deviation of flow velocity; RMSE: root mean square error. (a) Variation of the mean degradation coefficient with the standard deviation of flow velocity. (b) Variation of the standard deviation of the degradation coefficient with the standard deviation of flow velocity.

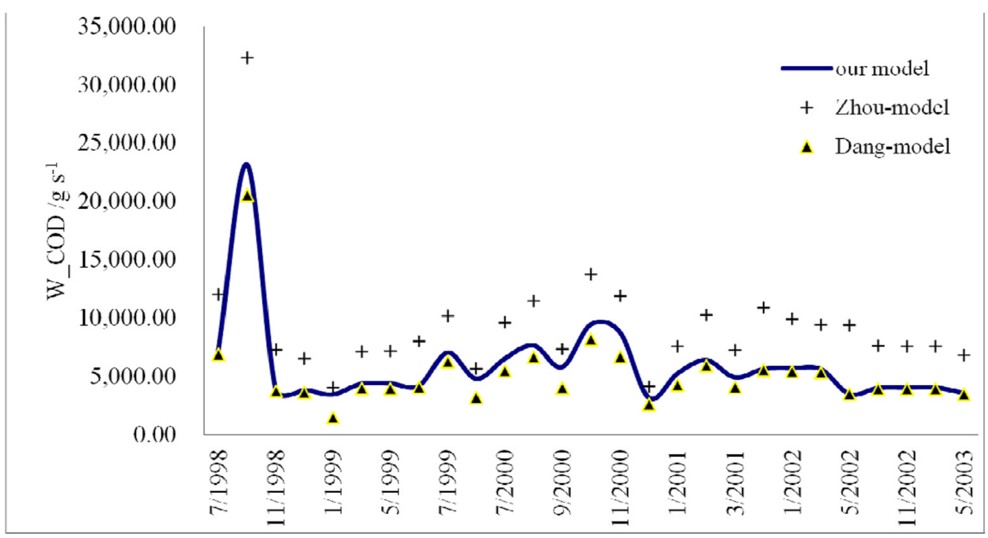

Fig. 8. Comparison of our model (WECA) with the Zhou- and Dang-models.

greatly spatially and therefore resulted in different surrogates for water quality in the two study areas. In brief, the multiple surrogates for water quality in Gomes and Wai (2014) are appropriate for a catchment with little agricultural and industrial activities. These surrogates, in a large-scale basin such as in the present study, do not feature prominently compared with COD. Thus, COD is deemed a suitable water quality surrogate for large-scale basins with heavy pollution resulting from agricultural and industrial activities (Chen et al., 2003; Li et al., 2011; Zhang et al., 2012), as exemplified by the Wei River basin.

4.2. Divergence in e-flow assessment

Over the three years (2007–2009), the annual streamflow (Q_0) continued to decrease (Fig. 4), especially during the wet season (July–October). Q_0 in the 2008 wet season was half that of 2007, and Q_0 in the 2009 wet season was a quarter that of 2007. Statistically more than 80% of the months need increasing the streamflow magnitude to satisfy e-flows requirement on quantity, through reducing water use for agriculture and industry etc., or diverting water from outside the watershed. Many water-diversion projects, e.g. the South-to-North Water Transfer Project in Shaanxi Province, have been put into practice in our study area but most diverted water were used by industry with a small portion used for ecological remediation (Chang and Jiang, 2011). Therefore, it is possible to satisfy e-flows quantity requirements by referring to the streamflow regulation coefficients presented in this study. Song et al. (2007) studied e-flows for the Wei River by considering streamflow quantity requirements for aquatic biotopes, seepage, evaporation, pollutant self-purification, and sediment transportation. Their results showed that the e-flows for physical habitat maintenance near station LJC ranged from 51.1 to 100.2 $m^3 s^{-1}$ in the wet season, while they ranged from 38.7 to 71.5 $m^3 s^{-1}$ in the dry season (January–June and November–December). Our results ranged from 43.0 to 148.96 $m^3 s^{-1}$ in the wet season and from 39.95 to 131.59 $m^3 s^{-1}$ in the dry season. On average, our results were higher than those in Song et al. (2007), in which they used the Montana (or Tennant) method (Tennant, 1976) to calculate the e-flows for aquatic ecosystems. A minimum 10% of the averaged measured streamflow was regarded as being necessary for maintenance of aquatic ecosystems. A minimum e-flow value may not be enough to maintain a healthy physical habitat (Arthington et al., 2006). Moreover, the method Song et al. (2007) used for physical habitat maintenance is more appropriate for rivers without human impacts and is generally used as a rough verification of other approaches (Liu et al., 2011) where human impacts exist.

According to Chen et al. (2013), most e-flow methods such as the Instream Flow Incremental Methodology (IFIM) have been subject to criticism because of their inability to consider discharge–biomass relationships. However, when considering these relationships, large data requirements limit the construction of stress-response relationships in data-scarce rivers, where the required information is not yet broadly available regionally or globally (Bobbi et al., 2014). Moreover, the failure to integrate water quality into e-flow assessments restricts their applicability to catchments with poor water quality because the e-flow assessment includes not only water quantity but also water quality (Brisbane Declaration, 2007). Scherman et al. (2003) used water quality information, biological assessment information and toxicological data to assess the water quality component of environmental flow assessments. Hart et al. (1999) defined a concentration–response relationship between a driving water quality parameter and ecosystem health. Paredes-Arquiola et al. (2014) integrated three essential components, i.e., water quantity, water quality and habitat suitability for aquatic species, into e-flow assessment, but the complex sub-models limit their application, especially in developing countries, as they require substantial detailed monitoring data of water quantity, quality and ecology.

The method presented in this paper deems fish species as the basic attribute, and closely couples their requirements with water quality by the re-establishment of water quality criteria concerning their tolerance levels. Moreover, our method recommends both pollutant control and streamflow regulation measures to satisfy e-flows, which is more practical than the pollutant dilution (self-purification) approach recommended by Song et al. (2007) under a background of decreasing runoff and heavy pollutant inputs. In their research, e-flows accounted for 41.5–77.5% of total streamflow in the Wei River in the wet season and 56.1–87.0% in the dry season. The simple percentages without dynamic regulation on both streamflow and pollutant discharge into rivers may have presented heavy constraints to regional development under decreasing streamflows and worsening water quality scenarios. The method presented in this paper with two coefficients recommended for dynamic streamflow regulation and pollutant discharge control can help reduce water use and is helpful for river administrators and stake holders to retain or rehabilitate the diversity of river ecosystems. In addition, the relatively low data requirement of our model makes it easy to use in rivers all over the world.

It should be noted that the range of flows in our results is small because there were not sufficient target species and streamflow data available under the condition of lacking detailed monitoring on taxa and habitat. If the constant small range of flows was strictly maintained without introducing bankfull or pulse flows, harmful events (e.g. extinction of some other taxa) would be triggered as a naturally variable regime of flow is required to sustain freshwater ecosystems (Poff et al., 2010). Therefore, under certain circumstances bankfull and pulse flows are expected to be introduced beside the small range of flows in order to sustain much more taxa since most adult fish could seek lower-velocity shelters.

Moreover, there is no differentiation between native and invasive fish species due to few invasive species reported in our study area. Actually invasive species, as the second cause of the extinction of world fish, result in declines and extinctions of native species which greatly reduces the native fish diversity (Clavero and García-Berthou, 2005). Mitigating the impact of invasive species and preventing future invasions to reduce the native fish diversity loss should be given the top priority (Hermoso et al., 2011). Had the difference of flow velocity requirement and pollutant tolerance between native and invasive species been known, it would be of great help to regulate streamflow and control pollutant discharge using the method in this paper to foster native species replacing invasive species whereby to prevent the proliferation of invasive species.

4.3. Uncertainties in the WECA model

Few WECA models consider the head-control of pollutant discharge. Among these, we selected two head-control models, the Zhou-model by Zhou et al. (1999) and the Dang-model by Dang et al. (2009), to compare our models. The WECs for COD were calculated and compared (Fig. 8).

Monthly river discharge datasets greater than zero were selected from 1998 to 2003. The Zhou-model, Dang-model and our model displayed similar trends in the rates of WEC for COD with the values of WEC calculated with our model lying between them. The comparisons revealed that our model is practical and robust in assessing water environment capacities, though some uncertainties may still exist. To reduce uncertainties in the method in this paper, determinations of ecological velocity (V_E) and integrated degradation coefficient (k) necessitate much more intensive information on the relationships between biomass and velocity, k and velocity, and k and water temperature based on long-term datasets of velocity, water quality and ecosystems. Furthermore, to efficiently rehabilitate aquatic ecosystem "hotspots", pollutant removal should be effectively identified by employing appropriate methods such as in Craig et al. (2008), with which the pollutant control coefficient recommended in our method could be more practical, and the recommended streamflow regulation coefficient could be more efficient. To be more effective, stream rehabilitation should be conducted as complementary to land-based best management practices (Craig et al., 2008).

The WECA model, which takes COD as a pollutant indicator to assess water environment capacity in a river section, performed satisfactorily in terms of the degradable organic pollutants. However, it was not tested for inorganic pollutants. There are many inorganic pollutants in waters, e.g., heavy metals, which can persist for long periods altering aquatic community structure, and their interaction with organic matter still remains unclear (Castro-Català et al., 2016; Wojtkowska et al., 2016). Chemical concentrations alone are insufficient to demonstrate their adverse environmental effects (Castro-Català et al., 2016). Therefore the WECA model may not be applicable when it comes to inorganic non-degradable pollutants.

5. Conclusion

A new method to integrate both the requirements of the ecosystem and pollution control into e-flow assessment closely couples the water quantity and quality requirements of aquatic ecosystems. This is accomplished by modifying water quality criteria with fish pollutant tolerance concentrations. Traditional water quality criteria for pollutants are usually determined for water use types (e.g., for industry, agriculture, and drinking), which are subject to human needs. In this paper, the tolerance of fish to pollutant concentrations was integrated into the determination of water-quality criteria with which the water environmental capacity (WEC) of a river-section could be calculated considering both human and ecosystem requirements.

Applications of the method in the Wei River, the largest tributary of the Yellow River, China, suggest that the actual streamflow in dry seasons failed to meet e-flows. Thus, multi-river or inter-river sections of water resource allocations are required to meet human and environmental demands. Pollutant levels, e.g., chemical oxygen demand (COD), exerted a strong influence on the aquatic ecosystem, with pollutant concentrations much higher than the tolerance threshold of the dominant fish species. Moreover, analysis of the integrated degradation coefficient suggests a river length of ~10 km in the Wei River is required for pollutants to mix completely. Moreover, both water temperature and flow velocity exerted great influences on the integrated degradation coefficient, which were greater in the downstream than in the upstream sections of the Wei River.

The advantages of the method in this paper include the ease of operation and relatively lower data requirement, as well as the recommended streamflow regulation and pollution control coefficients. These attributes give the method great potential to be widely used in developing countries/regions which may lack long-term hydrological, water quality and/or ecological datasets.

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