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Environmental flow assessments in estuaries related to preference of phytoplankton

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Abstract

We developed an approach to assess environmental flows in estuaries related to preference of phytoplankton considering the complex relationship between hydrological modification and biomass in ecosystems. As a first step, a relationship was established between biomass requirements for organisms of primary and higher nutritional levels based on the principle of nutritional energy flow of ecosystem. Then, diagnostic pigments were employed to represent phytoplankton community biomass, which indicated competition between two groups of phytoplankton in the biochemistry process. Considering empirical relationships between diagnostic pigments and critical environmental factors, responses of biomass to river discharges were established based on a convection–diffusion model by simulating distributions of critical environmental factors under action of river discharges and tide currents. Consequently, environmental flows could be recommended for different requirements of fish biomass. In the case study in the Yellow River estuary, May and October were identified as critical months for fish reproduction and growth during dry years. Artificial hydrological regulation strategies should carefully consider the temporal variations of natural flow regime, especially for a high-amplitude flood pulse, which may cause negative effects on phytoplankton groups and higher organism biomass.

1 Introduction

Estuaries are semi-enclosed coastal transition zones, where freshwater from rivers mixes with saltwater from the sea. The gradients of salinity and other environmental parameters provide critical habitats of migratory species (Sklar and Browder, 1998). However, alternation in freshwater inflows to ecosystems cause a reduction in available aquatic habitat, which in turn may have negative consequences for many aquatic species (Attrill et al., 1996). Environmental flow assessments, which define how much water may be withdrawn from an ecosystem before its ability to meet social, ecological and economic needs declines, become one of the major challenges for sustainable water resource management in estuaries (Richard, 1997; Arthington et al., 2006; Poff, 2009; Sun et al., 2008, 2012).

Successful environmental flow assessments require an accurate understanding of the linkages between flow events and biotic responses (Poff et al., 2009). Various empirical relationships were established between ecosystem biomass, communities, and biodiversity and long-term average river discharges (Arthington et al., 2010; Clements et al., 2011; Pasztalenieca and Poniewozik, 2010). It should be pointed out that the causality between river discharges and biological alterations often remains uncertain because of the complex nature of biological responses to hydrologic changes, which must be evaluated over a time-scale of decades (Petts, 2009). Accurate long-term records of flows and biological distributions are usually unavailable and/or very costly (Alcázar et al., 2008). The diversity of influencing factors and the complex food web results in significant uncertainty in the relationship between flow alteration and biological response (Webb et al., 2010). Arthington et al. (2006) argued that the lack of data and an understanding of the linkage between ecological conditions and specific flows has constrained comprehensive methods for environmental flow assessment.

Considering the complex relationship between hydrological modification and biomass in ecosystems, phytoplankton communities comprise a physical and energetic foundation of ecosystems, serving as indicator species for ecosystem health assessments (Pasztalenieca and Poniewozik, 2010). Due to the complexity and mobility of the phytoplankton bio-process, the parameters of phytoplankton models are usually determined through empirical formulas and measured experimental data. Furthermore, ecohydrodynamic models have become more and more complicated to describe hydrodynamic and biological processes in ecosystems that are also required detailed field data for calibration and validation of the model (Gupta et al., 2006; Pastres and Ciavatta, 2005). In recent studies, competition between groups of phytoplankton has also been given consideration in the biochemistry process (Pannard et al., 2008; Spitz et al., 2001). Investigation on the mechanisms of phytoplankton competition became significant to understand underlying hydrodynamic parameters that result in the compositional shift of these functional groups.

In this study, environmental flows were defined by relationship between phytoplankton community biomass and environmental factors. Based on the law of energy flow, the fish catch, related to the phytoplankton community biomass was taken as the objectives for ecological protection. In the case study of the Yellow River Estuary, the phytoplankton community was represented by the diagnostic pigments according to the field data. Suggestions for water resource management of the Yellow River Estuary are presented considering differences between river discharges and recommended environmental flows.

2 Methods

2.1 Relation between river discharge and biomass

In order to understand the complex relationship between biomass and hydrological alternation, an approach contains four steps was developed.

Step 1: Based on the nutrition requirements of higher organism biomass (i.e. fish), the nutrition level for primary organism biomass (i.e. phytoplankton) is calculated by the energy flows Eq. (1) as:

$$A_{\mathrm{p}} = A_{\mathrm{r}}/t^{\mathrm{r}-1} \tag{1}$$

where, A_{p} is the biomass of phytoplankton communities, t is the transference rate between two nutritional levels (10–20 %), A_{r} is the biomass of the rth nutrition level.

Step 2: Identify the diagnostic pigments of the phytoplankton community according to the field data in estuaries.

Step 3: Establish empirical relationships between diagnostic pigments and environmental factor with different temporal and spatial scale.

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Step 4: Define environmental flows considering different levels of biomass for different species by simulating distributions of critical environmental factors under action of river discharges and tide current in estuaries.

The relationship between environmental factor distributions and flow regime was established using a numerical model that simulates the spatial and temporal distributions of selected environmental factors as a combined function of the river discharge and tidal currents. The depth-integrated equations for conservation of motion and water are:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}(Hu) + \frac{\partial}{\partial y}(Hv) = 0 \tag{2}$$

$$\frac{\partial u}{\partial t} + \frac{\partial uu}{\partial x} + \frac{\partial vu}{\partial y} = \mathrm{f}v + g\frac{\partial \zeta}{\partial x} + g\frac{u\sqrt{u^2+v^2}}{HC^2} + \frac{\partial}{\partial x}\left(\varepsilon\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon\frac{\partial u}{\partial y}\right) \tag{3}$$

$$\frac{\partial u}{\partial t} + \frac{\partial uv}{\partial x} + \frac{\partial vv}{\partial y} = \mathrm{f}u + g\frac{\partial \zeta}{\partial y} + g\frac{v\sqrt{u^2+v^2}}{HC^2} + \frac{\partial}{\partial x}\left(\varepsilon\frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon\frac{\partial v}{\partial y}\right) \tag{4}$$

where t (s) is time, u and v are current velocities ($\mathrm{m\,s^{-1}}$) in the x and y directions, respectively, f is the Coriolis factor, C is the Chezy coefficient ($\mathrm{m^{1/2}\,s^{-1}}$) and H is the total depth (m) of the water from the water surface to the bottom ($H = \zeta + d$, where d is the local depth (m) of water measured from mean water level to the bottom and ζ is the water surface elevation (m) measured upwards from the mean water level), and g is gravitational acceleration ($\mathrm{m\,s^{-2}}$) and ε is a dispersion coefficient ($\mathrm{m^2\,s^{-1}}$).

The two-dimensional convection–diffusion equation integrated over water depth, which assumes vertical mixing, is written as

$$\begin{aligned}\frac{\partial(HS)}{\partial t} + \frac{\partial(HuS)}{\partial x} + \frac{\partial(HvS)}{\partial y} = &\frac{\partial}{\partial x}\left(K_{xx}H\frac{\partial S}{\partial x}\right) + \frac{\partial}{\partial x}\left(K_{xy}H\frac{\partial S}{\partial y}\right)\\ &+ \frac{\partial}{\partial y}\left(K_{yx}H\frac{\partial S}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}H\frac{\partial S}{\partial y}\right) + S_m\end{aligned} \tag{5}$$

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where S is the concentration of dissolved solutes (unit/volume), S_m, a source term; and K, the depth-averaged dispersion–diffusion coefficient ($m^2 s^{-1}$) for orientations x and y.

2.2 Temporal variability in environmental flows

Considering the close relationships between hydrological and biological processes in ecosystems, temporal changes in natural river discharge was selected as an indicator of the temporal variation objectives of environmental flows (Sun et al., 2013).

$$R_i = \sum_{j=1}^{n} W_{ji} / \sum_{j=1}^{n} W_j, \quad (6)$$

where R_i is the ratio (%) of the monthly (or daily) river discharge in month i (or day i) to the annual discharge, W_j, the annual river discharge (m^3) in year j, and W_{ji} is the river discharge (m^3) in month i (or day i) of year j.

After integrating the objectives for ecosystem protection for a particular time of the season that is crucial to reproduction, survival and/or growth of a target species, this process can also quantify the environmental flows to meet the objectives for other seasons.

3 Study area

The Yellow River, the second largest river in China, holds only 2 % of the water resources of the country of China but supplies water for 12 % of the population and irrigates 19 % of the farmland. The gap between water availability and demand has been increasing with the social and economic development that has been occurring in the regions along the River. The Yellow River Estuary is located in eastern Shandong province, west of the Bohai Sea (Fig. 1). The frequency of complete drying or

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ephemeral flow has been rising consistently since the early 1970s. Shortages of freshwater inflows results in severe deterioration of the ecosystem, including severe loss of wetlands, aggravating salinization of soil, decreasing vegetation area, and decreasing fish (by 40 %) and bird (by 30 %) populations in the estuary. Annual fish catches in the Yellow River Estuary and the Bohai Sea were 258, 117, 77.5, and 8.5 $kg\,ha^{-1}$ in 1959, 1982, 1992 and 1998 respectively, which indicated a sharp decline across the 40 yr period. During this forty years period, the nutritional level of fish in the Yellow River Estuary decreased from 4.1 to 3.4 (Zhang, 2005).

Phytoplankton communities were selected as the bio-indicators of ecosystem health of estuaries. And diagnostic pigments were used to indicate characteristics of phytoplankton communities. The dominant phytoplankton groups in the Yellow River estuary are diatoms (about 75 %) and dinoflagellates (about 15 %). These two phytoplankton groups were represented by the diagnostic pigments of fucoxanthin and pyridinin. Phytoplankton community biomass was determined by using the energy flows Eq. (1) based on the fish catches of different decades (Table 1).

Figure 2 shows the CCA relations of environmental factors and diagnostic pigments in different seasons based on field data. Salinity was identified as the critical environmental factors influence diagnostic pigments and empirical relationship between salinity and diagnostic pigments can be determined.

4 Results and discussion

The numerical model for salinity and water depth distributions with changes in river discharge and tidal current was validated with the hydrographic data from different monitoring stations in the estuary (Sun et al., 2012). On the basis of the validated numerical model, the relationships between freshwater inflow and distribution of salinity were established in the Yellow River Estuary. Based on the ecological objectives-characteristics of the diagnostic pigments, the threshold value of environmental flows

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can be calculated for the critical habitats (Fig. 3). Different levels of environmental flow requirements were determined for critical seasons in the estuary (Fig. 4).

The annual environmental flows were obtained based on the temporal variation objectives described by Eq. (6). The maximum, medium and minimum annual environmental flows for the critical habitats were $452.4-476.9\times10^8\,m^3$, $280.2-291.4\times10^8\,m^3$, and $136.4-139.4\times10^8\,m^3$ respectively, which account for 78.0–82.2 %, 48.3–50.2 %, and 23.5–24.0 % of natural runoff.

Comparison between different levels of environmental flows and the recorded river discharges from 1950 to 2000 indicated that the annual river discharge in 87 % ($n = 43$) of years were above the minimum environmental flows. In 57 % ($n = 28$) of years the discharge were greater than the medium environmental flows, and in 29 % ($n = 14$) of years were greater than the maximum environmental flows. Environmental flows cannot be fulfilled after the 1980s, and even less so in the 1990s. After 2000's, actual river discharge rates met the minimum environmental flows except April every year. However, the actual river discharges do not satisfy both the medium and maximum environmental flows (Fig. 5).

Figure 6 shows the comparison between monthly environmental flows and river discharge during wet, average and dry years. In dry years, only minimum environmental flows could be satisfied in the estuary. River inflows should be increased in May and October, which are critical months for fish reproduction and growth during dry years. In contrast, during wet and average years, it is necessary to adjust the temporal variation of river discharges to fulfill temporal variations of environmental flows. In periods from March to May, the environmental flows were significantly influenced by human activities.

The water-sediment regulation of the Yellow River was initiated in 2000. During the regulation the maximum inflow rate at the Lijin station reached $2500–3000\,m^3\,s^{-1}$. A high inflow may change the distribution of environmental factors in the Yellow River Estuary, and then the spatial distribution of phytoplankton. Therefore, the influence of the water-sediment regulation on the threshold values as well as the temporal variation

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of environmental flows needs to be investigated on the basis of the characteristics of phytoplankton communities. For example, in July 2002, the concentration of ammonia nitrogen in the Yellow River Estuary decreased rapidly at the inception of the regulation, then reached a nadir before subsequently returning upward slightly after completion of the regulation (Wang, 2007).

Comparisons between the daily discharge measured in 2005 and the environmental flows indicated that, during the period when the regulation was carried out, the daily discharge generally met the minimum level before the water-sediment regulation (Fig. 7). During the regulation, the discharge increased dramatically to vastly exceed the maximum level, and then decreased rapidly thereafter. After the regulation, the discharge returned to the minimum level. Compatibility with the environmental flows in the estuarine habitats should also be considered in the regulation operation. The discrepancy between the discharge (approximately 3000 $m^3 s^{-1}$) and the environmental flow is particularly large in June and August.

Figure 8 presents a comparison between the recorded monthly discharges and the maximum environmental flows in the estuary. It is indicated that if the regulation is carried out in August, September, or October, the discharges would be below the maximum environmental flows and the peak discharge would not adversely affect the ecosystem status of the estuary. In comparison, intensive regulation of the discharge in June would substantially change the natural river rhythm status and may adversely affect the health and stability of the estuarine ecosystems.

A high river discharge can reduce phytoplankton biomass and impact the stability of ecosystems. Water-sediment regulation in June is not compatible with the natural discharge pattern, cannot satisfy the environmental flows of the habitats. Although, regulation in August is compatible with the pattern of the natural discharge, it still may negatively affect the fishery resources to some extent. To reduce losses in fishery resources, the timing and intensity of peak discharge during artificial hydrological regulation should be appropriately controlled.

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5 Conclusions

We developed an approach to assess environmental flows in estuaries for different requirements of fish biomass related to preference of phytoplankton. The diagnostic pigments were employed to represent phytoplankton community biomass to involve the competition between groups of phytoplankton in the biochemistry process. In the case study of the Yellow River Estuary, Diatoms and dinoflagellates, which were represented by fucoxanthin and pyridinin diagnostic pigments, were identified as the dominant phytoplankton groups. Threshold values of environmental flows in the Yellow River Estuary were determined based on the relationship between ecological processes and hydrological processes. Maximum, medium, and minimum annual environmental flows of natural runoff in the Yellow River Estuary accounted for 78.0–82.2 %, 48.3–50.2 % and 23.5–24.0 % respectively. May and October were identified as critical months for fish reproduction and growth during dry years. Artificial hydrological regulation strategies should carefully consider the temporal variations of natural flow regime. Especially for high-amplitude flood pulse may cause negative effects on phytoplankton groups and higher organism biomass.

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Table 1. Ecological objective in the Yellow River Estuary (of diagnostic pigments).

	Spring			Autumn		
	Maximum	Medium	Minimum	Maximum	Medium	Minimum
Fish Biomass	5006.5–526.2	311.5–56.5	78.6–13.9	965.3–128.1	345.1–58.8	254.3–45.3
Chlorophyll *a* ($10^{-3}\,mg\,L^{-1}$)	12.36–1.30	0.77–0.14	0.19–0.03	2.38–0.32	0.85–0.15	0.63–0.11
Fucoxanthin (logarithm values)	1.83–0.19	−0.19–1.43	−1.19–2.45	0.71–0.94	−0.13–1.58	−0.38–1.79
Pyridinin (logarithm values)	0.699–0.07	−0.073–0.55	−0.46–0.94	0.15–0.20	−0.028–0.34	−0.081–0.38
Salinity	16.9–19.2	22.1–22.3	25.4–27.2	4.2–7.7	8.8–12.6	17.5–19.3

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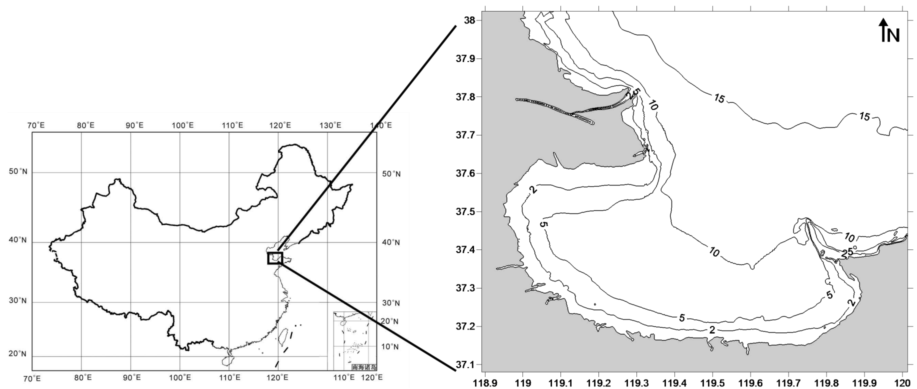

Fig. 1. Yellow River Estuary in China.

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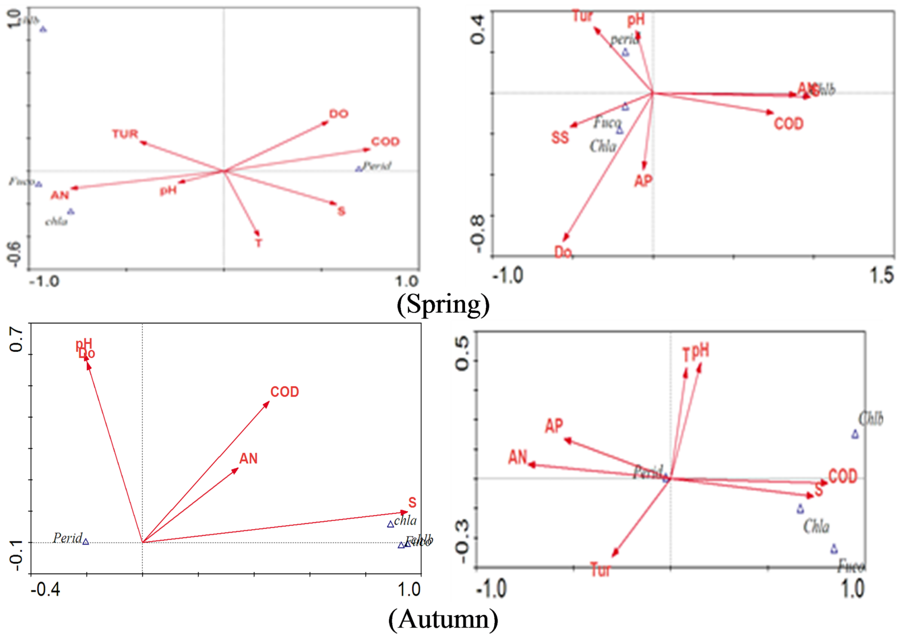

Fig. 2. Environmental factors and diagnostic pigments in two seasons.

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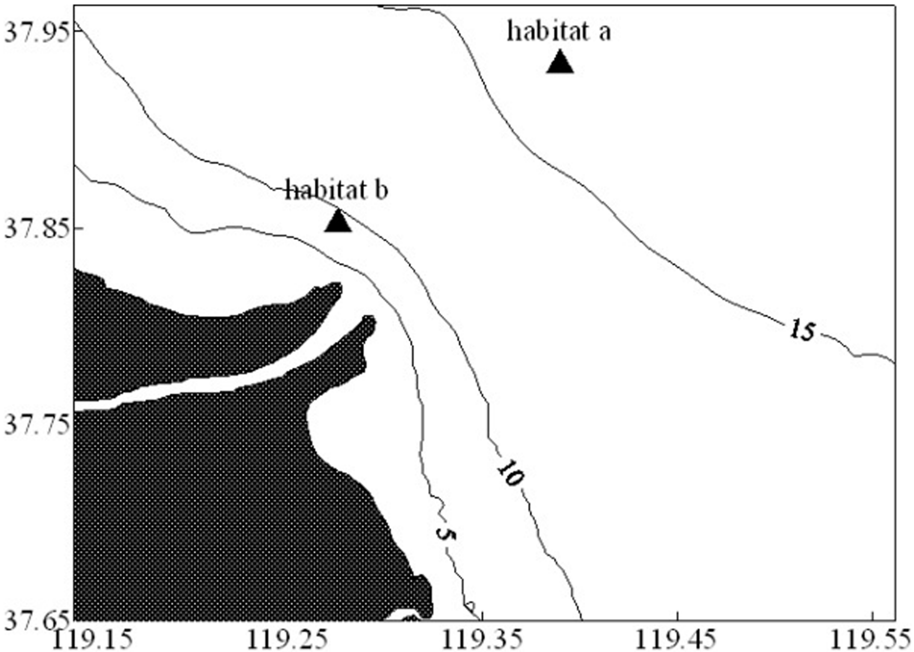

Fig. 3. Critical habitats in the Yellow River Estuary.

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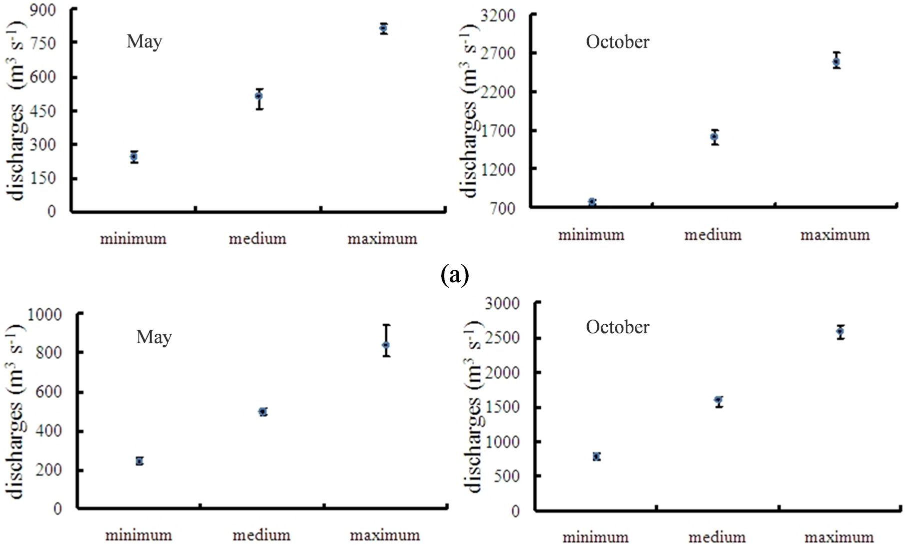

Fig. 4. Environmental flows for critical habitats (Habitat **(a)** and Habitat **(b)**) in different seasons.

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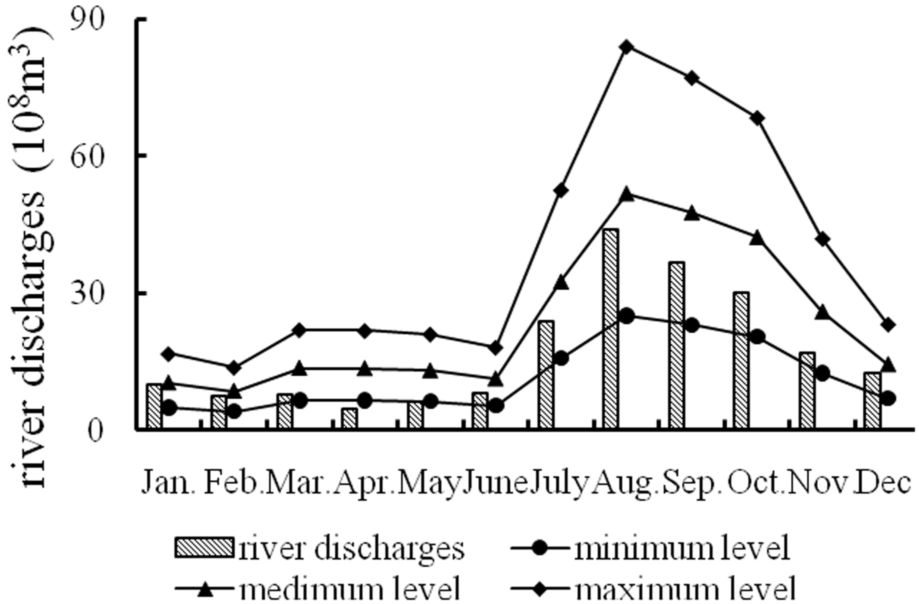

Fig. 5. Temporal variation of environmental flows for critical habitats and actual river water discharges after 1990.

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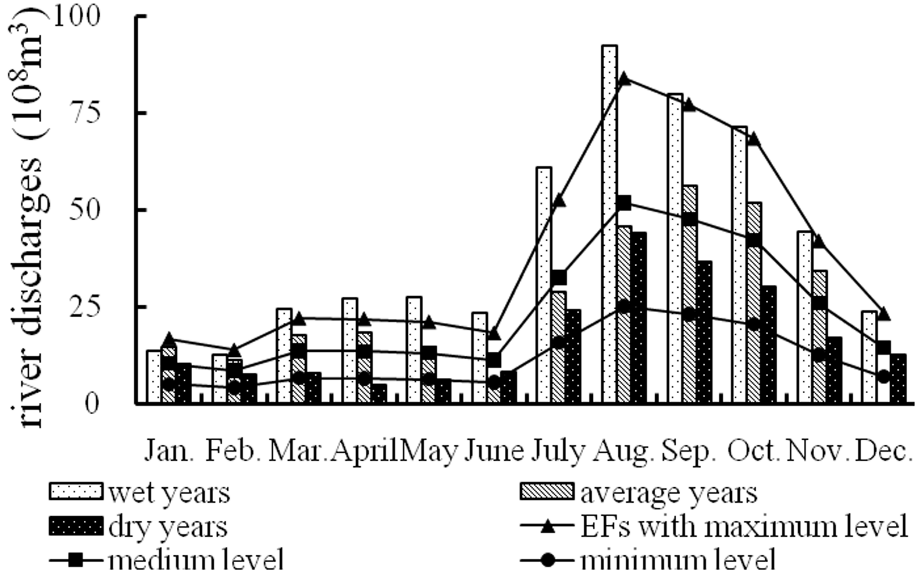

Fig. 6. Monthly environmental flows and river discharges in wet, average and dry years.

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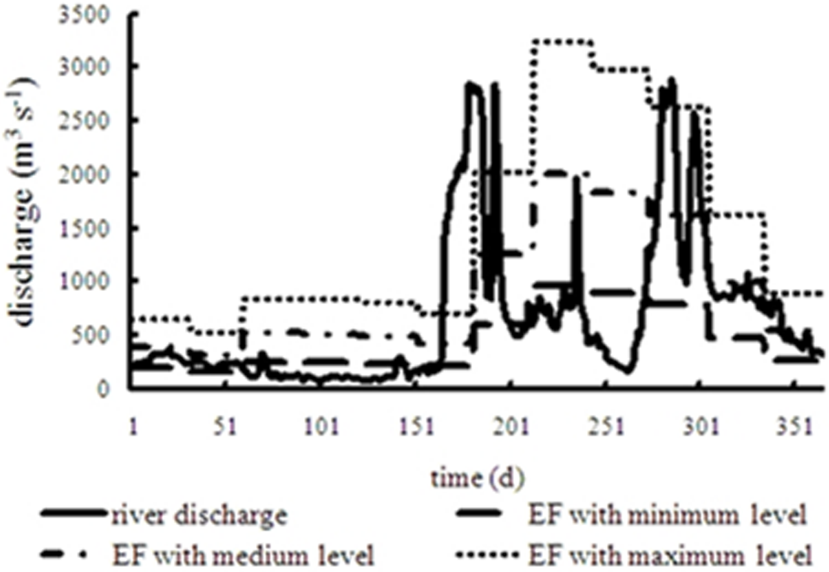

Fig. 7. Comparisons between actual daily discharges and environmental flows in the yellow River Estuary.

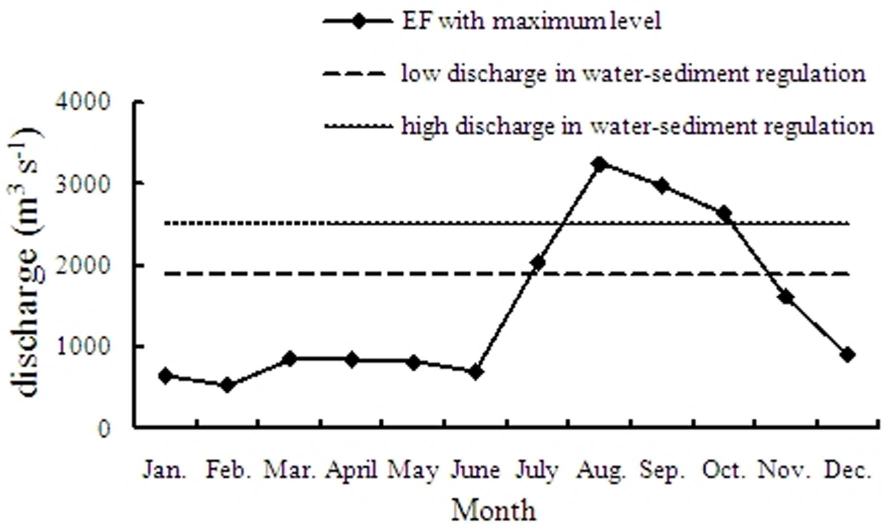

Fig. 8. Comparison of the discharge rate during water-sediment regulation and the maximum monthly environmental flow of the estuarine habitats.

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