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Ecological adaptation as an important factor in environmental flow assessments based on an integrated multi-objective method

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Abstract

An integrated multi-objective method for environmental flow assessments was developed that considered adaptation as a pivotal factor affecting how ecosystems respond to hydrological alterations. Responses of habitat area, and the magnitude of those responses as a result of fluctuations in river discharge, were established. The requirements of typical migrated species during pivotal life-stage seasons (e.g. reproduction and juvenile growth) were integrated into the flow-needs assessment. Critical environmental flows for a typical species were defined based on two primary objectives: (1) high level of habitat area and (2) low variability. After integrating the water requirements for various species with the maximum acceptable discharge boundary, appropriate temporal limits of environmental flows for ecosystems were recommended. The method was applied in the Yellow River Estuary in Eastern Shandong province, China. Our data show that, while recommended environmental flows established with ecological adaptation in mind may not necessarily benefit short-term survival of a typical resident organism on a limited temporal or spatial scale, they may encourage long-term, stable biodiversity and ecosystem health. Thus, short-term ecosystem losses are compensated by significant long-term gains.

1 Introduction

The intense regulation of water resources, including major hydraulic engineering projects, has significantly altered the natural flow of rivers worldwide (Döll et al., 2009). The resulting impacts to environmental gradients and species distribution, as well as the quality and quantity of many ecosystem habitats, have been further aggravated by global climate change (Pyron and Neumann, 2008; Arthington et al., 2010). One of the major challenges for sustainable water resource management and ecosystem protection is the accurate assessment of both available water and the volume that can be withdrawn from an aquatic ecosystem before its ability to meet social, ecological and economic needs significantly declines (Richter, 1997; Sun et al., 2008; McCartney et al., 2009). Environmental flows, also known as instream flows, describe the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human populations that depend on them (The Brisbane Declaration, 2007). Environmental flow assessments have become an important tool for ecosystem restoration, water resource management and reservoir management (Arthington et al., 2006; Vogel et al., 2007; Poff et al., 2009; Yang, 2011; Archer et al., 2010).

In general, hydrological alteration-ecological response relationships have been one of the critical issues considered during environmental flow assessments (Acreman and Dunbar, 2004; Arthington et al., 2006; Poff et al., 2009; Fleenor et al., 2010). Poff et al. (2009) suggested that successful environmental flow assessments require an accurate understanding of the linkages between flow events and biotic responses. To address that need, various empirical models have been developed that describe the relationships between ecosystem parameters (e.g. biomass, communities and biodiversity) and long-term average river discharge (Arthington et al., 2010; Pasztalenieca and Poniewozik, 2010; Clements et al., 2011). For example, a series of relationships between historic monthly inflow and fish catch were utilized in the TxEMP model to arrive at an optimized inflow/harvest relationship (Powell et al., 2002). In contrast with the direct linkages between flow and species and community responses observed in experimental research, habitat simulation models often incorporate preferred, optimal habitat for target species as an intermediate step in addressing environmental flow requirements (Townsend and Padovan, 2009; Sun et al., 2009; Shafroth et al., 2010).

Alteration of hydrological conditions can have either direct effects on habitat conditions and structure, or indirect effects on biological distributions and larger-scale impacts to ecosystems. Species vary in their ability to tolerate or adapt to habitat change, regardless of whether that change occurs due to natural or anthropogenic forces. Some species, for example, may be able to adapt their habitat site selection in response to changes in hydrological processes without significant population effects (Koehn et al., 2011). According to Buzan et al. (2009), floods may have short-term negative consequences for oyster harvesting but play a vital role in ensuring the long-term health of oyster populations. Cissoko et al. (2008) found that a recovery of production rates of freshwater bacteria and viruses will be followed by a sharp decline immediately after seawater addition. As with many biotic and abiotic factors, the impacts of hydrological alterations on any particular species will vary according to the vulnerability of that species and associated habitats (van de Pol et al., 2010). It is important to understand how key abiotic parameters within an ecosystem vary spatially and temporally across the full range of actual or projected hydrological change (Petts, 2009). Inclusion of these data is generally recognized as a key component of an ecological evaluation that must be addressed in environmental flow assessments.

In this study, ecological adaptation was analyzed as part of an environmental flow assessment using an integrated multi-objective method. The relationships between river discharges and adaptive habitats were established, with consideration of modification of habitat area and the degree of flux that occurs over a given period of time. The requirements of various environmental factors for typical species during critical seasons were incorporated into the assessments; preferred temporal variations in environmental flow and its adaptive boundaries were then recommended. The method was applied in the Yellow River Estuary, for which water resource management strategies were proposed.

2 Methodology

Because species vary in their water requirements and tolerance due to different and often conflicting life history strategies, we proposed an integrated multi-objective method to assess the impacts of changing environmental flows, utilizing a two-step process where environmental flow data were integrated for: (1) one typical species and (2) a wider variety of representative taxa.

2.1 Consideration of a typical representative species

Our a priori hypothesis for this evaluation was that species migrating into an area that is being affected by altered water flows may adapt their operable habitat to meet environmental changes but still encompass the ideal environmental factors for that species. The habitat can be accepted by the species only when every key factor falls within the acceptability limits.

As a key ecological factor, habitat area can be considered as an integrated index that represents the intertwined requirements of a variety of environmental factors. When three or more environmental factors are included in the study, the habitat area can be determined as:

$$A = \{A_1 = f_1(S_1) \cap \cdots \cap A_i = f_i(S_i) \cap \cdots \cap A_n = f_n(S_n)\} \tag{1}$$

where A is the required habitat area given various environmental factors, S_i is the environmental factor of number i, A_n is the habitat area under the index S_n, $f_i(S)$ is the relationship between the distribution of environmental factors and habitat area.

For any particular species, the key environmental factors are represented by a range demarcated by minimum and maximum boundaries. An excursion of the particular factor above (excess) or below (deficiency) those boundaries in either a quantitative or qualitative fashion may result in significant population decline or even extirpation from a given geographic area. For highly-specialized, localized populations, demonstrable deviations could lead to species extinction. As shown in Eq. (1), habitat area and variability associated with species survival can be defined to simultaneously meet the requirements posed by different ecological factors.

The presence of suitable habitat is driven by the distribution of favorable environmental factors, which vary with changes in river flow. The relationship between environmental factor distributions and flow regime can be established using a numerical model that simulates the spatial and temporal distributions of selected environmental factors:

$$S_i = g(Q) \tag{2}$$

where Q is the river discharge into the ecosystem, S_i is the distribution of environmental factors and $g(Q)$ is the relationship between ecological processes and flow regime. We established a numerical model that simulates the spatial and temporal distribution 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:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}(Hu) + \frac{\partial}{\partial y}(Hv) = 0 \tag{3}$$

$$\frac{\partial u}{\partial t} + \frac{\partial uu}{\partial x} + \frac{\partial vu}{\partial y} = fv + g\frac{\partial \zeta}{\partial x} + g\frac{u\sqrt{u^2+v^2}}{HC^2} + \frac{\partial}{\partial x}\left(\varepsilon\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon\frac{\partial u}{\partial y}\right) \tag{4a}$$

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

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:

$$\frac{\partial(HS)}{\partial t} + \frac{\partial(HuS)}{\partial x} + \frac{\partial(HvS)}{\partial y} = \frac{\partial}{\partial x}\left(K_{xx}H\frac{\partial S}{\partial x}\right) + \frac{\partial}{\partial x}\left(K_{xy}H\frac{\partial S}{\partial y}\right) + \frac{\partial}{\partial y}\left(K_{yx}H\frac{\partial S}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}H\frac{\partial S}{\partial y}\right) + S_\mathrm{m} \tag{5}$$

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

Suitable habitats are determined by distribution of critical environmental factors. The spatial extent of a habitat (total area as well as geographic orientation) may also change with hydrological processes. Consequently, species may adapt to changing ecological conditions by shifting their usable habitat.

2.2 Consideration of multiple species

Variations in the temporal and spatial distribution patterns of different species will cause incremental overlap, resulting in nearly identical, to highly disparate, water requirements. Consequently, what is suitable, or even preferential, for one species, is likely to be unacceptable for one or more other species. At the same time, biodiversity within an ecosystem generally corresponds to variations in river discharge, suggesting that fluctuations in river discharge may actually enhance and maintain ecosystem biodiversity. When considering ecosystem biodiversity health on a holistic basis, therefore, the recommended environmental flow for any given ecosystem is that which falls within the upper and lower tolerance thresholds, obtained by integrating the minimum and maximum water requirements of the keystone species:

$$E_\mathrm{min} = \mathrm{Min}(W_{1,\mathrm{min}}, \cdots, W_{j,\mathrm{min}}, \cdots, W_{n,\mathrm{min}}) \tag{6}$$

$$E_\mathrm{max} = \mathrm{Max}(W_{1,\mathrm{max}}, \cdots, W_{j,\mathrm{max}}, \cdots, W_{n,\mathrm{max}}) \tag{7}$$

where E_min and E_max are the minimum and maximum environmental flows, respectively, allowing for maintenance of an aquatic ecosystem, $W_{j,\mathrm{min}}$ and $W_{j,\mathrm{max}}$ is the minimum and maximum environmental flows, respectively, for habitat j, n is the number of species considered in the study, $\mathrm{Min}(a,b)$ and $\mathrm{Max}(a,b)$ are the minimum and maximum values, respectively, between a and b.

3 Study area

The Yellow River Estuary is located in Eastern Shandong province, west of the Bohai Sea (Fig. 1). With abundant freshwater and nutrient inputs, the Yellow River Estuary provides critical habitats for many ecologically and commercially important species (Dong et al., 2007).

Freshwater inflows in the Yellow River Estuary have decreased for several decades. The frequency of complete drying or ephemeral flow has been rising consistently since the early 1970s. In the early 1990s, the estuary experienced complete drying each year, with an average of 100 $\mathrm{d\,yr^{-1}}$ without water in the lower reaches. Reduction in freshwater inflows to estuaries causes a concurrent decrease in available aquatic habitat which, in turn, has negative consequences for many aquatic species (Attrill et al., 1996). In the Yellow River Estuary and the Bohai Sea, the species number, density, and biomass dropped by 38.7 %, 35.5 %, and 46.0 %, respectively, from 1982/1983 to 1992/1993 (Zhu and Tang, 2002; Fan and Huang, 2008).

Estuarine species tend to be euryhaline, although the ability to tolerate a wide range of salinities may not be equal in all life stages. Egg laying and maturation, as well as juvenile growth may need to occur in an environment that remains within a narrower salinity range. Maintaining a reasonable salinity balance is an essential environmental flow requirement for the Yellow River Estuary. Since recruitment strength, and therefore the future population, is mainly driven by the success of spawning events and the survival of young, understanding how the flow regime influences the early life history of species is critical to maintaining ecosystem health. Habitats that are utilized during the breeding and growth periods for typical species are usually located at shallow estuarine depths. Various studies have indicated that the acceptable depth and salinity requirements for these life stages vary by species (Table 1).

Four species were selected as keystone organisms for the evaluation of essential environmental flows on a wider, multi-species scale: Chinese shrimp (*Penaeus chinensis* larvae), Ridgepail prawn (*E. carinicauda*), Crab (*Eriocheir sinensis* Milne-Edwards) and Jellyfish (*Rhopilema esculenta* Kishinouye). These invertebrate species are functionally and economically different, but all depend on the estuary for completion of key life history events, including spawning and early life stage development.

It is not possible to identify every indicator or objective of ecosystem processes, particularly given the different spatial and temporal scales at which those processes are manifested. However, given the objectives of this study and the close relationships that are known to exist between hydrological and biological processes, temporal variation in natural river discharge was selected as an indicator of the temporal variation objectives of environmental flows. The temporal variation in objectives is expressed as the ratio of the monthly or daily river discharge to the annual discharge. Figure 2 illustrates the temporal variation in the monthly natural river discharge of the Yellow River Estuary. The average ratio of the temporal distribution of natural river discharges in the 1960s, 1970s, 1980s, and 1990s at the Lijin Station was considered to be representative of temporal variation in water availability.

4 Results

The relationships between variations in freshwater inflows and habitat areas for different species were established (Fig. 3). The numerical model for salinity and water depth distributions with changes in river discharge was validated with the hydrographic data from different monitoring stations in the Estuary (Sun et al., 2012). The finite-difference method was used to solve the partial differential equations.

There are no stable relationships between river discharge and average habitat area when river discharge is less than 500 $m^3 s^{-1}$. When river discharge rises to about 1000 $m^3 s^{-1}$, maximum habitat area can be derived for several different species, including those considered in this study. Habitat area remained relatively stable when river discharge exceeded 1000 $m^3 s^{-1}$; and tended to decrease above 2500 $m^3 s^{-1}$ (Fig. 4).

Changes in habitat area were driven by the combined influence of river flows and tidal currents.

It is reasonable to assume that a large habitat area and dampened variability of the key habitat parameter (e.g. water availability) would yield a more ideal environment for breeding and/or growth of any given species. For Chinese shrimp, there was a trend of increasing amplitude in habitat variability with increasing river discharge (Fig. 4). Therefore, given the goal of maintaining high habitat area, suitable river discharge for the Chinese shrimp is between 750 $m^3 s^{-1}$ and 2500 $m^3 s^{-1}$. Available habitat area is likely to decrease when discharge exceeds 2500 $m^3 s^{-1}$, where the energy of the discharge is sufficiently high to exacerbate erosion, negatively impact salinity, and result in water depths that are not conducive to shrimp survival and reproduction. Similarly for the crab, our data suggest that greater habitat area with low variability occurs when river discharge fluctuates between 750 $m^3 s^{-1}$ and 2000 $m^3 s^{-1}$.

The range of preferable environmental flows for the Chinese shrimp are the widest of any of the species studied, both in terms of discharge during critical seasons and annual volume in the Yellow River Estuary (Table 2). Based on the temporal changes in environmental flow variation objectives that occur over the course of a year (shown in Fig. 2), the acceptable annual environmental flows, which are different for different species, can be determined. These data were used to develop the integrated model of minimum and maximum flows, which is illustrated in Fig. 5. The delta between the upper and lower lines represents the range which is allowable in any particular month. Differences in flow requirements are driven primarily by the different ecological needs of each species at various stages in their life history.

When all of the studied species are considered, 25 % and 112 % of the average annual river discharge were defined as the environmental flow boundaries, which were set according to the minimum requirements of the Crab and maximum requirements of the Jellyfish. Establishing these quantitative boundaries is critical to the environmental flows assessment process, as they provide for the integration of different ecosystem objectives, and goals by which management success can be measured. By meeting these goals, biodiversity is encouraged and maintained within the ecosystem.

5 Discussion

In the Yellow River, dam construction, along with the corresponding regulation of hydraulic conditions, was intended to prevent disastrous floods and to withdraw water for crop irrigation and improving agricultural production. To provide a comparison of measured, historical flows with recommended environmental flows, data from six years (1956, 1962, 1971, 1982, 1995 and 2005) were selected that closely reflect the average river discharge over the corresponding decade (Fig. 6).

In 1956, monthly river discharges were greater than the maximum level of the environmental flows in February, June and July. In 1965, river discharges fluctuated within the range of the recommended environmental flows, except during the winter (December and January). In 1971, river discharge fell below the minimum environmental flow in June, and exceeded the maximum water requirement in November; other months were within the range of acceptable flows.

With the development of agriculture and industry in the Yellow River basin, water withdrawal for irrigation has grown at an increasing rate since the 1980s in the upstream area of the Yellow River Estuary. In 1982, river discharges dropped below the minimum required flows from April to June, which was directly related to irrigation withdrawals during this critical period in the upstream area of the estuary. Because of hydraulic regulation by dams for flood control in the upstream region, river discharge rose sharply in August. In the 1990s, with a climb in water demand for economic growth, freshwater inflows in the estuary were mainly concentrated in the flood periods in August and September. In 1995, river discharge met the minimum water requirements only in the winter (December and January) and summer (August to September).

In order to reduce or eliminate the occurrence of zero or ephemeral flow, the Yellow River Water Conservancy Committee has conducted the “water and sediment regulation” in June for the Yellow River Basin since 1999. In contrast to the situation in 1995, river discharge in the month of June has exceeded minimum water requirements each year since 2001 in the Yellow River basin. However, not even the minimum water requirements have been met during other periods.

While use of average river discharge is typical in environmental flow assessments, variability in flow should also be considered. In the 1950s, river discharge volumes exceeded the recommended boundaries for environmental flows in the summer (July to August) and winter (December and January) (Fig. 7). However, in the 2000s, fluctuations in monthly river discharges were much more substantial, frequently falling above and more often, below, recommended environmental flows. The most dramatic swings in discharge rates occurred in June and July, resulting in the maximum volume amplitude during this period of time. Although maximum river discharge that occurred during the summer season could fulfil the maximum water requirements, the minimum river discharges fell short of the minimum requirements.

The response time frame of habitat conditions to different river discharge scenarios is not instantaneous; there is always a delay in the effects to associated habitat and, subsequently, to the organisms that utilize those habitats. The impacts of river discharge excursions on available habitat also do not occur in isolation, but impose cumulative effects on the system, species, communities and ecosystems much more vulnerable to hydrological alteration. Figure 8 shows fluctuations in habitat area for typical species under a scenario of continuously-varying river discharge.

In the Yellow River Estuary, changes in habitat area lagged behind the freshwater inflow variations by $5 \sim 7$ d during the high amplitude flood pulses. The cumulative effects on habitat area do not occur linearly with the hydrological processes.

In general, the calculated environmental flows for typical species, based on ideal habitat objectives for that species, are often unsatisfactory for a broader array of organisms, making achievement of a holistic strategy for protection of the aquatic ecosystem difficult to construct. When environmental flows are established that encompass the requirements of a variety of typical habitats, those conditions may not be preferable for several species, or favourable for short-term survival for some organisms. However, the adaptability of populations over time may result in sustainable diversity and improved aquatic ecosystems health on extended spatial and temporal scales. In the presence of short-term tolerance and long-term adaptability of many aquatic and semi-aquatic species, it is possible to establish a wider range of acceptable environmental flows by integrating a diversity of environmental factors.

It is important to remember that the relationship between habitat area and hydrological alteration may be significantly impacted by additional environmental factors such as water temperature, velocity, total suspended and dissolved solids and others. These factors can also impact available habitat area and quality. Recommended environmental flows are also likely to require adjustment when additional species are included in the assessments. To overcome these uncertainties, data from long-term field studies are critical (Adams et al., 2002; Poff et al., 2003; Schreiber et al., 2004; Richter et al., 2006), as are adaptive management strategies for the implementation and adjustment of environmental flow regimes (Gregory et al., 2006; King et al., 2010).

6 Conclusions

Ecological adaptation in environmental flow assessments was analyzed using an integrated multi-objective method. A favourable adaptable relationship was established between ecological responses and freshwater inflow fluctuations that considered the adaptive positions of the critical habitats following incorporation of the requirements of various environmental factors. Whereas historical flow assessments may have only considered average river discharge, the overall amplitude of change over a given time period must also be considered in environmental flow assessments. The study objectives were a high level of habitat area and low environmental variability. After integrating the water requirements for various species, acceptable environmental flows for ecosystems over a given temporal range could be recommended.

Although environmental flows can be recommended that encompass a range of conditions under which populations can survive and ultimately adapt, ecological adaptation itself may increase the complexity and uncertainty in an environmental flow assessment. Valuable information can be derived from additional research focusing on ecosystem response to hydrological alterations under various time and spatial scales. Although the proposed methodology was applied in an estuary, the principle and approaches used to incorporate ecological adaptation can also be applied in other types of aquatic ecosystems.

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Table 1. Habitat requirements for four key indicator species in the Yellow River Estuary.

Indicator species	Salinity Minimum	Salinity Maximum	Water depth (m) Minimum	Water depth (m) Maximum	Critical periods	References
Chinese shrimp	8.77	29	1	6	Jun–Jul	Hu and Lu (1990) Zhang et al. (1998)
Ridgepail prawn	9	28	1.5	10	Oct	Deng et al. (1990) Wang and Cao (2010)
Crab	6	27	7	15	Oct	Xue et al. (1997)
Jellyfish	8	30	5	15	Apr–May	Song et al. (2009) Zhao et al. (2006) Lu et al. (1989)

Table 2. Environmental flows in the Yellow River Estuary.

Indicator organism	Environmental flows in critical seasons ($m^3 s^{-1}$)		Annual environmental flows ($10^9 m^3$)	
	Minimum	Maximum	Minimum	Maximum
Chinese Shrimp	750	2500	18.5	61.6
Ridgepail Prawn	1000	2000	19.7	39.4
Crab	750	2000	14.8	39.4
Jellyfish	1000	2000	32.4	64.8

Note: critical seasons include those when reproductive and key juvenile growth periods occur.

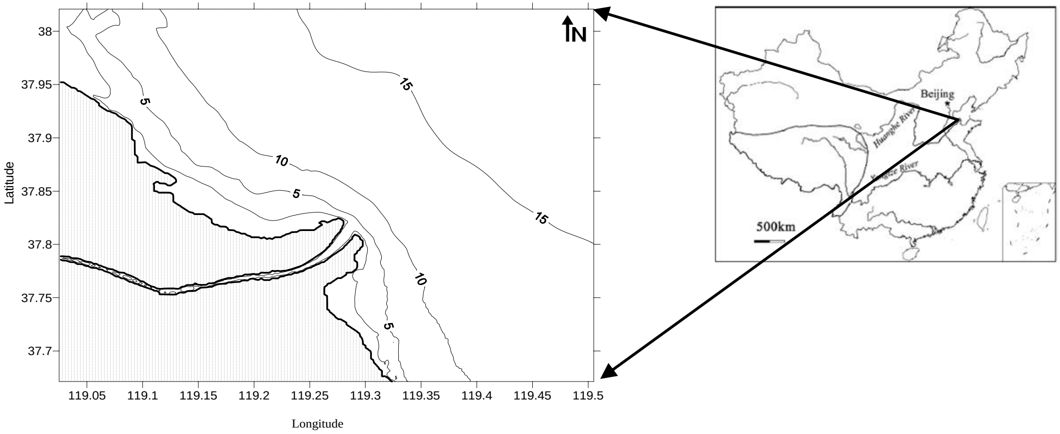

Fig. 1. Location of the Yellow River Estuary.

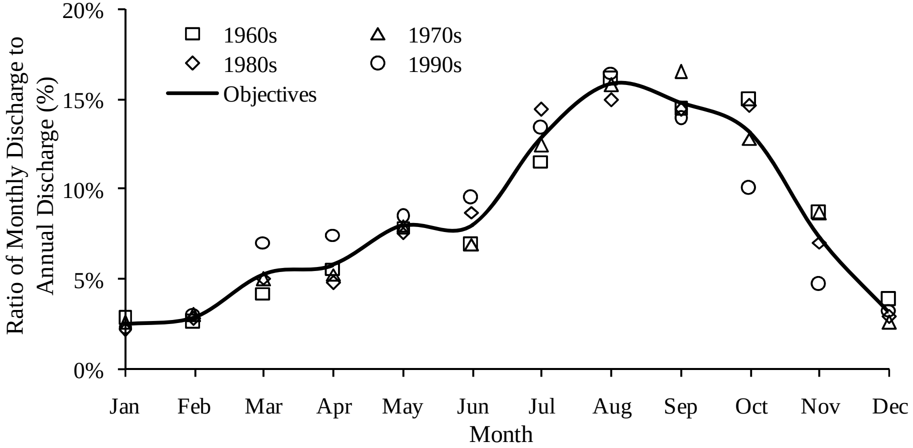

Fig. 2. Temporal variation objectives for environmental flows in the Yellow River Estuary. Each point represents the average flow during the indicated decade.

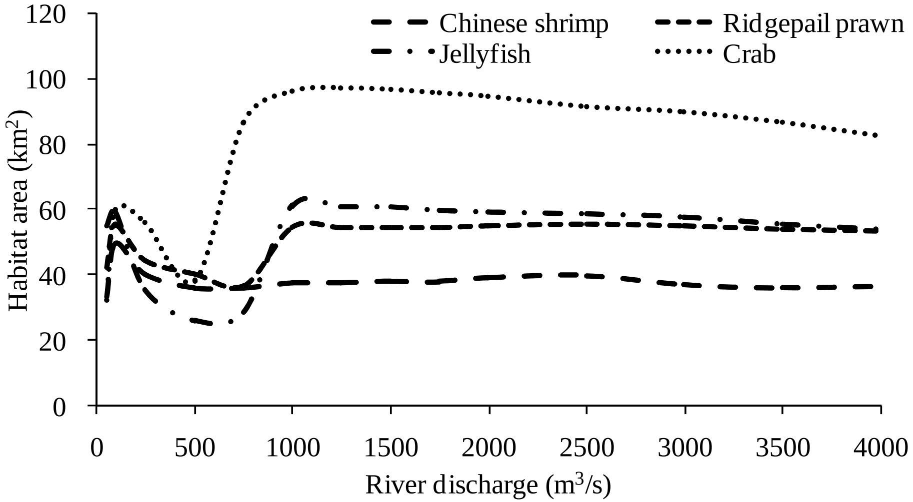

Fig. 3. Relationship between river discharge and habitat area for typical species.

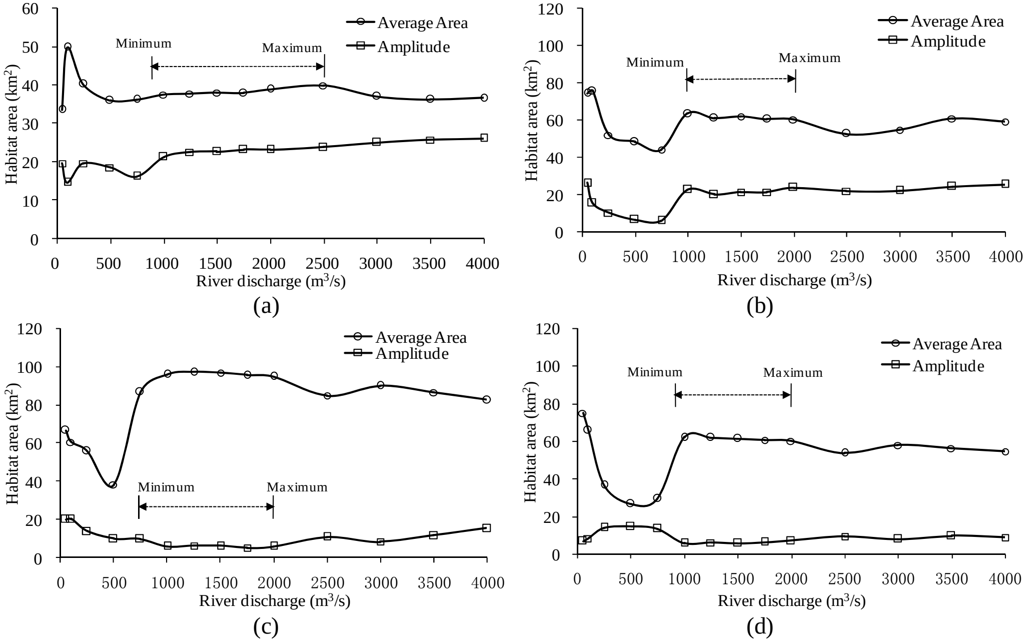

Fig. 4. Changes in habitat area with changes in freshwater inflows. **(a)** Chinese shrimp; **(b)** ridgepail prawn; **(c)** crab; **(d)** jellyfish.

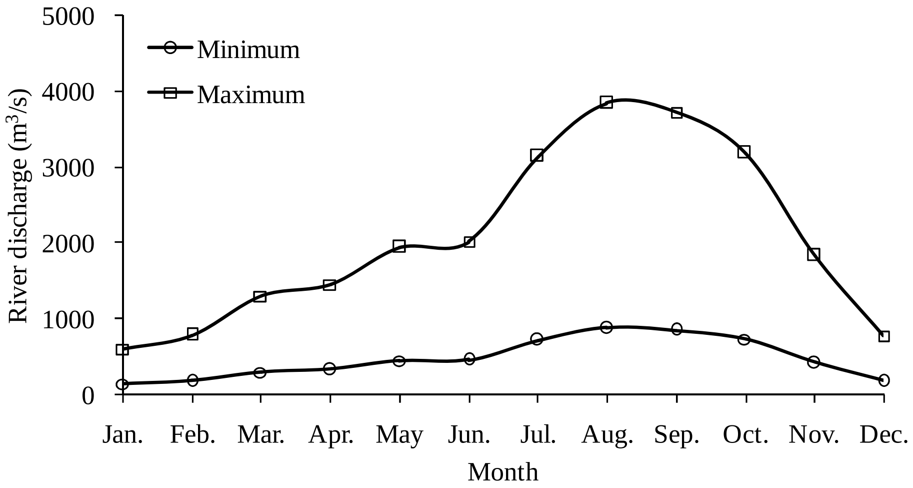

Fig. 5. Acceptable environmental flows in the Yellow River Estuary, calculated through the integration of multiple species needs.

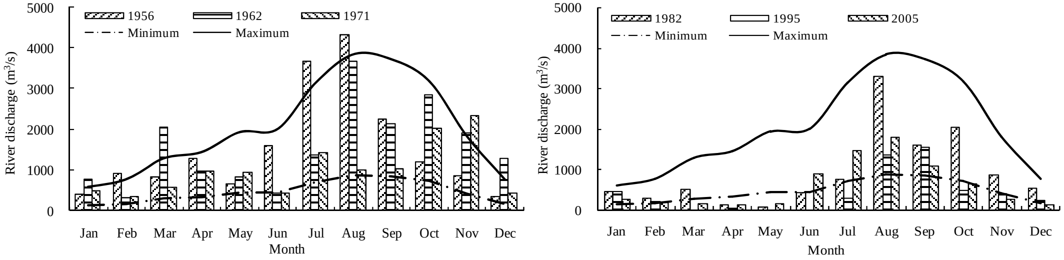

Fig. 6. Monthly river discharge during a typical year and the associated environmental flows boundary in the Yellow River Estuary.

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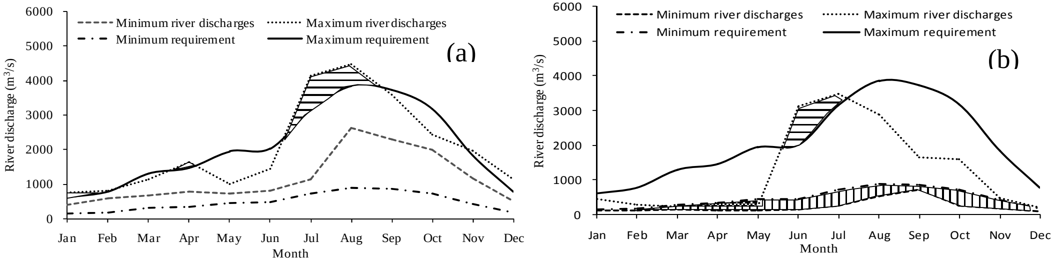
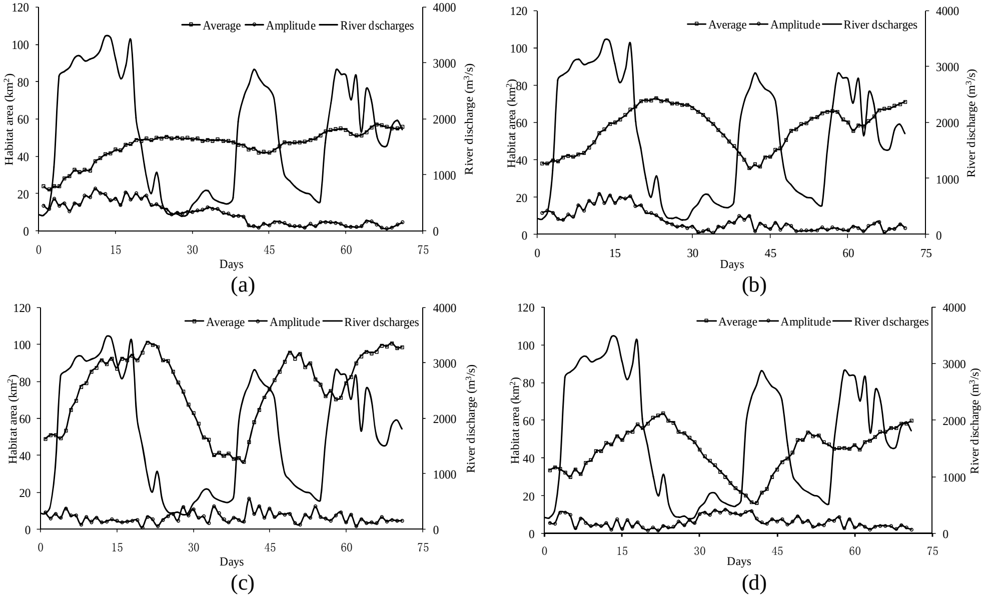


Fig. 7. Changes in monthly river discharge and the associated environmental flows boundary in **(a)** the 1950s and **(b)** the 2000s.



(a) (b)

(c) (d)

Fig. 8. Variations of habitat area with changes in river discharge. **(a)** Chinese shrimp; **(b)** Ridge-pail prawn; **(c)** Crab; **(d)** Jellyfish.