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Numerical modeling of the salinity distribution and environmental flows assessment in the Yellow River Estuary, China

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Abstract: Predication of environmental flows is a critical issue in water resources management integrated with ecological considerations. It is also a complex issue due to the relationship between ecological and hydrological processes with different temporal and spatial scales in estuarine ecosystems. The salinity gradient is a basic characteristic for an estuary ecosystem, which is largely affected by the alteration of freshwater inflows because of human activities. In this paper, a numerical model was developed for simulating the salinity distribution under the action of river discharge and tide current in the Yellow River Estuary. Environmental flow requirements were determined for critical periods in the Yellow River Estuary after identifying the salinity objectives for ecosystem health, and the salinity variability within sensitive habitats in response to fresh water inflow changes. The temporal variation of the environmental flows was determined using average monthly natural river discharge. The impacts of freshwater inflow alteration were assessed based on the comparison between different environmental flows and river discharges. It is concluded that the minimum annual environmental flow requirements can be fulfilled by river discharge under the action of water and sediment regulation since 2001. River discharge can meet environmental flow requirements in June, however, it cannot meet the medium even the minimum water requirements in other periods of time.
Key words: Environmental flow; Numerical modeling; Salinity gradient; Yellow River Estuary

1. Introduction

Environmental flows describe the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems (Brisbane Declaration, 2007). Different management approaches have been implemented in many countries to protect the environmental flows for estuaries. Based on the relationship between inflow and salinity, a rule called X2 (based on the distance from the Golden Gate Bridge to the 2 ppt isohaline) was established to identify the salinity ranges required by various natural resources in San Francisco Bay (Kimmerer, 2000). Successful environmental flow prescriptions require an accurate understanding of the linkages among flow events, and biotic responses. Due to a lack of data for describing eco-hydrological process in estuaries, numerical models are recommended to predict ecological responses to different managed flow scenarios, evaluate alternatives, guide implementation and inform adaptive management (Sun et al., 2009; Shafroth et al., 2010). However, numerical models for environmental flows assessment became more complicated in order to describe the complex flow alteration-ecological response relationships and their temporal and spatial scales variability in estuarine ecosystems, which limits their applications in water resources management (National Research Council of the National Academies, 2008). Identifying key aspects of the physical process and critical requirements for ecosystems become important for understanding complex flow alteration-ecological response relationship in am estuary.

Considering the temporal and spatial scale differences in eco-hydrological processes in estuaries, target salinities for the spawning habitat of Chinese shrimp (*Penaeus chinensis*) and river discharge were identified to be critical ecological objectives for ecosystem health in the Yellow River Estuary. In this paper, the relationship between salinity objectives and freshwater inflows was established based on the numerical modeling of salinity distribution in the Yellow River Estuary. Environmental flow requirements were proposed for the water sources management of the Yellow River Estuary.

2. Ecological objectives for environmental flows in the Yellow River Estuary

The Yellow River is the second largest river in China and the sixth largest river in the world. The Yellow River Estuary is located in eastern Shandong province, west of the Bohai Sea (Figure 1). Many important fishery species spend their whole or part of early life in the Yellow River Estuary. However, the frequency of complete drying or ephemeral flow has been increasing in the Yellow River since the early 1970s. In the early 1990s, drying took place annually, with an average of 100 days per year without water in the lower reaches. The mean annual penaeid shrimp catches in the Bohai Sea in autumn flood seasons decreased greatly in the past three decades.

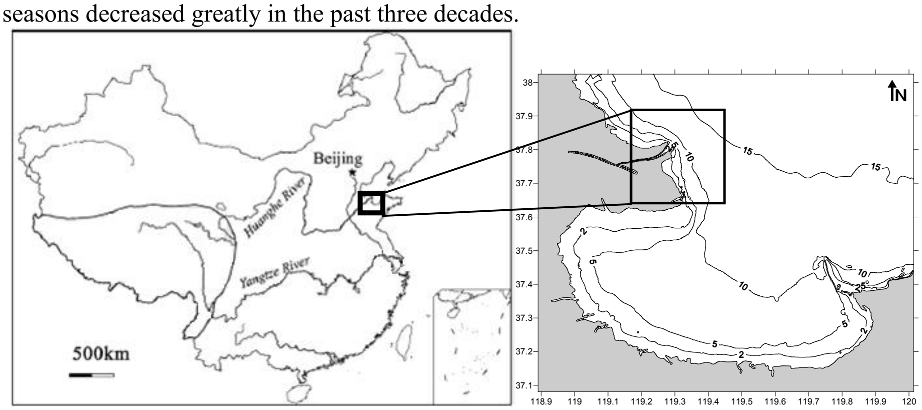


Fig.1 Yellow River Estuary in China

As an important spawning site and habitat for Chinese shrimp, the Yellow River Estuary was selected as a site for experimental releases of this shrimp in China. As shown in Table 1, the salinity requirements for this shrimp during the spawning season (Zhang, 1992), from May to June, were selected as ecological objectives for determining the environmental flows.

Table 1 Ecological objective for critical habitat and periods in the Yellow River Estuary

Indicator Species	Water Depth (m)	Critical Periods	Salinity
Acetes Chinensis	0.8-5.0		17-(21.18)-30
Chinese shrimp	1.0-5.0	June-July	8.77-25.8

In order to maintain a natural flow regime in an ecosystem (Poff, 2009), a monthly variation of natural river discharge was chosen as an indicator of the temporal variation objectives of environmental flows. The temporal variation is expressed as the ratio of the monthly river discharge to the annual discharge:

$$R_i = \sum_{j=1}^{n} W_{ji} \Big/ \sum_{j=1}^{n} W_j \tag{1}$$

Where R_i is the ratio (%) of the monthly river discharge in month i to the annual discharge, W_j is the annual river discharge (m^3) in year j, and W_{ji} is the river discharge (m^3) in month i of year j. Temporal variation in the natural river discharge of the Yellow River Estuary is shown in Figure 2.

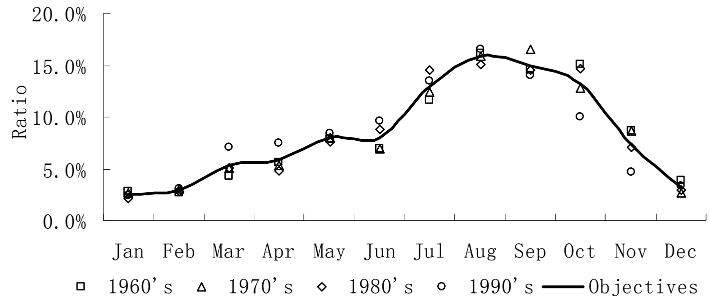


Fig. 2 Temporal variation objectives for environmental flows in the Yellow River Estuary

Based on the salinity objectives of the critical habitat during the critical periods in Table 1, and the temporal variation objectives in Figure 2, the spatial and temporal scale variability could be considered in the assessment of environmental flows.

3. Relationship between salinity and river flows

The relationship between ecological processes and flow regime can be determined using a numerical model that simulates the spatial and temporal distribution of salinity as a combined function of the river discharge and tidal currents. The depth-integrated equations for conservation of motion and water are written as:

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

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

$$\frac{\partial u}{\partial t}+\frac{\partial uv}{\partial x}+\frac{\partial vv}{\partial y}=fu+g\frac{\partial \zeta}{\partial y}+g\frac{v\sqrt{u^2+v^2}}{HC^2}+\frac{\partial}{\partial x}\left(\varepsilon\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon\frac{\partial v}{\partial y}\right) \tag{3b}$$

Where t is time (s); u and v are current velocities (m/s) in the x and y directions, respectively; f is the Coriolis factor; C is the Chezy coefficient ($m^{1/2}/s$); H is the total depth (m) of the water from the water surface to the bottom; and g is gravitational acceleration (m/s^2). ε is a dispersion coefficient (m^2/s).
The two-dimensional convection–diffusion equation integrated over water depth, which assumes vertically mixed, is written as:

$$\frac{\partial(HS)}{\partial t}+\frac{\partial(HuS)}{\partial x}+\frac{\partial(HvS)}{\partial y}=\frac{\partial}{\partial x}\left(K_{xx}H\frac{\partial S}{\partial x}\right)+\frac{\partial}{\partial x}\left(K_{xy}H\frac{\partial S}{\partial y}\right)+\frac{\partial}{\partial y}\left(K_{yx}H\frac{\partial S}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}H\frac{\partial S}{\partial y}\right)+S_m \tag{4}$$

Where S is the concentration of dissolved solutes (unit/volume); S_m is a source term; K is the depth-averaged dispersion–diffusion coefficient (m^2/s).
The numerical model was applied to establish the relationship between salinity distribution and river discharges. The length of the spatial step used in the calculation was $\Delta x=\Delta y$ =200 m and the time step was Δt = 10 s. The numerical model was validated using hydrographic data obtained from 25 to 26 August, 2003, and the recorded river discharge was 187 m^3/s at the station in upstream of the Yellow River Estuary (Shi, 2008). Figure 3 shows different stations located in the Yellow River Estuary.

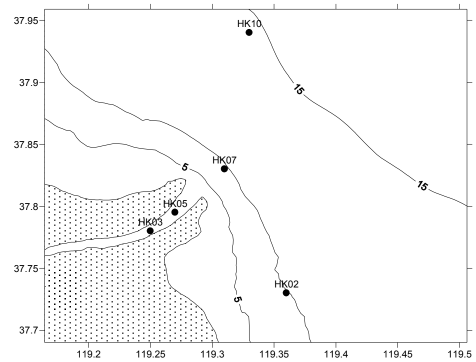
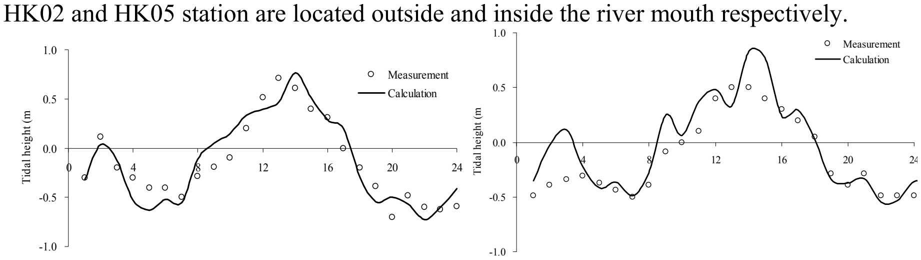


Fig. 3 Locations of the measurement stations in the Yellow River Estuary

The observed and modeled data of tidal heights at different stations are compared in Fig. 4. HK02 and HK05 station are located outside and inside the river mouth respectively.



HK02 HK05

Fig. 4 Observed tidal heights and calculated values at different stations

Figure 5 shows the comparison between measured and calculated salinity at different stations in the Yellow River Estuary.

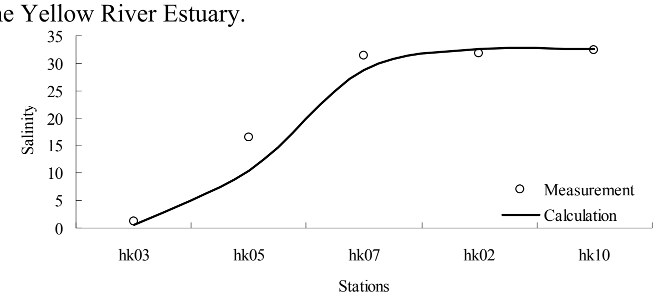


Fig. 5 Calculated and observed salinity at different stations in the Yellow River Estuary

The differences between the observed and predicted results at HK05 station were partly due to the complex mixing of fresh water and salt water and complicated topography around the river mouth. In order to get a more accurate result, additional research on numerical model will be needed to refine the numerical results in these areas.

4. Results and discussions

Based on the validated numerical model, the relationship between salinity in critical habitat and river discharges was established in the Yellow River Estuary (Fig.6). Freshwater inflows range from 200 m^3/s to 3000 m^3/s in different scenarios in the calculation.

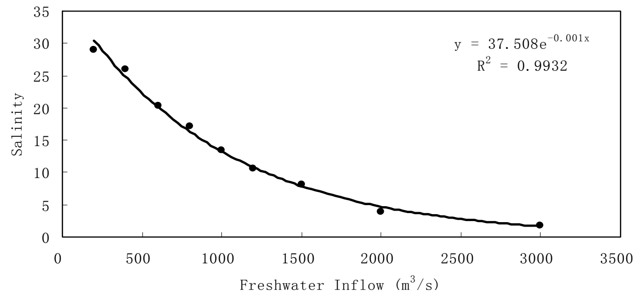


Fig.6 Relationship between salinity in critical habitat and freshwater inflows

Considering the relationship between salinity and freshwater inflows shown in Figure 6 and ecological objectives in Table 1and Figure 2, temporal variation of environmental flows can be evaluated in order to meet salinity objectives in the Yellow River Estuary. Fig. 7 shows the annual river discharge and different levels of environmental flow requirements in the Yellow River Estuary. Different levels of environmental flows were determined based on different salinity objectives listed in Table1.

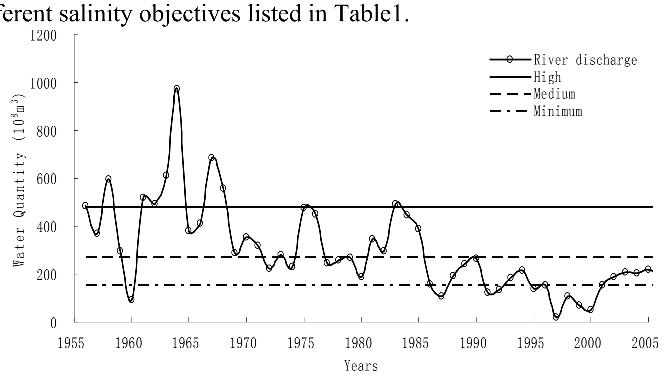


Fig.7 Comparison between river discharge and environmental flows

In the last 40 years, water utilization for agriculture, industry and municipalities has increased about 68.01%. As a result, river discharge has decreased and, in the past 20 years, has actually fallen below the projected minimum environmental flow levels (Fig. 7). In order to alleviate the conflict between increasing water demands and water shortages in the Lower Yellow River, the unified water resources regulation was applied to the Yellow River Basin in 2001.

The seasonal flow regime has been modified by water resources utilization for humans. Given the temporal variation objectives, 16% of the annual environmental flows should be maintained during May to June and August; and 13% of the annual environmental flows should be maintained in October. It is found that river discharge in 1956 and 1962 could meet medium level of water requirements (Fig. 8).

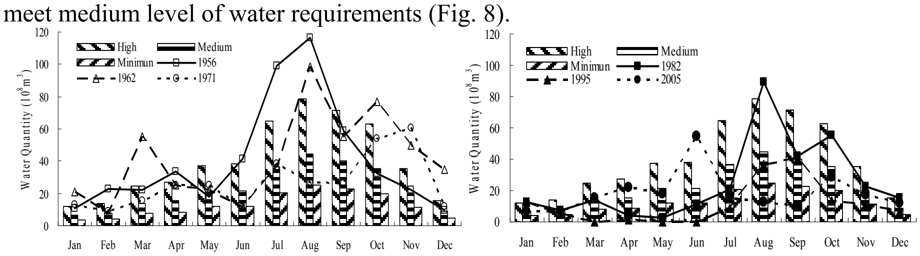


Fig. 8 Temporal variation of environmental flows and river discharge

In the 1970's and 1980's, the greatest discrepancies occurred in May and July, which was caused by water utilization for irrigation. In the 1990's, with increased requirements for different objectives such as agriculture and industry, freshwater inflow in the estuary was mainly focused on the periods of flood in August. After 2001, the maximum river discharge occurred in June because of water and sediment regulation. In 1996 and 2005, river discharge met the high level of environmental flow requirements in August and June, however, it cannot fulfill even the minimum water requirements in other periods.

5. Conclusions

An approach for environmental flow assessment was developed considering spatial and temporal scale differences of eco-hydrological processes in an estuary. The relationship between the ecosystem and river flows in the Yellow River Estuary was established by numerical modeling of salinity distribution in the Yellow River Estuary. And then, temporal variation of environmental flows could be determined considering the salinity objectives in critical periods and temporal variation objectives of river flows in the Yellow River estuary. It is concluded that the minimum annual environmental flow requirements can be fulfilled by river discharge using water and sediment regulations in force since 2001. River discharge can meet environmental flow requirements in June, but it cannot fulfill the medium even the minimum water requirements in other periods.

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