Environmental flow assessment in the Lower Yellow River using habitat simulation and hydrological reference system

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Abstract: The accuracy of the habitat simulation method is often questioned due to limited simulated elements and indicator species. This study established an environmental flow assessment method by coupling fish habitat simulation with hydrological reference system. The environmental flow obtained through the habitat simulation method was corrected by the statistical characteristics of natural flow regime. The environmental flow of the Huayuankou section in the Lower Yellow River was assessed. The results show that the environmental flow demand of the Huayuankou section is 7.9 - 15.4 billion m³/y without consideration of sediment transport. An environmental baseflow of 220 - 400 m³/s is required throughout the year. One to two high flow pulses are needed in the rising-water season to trigger spawning, followed by flow events of 350 - 500 m³/s with more than 1 week duration to create the spawning grounds.

1 Introduction

Most of the world's riverine ecosystems are in sharp decline due to increased demand over limited water resources and enhanced river regulation [1-2]. River flow is regarded as the main driver involved in maintaining a river's good ecological status [3]. Therefore, environmental flows are increasingly supplied to sustain freshwater and estuarine ecosystems and the human livelihoods and well being that depend upon these ecosystems [4-5].

The habitat simulation methods are based on the hydraulic-habitat preferences of species, offering a direct connection between flow and measurable habitat parameters [6]. The advantage of habitat simulation methods is that they take riverine ecosystems into consideration and give an acceptable environmental flow regime rather than fixed minimum environmental flows [7]. However, only a few species are chosen as indicator species in habitat simulation, while indicator species often have contrasting habitat requirements to other aquatic biota and little is known of the exact flow requirements to maintain a healthy and robust aquatic community [8-9].

The Yellow River Basin is the second largest basin in China. With the economic development in the Yellow River Basin, the socioeconomic water demand has rapidly increased, which has resulted in insufficient supply of environmental flow [10]. In the 1990s, flow cutoffs happened frequently in the Lower Yellow River. In 1997, the flow cutoff lasted for 226 days, and the length of dried up reach was 704 km [11]. The Chinese government has become aware of the ecological problems of the Yellow River. However, the current environmental flow standard

has some drawbacks: firstly, there is no clear correlation between environmental flow and riverine ecosystems; secondly, it mainly focuses on total water volume but does not elaborate on flow process.

This study establishes an environmental flow assessment method that couples fish habitat simulation with hydrological reference system. Taking the Lower Yellow River as an example, the environmental flow in a key section was studied.

2 Materials and Methods

2.1. Basic Compositions of Environmental Flow

Based on the components of the natural flow regime and their ecological functions [12], the environmental flow designed in this study mainly includes four components: environmental baseflow, high flow pulse, reproductive flow, and flood. The environmental baseflow determines the amount of habitats that can be utilized by aquatic organisms in riverine ecosystems for most of the year. Environmental baseflow is a continuous small river flow throughout the year. High flow pulse events are defined as periods where flow exceeds a certain threshold for a minimum duration [13]. Occurring in the rising-water season, high-flow pulses can stimulate the development of aquatic organisms and trigger their migration and reproduction. The function of reproductive flow is to create suitable spawning grounds for aquatic organisms. It is provided during the breeding season of aquatic organisms. Floods include overbank floods and non-overbank floods. Non-overbank floods can shape river patterns, stabilize habitat patterns, and transport

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sediments. Since there are a large amount of farmland and houses in the floodplain, and water shortage in the Yellow River Basin is severe, this study only considered non-overbank floods.

2.2. Fish Habitat Simulation

Fish are often regarded as effective indicators of riverine ecosystem health since they are at the top of the food chain of riverine ecosystem and often valuable in a social sense [14-15]. The indicator species was selected with consideration of ecological values, endangerment and economic values of native fish species. Afterwards stages of the life cycle of indicator species were identified, and the hydraulic preferences of indicator species in juvenile stage, adult stage and spawning stage were studied.

The simulated area was determined according to habitat distribution, topographic conditions, data acquisition, and distribution of protected areas. A two-dimensional hydraulic model was established to simulate the water depth and velocity distribution in the simulated area at different discharges. According to the preferences of indicator species, the distribution of adult fish habitats, juvenile fish habitats, and spawning grounds under different discharges were selected, and the variation of habitat area with discharge were identified.

According to the simulation results, the peak value of adult fish habitat area ($H_{1,max}$), the peak value of juvenile habitat area ($H_{2,max}$), and the peak value of spawning grounds ($H_{3,max}$) were identified. This study assumed that when the habitat area was no less than 1/3 of the peak value, it was suitable for indicator species to inhabit. According to the habitat area-discharge curve, the discharge ranges suitable for adult fish ($A_{min}-A_{max}$), juvenile fish ($J_{min}-J_{max}$), and spawning ($S_{min}-S_{max}$) were determined.

2.3. Hydrological Reference System

Native species have adapted to local natural flow regime during long-term evolution. The assumption that the natural flow regime is the most suitable to native species is well supported by substantial data and observations [16]. Therefore, this study assumed that natural flow regime could reflect the tolerance of native species to flow conditions. The natural flow regime was used as a reference system to correct the environmental flow produced from fish habitat simulation.

The minimum flow that occurs naturally is the worst hydrological condition that all native aquatic organisms have experienced and successfully survived. Therefore, the minimum natural flow (N_{min}) was counted as the lower flow limit that all native aquatic organisms could tolerate.

The high flow pulses under natural conditions have successfully triggered reproduction. Thus the characteristics of high flow pulses under natural conditions were used to design high flow pulses in the environmental flow. The number of high flow pulses that could be guaranteed in 80% of the years under natural conditions was counted as the number of high flow pulses required for environmental flow (N). The occurrence time

of high flow pulses under natural conditions was analyzed, and the main time when high flow pulses occurred was regarded as the suitable occurrence time of high flow pulses of environmental flow ($P_{t,1}, P_{t,2}, \dots P_{t,N}$). The duration, peak flow, flow rising rate (positive differences between consecutive daily mean flows), and flow falling rate (negative differences between consecutive daily mean flows) of high flow pulses under natural conditions was calculated. The interval from 1/3 quantile to 2/3 quantile was used as the appropriate range of the duration (P_d), the peak flow (P_{max}), the flow rising rate ($P_{rate,ri}$), and the flow falling rate ($P_{rate,fa}$) of high flow pulses of environmental flow. The average flow of high flow pulses under natural conditions was regarded as the appropriate average flow (P_{mean}) of high flow pulses of environmental flow.

Low flow events that last for days to weeks often occurred after high flow pulses. The low flow events could create slow flow and provide suitable spawning grounds for fish that produce adhesive eggs. The flow variation range ($N_{s,min}-N_{s,max}$) of the low flow events under natural conditions was calculated.

2.4. Coupling of Environmental Flow Assessment Methods

Taking the fish habitat simulation as the core and the natural flow regime as the reference, the two methods can complement and correct each other.

The environmental baseflow needs to be provided throughout the year, mainly considering three factors: the adult fish habitat, the juvenile fish habitat, and natural flow regime. The overlapping of the flow range suitable for adult fish, the flow range suitable for juvenile fish, and the natural flow variation range was taken as the variation range of the environmental baseflow ($E_{b,min}-E_{b,max}$), as shown in equations (1) and (2).

$$E_{b,min} = \max(A_{min}, J_{min}, N_{min}) \quad (1)$$

$$E_{b,max} = \min(A_{max}, J_{max}) \quad (2)$$

The high flow pulse assessed on the basis of the hydrological reference system was employed.

The overlapping of the flow range suitable for the spawning of the indicator species and the natural flow variation of low flow events in the rising-water season was taken as the variation range of the reproductive flow ($E_{s,min}-E_{s,max}$), as shown in equations (3) and (4).

$$E_{s,min} = \max(S_{min}, N_{s,min}) \quad (3)$$

$$E_{s,max} = \min(S_{max}, N_{s,max}) \quad (4)$$

In order to maintain the safety of life and property in the floodplain, only non-overbank floods were considered in this study. Based on the habit area-flow curve, the high flow range that was appropriate for the adult fish and juvenile fish to inhabit was selected.

3 Case study

3.1. Study Area

The study area was the Lower Yellow River (Figure 1). The Lower Reach of the Yellow River is 786 km. With

high sediment concentration and frequent swings of river channels, zonal distributed floodplain wetlands have been formed and provided habitats for a variety of organisms. The Lower Yellow River has been disturbed by human activities seriously and the ecological damage is severe in this region.

Figure 1. The Yellow River Basin and the study area.

3.2. Habitat Simulation Model Construction and Calibration

Carp (*Cyprinus carpio*) was selected as the indicator species for environmental flow assessment in the Lower Yellow River. The hydraulic preferences of carp at different life stages are shown in Table 1^[17].

Table 1. Hydraulic preferences of carp at different life stages in the Lower Yellow River.

Hydraulic condition	Habitat type		
	Adult fish habitat	Juvenile habitat	Spawning ground
Water depth/m	>1.5	>1	1-2
Velocity/(m/s)	0.1-0.8	<0.3	0.1-0.6

This study chose the Huayuankou section as an example to assess the environmental flow in the Lower Yellow River. A 20-km river reach around the Huayuankou section was chosen as the simulated area. The simulated area was approximately 20,000 ha, including the main channel and the floodplain. A two-dimensional hydraulic model was established using MIKE21, and was calibrated by the measured flow-depth relationship in the Huayuankou section. The simulation results of the hydraulic model were input into ArcGIS, and the grids with suitable water depth and velocity were selected to generate the distribution and area of carp habitat.

3.3. Hydrological Reference System Selection

The Sanmenxia Reservoir is located in the upstream of Huayuankou. This reservoir is the earliest reservoir on the

mainstream of the Yellow River whose construction started in April 1957. Before 1957, the Yellow River Basin had a small population and low productivity. There was no reservoir in the mainstream. The water withdrawal was small. Therefore, the measured runoff before 1957 could be regarded as natural runoff. Hence the measured flow regime before 1957 was used as the hydrological reference system.

4 Results and discussion

4.1. Habitat Distribution of Indicator Species

The simulation results of carp habitat under different discharges are shown in Figures 2. For adult fish, habitats were located throughout the main channel when the discharge was small. As the discharge increased, the habitat area rapidly increased, reaching a peak at 400-600 m³/s. The habitat area then decreased with increasing discharge, and the distribution of habitat gradually transferred to the edge of the water. The adult fish habitat area stabilized at a low level at 3000-7000 m³/s. Overbank flood happened at 7500 m³/s, but the water was shallow and did not form suitable habitat in the floodplain. When the discharge reached 8000 m³/s, adult fish habitat appeared in the floodplain. Then the habitat area rapidly increased with increasing discharge.

Figure 2. Relationship between the carp habitat area and discharge in the simulated area. The bankfull discharge in the simulated area is 7200 m³/s.

For juveniles, the habitat area was large at small discharges, and was mainly distributed at the edge of the adult fish habitat. Then the habitat area rapidly decreased as the discharge increased. At 800-7000 m³/s, the habitat area stabilized at a low level. When the discharge were more than 8000 m³/s, the habitat area of juvenile fish began increasing rapidly with the increase of discharge.

A large area of spawning grounds was formed in the simulated area at low discharge. Then the area of the spawning grounds decreased rapidly as the discharge increased. At 800-7000 m³/s, the spawning area stabilized at a low level. There was almost no suitable spawning ground at 1400-4000 m³/s. When overbank flood happened, slow-flowing water area was formed quickly in the floodplain, resulting in significantly increase of spawning grounds.

According to the habitat area-discharge curve of carp in the simulated area, it was obtained that the flow range suitable for adult carp (A_{min} - A_{max}) was 100-2300 m³/s; the flow range suitable for juvenile carp (J_{min} - J_{max}) was 100-400 m³/s; and the flow range suitable for the spawning of carp (S_{min} - S_{max}) was 100-500 m³/s.

4.2. Statistical Characteristics of Hydrological Reference System

The analysis of the measured daily runoff of the Huayuankou section before 1957 showed that the minimum daily runoff flow N_{min} was 220 m³/s.

According to the flow characteristics of the Huayuankou section during the rising-water season, a flow event with a discharge exceeding 1000 m³/s and a duration exceeding 3 days was regarded as a high flow pulse event. Since high flow events happen frequently in middle and late June as the flood season (July-October) is coming, and the time for spawning and hatching needs to be reserved, so only high flow pulses that occurred from April 1 to June 10 were counted.

The results showed that high flow pulses occurred 0 to 4 times a year, with an average of 2 times. The first high flow pulse generally occurred in early April, and the second high flow pulse generally occurred in early May. The high flow pulse duration was 5-35 days, and 80% high flow pulses' duration were no more than 20 days. The peak flow was 1120-2800 m³/s. The average flow was 1200 m³/s. The flow rising rate was greater than the flow

falling rate. The 1/3 quantile and the 2/3 quantile of high flow pulse duration, peak flow, flow rising rate, and flow falling rate are shown in Table 2.

The low flow event that occurs after a high flow pulse during the rising-water season can create spawning grounds for a variety of fish that produce adhesive eggs. The duration of the low-flow event was set as 7 days, taking into account the time required for fish spawning, egg hatching, and early development of juveniles in the Lower Yellow River. The characteristics of low flow events in the Huayuankou section before 1957 were analyzed. The results showed that the flow variation range of low flow events ($N_{s,min}$ - $N_{s,max}$) was 350-980 m³/s.

Table 2. Main parameters of high flow pulses required in the environmental flow of the Huayuankou section in the Lower Yellow River.

Key parameters	Variable symbol	Value
Number of high flow pulses per year	N	1-2
Occurrence time	$P_{t,1}$	Early April
	$P_{t,2}$	Early May
Duration	P_d	10-20 d
Peak flow	P_{max}	1500-2000 m ³ /s
Flow rising rate	$P_{rate,ri}$	60-200 m ³ /(s·d)
Flow falling rate	$P_{rate,fa}$	60-150 m ³ /(s·d)
Average flow	P_{mean}	1200 m ³ /s

4.3. Environmental Flow in the Lower Yellow River

According to equations (1) and (2), the environmental baseflow of the Huayuankou section is 220-400 m³/s. When the environmental baseflow is small, it is more suitable for juveniles to inhabit. When the environmental baseflow is large, it is more suitable for the growth and development of adult carp. The high flow pulse is determined by the statistical characteristics of the hydrological reference system, as shown in Table 2.

According to equations (3) and (4), the reproductive flow varied from 350 to 500 m³/s. The hatching of carp eggs takes 2-3 days, and the juvenile fish needs 2-4 days to leave the spawning ground, therefore, the reproductive flow duration needs to be no less than 7 d. The habitat area of adult carp and juvenile carp remained basically stable during non-overbank floods. The Yellow River has lots of sediment. Thus sediment transport is an important purpose of environmental flow. Therefore, the timing and magnitude of floods in the Huayuankou section mainly depends on the demand of sediment transport, which is not explicitly mentioned in this study. Without consideration of the sediment transport, the environmental flow of the Huayuankou section is 7.9-15.4 billion m³/y. The environmental flow assessed in this study is dissimilar to the natural flow regime. However,

offering high flow pulses at suitable time and releasing stable baseflow at other time is regarded as a cost-effective management strategy ^[18].

5 Conclusions

In this study, fish habitat simulation was used as the main environmental flow assessment method, while the natural flow regime was used as the reference system. The environmental flow of the Huayuankou section in the Lower Yellow River was assessed. Without consideration of floods for sediment transport, the annual environmental flow required in the Huayuankou section is 7.9-15.4 billion m³, and it is necessary to provide 1-2 high flow pulses in the rising-water season and to create flow events that generate suitable spawning grounds.

The habitat simulation model established in this study only considered the influence of flow velocity and water depth on the indicator species, whereas important factors such as water temperature and dissolved oxygen were not included. The improvement of the habitat simulation model is the future research directions of this study.

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