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Assessing the effect of the Three Gorges reservoir impoundment on spawning habitat suitability of Chinese sturgeon (*Acipenser sinensis*) in Yangtze River, China

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ABSTRACT

The Chinese sturgeon (*Acipenser sinensis*), a kind of maricolous anadromous migratory fish species, is endangered and protected in China. Historical spawning habitats were distributed in the lower reaches of Jinsha River and the upper reaches of Yangtze River. Since the establishment of the Gezhouba water conservancy pivot in 1981, the migratory route of Chinese sturgeon spawning was blocked. Therefore, the fish was forced to propagate in a new spawning ground which was mainly distributed in the 4-km-long mainstream from Gezhouba Dam to Miaozui in the middle Yangtze River. After water storage and power generation of the Three Gorges reservoir (TGR) in 2003, the propagation of Chinese sturgeon has been impacted gradually. According to field surveys, the fish used to spawn twice a year before TGR impoundment, but only once happened after that. Besides, the spawning scale is also declining with each passing year.

In order to simulate and evaluate the effect of TGR impoundment on spawning habitats of Chinese sturgeon, with consideration of their reproductive characteristics, an eco-hydrodynamic model was established by coupling a two-dimensional hydrodynamic model and a fuzzy fish habitat module based on fuzzy logic inference. Flow fields at the studied site in an impoundment scenario and an assumed no impoundment scenario were simulated with the 2D hydrodynamic model. Afterwards, by linking hydrodynamic conditions to the expert knowledge base, the fuzzy habitat model used fuzzy logic inference to compute habitat suitability of the Chinese sturgeon. In addition, the approach was used to propose a suitable instream flow range during the propagation period for Chinese sturgeon. The results indicated that the suitable instream flow needed for Chinese sturgeon spawning in middle Yangtze River should be between 10,000 m^3/s and 17,000 m^3/s and it also showed that after TGR was put into pilot impoundment operation at the designed water level of 175 m, the habitat suitability has decreased significantly in October. Besides, the water temperature of spawning habitat increased to a higher level in propagation period due to the impoundment of the TGR. All these alterations have had imposed tremendous impacts on the propagation of Chinese sturgeon. Therefore, adjusting impoundment schedule of the TGR to recover the water flow over spawning habitat in October is a crucial way to improve the habitat suitability. Furthermore, the presented method also provides a theoretical basis for further research on the assessment of habitat suitability of aquatic species at a micro-habitat scale.

1. Introduction

Most of the world's large rivers are fragmented by dams. Dam construction plays an important role in flood control, power generation, navigation and irrigation. However, for the alterations caused by dam construction to natural flow regimes, i.e. changes in flow magnitude, frequency, duration, timing, rate of change and hydraulic processes, the structure and functions of river ecosystem degenerate gradually (Jorde et al., 2008; Magilligan and Nislow, 2005). More specifically, alternations change environmental characteristics of fish habitats, which could deteriorate and decrease the abundance of fish species (Guo et al., 2011). In addition, problems like reduction of river connectivity, watershed fragmentation and reduction of species diversity are also incurred consequently (Mao et al., 2005; Tiemann et al., 2004).

Fish species, which is in the climax community of the aquatic ecosystem, is more sensitive to alterations of ecological environment and is actually considered to be the best indicator species of aquatic ecosystem health (Gao et al., 2009). And there is also demand for tools to analyze, evaluate, and quantify the impact from human activities on the ecosystem, which can assess the habitat quality of aquatic organisms.

Several models based on physical variables such as depth, flow velocity, and substrate, have been developed to simulate the hydraulic processes and predict local habitat suitability (Bovee, 1982; Gard, 2006; Jowett, 1997; Parasiewicz and Dunbar, 2001). These simulations

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of physical habitat models are particularly helpful to the evaluation of dam construction impacts or water abstraction outcome on river ecosystems, determination of the minimum flow requirements of aquatic populations, and effect assessment of restoration projects (Adriaenssens et al., 2006; Maddock, 1999; Shields et al., 1997; Shuler and Nehring, 1993).

Habitat models have become an important tool for river and water resource management since the 1980s (Armour and Taylor, 1991; Bockelmann et al., 2004). The Physical Habitat Simulation (PHABSIM) model (Bovee, 1982), which is considered to be the first fish habitat model and makes use of the Instream Flow Incremental Methodology (IFIM), is being applied around the world at present. Based on PHABSIM, other derivative models, including Norwegian River System Simulator (Alfredsen and Killingtveit, 1996), RHYHABSIM (Jowett, 1996), EVHA (Ginot, 1995), and MesoHABSIM (Parasiewicz, 2001) were developed to address some shortcomings of PHABSIM and were also widely used across the globe. In these models, the relation between physical variables and habitat suitability is described by means of univariate or multivariate preference functions (Bovee, 1982; Pasternack et al., 2008). However, there are three major shortcomings: (1) these models mentioned above are based on one-dimensional hydraulic simulation that is only effective for large-scale flow variations (Lacey and Millar, 2004). However generally, they are short of the resolution and accuracy required for localized applications on complex terrain and detailed assessment of habitat-specific conditions (Wang et al., 2011b); (2) physical variables of the habitat models are combined by user-defined equations such as minimum, geometric mean, arithmetic mean and product so that many possible interactions between them are neglected; and (3) the spatial links between habitats are ignored (Jorde et al., 2000; Mouton et al., 2007).

With the research going on, two-dimensional models (RIVER 2D) have been developed and can be applied to simulate spatially explicit habitat units for localized hydrodynamic analysis at the micro-habitat scale (Steffler and Waddle, 2002). These models are more suitable for simulating the water flow movement on complex terrain because of the ability of computing horizontal and vertical flow currents. Without compromising accuracy, RIVER 2D can reach a steady-state solution and also embed a fish habitat module by using IFIM. Besides, the Computer Aided Simulation Model for Instream Flow Requirements (CASiMiR), based on fuzzy sets and rules, has been developed for quality evaluation of fish habitats since the early 90s (Jorde et al., 2000; Schneider, 2001). This model allows working with fuzzy information from experience of fish biologists and monitoring data. It is observed that habitat requirements of species depend on life stage and river type (Jungwirth et al., 2000).

In recent years, instream ecological engineering has drawn a lot of considerable attentions, and habitat models have been widely applied to address alterations and evaluate the quality of aquatic habitats due to dam or other engineering structures such as weir, separation levee projects and irrigation channels (García et al., 2011; Mouton et al., 2007; Wang et al., 2011b). These models can help investigators to quantify the habitat quality and enhance the selection of restoration options readily. In China, because little attention has been paid to the effect of dams and other projects on surrounding habitats, the ecosystems of several rivers have been interfered significantly. Because of the constructions of large dams on the Yangtze River, the migration route to spawning sites for the Chinese sturgeon (*Acipensor sinensis*) was blocked. Consequently, the deterioration of reproductive habitats has resulted in a sharp reduction of this aquatic species population.

The aim of this study is to establish a habitat model based on fuzzy logic for the Chinese sturgeon, and to assess the effects of the impoundment in Three Gorges reservoir on suitability of the fish spawning habitat. In addition, the suitable daily discharge for Chinese sturgeon in the reproductive period was also calculated.

2. Species and study site

2.1. Chinese sturgeon in Yangtze River

The Yangtze River is the largest river in Asia and the world's third largest river in terms of water volume. Originating from the Qinghai–Tibet Plateau, Yangtze River flows through Qinghai, Tibet, Szechwan, Yunnan, Chongqing, Hubei, Hunan, Jiangxi, Anhui, Jiangsu and Shanghai from west to east before debouching into the East China Sea at Shanghai. The entire length of Yangtze River is about 6300 km, with a draining area of about 180×10^4 km^2 which covers 18.75% of the national land area. The annual average runoff volume of Yangtze River, which is nearly 9560×10^8 m^3, accounts for 36% of the whole country.

Chinese sturgeon is a kind of maricolous anadromous migratory fish. It grows up in coastal waters and swims upstream to get to its spawning site after sexual maturity for propagation from mid-October to early November in the Yangtze River. As one of the oldest existing vertebrates on the earth, the endangered fish is protected since it was classified as the First-Grade State Protection animal in China. The historical spawning grounds of Chinese sturgeon were distributed at the lower reaches of Jinsha River and the upper reaches of Yangtze River (Yang et al., 2007). In 1981, the migratory route was blocked after damming of the Gezhouba water conservancy pivot. According to the survey (Yu et al., 1983), the fish could still naturally reproduce at the downstream river of Gezhouba Dam, and a new spawning ground was formed. In the next few years, the continual monitoring showed that the Chinese sturgeon was forced to propagate in the spawning ground which was mainly distributed in the 4-km-long mainstream from Gezhouba Dam to Miaozui in middle Yangtze River (Fig. 1) and the length of the new spawning site became less than 1% of the historical sites (Tao et al., 2009; Wei et al., 1998). As a result, the population quantity of Chinese sturgeon has fallen gradually from 1990 (Yang, 2007). After reservoir filling and the launch of power generation of the Three Gorges Project Reservoir (TGR) in 2003, the monthly average discharge has been decreased from 17,290 m^3/s (period 1981–2003) to 13,290 m^3/s (period 2003–2008) in October, and it has also declined slightly in November. In consequence, the noticeable decline of the discharge in October caused more adverse effects on natural reproduction of Chinese sturgeon (Chen, 2007; Wang et al., 2011a). Many field surveys have been accomplished on Chinese sturgeon spawning site (Ban, 2011; Cai et al., 2010), but little attention has been paid on quantitative computation for assessing the impact of reservoir operating on habitat suitability.

2.2. Study site

This present study was conducted in a 4-km-long and about 800-m-wide reach, with the area of 2.7 km^2 in the middle Yangtze River (111°15′ E; 30°43′ N) from Gezhouba Dam to Miaozui (see Fig. 1). Specifically, this ground is the only known spawning habitat of the Chinese sturgeon so far (Ban, 2011). The mean annual flow at the research site is about 14,112 m^3/s (period 1882–2008). After the closure of Gezhouba dam, the water surface elevations at the study site are 45.38 ± 0.95 m and 42.54 ± 0.84 m (mean $\pm$ standard deviation) above sea level in October and November respectively (Yang et al., 2007). At present, the flow regime is controlled by Three Gorges cascade operation (Three Gorges Dam and Gezhouba Dam). Fig. 1 also shows the distribution of cross-sections in the study area, and all the data of velocity at the related cross-sections was obtained from Yang (2007). Owing to the water storage of TGR in October which is the spawning period of Chinese sturgeon, the decreasing flow gave rise to a severe area shrinking of spawning habitat. In addition, the alterations of aquatic eco-factors, including water depth, temperature, flow velocity, sediment concentration have also significantly influenced on the suitability of the spawning site (Yi et al., 2007).