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A habitat suitability model for Chinese sturgeon determined using the generalized additive method

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SUMMARY

The Chinese sturgeon is a type of large anadromous fish that migrates between the ocean and rivers. Because of the construction of dams, this sturgeon's migration path has been cut off, and this species currently is on the verge of extinction. Simulating suitable environmental conditions for spawning followed by repairing or rebuilding its spawning grounds are effective ways to protect this species. Various habitat suitability models based on expert knowledge have been used to evaluate the suitability of spawning habitat. In this study, a two-dimensional hydraulic simulation is used to inform a habitat suitability model based on the generalized additive method (GAM). The GAM is based on real data. The values of water depth and velocity are calculated first via the hydrodynamic model and later applied in the GAM. The final habitat suitability model is validated using the catch per unit effort ($CPUE_d$) data of 1999 and 2003. The model results show that a velocity of 1.06–1.56 m/s and a depth of 13.33–20.33 m are highly suitable ranges for the Chinese sturgeon to spawn. The hydraulic habitat suitability indexes (HHSI) for seven discharges (4000; 9000; 12,000; 16,000; 20,000; 30,000; and 40,000 m^3/s) are calculated to evaluate integrated habitat suitability. The results show that the integrated habitat suitability reaches its highest value at a discharge of 16,000 m^3/s. This study is the first to apply a GAM to evaluate the suitability of spawning grounds for the Chinese sturgeon. The study provides a reference for the identification of potential spawning grounds in the entire basin.

1. Introduction

A habitat is a multi-dimensional space consisting of biotic and abiotic factors where organisms live or exist (Koop et al., 2008). For many species, habitats have been degraded or lost because of increasingly intense human activity; as a result, many endangered species have disappeared, and biodiversity has decreased (Fischer and Lindenmayer, 2007; Gardner et al., 2008; Tilman et al., 2001). Establishing an appropriate habitat suitability model (HSM) to evaluate habitat suitability is an effective approach to guide conservation efforts for terrestrial and aquatic organisms. HSMs are based on abiotic variables that affect the distribution of species and are used to evaluate the quality of a habitat. Abundance and density often are used as ecosystem response variables to indicate how suitable the habitat is for the species of interest. Presence-absence is another measure used to predict the probability of a species' occurrence in a habitat (Ahmadi-Nedushan et al., 2006). The HSMs have been applied both in the terrestrial and aquatic ecological systems (Dayton and Fitzgerald, 2006; Questad et al., 2014; Vezza et al., 2014; Yi et al., 2014b; Zohmann et al., 2013). HSM applications in aquatic ecological systems are relatively less frequent than those in terrestrial ecological systems. In aquatic ecological systems, the HSMs must integrate flow-related changes in the habitat with the preferred hydraulic habitat conditions for target species or assemblages. Thus, HSM applications should consider the effects of channel morphology, geomorphic features, discharge variation processes, and water quality. HSMs have been regarded as the most suitable method at present for evaluation of the influence of human activities on aquatic organism habitats and the effects of river restoration (Acreman and Dunbar, 2004).

The target species that can be used for an aquatic habitat suitability simulation include endangered fish, important economic fish, benthos and dominant species, etc. (Costa et al., 2012; Li et al., 2009; Van Broekhoven et al., 2006). The Chinese sturgeon is a type of large anadromous fish that migrates between the ocean and rivers. Because of the construction of dams, its migration path has been cut off, which resulted in a sharp decrease of habitat area. This species is on the verge of extinction and has been listed in the International Union for Conservation of Nature (IUCN) Red List

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since 2010. Thus, urgent action must be taken to determine its habitat requirements and then to apply better reservoir management measures to restore the river system.

Generally, literature or expert-based models and statistical models are the two main types of HSMs (Wang, 2012; Yi et al., 2014a). Statistical models are becoming an increasingly important tool to predict the likely occurrence or distribution of species based on relevant variables in conservation planning and wildlife management (Ahmadi-Nedushan et al., 2006). Multiple linear regression, logistic regression, generalized linear models (GLMs), generalized additive models (GAMs), artificial neural networks, fuzzy logic, canonical correspondence analysis, and ridge regression are all types of statistical models that have been used to determine HSMs (Ahmadi-Nedushan et al., 2006). Each model has its advantages and disadvantages and its own scope of application. Unlike the other models, GAMs use a link function to establish the relation between the mean of the response variable and a smoothed function of the predictor variables. GAMs are flexible in model structure and able to deal with highly non-linear and non-monotonic response curves (Ahmadi-Nedushan et al., 2006). For this reason, GAMs are better suited for the analysis of non-linear relations between species distribution and environmental variables than the other statistical models (Ahmadi-Nedushan et al., 2006). The GAM has been used to predict the relation between species distribution and environmental factors. Bellido et al. (2001) used a GAM to analyze the intra-annual variation in the abundance of squid Loligo forbesi in Scottish waters and to study the key influencing factors. In addition to its application in seas, GAMs have also been used in lakes and rivers to simulate species distribution (Černý et al., 2003; Costa et al., 2012; Knapp and Preisler, 1999; Lehmann, 1998). Here, a GAM is used for the Chinese sturgeon to evaluate the available spawning grounds.

The study reported here developed a HSM based on a GAM to simulate the suitability of the available Chinese sturgeon spawning grounds. This model was a combination of a GAM and a two-dimensional hydrodynamic model. Coupling hydrodynamic model and habitat suitability functions is one effective approach to evaluate rehabilitation of a habitat (Crowder and Diplas, 2000; Pasternack et al., 2008). The hydrodynamic model was established first to simulate the hydraulic conditions in the study area. The computed hydraulic conditions served as input predictors for the GAM and then the GAM module was completed. The developed GAM module was validated using catch per unit effort ($CPUE_d$) data. Some knowledge can be extracted from the developed GAM, such as variable importance and the suitable variable range. Then, the GAM was used to evaluate the suitability for different discharges so that the hydraulic habitat suitability indexes could be calculated to describe the integrated habitat suitability of the entire area. Finally, the most suitable discharge for the Chinese sturgeon to spawn can be obtained.

2. Species and study area

The Chinese sturgeon is a type of large anadromous fish that migrates between the ocean and rivers. It can be more than 3 m in length. The Chinese sturgeon dates back 1.4 million years and is called a living fossil. The Chinese sturgeon inhabits the East China Sea and migrates to the upper Yangtze River to spawn after reaching sexual maturity. The sexually mature sturgeons in the East China Sea move to the Yangtze Estuary and further up to the middle reaches of the Yangtze River in July and August to prepare for reproduction. They arrive at the spawning grounds and reproduce during October and November (Wei, 2003). Generally speaking, the Chinese sturgeon prefers to spawn at deep water (>10 m). However, deep pools (>40 m) are not a perfect place for them because of the slow water velocity. Appropriate velocities keep the eggs in suspension and easier to be fertilized. Whereas few spawning actions take place at locations with velocities larger than 2 m/s (Wang, 2012).

Before the damming of the Yangtze River by Gezhouba Dam at Yichang in 1981, there were more than 20 spawning grounds in the Yangtze River (Yangtze Aquatic Resources Survey Group, 1988). The historical spawning sites for the Chinese sturgeon included high quality spawning sites and sporadic spawning sites (Yi et al., 2010b) (Fig. 1). The high quality spawning sites were all located upstream of the Gezhouba Dam, and the sporadic spawning sites were spread both upstream and downstream of the dam. After construction of the dam, the migration route of the sexually mature Chinese sturgeon was blocked. As a result, 16 historical spawning grounds upstream of the Gezhouba Dam were lost (Yangtze Aquatic Resources Survey Group, 1988). Moreover, the dam dramatically changed the hydrologic regime. Consequently, the suitable spawning area of the Chinese sturgeon decreased sharply. As a result, the stock of the Chinese sturgeon was dramatically reduced. In 1996, the Chinese Sturgeon was listed as an endangered species. In 2010, it became critically endangered in the IUCN Red List of threatened species.

After 1995, spawning activities were identified using ultrasonic telemetry below Gezhouba Dam. Until 2005, a reach of 4.8 km downstream from the dam became the main spawning area of the Chinese sturgeon (Institute of Hydrobiology, 2005). The study area considered in this study covers approximately 5 km of the reach downstream from Gezhouba Dam (Fig. 1). The study area is located on a transitional reach from a mountainous river to an alluvial river (Zhang et al., 2011). The average width of the study reach is 1000 m; most of the study area has depths greater than 30 m. During spawning seasons (October and November), the width of the study reach is 600–1670 m, and the average depth is 13 m (Zhang, 2009). From 1983 to 2004, the daily discharge during the spawning season was 7153–32,700 m^3/s (Zhang et al., 2011).

3. Methods

3.1. Data source

The spawning data used for model development and testing were recorded from 1996 to 2006 during a study conducted by Wei (2003); this study covered the reach from Gezhouba Dam to Miaozui, and the results were expressed as an HSI. The value of the HSI varies between 0 and 1. It is representative of catch per unit effort ($CPUE_d$), which is the quantity of eggs per unit of effort (1000 m^3). The distribution of the $CPUE_d$ data is uneven and the minimum, maximum, mean, median, and standard deviation of the $CPUE_d$ data are 0, 1272.3, 60.3, 1.385, and 203.7, respectively. Because the span of sampled $CPUE_d$ data is wide, to simplify the calculation, the $CPUE_d$ data were normalized to vary between 0 and 1. Water depth and water velocity were considered predictor variables of the habitat suitability. The water depth and velocity were calculated according to the known flow and topography data in the $CPUE_d$ collection location (Yi et al., 2014a). The scattered 3D-plot of the sampled data is shown in Fig. 2. Fig. 2 shows a likely trend of a unimodal-nonlinear relation between the HSI and the two hydrological predictor variables. Fig. 2 also indicates that spatial heterogeneity exists in the spawning suitability, which means that even with a similar water depth and velocity, the amount of spawning may still be very different.

3.2. Two-dimensional hydrodynamic model

The studied area was divided into 63×46 units in which 63 sections were set along the reach and 46 points were set across