RIVER RESEARCH AND APPLICATIONS
River. Res. Applic. (2009)
Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/rra.1341

APPLYING INSTREAM FLOW INCREMENTAL METHOD FOR THE SPAWNING HABITAT PROTECTION OF CHINESE STURGEON (*Acipenser sinensis*)

X. BAN,[a]* Y. DU,[a] H. Z. LIU[b] and F. LING[a]

[a] *Institute of Geodesy and Geophysics, Chinese Academy of Sciences, Wuhan, Hubei 430077, China*
[b] *Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan, Hubei 430072, China*

ABSTRACT

The Chinese sturgeon, *Acipenser sinensis*, is an anadromous species that spawns in the Yangtze River and Pearl River of China. Its population has declined dramatically since the construction of the Gezhouba Dam (GD) in 1981 and then with the impoundment of the Three Gorges Dam (TGD) upstream of the GD in 2003. This paper presents a quantitative method based on the instream flow incremental method to explore the relationship between the fish spawning habitat and the operations of the GD and TGD, aiming to find a solution for conservation of the species. A two-dimensional hydrodynamic model was built with the River2D to simulate the hydraulic behaviour of the stream below the GD. Habitat suitability index was determined by the biological data of the fish collected in the field. The two parts were then integrated through a geographical information system developed via ArcGIS to outline the fish habitat area variation with flows. The decision support system is applied to set up a habitat time series for validating the assumption that more habitats have the potential to support more fish. The fish habitat results for alternative instream flow schemes are then compared with one another for defining the optimal flow requirements and evaluating effects of reservoir operation alternatives in order to improve the operation management for the GD and TGD projects. The results show that the optimal flow for spawning of the fish is about 7000–13000 m^3/s and the optimal inlets combination is where the inflow comes from two power plants. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: Chinese sturgeon; Gezhouba Dam; Three Gorges Dam; hydraulics; habitat suitability index; decision support system

Received 27 January 2009; Revised 22 October 2009; Accepted 1 November 2009

INTRODUCTION

The Chinese sturgeon, *Acipenser sinensis*, is an anadromous species that grows in the East Sea of China, and presently only spawns in the Yangtze River and the Pearl River of China (Wu, 1963). The species reaches sexual maturity at ages between 8 to18 years in males and 13–26 years in females. Adults begin their freshwater migration in spring with immature gonads (Zhao *et al*., 1986). They migrated more than 3000 km from the estuary to upper reaches of the Yangtze River to lay eggs in May–August each year (Chang and Cao, 1999). After staying in freshwater of the Yangtze River nearly for a year without feeding, their gonads reach maturity and then they join spawning groups during October and November. The spawning activity of the Chinese sturgeon occurs at least once a year, sometimes twice a year (Chang and Cao, 1999).

In the late 20th Century, their population declined dramatically due to overfishing and habitat degradation (Wei *et al*., 1997). For one thing, the construction of the Gezhouba Dam (GD) in 1981 blocked the upstream migration route of this species, and also reduced their spawning ground length from 800 to 30 km. For another, Three Gorges Dam (TGD) located in upstream of the GD has its impoundment since 2003. It will not block the migration route of Chinese sturgeon but its impoundment will reduce the average discharge of the GD by 40% approximately, and this will seriously influence the spawning habitat of Chinese sturgeon. Despite banning commercial fishing since 1983, special protecting (Category I National Protected animals) since 1988 and artificial reproduction, the population of this fish still declined greatly (Chang and Cao, 1999). Investigations have shown that the population of Chinese sturgeon depends mainly on natural reproduction and little on artificial culturing (Xiao *et al*., 1999). Therefore, conservation of their spawning habitats is the best way to protect the Chinese sturgeon. There is a need to develop an effective method to maintain healthy aquatic ecosystems for the Chinese sturgeon.

The instream flow incremental method (IFIM) is a widely used decision support system, which designed to assess the effects of flow operations on river habitat and help water resource managers determine the benefits or consequences of different water management alternatives (Bovee, 1982). The IFIM uses measured cross sections of a river to predict water depth and velocity for a range of flows, and it also integrates other habitat factors, such as river substrate or

*Correspondence to: X. Ban, Institute of Geodesy and Geophysics, Chinese Academy of Sciences, Wuhan, Hubei 430077, China.
E-mail: banxuan@whigg.ac.cn

water temperature, which is then compared to a number of aquatic species habitat requirements (Bovee *et al*., 1998). This method makes use of recently available technologies, including two-dimensional hydraulic modelling software (River2D), geographic information system (GIS) and decision support system (DSS) to explore the feasibility and effectiveness of different alternatives for potential flow management schemes (Trihey and Stalnaker, 1985; Stalnaker *et al*., 1995). The results are a fish habitat modelling tools suitable for potentially assessing the instream flow requirements and effects of different flow managements on the fish habitat.

In recent years, IFIM has been adapted for a variety of other ecosystem components and situations (Tharme, 2000). For instance, Reiser *et al.* (1989) showed IFIM to be the most commonly used environment flow management in North America, applied in 38 states or provinces by the late 1980s, and the preferred methodology in 24 cases. Milhous (1998) reported its application in assessment of sediment flushing flows, while Flower and Thompson (2008) provided examples of its application in North African river restoration projects. Furthermore, a total of 616 IFIM applications, specifically by US Fish and Wildlife Service (USFWS) offices, were reported in 1988 (Armour and Taylor, 1991). The use of IFIM has accelerated tremendously since then, judging by the plethora of published case studies (Stalnaker, 1998); probably in part due to its long existence, the ready availability of the component software and well-developed training courses. It is, therefore, unsurprising that IFIM far exceeds other methodologies in use worldwide to date, with confirmed use in 20 countries (Stalnaker, 1998).

However, contrasting its worldwide applications, it is rarely mentioned in China. The paper will apply this mature method in studying the spawning habitat protection of Chinese sturgeon with an aim to provide scientific suggestions for environment flow management. For this purpose, a relationship is defined between different flow conditions and suitable habitat areas (SHA) of the Chinese sturgeon for finding the optimal flow requirement. Accordingly, an efficient scheme of management on both the GD and TGD is recommended.

STUDY AREA AND DATA INVESTIGATION

Study area

Historically, the spawning habitats of Chinese sturgeon were located in the main stream of the upper Yangtze and the lower Jinsha rivers, covering a stretch of about 800 km of the river length (Figure 1a) (YARSG, 1988). However, after the damming of the Yangtze River by the GD in YiChang (YC) on January 1981, their spawning areas were limited to a 30 km reach below the Dam (Hu *et al*., 1992) with only two favourable sites remaining, upstream and downstream spawn sites (Figure 1b). In this study, a 7 km segment below the GD was surveyed, which essentially covers the two present spawning sites of Chinese sturgeon (Yang *et al*., 2006).

Data investigation

Topography data of the riverbed in the study area were obtained through combination of relief map and field surveys in 1999 and 2004 by the Institute of Hydrobiology, Chinese Academy of Sciences (CAS). The navigation channel charts of the Middle Yangtze River adjacent to YC were also utilized. Topographic and hydraulic data were collected by a survey boat equipped with an echo sounder for depth, an Acoustic Doppler Current Profiler (ADCP) for

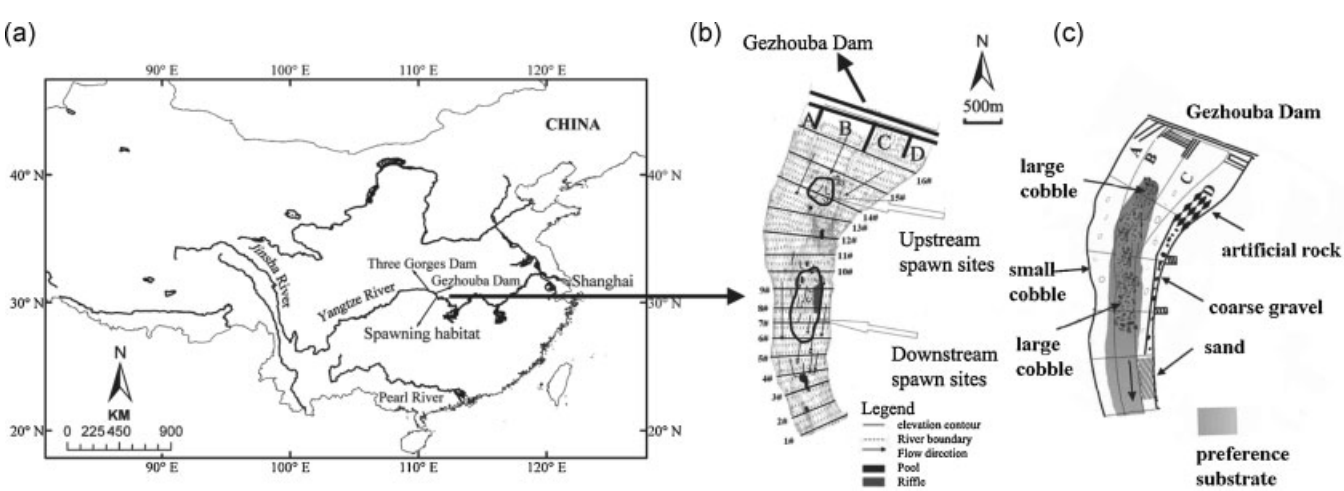

Figure 1. (a) Distribution of the spawning habitats of Chinese sturgeon in the Yangtze River. (b) Topography and measured transects in the spawning habitats downstream of Gezhouba Dam. A, B, C and D denote different inlets: (A) Ship lock, (B) Dajiang power plant, (C) Spillway, (D)Erjiang power plant. Also shown are 16 transects where depths and velocities were measured. The two spawning sites are marked with circles. (c) Substrate distribution in the spawning habitats

DOI: 10.1002/rra

velocity and a Trimble 5700 GPS for coordination. The data precision for the echo sounder is 10 cm, ADCP is 0.2 cm/s and GPS is 1 m. A total of 16 cross sections were surveyed for depths and velocities in three single phase of discharging in November 2004 (12139 m^3/s, 10415 m^3/s and 7977 m^3/s), each points by 50 m interval along the cross direction, the substrate map was also recorded synchronously (Figure 1c). The fish distribution data were collected using a Biosonics apparatus by Yangtze River Fisheries Research Institute, Chinese Academic of Fishery Science (Wei, 2003). The depths and velocities, as well as the substrate attributes were recorded in the position where the target fish was detected.

METHODS

Study procedure and assumptions

The IFIM processes the following several steps or procedures. Firstly, hydraulic model of the study area is constructed with River2D, a software package developed specifically for use in natural streams and rivers. Meanwhile, biological habits of the Chinese sturgeon are defined through the habitat suitability criteria (HSC) (Bovee, 1986). Then, a river habitat model is constructed with ArcGIS by integrating the hydraulic model and HSC for exploring the relationship between spatial variations in fish habitat area with flows. Subsequently, outputs from the habitat model are then inputted into the DSS to quantify the effects of different flow managements on the fish habitat.

For simplification, several assumptions have been made in application of IFIM. Firstly, we assume that a state of dynamic equilibrium has been reached in the surveyed river segments. This means that surveyed sites have not been seriously altered in our concerned times and can represent the past. If not the case, this site will be resurveyed. We also assume that our selected study sites were representative of the river segments, that the boundary conditions obtained from gage station rating curves closely approximated those at the sites, and that our survey data were accurate depictions of site topography. To some extent, the validity of these assumptions can be supported by the similarity of the normalized flow versus habitat functions. The similarity of the functions suggests that errors associated with sampling and data collection are consistent across all the sites; final model outputs are insensitive to these errors, or both. It is important to remember that the comparative statistics generated in the DSS are relative, not absolute. The advantage of relative scoring is that any inaccuracies of the models will be equally distributed in both the baseline and alternative simulations. In that sense, the effects of modelling inaccuracies are neutral.

A modified version of IFIM is used to quantify the variation of spawning habitat area with stream flows. Processing the IFIM involves the following four procedures: Firstly, set up the hydraulic model, which includes five steps: (1) collection of field topography and River bed mapping; (2) mesh preparation; (3) determining boundary conditions; (4) model calibration; (5) simulation of velocity and depth in different flow scenarios. Secondly, set up the HSC for getting suitable depth and velocity ranges. Thirdly, set up the habitat model for getting the SHA, which includes two steps: (1) classification of habitat with HSC; (2) mapping SHA using ArcGIS. Finally, operate DSS for getting the habitat time series, which includes three steps: (1) input habitat results to DSS for generating SHA as a function of flows; (2) Get the SHA time series corresponding to daily flow; (3) Contrast the SHA with the surveyed amount of spawned eggs. These are further elaborated in the following frame (Figure 2).

Hydraulic models in River2D

Overview. The hydraulic component of the River2D model is based on the two-dimensional, depth averaged St. Venant Equations expressed in conservative form. These three equations represent the conservation of water mass and of the momentum vector (Steffler and Blackburn, 2002).

Conservation of mass:

$$\frac{\partial H}{\partial t} + \frac{\partial q_x}{\partial t} + \frac{\partial q_y}{\partial t} = 0 \tag{1}$$

Conservation of x-direction momentum:

$$\frac{\partial q_x}{\partial t} + \frac{\partial}{\partial x}(Uq_x) + \frac{\partial}{\partial y}(Vq_x) + \frac{g}{2}\frac{\partial}{\partial x}H^2 = gH\left(S_{0x} - S_{fx}\right) + \frac{1}{\rho}\left[\frac{\partial}{\partial x}(H\tau_{xx})\right] + \frac{1}{\rho}\left[\frac{\partial}{\partial y}\left(H\tau_{xy}\right)\right] \tag{2}$$

Conservation of y-direction momentum:

$$\frac{\partial q_y}{\partial t} + \frac{\partial}{\partial x}\left(Uq_y\right) + \frac{\partial}{\partial y}\left(Vq_y\right) + \frac{g}{2}\frac{\partial}{\partial y}H^2 = gH\left(S_{0y} - S_{fy}\right) + \frac{1}{\rho}\left[\frac{\partial}{\partial x}\left(H\tau_{yx}\right)\right] + \frac{1}{\rho}\left[\frac{\partial}{\partial y}\left(H\tau_{yy}\right)\right] \tag{3}$$

where H is water depth; U and V are depth averaged velocities in the x and y coordinate directions respectively; q_x and q_y are the respective discharge intensities that are related to the average velocity components; g is the gravity acceleration and ρ is the density of water; S_{0x} and S_{0y} are the bed slopes in the x and y directions; S_{fx} and S_{fy} are the corresponding friction slopes; τ_{xx}, τ_{xy}, τ_{yx}, and τ_{yy} are the components of the horizontal turbulent stress tensor.

The governing equations (1)–(3) include two essential steps in computational model, discretization and solution. There are a number of alternatives for each step. Common discretization methods include finite difference, finite

DOI: 10.1002/rra

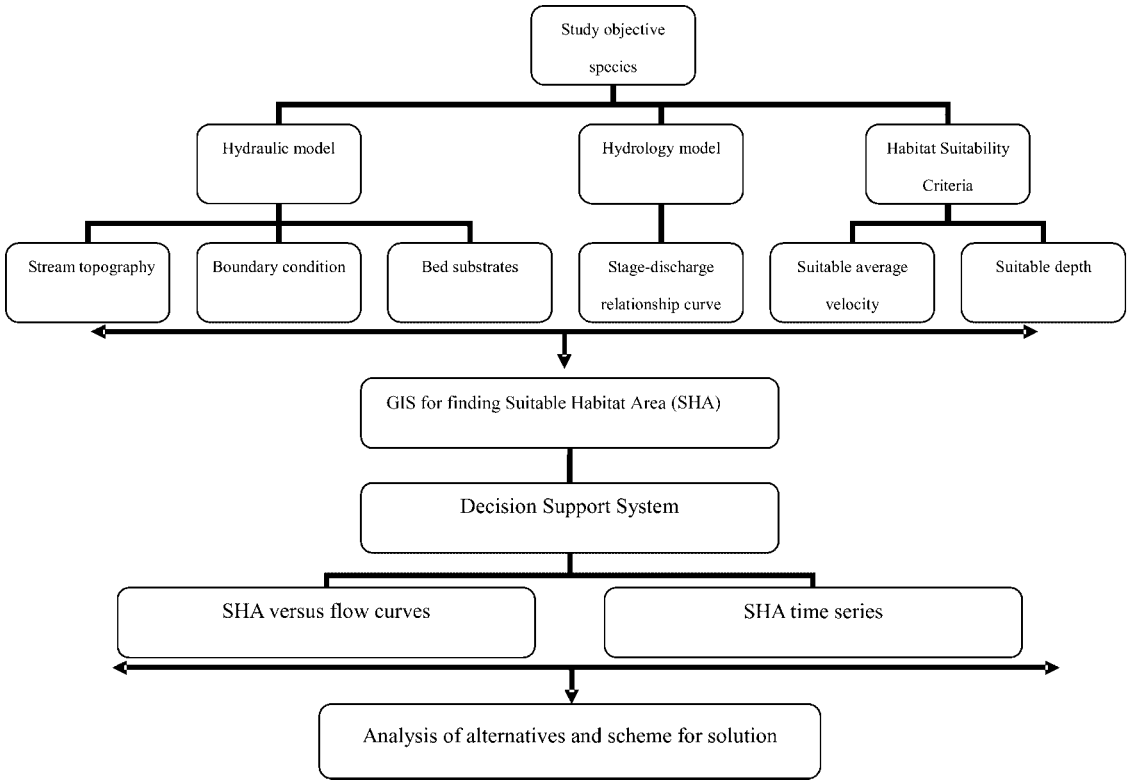

Figure 2. Basic components of a fish habitat model for IFIM

volume and finite element methods. Solution methods include explicit and implicit solvers (Steffler and Blackburn, 2002). River2D is a finite element model, whose basis is generally known as the weighted residual method. The governing equations can be solved approximately by use of a 'trial function', which is specific but has many adjustable degrees of freedom. In some way, the process is analogous to curve fitting to a group of observed data. Values for those two parameters are sought as to the least error. The Finite Element Method used in River2D's hydraulic model is based on the streamline upwind Petrov-Galerkin weighted residual formulation. In this technique, upstream biased test functions are used to ensure solution stability under a full range of flow conditions. As a result, there is no need for mixed interpolations or artificially large transverse diffusivities (Steffler and Blackburn, 2002).

The following are the detailed steps in building a hydraulic model in River2D for the study river segment.

Topography of the study area. The study uses topographic data surveyed by Institute of Hydrobiology in 1999 and 2004. These data are imported into ArcGIS 9.2 software (Environmental Systems Research Institute, USA) for analysis. Topographic survey data in 1999 and 2004 are compared to examine how bed elevation changed during the temporal interval. As shown in Figure 3, the middle of the spawning area has experienced a considerable amount of scouring and filling from 1999 to 2004. Therefore, different topographies should be considered in the hydraulic model. The topographic data from the ArcGIS 9.2 were inputted to River2D_Bed module for setting up a digital bed topography file.

Mesh preparation. The bed topography file is processed in River2D_Mesh module to develop a computational discretization mesh as inputs into River2D. The mesh is based on a finite element method with triangular shape. Border areas are refined with a higher grid density to ensure that these complex places have a higher resolution to enhance topographic agreement between the computational mesh and the bed topography file. Accordingly, a mesh with 4180 nodes and 8338 elements is initially constructed for the study area (Figure 4).

Define the boundary conditions for inlet and outlet. River2D requires input data for boundary conditions, such as a fixed inflow at the inlet boundary upstream and a fixed stage at the outlet boundary downstream. These data are determined by relationship between stage and discharge recorded at the YC gage station. In this study, two different boundary conditions should be considered.

(i) Flows: special flows are chosen after observing a range of daily flows recorded at the YC gage station downstream of the GD. For the inlet boundary upstream, we choose 3000–37000 m^3/s to be the interest flow range

DOI: 10.1002/rra

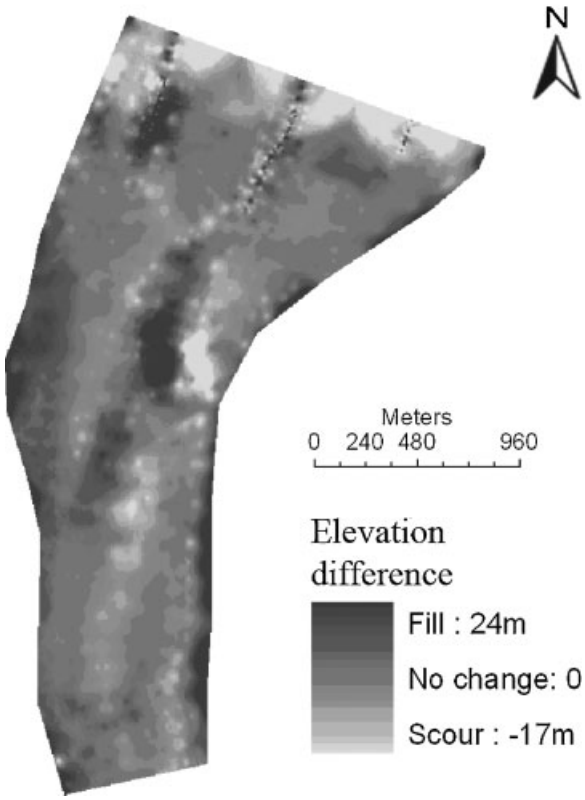

Figure 3. Changes in bed elevation from 1999 to 2004

Figure 4. Finite element mesh developed for the study area

because it essentially represents the observed flow conditions during a spawning period. SHA in spawning period is evaluated for each 2000 m^3/s flow interval. Simulated flow data at the study sites are shown in Table I. The corresponding flow percentiles in natural flow regime are calculated using daily flow data during spawning period recorded at the YC gage station in 1983–2006. The outlet boundary downstream for stage is calculated according to the discharge versus stage curves in spawning period of 1999 and 2004.

(ii) Inlets combinations: another boundary condition is that an inflow may come from different inlets or their combinations at the GD. The study river segment may have different hydraulic distributions depending mainly on different inlet conditions. Figure 1b shows 4 inlets of the GD, of which only B, C and D are considered for inlets area as the discharge from A is too small. According to the operation of the GD, there are four different inlets combinations: 1) B; 2) C; 3) B and D; 4) B, C and D.

Calibration. Calibration of the model is made through adjusting model parameters, such as roughness, mesh density and bed topography file. The model is rerun until reaching a reasonable match between the simulated and the observed profile of depth and average velocity at the calibrated discharge (Bovee *et al.*, 2007). Rather than attempting to achieve an exact match, the preferred solution is to produce a 'best fit' between them with the least error. We exploit 16 transects of depths and average velocities data surveyed in 2004 at three calibrated discharges to test the hydraulic model. Modelling starts with a uniform initial roughness value of 0.037 (Steffler and Blackburn, 2002). Roughness parameters for various substrate materials and mesh density are adjusted successively at each point in bed file until the simulated depth and average velocity match with the surveyed ones at each transect. The relative root mean square error of the final calibration is 0.16 for depth and 0.36 for average velocity.

Hydraulic simulation. The final step is to simulate the hydraulics under different flow scenarios, inlets combinations and topographies. There are 18 flow scenarios ranging from 3000 to 37000 m^3/s, four inlets combinations and two topographies (measured in 1999 and 2004 year), totalizing 144 (18 times 4 times 2) hydraulic conditions needed to deal with. Final results are obtained in the form of simulated depth and average velocity values at each node location under different flow scenarios.

DOI: 10.1002/rra

Table I. The percentile of the simulated upstream flow and downstream stage in a natural regime

Flow(m^3/s)	Flow percentile (%)	Stage from Q-H in 1999	Stage from Q-H in 2004
3000	0	40.09	38.01
5000	10	41.03	39.45
7000	34	41.93	40.81
9000	38	42.80	42.09
11000	79	43.64	43.29
13000	74	44.45	44.41
15000	100	45.23	45.45
17000	93	45.97	46.41
19000	66	46.68	47.29
21000	55	47.36	48.09
23000	26	48.01	48.81
25000	18	48.63	49.45
27000	11	49.21	50.01
29000	8	49.76	50.49
31000	6	50.28	50.89
33000	2	50.77	51.21
35000	1	51.34	51.44
37000	1	52.10	51.73

Determine the suitable range with habitat suitability criteria

Habitat suitability criteria (HSC) is used to discriminate environmental conditions that provide suitable habitat for a target species and those that are considered to be unsuitable. It is a quantitative method to predict the relationship between species and environment, which is based on the attribute of target habitat (Noss and Cooperrider, 1994). HSC can be classified as category I or II, and can be displayed and used as univariate curves or in binary format. Category I criteria are based on professional opinion instead of data. Category II criteria are based on the frequency distributions of microhabitat attributes measured at locations used by the target species. Univariate curves are often used to reflect habitat suitability index (HSI) values changing continuously from 0 to 1, where 0 indicates unsuitable conditions and 1 indicates suitable; values between 0 and 1 indicate intermediate suitability based on a normalized frequency distribution of the observed use by the target species (Bovee, 1986). As a special case, binary format depicts only two cases, either unsuitable (0) or suitable (1). Binary format is derived from the univariate curves, which could be used for a further process in the ArcGIS for reclassifying the SHA under certain water depth and velocity ranges.

In this study, we use category II criteria in binary format. Wei (2003) sampled 126 positions in the spawning habitat of Chinese sturgeon from 1997 to 1999, and counted the frequency number of the detected fish in different depth and velocity ranges. We normalized the frequency to get habitat suitability curves regarding depth and velocity (Figure 5). Here, depth and velocity preferences are assumed independent for all species. We adopt the HSI value of 0.707 to be the lowest limit for both the depth and velocity, corresponding to a composite HSI of 0.5 (0.707 times 0.707) (Mark, 2001). Accordingly, the suitable depths above the HSI value of 0.707 are between 9–14 m (Figure 5a) and the suitable average velocities above the HSI value of 0.707 are between 1.38–1.60 m/s (Figure 5b). The two ranges are then used to make a habitat reclassification in ArcGIS according to a binary format.

Habitat models

Hydraulic data and the suitable binary values for depth and average velocity are combined using the reclassification tools in ArcGIS to predict suitable habitat (Milhous *et al.*, 1989; Elliott *et al.*, 1996). Firstly, Results from River2D hydraulic model are inputted into GIS data layers via an ArcGIS project file containing the coordinate, depth and average velocity at each node in the computational mesh. Values between node locations are interpolated in order to create data layers with a grid size of 10 by 10 m. Then, depth and average velocity data layers are overlaid with preferred substrate habitat data layers for providing a comprehensive description of fish habitat at the study site. Figure 6 shows such an example of finding a suitable habitat area (SHA) at a flow scenario of 9000 m^3/s from inlet B. The depth and average velocity layers are developed from the results of River2D model and reclassified in ArcGIS for finding the suitable range (Figure 6a and Figure 6b). The preferred substrate layer underlying large cobble, which is independent of the flow scenario, is shown in Figure 6c. All these three layers are overlaid to form a suitable habitat area at the flow of 9000 m^3/s (Figure 6d). In this case, the suitable habitats include all areas with depths between 9–14 m, average velocities between 1.38–1.60 m/s and preferred substrate of the spawning Chinese sturgeon.

The procedure is repeated for 144 simulated hydraulic distributions derived from the River2D model for each flow scenarios. Polyarea of the suitable habitat are computed in the attribute tables of ArcGIS for each habitat map and exported to a spreadsheet for subsequent extraction of SHA values, and then development of the SHA versus flow curves used in habitat time series analysis.

Habitat time series with decision support system

DSS is composed of two essential parts, the daily habitat time series and the annual habitat time series, which is built on a Microsoft Excel procedure and visual basic language program and can be used as a tool for strategic planning of alternative scenarios. The SHA results for each year can be

DOI: 10.1002/rra

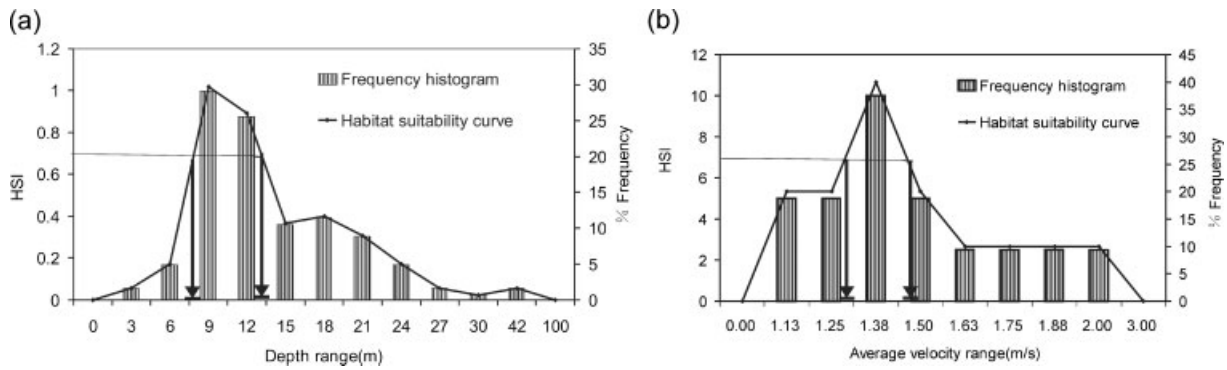

Figure 5. (a) Depth suitability curve for the Chinese sturgeon. (b) Velocity suitability curve for the Chinese sturgeon

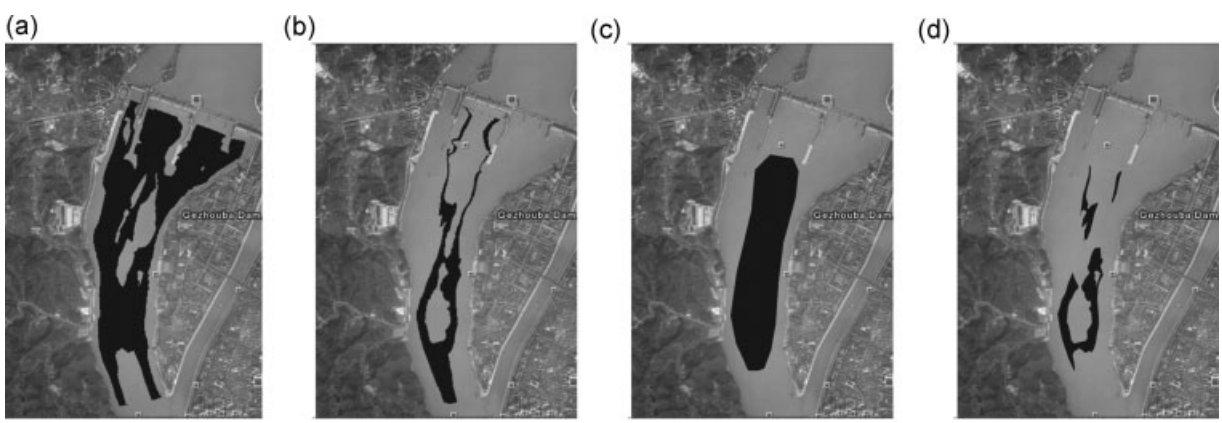

Figure 6. Suitable habitat area for the spawning habitat of Chinese sturgeon at 9000 m^3/s from InletB. The black areas in these figures illustrate the suitable range of depth, velocity, preferred substrate and habitat. (a) $9 < \text{Depth} < 14$ (m). (b) $1.38 < \text{Velocity} < 1.60$ (m/s). (c) Preference substrate. (d) Suitable habitat.

compared to quantify the effects of an alternative management on the habitat for a target organism (Bovee *et al.*, 1998).

Construction of a daily habitat time series is relatively straight-forward, requiring two essential components: a time series of daily flow and a SHA versus flow curve. For each flow in the time series, there is a corresponding SHA value from the SHA versus flow curve (Figure 8). Assembling a time series of habitat is merely a matter of translating the daily flow for each time step into their associated SHA values and recording the translated values back to the time step. Based on the same principle, an annual SHA can then be constructed by averaging the daily SHA time series for each year. The final outputs, often depicted as effective habitat time series or duration curves, are used for recommending environment flow requirements and evaluating alternative flow regulation scenarios (Waddle, 1998a, b).

RESULTS

Suitable habitat area versus flow Curves for different topographies

The relationship between SHA and flow in the spawning period of 1999 and 2004 is modelled with their respective topographies when the inflow from inlet B (Figure 7), a peak magnitude of SHA appears between 7000–13000 m^3/s during both the 2 years. However, the SHA in 2004 is apparently smaller than that in 1999, indicating a potential influence of topography on SHA in the spawning period of Chinese sturgeon.

Suitable habitat area versus flow curves for different inlets combinations

The influence of inlets combinations on SHA in spawning period is also simulated regarding the topography in 2004.

DOI: 10.1002/rra

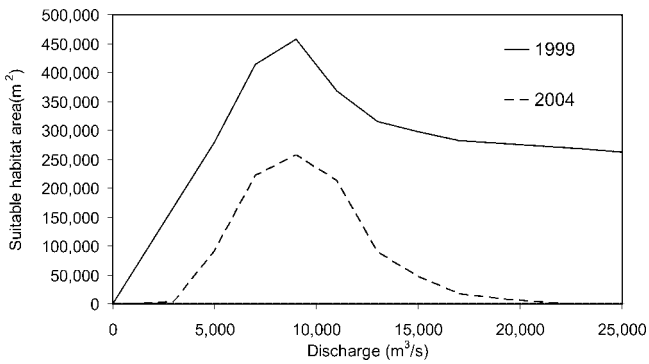

Figure 7. Suitable habitat area versus flow curves for 1999 and 2004 topographies with an inflow from inletB

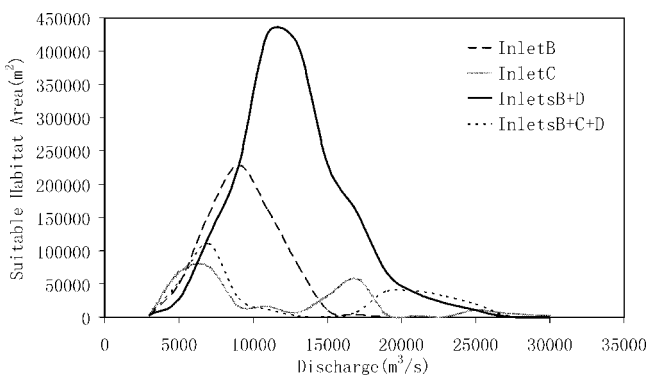

Figure 8. Suitable habitat area versus flow curves in 2004 for different inlets combinations

As shown in Figure 8, an optimal SHA appears when an inflow from combination of inlets B and D, a less from inlet B, and the least from inlet C or from combination of inlets B, C and D. These results indicate that a proper inlet management at the GD inlets can provide a good spawning habitat for Chinese sturgeon.

Habitat time series in spawning time

Since October and November are the spawning season of the Chinese sturgeon (Chang and Cao, 1999), we refer to this period as calculating SHA values in each year. One of the results for daily flow and daily SHA time series in 2004 is shown in Figure 9. From the results, we find that when the flow decreases from October to November, while the SHA increases by a large amount, which essentially agrees with the investigation that the Chinese sturgeon would mostly spawn during the receding flow period in November (Yang *et al.*, 2006). The annual SHA from 1996 to 2006 in spawning period (Figure 10) can be compared to the surveyed amount of spawned eggs in a normalization form. It is seen that the simulated SHA have a similar trend as the surveyed amount of spawned eggs annually (except the year of 1998, 1999 and 2003).

DISCUSSION

Interpretation and evaluation of results

In the IFIM, instream habitat is determined by the factors, such as discharge, topography, hydraulic distribution and the physical requirements of the aquatic organisms. With a few exceptions, a curve of discharge versus habitat area appears as a skewed bell-shaped curve. The common characteristic of these functions is that habitat area tends to increase as discharge increases in the low-to-moderate flow range, but then decreases as discharge continues to increase. Where channel structure and gradient are similar, the peak of the SHA versus flow curve would be expected to occur at or near the same relative (normalized) discharge, although the magnitude of habitat area will vary in bed elevation for different topographies (Figure 7).

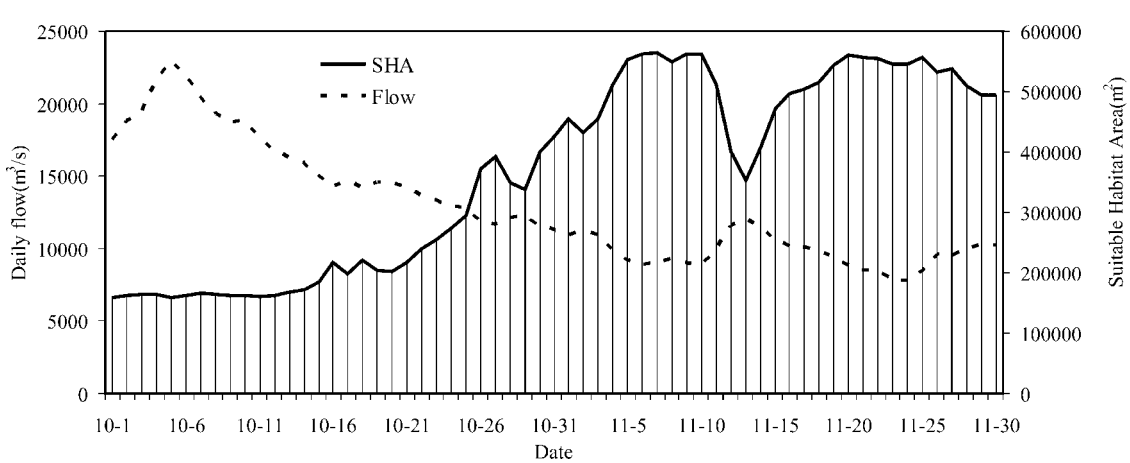

Figure 9. Daily flow and suitable habitat area time series in 2004

DOI: 10.1002/rra

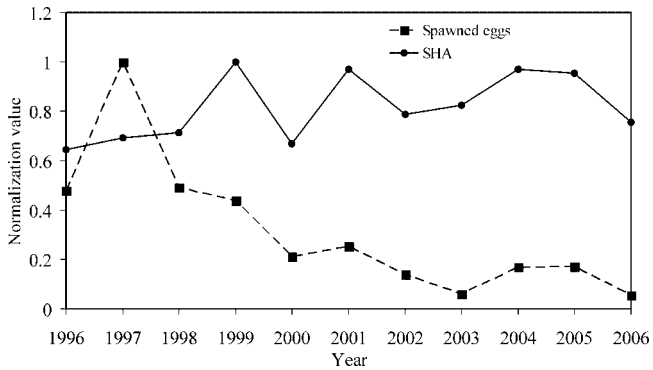

Figure 10. Contrast between annual SHA and spawned eggs

A scenario designed to increase the magnitude of low flows is usually presumed to result in an overall increase in habitat area. When the results displayed in DSS show no change or a negative change for the average SHA, one or two causal factors are often to blame. One common mechanism is reservoir depletion resulting from excessive releases to augment instream flows for habitat improvement. In this case, habitat area may be substantially increased during part of a hydroperiod, but decreased later in the season as reservoir storage is exhausted. It is worthwhile to review these habitat time series graphics routinely, because they may show a counterbalancing increase and decrease in habitat area throughout the hydroperiod despite little or no change to the average for the period (Figure 9). Then, the decision makers must evaluate the outcome to determine whether the change is positive, negative, or neutral. The second common mechanism for a counterintuitive result (reduced habitat area associated with increased base flows) is that the scenario may have resulted in an increased frequency of high-flow events. To help identify potential feedback surprises is advisable to generate flow duration and storage duration curves as routine input to the decision process. This simple step will provide early indications whether the scenario performed hydrologically as it was intended, or whether the scenario created unforeseen consequences.

Issues relating to the development and application of HSIs have generated much discussion in the IFIM literature (Gore and Nestler, 1988; Mäki-Petäys *et al*., 2002). Thomas and Bovee (1993) argued that HSIs are the most significant source of error in habitat modelling. Despite this, relatively few studies (particularly in Europe) have tested the predictive power of different HSIs by relating model output to empirical data on habitat selection by fish (Shirvell, 1989). Behrouz *et al.* (2006) provided an overview of the current statistical methodologies for developing HSIs, he concluded the choice of an appropriate model of developing HSIs depends on the goals and resources of study and especially on the types of measured environmental and response variables. This study developed the HSIs from the field investigation by counting the frequency of the captured fish in different positions, which is suited to apply on the big fish like Chinese Sturgeon in the Yangtze River.

A fundamental paradigm underlying the entire DSS habitat analysis portion is that fish populations respond somehow to changes in SHA. The general hypothesis is that more SHA have the potential to support more fish. Relations between habitat dynamics and population responses are more complex, however, because populations can be affected by variables not included in the habitat models, such as biological growth, life-stages and community interaction. As a result, an increase in adult habitat may have the unintended consequence of reducing recruitment, thereby causing a reduction in adult population over time. Indeed, the few empirical studies that have examined linkages between habitat and biology but failed to identify a unifying connection between the two. Some studies have shown strong relations between fish population size and habitat dynamics (Jowett, 1992; Nehring and Anderson, 1993; Bovee *et al*., 1994; Bowen, 1996; Freeman *et al*., 2001; Capra *et al*., 2003; Fjellheim *et al*., 2003; Souchon and Capra, 2004). However, some have found no relation at all (Irvine *et al*., 1987; Zorn and Seelbach, 1995), and at least one indicated a negative relation (Garciá de Jalón *et al*., 1996). Dunham *et al.* (2002) noted that the relations between habitat and fish populations in individual streams could be variable depending on biological factors, such as presence of non-native species, or spatial factors such as habitat connectivity.

Habitat management decisions must evaluate the differential responses of multiple habitat types to changes in flow. The issue is whether fish populations actually respond to habitat changes described by the model over spatial and temporal scales that are relevant to the decision makers. This study makes a contrast between the average annual SHA and annual spawned eggs (Figure 10), showing that the two variables have a same changing trend along with the year time axis, except the very few years (1998, 1999, 2003 year).

Given the uncertainties of how populations are influenced by habitat dynamics, the IFIM should not be viewed as a precise indicator of population response to flow regime. The IFIM, in its present form, can be used as a tool for strategic planning by some relevant authorities. It is not designed to perform as a tactical tool for daily operations and should not be used as such. Its strength is as a 'hypothesis screener', which can be used to distinguish among alternatives that may be effective or ineffective, feasible or infeasible, high-risk or low-risk. In many decision environments, such information is sufficient for policy makers to decide on a course of action and implement it.

DOI: 10.1002/rra

Application and adaptive management

It is the first time to apply IFIM on studying the aquatic habitat of Chinese sturgeon. We use IFIM method to analyse effects of different flow managements on the spawning habitat of Chinese sturgeon. The results show that the simulated habitat areas and the surveyed amount of spawned eggs in each year follow basically the same trends, indicating that there is a certain relationship between SHA and the reproductive quantity of the Chinese sturgeon; the SHA could reflect the reproductive conditions of the Chinese sturgeon. Therefore, we can use this habitat model to assess habitat conditions in different flow scenarios. Habitat time series, in conjunction with effective habitat analysis, allow the manager to determine if there are associations between weak or strong year-classes flows and patterns of habitat constriction or abundance of available habitat in the simulated history of the stream (Trihey, 1981). By adjusting the ratios of habitat required in different life stages, the manager can develop a time series of effective habitat that corresponds with population trends and patterns of year-class strength, calculated growth histories, and other aspects of the population status (Milhous *et al*., 1990).

Our analyses indicate that the spawning habitat of Chinese sturgeon is variously affected by discharge, channel topography, substrate quality and the inflow conditions at the GD. According the model results, some adaptive management schemes could be adopted for protecting the spawning habitat of Chinese sturgeon. Firstly, the spawning habitat area of Chinese sturgeon is mainly influenced by flow with the optimal rates ranging between 7000–13000 m^3/s in spawning time. So, the TGD could satisfy the inflow of the GD within this range in the spawning time of Chinese sturgeon; Secondly, Bed topography and substrate quality have a great influence on the spawning habitat of Chinese sturgeon. For keeping a stable spawning habitat, it is suggested that the construction activities of changing the bed topography should be kept at a minimum. Thirdly, the GD operation should avoid the flow released from the spillway and Erjiang power plant, because the flows released from the two positions scour the topography near the big bend of right bank, which are disadvantages for keeping a stable habitat topography and substrate; Fourthly, different inlets combinations may also influence the hydraulic distribution of the spawning habitat. The simulation results indicate the best inlets combination is the inflow from Dajiang and Erjiang power plants (Figure 1b). Conversely, the inflow from the spillway will make the SHA decline greatly, due to its scouring the topography and concomitant turbulent eddy, which would exceed the suitable binary velocity range. Accordingly, the GD operation should control the inlets management for preventing the inflow from the spillway in the spawning time.

CONCLUSION

This study has shown that IFIM can be successfully applied to the spawning habitat protection of Chinese sturgeon. The fish habitat modelling methods developed here show great promise for adaptation to instream flow assessment studies, such as for ecological flow management of TGD and GD projects. The results show that the optimal flow for the spawning habitat of Chinese sturgeon is about 7000–13000 m^3/s and the optimal inlets combination is the inflow from the two power plants. In addition, the topography may have a great influence on the spawning habitat of Chinese sturgeon. As changing the topography seems unrealistic and difficult to implement, the best potential scheme is to control a suitable range of inflow in the spawning time.

As its definition, the IFIM could be used as a precursor in making a reasonable and operational management, which can be tested in actual operation. As in the case of the GD and TGD projects, limited reservoir capacity and water supplies hinder full experimental control, but partial control is possible. Experimental control could be established by implementing the baseline operations of the reservoirs as depicted in the DSS for several years. During that time, reservoir releases, stream discharge, habitat dynamics and population (for example, year class strength, growth rates and adult populations) would be monitored. The experimental treatment would consist of monitoring the same variables for a similar length of time, but operating the reservoirs according the alternative depicted in the DSS. The TGD could operate the flow according to this research to provide an ecological inflow condition for the Chinese sturgeon. In the future, we believe linking the dynamics of habitat to the dynamics of fish populations and community characteristics will become increasingly important.

ACKNOWLEDGEMENTS

The work has received a great help in building River2D Model and practicing ArcGIS from Bovee Ken D and Terry J Waddle in US Geological Survey, Fort Collins Science Center. We are very appreciated with their technique and suggestions for the habitat research of Chinese sturgeon. This work is supported by the Knowledge Innovation Program of the Chinese Academy of Sciences (Grant No.kzcx2-yw-141) and funded by the National Natural Science Foundation of China (Grant No.50479037).

REFERENCES

Armour CL, Taylor JG. 1991. Evaluation of the instream flow incremental methodology by US Fish and Wildlife Service field users. *Fisheries* **16**(5): 36–43. DOI: 10.1577/1548-8446. (1991)16<0036:EOTI-0036:EOTIFI>2.0.CO;2

Behrouz AN, André SH, Michel B, Élaine R, Nathalie T, Bernard B. 2006. A review of statistical methods for the evaluation of aquatic habitat suitability for instream flow assessment. *River Research and Applications* **22**: 503–523.

Bovee KD. 1982. A guide to stream habitat analysis using the instream flow incremental methodology. US Fish and Wildlife Service FWS/OBS-82/26:248.

Bovee KD. 1986. *Development and evaluation of habitat suitability criteria for use in the instream flow incremental methodology.* US Fish and Wildlife Service Biological Report 86 (7). 235.

Bovee KD, Newcomb TJ, Coon TG. 1994. Relations between habitat variability and population dynamics of bass in the Huron River, Michigan: US Department of the Interior, National Biological Survey, Biological Report 21. 63.

Bovee KD, Lamb BL, Bartholow JM, Stalnaker CB, Taylor J, Henriksen J. 1998. *Stream habitat analysis using the instream flow incremental methodology.* US Geological Survey, Biological Resources Division Information and Technology Report 8. 131.

Bovee KD, Waddle TJ, Bartholow J, Burris L. 2007. *A decision support framework for water management in the upper Delaware River.* US Geological Survey Open-File Report 1172. 27.

Bowen ZH. 1996. *Relations between fishes and habitat in the Tallapoosa River system, Alabama*. Alabama, Auburn University, PhD dissertation: 109.

Capra H, Sabaton C, Gouraud V, Souchon Y, Lim P. 2003. A population dynamic model and habitat simulation as a tool to predict brown trout demography in natural and bypassed stream reaches. *River Research and Applications* **19**(5–6): 551–568. DOI: 10.1002/rra.729.

Chang JB, Cao WX. 1999. History and prospect of conservation on the Chinese sturgeon in the Yangtze River. *Acta Hydrobiologica Sinica* **23**: 713–720. (In Chinese).

Dunham JB, Cade BS, Terrell JW. 2002. Influences of spatial and temporal variation on fish–habitat relationships defined by regression quantiles. *Transactions of the American Fisheries Society* **131**: 86–98. DOI: 10.1577/1548-8659. (2002)131<0086:IOSATV>2.0.CO;2

Elliott CRN, Johnson IW, Sekulin AE, Dunbar MJ, Acreman MC. 1996. *Guide to the use of the physical habitat SImulation system. Environment Agency.* Bristol, UK. R&D Technical Report W20.

Fjellheim A, Barlaup BT, Gabrielsen SE, Raddum GG. 2003. Restoring fish habitat as an alternative to stocking in a river with strongly reduced flow. *International Journal of Ecohydrology and Hydrobiology* **3**(1): 17–26.

Flower RJ, Thompson JR. 2008. An overview of integrated hydro-ecological studies in the MELMARINA Project: monitoring and modelling coastal lagoons—making management tools for aquatic resources in North Africa. *Hydrobiologia* **622**(1): 3–14. DOI: 10.1007/s10750-008-9674-8

Freeman MC, Bowen ZH, Bovee KD, Irwin ER. 2001. Flow and habitat effects on juvenile fish abundance in natural and altered flow regimes. *Ecological Applications* **11**(1): 179–190. DOI: 10.1890/1051-0761 (2001)011[0179: FAHEOJ]. 2.0.CO;2

Gore JA, Nestler JM. 1988. Instream flow studies in perspective. *Regulated River: Research and Management* **2**: 93–101. DOI: 10.1002/rrr.3450020204

Garciá deJalón, D, Mayo M, Molles MC. 1996. Characterization of Spanish Pyrenean stream habitat relationships between fish communities and their habitat. *Regulated Rivers: Research and Management* **12**: 305–316. DOI: 10.1002/ (SICI) 1099-1646(199603) 12:2/3. <305:AID-RRR397> 3.0.CO;2-B

Hu DG, Ke FE, Zhang GL, Luo JD, Gong MH. 1992. Investigation on the spawning ground of *A. sinensis* down Gezhouba Dam. *Freshwater fisheries* **22**: 6–10. (In Chinese).

Irvine JR, Jowett IG, Scott D. 1987. A test of the instream flow incremental methodology for underyearling rainbow trout, Salmo gairdnerii, in experimental New Zealand streams. *New Zealand Journal of Marine and Freshwater Research* **21**(1): 35–40.

Jowett IG. 1992. Models of the abundance of large brown trout in New Zealand Rivers. *North American Journal of Fisheries Management* **12**: 417–432. DOI: 10.1577/1548-8675 (1992)12<0417:MOTAOL. >2.3.CO;2

Mark WW. 2001. *Two-dimensional fish habitat modeling for instream flow assessment in Texas. Las Cruces, New Mexico*. New Mexico State University. PhD dissertation. 59–59.

Mäki-Petäys A, Huusko A, Erkinaro J, Muotka T. 2002. Transferability of habitat suitability criteria of juvenile Atlantic salmon (Salmo salar). *Canadian Journal of Fisheries and Aquatic Science* **59**: 218–228.

Milhous RT, Updike MA, Schneider DM. 1989. Physical Habitat Simulation System Reference Manual-Version 2. Instream Flow Information Paper 26. USDI Fish and Wildlife Services, Biology Report 89 (16).

Milhous RT, Bartholow JM, Updike MA, Moos AR. 1990. Reference manual for the generation and analysis of habitat time series-version II US Fish and Wild life Service Biological Report 90 (16) 249.

Milhous RT. 1998. *Application of the principles of IFIM to the analysis of environmental flow needs for substrate maintenance in the Trinity River, northern California*. US Geological Survey, Biological Research Division and Water Research Institute, Fort Collins, and Water Research Institute, Report 98 (17) 50–552.

Nehring RB, Anderson RM. 1993. Determination of population-limiting critical salmonid habitats in Colorado streams using the Physical Habitat Simulation System. *Rivers* **4**(1): 1–19.

Noss RF, Cooperrider AY. 1994. *Saving Nature's Legacy.* Island Press: Wash. D.C; 416.

Reiser DW, Wesche TA, Estes C. 1989. Status of instream flow legislation and practise in North America. *Fisheries* **14**(2): 22–229.

Shirvell CS. 1989. Ability of PHABSIM to predict chinook salmon spawning habitat. *Regulated Rivers: Research and Management* **3**: 277–289. DOI: 10.1002/rrr.3450030127

Souchon Y, Capra H. 2004. Aquatic habitat modelling–biological validations of IFIM/Phabsim methodology and new perspectives. *Hydroecologie appliqué* **14**(1): 9–25.

Stalnaker CB, Lamb L, Henriksen J, Bovee K, Bartholow J. 1995. *The Instream Flow Incremental Methodology—A Primer for IFIM.US.* Department of the Interior, National Biological Service, Fort Collins, Colo. Biological Report 29: 156.

Stalnaker C, Bovee KD, Waddle TJ. *Importance of the temporal aspects of habitat hydraulics to fish population studies*. 1998. River Research and Applications **12**(3): 145–153.

Steffler P, Blackburn J. 2002. Two-dimensional depth averaged model of river hydrodynamics and fish habitat: Introduction to depth averaged modeling and users manual: Edmunton, Alberta, Canada, University of Alberta: 20.

Tharme RE. 2000. An overview of environmental flow methodologies, with particular reference to South Africa. In Environmental Flow Assessments for Rivers: Manual for the Building Block Methodology. Water Research Commission Technology Transfer Report No. TT131/00. Water Research Commission: Pretoria, South Africa: 15–40.

Thomas JA, Bovee KD. 1993. Application and testing of a procedure to evaluate transferability of habitat suitability criteria. *Regulated Rivers: Research and Management* **8**: 285–294. DOI: 10.1002/rrr.3450080307.

Trihey EW. 1981. Using time series stream flow data to determine project effects on physical habitat for spawning and incubating pink salmon. Acquisition and utilization of aquatic habitat inventory information, proceeding of a symposium. Western Division of the American Fisheries Society, Portland, Oreg: 232–240.

Trihey EW, Stalnaker CB. 1985. Evolution and application of insteam flow methodologies to small hydropower development: an overview of the issues. F.W. Olson: 176–183.

Waddle TJ, Blazkova S, Stalnaker CB, Novicky O. 1998a. Integrating microhabitat and macrohabitat. U.S. Geological Survey Biological Research Division and Water Research Institute Press: Praha.

Waddle TJ, Blazkova S, Stalnaker CB, Novicky O. 1998b. Development of 2-dimensional habitat models. U.S. Geological Survey Biological Research Division and Water Research Institute Press: Praha.

Wei QW, Ke FE, Zhang JM, Zhuang P, Luo JD, Zhou RQ. 1997. Biology, fisheries, and conservation of sturgeons and paddlefish in China. *Environmental Biology of Fishes* **48**: 241–255. DOI: 10.1023/A: 1007395612241

Wei QW. 2003. Reproductive Behavioral Ecology of *Acipenser sinensis* with its Stock Assessment, Institute of Hydrobiology, Chinese Academy of Sciences, WuHan, HuBei, China: 121 (in Chinese).

Wu XW. 1963. *Economic Animals of China (freshwater fishes)*. Science Press: Beijing. 126 (in Chinese).

Xiao H, Chang JB, Liu Y. 1999. Evaluation on status of artificial propagation and releasing of *A. sinensis* in the Yangtze River. *Acta Hydrobiologica Sinica* **23**: 572–576. (in Chinese).

Yangtze Aquatic Resources Survey Group (YARSG). 1988. The biology of the sturgeons and paddlefish in changjiang and their artificial propagation. Sichuan Scientific and Technical, Chengdu (in Chinese).

Yang DG, Kynard B, Wei QW, Chen XH, Zheng WD, Du H. 2006. Distribution and movement of *Acipenser sinensis* in spawning ground located below the Gezhouba Dam during spawning seasons. *J Appl Ichthyology* **22**: 145–151 (in Chinese).

Zhao Y, Huang X, Yu Z. 1986. Current Status of Juveniles of the Chinese sturgeon. *Reservior Fisheries* **6**: 38–41. (in Chinese).

Zorn TG, Seelbach PW. 1995. The relation between habitat availability and the short-termcarrying capacity of a stream reach for smallmouth bass. *North American Journal of Fisheries Management* **15**(4): 773–783. DOI: 10.1577/1548-8675. (1995)15<0773:TRBHAA>2.3.CO;2