Global Ecology and Conservation 23 (2020) e01060

Contents lists available at ScienceDirect

Global Ecology and Conservation

journal homepage: http://www.elsevier.com/locate/gecco

Original Research Article

Ecohydraulic model development and application: Evaluating the habitats and population of rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*), and flannelmouth sucker (*Catostomus latipinnis*) in Colorado River

Weiwei Yao

Department of Civil, Geo and Environmental Engineering, Technical University Munich, Munich, Germany

ARTICLE INFO

Article history:
Received 23 January 2020
Received in revised form 9 March 2020
Accepted 11 April 2020

Keywords:
Ecohydraulic model system
Fish number
Fish density distribution
Rainbow trout (*Oncorhynchus mykiss*)
brown trout (*Salmo trutta*)
Flannelmouth sucker (*Catostomus latipinnis*)

ABSTRACT

Ecohydraulics often requires the use of advanced numerical models and ecological theories, which are used for river and aquatic organism management. In this study, a 2D ecohydraulic model system was proposed and used to evaluate the habitat suitability index, weighted useable areas, overall suitability index, fish population number, and fish population density of Colorado River. The 2D ecohydraulic model system comprised hydrodynamic, hydromorphology, habitat, and population models. Three fish species were selected as target fish, which included rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*), and flannelmouth sucker (*Catostomus latipinnis*). Five computational domains of the Colorado River were selected for the ecohydraulic model. The surveyed fish data from 2000 to 2009 were used to calibrate the model system. Results indicated that the predicted fish number showed a good agreement with the surveyed fish. It is indicated that the rainbow trout and brown trout fish number showed decreasing trends from 2000 to 2009, while flannelmouth sucker showed increasing trend from 2000 to 2009. The proposed approach demonstrates that the ecohydraulic model system can be used to accurately simulate the river habitat quality and population status. The ecohydraulic model can be an efficient tool to improve understanding of the different scenarios and to assistant for multiple fish habitat and population prediction in river system. It can also provide decision-makers with valuable information to optimize their management.

1. Introduction

Ecohydraulics often requires the use or development of advanced numerical models and ecological theories, which can provide the most accurate results for river and aquatic organism management (Lancaster and Downes, 2010; Rice et al., 2010). Several researchers have explained hydraulic engineering and ecological requirements and have discussed meaningful research topics such as river and fish physical habitat and population models (Wang and Lin, 2013; Yao et al., 2014a,b,c; Zhang et al., 2016). With this advanced knowledge, ecohydraulics can be used for developing effective approaches to freshwater hydraulic and river infrastructure, for managing dam effect on river deformation, and for predicting trends in aquatic species

E-mail address: harry.yao@tum.de.

https://doi.org/10.1016/j.gecco.2020.e01060

number and density fluctuations (Lancaster and Downes, 2010). Therefore, evaluating the effects of physical variables on fish habitat, fish abundance, and density distribution is essential for the development of the ecohydraulic model system.

The Colorado River is an essential water resource in the western region of the United States of America, serving as the main source of drinking water for more than 25 million people and providing a unique ecosystem for the aquatic species thriving there. The Colorado River has been extensively engineered to meet these demands. The river has 22 major storage reservoirs and eight major out-of-basin diversions. The two largest storage projects—Hoover and Glen Canyon Dams—are located at the downstream and upstream ends of the Grand Canyon National Park. The Glen Canyon Dam is located just north of the Grand Canyon National Park, creating Lake Powell. At full capacity, Lake Powell holds 3.3×10^9 m^3 of water and is the key storage unit within the Colorado River Storage Project (Gloss et al., 2005).

The study covered the area of the Colorado River from Lees Ferry to 50 km upstream of Lake Mead in the State of Arizona, United States of America (latitude 35°30′N to 37°0′N, longitude 111°30′W to 114°0′, see Fig. 1). This area was divided into five subareas according to the U. S. Geological Survey's Grand Canyon Monitoring and Research Center. In each subarea, one segment was chosen to represent the hydraulic and ecological status of that stretch of the river. The averaged values of the five subareas were used to represent the whole river. In this case study, the hydrodynamics, hydromorphology, habitat quality, population numbers, and population densities for the years from 2000 to 2009 were simulated.

The Colorado River is a crucial and long-term fish monitoring and management area (Coggins, 2008). For example, since the 1990s, several artificial flow tests have been conducted to benefit endangered species, and since 2000, two fish monitoring trips have been conducted each year (Makinster et al., 2010, 2011). Fish monitoring operations indicate that both non-native fish species and native fish species live in the Colorado River. The rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*), and flannelmouth sucker (*Catostomus latipinnis)* were selected as target species and divided into four life stages: larval, juvenile, adult, and spawning (Allen, 1983). These target fish species have been affected by dam-induced changes since the completion of Glen Canyon Dam. The historical data of fish monitoring in the Colorado River indicates that both rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) are non-native and are the most abundant fish species in the studied river; by contrast, the flannelmouth sucker (*Catostomus latipinnis)* is a typical native fish (Tyus et al., 1982; Minckley et al., 2003; Makinster et al., 2010) (Fig. 2).

Herein, an ecohydraulic model system was used to estimate the population dynamics of the target fish by fitting the model to a variety of data collected from 2000 to 2009, including number of fish caught and fish length; population estimates of target fish in cases studied between 2000 and 2009. The target fish species were captured; sample site selection was relatively consistent; the target fish were captured during spring. To determine the abundance and life stage of these target fish species, fish numbers, total lengths, and weights for all captured rainbow trout, brown trout, and flannelmouth suckers were recorded. These data were treated as inputs to the ecohydraulic model system. The aim of this study was to propose an ecohydraulic model system, which is a habitat-dependent population structure, and apply the proposed ecohydraulic model system to evaluate the habitat and population conditions of the rainbow trout (*Oncorhynchus mykiss*), the brown trout (*Salmo trutta*), and the flannelmouth sucker (*Catostomus latipinnis*) based on historical flow, geometry records, and fish number data. The other key objective of the proposed model is to present sensitivity analysis for the ecohydraulic model system.

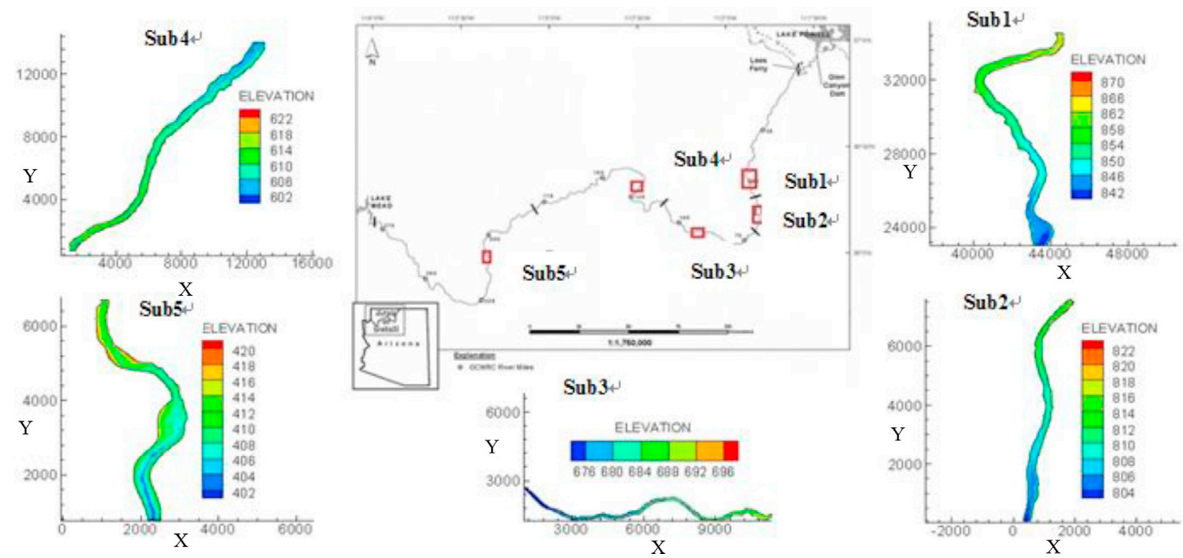

Fig. 1. Scheme of study area in the Colorado River and computational domain of the meshes in the five subareas.

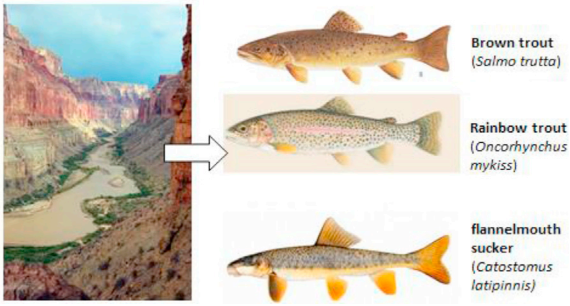

Fig. 2. The three main fish species living in Colorado River (rainbow trout (*Oncorhynchus mykiss*), Brown trout (*Salmo trutta*) and flannelmouth sucker (*Catostomus latipinnis*)). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2. Model system frameworks

The ecohydraulic model system is designed to incorporate hydrodynamic and hydromorphology models into fish habitat models and fish population models. A conceptual framework of the model system is presented in Fig. 3, where the population models are divided into a logistic population model and a fish length population model. Detailed model descriptions can be found in Yao (2016).

2.1. Hydrodynamic and hydromorphology models

In ecohydraulic management, numerical simulation has been widely accepted as an engineering practice tool and a cost-effective design tool. Hydrodynamic and hydromorphology models are the foundation of ecohydraulic management. In the present study, the updated OPEN-TELEMAC source codes were proposed and used to predict the fluvial process (Dobler et al., 2014; Riadh et al., 2014). The 2D shallow water equation, turbulence model, bed deformation based on equilibrium bed load formulae, and grain size distribution in the riverbed were applied. The five subareas of the computation domain had representation areas of 7,732,385, 1,831,706, 1,459,146, 9,481,128, and 2,607,416 m^2; they were named Sub1, Sub2, Sub3, Sub4, and Sub5, respectively. The computational grid was developed to cope with flow discharges ranging from 2000 to 2009. The grid system is composed of triangular grids with 5709 mesh cells and 10,549 nodes for Sub1, with 6059 mesh cells and 11,225 nodes for Sub2, with 6216 mesh cells and 11,010 nodes for Sub3, with 6858 mesh cells and 12,736 nodes for Sub4, and with 7525 mesh cells and 14,260 nodes for Sub5.

2.2. Fish habitat model

Only three vital indices velocity, water depth, and substrate distribution were considered in this study. In the Colorado River, the reason for choosing these three parameters is that the velocity, depth, and substrates override the role of other physical parameters and appear to have critical effects on the three chosen target fish species living in the Colorado River. The SI curves were created based on the observed fish data, scientific reports, professional judgments, and laboratory information on the effect of each parameter on the rainbow trout, the brown trout, and the flannelmouth sucker. The three selected fish species were divided into four life stages (larval, juvenile, adult, and spawning); the SI curves of each life stage are shown in Fig. 4; the source terms are indicated in Table 1. The habitat suitability index (HSI) was used to evaluate the habitat quality and suitable areas. The habitat model provides a method for assessing the existing habitat conditions for fish by measuring how well each habitat variable meets the habitat requirements of the target species' life stage. The HSI was calculated for each mesh cell and each time step using Equation (1). Equations (2) and (3) were used to calculate the weighted useable area (WUA) and the overall suitability index (OSI), respectively. This approach has also been tested and verified by previous researchers (Moir et al., 2005; Mouton et al., 2007; Yi et al., 2010). In the present study, HSI, WUA, and OSI for the three selected fish species and four life stages in all five subareas were simulated.

$$HSI_{i,\ t} = (SI_v \cdot SI_d \cdot SI_s)^{1/3} \tag{1}$$

$$WUA = \sum_{i=1}^{M} A_i HSI_i \tag{2}$$

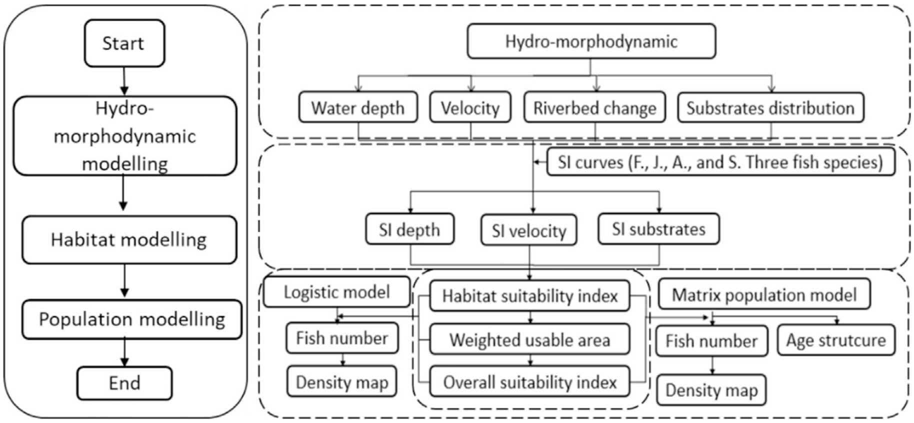

Fig. 3. The schematic flowchart of the ecohydraulic modeling.

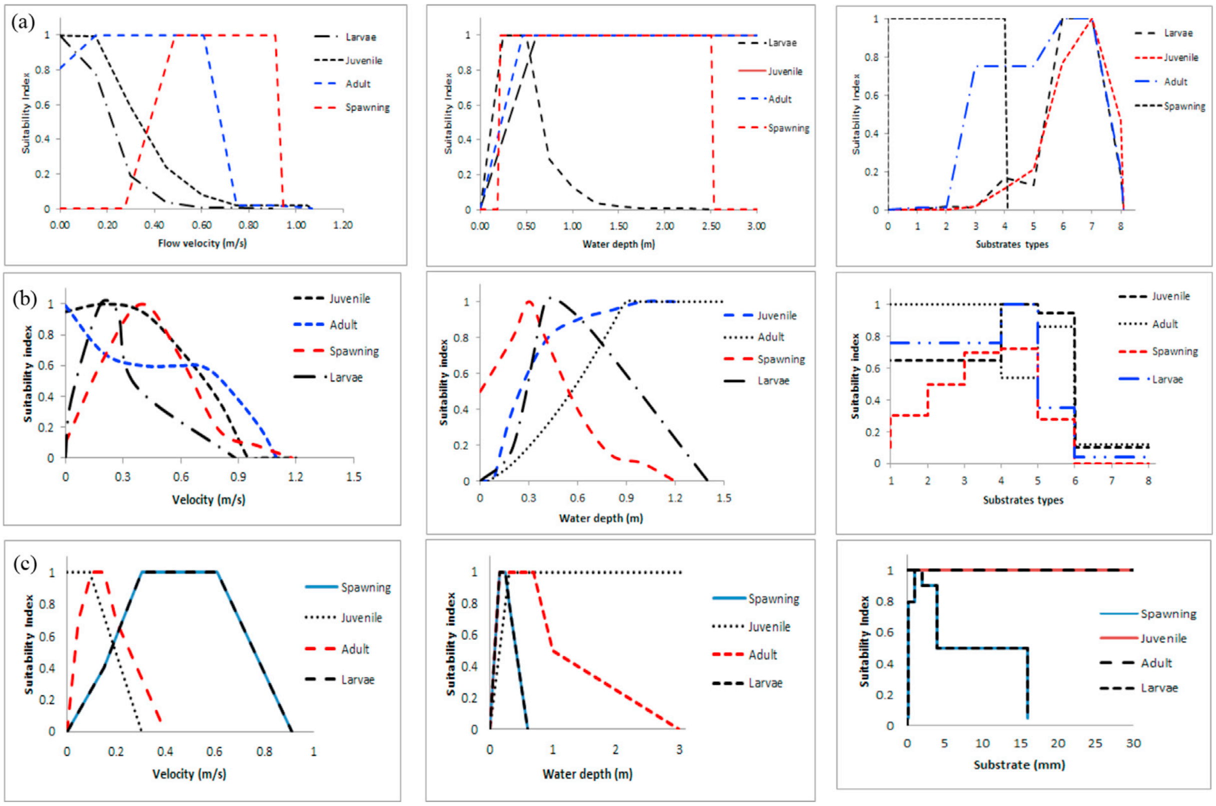

Fig. 4. Fish preference curves of rainbow trout (a), brown trout (b), and flannelmouth sucker (c) (Substrates types: 1 = plant detritus/organic material, 2 = mud/soft clay, 3 = silt (particle size < 0.062 mm), 4 = sand (particle size 0.062–2.000 mm), 5 = gravel (particle size 2.0–64.0 mm), 6 = cobble/rubble (particle size 64.0–250.0 mm), 7 = boulder (particle size 250.0–4000.0 mm), 8 = bedrock (solid rock)). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

$$OSI = \frac{\sum_{i=1}^{M} A_i HSI_i}{\sum_{i=1}^{M} A_i} \tag{3}$$

Table 1
Suitability indexes for Rainbow trout, Brown trout and Flannelmouth sucker.

Fish species	Index	Fish preference curve source
Rainbow trout	Velocity	Raleigh et al. (1984)
	Water depth	Raleigh et al. (1984)
	Substrates	Raleigh et al. (1984)
Brown trout	Velocity	Raleigh, Zuckerman & Nelson (1986)
	Water depth	Raleigh, Zuckerman & Nelson (1986)
	Substrates	Raleigh, Zuckerman & Nelson (1986)
Flannelmouth sucker	Velocity	Rees et al. (2005), Kightlinger (2006), McKinney (1999), Twomey (1984)
	Water depth	Rees et al. (2005), Kightlinger (2006), McKinney (1999), Twomey (1984)
	Substrates	Rees et al. (2005), Kightlinger (2006), McKinney (1999), Twomey (1984)

where SI_v, SI_d, and SI_s are the suitability indices for velocity, water depth, and substrates, respectively; A_i is the horizontal surface of mesh cell i (m^2), HSI_i is the HSI of mesh cell i, and M the number of meshes in the studied stretch of the river.

2.3. Fish population model

Two robust population models, the logistic and fish length population models, were used to simulate and predict the fish population numbers and density changes with time. The logistic population model is composed of the growth rate and the fish numbers that the river habitat can support. In this model, the WUA and OSI were used to represent the maximum number and the growth rate, respectively, to predict the changes of total fish population number, which can be calculated as follows (Yao et al., 2014; Yao, 2016):

$$P^F_{t+\Delta t} = \frac{\beta \times WUA^F_{t+\Delta t} \times P^F_t \times e^{\alpha \times \left(OSI^F_{t+\Delta t} - OSI^F_t\right)}}{\beta \times WUA^F_{t+\Delta t} + P^F_t \times \left(e^{\alpha \times \left(OSI^F_{t+\Delta t} - OSI^F_t\right)} - 1\right)} \tag{4}$$

The fish length population model was converted from matrix population model and it presented as follows:

$$\begin{bmatrix} NL_{1,t+\Delta t} \\ NL_{2,t+\Delta t} \\ \dots \\ NL_{i,t+\Delta t} \\ \dots \\ NL_{j,t+\Delta t} \\ \dots \\ NL_{n-1,t+\Delta t} \\ NL_{n,t+\Delta t} \end{bmatrix} = \begin{bmatrix} F_{1,t} & F_{2,t} & \dots & F_{i,t} & \dots & F_{j,t} & \dots & F_{n-1,t} & F_{n,t} \\ S_{1,t} & 0 & \dots & 0 & \dots & 0 & \dots & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & 0 & \dots & 0 & \dots & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & 0 & \dots & 0 & \dots & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & 0 & \dots & 0 & \dots & 0 & 0 \\ 0 & 0 & \dots & 0 & \dots & 0 & \dots & S_{n-1,t} & S_{n,t} \end{bmatrix} \times \begin{bmatrix} NL_{1,t} \\ NL_{2,t} \\ \dots \\ NL_{i,t} \\ \dots \\ NL_{j,t} \\ \dots \\ NL_{n-1,t} \\ NL_{n,t} \end{bmatrix} \tag{5}$$

with

$$\begin{aligned} F_{i,t} &= f_{i,t} \times \left(1 + \frac{e^{\left(OSI_{i,t}-a\right)} - e^{-\left(OSI_{i,t}-a\right)}}{e^{\left(OSI_{i,t}-a\right)} + e^{-\left(OSI_{i,t}-a\right)}}\right); \\ S_{i,t} &= s_{i,t} \times \left(1 + \frac{e^{\left(OSI_{i,t}-b\right)} - e^{-\left(OSI_{i,t}-b\right)}}{e^{\left(OSI_{i,t}-b\right)} + e^{-\left(OSI_{i,t}-b\right)}}\right) \end{aligned} \tag{6}$$

where $NL_{i,t}$ and $NL_{i,t+1}$ are the fish numbers at time t and t+Δt for fish length i stage; the other parameters are the same as mentioned before. By using the logistic population model and fish length population model, the selected fish species numbers can be calculated. However, to consider the fish density distribution in the river, the fish population density equation was also applied. In this study, the population density $P^F{}_{i,t}$ in mesh cell i at time t is defined as

$$P^F_{i,t} = \frac{A_{i,t} \times HSI^F_{i,t} \times P^F_t}{WUA^F_t} \tag{7}$$

where A_i is the horizontal surface of mesh cell i (m^2), HSI_i is the HSI of mesh cell i (−). $P^F{}_{i,t}$ is the population density (fish number/per mesh cell).

The performance levels of the population models were examined with the modified root mean squared error (RMSE), mean absolute error (MAE), and percentage bias (PBIAS). This concept is based on the concepts of RMSE, MAE, and PBIAS as explained in a published study (Yao et al., 2011).

$$MAE = \frac{\sum_{1}^{n}\left|\frac{P_{i,t}^{sim(F)}}{P_{\max,t}^{sim(F)}} - \frac{P_{i,t}^{obs(F)}}{P_{\max,t}^{obs(F)}}\right|}{n} \times 100\% \tag{8}$$

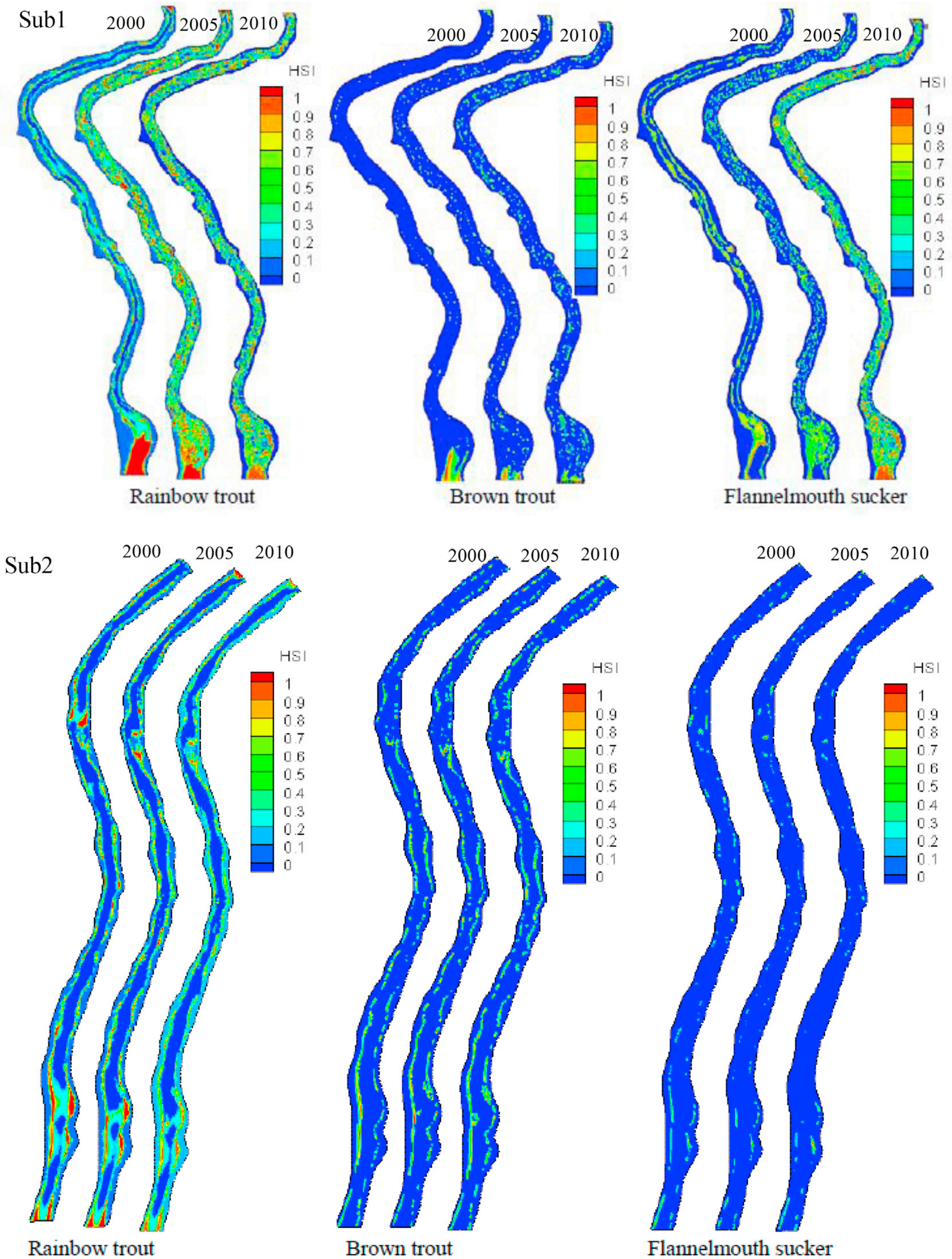

Fig. 5. The simulated habitat suitability index distribution for the adult rainbow trout, brown trout, and flannelmouth sucker in river stretch Sub1, Sub2, Sub3, Sub4 and Sub5. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

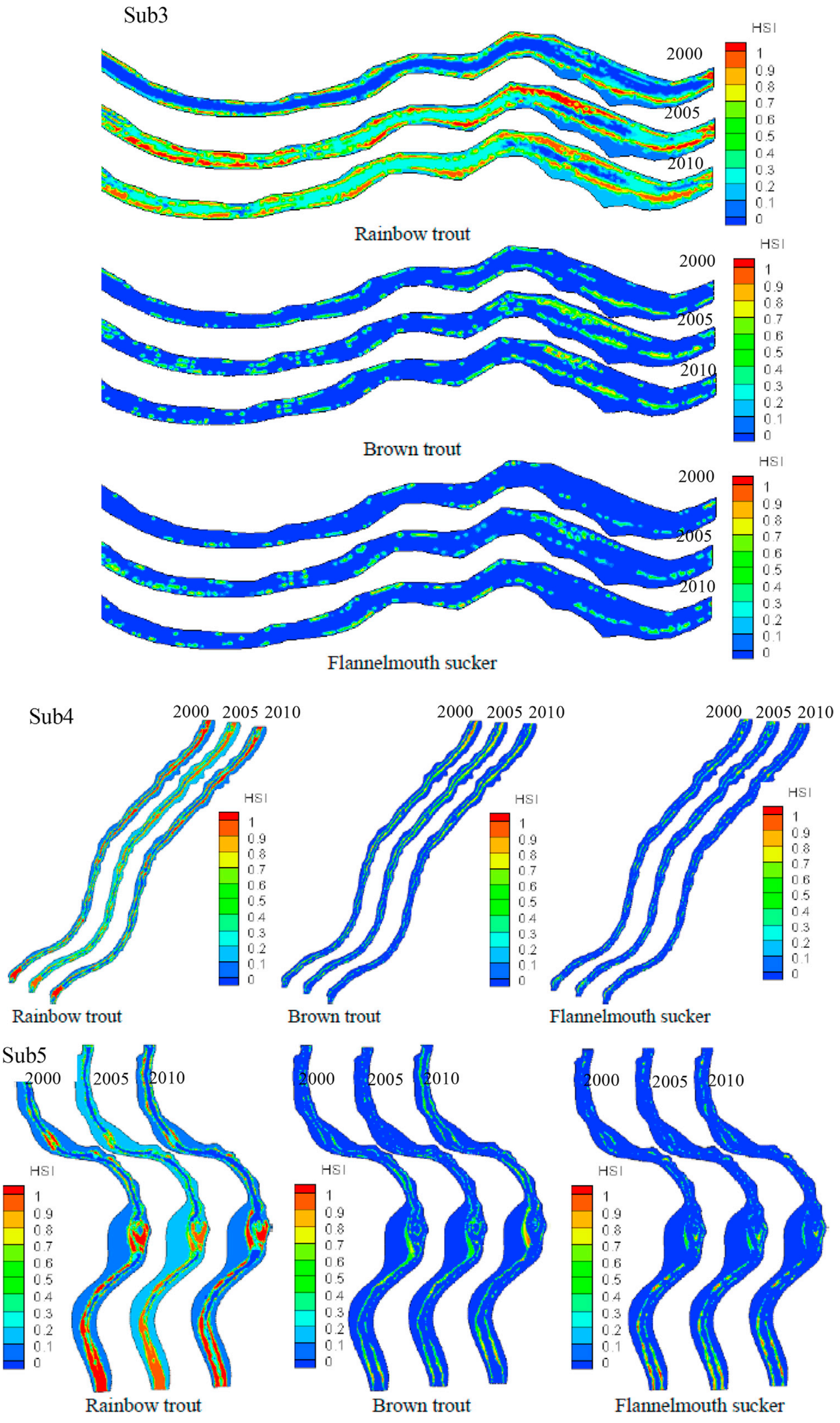

Fig. 5. (*continued*)

$$RMSE = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{P_{i,t}^{sim(F)}}{P_{\max,t}^{sim(F)}} - \frac{P_{i,t}^{obs(F)}}{P_{\max,t}^{obs(F)}}\right)^2} \quad for\ \ i = 1, 2, ..., n \tag{9}$$

$$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(\frac{P_{i,t}^{sim(F)}}{P_{\max,t}^{sim(F)}} - \frac{P_{i,t}^{obs(F)}}{P_{\max,t}^{obs(F)}}\right) \times 100}{\sum_{i=1}^{n}\frac{P_{i,t}^{obs(F)}}{P_{\max,t}^{obs(F)}}}\right] \tag{10}$$

where n is the total number of data points in each case, $P_{i,t}{}^{sim(f)}$ is the ith simulated data, and $P_{i,t}{}^{obs(f)}$ is ith observed data. $P_{\max,t}{}^{sim(f)}$ is the maximum simulated data and $P_{\max,t}{}^{obs(f)}$ is maximum observed data. The MAE can potentially identify the presence of bias. The RMSE gives an overall measure of the amount by which the data differ from the model predictions, whereas PBIAS is the deviation of data being evaluated and is expressed as a percentage.

2.4. Model system setup

All models in ecohydraulic model system were linked together at the computational program level and solved by the finite volume method. The initial condition, boundary condition, and convergence criterion were also set. When the ecohydraulic model system was set up, the velocities, water depths, and substrate dynamic distributions were simulated. The SI, HSI, WUA, OSI, P_t^F, $N_{i,t}$, $NL_{i,t}$, and $P_{i,t}$ values at each time step were predicted.

3. Results

The five subareas of Colorado River in USA and three fish species were chosen, which are namely the rainbow trout, brown trout and flannelmouth sucker, to simulate habitat status for the three fish species from 2000 to 2009. The HSI values for four life stages of the three fish species were simulated in all the five subareas. Two population models: the logistic population model and the matrix population model have been applied to simulate the fish population numbers and density distributions. The fish monitoring data in those five subareas were also used to verify the fish number fluctuation and fish density variation.

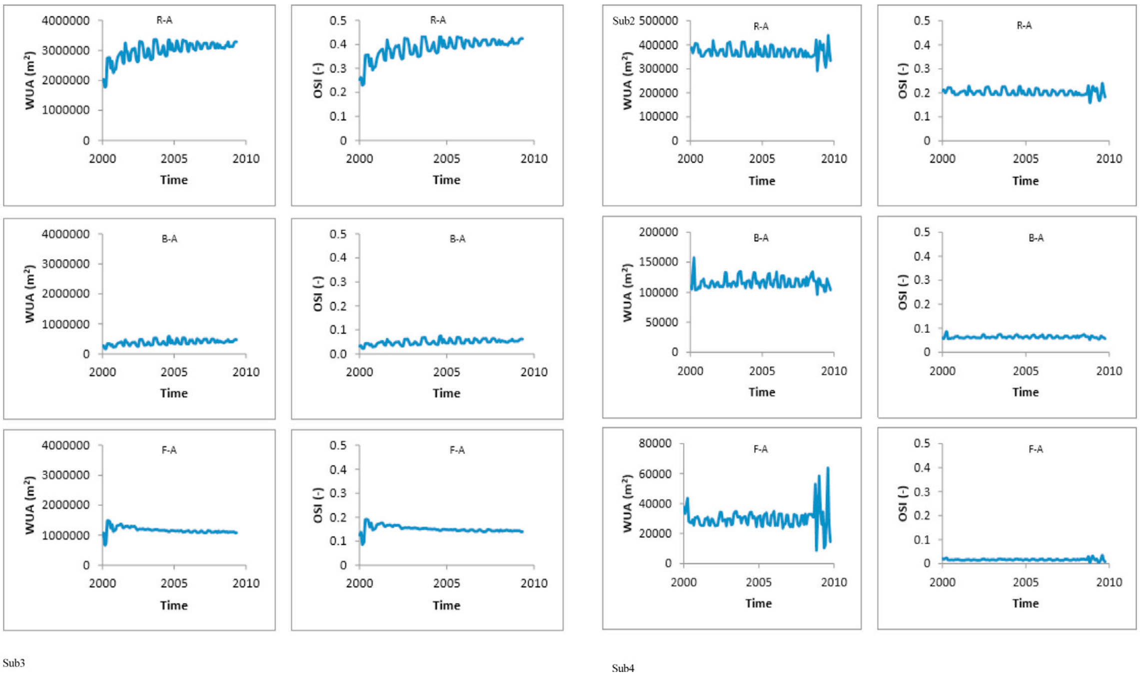

Fig. 6. The adult WUA and OSI distribution for rainbow trout, brown trout, and flannelmouth sucker from 2000 to 2009 in Sub1, Sub2, Sub3, Sub4, Sub5, and the whole Colorado River (R-A is rainbow trout, B-A is Brown trout, F-A is Flannelmouth sucker). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

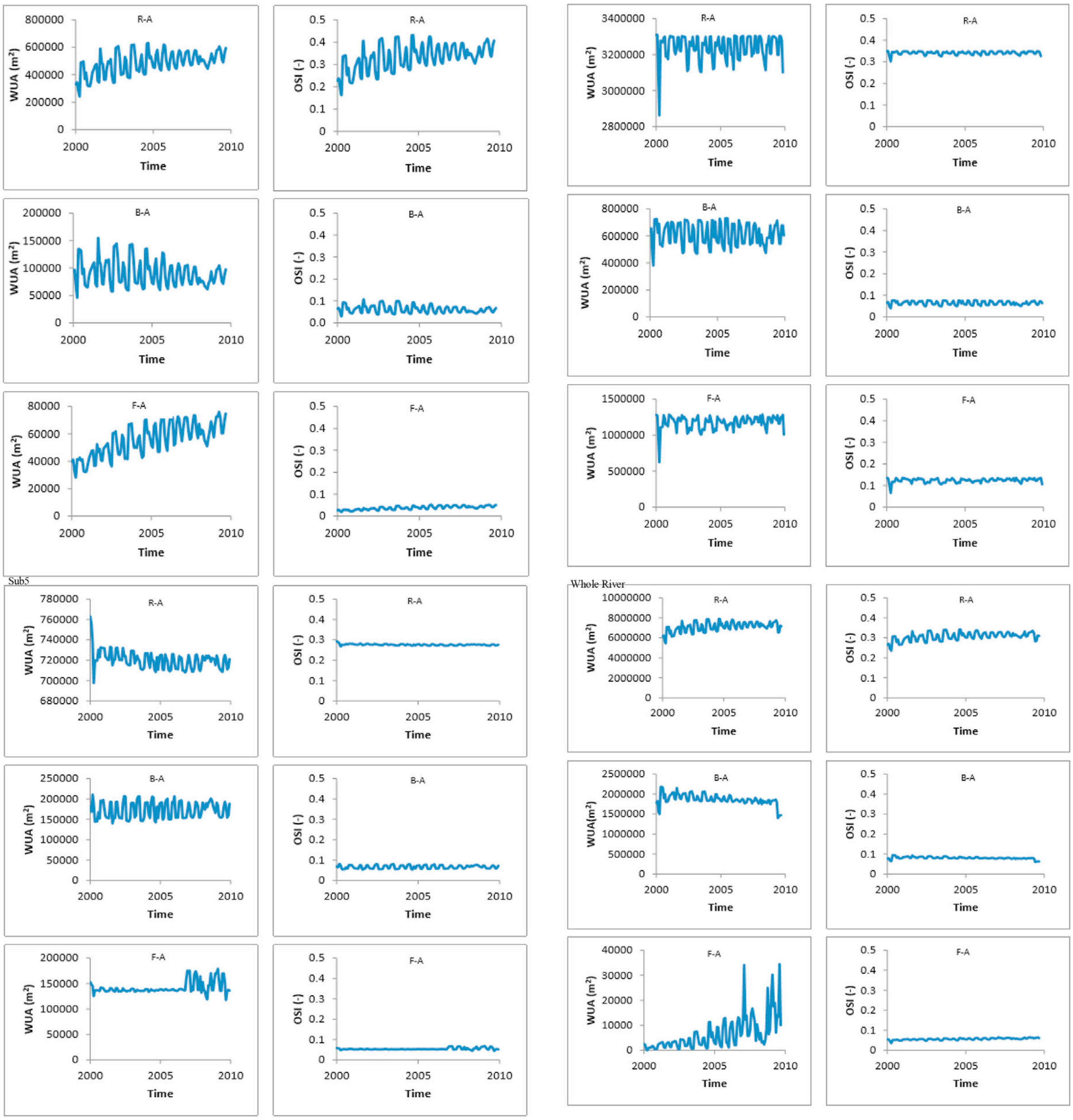

Fig. 6. (*continued*)

3.1. Fish habitat quality in all five subareas

The HSI values for four life stages of rainbow trout, brown trout, and flannelmouth sucker were simulated in all the five subareas. In Fig. 5, the adult life stage is chosen to illustrate the quality changes in the habitat of the three fish species from 2000 to 2009. In Sub1, in 2000, the rainbow trout in the adult life stage had good habitat suitability conditions in the areas downstream near the outlet and along the riverbank. For the adult life stage of brown trout, the HSI values in Sub1 is almost 0, except for a small area downstream near the outlet. The substrates are the main reason for the low HSI values for brown trout. The habitat suitability qualities for flannelmouth sucker showed a similar trend as the rainbow trout habitat suitability qualities. However, the habitat quality was far from satisfactory with HSI distribution in most regions of this subarea.

The HSI distribution in 2005 was relatively high for the rainbow trout adult stage, with every part of Sub1 filled with high HSI values. The adult brown trout still remained at a low HSI values, but with relatively high values at the outlet of Sub1. Compared with the adult brown trout habitat quality in 2000, the adult brown trout habitat quality was slightly higher in

2005. The velocity was the main reason for the low HSI values for the brown trout in 2005. In 2005, the HSI values for adult flannelmouth sucker were more evenly distributed throughout Sub2, and the habitat qualities were similar to the habitat quality in 2000. In 2009, the adult life stage of brown trout showed lower HSI values but the habitat quality was higher than the habitat quality in 2005. The flannelmouth sucker habitat quality was suitable for many areas in Sub1, and also showed a slightly increasing trend as compared with the habitat quality in 2005.

In Sub2, Sub3, Sub4, and Sub5, the adult life stage of rainbow trout habitat qualities were better than the habitat qualities of adult brown trout and flannelmouth sucker for all simulation times. Compared with the HSI values variations in Sub1, the three fish species habitat quality in Sub2, Sub4, and Sub5 remained at a stable level in the simulation time from 2000 to 2009. Moreover, in all simulation times, compared with rainbow trout habitat qualities, the brown trout and flannelmouth sucker habitat qualities in Sub2 were not well suitable. For Sub4, the rainbow trout HSI values remained stable, whereas the brown trout HSI distribution had high values downstream of Sub4, and the river bank also had higher values than the middle of the river. For Sub5, the adult flannelmouth sucker exhibited the poorest habitat quality, with HSI values of nearly 0 in a majority areas.

3.2. Fish habitat sensitivity analysis all five subareas

The sensitivity analysis of the rainbow trout, brown trout, and flannelmouth sucker habitats used the WUA and OSI. The WUA and OSI values showed an exactly the same trend, and the OSI had different values at different life stages for the three selected fish species. In Sub1, the WUA values for adult rainbow trout increased steadily from 1,959,144 m^2 in 2000 to 3,038,518 m^2 in 2005, and increased slightly until the end of 2009 with a value of 3,284,021 m^2. The adult rainbow trout OSI values increased from 2000 to 2005, and to 2009 with values of 0.25, 0.38, and 0.42, respectively. The adult brown trout WUA values grew from 2.5×10^5 m^2 in 2000 to 4.7×10^5 m^2 in 2009, and the corresponding OSI values were 0.031 and 0.061. The adult, flannelmouth sucker WUA values showed a great increasing trend at first and then showed slight decreasing trend. The maximum WUA and OSI values for the adult flannelmouth sucker were 1.45×10^6 m^2 and 0.18, respectively (Fig. 6).

In Sub2, the adult rainbow trout WUA and OSI values were kept stable at approximately 3.8×10^5 m^2 and 0.21, respectively. The adult brown trout WUA and OSI values were stable at the level of 1.15×10^5 m^2 and 0.05, respectively. The adult

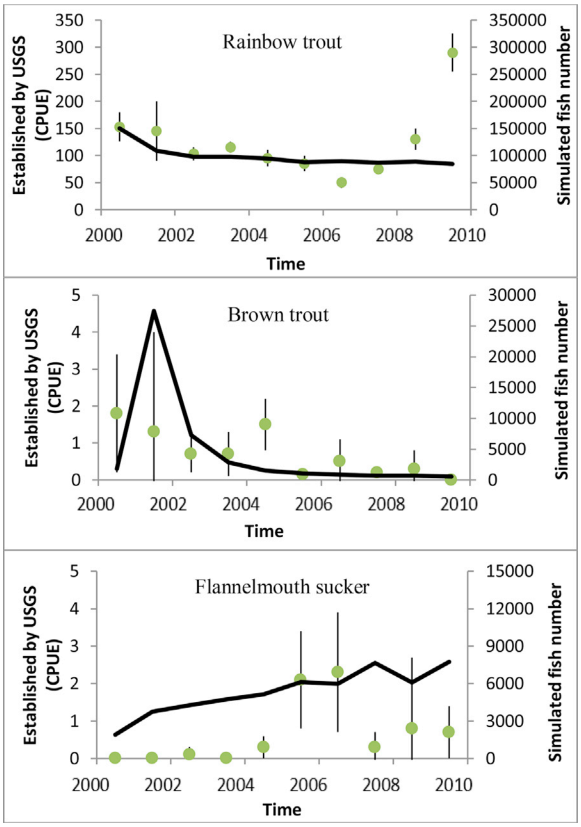

Fig. 7. The variations of rainbow trout (upper), brown trout (middle) and flannelmouth sucker (lower) population numbers from 2000 to 2009 in the river stretch Sub1 (time step is one year; CPUE is the mean catch per unit effort; ⧫ is the USGS result; ━ is the simulated fish number). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

flannelmouth sucker WUA and OSI values experienced a slightly decrease for the year 2000 and then showed an increase in later years. For the flannelmouth sucker, the adult WUA and OSI values changed significantly in the years of 2008 and 2009 (Fig. 6).

In Sub3, the adult rainbow trout WUA and OSI values increased slightly over 10 simulation years. The adult brown trout WUA values showed the same trend with a slightly increasing trend from 2000 to 2004 before decreasing from 2005 to 2009. The adult life stage of brown trout OSI values had exactly the same trend as the WUA values, with average values of 0.06 over 10 simulation years. For the flannelmouth sucker, the adult WUA increased steadily from 4.0×10^4 m^2 in 2000 to 6.4×10^4 m^2 in 2007, and experienced a decreasing trend with a value of 6.4×10^4 m^2 in 2008, which increased again with a value of 6.0×10^4 m^2 in 2009. The adult flannelmouth sucker OSI values increased from 2000 to 2007 and showed a decreasing trend in 2008, and increased again in 2009 with values of 0.025, 0.045, 0.041, and 0.047, respectively (Fig. 6).

In Sub4, the rainbow trout WUA and OSI values experienced a decreasing trend in 2000 and then experienced an increasing trend. Thereafter, the WUA and OSI values remained stable with, average values of 3.2×10^6 m^2 and 0.33, respectively. The adult brown trout fish life stages' WUA values remained at the level of 6.0×10^5 m^2, and the OSI values were nearly 0.055 over all simulation times. For the flannelmouth sucker, the adult WUA values were at the level of 1.2×10^6 m^2 in most years. The flannelmouth sucker adult OSI values remained at the value of nearly 0.13 over all simulation times (Fig. 6).

In Sub5, the adult WUA and OSI simulation results are shown in Fig. 6. From the simulation results, it can be seen that the adult rainbow trout WUA values showed a decreasing trend from 2000 to 2009. The WUA values were decreased from 7.6×10^5 m^2 in 2000 to 7.6×10^5 m^2 in 2009. The corresponding OSI values also decreased from 0.3 in 2000 to 0.28 in 2009. The adult life stage of brown trout WUA values slightly fluctuated with mean value 1.4×10^5 m^2 from 2000 to 2009. The corresponding OSI values had a relatively stable value of 0.055 from 2000 to 2009. The WUA values of the adult flannelmouth sucker stayed at the value of 1.4×10^5 m^2 from 2000 to 2007 and then changed between 1.2×10^5 m^2 and 1.7×10^5 m^2 in the later simulation times. The average OSI value of the adult flannelmouth sucker was 0.05 from 2000 to 2009.

The entire Colorado River, from Lees Ferry to 50 km upstream of Lake Mead, is represented by the average value of OSI in all five subareas for the adult fish life stage. The WUA values for the whole Colorado River can be represented by the sum of WUA values in all five subareas. It can be seen that the rainbow trout's WUA and OSI values remained at a stable level during the simulation time from 2000 to 2009, with value of 6.7×10^6 m^2 and 0.3 for WUA and OSI, respectively. For the brown trout, the

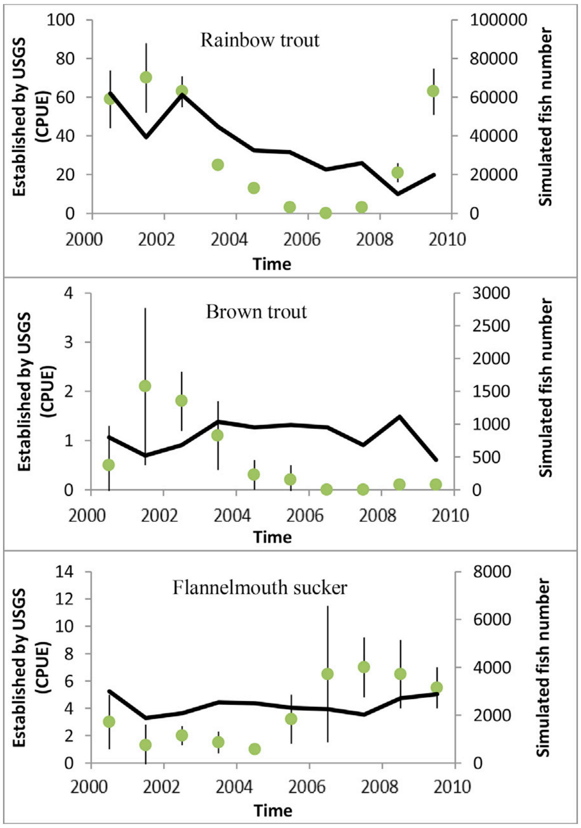

Fig. 8. The variations of rainbow trout (upper), brown trout (middle) and flannelmouth sucker (lower) population numbers from 2000 to 2009 in the river stretch Sub2 (time step is one year; CPUE is the mean catch per unit effort; ♦ is the USGS result; ▬is the simulated fish number). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

WUA and OSI values showed a slightly decreasing trend from 2000 to 2009. By contrast, the flannelmouth sucker's WUA and OSI values showed increasing trends from 2000 to 2009, with maximum values of 3.4×10^4 m^2 and 0.05, respectively.

3.3. *Fish population number based on the logistic population model*

The comparison of the simulated and surveyed results in Sub1 is shown in Fig. 7. It can be seen that the rainbow trout number surveyed in 2009 (290 ± 35 fish) was the highest number observed during all simulation times. The rainbow trout numbers surveyed generally declined from 150 in 2000 to 50 in 2006, and then the fish number surveyed showed an increasing trend after 2006. The maximum rainbow trout numbers surveyed happened in 2009 with a value of 290. The simulation results in Sub1 showed that the rainbow trout number decreased from 2000 to 2007, and then remained at a stable level over the simulation time from 2007 to 2009. The brown trout numbers surveyed in Sub1 showed that: the brown trout declined from 2000 (1.8 ± 1.6 fish) to 2009 (0 ± 0 fish) except in the year 2004 (1.5 ± 0.7 fish). The simulated brown trout numbers increased from 2000 to 2001 and then showed a decreasing trend until the end of the simulation time. The flannelmouth sucker numbers surveyed increased from 2000 to 2006, and then significantly declined in 2007 before slightly increasing again during the simulation time. The simulated flannelmouth sucker numbers also showed a similar trend within the surveyed fish data.

In Sub2, the rainbow trout numbers surveyed in 2001 (70 ± 18 fish) were the highest observed fish numbers since 2000 (59 ± 15 fish). The surveyed rainbow trout numbers showed a slightly increasing trend from 2000 to 2001, and then the fish numbers declined from 2001 to 2006, and increased again from 2006 to 2009. The simulated rainbow trout numbers had a slightly different trend in these years from 2000 to 2002. The surveyed brown trout fish numbers declined from 2001 (2.1 ± 1.6 fish) to 2006 (0 fish), and then remained at a relatively low level with a value of nearly 0. The simulated brown trout numbers remained relatively stable at the level of 1000, which did not match well with the fish number observations. For the flannelmouth sucker in Sub2, the fish numbers surveyed declined from 2000 (3 ± 2 fish) to 2004 (1 ± 0.4 fish), and then increased from 2004 to 2007 (7 ± 2.2 fish) before the fish numbers decreased again to 5.5 in 2009. The simulated flannelmouth sucker numbers showed the same trend as the fish number surveyed except for the years from 2006 to 2007 (Fig. 8).

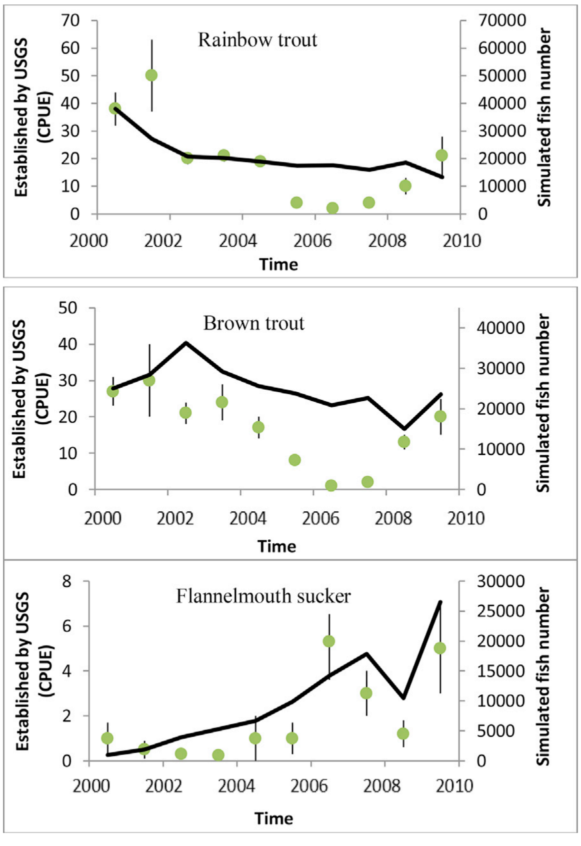

Fig. 9. The variations of rainbow trout (upper), brown trout (middle) and flannelmouth sucker (lower) population number from 2000 to 2009 in the river stretch Sub3 (time step is one year; CPUE is the mean catch per unit effort; ⧫ is the USGS result; ▬is the simulated fish number). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

On the basis of the fish numbers surveyed in Sub3, it was found that the mean value of rainbow trout numbers also declined from 2001 to 2006 and increased from 2006 to 2009 (21 ± 7 fish) with the maximum value of 50 ± 13 fish in 2001. The simulated maximum rainbow trout numbers were in 2000 with a value of 38,000. The simulated rainbow trout number variations did not match well in 2007 and in 2009. The brown trout fish numbers surveyed declined from 2001 (30 ± 10 fish) to 2006 (1 ± 0.5 fish), and the fish numbers remained relatively low in 2006 and in 2007. Subsequently, the brown trout numbers dramatically increased in 2008 (13 ± 2 fish) and 2009 (20 ± 5 fish). The simulated brown trout numbers increased from 2000 (25,000 fish) to 2002 (36,365 fish), and then the fish numbers decreased before increased again in 2009 (23,602 fish). The flannelmouth sucker numbers surveyed remained relatively low from 2000 (1 ± 0.7 fish) to 2005 (1 ± 0.7 fish), and then the fish numbers dramatically increased in 2006 (5.3 ± 1.7 fish). After that, the mean surveyed numbers fluctuated between 3 and 5. The simulated flannelmouth sucker numbers variation trend matched well with fish data the surveyed, with the maximum fish number of 26,523 in 2009 (Fig. 9).

In Sub4, the rainbow trout numbers surveyed in 2001 (30 ± 8 fish) were the highest fish numbers of all simulation times. The number of rainbow trout surveyed fish decreased from 2001 to 2007 (2 ± 0.5 fish), and then increased again in 2008 (10 ± 3 fish) and in 2009 (26 ± 6 fish). The simulated rainbow trout number demonstrated a similar trend as the fish numbers surveyed except in the years from 2005 to 2007. The maximum fish numbers were in 2001 with a value of 18,759. The number of brown trout increased from 2000 (2.5 ± 1.1 fish) to 2002 (6 ± 1.6 fish) but decreased in later years and remained at a relative low value. In contrast to the surveyed brown trout numbers, the simulated fish numbers did not change so dramatically, with a value of 7903 in 2001 and 3465 in 2008, respectively. From 2000 to 2009, the flannelmouth sucker fish numbers increased from 2000 (1 ± 1 fish) to 2006 (23 ± 3 fish) and experienced a decreasing trend in later years, with a fish number of 12 in 2009. During the simulation time, the simulated fish number showed the same trend as in the surveyed data except in 2001. The maximum simulated fish number was 223 in 2001, and the minimum fish number was 75 in 2003 (Fig. 10).

In Sub5, the rainbow trout fish numbers surveyed remained at a relatively low value except in the years 2000 (7.5 ± 4.5 fish) and 2001 (6 ± 3 fish). The simulated rainbow trout fish numbers decreased from 2000 (8000 fish) to 2009 (2329 fish). The brown trout numbers surveyed decreased from 2002 (0.9 ± 0.7 fish) to 2007 (0.05 ± 0.05 fish) with the highest value of 0.9 in 2002. In contrast to the surveyed data, the simulated brown trout number had the highest numbers in 2008, with a value of 1210. The number of flannelmouth sucker surveyed remained at low from 2000 (1 ± 1 fish) to 2007 (5 ± 1 fish), but

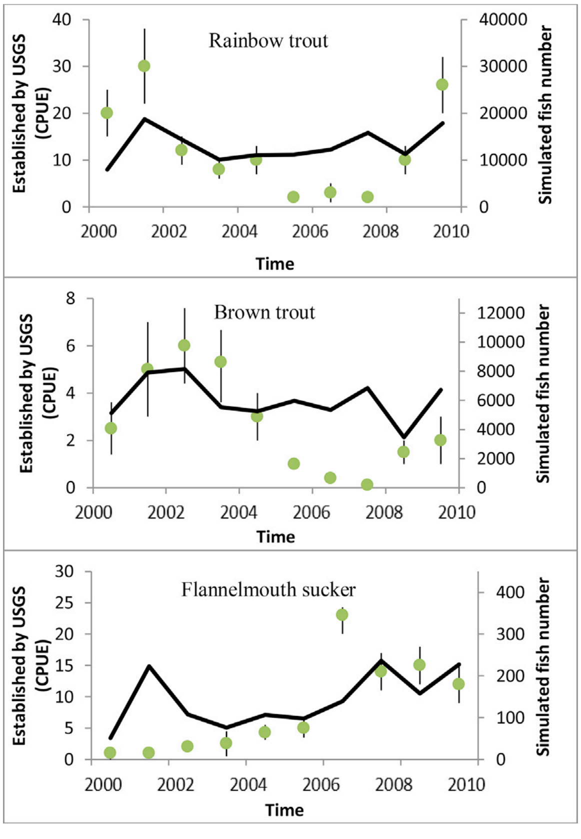

Fig. 10. The variations of rainbow trout (upper), brown trout (middle) and flannelmouth sucker (lower) population numbers from 2000 to 2009 in the river stretch Sub4 (time step is one year; CPUE is the mean catch per unit effort; ⧫ is the USGS result; ▬is the simulated fish number). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

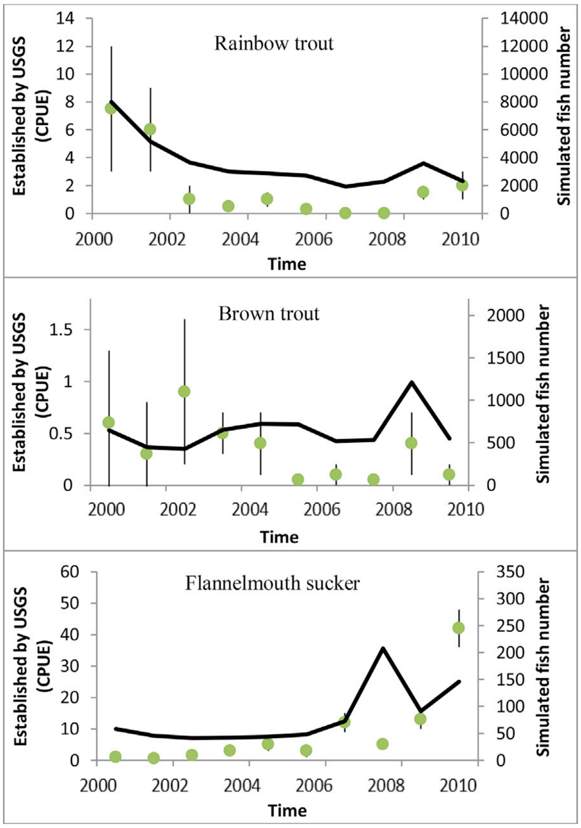

Fig. 11. The variations of rainbow trout (upper), brown trout (middle) and flannelmouth sucker (lower) population numbers from 2000 to 2009 in the river stretch Sub5 (time step is one year; CPUE is the mean catch per unit effort; ⧫ is the USGS result; ▬is the simulated fish number). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

then increased in 2008 and 2009. The simulated flannelmouth sucker numbers followed the same trend as the fish numbers surveyed, except in the year 2007 (Fig. 11).

For the entire Colorado River, the rainbow trout, brown trout, and flannelmouth sucker simulated fish numbers matched well with the surveyed fish numbers established by the USGS. The highest surveyed rainbow trout numbers were observed in 2009, with a value of 62. The rainbow trout number surveyed declined from 2000 to 2006 and then the fish numbers increased after 2006. The rainbow trout fish numbers surveyed increased from 2008 to 2009 dramatically. The simulated rainbow trout population numbers showed exactly the same trend as the rainbow trout number surveyed. In contrast to the rainbow trout numbers, which fluctuated from 2000 to 2009, both the surveyed brown trout number and simulated brown trout number showed a decreasing trend during the simulation times. In contrast to the brown trout, both the surveyed flannelmouth sucker numbers and simulated flannelmouth sucker numbers showed an increasing trend from 2000 to 2009 (Fig. 12).

3.4. Fish population density based on the logistic population model

On the basis of the fish density distribution equation (Equation (7)) in the logistic population model, the three selected fish population distributions were simulated. The rainbow trout, brown trout, and flannelmouth sucker population densities in all five subareas from 2000 to 2009 are shown in Fig. 13. The fish population density distribution showed trends very similar to the HSI distribution from 2000 to 2009. Relative to the brown trout and flannelmouth sucker, the rainbow trout densities are higher than the fish densities of brown trout and flannelmouth sucker. When compared with the fish density in all five subareas, it can be seen that the rainbow trout densities in Sub1 were higher than the fish densities in other subareas. In Sub1, the fish densities were distributed along the stretch of river with relative evenness. The rainbow trout population densities had the highest value, while the brown trout densities had the lowest value. In Sub2, the high fish population densities were mainly located along the river bank. In Sub3, the population densities for rainbow trout and brown trout showed a decreasing trend from 2000 to 2009. The flannelmouth sucker population densities remained at a relatively stable level from 2000 to 2009. In Sub4 and Sub5, the three fish population densities in the middle of the river were higher than those along the river bank.

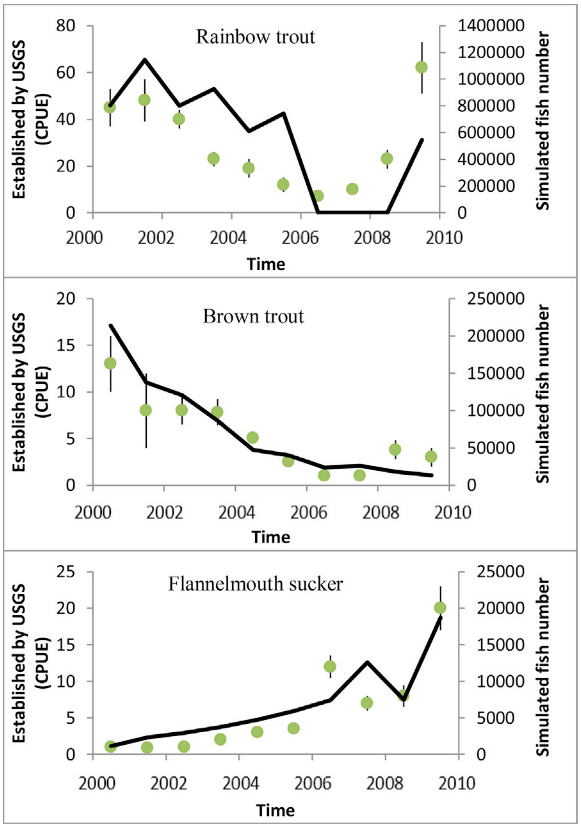

Fig. 12. The variation of rainbow trout (upper), brown trout (middle) and flannelmouth sucker (lower) population number from 2000 to 2009 over the whole river stretch (time step is one year; CPUE is the mean catch per unit effort; ⧫ is the USGS result; ▬is the simulated fish number). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.5. Fish population based on the fish length population model

To simulate the fish population number at each life stage, the fish length population model was applied. The WUA and OSI for larval, juvenile, and spawning fish species were also simulated. On the basis of the fish length population model (Equation (5)) and OSI values, the total fish number and each length stage population numbers were obtained (Fig. 14). The fish length category nine, with rainbow trout length between 390 and 410 mm; brown trout length between 370 and 400 mm; and flannelmouth sucker between 350 and 380 mm, was also presented (Fig. 15). The general trends of the rainbow trout, brown trout, and flannelmouth sucker population numbers had a good agreement with the three surveyed fish number variations. Moreover, for specific length comparison based on the fish length population model, the agreement between simulation and the surveyed fish data was also considerably good.

4. Discussions

4.1. Error analysis on logistic population and fish length population models

The performance of the logistic and fish length population models is presented in Table 2. The simulated fish population numbers in all five subareas of the Colorado River fit the fish numbers surveyed, whereas only a few simulation results did not match the fish data surveyed. MAE values are indicative of good model performance. More specifically, the average values of MAE are 27%, 36%, and 39%, respectively for rainbow trout, brown trout, and flannelmouth sucker in all five subareas. The average values of RMSE are 0.29, 0.42, and 0.41 for rainbow trout, brown trout, and flannelmouth sucker, respectively. The absolute value of PBIAS varied from 0.32 to 0.69 for the rainbow trout, varied from 3.4 to 0.49 for the brown trout, and varied from 0.26 to 0.93 for the flannelmouth sucker. Overall, the simulated results support the accuracy of the model system, and the performance of the model system indicates the reliability of the model's simulation.

It is indicated that both the logistic population model and fish length population model have reasonable simulation accuracy. Both models indicate that the rainbow trout population numbers decreased from 2000 to 2007, and then the

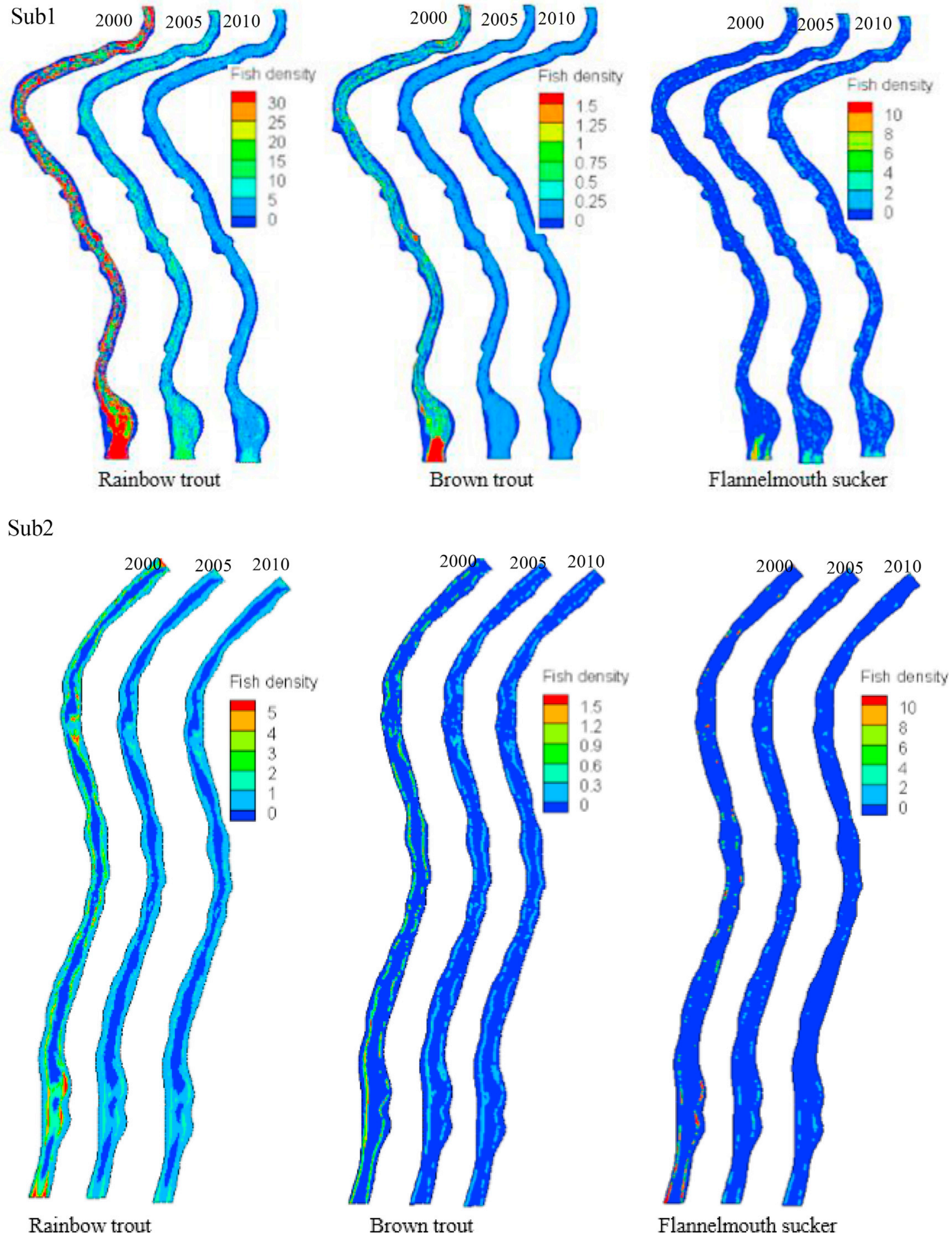

Fig. 13. The rainbow trout, brown trout and flannelmouth sucker population density distribution in the all subareas river stretch. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

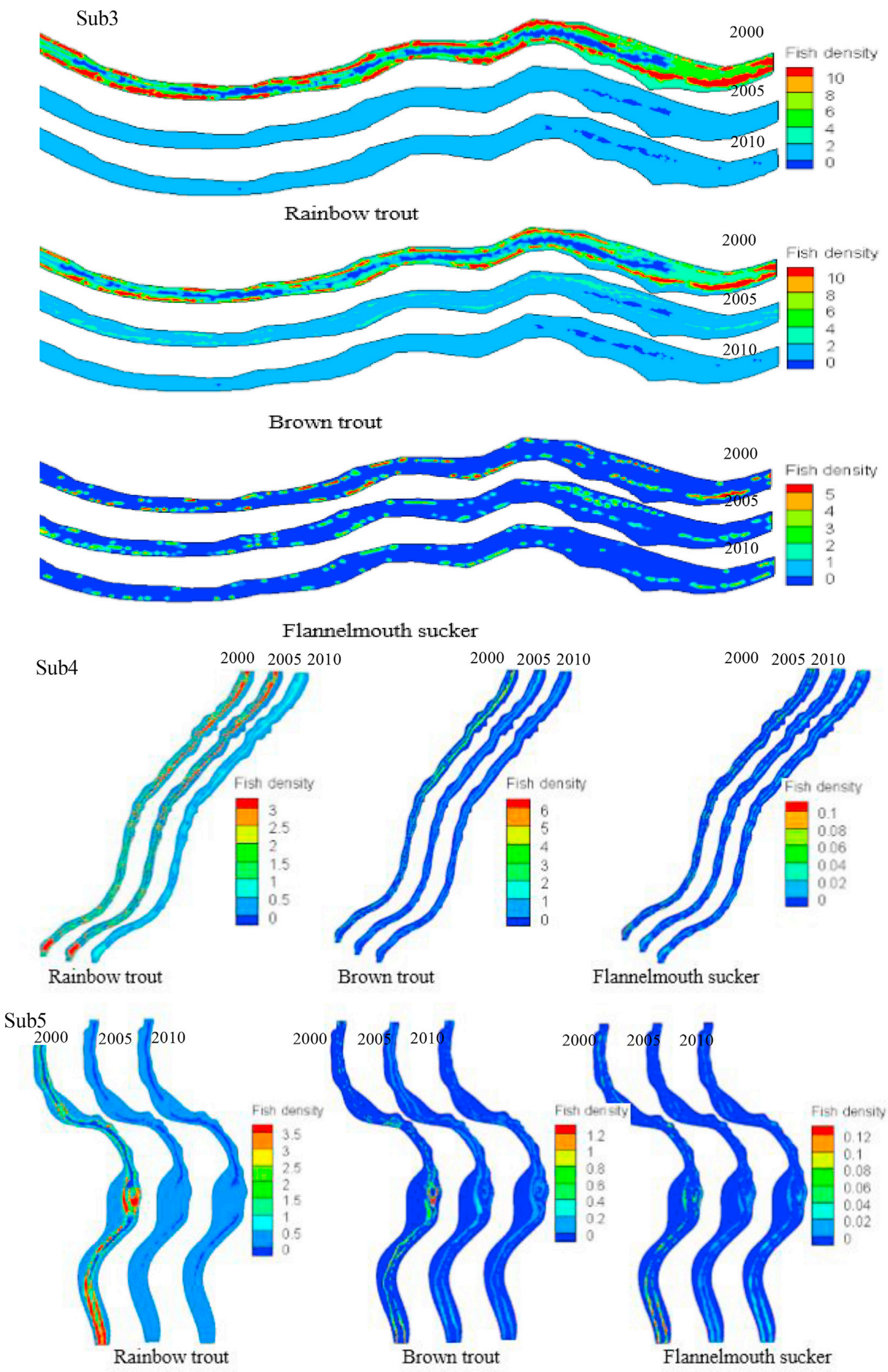

Fig. 13. (*continued*)

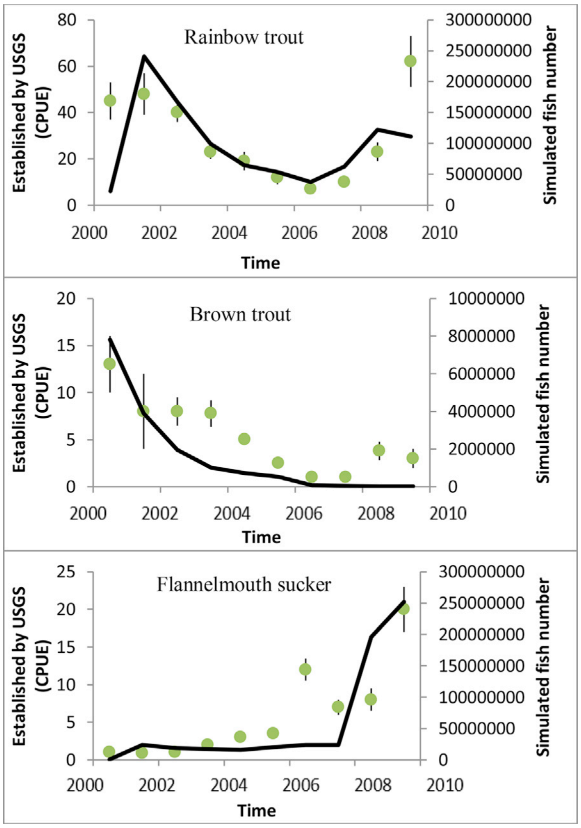

Fig. 14. The variation of rainbow trout (upper), brown trout (middle) and flannelmouth sucker (lower) population numbers from 2000 to 2009 based on the fish length population model (CPUE is the mean catch per unit effort; ⧫ is the USGS result; ▬is the simulated fish number). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

population numbers showed an increasing trend. Moreover, from 2000 to 2009, the non-native fish brown trout population numbers decreased steadily, while the native fish flannelmouth sucker population number increased slightly.

4.2. The model limitation and future suggestions

Additional efforts are required to evaluate the multiple species habitat and population modeling frameworks for combining the hydrodynamic, hydromorphology, and fish SI curves. Habitat quality could be determined by classic methods, fuzzy methods. Given a valid SI curves habitat model, SI curves should be highly precise. With respect to the fuzzy logic habitat model, the fuzzy rules need more testing. Moreover, in the habitat model, other parameters such as water temperature and flow oxygen density distribution should also be considered. In addition, the ecohydraulic model system should be combined with multiple dams, which would be beneficial in countries with many large dams. For a river with multiple hydroelectric stations, resources operation plays a vital role in managing the local ecosystem. Ecohydraulic modeling could be used as an optimal tool for planning and operation of water resources without damaging freshwater ecosystems.

Basically, even the model limitations have been existed, the ecohydraulic model system provides the link between density-dependent habitat use and population distribution was validated based on the qualitative and quantitative differences between habitats. Moreover, the ecohydraulic model has several advantages. This model can be used to evaluate localized management actions, such as dam management, non-native fish control, and stocking effects for non-native and native fish. The fish abundance distribution can also more precisely be used to indicate fish density in the computational domains.

5. Conclusions

In this study, the Colorado River in the USA was selected and three fish species were chosen as target fish species to simulate the habitats statuses for the from 2000 to 2009. In the present study, two population models, namely the logistic population model and the fish length population model, were applied to simulate the fish population numbers and density distributions. The fish monitoring data were used to verify the fish number fluctuations and fish density variations. The model results showed that the ecohydraulic model system can correctly predict the habitat qualities and population number

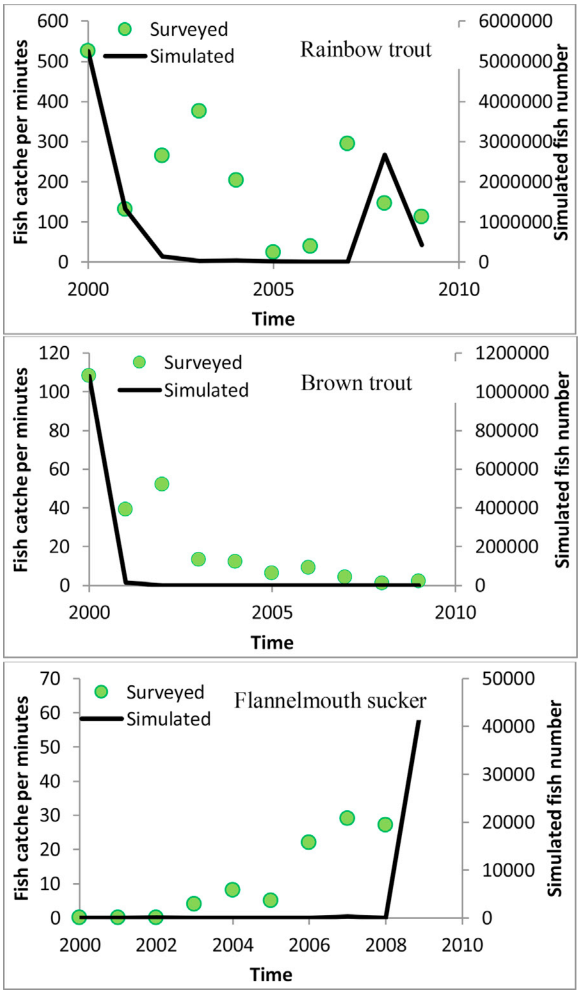

Figure 15. Comparing simulation rainbow trout (390 – 410 *mm*), brown trout (370 – 400 *mm*), and flannelmouth sucker number (350 – 380 *mm*) with surveyed fish number per minute.

Table 2
Correlation coefficients between simulated and measured fish numbers in the five subareas of the Colorado River (W. River is whole river).

		Rainbow trout			Brown trout			Flannelmouth sucker		
		MAE	RESE	PBLAS	MAE	RESE	PBLAS	MAE	RESE	PBLAS
Logistic population Model	Sub1	0.25	0.27	0.40	0.32	0.42	−3.45	0.43	0.44	0.45
	Sub2	0.23	0.26	0.32	0.69	0.74	0.69	0.33	0.41	0.28
	Sub3	0.24	0.27	0.49	0.25	0.32	0.36	0.53	0.56	0.26
	Sub4	0.36	0.38	0.55	0.23	0.31	0.24	0.53	0.54	0.93
	Sub5	0.26	0.26	0.69	0.29	0.33	0.49	0.11	0.12	0.37
	W. River	0.27	0.29	0.49	0.36	0.42	−0.33	0.39	0.41	0.46
Fish length Population model	W. River	0.11	0.20	0.3	0.20	0.26	1.93	0.14	0.23	0.22

fluctuations in the Colorado River. It can also provide decision-makers with valuable information to optimize their management. The model can be an efficient tool to assistant for multiple fish habitat and population prediction in Colorado River.

Declaration of competing interest

No potential conflict of interest was reported by the author.

Acknowledgements

This paper reflects my research time in the Technical University Munich, Germany. The work forms part of Weiwei Yao's PhD work. The author gives thanks for the valuable comments from Department of Civil, Geo and Environmental Engineering in TUM, from ETH Zurich and U. S. Geological Survey.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2020.e01060.

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