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Modeling of River Velocity, Temperature, Bed Deformation and its Effects on Rainbow Trout (*Oncorhynchus mykiss*) Habitat in Lees Ferry, Colorado River

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ABSTRACT: Quantification of the habitat available for fish species named Rainbow Trout (*Oncorhynchus mykiss*) were evaluated in Lees Ferry, Colorado River using water depth, water temperature, sediment transport, flow velocity in 2004 as environmental index. For the flow velocity and temperature distribution calculations in the river, the Navier-Stokes equation and energy conservation equations with finite volume approach has been employed. Sediment transport and river bed deformation in Lees Ferry were also calculated based on Engelund-Hansen equations. The suitability index (SI) curves based on these four biological, ecological and hydraulic factors were obtained and fish habitat suitability function was established. The HSI (habitat suitability index), WUA (weighted useable area), OSI (overall suitability index) of the fish species were quantitatively calculated using SI curves coupled with habitat suitability function. The effects of these variables on the Lees Ferry river areas were analyzed. The results showed that the model system can correctly represent the Rainbow Trout living situation. The WUA and OSI are generally low in Less Ferry and the proportions of high quality of OSI (HSI ≥ 0.7) are even less which is in accordance with the real situation. The results also revealed that there is a nonlinear relationship between flow discharge and suitable habitat areas.

Key words: Rainbow trout habitat model, CFD model, Sediment transport, Weighted usable area (WUA), Overall suitability index (OSI)

INTRODUCTION

Managers of streams and their associated habitat for aquatic species face problems of assessing habitat fluctuation during the year and evaluating the effectiveness of fish habitat improvement projects (Frissell et al., 1986; Palmer *et al.,* 2005). Previous research has found that the distribution and abundance of fishes are strongly influenced by their habitat and believed that physical habitat features are the key determining factors of river community potential (Schlosser, 1987; Plafkin et al., 1989; Panfil et al., 1999; Freeman et al., 2001; Booker & Dunbar, 2004; Fu *et al.,* 2007; Mouton *et al.,* 2007; Nagaya et al., 2008; Wang *et al.,* 2009; Yi *et al.,* 2010). Therefore, it is meaningful for the development of research tool to quantify the impact of the physical habitat variables on fish species abundance and diversity.

Starting in the 1980s, there have been developed and applied habitat model in management (Beland *et al.*, 1982; Milhous *et al.,* 1989; Stillman *et al.,* 2001; Armstrong *et al,* 2003; Gard, 2009, 2010). For example, the physical habitat simulation model (PHABSIM) model, EVHA, instream flow requirements (CASiMiR), MesoHABSIM, River2D and HABSCORE were applied to derive predictive relationships between abundance and stream habitat features (Bovee, 1982, 1986, 1998; Ginot, 1995; Jorde, 1996; Spence & Hickley, 2000; Parasiewicz, 2001; Steffler & Blackburn, 2002; Armstrong *et al.,* 2003; Moir et al., 2005; Mouton *et al.,* 2007; Nagaya *et al.,* 2008).

Based on the concepts of previous habitat models, a new two-dimensional model system has been developed by the authors for detailed hydraulic analysis of spatially explicit habitat units at the river. Lees Ferry was selected to be the targeted river and Rainbow Trout (*Oncorhynchus mykiss*) was chose as targets fish to apply our model which is in Colorado

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River downstream of Glen Canyon. The objective of this paper aims to (1) Develop a hydraulic model and temperature distribution model for rivers, (2) Calculate the sediment or substrates transport and deformation on river bed (3) Develop fish habitat model based on the variables from 1, 2 and fish preference curves and (4) Use the calculated bed deformation results to evaluate effects on rainbow trout (*Oncorhynchus mykiss*) habitat in Lees Ferry and to provide a base for better river management on both the river and the species under study.

MATERIALS & METHODS

The study area Lees Ferry is shown in Fig. 1 and the river bed deposits forms, particle size distribution (Fig. 2), cross-section information, flow temperature information, air temperature and flow discharge in 2004 were collected (Fig. 3) (Lucchitta, 1994; Hereford *et al.*, 2000; Graf, *et al.*, 1995; Flynn et al., 2003; Akahori, *et al.*, 2008; Magirl et al., 2008). The Rainbow information was also collected (Coggins, 2008; Korman *et al.*, 2010; Makinster *et al.*, 2010, 2011). The model system contains four components: hydrodynamic, heat transfer, river bed deformation and physical habitat model. The flow chart of model structure is shown in Fig. 4.

The equations governing the flow and thermal properties simultaneously in the river are the incompressible continuity equation, the Navier-Stokes equation and heat transfer equations. For the simulation of turbulence in the flow, the k-ε turbulent viscosity model is employed (Launder and Spalding 1972, Launder and Spalding 1974). The equations are shown in the following expressions.

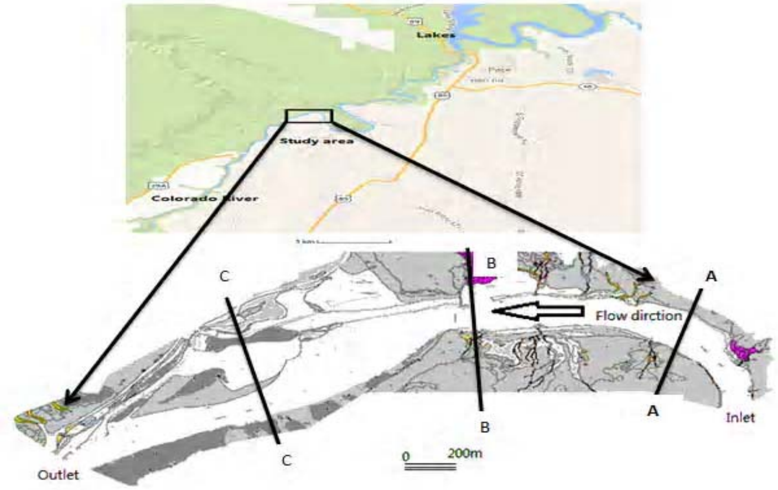

Fig.1. Photogrammetric base map of the Lees Ferry reach on the Colorado River

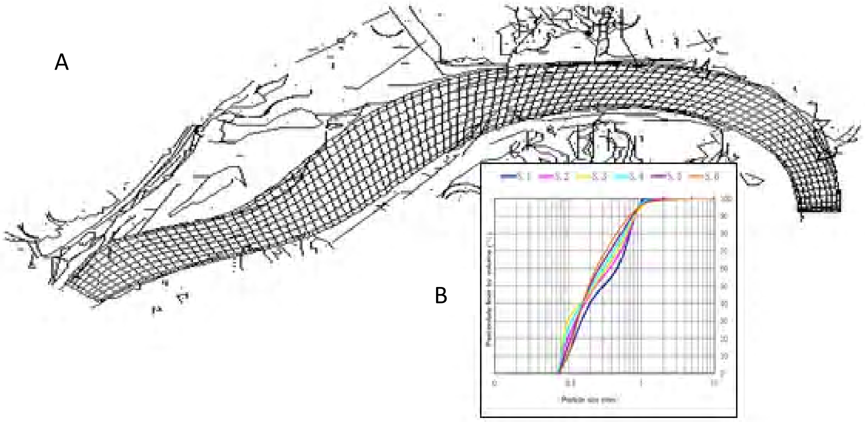

Fig. 2. Maps of the Lees Ferry finite volume mesh. (A) shows the river bed topography and (B) shows the grain size of Lees Ferry sediments tested in this study

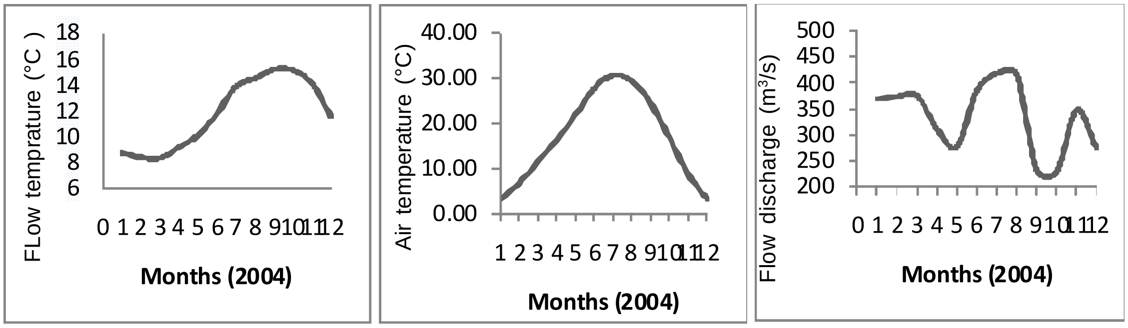

Fig. 3. Monthly mean discharge and inlet (flow temperature) and wall boundary (air temperature) temperature on Lees Ferry during 2004

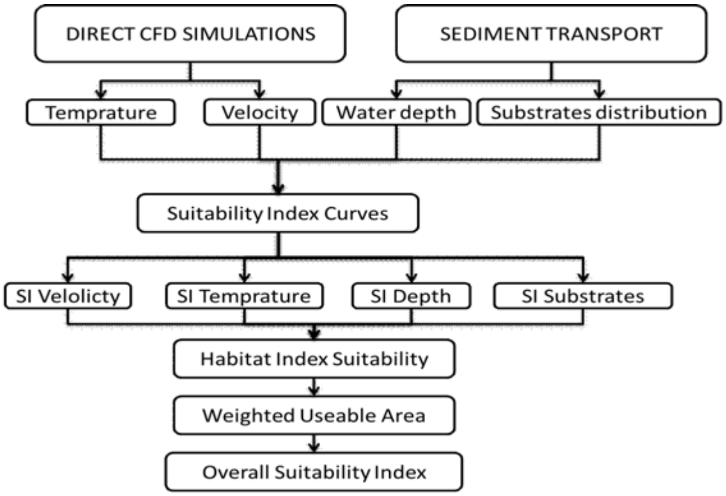

Fig. 4. Schematic flow chart of model structure on Lees Ferry, Colorado River, Arizona, USA

Continuity equation

$$\frac{\partial \rho}{\partial \tau} + \nabla(\rho \cdot \mathbf{U}) = 0 \tag{1}$$

Momentum equation

$$\frac{\partial \mathbf{U}}{\partial \tau} + \mathbf{U} \cdot (\nabla \mathbf{U}) = \nabla \cdot [-\mathbf{P} + \chi_U (\nabla \mathbf{U})]$$

$$+ \nabla \cdot (\chi_U \nabla \mathbf{U}^T) - ArT \cdot \mathbf{e}_g \tag{2}$$

Heat transfer equation

$$\frac{\partial T}{\partial \tau} + \mathbf{U} \cdot (\nabla T) = \nabla \cdot (\chi_T \nabla T) \tag{3}$$

Turbulent kinetic energy equation

$$\frac{\partial K}{\partial \tau} + \mathbf{U} \cdot (\nabla K) = \nabla \cdot (\chi_K \nabla K) - E - G_b + G_k \tag{4}$$

Dissipation rate equation

$$\frac{\partial E}{\partial \tau} + \mathbf{U} \cdot (\nabla E) = \nabla \cdot (\chi_E \nabla E) -$$

$$\frac{C_2 E^2}{K} - C_1 C_3 G_b \frac{E}{K} + C_1 \frac{E}{K} G_k \tag{5}$$

Where τ is time; U is velocity; T is temperature; P is pressure which is used to calculate the water depth; ρ is density; K and E are kinetic energy and its dissipation rate; X_K is diffusion coefficients; G_k and G_b are turbulent kinetic energy; C_1, C_2 and C_3 are constant number.

The sediment continuity equation and transport equation is represented by (Engelund & Hansen 1967; US-ACEHECUS Army, 2010):

$$(1-\lambda_p)B\frac{\partial Z}{\partial t} = -\frac{\partial Q_s}{\partial x} \tag{6}$$

$$Q_s = 0.05 r_s V^2 \sqrt{\frac{d_{50}}{g(\frac{r_s}{r}-1)}}\left[\frac{\tau_0}{(r_s-r)d_{50}}\right]^{3/2} \tag{7}$$

$$\tau_0 = 0.5C_1 rV \tag{8}$$

Where B is the river width; Z is channel elevation; λ_p is the active layer porosity; t is time; x is distance; Q_s is transported sediment load; r is weight of water metric; r_s is unit density of solid particles; V is average channel velocity; τ_0 is bed level shear stress; d_{50} is particle size of which 50% is finer. C_1 is empirical parameter (0.19 is chosen in our study).

The Habitat Suitability Index (HSI) (Fig. 5), weighted usable area (WUA) and overall suitability index (OSI) were defined for each grid mesh and for each time step. The defined is as follows:

$$HSI = (SI_v \times SI_d \times SI_s \times SI_t)^{1/4} \tag{9}$$

$$WUA = \sum_{i=1}^{M} A_i HSI_i \tag{10}$$

$$OSI = \frac{\sum_{i=1}^{M} A_i HSI_i}{\sum_{i=1}^{M} A_i} \tag{11}$$

Where represents the suitability index of velocity; represents the suitability index of water depth; and represent the suitability index of substrates and flow temperature respectively; M is the total number of grid mesh; HSI_i is the habitat suitability index of a single grid mesh; A_i is the area of the single mesh.

The finite volume method, QUICK scheme, tri-diagonal matrix algorithm (TDMA) and the successive over relaxation (SOR) are used to solve the model system. Flow discharge is set in inlet and zero gradient outflow boundaries are adopted for variables including tangential velocities, turbulent kinetics and its dissipation rate and temperature. The isothermal wall boundary conditions are set for heat transfer equations which is equal to the air temperature. More detail can be found in Yao *et al.*, (2014, 2014).

RESULTS & DISCUSSION

The site of Rainbow Trout living in Lees Ferry was analyzed - reaching from downstream of Glen Canyon Dam - to verify the flow velocity, bed deformation and quality of habitat suitability index which may change with time. The river terrain of Lees Ferry is shown in Figure 1 and the study area of 600000 m^2 with mesh of 103×10 was used in the simulation. Our model runs spanned the discharge range established from historical stream flow records of 2004. We have organized and displayed highest discharge, lowest discharge and average discharge model output in map views for flow velocity, temperature

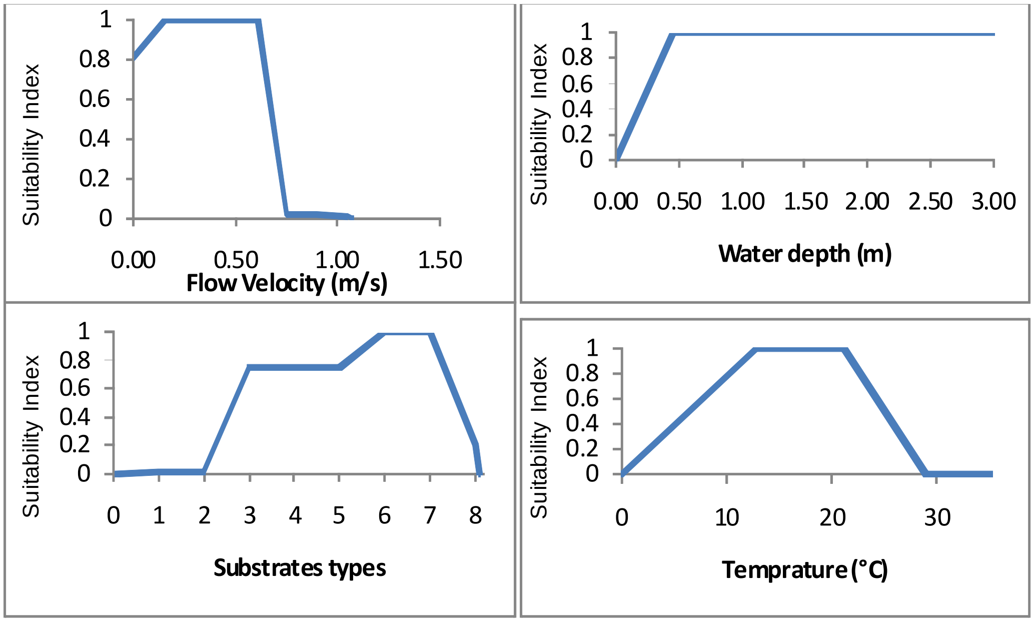

Fig. 5. Habitat suitability index curves developed for the Rainbow Trout in the Lees Ferry, Colorado River, Arizona showing habitat variables for flow temperature, flow velocity, substrates distribution and water depth.

distribution, water depth and HSI distributed. The distributions of WUA and OSI are presented for all the year as lines graph.3 Cross sections in Lees Ferry are also shown to illustrate the river deformation in 2004.

Figs 6, 7, 8 shows simulated flow velocity, water depth and temperature distribution in July (highest discharge Q = 418.26 m^3/s), October (lowest discharge Q = 227.00 m^3/s) and November (mean discharge Q = 347.18 m^3/s). The hydraulic simulation results illustrate the relationship in river flow velocities and water depth with river discharge. For example, the overall drop in flow depths and velocities with declining discharge and vice versa have been demonstrated. Of all discharges, for the highest discharge, the flow velocity was reached to 0.93 m/s and the max water depth was 2.6 m. The lowest discharge was observed on December of 2004 with the flow velocity and max water depth 0.58 m/s and 2.4 m respectively. The water depth and velocity of mean discharge is higher than lowest discharge and lower than highest discharge. The velocity simulation results were reasonably meeting the arrangement of the corresponding method proposed by Graf (1995).

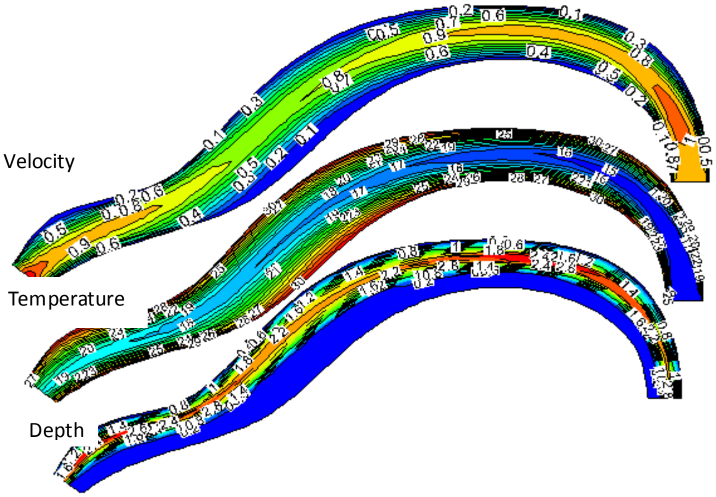

Fig. 6. Model output of velocity, water depth and temperature distribution on Lees Ferry with highest discharge Q = 418.26 m^3/s (in July)

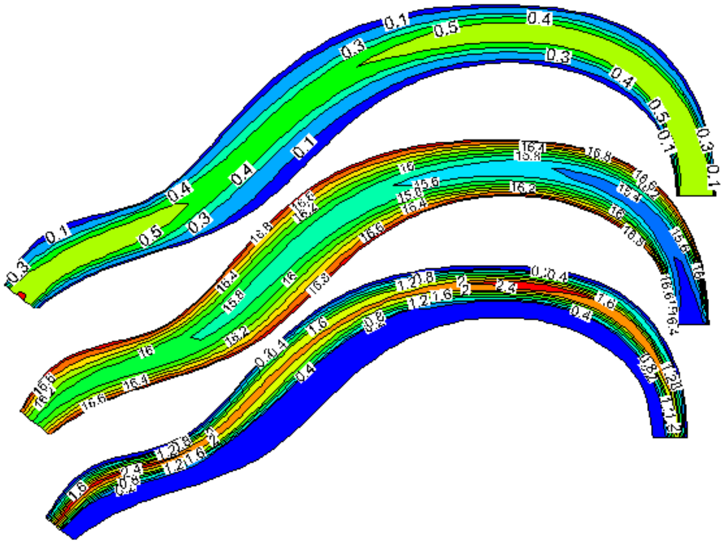

Fig. 7. Model output of velocity, water depth and temperature distribution with lowest discharge Q = 227.00 m^3/s (in October)

The flow temperature distribution in July shows that from upstream to downstream the temperature distribution has not much variation in the middle of the river. However, the temperature on the sides of river is showing substantial departure from that of middle of the river with values being 30 degrees on the river sides and only 17 degrees in the middle of the river. The flow temperature in October and November is not much different. Comparing the results of the temperature distribution, it appears that the air temperature can affect the river temperature distribution when there is a huge disparity between air temperature and flow temperature.

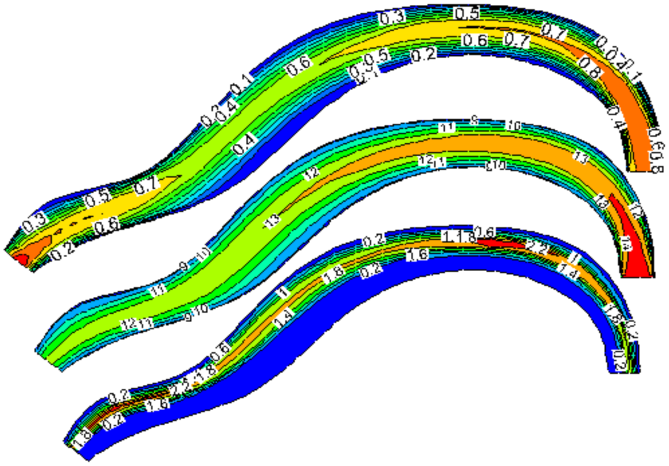

Fig. 8. Model output of velocity, water depth and temperature distribution with mean discharge Q = 347.18 m^3/s (we choose November as mean discharge)

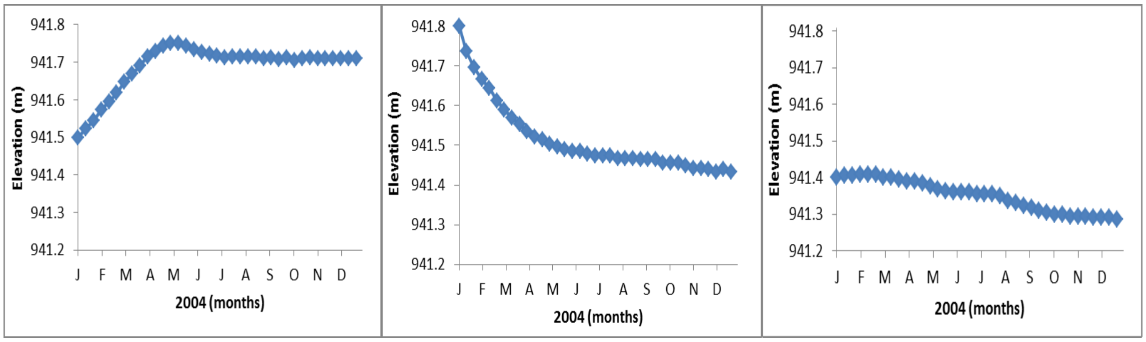

Fig. 9. Sediment time series from January to December of 2004 on lowest river bed of cross section A -A, B - B and C – C. (J, F, … D represent January, February, … December)

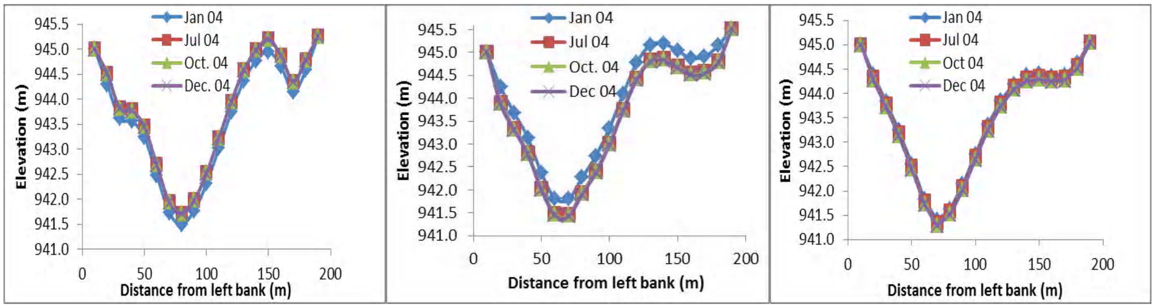

Fig. 10. River bed deformation on cross-section A -A, B - B and C - C during Jan, July, October and December (from left bank)

The default river bed elevation and substrates distribution was taken from U.S. Geological Survey (Kaplinski *et al;* 2009). Initial sediment distribution in Lees Ferry, Colorado River were then obtained by assigning the default size-fraction distribution to all river bed throughout the calculated domain. Fig. 9 shows the calculated distribution to the river bed change during the year of 2004, using non-uniform transport model with critical Shields value 0.047.

According to our simulation results, we could know that the scour occurs at the cross section B-B and C-C, while at cross section A-A there had deposition until May (Fig. 9). The scour also took place on cross section A-A in June and July with the discharge increase. After that no scouring and deposition occurs in cross section A-A which implies that the river bed shear stress is smaller than the critical shear stress. The scours in cross section B-B and C-C reduced because the active layer in river bed has already been scoured. The simulated maximum scour depth occurs at the cross section B-B was 0.4 m, while the maximum deposition happened in cross section A-A was 0.2m. Figure 10 also indicates the similar trend. The water depth has also changed accordingly. However, the scour and deposition affects are relatively small in comparison with the flow discharge which affects the water depth.

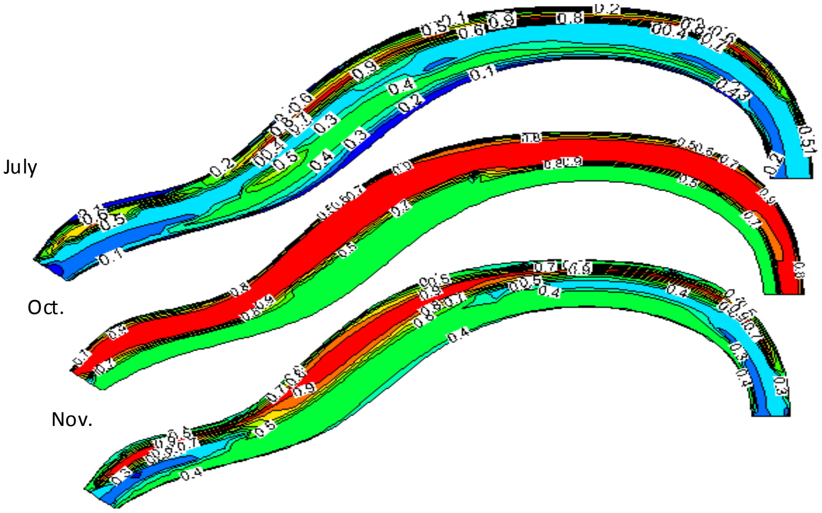

Fig. 11. Model output of habitat suitability index distribution in July (with highest discharge), October (with low discharge) and November (with mean discharge)

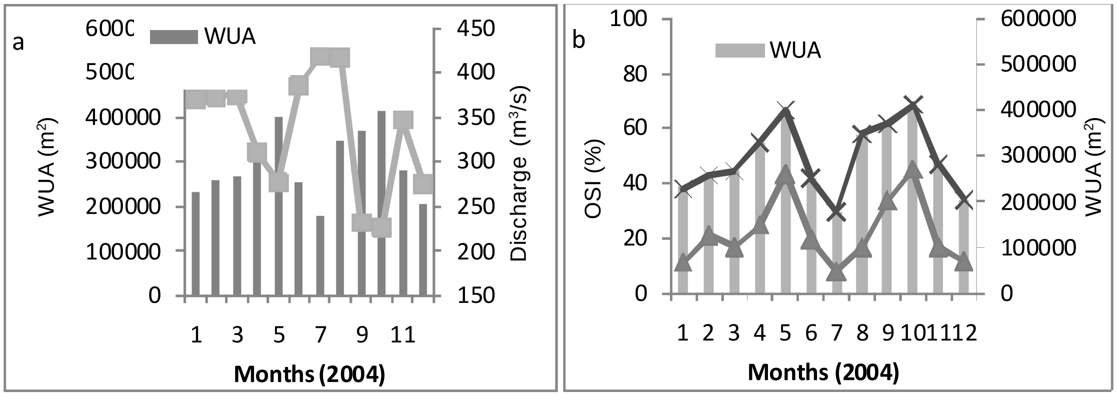

Fig. 12. (a) The relationship between WUA for adult Rainbow Trout and flow discharge from January to December of 2004 in study reach. (b) Sensitivity analyses of the OSI, High OSI and WUA duration curves for adult Rainbow Trout in 2004

Table 1. Description of the rainbow trout habitat suitability in lowest, mean, highest discharge in Lees Ferry (total area 600000 m^2)

Discharge (m^3/s)	HSI, WUA and OSI description
227.00	WUA =412743.25, High WUA =270873.75, OSI =0.69, High OSI =0.45
347.18	WUA =281442.50, High WUA =101941.75, OSI =0.47, High OSI =0.17
418.26	WUA =177481.25, High WUA =48932.00, OSI =0.30, High OSI =0.08

As mentioned above, the objective of habitat modeling was to evaluate the habitat suitability with the value ranging from 0 (unsuitable) to 1 (most suitable). The suitability varies dynamically with the variables such as flow velocity, flow temperature, water depth and river bed substrata which were calculated from CFD model and river deformation model. Thus, according to fish preference graph, the areas with high flow velocity, high flow temperature, low water depth and large substrata are not suitable for the fish species under study for living. In contrast, the areas which have low velocity, high water depth, middle temperature and with cobble or boulder as substrata are preferred by Rainbow Trout. The habitat suitability indicates that the most suitable areas in the computational domain are located on the right side of the river bank (Fig. 11). Comparing three types of the results of the HSI distribution (July, October, November), it appears that in October (lowest discharge) the suitability area for rainbow trout are higher that July (highest discharge) and November (mean discharge) (Fig. 11). Over all, the calculation results show that there is a nonlinear relationship between flow discharge and suitable habitat areas.

Sensitivity of habitat suitability index to the flow discharge also can be analyzed in terms of WUA and OSI. From the Figure 12a, we could know that the WUA rose steadily and reached the point 1599.98 on May before dropping dramatically to 709.93 in July. After that the WUA noticed a dramatic increase during July to October and then decreased again. Comparing the WUA and discharge, it can be shown that in the month of 1st, 2nd, 7th, 11th and 12ththe WUA have the similar trends with discharge. However, in the other months WUA have opposite trends with discharge.Table1 shows the fluctuation of WUA and OSI in the different habitat suitability types for the highest discharge and lowest discharge in comparison to the static mean discharge. Comparing the lowest discharge and highest discharge situation, the WUA and OSI are bigger in lowest discharge than the WUA and OSI in highest discharge. The mean discharge situation is better than the highest discharge but worse than the lowest discharge. From the Figure 13, we could also know that the proportion in Lees Ferry with habitat suitability index large than 0.7 have the same trends with the WUA and OSI. This result differs from that of Yi et al (2010) who studied Yangtze River. However, it is similar to the results of Panfil et al. (1999). Basically, even the WUA and OSI were high on May and October, the low number of WUA and OSI during rest of the time and the high OSI are less than 0.25 (Fig. 12b)gives confidence to say the study areas are not suitable for rainbow trout for living in 2004.

CONCLUSION

The computer system combines CFD, sediment transport modeling with habitat preferences of fish species and habitat distribution models to calculate the temporal variation of the size and quality of physical habitat. The WUA and OSI have been figured out to quantify the entire studied area. The principal results can be summarized as follows: (1) Modeling provides a means to quantify spatially and temporally variable aquatic habitats and a means to visualize hydraulic conditions and substrates distribution at discharges which are difficult to measure in the field. (2) Our simulation results of the habitat classification demonstrate the non-linear relationship between discharge and WUA for fish species. (3) Focus on the HSI, WUA, OSI and high OSI that have the significant impact on fish increase and decrease. This habitat model therefore represents an important tool in the design and implementation of fish species habitat studies.

This model system is used to calculate flow distribution, sediment transport and HSI distribution in Lees Ferry, Colorado River; it can be used to evaluate other stretches and other rivers. This model system can be used to estimate the effects of changes in river regime due to constructions, or the improvement of habitat quality resulting from rehabilitation efforts. It is can also be used in judging the river habitat based on ecological discharge. Due to the scarcity of enough data for setting up as well as for calibrating the model, a reliable quantitative prediction of the model system cannot be guaranteed currently. However, the agreement between simulation and evaluation gives confidence to accept the model system. In order to improve the quantitative predictions of the model system, further model verification need to carry out by detailed and accurate data.

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