ANALYSIS OF AQUATIC HABITAT SUITABILITY USING A DEPTH-AVERAGED 2-D MODEL

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Abstract Physical habitat modeling is mostly based on hydraulic and morphological variables, such as water depth, velocity, bathymetry and substrate as the main factors influencing distribution and abundance of organisms and species in aquatic ecosystems. However, the hydrological and biochemical characteristics in these systems are much more complex than this, due to the effects of hydraulic structures, sediment transport, channel evolution, vegetation, pollutant transport, biochemical processes, etc. This paper presents a depth-averaged 2-D model that simulates flow, sediment transport, vegetation, water quality and ecology in aquatic systems. The model predicts the temporal variation and horizontal distribution of habitat suitability for various fish species in a river reach using the simulated flow, sediment and water quality parameters. The established model was applied to evaluate the fish habitat in the Little Topashaw Creek, Mississippi. It was shown that large wood structures improved fish habitat quality. Weighted usable area and overall habitat suitability index were increased by the constructed structures.

INTRODUCTION

Human activities, such as urbanization, navigation, power generation, irrigation, water supply, wastewater treatment and flood control, have significantly altered the flow regime and channel dynamics of rivers. This has resulted in degradation of habitats for numerous aquatic species. Protecting and enhancing aquatic habitats thus becomes very important. To support these efforts, it is needed to comprehensively understand the complex processes and functions of aquatic ecosystems, and develop reliable tools for evaluating aquatic habitat availability and quality.

In traditional habitat modeling, instream habitat characterization, such as the distribution of flow depth and velocity at the study site, is typically estimated using one-dimensional (1-D) modeling techniques, which assume that the flow follows essentially parallel streamlines. One of the most common 1-D techniques is the Physical Habitat Simulation System (PHABSIM) (Bovee, 1986 and Milhous et al., 1989), which was developed as a water management tool to assist in the establishment of instream flow requirements for supporting water control and allocation activities. PHABSIM adopts the methodology known as the Instream Flow Incremental Methodology (Bovee, 1982 & 1986). At first, PHABSIM uses a 1-D hydraulic model to predict depth and velocity throughout a river reach. This information combined with data regarding the types of substrate and cover found within the river is then compared to habitat suitability criteria to estimate the quality and quantity of habitat within the modeled section. The PHABSIM model has been used by many scientists such as Carling (1995), Gore and Hamilton (1996), FAO (1998), Milhous (1999), Michael et al., (1999), etc.

However, 1-D habitat models neglect transverse flow and eddies, which are important components of the flow field, and hence, the physical habitat. Natural rivers, streams and wetlands usually have multiple diverging flow paths and considerable variability in depth; thus, the 1-D approximation is subject to considerable uncertainty. In particular, stream restoration design criteria for instream structures need to be habitat-based and integrated with hydraulic engineering specifications, but 1-D hydrodynamic models cannot predict complex flow patterns that are ecologically relevant to structural designs (Schwartz et al., 2004). Shirvell (1989) tested the ability of PHABSIM to predict the amount of useable habitat for Chinook salmon in the Nechako River, and found that PHABSIM overestimated the amount of useable spawning habitat by 210 to 600 percent depending on the cell sizes and other inputs employed in PHABSIM. A main reason for the overestimation was due to the 1-D assumption that habitat conditions, such as depth and velocity values, are uniform within each cell. Shirvell suggested that the ability to consider the changes in depth and velocity within a cell would improve useable habitat computations. Considering the nature of the problem, a horizontal 2-D model should be used for better understanding and predicting the aquatic habitat. This has been ascertained by many researchers such as Ghanem et al. (1994), Crowder and Diplas (2000), Gard (2003), Loranger and Kenner (2004), and Mussetter et al. (2004).

Note that the aforementioned habitat modeling approaches are mostly based on hydrological, morphological and hydraulic parameters such as water depth, velocity, bathymetry and substrate as the main factors influencing the aquatic ecosystems. The complexity of hydrological and biochemical characteristics in aquatic systems is far beyond this. Hydraulic structures, sediment transport, channel morphological evolution, vegetation, etc. would dynamically change the physical conditions of habitat systems. Habitat suitability is also controlled by many biochemical factors present in aquatic systems, including water temperature, dissolved oxygen, PH, turbidity, light penetration, pollutant transport, water quality, food resources, etc. Therefore, a depth-averaged 2-D model that comprehensively considers the effects of all these factors on aquatic habitat is needed. To reach this goal, the FVM-based CCHE2D model has been developed. Some capabilities of this model are introduced here.

FVM-BASED CCHE2D MODEL

The FVM-based CCHE2D model is a depth-averaged 2-D model for flow, sediment transport, water quality, and ecology in aquatic systems (Wu, 2004; Wu et al., 2005). The hydrodynamic module solves the depth-averaged 2-D shallow water equations using the finite volume method on a non-staggered, curvilinear grid. It uses SIMPLE(C) procedures with Rhie and Chow’s momentum interpolation technique to handle the pressure-velocity coupling, and employs Stone’s Strongly Implicit Procedure to solve the discretized algebraic equations. The flow module handles the drying and wetting processes very well.

The sediment transport module simulates the nonequilibrium transport of nonuniform total-load sediment. Non-cohesive sediment transport capacity is determined by the user’s choice of one of four formulas, which all account for the hiding and exposure effects among different size classes.

The influence of helical flow motions on the main flow and sediment transport in curved channels is taken into account by modeling the dispersion terms in the momentum equations and the suspended-load transport equation as well as modifying the transport angle of bed load. The model is enhanced to simulate the local scour process around bridge piers and spur-dikes, and also to calculate vegetation effects on flow, sediment transport, and channel morphological changes. The model simulates cohesive sediment transport, considering flocculation, erosion, deposition, and consolidation processes. The sediment transport equations are discretized by the same finite volume method used in the flow module. The flow and sediment transport are computed in a decoupled way, but a coupling procedure is adopted for the three components of sediment module: sediment transport, bed change, and bed material sorting.

The model simulates heat transport considering the effect of solar radiation and exchange between water and air. It also simulates pollutant transport and water quality in aquatic systems.

The habitat module computes the weighted usable area (*WUA)* and the overall habitat suitability index (*OSI*) for a particular species in a life stage of interest under a given flow discharge using the concepts in PHABSIM. In the determination of usable habitat area, the model weights each cell using habitat suitability curves that assign a relative value between 0 and 1 for the target species. The weighted usable area (*WUA*) for all cells in a stream reach is then evaluated as

$$WUA = \sum_{i}^{M} CSI_i \cdot \Delta A_i \tag{1}$$

where M is the total number of wetted grid cells; ΔA_i is the area of grid cell i; and CSI_i is the combined suitability index of grid cell i. CSI can be determined using several methods, but in the current model, it is determined as a product of the corresponding suitability weights for water velocity, depth, and channel property (substrate), as suggested by Milhous (1999). More habitat suitability weights related to temperature, dissolved oxygen, etc. will be implemented in the near future. Theoretically, the value of *CSI* is up to 1.0 for a cell with best habitat quality, and low as 0.0 for a cell without any suitable habitat.

The overall suitability index (*OSI*) is defined as the ratio of the weighted usable area and the total flow area in the horizontal plane, i.e.

$$OSI == \sum_{i}^{M} CSI_i \cdot \Delta A_i \Big/ \sum_{i}^{M} \Delta A_i \tag{2}$$

COMPARISON WITH EXISTING MODEL

Due to the limited available data, an example provided in the tutorial of River2D (Steffler and Blackburn, 2002) is chosen to test the present CCHE2D fish habitat model. The Fortress site along the Kananaskis River in Alberta is simulated by River2D and CCHE2D, respectively. Both models calculate the weighted usable area for adult Brown Trout. Figure 1 gives the comparison of combined suitability indices calculated by two models. The weighted usable areas obtained by CCHE2D and River2D are 164.6 and 170.4 m^2, respectively. The agreement is generally good.

Slight difference exists between two models' results perhaps due to differences in numerical methods and conversion of the channel topography from River2D finite element mesh to CCHE2D finite volume mesh.

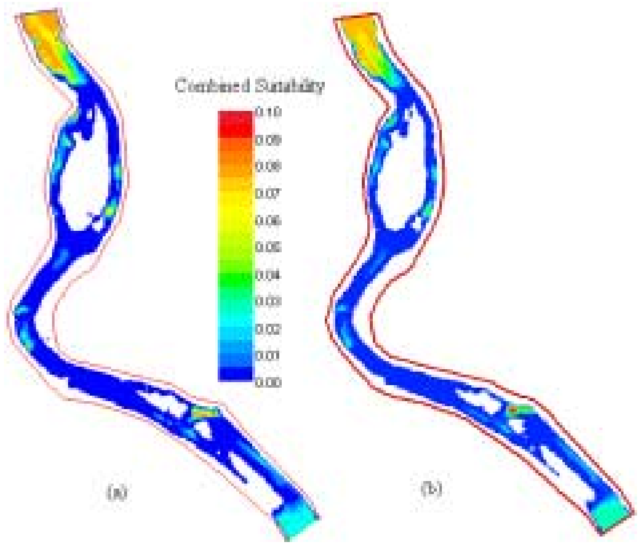

Figure 1 Combined Suitability Indices (*CSI*) Predicted by (a) River2D and (b) CCHE2D

MODEL APPLICATION

The FVM-based CCHE2D model has been used to analyze the fish habitat in several river reaches. Due to the limited length of the paper, presented here is only the application to the Little Topashaw Creek, North Central Mississippi. The study reach was a deeply-incised sharp bend, as shown in Figure 2, in which the shaded polygons are large wood structures (LWS) and contours represent bed elevation in m. Five structures made from felled trees were placed along the outside of the study bend in the summer of 2000 in order to stabilize the channel and create aquatic habitats (Shields et al., 2004). The crests of structures were 1.1 to 3.2 m higher than the bed and were emergent at low flow and submerged at high flow. Logs running transverse to the flow direction were about 6 m long and were anchored into the bank toe. Wu et al. (2005) simulated the flow, sediment transport and bed change due to the effect of the large wood structures during a period of about 1 yr after the structures were constructed. The mesh, flow and sediment conditions, and model validation are described by Wu et al. (2005).

The habitat conditions for Gizzard Shad (*Dorosoma Cepedianum*) Juvenile before and after the structure construction in this study reach were analyzed. The effects of water depth and velocity were considered. The relevant habitat suitability curves are shown in Figure 3 (Williamson and Nelson, 1985). Figure 4 shows the comparison of the simulated flow fields with and without the large wood structures (under discharge of 15.5 m^3/s). It can be seen that the flow was retarded by the structures along the outer bank and accelerated in the main channel. Figures 5, 6 and 7 give the comparison of combined suitability indices under high, medium and low discharges, respectively. It is shown that the habitat suitability along the outer bank where was covered by large wood structures was increased. The weighted usable areas and overall habitat suitability indices with and without the structures under three different discharges are compared in Table 1.

One can see that the structures improved the quantity and quality of fish habitat. Figure 8 shows the simulated bed change and the combined suitability index 1 yr after the structure construction (under discharge of 15.5 m^3/s). Deposition occurred along the outer bank where the large wood structures located and erosion happened in the main channel. This resulted in further improvement of the habitat suitability, as shown in Table 2.

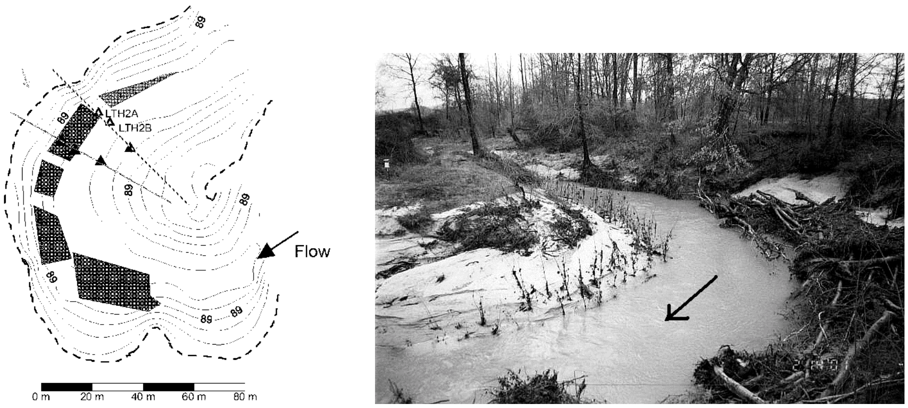

Figure 2 (left) Map of study site, Little Topashaw Creek; (right) Photo facing upstream

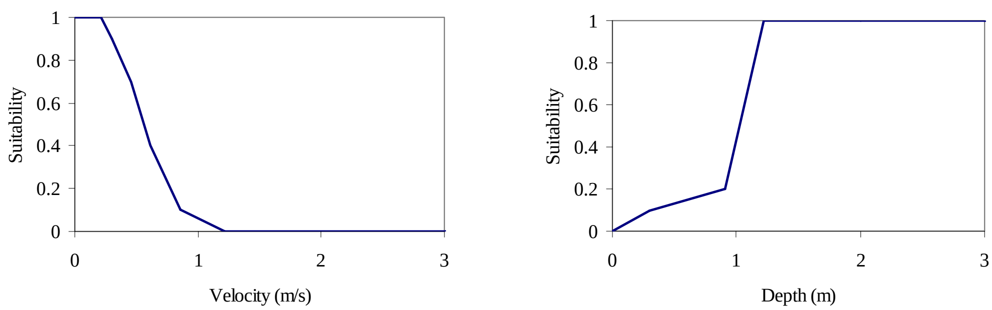

Figure 3 Suitability curves for Gizzard Shad Juvenile

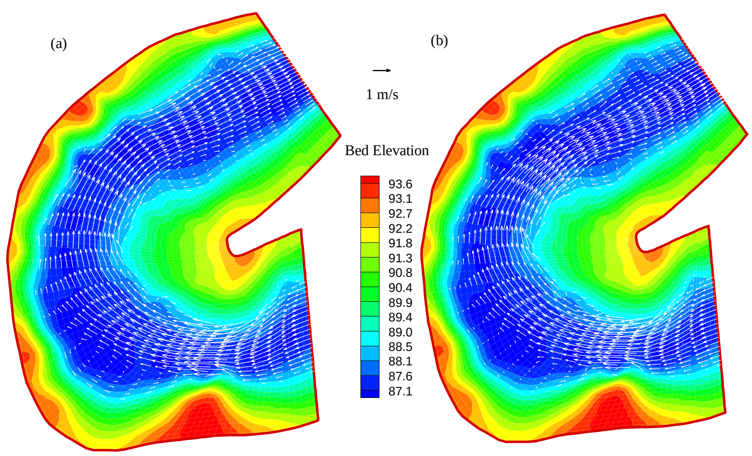

Figure 4 Simulated flow fields (a) without and (b) with LWS

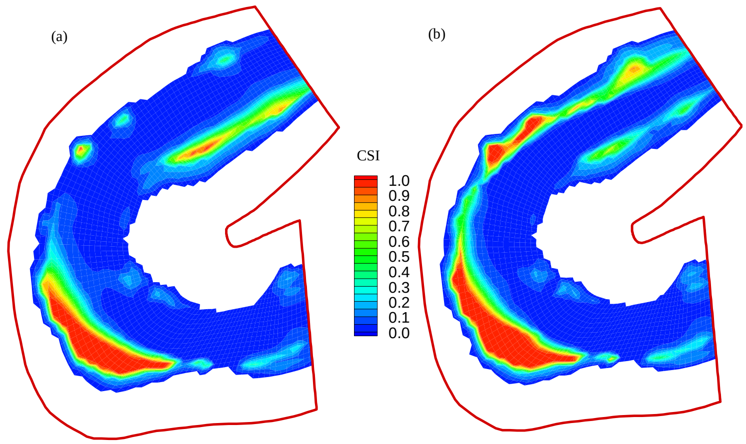

Figure 5 Combined suitability indices under high discharge (15.5 m^3/s)
(a) without and (b) with LWS

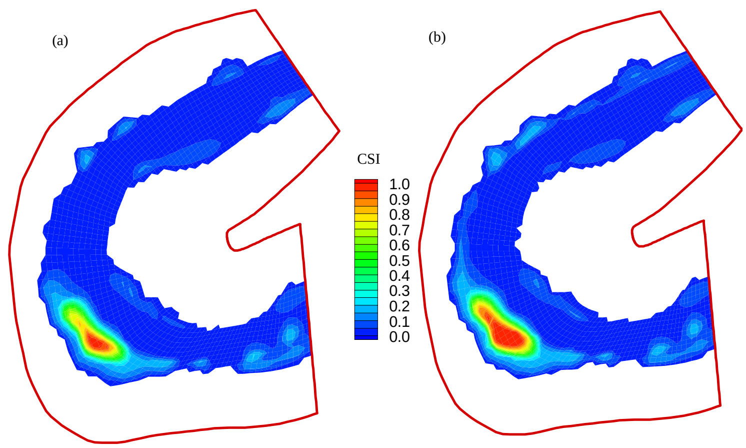

Figure 6 Combined suitability indices under medium discharge (5.0 m^3/s)
(a) without and (b) with LWS

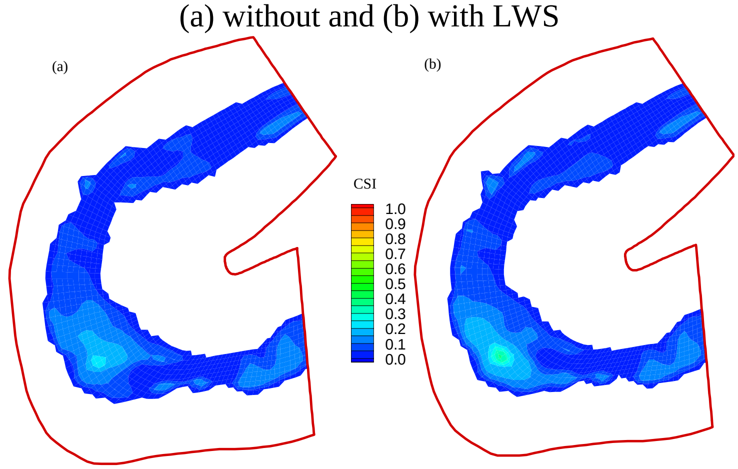

Figure 7 Combined suitability indices under low discharge (1.5 m^3/s)
(a) without and (b) with LWS

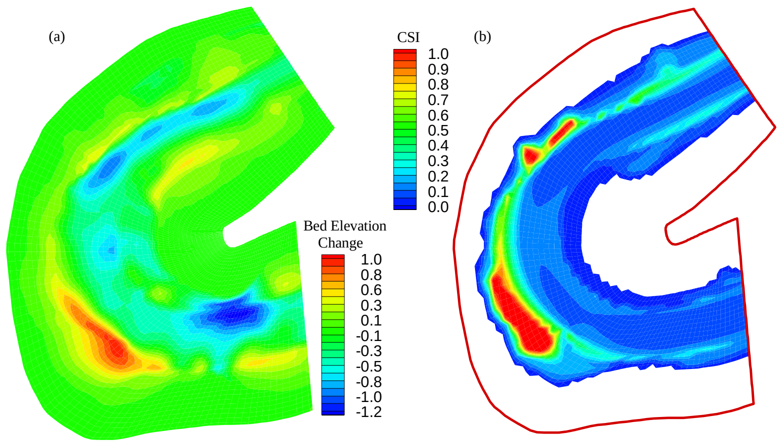

Figure 8 (a) Bed change and (b) combined suitability index after 1 yr

Table 1 Weighted usable area and overall suitability index under different discharges

Discharge (m^3/s)		Weight Usable Area (m^2)		Overall Suitability Index	
		Without LWS	With LWS	Without LWS	With LWS
High	15.5	238.93	298.98	0.164	0.205
Medium	5.0	75.70	97.02	0.073	0.093
Low	1.5	53.01	57.81	0.065	0.070

Table 2 Overall suitability index at initial time and after 1 yr

Discharge (m^3/s)		Overall Suitability Index	
		Initial	After 1 yr
High	15.5	0.205	0.207
Medium	5.0	0.093	0.095
Low	1.5	0.070	0.120

CONCLUSION

Distribution and abundance of organisms and species in aquatic systems are dynamically affected by a number of hydrological, morphological, physical, chemical and biological factors. Reliable evaluation of quantity and quality of habitats requires a depth-averaged 2-D model that comprehensively considers the effects of these factors. The FVM-based CCHE2D model has been designed for this purpose. This model is very efficient and has broad capability of simulating flow, sediment transport, heat transport, pollutant transport, water quality and ecology in aquatic systems. The application in the Little Topashaw Creek has demonstrated that this model is capable of analyzing the effect of large wood structures on aquatic habitats. It has been shown that the large wood structures can not only stabilize channel banks (Shields et al. 2004), but also improve fish habitat.

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