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COMPARISON OF 1-D AND DEPTH-AVERAGED 2-D FISH HABITAT SUITABILITY MODELS

Weiming Wu[1], Podjanee Inthasaro[2], Zhiguo He[3], and Sam S.Y. Wang[4]

ABSTRACT

Habitat evaluation, a state-of-the-art technique for impact assessment and resource management, becomes an important tool for estimating the amount of habitat available for a given fish species within a study reach. This paper presents a comparison of one-dimensional (1-D) and depth-averaged two-dimensional (2-D) fish habitat suitability models. The recently developed CCHE1D and CCHE2D*fvm* habitat suitability models as well as the Physical Habitat Simulation System (PHABSIM) are compared in estimation of the weighted usable area and overall suitability index for adult cutthroat trout in the East Fork River in Wyoming at different flow discharges. To enhance the accuracy in determining flow depth and velocity in CCHE1D, a cross section is divided into a suitable number of vertical panels and the flow velocity at each panel is calculated using Manning's equation. It has been found that 1-D and 2-D models give close estimations for cross sections with simple geometry, but differences exist for those with complex geometry since complex flow features are neglected in the 1-D models.

1. INTRODUCTION

Protecting and enhancing aquatic habitats becomes very important, due to the fact that many human activities, such as urbanization, navigation, power generation, irrigation, water supply, wastewater treatment, and flood control, significantly alter flow regimes and channel dynamics and degrade habitats in aquatic systems. Thus, it is needed to comprehensively understand the complex processes and functions of aquatic ecosystems and develop reliable tools for analyzing aquatic habitat quality.

The U.S. Fish and Wildlife Service developed the Instream Flow Incremental Methodology (IFIM) to evaluate the effects of altered stream flow on fish habitat (Bovee, 1982). An integral part of the IFIM is the Physical Habitat Simulation System (PHABSIM), which is one of the most common 1-D techniques used to assist in the establishment of instream flow requirements for supporting water control and allocation activities. The PHABSIM model has been used by many scientists, e.g. Shirvell (1989), Huusko and Yrjana (1997), Scruton et al. (1998), Holm et al. (2001), and Loranger and Kenner (2004). In PHABSIM, streams are represented by large rectangular cells within which the velocity and depth are assumed to be constant. This approach neglects transverse

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flow and eddies, which are important components of the flow field, and hence the physical habitat. Shirvell (1989) examined the ability of PHABSIM to predict the amount of usable habitat for Chinook salmon in the Nechako River, and found that PHABSIM overestimated the amount of usable spawning habitat by 210 to 600% depending on the cell sizes and other inputs employed in PHABSIM. A main reason for the overestimation was attributed to the assumption that habitat conditions (water depth and velocity) are uniform within each cell. Shirvell suggested that the ability to account for the changes in depth and velocity within a cell would improve usable habitat computations.

To improve the estimation of hydraulic conditions, recent studies have replaced the traditional 1-D models with 2-D models, such as River2D, Surface water Modeling System (SMS), and CCHE2D*fvm*, which have been developed for detailed hydraulic analysis of spatially explicit habitat units at the microhabitat scale (Steffler and Blackburn, 2002; Henderson and Kenner, 2003; Mussetter et al., 2004; Pasternack et al., 2004; Wu et al., 2006). In principle, a 2-D hydrodynamic model should be more suitable and give more accurate estimations for flow velocity and water depth since the lateral properties are taken into account during the simulation.

Loranger and Kenner (2004) compared the weighted usable areas (WUA) estimated by PHABSIM and River2D models for several study cases. The difference is mostly in the range of 67-167%. They concluded that PHABSIM is just as effective in evaluating relative changes in WUA as River2D, but it is not if the spatial variation of WUA is considered. Wu et al. (2006) compared the CCHE2D*fvm* and River2D habitat models in calculating the weighted usable area for adult brown trout at the Fortress site of the Kananaskis River in Alberta. The weighted usable areas obtained from both models are in a good agreement. Slightly difference exists between two model results perhaps due to the differences in numerical methods and conversion of channel topography from River2D finite element mesh to CCHE2D finite volume mesh. Therefore, the present study focuses on the comparison among CCHE1D, CCHE2D*fvm*, and PHABSIM models.

2. CCHE1D AND FVM-BASED CCHE2D HABITAT MODELS

Physical habitat modules have been recently developed in the 1-D channel network model CCHE1D and the depth-averaged 2-D finite-volume model (FVM) CCHE2D*fvm*. The CCHE1D and CCHE2D*fvm* models compute unsteady flow, nonuniform sediment transport, and water quality in aquatic systems. The CCHE1D can be used to simulate flow and sediment transport in a dendritic channel network. The flow is simulated by either diffusive or dynamic wave model, taking into account the difference between flows in main channel and flood plains of a compound channel, and the influence of hydraulic structures such as culverts, measuring flumes, bridge crossing, and drop structures. The flow model can be used with or without sediment calculation (Wu and Vieira, 2002). The CCHE2D*fvm* 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 (Wu, 2004; Wu et al., 2006).

The 1-D and 2-D hydrodynamic models give the cross-section- and depth-averaged quantities, respectively. The 2-D model can perfectly account for the lateral variation of flow properties and then give reasonable estimation of the habitat suitability index. In order to consider the lateral variation of flow depth and velocity in the 1-D model, the cross section is divided into a suitable number of vertical panels and the flow velocity at each panel is determined using Manning’s equation. This procedure can enhance the accuracy of the calculated flow velocity and depth in the 1-D model.

In both CCHE1D and CCHE2D*fvm* models, the habitat modules compute the weighted usable area and overall habitat suitability index for a particular species in a life stage of interest under a given flow discharge using the concept in PHABSIM. Physical parameters such as water depth and flow velocity are used to evaluate the habitat suitability by comparing to the relevant Habitat Suitability Index (HSI) curves. The HSI is scaled between 0 (unsuitable habitat) and 1 (optimal habitat). The combined suitability index (CSI) of each cell can be determined using several methods, but in this study, it is determined as the product of the corresponding suitability weights for flow depth and velocity as suggested by Milhous (1999). More habitat suitability weights related to temperature, dissolved oxygen, etc. are being implemented. Thus, the combined suitability index in each grid cell can be calculated as

$$CSI_i = DI_i \cdot VI_i \tag{1}$$

where DI_i and VI_i are the depth and velocity habitat suitability indices of grid cell *i*, respectively. Subsequently, the WUA for all cells in the reach of interest is evaluated as

$$WUA = \sum_i^M CSI_i \cdot \Delta A_i \tag{2}$$

where M is the total number of wetted grid cells and ΔA_i is the area of grid cell *i* in the horizontal plane. Finally, the overall suitability index (OSI), which is defined as the ratio of the weighted usable area and the total flow area in the horizontal plane, can be expressed as

$$OSI = \sum_i^M CSI_i \cdot \Delta A_i \Big/ \sum_i^M \Delta A_i \tag{3}$$

3. CASE STUDY

The East Fork River originates in the Wind River Range of Wyoming, west of the Continental Divide and east and south of Mt. Bonneville. The 3.3-km-long study reach shown in Figure 1 is analyzed using the three fish habitat models mentioned above. The drainage area of the East Fork River at downstream is about 500 km^2 and the bankfull discharge in this reach is about 20 m^3/s. Along the study reach, the East Fork River meanders in a floodplain averaging 100 m in width (Leopold and Emmett, 1997).

Native fish species inhabiting this river include Yellowstone cutthroat trout (*Oncorhynchus clarki bouvieri*), white sucker (*Catostomus commersonii*), mountain sucker (*Catostomus platyrhynchus*), and mountain whitefish (*Prosopium williamsoni*). The most abundant sport fish are rainbow trout (*Oncorhynchus mykiss*), brook trout (*Salvelinus fontinalis*), and brown trout (*Salmo trutta*). Non-game fish includes Longnose Sucker (*Catostomus catostomus*). Due to large sediment input, irrigation, human activities, etc., the abundance and purity of the Yellowstone cutthroat trout are undermined. For this reason, the Yellowstone cutthroat trout is the native fish species of most concern for fisheries management (The Wyoming Game and Fish Department, 2006).

The Yellowstone cutthroat trout is a subspecies of cutthroat trout (*Oncorhynchus clarki*) that is a species of freshwater fish in the salmon family. Cutthroat trout is native to western North America. Some populations live in the Pacific Ocean as adults and return to fresh water to spawn in the spring. Other subspecies of cutthroat trout include Colorado cutthroat trout (*Oncorhynchus clarki* *pleuriticus*), Snake River fine-spotted cutthroat trout (*Oncorhynchus clarki*), etc. The physical habitat of cutthroat trout is quantified using depth and velocity suitability index curves developed by experts in the field of fisheries biology. The habitat suitability index curves associated with water depth and velocity for the adult cutthroat trout are shown in Figure 2. The optimum cutthroat trout riverine habitat is characterized by clear, cold water; well vegetated stream banks; abundant instream cover; and relatively stable water flow, temperature regimes, and stream bank. For the adult cutthroat trout, dissolved oxygen requirements vary with species, age, prior acclimation temperature, water velocity, and concentration of substances in the water (Hickman and Raleigh, 1982).

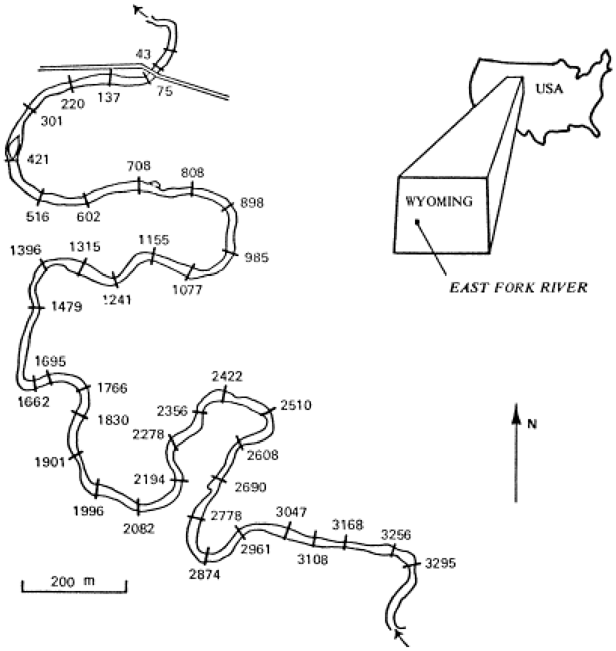

Figure 1 Map of the study reach in the East Fork River

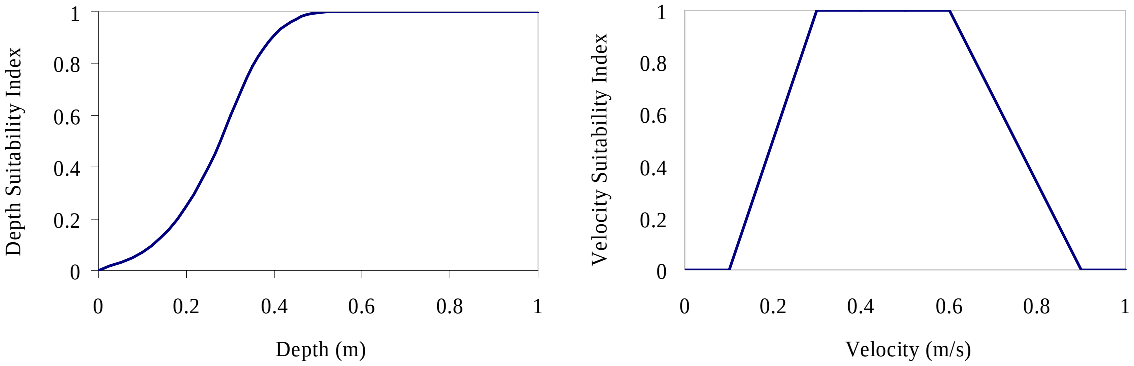

Figure 2 Habitat suitability index curves for adult cutthroat trout

The CCHE2D*fvm* model uses 481x36 computational nodes in the longitudinal and transverse directions, respectively, to represent the study reach. Both PHABSIM and CCHE1D models use 121 cross sections and 36 vertical panels for each cross section. The 1-D cross sections are selected from the 2-D mesh by skipping three cross sections consecutively. Steady flows at flow discharges of 10 and 20 m^3/s are simulated. The outlet water surface elevation is set at 5.4 m. Due to the fact that the 2-D model considers the horizontal diffusion through the diffusion term but 1-D models lump this through Manning's *n*, the 2-D model usually gives slightly higher water depth than 1-D models for the same Manning's *n*. Therefore, to obtain the approximately same water surface profile, the Manning's *n* is given 0.030 in CCHE1D and PHABSIM models, while it is set to 0.028 in CCHE2D*fvm* model. The longitudinal profiles of water surface elevation simulated by CCHE2D*fvm*, CCHE1D, and PHABSIM at the discharge of 10 m^3/s are shown in Figure 3, while the simulated average water depth and flow velocity profiles are shown in Figure 4. PHABSIM has bigger deviations from the 2-D water surface than CCHE1D. Since the 2-D model uses more cross sections, it provides more details for the longitudinal variations of flow depth and velocity.

Figure 5 presents the water depth and flow velocity contours in the study reach simulated by CCHE2D*fvm* at the discharge of 10 m^3/s. In each grid, simulated water depth and velocity are used to determine the depth suitability index (DI) and velocity suitability index (VI) by applying the suitability curves shown in Figure 2. The depth and velocity suitability index contours simulated by CCHE2D*fvm* at 10 m^3/s are shown in Figure 6. These two suitability weights are subsequently multiplied together to obtain the combined suitability index (CSI). The CSI contours simulated at 10 and 20 m^3/s are shown in Figure 7.

The longitudinal profiles of cross-sectionally averaged CSI values simulated by PHABSIM, CCHE1D, and CCHE2D*fvm* models at 10 and 20 m^3/s are compared in Figures 8 and 9, respectively. The simulation results from all habitat models are in a similar pattern. The cross-sectionally averaged CSI values range between 0.1 and 0.8 with an average value of 0.6 along the reach for the discharge of 10 m^3/s, and vary from 0 to 0.6 with an average value of 0.3 for 20 m^3/s. Both suitability estimations from 1-D habitat models are almost identical, only slightly different results occurred at a few cross sections. The cross-sectionally averaged combined suitability indices simulated by CCHE2D*fvm* model are relatively different from those simulated by PHABSIM and CCHE1D models. The relative differences between the cross-sectionally averaged CSI estimated by CCHE1D and CCHE2D*fvm* models are in the range of 67-167% for 82% of the 121 cross sections (used in 1-D models) at the discharge of 10 m^3/s, and for 50.4% of the 121 cross sections at 20 m^3/s. The differences between PHABSIM and CCHE2D*fvm* are at the same levels. The difference is particularly noticeable in regions where recirculation, divergence, convergence, and other complex flow patterns exist. The difference is also due to different methods and different mesh sizes.

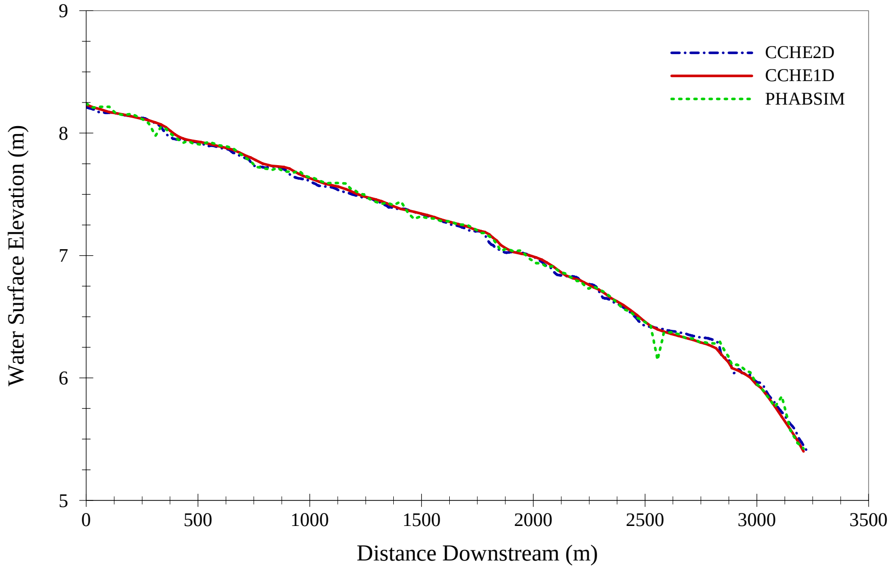

Figure 3 Water surface profiles along the East Fork River simulated at 10 m^3/s

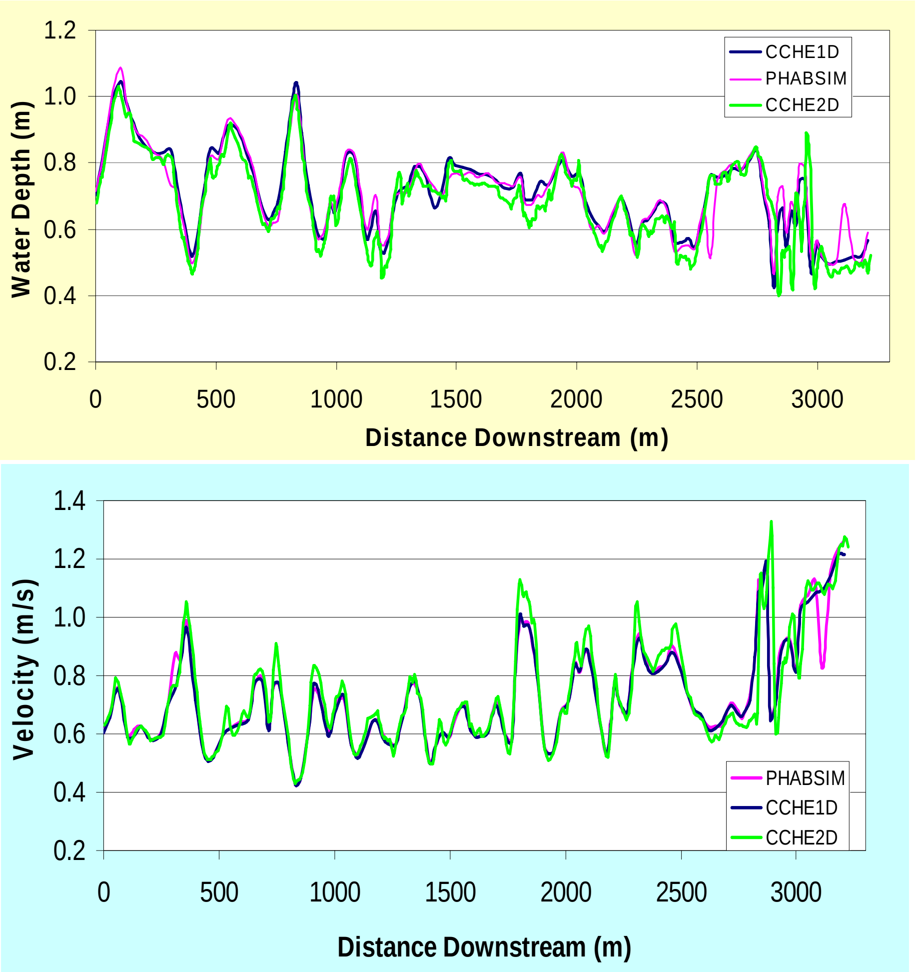

Figure 4 Flow depth and velocity profiles along the East Fork River simulated at 10 m^3/s

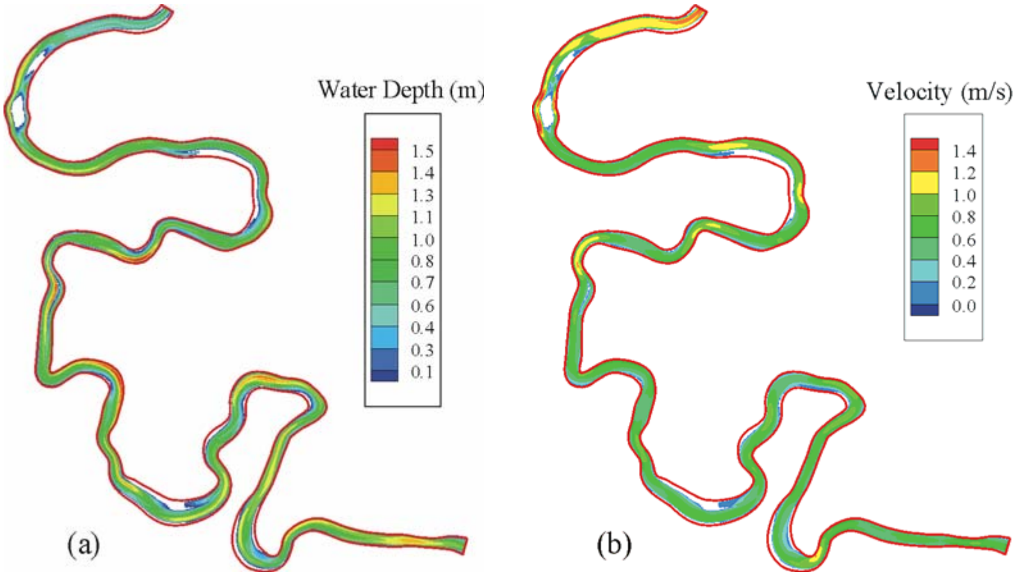

Figure 5 (a) Water depth and (b) flow velocity simulated by CCHE2D*fvm* at 10 m^3/s

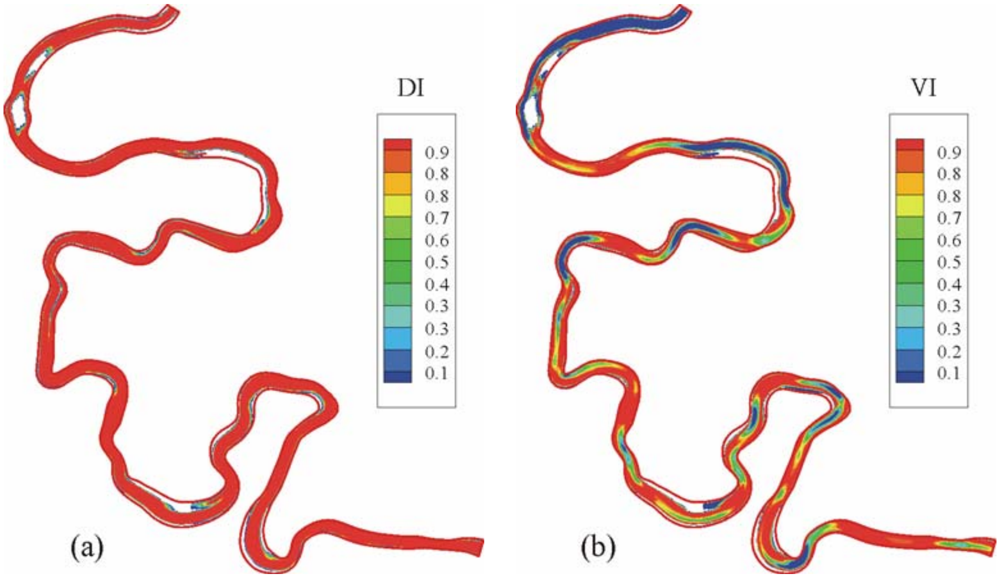

Figure 6 (a) Depth and (b) velocity suitability index contours simulated by CCHE2D*fvm* at 10 m^3/s

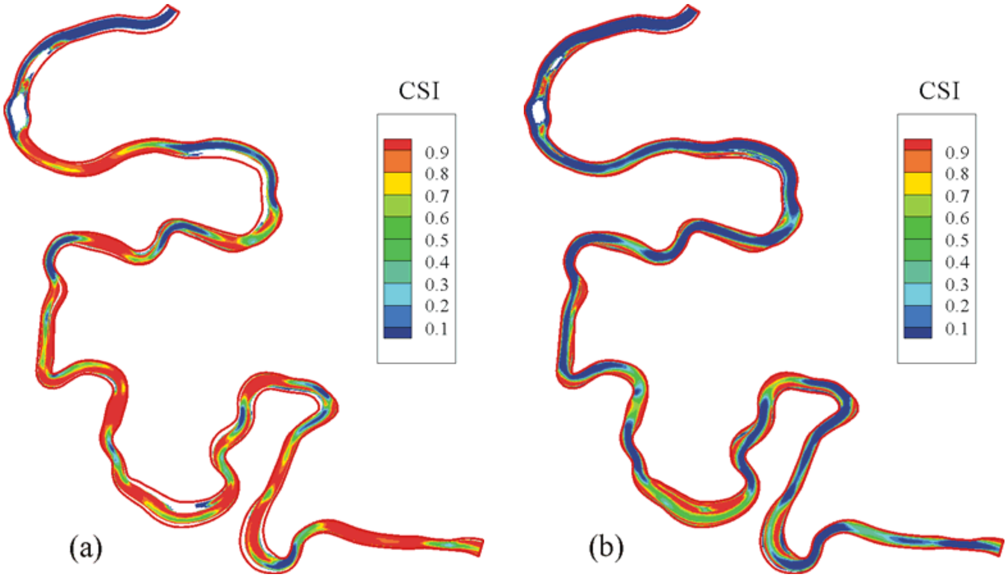

Figure 7 Combined suitability indices simulated by the CCHE2D*fvm* model
(a) 10 m^3/s and (b) 20 m^3/s.

Total flow areas in the horizontal plane, weighted usable areas, and averaged overall suitability indices (OSI) along the study reach simulated by CCHE2D*fvm*, CCHE1D, and PHABSIM at the two flow discharges are compared in Table 1. Although the cross-sectionally averaged combined suitability indices from 1-D habitat models are different from those estimated by

2-D model as presented in Figures 8 and 9, one can see that the total area, WUA, and the averaged OSI from all models are similar. Actually, 1-D simulation may have inaccurate results at certain cross sections. However, the positive and negative errors may compensate so that the overall suitability indices along the study reach estimated by 1-D and 2-D models appear to be close.

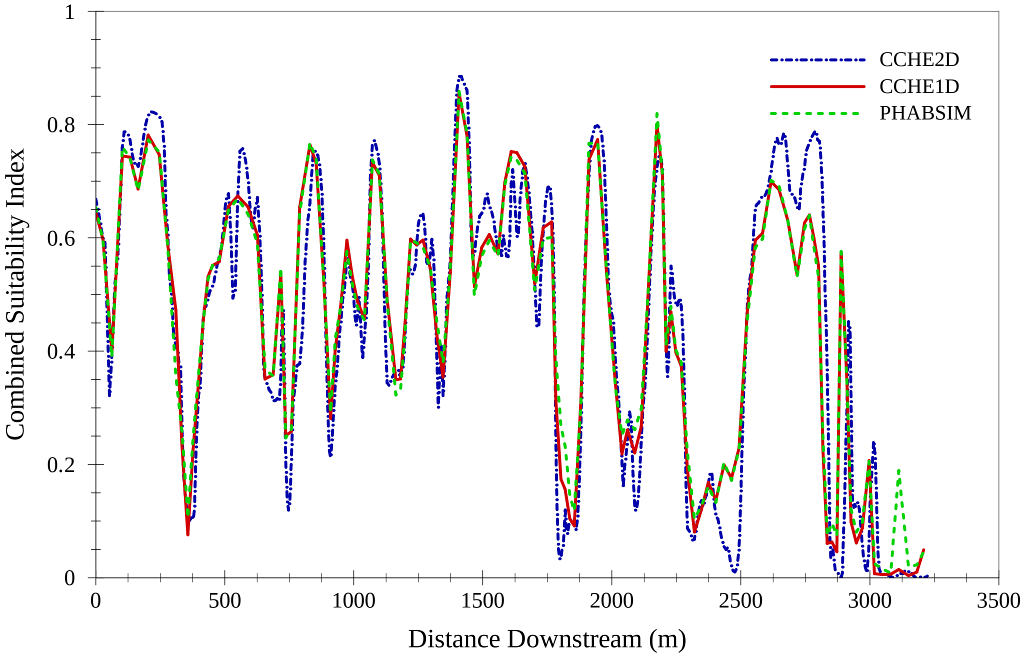

Figure 8 Longitudinal profiles of the combined suitability indices simulated by CCHE2D*fvm*, CCHE1D, and PHABSIM at10 m^3/s.

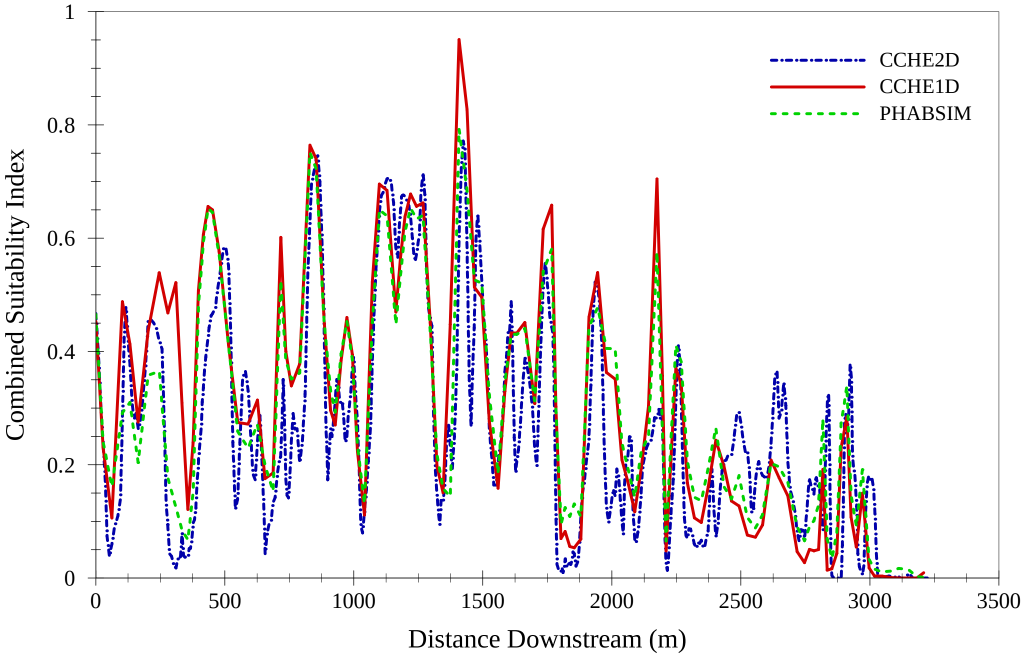

Figure 9 Longitudinal profiles of the combined suitability indices simulated by CCHE2D*fvm*, CCHE1D, and PHABSIM at 20 m^3/s.

Table 1 Comparison of total area, WUA, and OSI simulated at 10 and 20 m^3/s

Discharge	10 m^3/s			20 m^3/s		
	Total Area (m^2)	WUA (m^2)	OSI	Total Area (m^2)	WUA (m^2)	OSI
CCHE2D*fvm*	62602	37870	0.605	80358	27279	0.339
CCHE1D	66277	39622	0.598	77396	26700	0.345
PHABSIM	66709	38852	0.582	79524	26872	0.338

4. CONCLUSIONS

The existing habitat suitability model, PHABSIM, and the habitat suitability modules recently developed in CCHE1D and CCHE2D*fvm* are used to estimate the weighted usable area for adult cutthroat trout in the East Fork River, Wyoming. The habitat suitability indices are calculated at two constant flow discharges of 10 and 20 m^3/s. The cross-sectionally averaged combined suitability indices range between 0.1 and 0.8 for the discharge of 10 m^3/s and from 0 to 0.6 for 20 m^3/s. Differences exist between the cross-sectionally averaged combined suitability indices estimated by 1-D and 2-D models. However, the weighted usable areas and overall suitability indices calculated by 1-D habitat models are similar to those by the 2-D model. These differences in the habitat analysis are rooted from different flow properties simulated by different hydrodynamic models. In particular, differences can be seen noticeably when the simulation is performed in a detailed scale and when the computational domain includes complex structures.

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