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One-dimensional and two-dimensional hydrodynamic modeling derived flow properties: impacts on aquatic habitat quality predictions

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ABSTRACT: Studies of the effects of hydrodynamic model dimensionality on simulated flow properties and derived quantities such as aquatic habitat quality are limited. It is important to close this knowledge gap especially now that entire river networks can be mapped at the microhabitat scale due to the advent of point-cloud techniques. This study compares flow properties, such as depth and velocity, and aquatic habitat quality predicted from pseudo-2D and fully 2D hydrodynamic modeling. The models are supported by high-resolution, point-cloud derived bathymetries, from which close-spaced cross-sections were extracted for the 1D modeling, of three morphologically and hydraulically different river systems. These systems range from small low-gradient meandering pool–riffle to large steep confined plane-bed rivers. We test the effects of 1D and 2D models on predicted hydraulic variables at cross-sections and over the full bathymetry to quantify the differences due to model dimensionality and those from interpolation. Results show that streambed features, whose size is smaller than cross-sectional spacing, chiefly determine the different results of 1D and 2D modeling whereas flow discharge, stream size, morphological complexity and model grid sizes have secondary effects on flow properties and habitat quality for a given species and life stage predicted from 1D and 2D modeling. In general, the differences in hydraulic variables are larger in the bathymetric than in the cross-sectional analysis, which suggests that some errors are introduced from interpolation of spatially disaggregated simulated variables with a 1D model, instead of model dimensionality 1D or 2D. Flow property differences are larger for velocity than for water surface elevation and depth. Differences in weighted usable area (WUA) derived from 1D and 2D modeling are relatively small for low-gradient meandering pool–riffle systems, but the differences in the spatial distribution of microhabitats can be considerable although clusters of same habitat quality are spatially comparable. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS: one-dimensional and two-dimensional hydrodynamic models; stream morphology; habitat modeling; aquatic habitat quality distribution; longitudinal scales of topographical features

Introduction

One of the most common approaches to assess aquatic habitat quality is the in-stream flow incremental methodology (IFIM) (Bovee, 1978, 1982; Bovee *et al.*, 1998). IFIM evaluates habitat quality based on values of physical properties, such as water depth, flow velocity and shear stress, relative to ranges of these attributes defined by the biological requirements of different species and life stages (Bovee *et al.*, 1998). This technique has been used to analyze riverine habitat for many purposes including stream rehabilitation, enhancement and restoration (Newson and Newson, 2000; Pasternack *et al.*, 2004; Wheaton *et al.*, 2004). Flow hydraulic properties are integrated with biological requirements, typically via univariate curves (Bjornn and Reiser, 1991), to quantify habitat availability, which is expressed at the reach scale with two indices: the weighted usable areas (WUA) and hydraulic habitat suitability (HHS). At the local microhabitat scale, habitat quality is expressed with the cell suitability index, which combines local physical variables that may include flow properties, sediment properties and distance from cover with biological requirements.

Flow properties can be measured in the field (Bovee *et al.*, 1998), predicted with statistical methods (Lamouroux *et al.*, 1995, 1998), evaluated with analytical solutions (Brown and Pasternack, 2009) or estimated with numerical hydrodynamic models (Leclerc *et al.*, 1995; Bates and Roo, 2000; Horritt and Bates, 2002; Pasternack *et al.*, 2006; Tonina and Buffington, 2009; Daraio *et al.*, 2010; Tonina *et al.*, 2011; Maturana *et al.*, 2014; McKean and Tonina, 2013). Usually, the hydrodynamic characteristics are simulated by one-dimensional (1D) (García *et al.*, 2011) or two-dimensional (2D) hydrodynamic models (Leclerc *et al.*, 1995), with three-dimensional modeling still rare and used for special cases (Tonina and Jorde, 2013). Direct measurements of depth and velocity in natural channels to inform aquatic habitat modeling are less common because they are time consuming, especially in reaches with complex topography, such as meandering or braided streams (Whiting, 1997).

The choice of 1D versus 2D hydrodynamic models could potentially affect IFIM results. 1D models solve the cross-sectional-averaged Reynolds Averaged Navier–Stokes Equations (RANS) to predict water surface elevation (WSE) and cross-sectional-averaged flow velocity. They do not require the full stream bathymetry but only stream cross-sections to describe the stream geometry (Tonina and Jorde, 2013). When used for habitat modeling, the 1D models are actually 1.5D or pseudo-2D as they employ simplified equations to estimate the transverse velocity and depth profiles (Tonina and Jorde, 2013; Benjankar et al., 2014). First-order predictions of local depths are estimated as a difference between predicted cross-sectional-averaged water surface elevation and the streambed elevation. Then, local velocities are scaled with the estimated local depth using uniform flow equations (Bovee, 1982; García *et al.*, 2011; Benjankar *et al.*, 2013). The fundamental assumptions are that velocity is a function of local depth and energy slope, and that flow vectors have only the longitudinal direction. Here, we use the term 1D to refer to 1.5D or pseudo-2D modeling (Tonina and Jorde, 2013). In contrast, 2D models require the complete stream bathymetry to predict flow properties by solving the vertically-averaged RANS equations.

Previous studies have shown that 1D and 2D models can provide comparable cross-sectional-averaged flow properties in simple uniform channels, but 1D and 2D modeling may predict very different flow proprieties in morphologically complex channels (Brown and Pasternack, 2009). Comparison between 1D and 2D model results and WUA predictions found insignificant difference in small rivers when distances between cross-sections were less than 25 m (Tarbet and Hardy, 1996). However, aquatic habitat quality may vary spatially and comparison of WUA or hydraulic habitat suitability (HHS) alone lacks spatial consideration (Conner and Tonina, 2014).

The spatial distribution of habitat quality strongly depends on local flow properties, which may be spatially heterogeneous in natural streams. 2D models can simulate complex flow structures, such as horizontal eddies and recirculating zones that may be important habitats (Crowder and Diplas, 2000, 2002; Horritt, 2000; Pasternack and Senter, 2011). They can provide a map of flow properties such as water surface elevation, water depth, depth-averaged velocity and bottom shear stress (Nelson and Smith, 1989; Nelson *et al.*, 2003). Until recently, they have been applied mostly on short reaches where detailed bathymetries were available and generally for steady state conditions because of their computational burden (Pasternack and Senter, 2011). 2D modeling predictive ability directly depends on the quality and resolution of the surveyed bathymetry (Conner and Tonina, 2014; Tonina and Jorde, 2013). However, advances in point-cloud survey techniques such as airborne bathymetric lidar (McKean *et al.*, 2009), multi-beam sonar (Conner and Tonina, 2014), RTK DGPS techniques, optical methods (Marcus *et al.*, 2003) or a combination of different techniques (Pasternack and Senter, 2011; Tonina and Jorde, 2013) have reduced the spatial limitation caused by the logistics of detailed field surveys for 2D modeling (McKean and Tonina, 2013). Furthermore, advances in numerical modeling and computational power allow 2D modeling over long reaches and for unsteady conditions not just on workstations in research centers but also on desktop PCs (Tonina and McKean, 2010; Pasternack and Senter, 2011; Tonina *et al.*, 2011). As suggested by Pasternack and Senter (2011) this will allow a "near-census" of stream flow physical conditions. Consequently, they are expected to become the most common tool in aquatic habitat modeling (Tonina and Jorde, 2013).

Conversely, 1D modeling cannot represent the complex flow patterns because it depends on cross-sectional-averaged properties of the streambed (Mason *et al.*, 2003). Despite their inability to resolve flow details, 1D models are still very useful as they are computationally efficient and they can simulate first-order conditions over much larger stream domains and over much longer periods than 2D models (Benjankar, 2009; Burke *et al.*, 2009). New GIS tools such as HEC-GeoRAS (Ackerman, 2011) and MIKE11GIS (DHI, 2011c), which provides automated centerline and cross-section generation for 1D modeling from a high-resolution DEM, may simplify and facilitate the task to develop 1D modeling over large systems. Thus, 1D modeling could be applied at the watershed scale with close-spaced cross-sections, for instance at intervals less than a channel width, extracted from high-resolution streambed bathymetry. However, before using them broadly for purposes of habitat prediction, we must establish how accurately 1D models perform in a variety of flow and channel conditions.

In this work, we quantify the difference in water depth, velocity and water surface elevation (WSE) simulated with pseudo-2D (herein referenced as 1D modeling) and 2D model approaches supported with high-resolution bathymetries and close-spaced cross-sections. We investigate the effects of model dimensionality and error induced by linear interpolation between cross-sections on WUA and HHS values and on habitat quality spatial distribution. We hypothesize that 1D models supported by close-spaced (less than a channel width) cross-sections extracted from high-resolution and detailed bathymetry may provide habitat distribution comparable with 2D models because organisms' preference curves are defined over a range of physical conditions. These ranges may smooth the uncertainties resulting from model dimensionality. Because flow values depend on numerical grid size, we analyze the effects of flow grid resolution on hydraulics and habitat characteristics predicted with 1D and 2D models. We test this effect considering three different grids of 1 m, 3 m, and 5 m size. We use three morphologically and hydraulically different river systems (South Fork Boise, Bear Valley and Deadwood River, Idaho, USA) to investigate the effects of stream size, morphology and discharge. In each stream, we analyze two discharges, a high near bankfull flow and a low near base flow, and two morphologically different reaches, a complex (with pools, riffles, runs, rapidly varying channel width and sinuous) and a simple (mostly straight, with subdued topography and gradually varying channel width) reach. We use the error matrix (Congalton and Green, 2008), which quantifies model differences while considering spatial distribution of the results, and visual inspection to compare the agreement between habitat maps generated from 1D and 2D models.

Methodology

Study area

The three central Idaho river systems are shown in Figure 1 and their characteristics are presented in Table I. A simple reach is characterized by relatively straight and a sinuosity less than 1.2, which is similar to A type in Rosgen's stream classification (Rosgen, 1994), runs, and low channel width variability (Table II). Conversely, complex reaches have sinuosity greater than 1.2, frequent pool–riffle structures and high channel width variability. Bear Valley Creek is a highly sinuous system, therefore we just considered the complex reach, whereas South Fork Boise and Deadwood Rivers have both simple and complex reaches (Table II).

South fork boise river

The South Fork Boise River is located in southwestern Idaho at the edge of the Sawtooth Mountain Range (DEQ, 2008). It has a

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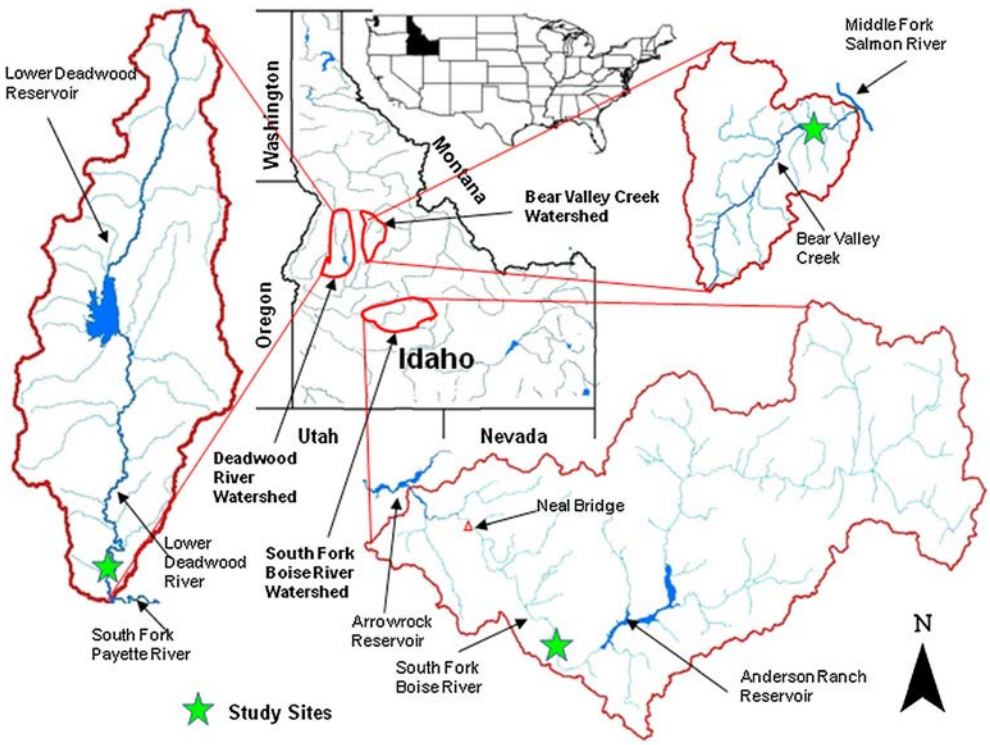

Figure 1. Study sites. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

forested watershed area of approximately 3382 km^2 with elevations varying between 975 and 3000 m. The basin hydrologic regime is snowmelt dominated, with snowmelt runoff occurring from late March to May and average annual precipitation ranging from 0.5 to 1.27 m (cf. DEQ, 2008). Stream flows are regulated between 5.5 and 71 m^3/s by Anderson Ranch Dam, which is operated for irrigation, flood control and power production.

Our study reach is confined in a canyon, which is 10 km downstream from the Anderson Ranch Dam. The bed material is dominated by cobbles and scattered boulders larger than 30.5 cm diameter (Wade *et al.*, 1978). We divided the reach into a simple and a complex domain. We used 11 (lowest mean monthly) and 63 m^3/s (highest mean monthly) flows below Anderson Ranch Dam as low and high discharges, respectively.

Bear valley creek

Bear Valley Creek is a tributary of the Middle Fork Salmon River (Figure 1). The watershed area upstream of the study site is approximately 161 km^2 and elevation varies from 1966 m to 2660 m. The watershed hydrology is snowmelt dominated with an average precipitation rate of about 0.77 m. Bankfull discharge is approximately 7 m^3/s, and base flows during the autumn and winter range between 0.8 and 1.3 m^3/s (Gariglio *et al.*, 2013; McKean and Tonina, 2013).

The substrate of Bear Valley Creek is mostly clean gravels with a $D_{50} = 54$ mm. The channel flows through an extensive meadow system and is highly sinuous (sinuosity index = 1.5) (McKean and Tonina, 2013). The stream is classified as a pool–riffle reach following the system of Montgomery and Buffington (1997). Overbank flows are common during spring runoff and annually cause several weeks of inundation of the meadow surface (McKean and Tonina, 2013). The study site is an 1800 m-long highly sinuous reach (Tables I and II) and we simulated flow depth and velocity at low (2 m^3/s) and bankfull (7 m^3/s) discharges.

Lower deadwood river

The Deadwood River is a major tributary of the South Fork Payette River with total watershed area of 614 km^2 (Figure 1). The hydrology of the basin is snow dominated, with an average annual precipitation of 0.72 to 1.40 m. The lower Deadwood River, is the stream segment between Deadwood Reservoir and the confluence with the South Fork Payette. The Deadwood Reservoir is managed mainly for irrigation storage and flood control (Jimenez and Zaroban, 1998) and is operated to maintain a winter flow of 2.84 m^3/s (USFWS, 2002). The lower Deadwood is an alluvial reach flowing within a deep and narrow canyon with bedrock controlling and limiting lateral development and migration. On average, it is about 30 m wide and has a slope of approximately 1.2%. However, the local gradient of the river changes considerably with geomorphic controls. Its morphology is predominately plane-bed but with some localized deep pools and subdued riffles and runs. The dominant substrate is large cobbles with boulders having typical diameters of 0.5 to 0.75 m randomly scattered on the bed.

Our study area is about 800 m long near the confluence with the South Fork Payette River (~36 km downstream from the Deadwood Dam). We divided the study reach into complex and simple domains (Table II). The simple reach is characterized by runs, minimal lateral variability and scattered large boulders (approximate 0.60 m in diameter). The complex reach is characterized by a deep localized pool followed by a subdued riffle and a run, here the channel width changes frequently and large boulders are randomly scattered on the bed. Flow magnitudes of 2.8 (the average winter flow through Deadwood Dam) and 26.9 m^3/s (the largest flow through Deadwood Dam during the irrigation season) were used as low and high discharges, respectively.

Hydraulic model setup

We used the MIKE11(DHI, 2011a) and MIKE21 (DHI, 2011b) software as the 1D and 2D hydraulic models, respectively.

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Table I. River characteristics, simulated discharges and RMSE between 1D and 2D model along channel thalweg

				Discharge		*RMSE		Depth[α]	
	Slope	Average width	Reach length	LQ	HQ	LQ	HQ	LQ	HQ
River	%	m	m	m^3/s	m^3/s	m	m	m	m
SFB-1m	0.43	41	1350	10.7	63.4	0.06	0.10	0.62	1.09
SFB-3m	"	"	"	"	"	0.07	0.09	-	-
SFB-5m	"	"	"	"	"	0.07	0.07	-	-
BV-1m	0.35	15	1830	2	7	0.06	0.05	0.34	0.55
DW-1m	1.20	30	810	2.8	26.9	0.18	0.13	0.29	0.69

*Root Mean Square Error between 1D and 2D models for high and low simulated discharges
[SFB]South Fork Boise [BV]Bear Valley [DW]Deadwood
[LQ]Low discharge [HQ]High discharge
[SFB-1m]Denotes South Fork Boise with 1 m grid size
"Same value as for 1 m grid size
[α]Average water depths based on 2D model simulation

One-dimensional model

The hydrodynamic model MIKE11 (1D) was used with the river network, the cross-section bathymetry, and upstream (discharge) and downstream (water surface elevation or stage discharge relationships) boundary conditions defined for each stream. MIKE11 utilizes an implicit, finite-difference scheme for computing unsteady flows in rivers and estuaries. It solves the unsteady one-dimensional De-Saint Venant equations (DHI, 2011a). We extracted cross-sections every 5 m longitudinally with 1 m transverse resolution from high-resolution DEMs surveyed with the Experimental Advanced Airborne Research Lidar (EAARL) (McKean *et al.*, 2009; Skinner, 2011).

We used the fish habitat model CASiMIR to generate spatially distributed water depth and velocity at each cell, whose size was equal to that of the 2D model, from the cross-section based 1D hydraulic model (Schneider *et al.*, 2010). The inputs for the CASiMIR model are cross-section topography and water surface elevation predicted at each cross-section with the 1D hydraulic model for each discharge. CASiMIR calculates water depth and velocity at each cross section and interpolates stream bathymetry and flow properties between and within cross-sections at a user specified grid size. It utilizes a linear interpolation algorithm to calculate bathymetric elevation and water depth and the Darcy–Weisbach uniform flow equation to calculate local velocity (Schneider *et al.*, 2010):

$$v_i = f_w \frac{1}{\sqrt{\lambda}} \sqrt{8g\, h_i\, I} \tag{1}$$

where, v_i = flow velocity in the i-th cell (m/s); f_w = conveyance factor; λ = Darcy–Weisbach roughness coefficient; g = acceleration due to gravity (m/s^2); h_i = water depth in the i-th cell (m/s^2); I = energy slope. The conveyance factor, f_w, is a parameter included in the equation to account for back-water and recirculation phenomena (Schneider *et al.*, 2010).

Two-dimensional model

The MIKE 21 flow model simulates unsteady two-dimensional hydraulic properties such as water surface elevations, depth-averaged flow velocities and bottom shear stresses with the defined bathymetry and other parameters, which include bed resistance and eddy coefficients, using a finite difference algorithm (DHI, 2011b). It solves the time-dependent, vertically-integrated RANS equations of mass and momentum conservation in two-horizontal directions. We constructed 2D models utilizing high-resolution (1 m grid cell) DEMs, upstream discharge and downstream water surface elevation as boundary conditions for all three river systems.

We also developed 2D models with grid sizes of 3 and 5 m for the South Fork Boise River to analyze the effect of grid resolutions on the 1D and 2D simulated hydraulics and habitat characteristics. The original 1 m grid size raster was resampled with the nearest neighborhood method to develop two new DEMs with 3 and 5 m grid sizes. Resampling is the process of interpolating grid values when transforming raster dataset from one resolution to another. We used these DEMs with 3 and 5 m grid sizes, to support numerical modeling with 3 and 5 m grid sizes.

Model parameter specification

Water surface elevations are the benchmark for evaluating 1D and 2D model performance. Therefore, to compare the hydraulic predictions of the 1D and 2D techniques, the two models first needed to be calibrated to have comparable water surface elevations at the selected discharges. Thus, we adjusted the roughness parameter of the models until the water surface elevations of the 1D and 2D models closely matched at every 30 m interval along the channel thalweg for all three study sites (Figure 2). We used the values of the water surface elevation at the thalweg because the 2D modeling provides transverse gradients of the water surface elevation whereas the 1D modeling predicts only one averaged value.

Previous work had calibrated the roughness for the 1D model in the Deadwood River to simulate water surface elevation (Tiedemann, 2013), which was then used to calibrate the 2D model. We used similar Manning's n as in previous study (McKean and Tonina, 2013) for Bear Valley Creek to simulate water surface elevations with the 2D model and calibrated the 1D model. Water surface elevations are not available for the South Fork Boise River at any discharge and a Manning's n value was selected from the literature and from experience working in similar streams.

The final water surface elevation root mean square errors (RMSE) were 0.06, 0.06 and 0.18 m in the South Fork Boise, Bear Valley and Deadwood Rivers, respectively, for the low discharge (LQ) scenario and 0.10, 0.05, and 0.13 m for the high discharge (HQ) (Table I). Exact specification of roughness values for a study reach is not critical to our investigation, because we are not making absolute hydrodynamic predictions, but rather comparing the two models. Thus, using predicted water surface elevations as benchmark for the two models or specifying the water surface elevation with one model after selecting a roughness value and then changing the roughness

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Table II. Root mean square errors in flow depth, velocity and water surface elevation between 1D and 2D models with cross-sectional and bathymetric analysis for high and low discharges and models with 1 m, 3 m and 5 m grid sizes

				Low discharge$^{\Delta}$						High discharge$^{\Delta}$					
		Bathymetry		Depth		Velocity		WSE		Depth		Velocity		WSE	
River	Reach	CA	BA	CA	BA	CA	BA	CA	BA	CA	BA	CA	BA	CA	BA
SFB-1m	S	0.05	0.14	0.09	0.15	0.09	0.09	0.08	0.09	0.10	0.17	0.20	0.20	0.09	0.10
	C	0.05	0.15	0.06	0.13	0.23	0.21	0.05	0.05	0.09	0.16	043	0.41	0.08	0.08
SFB-3m	S	0.04	0.10	0.07	0.11	0.07	0.07	0.06	0.06	0.10	0.14	0.17	0.17	0.09	0.09
	C	0.05	0.10	0.06	0.10	0.19	0.18	0.04	0.04	0.08	0.13	0.35	0.35	0.07	0.07
SFB-5m	S	0.06	0.06	0.09	0.10	0.06	0.06	0.08	0.08	0.08	0.08	0.15	0.15	0.06	0.06
	C	0.06	0.06	0.07	0.07	0.18	0.18	0.04	0.04	0.09	0.09	0.34	0.35	0.07	0.07
BV	C	0.02	0.06	0.07	0.08	0.17	0.16	0.06	0.06	0.05	0.08	0.16	0.16	0.05	0.05
DW	S	0.04	0.17	0.25	0.26	1.49	1.50	0.24	0.24	0.22	0.28	0.67	0.67	0.21	0.21
	C	0.04	0.15	0.19	0.22	1.45	1.59	0.18	0.18	0.22	0.27	0.81	0.79	0.21	0.21

^{C}Complex reach ^{S}Simple reach ^{WSE}Water Surface Elevation ^{SFB}South Fork Boise
^{BV}Bear Valley ^{DW}Deadwood ^{CA}Cross-sectional analysis ^{BA}Bathymetric analysis
$^{\Delta}$Root Mean Square Differences between 1D and 2D simulated values

for the other one to produce a water surface match will have similar results for our application.

Habitat model development

Habitat suitability is a dimensionless index ranging between 0 (poor quality) and 1 (excellent quality). At the cell scale, it describes whether physical parameters, like depth and velocity, are within those required by individual species and particular life stages (Bovee, 1978) (Figure 3, left). We used the geometric product of the suitability indices, *SI*, of the *m* physical parameters to determine the overall combined cell suitability index (*CSI*) for each *i*-th cell (Moir *et al.*, 2005; Tonina *et al.*, 2011).

$$CSI_i = \left(\prod_j SI_{i,j}\right)^{1/m} \tag{2}$$

where $\prod$ is the product operator, subscripts *i* and *j* indicates the *i*-th cell and the *j*-th physical parameter. The value of *CSI* varies spatially and with discharge. This method assumes hydraulic parameters such as velocity and depth are independent variables in characterizing habitat, and neglects biotic factors such as food availability, predator presence, and water quality. Parameters like weighted useable area (WUA) and the hydraulic habitat suitability (HHS) are derived from *CSI* and commonly used to describe habitat quality at the reach scale (Bovee, 1978). Both WUA and HHS are functions of discharge and have the following expression:

$$WUA = \sum_{i=1}^{p} CSI_i A_i \tag{3}$$

$$HHS = \frac{WUA}{A_W} \tag{4}$$

where *p* is the number of cells within the wetted area A_w of the reach and A_i is the area of the *i*-th cell. To test the effect of model dimensionality on predicted aquatic habitat quality, we used univariate rearing habitat preference criteria of Chinook salmon, which is an iconic species for the Pacific Northwest of United States (Smith, 1973; Raleigh *et al.*, 1984; Hampton, 1988; Bjornn and Reiser, 1991; Groves and Chandler, 1999; Tonina *et al.*, 2011) (Figure 3, left). We selected rearing because this life stage lasts an entire year, whereas other life stages, like spawning, occur only in some parts of the year with well-defined discharges. Although this species occurs in Bear Valley Creek but has not been reported in the Deadwood and South Fork Boise Rivers, we use it because rearing habitat suitability curves are well defined in Idaho and employing the same benchmark for all three systems makes the results easier to interpret. We selected the *SI* for depth (SI_D) and velocity (SI_V) because these variables are common and most important variables,which are derived from hydraulic models, used in aquatic habitat modeling (Hanrahan *et al.*, 2004). Thus, Equation 2 simplifies to:

$$CSI_i = \sqrt{SI_{V,i}\, SI_{D,i}} \tag{5}$$

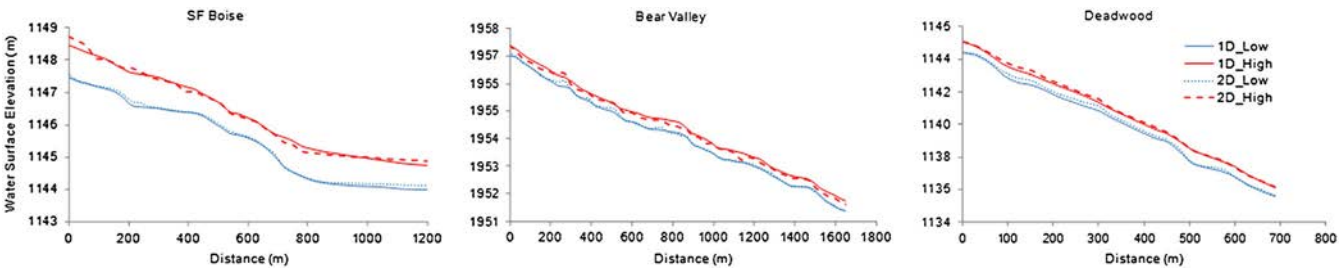

Figure 2. Simulated water surface elevations (WSE) with 1D and 2D hydraulic models in South Fork Boise, Bear Valley and Deadwood Rivers for low and high discharge scenarios. The 0 chainage in each graph is the first point where WSE is compared (not the beginning of the study reach). WSEs were just compared at the locations where we assumed there are no boundary effects (upstream and downstream). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

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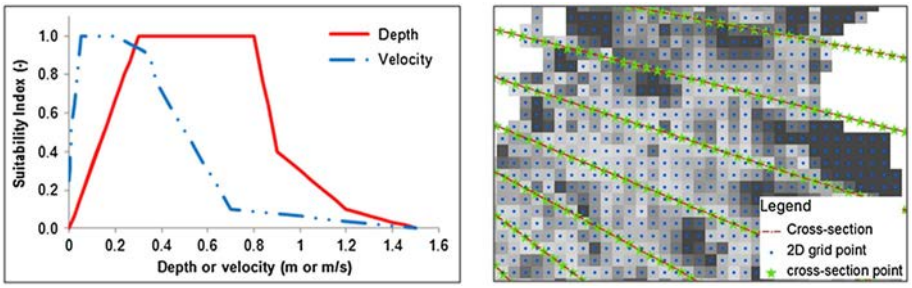

Figure 3. Rearing habitat suitability curves for Chinook salmon (left). Cross-section and 2D model grid point locations used for cross-sectional and bathymetric analyses (right). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

We calculated the spatial distribution of habitat quality based on the suitability index of velocity and depth values separately and combined in the cell suitability index. Then we calculated the WUA and HHS using Equations 3 and 4. We quantified these values with velocity and depth predicted with both 1D and 2D modeling and with varying grid cell resolution.

Comparison between 1D and 2D models

GIS tools have been used in ecological modeling to analyze results at different spatial and temporal scales (Radeloff *et al.*, 1999; Benjankar *et al.*, 2011, 2012) and to extrapolate spatially from point results (Osborne *et al.*, 2001). We used a raster format and specific point data to analyze the difference in results from 1D and 2D models. These raster maps also describe the spatial variation of each hydraulic variable and the cell suitability index.

Residual analysis

We analyzed differences (hereafter residuals) between simulated hydraulic variables (flow depths and velocities) predicted with the 1D and 2D simulations for each discharge scenario and morphologic reach. These analyses were performed on a cell by cell basis throughout the 2D model inundated domain. We generated spatially distributed residuals (differences in 1D and 2D simulated hydraulic variables) for water depth and velocity to quantify and visualize differences spatially.

Absolute value analysis

We also compared absolute values of hydraulic variables water depth, velocity and water surface elevation (WSE) simulated from 1D and 2D models at the specific point locations to analyze correlation (R^2) and root mean square error (RMSE). WSEs were calculated as a sum of bathymetric elevations and water depths in the 1D model. We analyze the predicted values at cross-sections (hereafter cross-sectional analysis) and over the full bathymetry (hereafter bathymetric analysis) to quantify the errors due to model dimensionality (cross-sectional analysis) and those from interpolation (bathymetric analysis) (Figure 3, right). Furthermore, the analysis also shows the range of errors between 1D and 2D modeling for each absolute value of the hydraulic properties. Additionally bathymetry input to the 2D model and cross-section interpolated bathymetry (output from the 1D model) were compared (hereafter bathymetric elevation) to study differences in simulated hydraulic variables caused by the varying bathymetry representations in the 1D and 2D cases.

Habitat suitability

We compared the spatially distributed *CSI* calculated from 1D and 2D models using the error matrix method (Congalton and Green, 2008). This is a standard technique for quantifying the accuracy among maps and is specifically designed for raster comparisons. The error matrix compares maps by calculating overall accuracy (OA) and the agreement index between the maps using the Kappa statistic (K). A K value of 1 indicates perfect agreement, whereas a K value of 0 indicates agreement equivalent to chance. The overall accuracy is a ratio between the numbers of correctly predicted cells to total number of cells considered in the analysis. *CSIs* were separated into classes of 0 = 0, 0–0.19 = 1, 0.20–0.39 = 2, 0.4–0.59 = 3, 0.60–0.79 = 4, and 0.80–1.00 = 5 in order to estimate the K statistic using the error matrix. Because the K statistic is a very strict and may exaggerate errors (Pontius, 2002), we paired it with visual comparison of the maps. Finally, we also assessed the difference between 1D and 2D estimated WUA and HHS.

Comparison between different grid resolution

We used simulated hydraulics and habitat parameters from 1D and 2D models for the South Fork Boise River reaches with grid size of 1, 3 and 5 m at low and high discharge scenarios to estimate the effect of grid cell resolutions. We anticipated smaller differences between 1D and 2D output bathymetry, average depth and velocity as well as habitat parameters as grid cell size increases because of the linear interpolation associated with the 1D (CASiMIR) model and the greater smoothing of flow parameters in grids with a coarser spatial resolution.

Results

Residual analysis

Most water depth residuals are less than 0.1 m for all scenarios and river systems (Figures 4–9). Residuals of bathymetric elevations also followed similar trend as water depths (Figure 9). Most velocity differences are between 0.1 and 0.3 m/s in the South Fork Boise River and Bear Valley Creek, except for low discharges, whereas differences are greater than 0.5 m/s in the Deadwood River (Figure 9). The majority of large (>0.5 m/s) velocity differences are observed along the water edges and channel banks in both simple and complex reaches of the South Fork Boise River (Figures 4 and 5). However, large velocity (>0.5 m/s) differences are randomly distributed over the entire reach in the Deadwood Rivers (Figures 7 and 8). This velocity class (>0.5 m/s) is more evident in the complex than simple reach of the South Fork Boise River, but such a trend is not observed in the Deadwood River.

Absolute value analysis

Bathymetric elevation

The bathymetric elevation differences between 1D and 2D models are practically similar for both complex and simple reaches in the South Fork Boise and Deadwood Rivers (Table II)

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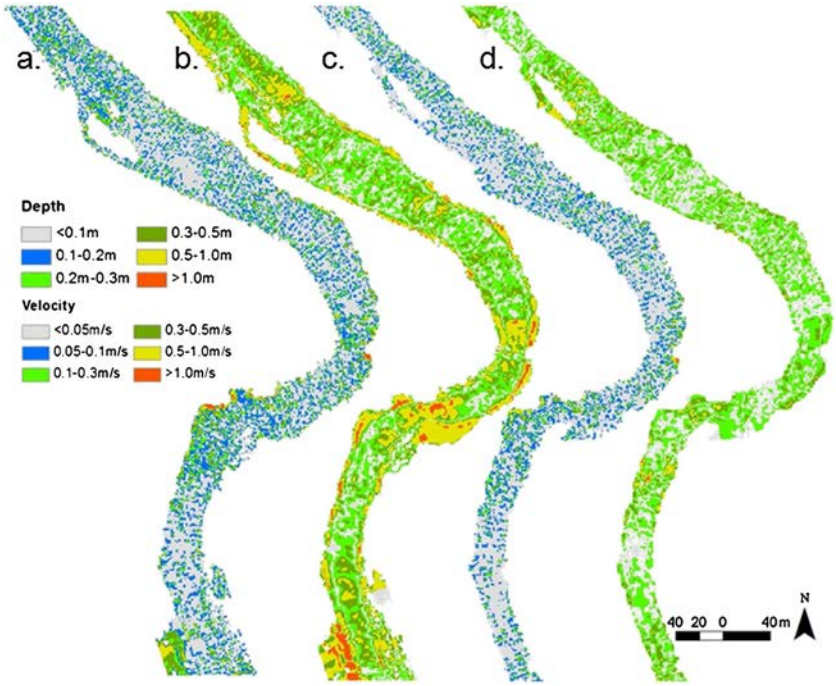

Figure 4. Spatial distribution of residuals of flow characteristics for the sinuous reach in the South Fork Boise River. (a) Depth for high discharge (HQ), (b) velocity for HQ, (c) depth for low discharge (LQ), (d) velocity for LQ. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

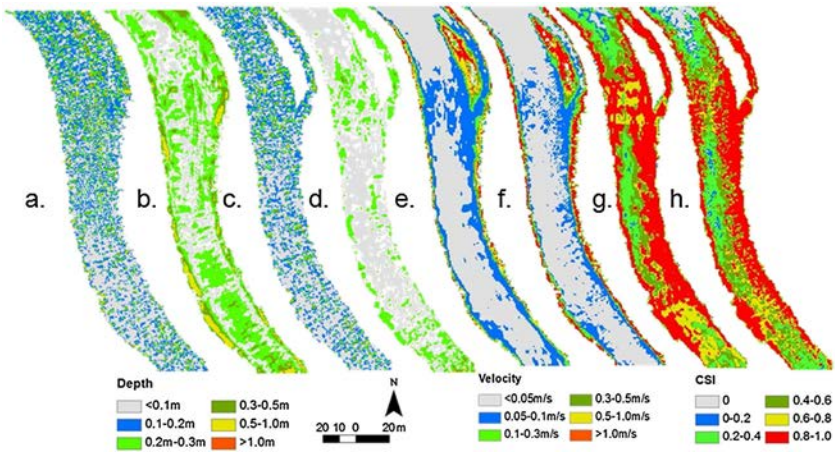

Figure 5. Spatial distribution of residuals of flow characteristics and habitat suitability for the simple reach of the South Fork Boise River. (a) Depth for high discharge (HQ), (b). velocity for HQ, (c) depth for low discharge (LQ), (d) velocity for LQ, (e) combined cell suitability index (CSI) from 1D model for HQ, (f) combined CSI from 2D model for HQ, (g) combined (CSI) from 1D model for LQ, (h) combined CSI from 2D model for LQ. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

based on cross-sectional and bathymetric analysis. The smallest difference is calculated in the low-gradient pool–riffle Bear Valley Creek, whereas the largest differences in bathymetric elevation is observed in the steep-gradient confined plane-bed Deadwood River based on cross-sectional and bathymetric analyses (Table II). As expected, the differences in bathymetric elevations are greater with the bathymetric than the cross-sectional analysis for all three river systems.

Hydraulic variables

The largest water depth and WSE differences are observed in the Deadwood River in both simple and complex reaches, whereas the lowest differences are in Bear Valley Creek (Table II). The largest velocity differences are also in both Deadwood River reaches. Differences in depth and water surface elevations (WSE) are greater in the simple than complex reach in the South Fork Boise and Deadwood Rivers but the other way around for velocity, except for the cross-sectional analysis with low discharge for the Deadwood River (Table II).

Differences in hydraulic variables are generally greater in the bathymetric than cross-sectional analysis. The exceptions are for the velocities at both discharges in the complex reach of the South Fork Boise, low discharge in the Bear Valley Creek and in the complex reach of the Deadwood River. Overall, the differences in velocity residuals between the bathymetric and cross-section analyses are generally less than 0.02 m/s except for the low discharge in the Deadwood River (Table II).

The correlations of hydraulic variables simulated by 1D and 2D models using cross-sectional and bathymetric analyses are generally good with the poorest correlations for velocity in the Deadwood River (Figures 10 and 11). The coefficients of determination for velocity are lowest in both reaches of Deadwood River and greater than 0.51 in South Fork Boise River and Bear Valley Creek for both bathymetric and cross-sectional analyses.

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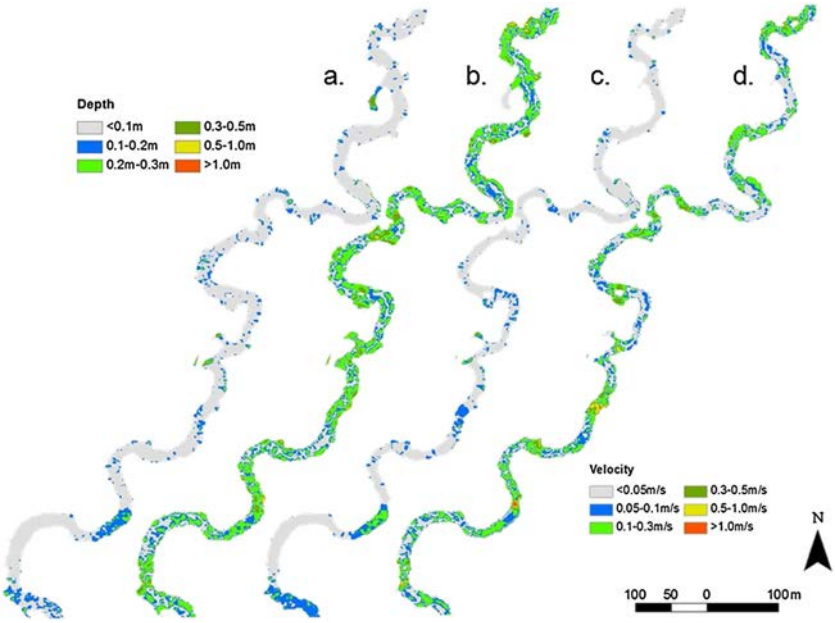

Figure 6. Spatial distribution of residuals of flow characteristics for Bear Valley Creek. (a) Depth for high discharge (HQ), (b) velocity for HQ, (c) depth for low discharge (LQ), and (d) velocity for LQ. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

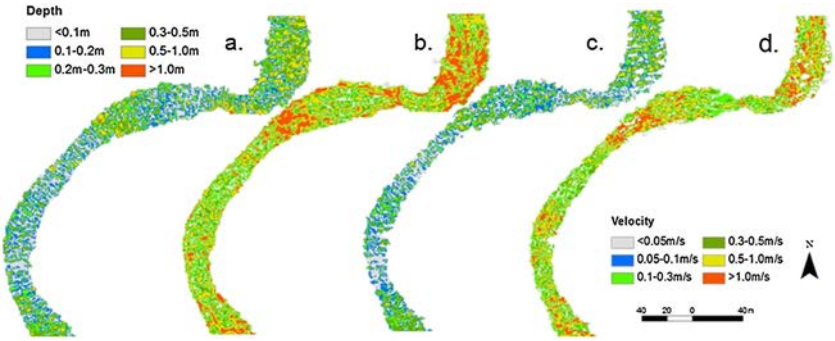

Figure 7. Spatial distribution of residuals of flow characteristics for a sinuous reach in the Deadwood River. (a) Depth for high discharge (HQ), (b) velocity for HQ, (c) depth for low discharge (LQ), and (d) velocity for LQ. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

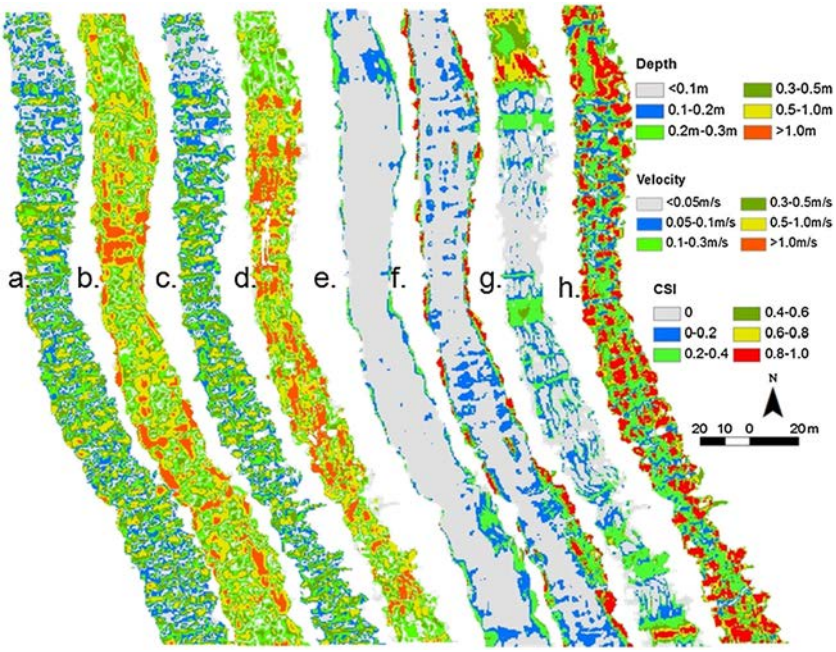

Figure 8. Spatial distribution of residuals of flow characteristics and habitat suitability for the simple reach in the Deadwood River. (a) Depth for high discharge (HQ), (b) velocity for HQ, (c) depth for low discharge (LQ), and (d) velocity for LQ, (e) combined cell suitability index (CSI) from 1D model for HQ, (f) combined CSI from 2D model for HQ, (g) combined (CSI) from 1D model for LQ, (h) combined CSI from 2D model for LQ. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

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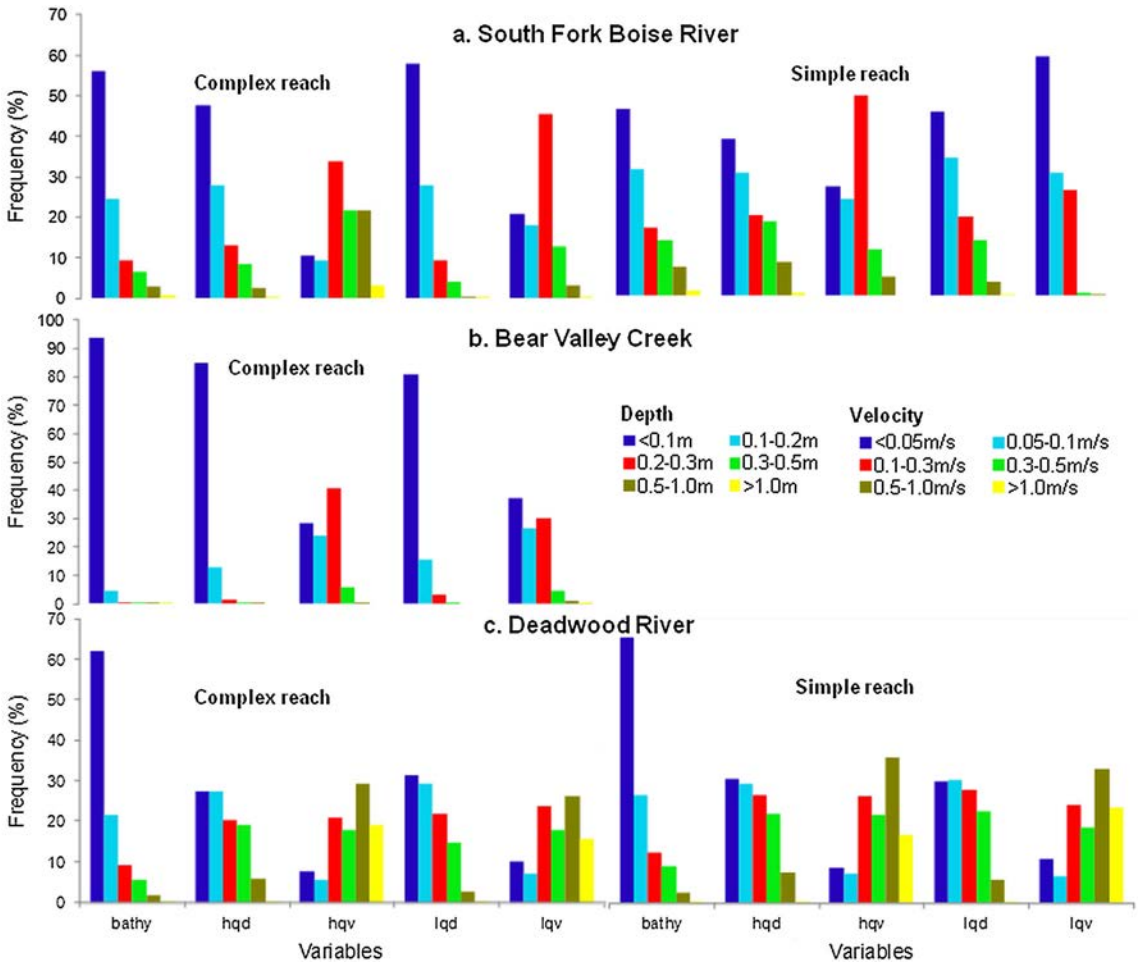

Figure 9. Frequency distribution of residuals (differences) for bathymetry (bathy), high discharge depth (hqd) and velocity (hqv) and low discharge depth (lqd) and velocity (lqv) in simple and complex reaches of South Fork Boise, Deadwood and Bear Valley rivers. Dotted vertical line separates complex and simple reaches. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

The cross-section analysis shows that the 1D model is able to predict water depths comparable to 2D models for all depth ranges (0 to 2.5 m) in the South Fork Boise River and Bear Valley Creek (Figures 10 and 11). The 1D model under-predicted water depths compared with the 2D model in the Deadwood River. The 1D model predicted water surface elevations that corresponded well with those of the 2D model with one exception in which the 1D model under-predicted the water surface elevation in the simple reach of the South Fork Boise River. In the South Fork Boise River, 1D models over-predict velocities compared with the 2D models for low velocities (less than about 1 m/s) and under-predict for velocities greater larger than 1 m/s. Velocities are over-predicted by the 1D model for all velocity ranges (0 to 2.5 m/s) in the Deadwood River. In Bear Valley Creek, the velocity predictions generally match well between the models with the 2D prediction being slightly low at velocities less than about 0.5 m/s.

Habitat suitability

Our analyses did not show either 1D or 2D model predicts larger WUA than those of other model. As expected from Equations 3 and 4, HHS follows the WUA trend. Agreement (K) and overall accuracy (OA) between the two maps generated with 1D and 2D simulations are generally larger in the simple than complex reach for both discharge scenarios for all streams, except in Deadwood River for low discharge (Table III). Based on a visual inspection of the spatially distributed *CSI* (Figures 5, 8, 12, 13 and 14), the largest differences are near the channel banks, where 2D models generally predict greater *CSI* classes than those predicted with the 1D model.

The agreement between two maps is the lowest for the Deadwood River and highest for the Bear Valley Creek (Table III). The spatially distributed *CSI* (1D and 2D) differences are evident over the entire reach for the low discharge and in both simple and complex reaches of the Deadwood River, but limited to near the edge of the water at the high discharge (Figures 8 and 14).

Comparison between different grid resolution

The grid resolution analysis shows a decrease of bathymetric elevation differences with increasing grid sizes with bathymetric analysis, but this trend is not observed in the cross-sectional analysis (Table II). The depth and velocity differences between 1D and 2D models decreased with larger grid sizes for all scenarios. The WSE differences follow a similar trend as the depth and velocity except in the 5 m grid model. However, WSE differences decrease for the 5 m grid model than for 3 m in both cross-sectional and bathymetric analyses for high discharges (Table II).

In general, there is no increasing or decreasing trend in the WUA differences simulated from 1D and 2D model as model grid size increases (Table III). As a result, the K

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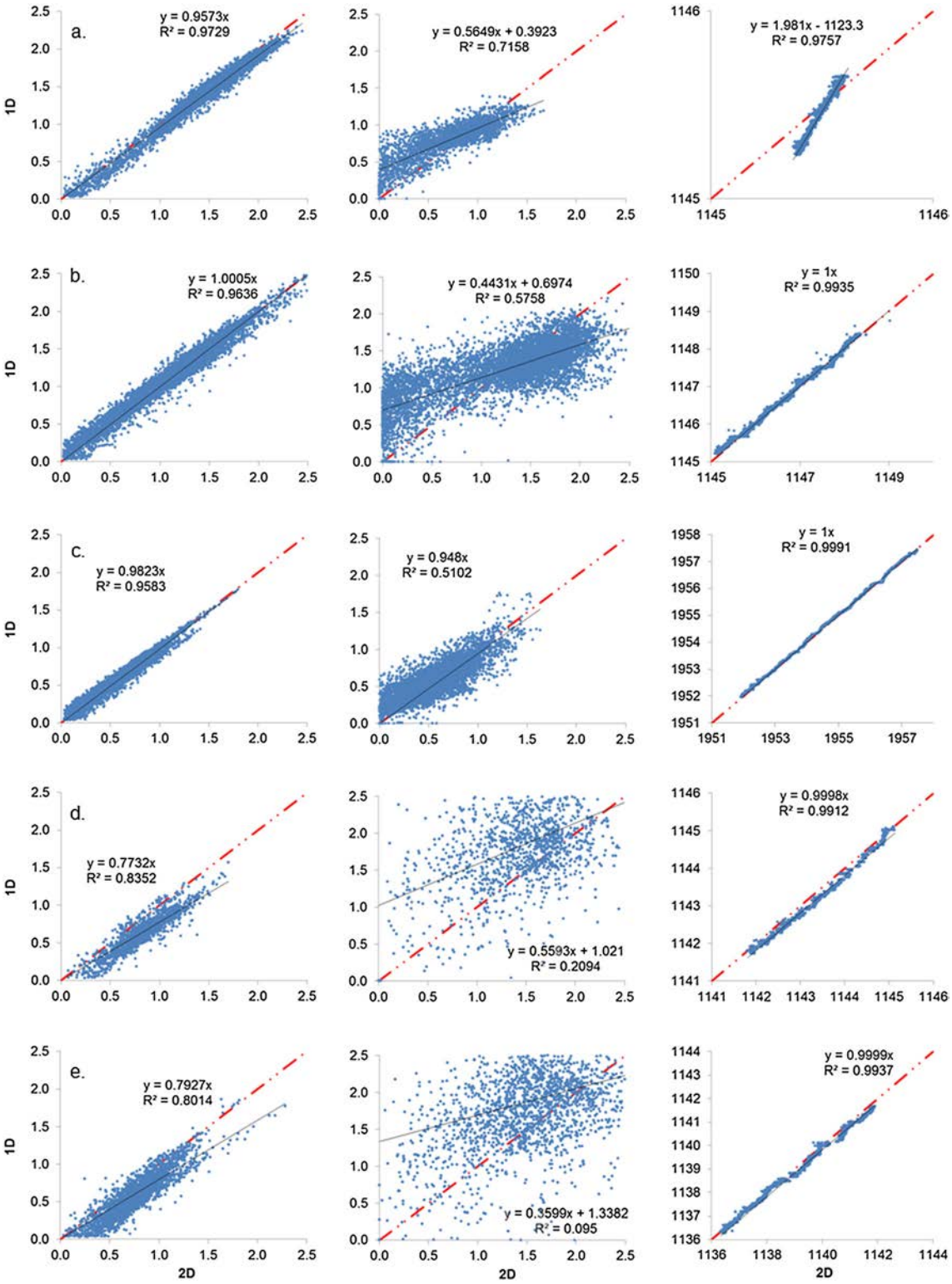

Figure 10. Correlation between 1D and 2D predicted water depth (first column), velocity (second column) and water surface elevation (third column) for high discharge based on cross-sectional analysis for all the river system. Sub-figures denote: (a) and (b) simple and complex reaches of South Fork Boise River; (c) Bear Valley Creek; (d) and (e) simple and complex reaches of Deadwood River. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

agreements between maps also do not follow any trend with increase in model grid size.

Discussion

The RMSE of 0.05 to 0.18 m (Table I) between predicted 1D and 2D water surface elevations along channel thalweg at every 30 m during model parameter specification (also known as calibration) are acceptable considering that water surface elevations (WSE) vary both longitudinally and transversally in 2D modeling, whereas they are a single value for the entire cross-section in the 1D modeling. These errors are also within values commonly reported in the literature (Hammersmark *et al.*, 2005). The RMSE is smaller for the South Fork Boise River and Bear Valley Creek than for the Deadwood River (Table I).

The study sites of Bear Valley Creek and South Fork Boise River have well-defined pool–riffle topographies with length scale

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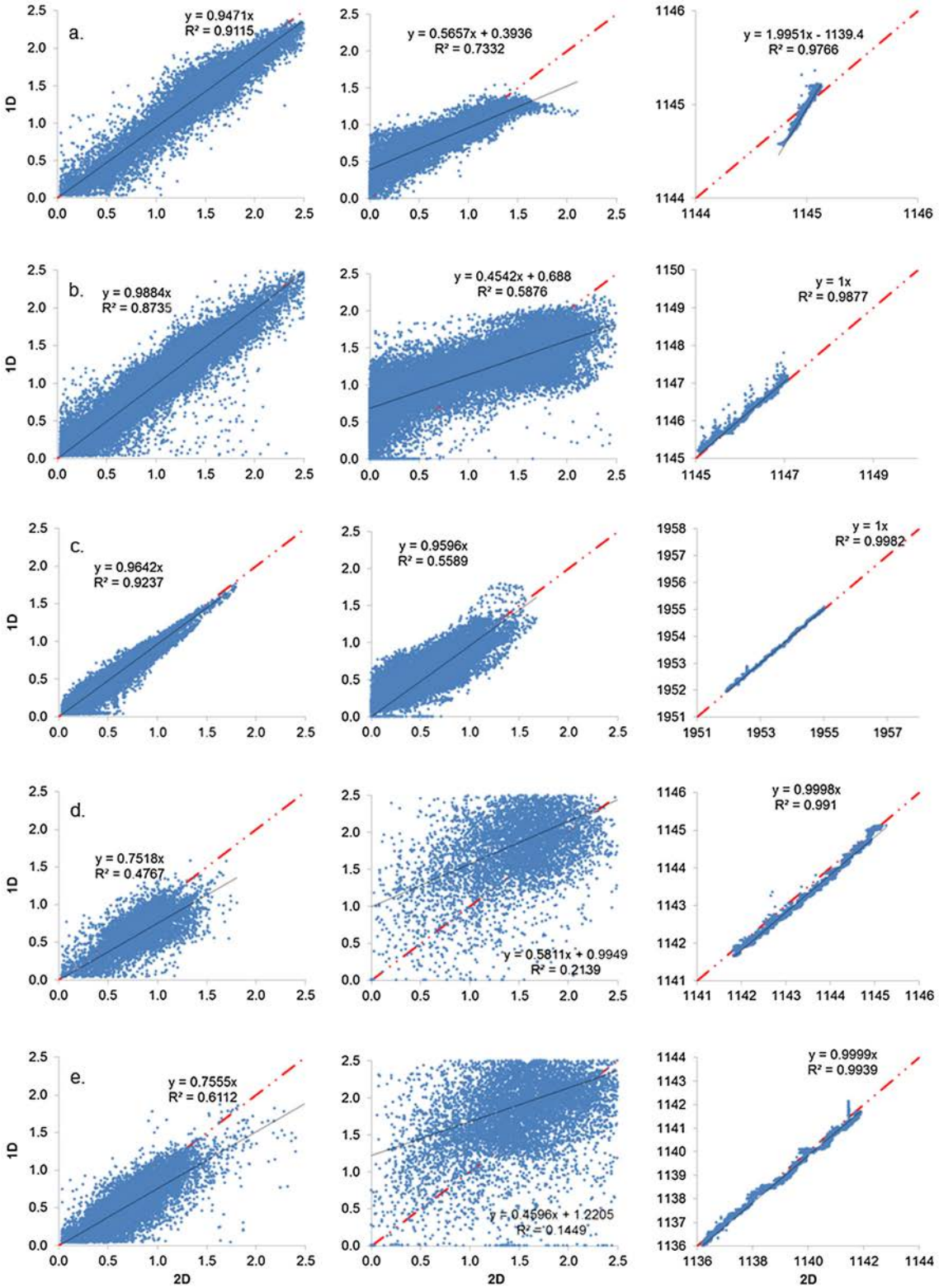

Figure 11. Correlation between 1D and 2D predicted water depth (first column), velocity (second column) and water surface elevation (third column) for high discharge based on bathymetric analysis for all the river system. Sub-figures denote: (a) and (b) simple and complex reaches of South Fork Boise River; (c) Bear Valley Creek; (d) and (e) simple and complex reaches of Deadwood River. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

variations of the order of 2 to 3 channel widths in the complex reaches. This allows several cross-sections within any important topographical feature. Both streams have low relative submergence and ratio between grain size and water depth. Conversely, the study sites of Deadwood River have subdued macro-topography, like riffles and runs, with localized small and deep pools and this streambed is characterized by large cobbles and randomly placed small boulders and cobbles randomly displaced. These large particles are topographical features smaller than the cross-sectional spacing and they protrude through the water surface at low flows and nearly through the water column at high flows. Consequently, they have a large impact on flow properties. 1D modeling does not capture this influence primarily for two reasons. The interpolation between cross-sections is too coarse to account for them and these large features generate 2D and 3D flows, which are lost in the cross-sectional

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Table III. Differences in WUA, HHS from 1D and 2D models for high and low discharges and agreement between the maps using error matrix

		Low Q							High Q						
		WUA (1000 m^2)		δ	Agreement (–)		HHS (–)		WUA (1000 m^2)		δ	Agreement (–)		HHS (–)	
River	Reach	1D	2D	%	K	OA	1D	2D	1D	2D	%	K	OA	1D	2D
SFB-1m	S	11.29	10.57	−7	0.39	0.56	0.68	0.64	2.50	3.16	21	0.54	0.71	0.13	0.16
	C	11.93	12.55	5	0.27	0.48	0.43	0.45	3.30	5.60	41	0.40	0.61	0.09	0.16
SFB-3m	S	11.28	10.73	−5	0.46	0.61	0.69	0.65	2.45	3.10	21	0.57	0.73	0.13	0.16
	C	11.81	12.18	3	0.30	0.51	0.43	0.44	3.40	4.91	31	0.43	0.64	0.10	0.14
SFB-5m	S	11.08	10.54	−5	0.41	0.57	0.66	0.63	2.49	3.09	19	0.61	0.75	0.13	0.16
	C	11.49	12.38	7	0.29	0.51	0.41	0.44	3.27	3.28	0	0.41	0.62	0.09	0.15
BV-1m	C	15.60	16.89	8	0.32	0.49	0.62	0.68	14.72	15.26	4	0.40	0.57	0.46	0.50
DW-1m	S	0.75	2.66	72	0.01	0.11	0.14	0.52	0.22	0.53	59	0.20	0.64	0.04	0.09
	C	1.40	3.93	64	0.02	0.15	0.18	0.51	0.31	0.81	62	0.12	0.60	0.03	0.09

[C]Complex reach [S]Simple reach [WUA]Weighted usable area [HHS]Hydraulic habitat suitability
[δ]Difference in WUA between 1D and 2D models [K]Kappa coefficiet [OA]Overall accuracy
[SFB]South Fork Boise [BV]Bear Valley [DW]Deadwood
[SFB-1m]Denotes South Fork Boise with 1m grid size

averaging. Consequently, we expect that RMSE is smaller for stream systems with well-defined large bedforms, which can be sampled by multiple cross-sections, than for streams with irregular topography and scattered features that are large enough to protrude through most of the water depth but are smaller than the cross-sectional spacing.

Bathymetric elevation

The bathymetry generated in the 1D model from linear interpolation between cross-sections differs from the full high-resolution bathymetry used in the 2D models, even for the very-close-spaced 5 m-apart cross-sections (Figure 9 and Table II). Despite similar differences in all three river systems with the cross-sectional analysis (Table II), the largest and smallest differences in bathymetric elevation are estimated for the simple reach of the Deadwood and Bear Valley Creek, respectively with the bathymetric analysis. This result supports the important role that topographical features have on channel bathymetry, which are smaller than the cross-sectional spacing. Deadwood study sites have very subdue small features such as localized pools, riffles and runs, with large randomly spaced boulders and particles (Wade *et al.*, 1978), whose scale is much smaller than the cross-section spacing. The difference is almost similar between the reaches of the South Fork Boise River because large scattered particles are smaller and fewer in both reaches than in the Deadwood River. Streambed topography complexity at a scale smaller than the cross-section spacing with vertical size comparable with water depth can increase the error between full bathymetry and cross-section derived bathymetry.

Hydraulic variables

Water depth differences are less than 0.06 m in all cases using a cross-sectional analysis (Table II) and around 0.15 m when

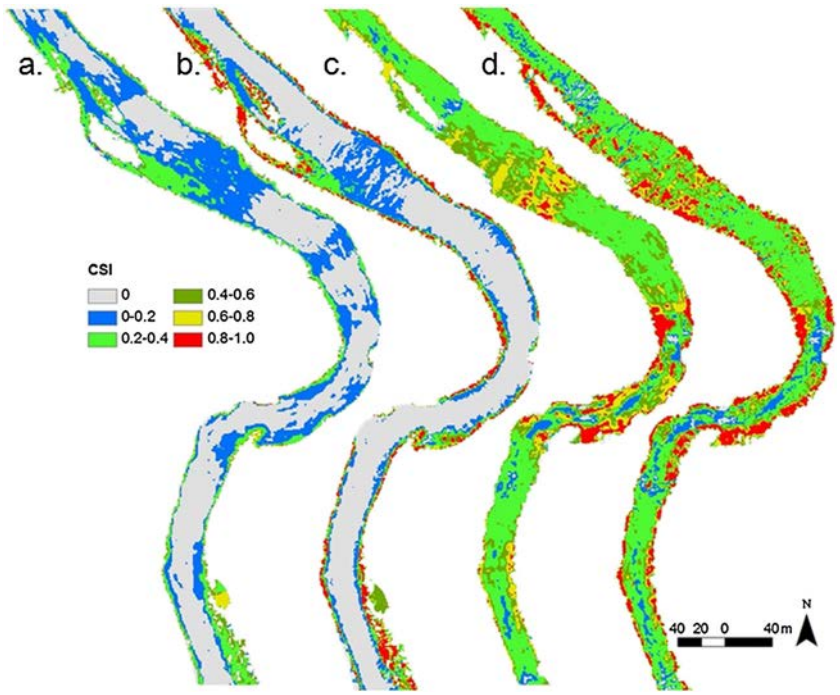

Figure 12. Spatially distributed habitat suitability distribution (CSI) for sinuous in the SF Boise River. (a) 1D model for HQ, (b) 2D model for HQ, (c) 1D model for LQ, and (d) 2D model for LQ. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

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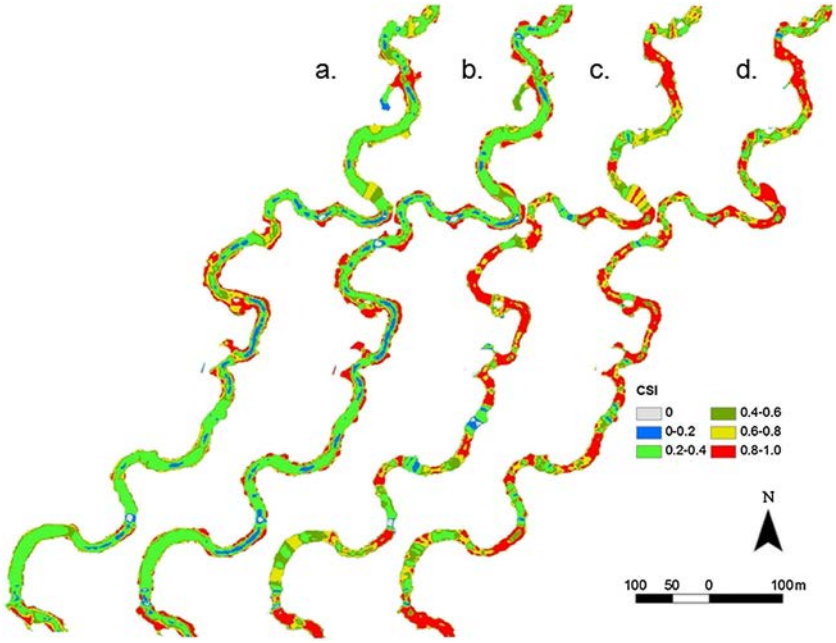

Figure 13. Spatially distributed habitat suitability distribution (CSI) for complex reach in the Bear Valley River. (a) 1D model for HQ, (b) 2D model for HQ, (c) 1D model for LQ, and (d) 2D model for LQ. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

using the bathymetric analysis except in the Deadwood River. These differences are relatively small and are comparable with uncertainty of point-clouds techniques (root mean square errors <0.15 m) (McKean *et al.*, 2009, 2014). Similar to the bathymetry, flow depth, WSE and velocity have smaller differences for the cross-sectional than bathymetric analyses. This further supports the observation that part of the error between 1D and 2D flow predictions is due to the linear interpolation between cross-sections rather than model dimensionality. However, reducing the error due to interpolation by decreasing the cross-sectional spacing could be difficult in certain systems. Our cross-sectional spacing of 5 m is very small and smaller spacing could be difficult to achieve in sinuous streams because cross-sections may overlap. The overlap may not be a problem for 1D modeling of channel, but it violates the fundamental law of flow when water surface elevation values in the cross-section are used to interpolate between them in the pseudo-2D. These results indicate differences in water depths are also somewhat attributable to linear interpolation between cross-sections, bathymetric elevation difference and surface roughness used during model calibration rather than just the model dimensionality (Horritt and Bates, 2002; Thomas and Nisbet, 2007).

We expected to have smaller differences between 1D and 2D model predictions in the simple reaches with homogenous channel geometry than in the more complex channels (Mason *et al.*, 2003; Brown and Pasternack, 2009). Our results do not support this hypothesis because the selected simple reaches with plane-bed bed forms have complex topographical variations at a scale smaller than the selected cross-sectional spacing, but large enough to penetrate most of the water column. This is an important result because it highlights the effect of topographic scale. Large regular bed forms generate flow properties that a 1D analysis may predict with a first-order accuracy if the model is supported by close-spaced cross-sections. However, topographical irregularities at a scale smaller than the cross-section spacing, here <5 m, may have a larger relative importance in 1D analyses of plane-bed than pool–riffle streams because their size may be comparable with the local water depth (Montgomery and Buffington, 1997).

Patterns of differences in velocity predictions are dissimilar to those of flow depth and WSE. The differences are larger in the complex than simple reaches and, in some cases, in the cross-sectional analysis relative to the bathymetric analysis. Furthermore, despite the relatively small difference in flow depth, less than 0.09 m with cross-sectional analysis for both discharge scenarios in the South Fork Boise River, velocity differences are large, ranging between 0.09 and 0.41 m/s (Table II). This underscores the capability of 2D models to simulate complex flows and to account for topographical steering and local

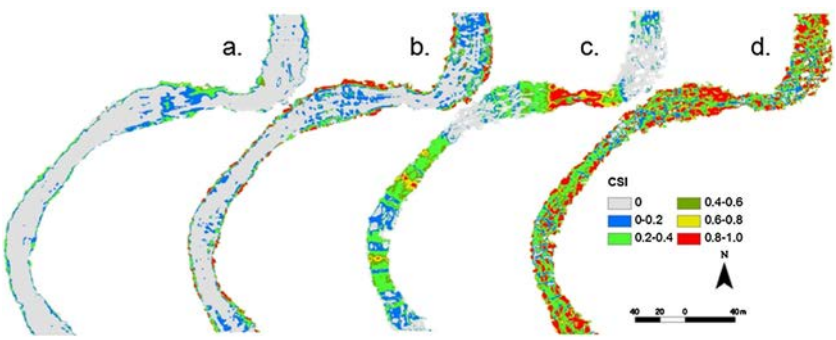

Figure 14. Spatially distributed habitat suitability distribution (CSI) for complex reach in the Deadwood River. (a) 1D model for HQ, (b) 2D model for HQ, (c) 1D model for LQ, and (d) 2D model for LQ. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

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bed form resistance, while these effects are not addressed in 1D models (Morvan *et al.*, 2008; Brown and Pasternack, 2009). Pseudo-2D or 1.5D models scale velocity with local depth such that the highest velocities are associated with the deepest waters. This is not always the case for flows over complex bathymetry (Dietrich and Smith, 1983). Additionally, resistance in 1D modeling is applied at the reach scale and does not vary spatially due to the interaction between flow and topography unless it is explicitly accounted for in a spatially varying Manning's *n*. Instead, this flow resistance is typically assumed spatially constant over the reach scale but may vary with discharge. Unlike water surface elevation, the flow velocity varies rapidly in magnitude and direction, and in space and time as a result of often irregular channel geometry and resistance (Hsu *et al.*, 1999; Papanicolaou *et al.*, 2011). Furthermore, velocity can be influenced by many factors such as water surface elevation slope, bathymetric elevation and surrounding topography, and channel roughness. Large differences between 1D and 2D velocity predictions are observed near channel banks, riffles and deep pools (Figures 4–8) especially at transitional points near the crest of riffle and in pools. In contrast, in plane-bed topography the distribution of velocity differences follows the scattered distribution of the large boulders.

The largest velocity differences are <0.43 m/s with the cross-sectional analysis in the South Fork Boise River (Table II), which is slightly above the normal uncertainty associated with measured and predicted velocities, that is typically around 0.1 to 0.2 m/s (Tonina and Jorde, 2013).The velocity difference is less than 0.17 m/s with the cross-sectional analysis in Bear Valley Creek, which shows that 1D modeling may be capable of predicting velocity comparable to the 2D modeling in low gradient pool–riffle systems with local features larger than the cross-section spacing.

Differences in velocity are substantial in the Deadwood River (Table II). This result is consistent with those presented by Gallagher (1999) for a system dominated by cobbles and boulders. This highlights the importance of large local topographical variations, as errors are caused by the poor description of channel geometry in the 1D models. In hydraulic simulations of natural channels like the Deadwood River, large boulders can significantly impact predicted flow parameters such as velocity gradients and transverse flows. A model is not able to simulate these phenomena when the topography generating those flow structures is not incorporated into the hydraulic model (Crowder and Diplas, 2000). Thus, these differences in hydraulic variables are due to the different bathymetric representation in 1D and 2D modeling, linear interpolation between cross-sections and complex flow phenomena simulated by 2D models and not captured by 1D modeling (Tarbet and Hardy, 1996).

Habitat suitability

Previous works show that 2D modeling may predict larger (Loranger and Kenner, 2004), or smaller (Loranger and Kenner, 2004; Hay and Young, 2007; Wu and Mao, 2007) WUA and HHS than 1D and our results agree with this finding. This lack of systematic behavior is because there are no theoretical nor numerical reasons suggesting that 2D models should consistently report greater aquatic habitat quality than 1D modeling. It is important to notice that our analysis shows the difference between aquatic habitat and hydraulic variables predicted with 1D and 2D modeling but it cannot conclude which is the most accurate because we have not compared their predictions with field surveyed hydraulics and aquatic habitat data.

What is interesting in our results is that 1D and 2D derived WUA and HHS depict similar aquatic habitat characteristics in all but the steep plane-bed system (Deadwood River). WUA and HHS values are very similar at low discharges, with less than 10% difference, except for the steep plane-bed system, which shows differences larger than 50%. The difference in WUA increases with discharge due primarily to organisms' habitat preference rather than differences in hydraulic variables simulated with 1D and 2D models. Although the difference in WUA is about 41% for the large pool–riffle system like South Fork Boise River, the difference in HHS values are relatively small less than 0.1. High differences in HHS at these ranges are less critical. For instance, a value of HHS of 0.06 or 0.12 either portrays low habitat quality even though the percentage difference is high (100%). Conversely, Bear Valley Creek presents high quality habitat (HHS around 0.5) at both discharges and the difference in HHS and WUA between 1D and 2D modeling are small (less than 0.06 and 8% in HHS and WUA respectively). This highlights that 1D supported by close-spaced cross-sections may be an adequate tool to calculate overall aquatic habitat for compound variables such as WUA.

Although, the difference in WUA can be as small as 4%, the difference in spatial distribution of cell suitability can be considerable when estimated with K and OA metrics (see Bear Valley Creek). The cell-by-cell comparison in the error matrix is a very strict method to compare agreement between two maps, because it only contains information about any specific cell. It yields zero agreement when a cell is not exactly overlapped with the same category in the second map, although the correct category may be in a neighboring cell (Pontius, 2002). Therefore, it may be useful to compare specific categories within representative areas (windows) of different sizes using aggregate techniques (Benjankar *et al.*, 2010), which provide additional information about near or far misses.

Visual inspection of the *CSI* maps confirms this limitation of the K and OA methods. Comparison among Figure 5(e)–(h), Figure 12(a)–(d) and Figure 13(a)–(d) show that both 1D and 2D modeling predict a similar *CSI* distribution for the South Fork Boise and Bear Valley systems. Although, the same cell may not have exactly the same class, the same class values occur in nearby locations and the difference is typically only one-quality class. Conversely, Figures 8 and 14 show very different *CSI* distributions in systems like Deadwood, where important topographical features are smaller than the cross-section spacing but as large as the water depth.

Comparison between different grid resolution

In general, the differences for most of hydraulic variables decrease with larger grid sizes for both high and low discharge scenarios, cross-sectional and bathymetric analyses and in complex and simple reaches, except in few cases (Table II). However, simulated habitats (WUA and HHS) do not follow a similar trend as hydraulic variables although habitat is a function of flow depth and velocity. Thus, the result can be interpreted as model grid sizes have secondary influence on differences on hydraulic and habitat variables simulated with 1D and 2D models.

Model selection

Our results suggest significant differences in simulated hydraulic variables such as depth and velocity between 1D and 2D models for river systems with important bathymetric features whose sizes are smaller than the cross-sectional spacing (see

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Deadwood River, Table II). Conversely, differences are smaller in systems with well-defined bed forms, whose length scales are larger than the cross-sectional spacing. Furthermore, the differences are smaller within cross-section locations than entire bathymetric areas. Thus, for systems where several cross-sections can span the important topographical features, 1D modeling may provide a viable first-order assessment of the aquatic habitat.

This study shows that selection of the appropriate model dimensionality, 1D or 2D, in aquatic habitat modeling studies to simulate hydraulic variables, e.g. flow depth and velocity is a complex task. For example, a 2D model may be required for a habitat study that focuses on the micro-spatial scale and spatially distributed flow patterns, whereas a 1D model may be sufficient for a study requiring only a description of the river's more general flow patterns (e.g. flow depth and water surface elevation) at a macro-spatial scale (Crowder and Diplas, 2000). 2D models can simulate 2D (natural) flow features, whose size is larger than the survey data (Bovee, 1996; Lane, 1998; Kondolf *et al.*, 2000). Furthermore, 2D models can predict WUA for large areas consisting of many micro-habitat types, such as pool, riffle and run, which allows a more quantitative evaluation of spatial and hydraulic factors potentially controlling aquatic habitat (Hardy, 1998). Bovee (1996) suggested that if 1D modeling predicted depth and velocity error are less than 10%, it is considered acceptable. However, differences in WUA and HHS were less than those differences in hydraulic variables suggesting that because organisms adapt to ranges of physical values without typically sharp boundaries, these ranges decrease the effect of uncertainty of predicted flow velocity and depth on aquatic habitat. Furthermore, other factors such as objective of a study, computation time, available resources (fund, data and expertise) may influence the choice of a hydraulic modeling. Thus modelers, biologists and ecologists should jointly select the type of hydraulic model (1D or 2D), spatial resolution, required accuracy and hydraulic variables for the analysis (Crowder and Diplas, 2000).

Conclusions

Our analyses show that most differences in derived hydraulic variables and habitat quality predicted with 1D versus 2D modeling occur when bathymetric features are present that have a size comparable to the water depth but smaller than the cross-section spacing. 1D modeling coupled with high-resolution bathymetry may provide assessments of aquatic habitat quality at the reach scale comparable to 2D modeling only if the cross-sectional spacing allows capturing the main topographical features of the streambed, regardless of stream size and discharge. We used close-spaced cross-sections, less than a channel width. Results show large differences in hydraulic variables and WUA in a plane-bed reach with streambed irregularities, whose size is smaller than the cross-sectional spacing but comparable to the mean water depth. Furthermore, the analysis suggests that the difference in hydraulic variables is not solely due to model dimensionality, but also results from spatial disaggregation of the simulated variables and their interpolation between cross-sections.

Reach-scale aquatic habitat indices such as WUA and HHS showed small differences between 1D and 2D modeling for the studied species and life stage. Despite small differences in WUA and HHS, dissimilarities in *CSI* distributions could be large if based on a strict cell by cell comparison, as done for example by the error matrix analysis. Visual inspection of *CSI* maps developed with 1D and 2D modeling shows comparable clustering by habitat quality. The comparison showed a lower match for reaches with subdued topography and large scattered boulders than for reaches with well-defined bed forms with a length scale larger than the cross-sectional spacing.

Our analysis suggests that discharge and stream size have minor effects on the differences between flow properties and habitat quality predicted with 1D and 2D modeling. Similarly, our results show comparable differences between complex and simple reaches for the South Fork Boise River. A key component is the scale at which WUA, HHS and hydraulic properties are quantified, because topographical features that are smaller than the cross-section spacing and interpolation to generate spatially distributed variables induced most of the observed differences. The grid resolution effect on simulated hydraulics and habitats revealed that in general large grid dimensions decrease differences between 1D and 2D model simulated flow parameters, but derived habitats do not follow such trend. Depending on the chosen uncertainty, species and its life stage, hydraulic variables simulated with 1D models supported with high-resolution bathymetry could be useful to derive aquatic habitat considering its efficiency in large-scale studies.

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