Title

Comparison of methods for analysing salmon habitat rehabilitation designs for regulated rivers

Permalink

https://escholarship.org/uc/item/66f1p8vq

Journal

River Research and Applications, 25(6)

ISSN

1535-1459

Authors

Brown, Rocko A
Pasternack, Gregory B

Publication Date

2009-07-01

DOI

10.1002/rra.1189

Full Title: Comparison of Methods for Analyzing Salmon Habitat Rehabilitation Designs For Regulated Rivers

Short title: Comparing Tools for River Rehabilitation

Authors:

Rocko A. Brown and Gregory B. Pasternack*

*Corresponding Author

Affiliations and Addresses:

Department of Land, Air, and Water Resources, University of California, One Shields Avenue, Davis, CA 95616. Phone (530) 754-9243; Fax (530) 752-5262; gpast@ucdavis.edu

Sponsored by USBR (Award #03FG230766) and CALFED (USFWS Agreement DCN#113322G003).

Cite as: Brown, R. A. and Pasternack, G. B. 2009. Comparison of Methods for Analysing Salmon Habitat Rehabilitation Designs For Regulated Rivers. River Research and Applications 25:745-772. DOI: 10.1002/rra.1189

Key words: river restoration, river modeling, river hydraulics, gravel-bed rivers, physical habitat quality, sediment transport regime

ABSTRACT

River restoration practices aiming to sustain wild salmonid populations have received considerable attention in the Unites States and abroad, as cumulative anthropogenic impacts have caused fish-population declines. An accurate representation of local depth and velocity in designs of spatially complex riffle-pool units is paramount for evaluating such practices, because these two variables constitute key instream habitat requirements and they can be used to predict channel stability. In this study, three models for predicting channel hydraulics- 1D analytical, 1D numerical, and 2D numerical- were compared for two theoretical spawning habitat rehabilitation designs at two discharges to constrain the utility of these models for use in river-restoration design evaluation. Hydraulic predictions from each method were used in the same physical habitat quality and sediment transport regime equations to determine how deviations propagated through those highly nonlinear functions to influence site assessments. The results showed that riffle-pool hydraulics, sediment transport regime, and physical habitat quality were very poorly estimated using the 1D analytical method. The 1D and 2D numerical models did capture characteristic longitudinal profiles in cross-sectionally averaged variables. The deviation of both 1D approaches from the spatially distributed 2D model was found to be greatest at the low discharge for an oblique riffle crest with converging cross-stream flow vectors. As decision making for river rehabilitation is dependent on methods used to evaluate designs, this analysis provides managers with an awareness of the limitations used in developing designs and recommendations using the tested methods.

INTRODUCTION

Spawning habitat rehabilitation (SHR) is widely performed for regulated rivers in the western United States and other semi-arid regions globally (Zeh and Donni, 1994; Wheaton et al., 2004a; Gard, 2006; Elkins et al., 2007) to mitigate the decline in anadromous fish populations associated with dam impacts and excessive fishing (Yoshiyama et al., 1998; Graf, 2001). A component of SHR involves adding washed gravel and cobble, 8-256 mm in diameter, to a stream (aka gravel augmentation) to increase the quantity and quality of spawning habitat at a placement site (Harper et al., 1998; Wheaton et al., 2004a) as well as to provide coarse sediment to transport downstream where it may form diverse habitats (Trush et al., 2000). In past decades, the design and construction of instream alluvial spawning habitat using augmented gravels largely involved creating flat homogenous spawning beds supported by rock weirs (Kondolf et al., 1996; Walker et al., 2004; Slaney et al., 1997; Newbury et al., 1997; CDFG, 1998; CDWR, 2000; Saldi-Caromile et al. 2004). Moreover, the analysis and evaluation of these features also relies on the assumption of steady, uniform flow to estimate hydraulic variables used in subsequent geomorphic and ecological predictions.

Based on observed deficiencies of past projects, there is a growing recognition of the importance of design and implementation of complex alluvial features that utilize channel non-uniformity to promote habitat heterogeneity (Pasternack et al., 2004; Wheaton et al. 2004b, c; Elkins et al., 2007; Sawyer et al., 2008). There is also a growing need for accurate and cost-effective means to represent habitat (Maddock, 1999; Moir and Pasternack, 2008). Consequently, this study presents a comparison of three contemporary analytical and numerical methods used for predicting channel hydraulics, spawning habitat quality, and sediment transport regime (as defined by ranges in dimensionless Shields stress; see methods section) over riffles and pools typical of regulated rivers where salmon spawn.

The overall goal of this study was to determine what quantitative differences arise from the three different approaches for estimating channel hydraulics over riffle and pool sections and to what extent, if any, the differences impact physical habitat quality and sediment transport predictions. Specific questions were: 1) How do velocity and water surface profiles compare between each approach for two different discharges and two different riffle-pool morphologies- one with orthogonal and one with oblique gravel bars?, 2) What are the effects of 1D and 2D hydraulic models on the prediction of sediment transport regime and spawning habitat quality?, 3) Can the hydraulics of even a spatially uniform broad flat riffle be determined within reason using only a 1D analytical approach?, 4) How does a blanket-fill gravel placement design differ in sediment transport regime and physical habitat quality from one that strongly accentuates riffle-pool relief?, and 5) What would be the implications of each approach on decision making for the test designs? The significance of this study lies in the practical aid it provides regulated-river managers in deciding what level of detail they need in their design evaluation framework to reasonably predict the outcome of their habitat rehabilitation projects in terms of ecological success and geomorphic stability.

Riffle-Pool Units

Riffles and pools are respectively defined as topographic highs and lows along a channel thalweg (Leopold et al., 1964; Richards, 1976; Wohl et al., 1993). They are a common geomorphic unit for the aquatic community in gravel-bed rivers with slopes ranging from 0.001-0.02, and are thus very important components in spawning habitat rehabilitation projects involving direct gravel augmentation (NRC, 1992; Newbury et al., 1997; Kondolf, 2000; Wheaton et al., 2004a,b; Saldi-Caromile et al., 2004; Elkins et al., 2007). Naturally sustained riffles and pools are used by anadromous fish species through multiple life-stages (Bjornn and Reiser, 1991) and represent contrasting hydraulic and geomorphic environments as indicated by variations in water surface and energy gradients (Leopold et al., 1964; Keller, 1971; Richards,1976; Wohl et al., 1993), mean and local bed hydraulic parameters such as velocity and shear stress (Keller, 1971; Carling, 1990; Clifford and Richard, 1992; MacWilliams et al., 2006), grain size (Keller, 1971; Lisle, 1979; Milne, 1982), and channel area, which lead to further variations in flow divergence and convergence (Thompson et al., 1999; MacWilliams et al., 2006). Water-surface and energy gradients over riffles are typically steeper than over pools at low flows and generally converge as stage increases and relative roughness decreases (Leopold et al., 1964; Keller, 1971; Richards, 1976; Wohl et al., 1993). Similarly, mean velocity and shear stress are greater over riffles than pools at lows flows, but the reverse may occur at high flows where channel conditions promote that phenomenon (Keller, 1971; Carling, 1991; Clifford et al., 1993; Wilkinson et al., 2004; MacWilliams et al., 2006, Harrison et al., 2007). Variations in depth, velocity, and water surface gradients between riffles and pools at low flows lead to distinct sediment sorting patterns that may even persist at high flows and affectchannel hydraulics (Keller, 1971; Lisle, 1979). The convergence and/or "reversal" of riffle-pool water surface elevation and velocity profiles can also cause sediment transport capacity to become greater through pools than riffles (Sear, 1996).

The contrasting hydraulic and geomorphic environments provided by riffle and pool units also yield a nested hierarchy in the ecological community. In the context of SHR, spawning habitat, defined as suitable areas for salmon to deposit eggs and for those eggs to incubate, is typically associated with riffle areas, while adult holding habitat is typically located in pools (Hunter, 1991; Wheaton et al., 2004b; Gard 2006; Brown and Pasternack, 2008). The linkage between channel hydraulics and what organisms do is often through what is termed “physical habitat”. Physical habitat quality refers to the degree of suitability of local depth, velocity and river-bed substrate size in a stream to support a particular ecological function. It is a common metric used to evaluate existing channel conditions for instream flow needs (Smith, 1973, Milhous et al., 1989, Bovee et al., 1998, Lacey and Millar, 2004, Brown and Pasternack, 2008) as well as in design evaluation for SHR projects (Pasternack et al., 2004; Gard, 2006; Elkins et al., 2007). Although other variables such as temperature, primary and secondary productivity, and water quality affect the location where fish choose to spend time during a given lifestage (Torgersen et al., 1999; Merz and Setka, 2004), it has been shown that physical habitat quality is often a very strong predictor of some lifestages, especially spawning (Leclerc et al., 1995; Elkins et al., 2007).

Predicting channel stability and physical habitat quality are important components of evaluating SHR project designs. The manipulation of channel form that is typical of SHR is related to these key goals through channel hydraulics, which can be represented at different spatial scales. Engineering and design aspects of direct gravel augmentation for SHR often require that target depths and velocities are present and that gravels are stable at low discharges when spawning and embryo incubation are occurring (Merz et al., 2004). In contrast, channel change and bed turn-over are desired at other times of the year, because the gravel bed needs to be kept free of silt and fine sand that can cause subsurface oxygen deficits and embryo death (Merz and Setka, 2004; Merz et al., 2004; Merz et al., 2006). This requirement of bed turnover has stimulated research into design of “flushing flows” that partially mobile the bed (Wilcock et al., 1996a). Gravel stability and bed-material transport are both related to channel conditions through shear stress, which is a direct function of channel hydraulics (Yalin, 1977; Chang, 1998).

As physical habitat is also directly linked to channel hydraulics, capturing and distinguishing the hydraulic attributes of riffles and pools is a key need in the successful design and evaluation for SHR projects (Ghanem et al., 1996).

METHODS

To answer the study questions, a hydraulic analysis was performed using three methods for two hypothetical SHR designs (Fig. 1) actually proposed for an individual pool-riffle-pool sequence in the Lewiston Dam Reach (river mile 111.8-111.2; USFWS 1999) of the Trinity River in Northern California. Since the test designs are hypothetical constructs, the numerical models could not be validated for these specific scenarios. However, the models were validated for the real Lewiston Dam Reach on the Trinity River (Brown and Pasternack, 2008), so the use of these models for this investigation is appropriate. The hydraulic output for each test method was propagated into standard sediment transport regime and spawning habitat quality algorithms to evaluate the sensitivity of these metrics to choice of hydraulic estimation method. The sediment transport regime was characterized by ranges of Shields stress reported in the literature to produce various transport intensities in gravel-bed rivers. Spawning habitat quality was characterized using a global habitat suitability index based on depth and velocity. Both of these indices are described in more detail below. Although a specific river was used to obtain a baseline topography and flow regime, the results should be applicable to channels worldwide with similar non-dimensional geometric and Froude number scaling.

The comparison of three hydraulic estimation methods required establishing some values for variables and parameters common to all three methods. To account for the flow dependence of sediment transport regime and physical habitat quality, the three methods were evaluated at two discharges- the prescribed spawning and embryo incubation discharge for the Trinity River (8.5 m^3/s) and the maximum flow release that occurred 1999-2004 (170 m^3/s). For all calculations of design bed material, the D_{50} (i.e. median size) and D_{90} (i.e.size that 90% of grains are smaller than) were assumed to be 76.2 mm and 152.4 mm respectively, based on consultant-recommended grain sizes for gravel placed into the Trinity River (McBain and Trush, 2003). Similarly, for all parameterizations of channel roughness, Manning's n was used and set at 0.043, which is typical of the channel roughness of well-mixed, double-washed placed gravels (Pasternack et al., 2004). This value has been validated for use on the Trinity River in the rehabilitation reach at Lewiston Dam over the range of flows evaluated (Brown and Pasternack, 2008). Effects of channel curvature were not evaluated in this study of straight-channel mechanics, but would be important to consider for designs of meandering channels.

Test Designs

Each test design was situated within the LHR giving the test scenarios several physical constraints. The average channel width is 35 m at low-flow (8.5 m^3/s and the reach is approximately 600 m long with a slope of 0.0022 under current conditions. However, for this study, the test scenarios were only for the upper 350 m of the reach. For more information on the LHR the reader is referred to Brown and Pasternack (2008).

The morphological features of design 1 (Fig.1a) involved a "blanket-fill" of gravel with all areas receiving a moderate amount of material. The riffle crests were oriented orthogonal to the channel and included a broad flat riffle (BFR), an "L-shaped" central bar (LCB), and two constricted pools (hereafter referred to as Pool One and Pool Two). The BFR is a commonly used SHR structure when design is based on 1D methods (Kondolf et al., 1996; CDFG, 1998; CDWR, 2000; Saldi-Caromile et al., 2004). The LCB is an analog to the central bar, an alluvial morphology that has been found to provide habitat for multiple life stages of salmonids (Wheaton et al., 2004b). The middle of the LCB has an asymmetrical cross-section where there is a deeper chute on the river left. Constricted pools were used downstream of the BFR and the LCB to potentially invoke hydraulic reversal and channel self-stability by nature of the riffles being somewhat wider than pools (Carling, 1990; MacWilliams et al., 2006).

Design 2 (Fig. 1b) involved placing gravel everywhere, but strongly accentuating the relief between the main riffle crest and the pools around it. The primary feature was a transverse oblique riffle (TOR) crest in between two pools. The crest in this case was narrow and attached to an alternate-type bar on river right. This type of bar has been seen in both natural and artificial riffles. It is similar in function to chevron-shaped riffles, but converges flow along one bank preferentially, which may enhance local scour there, promoting habitat heterogeneity.

Digital terrain models (DTMs) of both designs were based on the actual channel topography of the Lewiston Dam reach, which was mapped in august 2003 with a resolution of ~1.4 points per m^2 (Brown and Pasternack, 2008). For this study, that real surface was re-contoured in AutoCAD Land Desktop 3 to obtain the desired channel features for each design. The design DTMs (Fig. 1) were used to generate the topographic inputs for each test method.

Hydraulic Prediction

Hydraulic variables in regulated rivers serve as key metrics for a plethora of management issues from habitat assessment, sediment management issues, and flood control. In the realm of professional practice and applied science they aid decision making by facilitating the prediction of other key parameters of interest to the management of regulated rivers. Since hydraulic variables such as depth and velocity are now widely used as intermediate links connecting flow processes (i.e. sediment transport and deposition) with ecological conditions in habitat evaluation (Bovee et al., 1998; Maddock, 1999; Gard, 2006; Elkins et al., 2007), as well as geomorphic processes associated with sediment transport and deposition, their accuracy is vital in attempts to manage and restore regulated rivers (Pasternack et al., 2006). Currently in professional practice there are three main approaches for predicting channel hydraulics that can be delineated by the solution procedure and the physical dimensions they are capable of predicting, and they include a 1D analytical procedure, a 1D numerical model, and a 2D numerical model.

1D Analytical

The 1D analytical method involves predicting open channel processes by coupling some combination of a mass-conservation equation, empirical hydraulic-geometry equations, empirical flow-resistance equation, and an empirical or semi-empirical sediment-transport equation (Dunne and Leopold, 1978; Yen, 1991; Rosgen, 1996; Chang, 1998). Flow resistance equations have been typically derived from non-alluvial channel boundaries under steady, uniform flow and use roughness coefficients that have no true theoretical basis (Yen, 1991). Because they assume steady, uniform flow conditions, they are the easiest to perform and represent the lowest cost approach to quantitative design evaluation (Shields et al., 2003).

The Manning-Gauckler equation, hereafter referred to as the Manning Equation, is a frequently prescribed flow resistance equation used in the United States for evaluating channel hydraulics for physical habitat and sediment transport (Rosgen, 1996; Bovee et al., 1998; Saldi-Caromile et al. 2004), so it was used in this study to calculate cross-sectionally averaged velocity

($\overline{V}$) for each specified water surface elevation (WSE):

$$\overline{V} = \left(\frac{1}{n}\right) R^{2/3} S^{1/2} \text{ and } \quad Q = A\overline{V} \tag{1,2}$$

where Q is discharge (m^3/s), R is hydraulic radius (m), A is cross-sectional area (m^2), n is Manning's roughness coefficient, and S is typically the average bed slope. R and the corresponding A were obtained iteratively in AutoCAD Land Desktop 3 until the continuity equation was solved for the discharge of interest. The equation is very sensitive to S, and the local slope can vary considerably in a gravel bed river, depending on the spatial scale being examined. To avoid bias, it was assumed that S was related to geomorphic slope, defined as the elevation difference between an upstream feature and the next downstream feature of the same type (i.e. bar or pool) divided by the distance between them (Fig. 2).

As the 1D analytical method is based on the concept of steady-uniform flow, in which temporal and spatial changes are neglected and driving and resisting forces balance each other out (Yen, 1991), relevant hydraulic processes within and between cross-sections may not be accounted for. In particular, backwater effects and other forms of channel-wide and local convective accelerations are not accounted for using one-dimensional methods. These phenomena have been shown to influence both pool-riffle hydraulics, sediment transport regime, and physical habitat predictions (MacWilliams et al., 2006; Elkins et al., 2007).

1D Numerical Model

Numerical approaches to hydraulic estimation employ computers to approximate solutions of 1D, 2D, or 3D equations of motion where the solution procedures are dependant either on adjacent nodes or cross sections. 1D models such as HEC-RAS and MIKE11 can consider unsteady conditions and to some extent non-uniform conditions. They cannot account for transitional dynamics where no cross-sections are measured, nor can they account for secondary flow processes that may occur at measured cross sections (Darby and Van de Wiel, 2003; Nelson et al., 2003). They use a standard step method to iteratively solve the energy equation from one cross section to the next to calculate water surface profiles. These models solve the energy equation for steady gradually varied flow and are also capable of calculating subcritical, super critical, and mixed flow regime water surface profiles (Brunner, 1998). The energy equation at two cross-sections denoted by subscript numbers 1 and 2 is described as

$$\overline{H}_2 + Z_2 + \frac{\alpha_2 \overline{V_2}}{2g} = \overline{H}_1 + Z_1 + \frac{\alpha_1 \overline{V_1}}{2g} + h_e \qquad (3)$$

where $\overline{H}$ is cross-sectionally averaged water depth (m), Z is the invert elevation (m), α is the velocity weighting coefficient, g is gravitational acceleration (m/s^2), and h_e is energy head loss (m). Eq. (1) is used implicitly in the solution of (Eq. 3).

HEC-RAS was used in this study and the boundary conditions required to run it were the discharge entering the upstream boundary, the associated downstream water surface elevation, and channel topography at designated cross-sections. Cross sections were sampled from the DTM of each test design in 7.6-m increments. Some additional cross sections were augmented to capture transitional dynamics and to match cross section locations used for the 1D analytical method.

1D hydraulic models usually provide fairly accurate predictions of water surface elevation for flood stages where relative roughness is low and/or there are gradual changes in bed slope and channel width (Ghanem et al., 1996; Brunner, 1998; Lacey and Millar, 2004). They have the advantage over 1D analytical approaches in that they can account for cross-sectionally averaged convergence and divergence effects at cross-sections. They cannot account for topographic variability between cross-sections nor even localized convective accelerations within only a small part of a cross-section, such as in the vicinity of a boulder cluster. Previous studies highlight that these models may not be appropriate for predicting channel hydraulics at the spatial scales necessary to represent physical habitat and sediment transport (Ghanem et al., 1996; MacWilliams et al., 2006; Lacey and Millar, 2004). Despite this, they are readily available, require relatively sparse information, and are frequently used by professional consultants.

2D Numerical Model

2D (depth-averaged) models such as FESWMS, RIVER2D, HIVEL2D, RMA2, MIKE21, SRH-2D, TUFLOW, and TELEMAC further add the ability to consider full lateral and longitudinal variability down to the sub-meter scale, including effects of alternate bars, transverse bars, islands, and boulder complexes, but require highly detailed topographic maps of channels and floodplains (French and Clifford, 2000). 2D models are also more realistically linked to flow, sediment transport, and biological variables measured in the field at the same spatial scale (Ghanem et al., 1996; Lacey and Millar, 2004; Pasternack et al., 2006). 2D models have been used to study a variety of hydrogeomorphic processes (Bates et al. 1992; Leclerc et al. 1995; Miller and Cluer 1998; Cao et al., 2003). Recently, they have been evaluated for use in regulated river rehabilitation emphasizing spawning habitat rehabilitation by gravel placement (Pasternack et al., 2004, Wheaton et al., 2004b; Pasternack et al., 2006; Elkins et al., 2007; Brown and Pasternack, 2008).

In this study, the 2D model known as Finite Element Surface Water Modeling System

3.1.5 (FESWMS) was used to simulate hydraulics (Froehlich, 1989). FESWMS solves the vertically integrated conservation of momentum and mass equations using a finite element method to acquire depth-averaged 2D velocity vectors and water depths at each node in a finite element mesh. The model is capable of simulating both steady and unsteady 2-D flow as well as subcritical and supercritical flows. The basic governing equations for vertically integrated momentum in the x- and y- directions under the hydrostatic assumption are given by

$$\begin{aligned}&\frac{\partial}{\partial t}(HU)+\frac{\partial}{\partial x}(\beta_{uu}HUU)+\frac{\partial}{\partial y}(\beta_{uv}HUV)+gH\frac{\partial z_b}{\partial x}+\frac{1}{2}g\frac{\partial H^2}{\partial x}\\&+\frac{1}{\rho}[\tau_x^b-\frac{\partial}{\partial x}(H\tau_{xx})-\frac{\partial}{\partial y}(H\tau_{xy})]=0\end{aligned}\tag{4a}$$

and

$$\begin{aligned}&\frac{\partial}{\partial t}(HV)+\frac{\partial}{\partial x}(\beta_{vu}HVU)+\frac{\partial}{\partial y}(\beta_{vv}HVV)+gH\frac{\partial z_b}{\partial y}+\frac{1}{2}g\frac{\partial H^2}{\partial y}\\&+\frac{1}{\rho}[\tau_y^b-\frac{\partial}{\partial x}(H\tau_{yx})-\frac{\partial}{\partial y}(H\tau_{yy})]=0,\end{aligned}\tag{4b}$$

where H is local water depth (m), U and V are local depth-averaged velocity components (m/s) in the horizontal x- and y- directions, respectively, z_b is the bed elevation (m), β_{uu}, β_{uv}, β_{vu}, and β_{vv} are the momentum correction coefficients that account for the variation of velocity in the vertical direction, $\tau^b{}_x$ and $\tau^b{}_y$ are the bottom shear stress components (Pa) acting in the x- and y-directions, respectively, and τ_{xx}, τ_{xy}, τ_{yx}, and τ_{yy} are the shear stress components (Pa) caused by fluid turbulence. Conservation of mass in two-dimensions is given by

$$\frac{\partial H}{\partial t}+\frac{\partial}{\partial x}(HU)+\frac{\partial}{\partial y}(HV)=0.\tag{5}$$

FESWMS was implemented using Surface Water Modeling System v. 8.1 graphical user interface (EMS-I, South Jordan, UT). The boundary conditions required to run FESWMS were the input hydrograph, the exit water surface elevation, and high-resolution channel topography. In addition, model parameters are needed to describe channel roughness and provide turbulence closure. Values for all boundary conditions and parameters were selected to be physically realistic and were not numerically calibrated. The turbulence parameter eddy viscosity (E) was a variable in the system of model equations, and it was computed as $E = c_o+0.6 \cdot H \cdot u^*$, where u^* is shear velocity (m/s) and c_o is a minimal constant added for numerical stability. This equation was implemented in FESWMS to allow eddy viscosity to vary throughout the channel, which yields more accurate transverse velocity gradients. However, a comparison of 2D and 3D models for a shallow gravel-bed river demonstrated that even with this spatial variation, it is not enough to yield as rapid lateral variations in velocity as occurs in natural channels, presenting a fundamental limitation of 2D models like FESWMS (MacWilliams et al., 2006). Although eddy viscosity is an oversimplifying turbulence closure parameter, observations of depth and velocity may be used to compute values for it as a check on model performance (Fischer et al., 1979). This model has previously been heavily validated for use in shallow gravel-bed rivers (Pasternack et al., 2004; Wheaton et al., 2004b, Pasternack et al., 2006; Elkins et al., 2007; Brown and Pasternack, 2008; Moir and Pasternack, 2008).

DEM {x,y,z} contour and grid points for each test design were imported from AutoCAD into the 2D model where they were used to interpolate the elevations of the nodes in a finite element mesh consisting of triangular and quadrangular elements. Inter-nodal spacing ranged from 0.2-0.6 m. To reduce model instability associated with mesh-element wetting and drying at a threshold of 9-cm depth, meshes were iteratively trimmed to exclude dry areas, yielding slightly different final meshes for each discharge simulation.

3D models such as UNTRIM and SSIIM go further by including vertical fluid fluxes, but do not require much more data input than 2D models to get going (MacWilliams et al., 2006). However, model validation of 3D processes is difficult and time-consuming. Also, few ecological and geomorphic processes have been quantitatively linked to 3D flow dynamics yet, limiting the interpretation of 3D model output for practical applications, such as SHR design. Consequently, 3D models are not considered in this study.

There are obvious discrepancies between analytical calculations versus 1D and 2D hydraulic models (Cao and Carling, 2002), however, the effect of these differences on sediment transport regime and physical habitat predictions for riffle and pool units have not been explored. Some previous studies have shown that 1D numerical models are insufficient to describe hydraulics and sediment transport through pool-riffle sequences (Keller et al., 1993; Rathburn et al., 2003). Moreover, studies have shown that 2D models provide a better description of channel hydraulics and physical habitat than 1D models (Ghanem et al., 1996; Lacey and Millar, 2004; MacWilliams et al., 2006). Such efforts provide a foundation for a thorough investigation of the trade-offs when using models for river-rehabilitation design evaluation.

Sediment Transport Regime Predictions

In both analytical and numerical approaches Shields stress was used as the representative variable that indicates channel stability via a sediment transport regime, defined below. For purposes of comparison Shields stress was calculated as a section average for 1D analytical and numerical approaches and on a node basis for the 2D numerical approach. Shields stress is defined as

$$\tau^* = \frac{\tau_b}{(\gamma_s - \gamma_f)D_{50}} \tag{6}$$

where, τ^* is Shields stress, τ_b is the predicted bed shear stress (Pa), γ_s is the specific weight of sediment (N/m^3), γ_f is specific weight of water (N/m^3), and D_{50} is the median grain size of the bed surface (m). The sediment transport regime was characterized by the range of values that τ^* falls into, as defined by Lisle et al. (2000): Values of $0.00 < \tau^* < 0.01$ mean no transport is occurring, $0.01 < \tau^* < 0.03$ indicates intermittent, localized transport in response to infrequent turbulent bursts and/or bed vibrations, $0.03 < \tau^* < 0.06$ corresponds with Wilcock's (1996b) domain of "partial transport" in which grains move in proportion to their relative exposure on the bed surface, and $\tau^* > 0.1$ represents full mobility of a "carpet" of sediment 1-2·D_{90} thick. Higher thresholds for channel-altering conditions may exist, but have not been delineated in the literature. These threshold delineations may vary depending on how well compacted the bed is and other factors, but they provide a reasonable basis for characterizing sediment transport conditions. At present there is disagreement as to the breadth of applicability of these dimensionless ranges across all types of gravel- and sand-bed rivers. However, a review of sediment transport studies in gravel-bed rivers with the characteristics of the LHR found that they are applicable for the purposes of this study.

To obtain τ^*, predictions of τ_b were made using the hydraulic predictions from each method in the same Einstein's log-velocity equation for turbulent flows over rough beds

$$\tau_b = \rho_w \left(\bar{u} \Big/ \left(5.75 \log\left(\frac{12.2H}{2D_{90}} \right) \right) \right)^2 \qquad (7)$$

where $\bar{u}$ is depth-average velocity (m/s), D_{90} = grain size in which 90% are finer than (m). When used with the 1D analytical method, $\bar{V}$ and R are substituted for $\bar{u}$ and H, respectively. With the 1D numerical method, $\bar{V}$ and $\bar{H}$ are substituted for $\bar{u}$ and H, respectively. With the 2D numerical method, $\bar{u}$ is taken to be the magnitude of the velocity vector at a point.

Physical Habitat Predictions

A global habitat suitability index (GHSI) for Chinook salmon spawning habitat quality was calculated using depth (DHSI) and velocity (VHSI) habitat suitability curves that were previously derived for the Trinity River based on field observations of flow conditions at spawning sites (USFWS, 1997). These curves are typical across rivers in California. The best-fit numerical equations using H or $\bar{H}$ to match reported DHSI were

$$\text{For } H<0 \text{ and } H>1.374 \text{ m: DHSI}=0 \tag{8a}$$

$$\begin{gathered}\text{For } 0<H<1.374 \text{ m:}\\ \text{DHSI} = 0.0351-0.7248\cdot(H/0.3048)+4.9307\cdot(H/0.3048)^2-\\ 5.2964\cdot(H/0.3048)^3+2.4818\cdot(H/0.3048)^4-0.6007\cdot(H/0.3048)^5+0.007235\cdot(H/0.3048)^6-\\ 0.002514\cdot(H/0.3048)^7-0.000274\cdot(H/0.3048)^8+2.1277\cdot(H/0.3048)^9\end{gathered} \tag{8b}$$

Similarly, using either U or $\bar{V}$ those for VHSI were

$$\text{For } U<0.01 \text{ and } U>1.68 \text{ m/s: VHSI}=0 \tag{9a}$$

$$\begin{gathered}\text{For } 0.01<U<0.40 \text{ m/s: VHSI} = -0.0131+0.5523\cdot(U/0.3048)-\\ 0.8246\cdot(U/0.3048)^2+1.8208\cdot(U/0.3048)^3-0.8013\cdot(U/0.3048)^4\end{gathered} \tag{9b}$$

$$\begin{gathered}\text{For } 0.40<U<1.68 \text{ m/s:}\\ \text{VHSI} = -5.1205+13.1440\cdot(U/0.3048)-9.5769\cdot(U/0.3048)^2+\\ 2.2576\cdot(U/0.3048)^3+0.4525\cdot(U/0.3048)^4-0.3746\cdot(U/0.3048)^5+0.08619\cdot(U/0.3048)^6-\\ 0.009046\cdot(U/0.3048)^7+0.000369\cdot(U/0.3048)^8\end{gathered} \tag{9c}$$

Similar analyses were done for steelhead and coho as well as for all three species in fry, juvenile, and adult life stages, but only the Chinook spawning analysis is presented here for brevity to exemplify the results and how differences in computing depth and velocity propagate through a typical habitat suitability equation. An analysis of all species' lifestage habitats in the Lewiston Dam reach of the Trinity river is available in Brown and Pasternack (2008). We assumed the test scenarios in this study all had similar grain size distributions, making the use of a substrate suitability index null in this particular study. DHSI and VHSI were combined using the standard

$$\mathrm{GHSI} = \mathrm{DHSI}^{0.5} \times \mathrm{VHSI}^{0.5} \qquad (10)$$

GHSI was classed as very poor (0-0.1), low (0.1-0.4), medium (0.4-0.7), and high (0.7-1.0) quality habitat (Leclerc et al., 1995). One-dimensional analytical predictions were made using $\overline{\overline{V}}$ and R, while 1D numerical predictions were made with $\overline{\overline{V}}$ and $\overline{\overline{H}}$. The 2D model calculated GHSI on a nodal basis to estimate physical habitat for the design. GHSI values are only reported at the low flow, because at the high flow the depths and velocities were too high to yield much habitat.

Comparison Between Methods

Although, the three approaches use somewhat different variables in their equations it was possible to calculate comparable quantities to understand similarities and differences. Water surface elevation is a common variable produced by all models, and thus is directly comparable. Because the 2D model provides U-values and H-values at all computational nodes across the channel, weighted nodal averages of each comparable to $\overline{\overline{V}}$ and $\overline{\overline{H}}$ were calculated by accounting for the width along which each node's values were representative. To compare 1D section-averaged values of τ* among methods, two different averaging methods were used to obtain section-averages from the 2D model output. First, equations 6-7 were applied at each node, and then weighted nodal averages of τ* across the channel were computed using the same approach described above for U, H, and GHSI. Second, weighted nodal averages of U and H were put into equations 6-7. This “smoothed” method ought to be less representative, but was thought to be useful for evaluating the effects of different averaging methods on assessing erosion potential.

Given a set of test metrics common to all three methods evaluated in this study, the key analysis is the determination of the degree of deviation in the metrics that constitutes a “significant” difference. Rather than using a statistical characterization of significance that assumes values are probabilistically distributed, the appropriate approach for evaluating a deterministic system is to identify the processes that ought to be operating and then evaluate the different models relative to their ability to capture those processes. For the basic hydraulic variables (WSE, $\overline{\overline{H}}$, and $\overline{\overline{V}}$), the key process evaluated was the degree to which each model captured the longitudinal variations associated with backwater conditions upstream of riffle crests and flow acceleration downstream of them. For the geomorphic and ecologic variables (τ^* and GHSI), evaluation focused on whether deviations in values were large enough to cause the method to predict the wrong sediment transport regime or habitat quality type, since sharp thresholds delineated classes for these variables. Given that the differences in the predictions between the methods were in fact large enough to cause such misidentification of classes, this analytical approach provides an objective and useful basis for comparison. How badly a model must perform before it is rejected is ultimately a philosophical question that each individual and the river-management community at large must wrestle with.

RESULTS

Hydraulic Prediction

Test Design 1

Direct comparison of the three test methods for design 1 at the low flow, 8.5 m^3/s, found that the two numerical methods yielded very similar cross-sectionally averaged velocity and water surface elevation values down the channel (Table 1), with the 2D velocity values showing slightly greater longitudinal variation (Fig. 3a,b). In contrast, the 1D analytical method yielded a highly uniform longitudinal velocity profile that was insensitive to the bed variation. Also, it predicted a water surface profile that paralleled the bed profile. Consequently, it overpredicted pool velocity and underpredicted riffle velocity, which was the expected outcome of neglecting backwater effects. A useful attribute of the 2D numerical method was the provision of a range of velocities across each section, not just an average (Fig. 3a). This at-a-section lateral variability varied downstream in response to local flow convergence and divergence, as indicated by flow vectors (Fig. 4b).

The hydraulic-variable profiles at 170 m^3/s for numerical models in design 1 exhibited similar relative predictions as found at low discharge (Table 2; Fig. 3c,d). In this case, the 1D numerical model predicted slightly higher values than the 2D model. Meanwhile, the 1D analytical method yielded greater variations than at low flow, with generally lower velocities and higher water surface elevations than the numerical models. The lateral variation in velocity predicted by the 2D model was much stronger at high flow than low flow, with peak velocities focused in the channel center (Fig. 5b). Also, the longitudinal location of peak velocities shifted at high flow from riffle exits to riffle entrances.

Test Design 2

Direct comparison of the three test methods for design 2 at 8.5 m^3/s (Table 3) revealed dramatic differences between analytical and numerical predictions. The high-relief riffle crest at 30 m downstream produced a strong backwater effect with higher water surface elevations and lower velocities in both numerical models (Fig. 6a,b). In contrast, the analytical method predicted that the water surface would step up with the bed surface, which was wrong. In terms of velocity, the methods yielded similar values over the riffle crest, but the 1D analytical method significantly overpredicted pool velocity (Table 3). The 2D model showed greater hydraulic complexity and lateral variation in velocity in design 2 compared with design 1, which was caused by the transverse oblique riffle (TOR). This is exemplified by the presence of two distinct peak-velocity zones and two whirlpools (Figs. 7a,b). One peak-velocity zone occurred where flow converged vertically over the oblique section of the riffle crest. The other occurred in the laterally convergent, horseshoe-shaped (in plan view) riffle exit on river right. Both whirlpools occurred on river left behind submerged lateral bars with very steep backslopes (Fig. 7b).

For the high discharge test, the 1D analytical method was even worse off than at low discharge (Table 4; Figs. 6c,d). It predicted the peak velocity over the pool and minimum velocity over the riffle crest, whereas the numerical methods yielded the opposite pattern, correctly accounting for the pool backwater effect and convective acceleration leading into the riffle crest. A stronger difference between 1D and 2D numerical velocity predictions was evident in design 2 compared with design 1, driven by the stronger lateral channel non-uniformity in design 2. Both methods did show that the location of peak velocity moved from the riffle exit to the riffle entrance from low flow to high flow. Also, the 2D model flow vectors did not show any whirlpools (Fig. 8a,b).

Sediment Transport Regime Prediction

In light of the strong differences between the 1D analytical method and the numerical models, one would anticipate that propagation of the error into highly nonlinear functions, such as those for sediment transport regime assessment, would accentuate the differences further. Lumping all cross sections for all four tests, the mean and median differences of Shields stress between the 1D analytical method and the 2D model were 175 and 41 %, respectively. Only one out of 20 comparisons had less than a 10 % difference in Shields stress. Comparing the 1D and 2D models similarly, the mean and median differences of Shields stress were only 14 and 5 %, respectively. In light of the poor predictive capability of the 1D analytical method, the use of broadly defined classes of sediment transport regime did helped diminish the impact, but 11 out of 20 locations were misclassified by that method. In comparison, only one out of 20 locations were classified differently between the 1D and 2D models, and that was the TOR exit at low flow, where the 1D model could not handle strong local flow convergence properly.

Differences in predictions of Shields stress between methods varied sharply between the two test designs. The mean difference in Shields stress between the 1D analytical method and 2D model was 4.6 times higher for design 2 than for design 1. Similarly, the mean difference in Shields stress between the 1D and 2D models was 3.1 times higher. Overall, design 2 was predicted to be much more at risk of riffle destruction at low and high flows than design 1.

Test Design 1

Among the six cross-sections analyzed for design 1 at 8.5 m^3/s, most Shields stress predictions were in the range of 0-0.01, corresponding with no transport (Table 1, Fig. 9a). For most channel units, the 1D analytical predictions had a high range, but still remained in the intermittent transport regime. The 1D analytical model underpredicted Shields stress on the two riffle crests, likely yielding an incorrect classification of no transport, instead of intermittent transport, as predicted by the more sophisticated numerical models. The spatial pattern predicted by the 2D model showed longitudinal variation between riffle crests and pools, but little lateral variation (Fig. 4c) given the simple channel geometry.

At 170 m^3/s, maximum Shields stresses corresponding to a state of partial transport were predicted by all methods to occur over the broad flat riffle (BFR) (Table 2, Fig. 9b). In Pool 1, the numerical models predicted continued partial transport due to the steep water surface slope and associated acceleration, whereas the 1D analytical method predicted intermittent transport. Over the middle of the LCB, the numerical models predicted intermittent transport due to the backwater effect behind the next crest, whereas the 1D analytical model predicted partial transport, neglecting any backwater effect. On the LCB riffle crest, the numerical models predicted partial transport driven by vertical convergence, whereas the 1D analytical method only predicted intermittent transport. Very little difference in quantitative or qualitative prediction of cross-sectionally averaged shear stress was evident between the 1D and 2D numerical models. The only place in design 1 where there was significant cross-channel variability in the 2D model that could not be captured by the 1D model was in Pool 1. In that case, the center of the channel was predicted to be in partial transport and the lateral margins in intermittent transport (Fig. 5c).

Test Design 2

For test design 2, the 1D analytical method performed very poorly at 8.5 m^3/s, predicting the wrong sediment transport regime at three of the four cross-sections, with the fourth one barely correct (Table 3; Fig. 10a). The 1D and 2D numerical models yielded similar outcomes everywhere except the TOR exit, where the 1D model predicted intermittent transport and the latter predicted partial transport. The smoothed averaging using the 2D model, performed poorly at this location relative to the nodal averaging method for estimating Shields stress. Looking at the spatial pattern of Shields stress predicted by the 2D model (Fig. 7c), the 2D model predicts a significant zone of full bed mobility on the riffle crest and along the left bank. Partial transport is predicted in the horseshoe (in plan view) convergence zone along the right bank.

At 170 m^3/s, the numerical models continued to predict the maximum shields stress corresponding to partial transport over the TOR crest, while the 1D analytical method predicted the maximum over Pool One (Table 4; Fig. 10b). The 1D analytical method predicted the same sediment transport regime as the numerical models in two of four cross-sections, but the magnitude of Shields stress in the TOR exit was close to the lower threshold for partial transport. The difference in cross-sectionally averaged conditions between 1D and 2D models was diminished at the high discharge. The spatial pattern of Shields stress predicted by the 2D model showed the same lateral variation as seen in design 1, but with full mobility in the channel center and partial transport along the banks (Fig. 8c).

Habitat Quality Prediction

The governing habitat suitability equations (equations 8 and 9) are best-fit functions and highly nonlinear, yielding dramatic differences between the hydraulic models in the assessment of habitat quality for Chinook spawning. Lumping all cross-sections for both test designs, the mean and median differences in predicted GHSI between the 1D analytical method and the 2D model were 118 and 73 %, respectively. Only two of 10 comparisons had less than a 20 % difference in GHSI. Comparing the 1D and 2D models similarly, the mean and median differences of GHSI were 38 and 27 %, respectively. Only one of 10 comparisons had less than a 5 % difference in GHSI. Even using broad quality classes did not help diminish the differences between test methods, with seven out of ten locations misclassified by the 1D analytical method. In comparison, three out of ten locations were classified differently between the 1D and 2D models. Most importantly, the 1D analytical method and 1D model both consistently predicted significantly higher quality of physical habitat than the 2D model.

Differences in GHSI predictions between methods varied about the same as those for Shields stress between the two test designs. The mean difference between the 1D analytical method and 2D model was 3.9 times higher for design 2 than for design 1. Similarly, that between the 1D and 2D models was 2.8 times higher. Median differences showed a similar effect. Overall, design 1 yielded significantly higher quality spawning habitat than design 2.

Test Design 1

For test design 1 at low discharge, the numerical models exhibited the expected longitudinal variation of cross-sectionally averaged habitat quality (i.e. riffles are higher quality and shallow pools are lower quality), while the 1D analytical and 2D smoothed averages did not (Table 1; Fig. 11a). The 1D analytical method significantly overpredicted habitat quality, because it predicted uniform, high velocities for this design. The 1D model also consistently predicted higher quality habitat than the 2D model, with the largest difference occurring for the BFR crest. The 2D model predicted the highest quality spawning habitat on the middle of the

BFR, the river right of Pool One and the LCB middle, the LCB crest, and the exit slope of the LCB crest (Fig. 4d). Low quality habitat was predicted in deepest section of Pool 1, the river left of the LCB chute, and the deepest section of Pool 2.

Test Design 2

A similar pattern of longitudinal variation in GHSI for design 2 at low flow as a function of morphological unit type was observed for the test methods as reported for design 1, but with significantly different GHSI values across methods (Table 3; Fig. 11b). The 1D analytical method predicted high quality habitat at three of four cross-sections, the 1D model predicted medium quality habitat at three of four, and the 2D model predicted medium quality habitat at two and low quality habitat at two. The 2D model's spatial pattern of GHSI for design 2 showed a paucity of high quality habitat, except for the channel margin and the entrance and exit slopes of the TOR (Fig. 7d). High quality habitat was only predicted on riffle crests and the TOR riffle exit leading to Pool 2, while medium quality habitat was predicted along the right side of the TOR. Low quality habitat was predicted along the channel margins of both pools, while very poor habitat was predicted in the center of both pools.

DISCUSSION

The focus of this paper was evaluating the hydraulic predictions associated with three test methods using two different riffle-pool unit types at two different discharges to determine what impact method choice has on sediment transport regime and physical habitat quality predictions relevant for river rehabilitation design evaluation. The results illustrate not only the differences between the test methods, but also how different riffle-pool morphologies function in a straight channel with no floodplain connectivity.

Evaluation of Hydraulic Predictions

Considering known patterns of water surface and velocity profiles over riffle and pool sequences, methodologies and tools to assess said features should at least account for general trends found in the stream-wise direction. For example, based on common observation, when discharge is at or below bankfull, flow over riffles should be shallow and fast, while over pools it should be deep and slow. During rising floods, as the ratio of water depth to local bed variation decreases, water surface slope, depth, and velocity should become more uniform. At the very least, tools used to assess channel hydraulics over riffles and pools for any purpose should capture these basic traits. In this study, the test designs represented two different types of channel morphologies- one with features generally orthogonal to the channel banks and one with a single large feature oblique to the channel banks. The topographical setting of these designs had a direct impact on the performance of each approach to represent channel hydraulics and thus, they are discussed individually.

The key result consistently observed in this study was that the 1D analytical method performed poorly at predicting depth and velocity. This divergence in predictive capability between analytical and numerical methods lay in the ability of each approach to properly account for complex flow dynamics resulting from channel non-uniformities associated with riffle-pool units common to gravel-bed rivers. Complex hydraulics involve convective accelerations and decelerations at the scale of the entire cross-section (i.e. those due to channel-wide narrowing and widening or channel deepening and shallowing between cross-sections) as well as those at the sub-section scale (i.e. a slice of an oblique feature, a boulder cluster, a small gravel bar, etc).

Neither of these scales of variation is accounted for in the 1D analytical method. Only the former is accounted for in a 1D numerical model. A 2D model can account for both of these realities.

The comparison of 1D and 2D numerical models found that they both yielded the same longitudinal patterns in cross-sectionally averaged hydraulic variables. The values for these variables were close enough that there was no objective way to determine which was more correct in the absence of observational data for a real stream. However, the fact that the predictions for design 2, with its complex oblique morphology, had larger differences than those for design 1, suggests that the 1D model was the one that was deficient in that case. For the low-flow test, the velocity vectors predicted by the 2D model showed strong convergence and divergence at the sub-section scale as well as two sizable whirlpools- all between the cross-sections where the two models were compared. The whirlpools were large enough that sediment in transport could deposit there and fish searching for desirable adult holding habitat could choose to rest there. We have even observed fish building “backwards” redds on the Yuba River, where whirlpools create adequate upstream velocities. In the high-flow test, the 2D model showed very strong lateral velocity gradient for the TOR design, so it is likely that the 1D model’s simple average was in error in that case.

Sediment Transport Regime Prediction

The ability of the different test methods to predict Shields stress and sediment transport regime varied strongly and was different between the two test designs. Even though 1D analytical methods are the dominant approach used to estimate Shields stress in a wide range of fluvial geomorphic applications, including habitat assessments, flood impact assessments, and landscape evolution models, this study found that more than half of the cross-sections were misidentified for their sediment transport regime. The worst Shields stress value predicted using the 1D analytical model was off by 1450 %, while the best was off by 8 %, creating large uncertainty. Also, while the 1D numerical model performed well overall, it was unable to correctly identify the special risk of erosion associated with convergent, horseshore-shaped (in plan view) riffle exits where knickpoint migration can lead to systemic failure of gravels placed in any curved morphology, such as the commonly used chevron, which has two downstream converging horseshoes- one along either bank. Many riffles in natural are associated with oblique bars that also have convergent, horseshoe-shaped locations along their riffle exits.

Physical Habitat Prediction

Physical habitat quality is a common metric for predicting fish utilization of instream channel units. While this approach does not capture all relevant parameters (e.g. bioenergetics, temperature, predation, and water quality), it does provide an objective basis for assessing competing methods to predict channel hydraulics. Physical spawning habitat should exhibit longitudinal variations that correspond with riffle and pool topography, with riffle sections having a higher quality habitat than pools. Both numerical models showed that pattern, while the 1D analytical method did not. However, the 1D approaches consistently overpredicted habitat quality relative to the 2D model. Also, relative to their ability to predict Shield stresses, both 1D approaches performed worse at predicting GHSI values, likely due to the highly nonlinear nature of the empirical functions describing habitat conditions. Since fish species in any freshwater lifestage are capable of distinguishing and utilizing laterally isolated pockets of habitat, the unique ability of the 2D model to resolve those features, as demonstrated for both design morphologies tested (Figs. 4d, 7d), is notable and useful for design evaluation. Even though 3D models can further resolve vertical velocity gradients that we have observed fish utilize, we are not aware of any habitat suitability metric for velocity that is available in 3D at this time, nor does it seem cost-effective or likely that biologists will pursue that capability in the near future.

Broad Flat Riffles

The broad flat riffle, as the name implies, is a uniformly graded riffle that has cross sectional symmetry about its midpoint. Consequently, it is a frequently used feature in SHR for its apparent ease in design, evaluation, and constructability. However, this study shows that broad flat riffles do not exhibit the hydraulic uniformity assumed in many designs, especially over the crest of the structure. Consequently, even using the 1D analytical method at BFR's is highly problematic. This is illustrated by comparing predictions for the cross sections at the middle and crest of the BFR in design 1 (Fig. 1, first two cross-sections). Both numerical models show the flow accelerating toward the crest, which the 1D analytical method does not (Fig. 3a). Consequently, the 1D analytical method underpredicted Shields stress on the BFR crest. In the high-discharge test, the BFR crest was predicted by the numerical models to be in the upper range of partial transport, whereas the 1D analytical method barely predicted partial transport at all (Fig. 9b). Even at low flow, the numerical models predict moderate intermittent transport, which for freshly placed, loose gravels could actually correspond with partial transport, not intermittent transport. These considerations explain why commonly built BFR's with uniform gravels fail rapidly, even though designers do not expect them to. To make matters worse, both 1D methods predicted high spawning habitat quality over the BFR crest, whereas the 2D model predicted medium quality habitat there. This explains why designers are likely to think that

BFR's are more desirable than they end up being. We have heard several anecdotal stories by SHR project managers that BFR projects failed to be used by fish after being built. Overall, use of the 1D analytical method overpredicts habitat quality and channel stability, and thus leads to an overvaluing of broad flat riffles in SHR design.

Comparison of Design Features

The two different designs tested in this study have been pointed out to differ in the orientations of their features relative to the channel banks. Both the BFR and the LCF were orthogonal to channel banks, while the TOR was oblique to them. This difference resulted in the 1D methods performing worse than the 2D model in characterizing the conditions at the TOR, because such bed features invoke flow patterns that are predominantly controlled by local bar topography (Whiting and Dietrich, 1991). Many natural and artificial riffles have oblique features, and thus it is evident from this study that they need to be analyzed using a 2D model, even to obtain accurate cross-sectionally averaged predictions, let alone to characterize sub-section variability. Without a 2D model, it would not be possible to evaluate the risk posed by convergent, horseshoe-shaped riffle exits to riffle stability.

Another important distinction between design 1 and design 2 is that design 1 involved a "blanket" fill approach that entails placement of a moderate amount of gravel everywhere, whereas design 2 was an accentuated fill involving most gravel being placed on the riffle crests. The advantage of accentuating topography as in design 2 is that it creates much more complex hydraulics and thus more diverse habitats. Each freshwater lifestage of a fish species has different needs, and design 2 is more likely to have habitat for all lifestages. However, design 2 not only imposed prediction-based problems, but the results of this study suggest that design 2 would not be geomorphically stable. One reason for that is that the channel has uniform width, and thus it is highly improbable that a stage-dependent reversal in cross-sectional area, velocity, and Shields stress between riffles and pools can be established to maintain channel relief (MacWillians et al., 2006). No such reversal was evident in the test at 170 m^3/s, which was 20 times higher than the low-flow test. The other reason is that the steep drop-off at each riffle exit inevitably creates excessive velocities and localized bed scour. This can cause knickpoint migration that can quickly cut through the entire feature. Such an effect was observed for the 2001 project site on the lower Mokelumne River (Merz et al., 2006) when less gravel was provided than called for bythe design of Wheaton et al. (2004b), resulting in a steep, horse-shoe shaped riffle exit at the downstream end of the project site. For the actual SHR project on the Trinity River, a thorough analysis was done for three different accentuated-relief designs and three different blanket-fill designs. In the end, the selected design was a blanket-fill morphology using one broad flat riffle and two L-shaped bars. Details of all these designs and their evaluations are available at http://shira.lawr.ucdavis.edu/trinity.htm.

Implications to SHR Design and Decision Making

Decision making for river management often relies on model predictions of physical habitat to forecast potential impacts of flow regime changes as well as for evaluating potential gravel augmentation designs. In this study a sediment transport regime metric and a global habitat suitability index were used to transform quantitative hydraulic predictions into relevant qualitative descriptors of geomorphic and ecologic conditions. Deviations in hydraulic predictions led to contrasting results for section-average Shields stress and GHSI for each test design, ultimately being related to whether the topography of the features initiated cross-stream flow vectors and lateral variation in stream-wise vectors that deviated from cross-sectionally averaged estimates.

Manning's equation and other analytical flow resistance equations are often considered adequate for engineering tasks involving open channel flows in deep channels with a high depth to bed-feature height ratio (>100-1000 as a conservative estimate). In this study, that ratio ranged from ~1-10. The results of this study show that for shallow gravel-bed rivers with complex morphologies, including common river rehabilitation design structures of simple geometry, the 1D analytical method is inappropriate for estimating depth and velocity. These limitations can be further assumed to affect any non-uniform channel section with a width to depth ratio in this range, and probably up to at least 50. Despite this inadequacy, there is a practice of "fine-tuning" Manning's equation using detailed accounting of roughness in the channel and velocity-profile effects. The benefits of these and other attempts to bend Manning equation to fit the desire for a simple method are unlikely to be of use for SHR design evaluation.

The results of this study suggest that a river manager, policy maker, scientist, or engineer faced with evaluating the effect of a potential gravel augmentation design, a channel modification, or a flow regime change on physical habitat would come to very different conclusions depending on whether the hydraulics of the channel were evaluated using Manning's equation or a 1D or 2D numerical model. The quality of spawning habitat was consistently over predicted by 1D methods. Moreover, considering reach scale (10^2-10^3 channel widths) averages of spawning habitat quality by averaging GHSI among sections for both designs, 1D methods still grossly over-predict habitat such that medium and low quality habitat would be predicted as high quality habitat. As 1D reach-scale approaches to physical habitat are the most prevalent, this could lead decision makers to believe that existing and proposed physical habitat is of higher quality and quantity, leading to false conclusions about river health. Considering the rapid decline of salmonids despite the known linkages to habitat degradation, it is not implausible to postulate these over-predictions of existing and proposed physical habitat have already manifested themselves into key management plans of gravel bed rivers and dam re-licensing.

Predictions regarding channel stability and sediment transport would be impacted as well from using analytical or numerically based tools. Under predicting Shields stress over riffle crests could be catastrophic to SHR based gravel augmentation as knickpoint migration at the riffle crest could lead to systemic failure, especially for a sequence of riffle crests, which could experience a "reverse domino" toppling of bedforms (Pasternack et al., in press). Moreover, small areas of high stress may be present that no section averaged approach can capture. Failure to identify these areas could also lead to riffle failure.

CONCLUSIONS

Typical goals of most spawning habitat rehabilitation projects involve increasing quantity and quality of one or more life stages of a species. Placed gravels must be stable during low discharges to avoid embryo mortality and have some sediment transport at high discharges to rejuvenate gravels by removing aquatic vegetation and interstitial fines. Generally speaking, a project is considered successful if the number of redds and consequent fry production increases and the project is stable during the spawning and incubation seasons, with some transport during large flow events after incubation. Therefore, the evaluation of potential designs rests on two key parameters- sediment transport regime and physical habitat quality. In this study, three methods were tested against two different channel morphologies at two different discharges.

Numerical models captured the general stream-wise hydraulics associated with riffles and pools that a 1D analytically method could not predict. Failure to account for convective accelerations within and between riffles and pools explains why the 1D analytical method was wrong in most of its predictions. Although 1D and 2D numerical predictions of cross-sectionally averaged values had good agreement for both designs at both discharges, significant variations in between cross-sections and at the sub-section scale were not resolved by the 1D model. For example, the 2D model properly predicted the presence of whirlpools and zones of convergent flow in horseshoe-shaped riffle exits. For spatially distributed phenomena such as patterns of sediment erosion and fish habitat quality, it is highly recommended that 2D models be used to resolve lateral variations, without which 1D models appear to over-predict habitat quality, affecting long-term river management policies and practices.

ACKNOWLEDGEMENTS

Financial support for this work was provided by USBR Award #03FG230766 and USFWS Agreement DCN#113322G003 awarded by CALFED. We gratefully thank and acknowledge Eve Elkins, Marisa Escobar, Peng Gao, Mark Grismer, Joe Merz, Hamish Moir, Jeff Mount, and Joe Wheaton for their input on this manuscript. We thank Michael Bounrisavong and Kaushal Parikh for their help on technical modeling issues. We thank Carlos Alvarado, Evan Buckland, Cameron Poya, and Dave Van Herick for field assistance.

REFERENCES

Bates PD, Anderson MG, Baird L, Walling DE, Simm D. 1992. Modeling floodplain flow with a two-dimensional finite element scheme *Earth Surface Processes and Landforms* **17**: 575-588.

Bjornn TC, Reiser DW. 1991. Habitat requirements of salmonids in streams. In *Influences of forest and rangeland management on salmonid fishes and their habitats*, Meehan WR. (Ed). *American Fisheries Society Special Pubication*. **19**: 83-138.

Bovee K D, Lamb BL, Bartholow JM, Stalnaker C.B, Taylor J, and Henriksen, J. 1998. Stream habitat analysis using the instream flow incremental methodology. *United States Geological Survey, Information and Technology Report USGS/BRD/ITR-1998-0004*. Fort Collins, CO.

Brown RA, Pasternack, GB. 2008. Engineered Channel Controls Limiting Spawning Habitat Rehabilitation. *Geomorphology* **97**: 631-654. .

Brunner GW. 1998. HEC-RAS: River Analysis System. *Unpublished Users Manual, Version 2.2*. U.S. Army Corps of Engineers: CA.

Carling P A. 1991. An appraisal of the velocity-reversal hypothesis for stable pool-riffle sequences in the River Severn, England. *Earth Surface Processes and Landforms* **16**: 19-31.

California Department of Fish and Game. 1998. *California Salmonid Stream Habitat Restoration Manual*. 3rd edition.

California Department of Water Resources. 2000. *Merced River Robinson-Gallo Project - Ratzlaff Reach Engineering Report*.

Cao Z. and Carling PA. 2002. Mathematical modeling of alluvial rivers: reality and myth. Part 1: general overview. *Water and Maritime Engineering*, **154**: 207-219.

Cao Z, Carling P, Oakey R. 2003. Flow Reversal over a Natural Pool-Riffle Sequence: A Computational Study. *Earth Surface Processes and Landforms* **28**: 689-705.

Chang HH. 1998. *Fluvial Processes in River Engineering*. John Wiley and Sons: New York, NY,

Clifford NJ, Richard KS. 1992. The Reversal Hypothesis and the Maintenance of Riffle-Pool Sequences: A Review and Field Appraisal. In *Lowland Floodplain Rivers: Geomorphological Perspectives*, Carling, PA, Petts J. (Eds). Wiley and Sons: USA.

Darby SE, Van de Wiel MJ. 2003. Models in fluvial geomorphology. In *Tools in fluvial geomorphology*, Kondolf, GM. Piégay, H (Eds). Wiley: Chichester.

Dunne T, Leopold LB. 1987. *Water in Environmental Planning*. W. H. Freeman: San Francisco, CA.

Elkins EM, Pasternack GB, Merz, JE. 2007. The use of slope creation for rehabilitating incised, regulated, gravel-bed rivers. *Water Resources Research* **43.** DOI:10.1029/2006WR005159.

Fischer HB, List JE, Koh CR, Imberger J., Brooks, NH. 1979. *Mixing in Inland and Coastal*

*Waters***.** Academic Press, Inc: New York, NY.

French JR, and Clifford NJ. 2000. Hydrodynamic modeling as a basis for explaining estuarine environmental dynamics: some computational and methodological issues. *Hydrological Processes* **14**: 2089-2108.

Froehlich DC. 1989. HW031.D - Finite Element Surface-Water Modeling System: Two-Dimensional Flow in a Horizontal Plane-Users Manual. *Federal Highway Administration. Report FHWA-RD-88-17.* Federal Highway Administration: Washington DC.

Gard M. 2006. Modeling changes in salmon spawning and rearing habitat associated with river channel restoration. *International Journal of River Basin Management.* **4**: 1-11.

Ghanem A, Steffler P, Hicks F. 1996. Two-dimensional hydraulic simulation of physical habitat conditions in flowing streams. *Regulated Rivers Research and Management* **12**: 185-200.

Graf WL. 2001. Damage Control: Dams and the Physical Integrity of America's Rivers. *Annals of the Association of American Geographers* **91**: 1-27.

Harper D, Ebrahimnezhad M, Cot FCI. 1998. Artificial riffles in river rehabilitation: setting the goals and measuring the successes. *Aquatic Conservation-Marine and Freshwater Ecosystems* **8**: 5-16.

Harrison, LR, Keller EA. Modeling forced pool--riffle hydraulics in a boulder-bed stream, southern California.*Geomorphology* **83**: 232-248

Hunter CJ. 1991. *Better Trout Habitat: A Guide to Stream Restoration and Management.* Montana Land Alliance. Island Press: New York. NY.

Keller EA. 1971. Areal sorting of bed-load material; the hypothesis of velocity reversal. *GSA Bulletin* **82**: 753-756.

Keller EA. Florsheim JL. 1993. Velocity-Reversal Hypothesis: A Model Approach. *Earth Surface Processes and Landforms* **18**: 733-740.

Knighton, A.D., 1998. Fluvial Forms and Processes: A New Perspective. Arnold, London.

Kondolf GM, Vick JC, Ramirez TM. 1996. Salmon spawning habitat rehabilitation on the Merced River, California: An evaluation of project planning and performance. *Transactions of the American Fisheries Society* **125**: 899-912.

Kondolf GM. 2000. Some suggested guidelines for geomorphic aspects of anadromous salmonid habitat restoration proposals. *Restoration Ecology* **8**: 48-56.

Lacey RW, Millar RG. 2004. Reach scale hydraulic assessment of instream salmonid habitat restoration. Journal of the AmericanWater Resources Association 40: 1631–1644.

Leclerc M, Boudreault A, Bechara JA, Corfa G. 1995. 2-Dimensional Hydrodynamic Modeling - a Neglected Tool in the Instream Flow Incremental Methodology. *Transactions of the American Fisheries Society* **124**: 645-662.

Leopold LB, Wolman MG, Miller JP. 1964. *Fluvial Processes in Geomorphology*. W.H. Freeman and Company: San Francisco, CA.

Lisle T. 1979. A sorting mechanism for a riffle-pool sequence. *Geological Society of America Bulletin* **11**: 1142-1157.

Lisle TE, Nelson JM, Pitlick J, Madej MA, Barkett BL. 2000. Variability of bed mobility in natural, gravel-bed channels and adjustments to sediment load at local and reach scales. *Water Resources Research* **36**: 3743-3755.

MacWilliams ML, Wheaton JM, Pasternack GB, Kitanidis PK, Street, RL. 2006. The Flow Convergence-Routing Hypothesis for Pool-Riffle Maintenance in Alluvial Rivers. *Water Resources Research* **42**, W10427, doi:10.1029/2005WR004391.

Maddock I, 1999. The importance of physical habitat assessment for evaluating river health. *Freshwater Biology* **41**.

McBain, S, Trush, B. 2003. *Trinity River Coarse Sediment Management Plan*.

Merz JE, Setka JD. 2004. Evaluation of a Spawning Habitat Enhancement Site for Chinook Salmon in a Regulated California River. *North American Journal of Fisheries Management*: **24**, 397–407.

Merz JE, Pasternack GB, Wheaton JM. 2006. Sediment Budget for Salmonid Spawning Habitat Rehabilitation in the Mokelumne River. Geomorphology: **76**, 207-228.

Merz JE, Pasternack GB, Wheaton JM. 2004. Predicting benefits of spawning habitat rehabilitation to salmonid fry production in a regulated California river. *Canadian Journal of Fisheries and Aquatic Science*, **61**:1433-1446.

Milhous RT, Updike M, Schneider DM. 1989. Physical Habitat Simulation System Reference Manual - Version II. *U.S. Fish and Wildlife Service Instream Flow Information Paper No. 26*. Fort Collins, CO.

Milne, JE. 1982. Bed-material size and the riffle-pool sequence. *Sedimentology* **29**: 267–278.

Miller AJ, Cluer BL. 1998. Modeling considerations for simulation of flow in bedrock channels. In *Rivers Over Rock: Fluvial Processes in Bedrock Channels*, Wohl EE, Tinkler KJ (Eds). American Geophysical Union: Washington, DC; 61–104.

Moir, HJ, Pasternack, GB. 2008. Relationships between mesoscale morphological units, stream hydraulics and Chinook salmon (Oncorhynchus tshawytscha) spawning habitat on the Lower Yuba River, California. *Geomorphology*. doi:10.1016/j.geomorph.2008.02.001

Nation Research Council. 1992. *Restoration of Aquatic Ecosystems: Science, Technology, and Public Policy*. NRC committee on Restoration of Aquatic Ecosystems, Washington, DC.

Nelson JM, Bennett JP, Wiele SM. 2003. Flow and sediment-transport modeling. In *Tools in fluvial geomorphology*, Kondolf GM, Piégay, H (Eds). Wiley, Chichester, 539-576.

Newbury R, Gaboury M, Bates D. 1997. Restoring Habitats in Channelized or Uniform Streams Using Riffle and Pool Sequences. Chapter 12. *Fish Habitat Rehabilitation Procedures. Watershed Restoration Technical Circular No. 9*. British Columbia Watershed Restoration Program: Vancouver, BC

Pasternack GB, Bounrisavong MK, Parikh KK. 2008. Backwater Control on Riffle-Pool Hydraulics, Fish Habitat Quality, and Sediment Transport Regime in Gravel-Bed Rivers. *Journal of Hydrology* **357**:1-2:125-139.

Pasternack GB, Wang CL, Merz J. 2004. Application of a 2D hydrodynamic model to reach-scale spawning gravel replenishment on the lower Mokelumne River, California. River Research and Applications **20**: 205-225.

Pasternack GB, Gilbert AT, Wheaton JM., Buckland EM. 2006. Error Propagation for Velocity and Shear Stress Prediction Using 2D Models For Environmental Management. *Journal of Hydrology* **328**:227-241.

Rathburn S. Wohl EE. 2003. Predictimg Fine Sediment Dynamics along a Pool-Riffle Mountain Channel. *Geomorphology* **55**: 111-124.

Richards KS. 1976. The Morphology of Riffle-Pool Sequences. *Earth Surface Processes and Landforms* **1**: 71-88.

Rosgen D. 1996. *Applied River Morphology*. Wildland Hydrology: Pagosa Springs, CO.

Saldi-Caromile K, Bates K, Skidmore P, Barenti J, Pineo D. 2004. *Stream Habitat Restoration Guidelines: Final Draft.* Washington Departments of Fish and Wildlife and Ecology and the U.S. Fish and Wildlife Service: Olympia, Washington.

Sawyer AM, Pasternack GB, Merz JE, Escobar M., Senter AE. 2008. Construction constraints on geomorphic-unit rehabilitation on regulated gravel-bed rivers. *River Research and Applications*. doi: 10.1002/rra.1173.

Sear DA. 1996. Sediment transport processes in pool-riffle sequences. *Earth Surface Processes and Landforms* **21**: 241-262.

Shields FD, Copeland RR, Klingeman PC, Doyle, MW, Simon A. 2003. Design for stream restoration. *Journal of Hydraulic Engineering* **129**: 575-584.

Slaney PA, Zaldokas D. 1997. *Fish Habitat Rehabilitation Procedures*. Watershed Restoration Technical Circular No. 9. Ministry of Environment Lands and Parks: Vancouver, BC

Smith AK. 1973. Development and application of spawning velocity and depth criteria for Oregon salmonids. *Transactions of the American Fisheries Society* **102**: 312-316.

Thompson DM, Wohl EE, Jarrett RD. 1999. Velocity reversals and sediment sorting in pools and riffles controlled by channel constrictions. *Geomorphology* **27**: 229-241.

Torgersen CE, Price DM, Li HW, McIntosh BA. 1999. Multiscale thermal refugia and stream habitat associations of chinook salmon in northeastern Oregon. *Ecological Applications* **9**: 301–319.

Trush WJ, McBain SM, Leopold L B. 2000. Attributes of an alluvial river and their relation to water policy and management. *Proceedings of the National Academy of Sciences of the United States of America* **97**: 11858-11863.

United States Fish and Wildlife Service. 1997. *Microhabitat Suitability for Anadramous Salmonids of the Trinity River*. U.S. Fish and Wildlife Service: Sacramento, CA.

United States Fish and Wildlife Service. 1999. *Trinity River Flow Evaluation*. Department of the Interior: Washington, DC.

Walker DR, Millar RG, Newbury RW. 2004. *Hydraulic design of riffles in gravel-cobble bed rivers. Journal of River Basin Management* **2**: 291-299.

Wheaton JM, Pasternack GB, Merz JE. 2004a. Spawning Habitat Rehabilitation - 1. Conceptual Approach & Methods. *International Journal of River Basin Management* **2**: 3-20.

Wheaton JM, Pasternack GB, Merz JE. 2004b. Spawning Habitat Rehabilitation - 2. Using hypothesis development and testing in design, Mokelumne River, California, U.S.A. *International Journal of River Basin Management* **2**: 21-37.

Wheaton JM, Pasternack GB, Merz JE. 2004c. Use of habitat heterogeneity in salmonid spawning habitat rehabilitation design. In *Fifth International Symposium on Ecohydraulics: Aquatic Habitats: Analysis and Restoration*. IAHR-AIRH: Madrid, Spain.

Whiting, P. J., and W. E. Dietrich, 1991, Convective accelerations and boundary shear stress over a channel bar. *Water Resources. Research* **27:** 783-796.

Wilcock PR, Kondolf GM, Matthews WV, Barta AF. 1996a. Specification of sediment maintenance flows for a large gravel-bed river. *Water Resources Research* **32**:2911-2921.

Wilcock PR, Barta AF, Shea CC, Kondolf GM, Matthews WVG, Pitlick JC. 1996b. Observations of flow and sediment entrainment on a large gravel-bed river. *Water Resources Research* **32**: 2897–2909.

Wilkinson SN, Keller RJ, Rutherfurd ID. 2004. Phase-shifts in shear stress as an explanation for the maintenance of pool-riffle sequences. *Earth Surface Processes and Landforms* **29**: 737-753.

Wohl EE, Kirk VR, Merritts DJ. 1993. Pool and Riffle Characteristics in Relation to Channel Gradient. *Geomorphology* **6**: 99-110.

Yalin MS. 1977. *Mechanics of Sediment Transport*. 2nd Ed. Peragamon.

Yen, B,C. 1991. *Channel Flow Resistance: Centennial of Manning's Formula*. Water Resources Publications: Littleton, CO.

Yoshiyama RM, Fisher FW, Moyle PB. 1998. Historical abundance and decline of chinook salmon in the Central Valley region of California. *North American Journal of Fisheries Management* **18**: 487-521.

Zeh, M., and Donni, W. 1994. Restoration of Spawning Grounds for Trout and Grayling in the River High-Rhine. *Aquatic Sciences* **56**: 59-69.

LIST OF FIGURES

Figure 1. Design topography for test design (a) one and (b) two. Note that in Design 1 the riffle crests are convergent being mostly orthogonal to the channel bank, while in Design 2 the topography of the riffle crest is transverse to the channel banks.

Figure 2. Definition sketch of geomorphic slope (Modified after Knighton, 1998). In this study the geomorphic slope is defined as the elevation difference between an upstream feature and the next downstream feature of the same type (i.e. bar or pool) divided by the distance between them.

Figure 3. Design 1 comparison plots of (a) velocity and (b) water surface elevation at 8.5 m^3/s and (c) velocity and (d) water surface elevation at 170 m^3/s. The morphological unit labels refer to cross section locations where section-averaged values of depth, velocity, Shields stress, and GHSI were compared. Lightly shaded area is region within 2 standard deviations of the mean value predicted by the 2D model. Dark shaded area represents the region under the river bed.

Figure 4. Design 1, 2D model plots of (a) depth, (b) velocity, (c) Shields stress, and (d) GHSI for 8.5 m^3/s. The vertical lines refer to cross section locations where section-averaged values of depth, velocity, Shields stress, and GHSI were compared.

Figure 5. Design 1, 2D model plots of (a) depth, (b) velocity, (c) Shields stress for 170 m^3/s. The vertical lines refer to cross section locations where section-averaged values of depth, velocity, Shields stress, and GHSI were compared.

Figure 6. Design 2 comparison plots of (a) velocity and (b) water surface elevation at 8.5 m^3/s and (c) velocity and (d) water surface elevation at 170 m^3/s. The morphological unit labels refer to cross section locations where section-averaged values of depth, velocity, Shields stress, and GHSI were compared. Lightly shaded area is region within 2 standard deviations of the mean value predicted by the 2D model. Dark shaded area represents the region under the river bed.

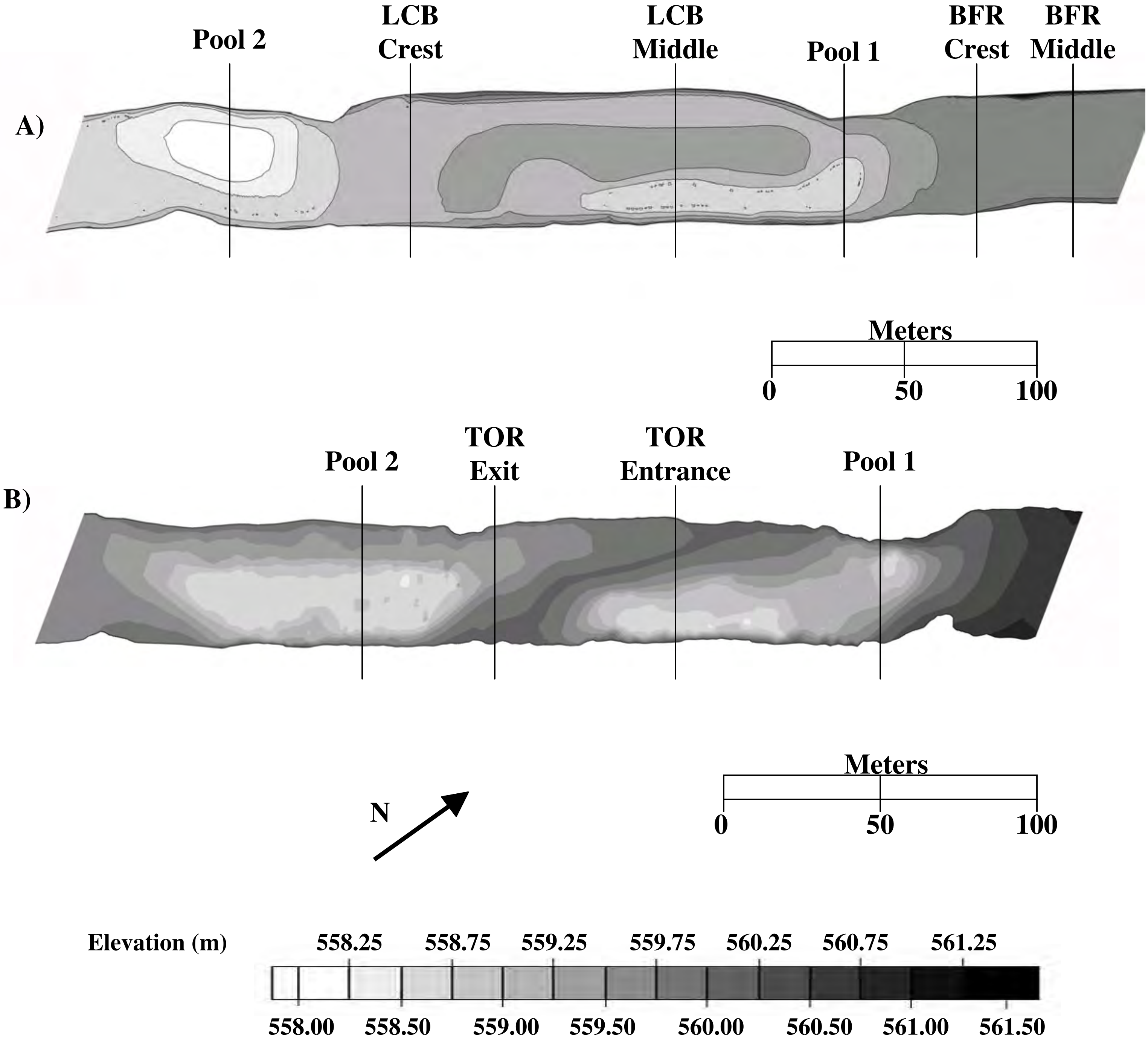
Figure 7. Design 2, 2D model plots of (a) depth, (b) velocity, (c) Shields stress, and (d) GHSI for 8.5 m^3/s. The vertical lines refer to cross section locations where section-averaged values of depth, velocity, Shields stress, and GHSI were compared.

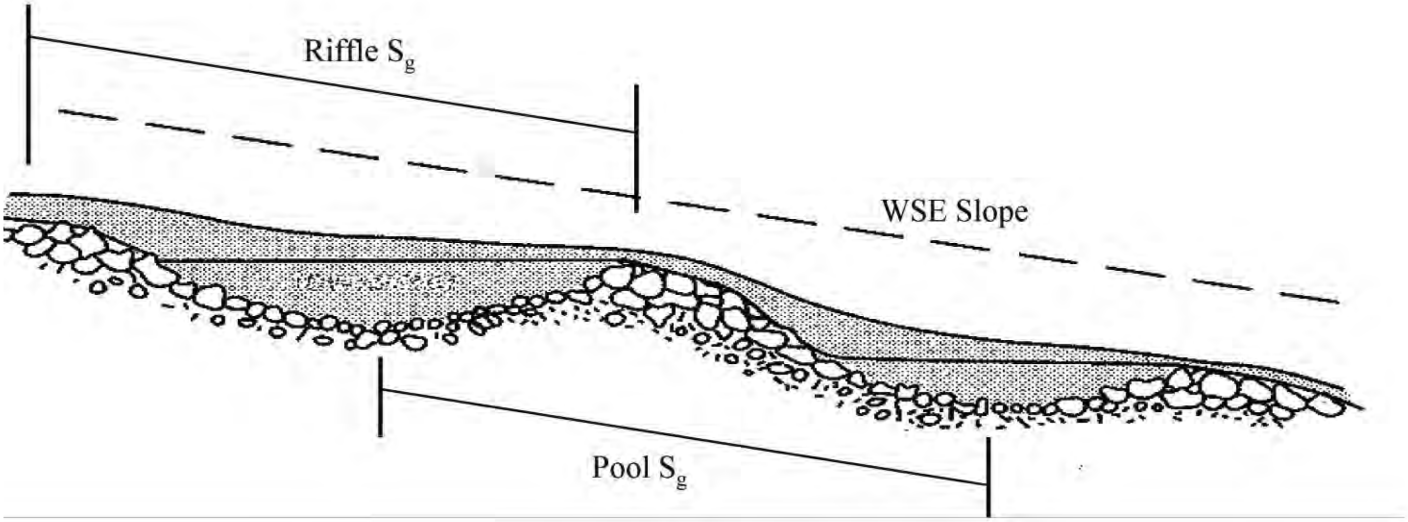
Figure 8. Design 2, 2D model plots of (a) depth, (b) velocity, (c) Shields stress for 170 m^3/s. The vertical lines refer to cross section locations where section-averaged values of depth, velocity, Shields stress, and GHSI were compared.

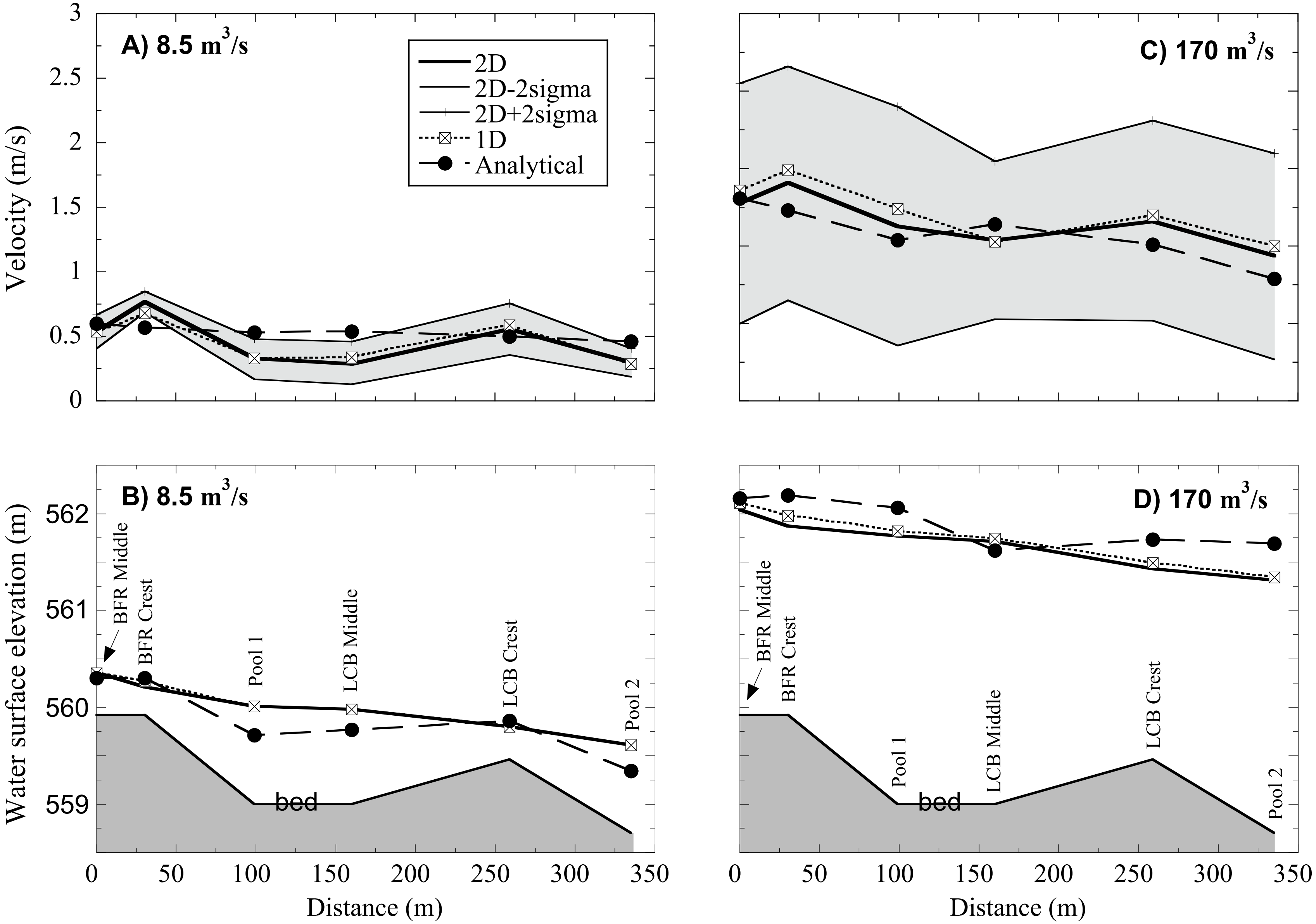
Figure 9. Design 1 comparison of Shields stress at (a) 8.5 m^3/s and (b) 170 m^3/s. The "*" results were calculated using a smoothed averaging method based on mean depth and velocity as opposed to values obtained from nodal averaging.

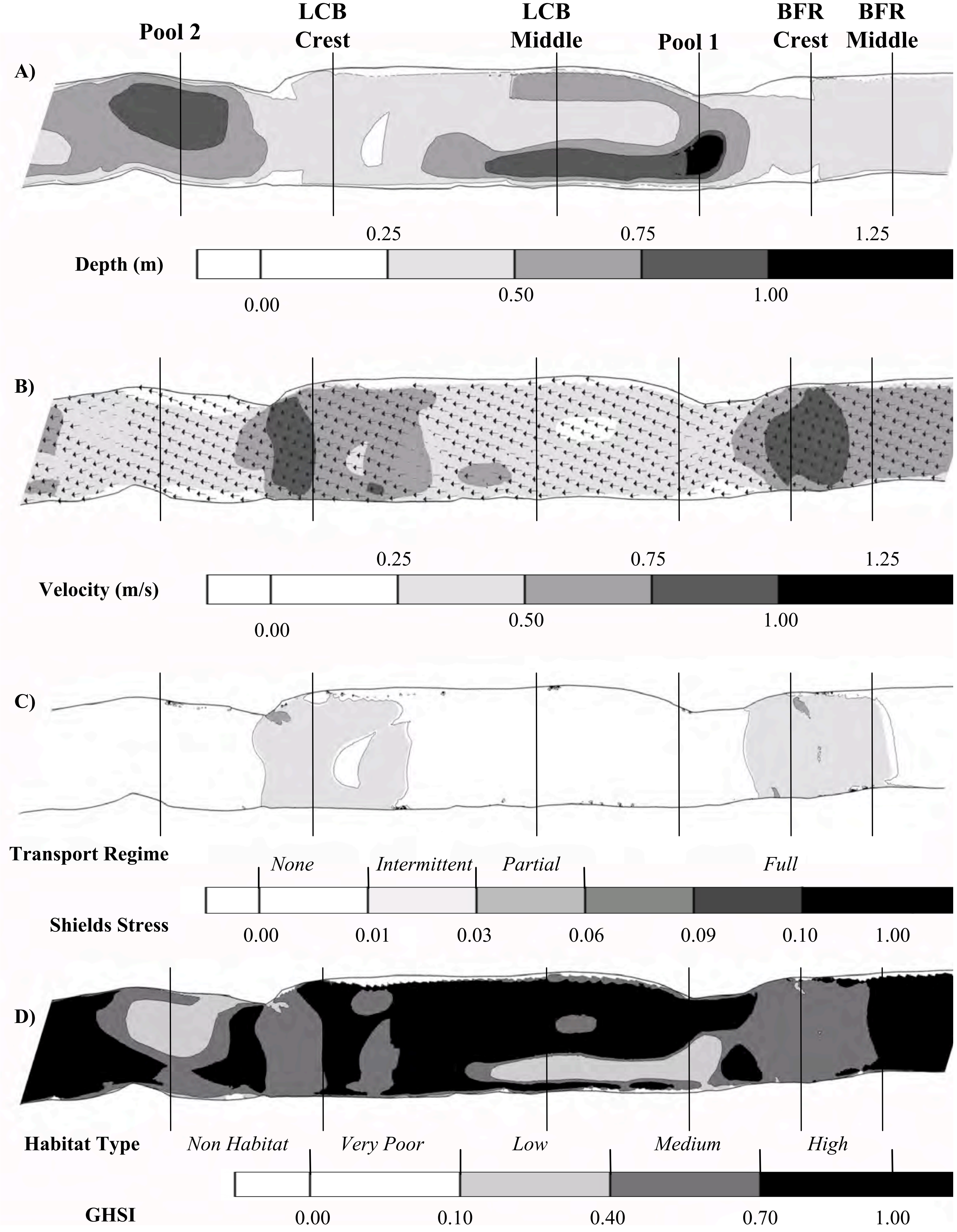
Figure 10. Design 2 comparison of Shields stress at (a) 8.5 m^3/s and (b) 170 m^3/s. The “*” results were calculated using a smoothed averaging method based on mean depth and velocity as opposed to values obtained from nodal averaging.

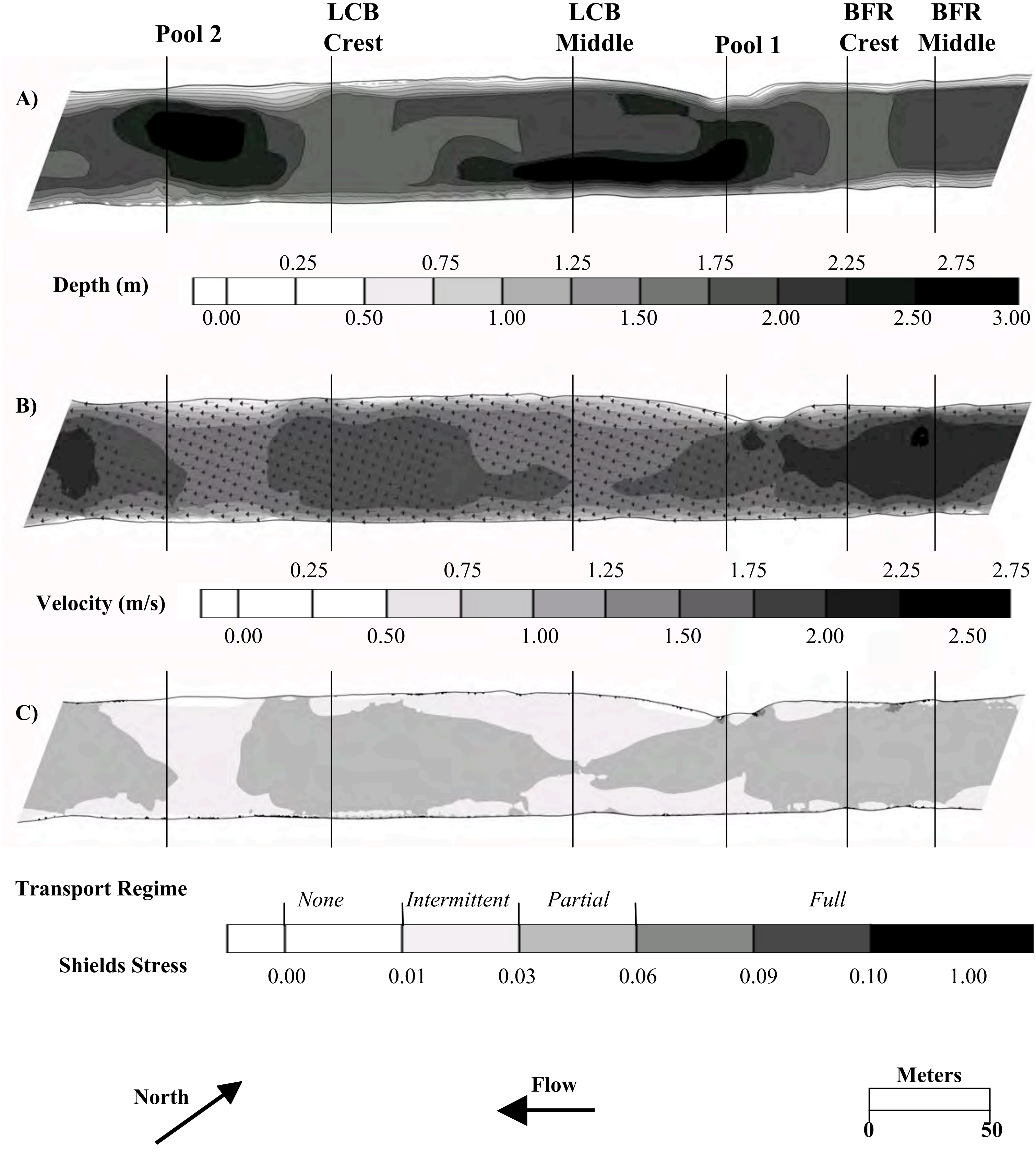
Figure 11. GHSI comparison of (a) design 1 and (b) design 2 at 8.5 m^3/s. The “*” results were calculated using a smoothed averaging method based on mean depth and velocity as opposed to values obtained from nodal averaging.

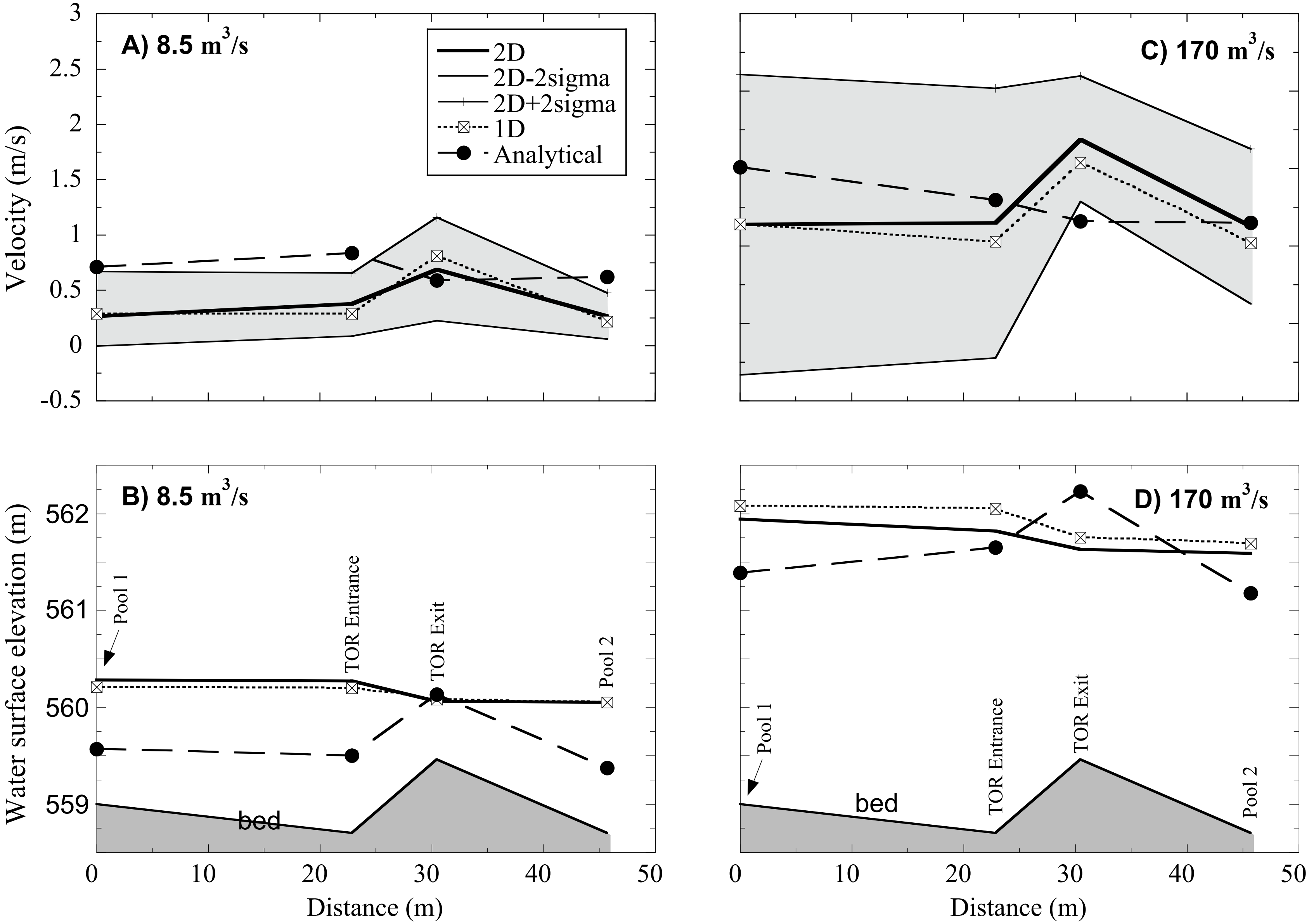

A)
Pool 2
LCB
Crest
LCB
Middle
Pool 1
BFR
Crest
BFR
Middle
Meters
0
50
100
B)
Pool 2
TOR
Exit
TOR
Entrance
Pool 1
N
Meters
0
50
100
Elevation (m)
558.25
558.75
559.25
559.75
560.25
560.75
561.25
558.00
558.50
559.00
559.50
560.00
560.50
561.00
561.50

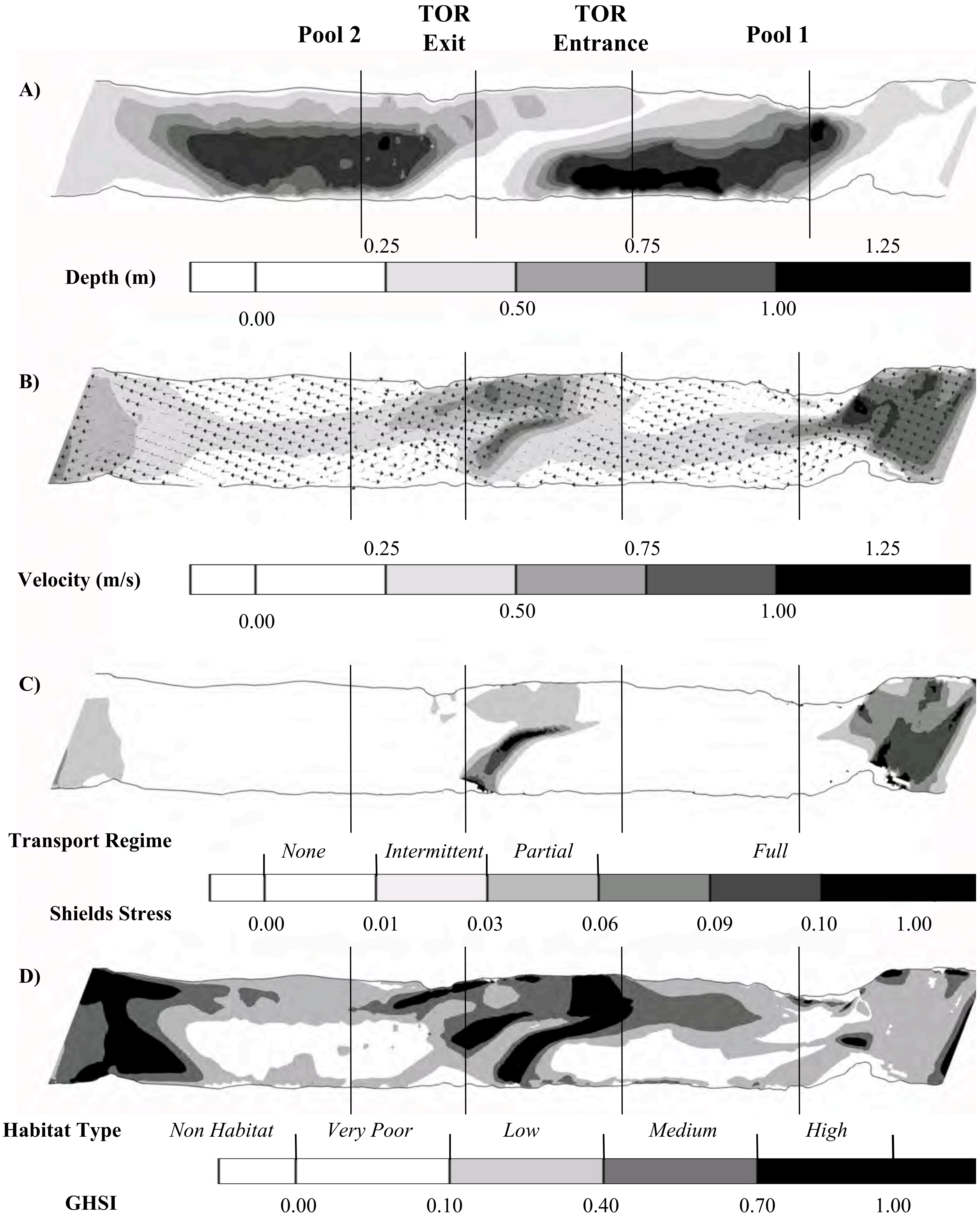

Riffle S_g
WSE Slope
Pool S_g

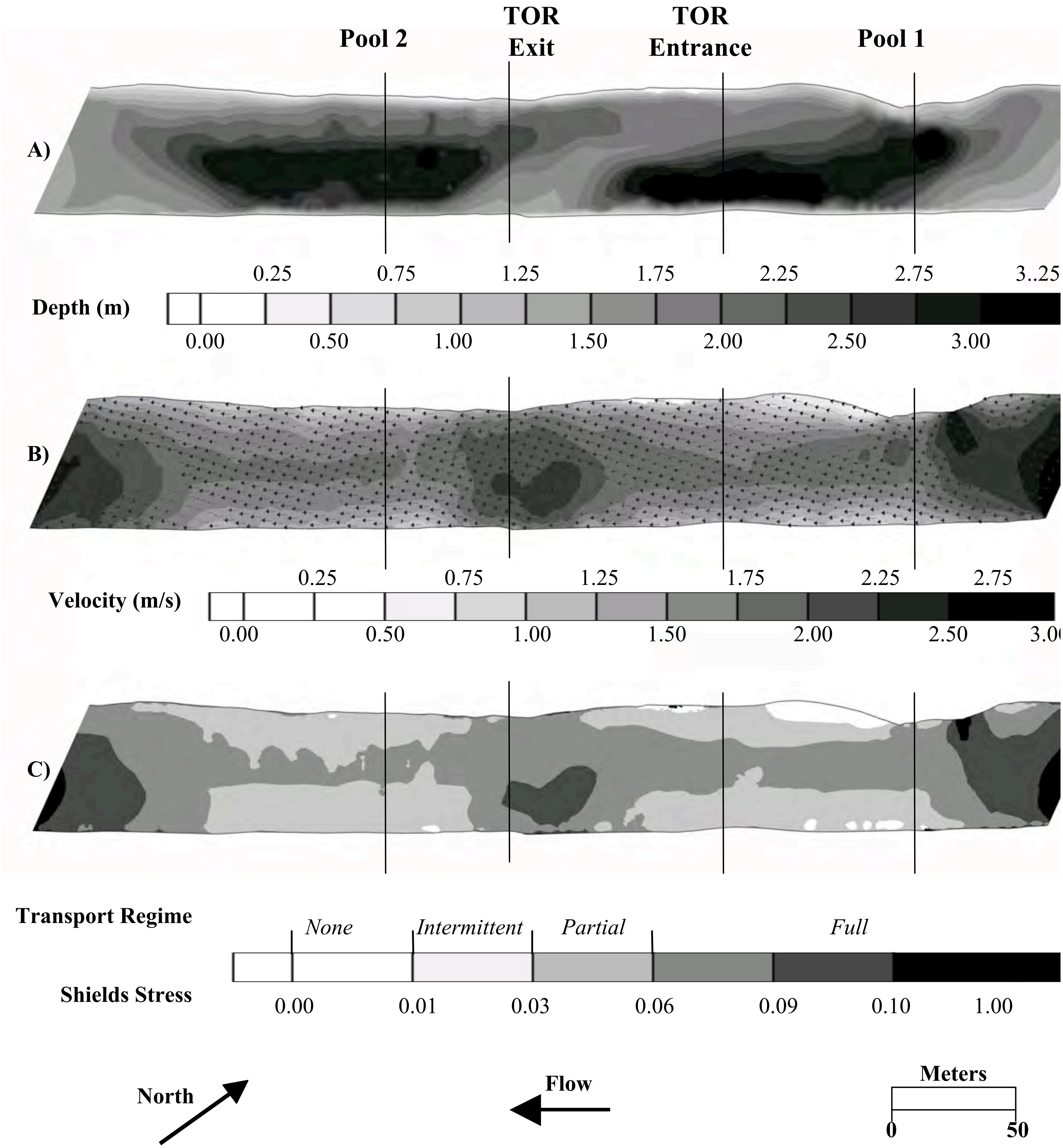

A) 8.5 m^3/s
C) 170 m^3/s
B) 8.5 m^3/s
D) 170 m^3/s
2D
2D-2sigma
2D+2sigma
1D
Analytical
Velocity (m/s)
Water surface elevation (m)
Distance (m)
0
0.5
1
1.5
2
2.5
3
559
560
561
562
0
50
100
150
200
250
300
350
BFR Middle
BFR Crest
Pool 1
LCB Middle
LCB Crest
Pool 2
bed

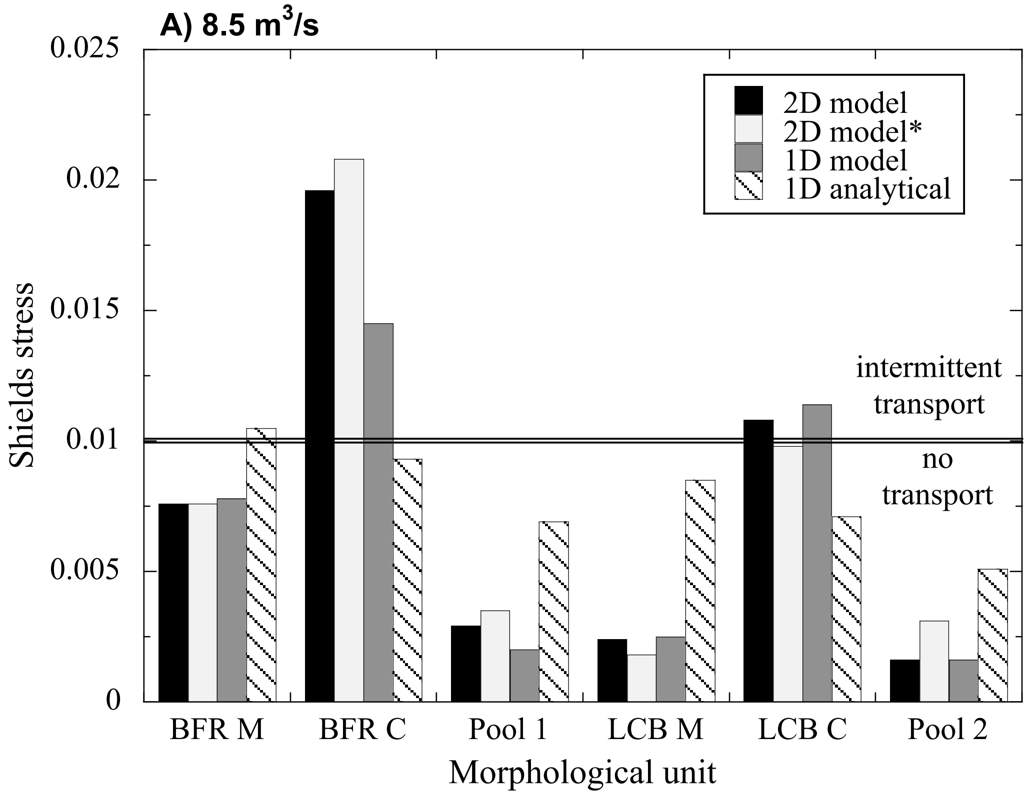

Pool 2
LCB Crest
LCB Middle
Pool 1
BFR Crest
BFR Middle
A)
Depth (m)
0.25
0.75
1.25
0.00
0.50
1.00
B)
Velocity (m/s)
0.25
0.75
1.25
0.00
0.50
1.00
C)
Transport Regime
None
Intermittent
Partial
Full
Shields Stress
0.00
0.01
0.03
0.06
0.09
0.10
1.00
D)
Habitat Type
Non Habitat
Very Poor
Low
Medium
High
GHSI
0.00
0.10
0.40
0.70
1.00

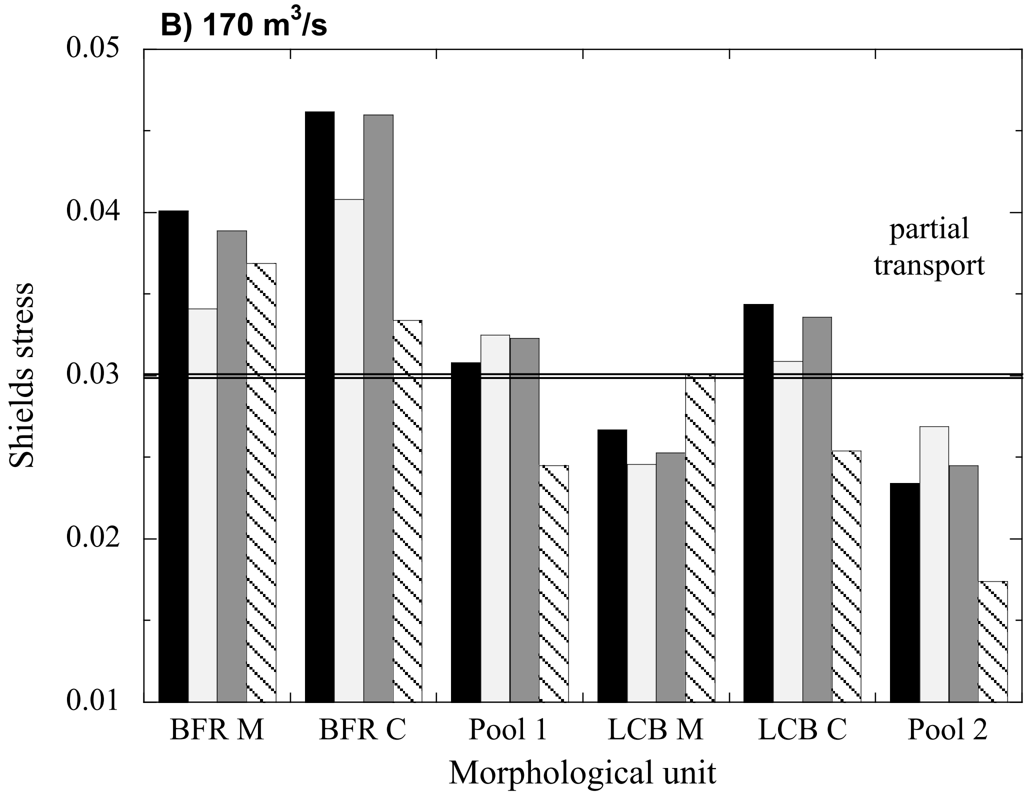

Pool 2
LCB Crest
LCB Middle
Pool 1
BFR Crest
BFR Middle
A)
Depth (m)
0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00 2.25 2.50 2.75 3.00
B)
Velocity (m/s)
0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00 2.25 2.50 2.75
C)
Transport Regime
None
Intermittent
Partial
Full
Shields Stress
0.00 0.01 0.03 0.06 0.09 0.10 1.00
North
Flow
Meters
0
50

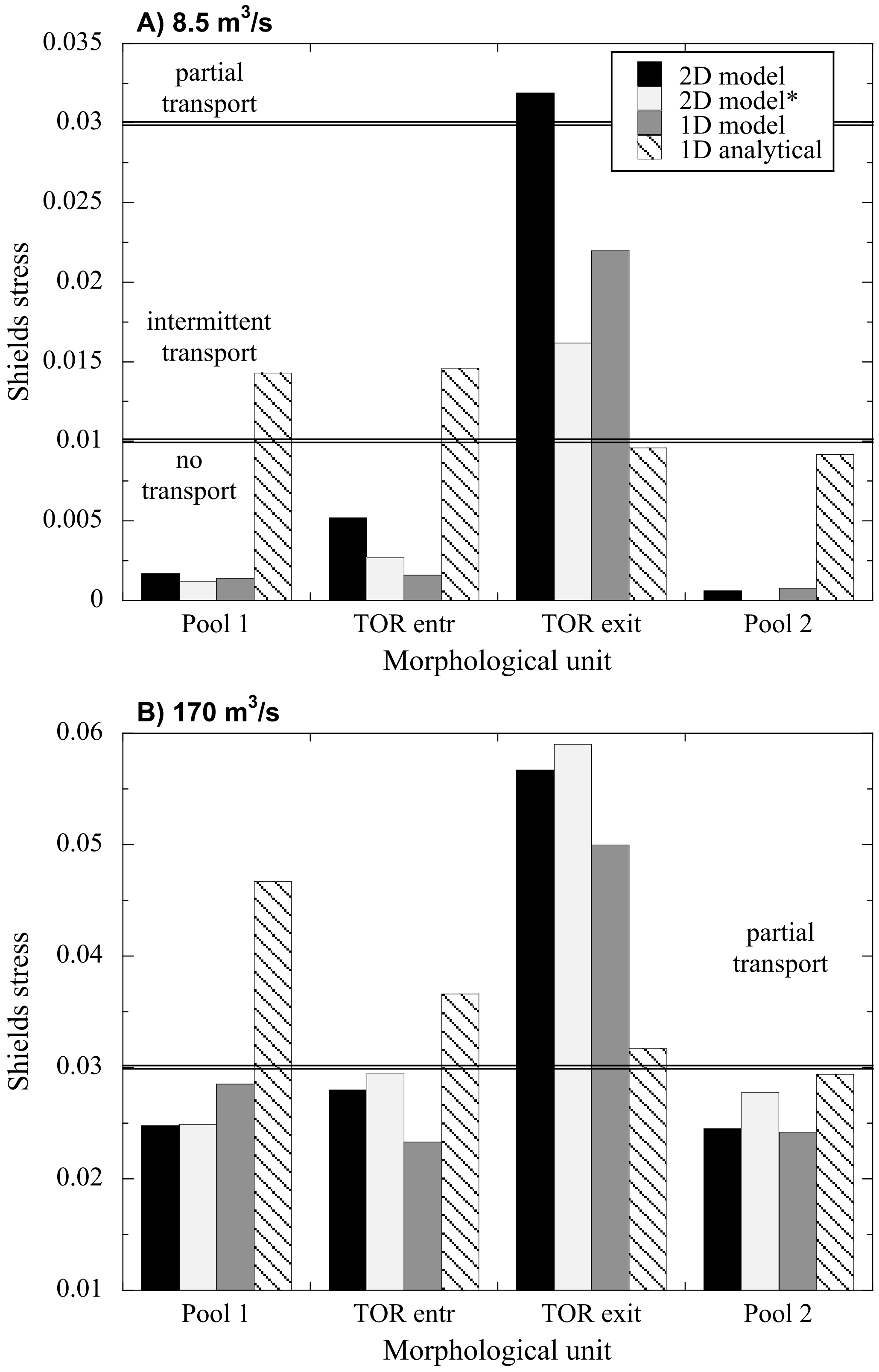

A) 8.5 m³/s
C) 170 m³/s
B) 8.5 m³/s
D) 170 m³/s
2D
2D-2sigma
2D+2sigma
1D
Analytical
Velocity (m/s)
Water surface elevation (m)
Distance (m)
Pool 1
TOR Entrance
TOR Exit
Pool 2
bed
3
2.5
2
1.5
1
0.5
0
-0.5
562
561
560
559
0
10
20
30
40
50

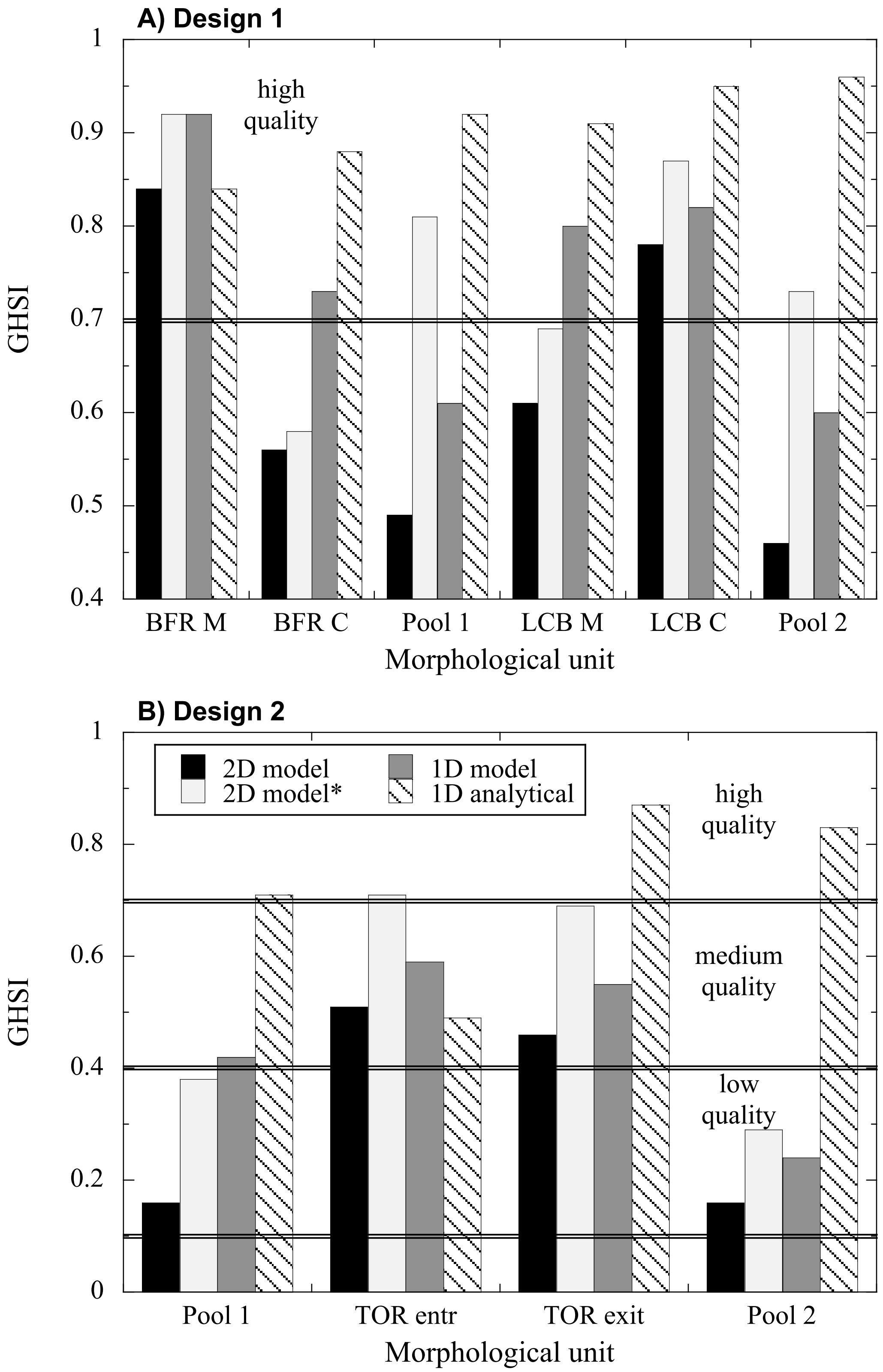

Pool 2
TOR Exit
TOR Entrance
Pool 1
A)
0.25
0.75
1.25
Depth (m)
0.00
0.50
1.00
B)
0.25
0.75
1.25
Velocity (m/s)
0.00
0.50
1.00
C)
Transport Regime
None
Intermittent
Partial
Full
Shields Stress
0.00
0.01
0.03
0.06
0.09
0.10
1.00
D)
Habitat Type
Non Habitat
Very Poor
Low
Medium
High
GHSI
0.00
0.10
0.40
0.70
1.00


Pool 2
TOR Exit
TOR Entrance
Pool 1
A)
0.25
0.75
1.25
1.75
2.25
2.75
3..25
Depth (m)
0.00
0.50
1.00
1.50
2.00
2.50
3.00
B)
0.25
0.75
1.25
1.75
2.25
2.75
Velocity (m/s)
0.00
0.50
1.00
1.50
2.00
2.50
3.0
C)
Transport Regime
None
Intermittent
Partial
Full
Shields Stress
0.00
0.01
0.03
0.06
0.09
0.10
1.00
North
Flow
Meters
0
50


A) 8.5 m^3/s
Shields stress
0.025
0.02
0.015
0.01
0.005
0
2D model
2D model*
1D model
1D analytical
intermittent transport
no transport
BFR M
BFR C
Pool 1
LCB M
LCB C
Pool 2
Morphological unit


B) 170 m^3/s
Shields stress
0.05
0.04
0.03
0.02
0.01
partial transport
BFR M
BFR C
Pool 1
LCB M
LCB C
Pool 2
Morphological unit


A) 8.5 m^3/s
Shields stress
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
partial transport
intermittent transport
no transport
2D model
2D model*
1D model
1D analytical
Pool 1
TOR entr
TOR exit
Pool 2
Morphological unit
B) 170 m^3/s
Shields stress
0.06
0.05
0.04
0.03
0.02
0.01
partial transport
Pool 1
TOR entr
TOR exit
Pool 2
Morphological unit


A) Design 1
GHSI
1
0.9
0.8
0.7
0.6
0.5
0.4
high
quality
BFR M
BFR C
Pool 1
LCB M
LCB C
Pool 2
Morphological unit
B) Design 2
GHSI
1
0.8
0.6
0.4
0.2
0
2D model
2D model*
1D model
1D analytical
high
quality
medium
quality
low
quality
Pool 1
TOR entr
TOR exit
Pool 2
Morphological unit