

COMPARISON OF METHODS FOR ANALYSING SALMON HABITAT REHABILITATION DESIGNS FOR REGULATED RIVERS

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ABSTRACT

River restoration practices aiming to sustain wild salmonid populations have received considerable attention in the United 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 (SHR) 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. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: river restoration; river modelling; river hydraulics; gravel-bed rivers; physical habitat quality; sediment transport regime

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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; Newbury *et al.*, 1997; Slaney and Zaldokas, 1997; CDFG, 1998; CDWR, 2000; Saldi-Caromile *et al.*, 2004; Walker *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

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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 (BFR) 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 to 0.02, and are thus very important components in SHR projects involving direct gravel augmentation (NRC, 1992; Newbury *et al.*, 1997; Kondolf, 2000; Saldi-Caromile *et al.*, 2004; Wheaton *et al.*, 2004a,b; 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; Lisle, 1979; Milne, 1982; Carling, 1990; Clifford and Richard, 1992; MacWilliams *et al.*, 2006), grain size (Keller, 1971) 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 low flows, but the reverse may occur at high flows where channel conditions promote that phenomenon (Keller, 1971; Carling, 1991; Clifford and Richard, 1992; Wilkinson *et al.*, 2004; MacWilliams *et al.*, 2006; Harrison and Keller, 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 affect channel hydraulics (Keller, 1971; Lisle, 1979). The convergence and/or 'reversal' of riffle-pool water surface elevation (WSE) 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, 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 (Figure 1) actually proposed for an individual pool-riffle-pool sequence in the Lewiston dam reach (river mile 111.8–111.2; United States Fish and Wildlife Service, 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

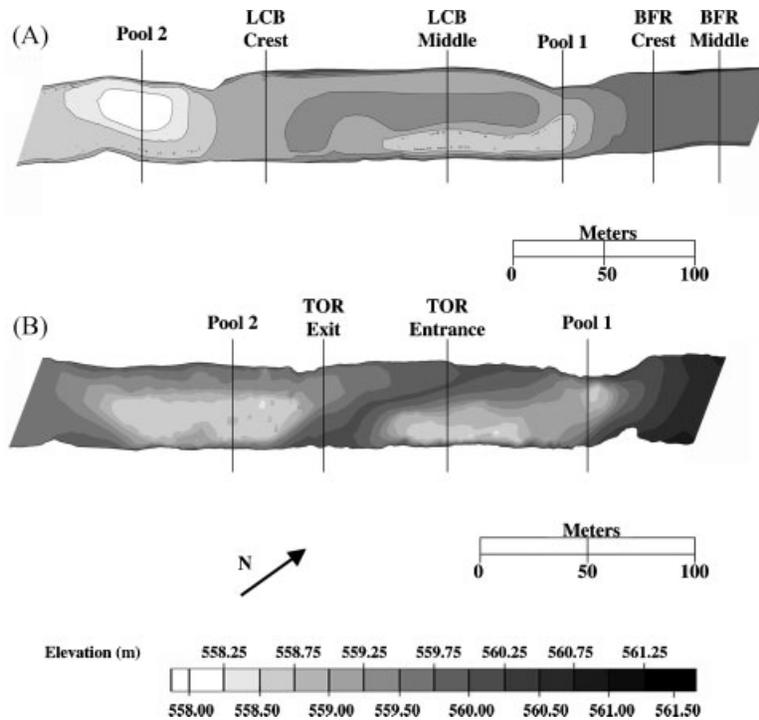


Figure 1. Design topography for test design (A) 1 and (B) 2. Note that in design 1 the riffle crests are convergent being mostly orthogonal to the channel bank, while in design 2 the topography of the riffle crest is transverse to the channel banks

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 ($8.5 \text{ m}^3/\text{s}$), and the maximum flow release that occurred during 1999–2004 ($170 \text{ m}^3/\text{s}$). 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 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 ($8.5 \text{ m}^3/\text{s}$) 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 (Figure 1(A)) 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 BFR, an 'L-shaped' central bar (LCB), and two constricted pools (hereafter referred to as Pool 1 and Pool 2). 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 analogue 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 (Figure 1(B)) 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 (Figure 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.

One-dimensional 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 (\bar{V}) for each specified WSE:

$$\bar{V} = \left(\frac{1}{n}\right)R^{2/3}S^{1/2} \quad (1)$$

and

$$Q = A\bar{V} \quad (2)$$

where Q is the discharge (m^3/s), R the hydraulic radius (m), A the cross-sectional area (m^2), n the 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 (Figure 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 1D 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).

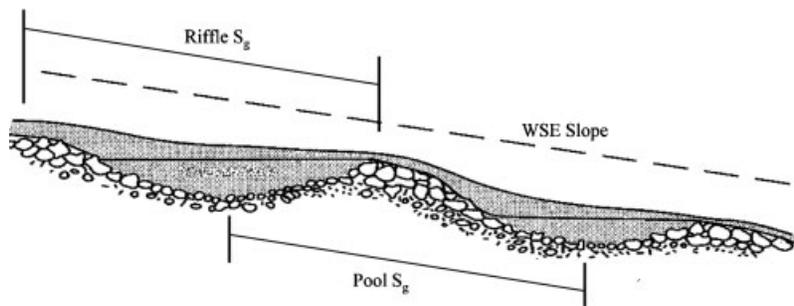


Figure 2. Definition sketch of geomorphic slope (Modified after Knighton, 1998). In this study the geomorphic slope is defined as the elevation difference between an upstream feature and the next downstream feature of the same type (i.e. bar or pool) divided by the distance between them

One-dimensional 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. One-dimensional 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:

$$\bar{H}_2 + Z_2 + \frac{\alpha_2 \bar{V}_2^2}{2g} = \bar{H}_1 + Z_1 + \frac{\alpha_1 \bar{V}_1^2}{2g} + h_e \quad (3)$$

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

One-dimensional hydraulic models usually provide fairly accurate predictions of WSE for flood stages where relative roughness is low and/or there are gradual changes in bed slope and channel width (Lacey and Millar, 2004; Ghanem *et al.*, 1996; Brunner, 1998). 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 (Lacey and Millar, 2004; Ghanem *et al.*, 1996; MacWilliams *et al.*, 2006). Despite this, they are readily available, require relatively sparse information and are frequently used by professional consultants.

Two-dimensional numerical model. Two-dimensional (depth-averaged) models such as finite element surface water modelling system 3.1.5 (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). Two-dimensional models are also more realistically linked to flow, sediment transport and biological variables measured in the field at the same spatial scale (Lacey and Millar, 2004; Ghanem *et al.*, 1996; Pasternack *et al.*, 2006). Two-dimensional 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 SHR by gravel placement (Pasternack *et al.*, 2004, 2006; Wheaton *et al.*, 2004b; Elkins *et al.*, 2007; Brown and Pasternack, 2008).

In this study, the 2D model known as 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 2D 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

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

and

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

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 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, τ_x^a and τ_x^b 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

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

FESWMS was implemented using surface water modelling 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 WSE 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 $E = c_0 + 0.6Hu^*$, where u^* is shear velocity (m/s) and c_0 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, 2006; Wheaton *et al.*, 2004b; 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 to 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.

Three-dimensional 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 and Florsheim, 1993; Rathburn and Wohl, 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:

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

where, τ^* is Shields stress, τ_b the predicted bed shear stress (Pa), γ_s the specific weight of sediment (N/m^3), γ_f 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 $1-2D_{90}$ 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

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

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
For $H < 0$ and $H > 1.374$ m:

$$\text{DHSI} = 0 \quad (8a)$$

For $0 < H < 1.374$ m:

$$\begin{aligned} \text{DHSI} = & 0.0351 - 0.7248(H/0.3048) + 4.9307(H/0.3048)^2 - 5.2964(H/0.3048)^3 \\ & + 2.4818(H/0.3048)^4 - 0.6007(H/0.3048)^5 + 0.007235(H/0.3048)^6 \\ & - 0.002514(H/0.3048)^7 - 0.000274(H/0.3048)^8 + 2.1277(H/0.3048)^9 \end{aligned} \quad (8b)$$

Similarly, using either U or \bar{V} those for VHSI were
For $U < 0.01$ and $U > 1.68$ m/s:

$$\text{VHSI} = 0 \quad (9a)$$

For $0.01 < U < 0.40$ m/s:

$$\begin{aligned} \text{VHSI} = & -0.0131 + 0.5523(U/0.3048) - 0.8246(U/0.3048)^2 + 1.8208(U/0.3048)^3 \\ & - 0.8013(U/0.3048)^4 \end{aligned} \quad (9b)$$

For $0.40 < U < 1.68$ m/s:

$$\begin{aligned} \text{VHSI} = & -5.1205 + 13.1440(U/0.3048) - 9.5769(U/0.3048)^2 + 2.2576(U/0.3048)^3 \\ & + 0.4525(U/0.3048)^4 - 0.3746(U/0.3048)^5 + 0.08619(U/0.3048)^6 \\ & - 0.009046(U/0.3048)^7 + 0.000369(U/0.3048)^8 \end{aligned} \quad (9c)$$

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' life stage 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:

$$\text{GHSI} = \text{DHSI}^{0.5} \times \text{VHSI}^{0.5} \quad (10)$$

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 \bar{V} and R , while 1D numerical predictions were made with \bar{V} and \bar{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. WSE 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 \bar{V} and \bar{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) and (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) and (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, \bar{H} and \bar{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, $8.5 \text{ m}^3/\text{s}$, found that the two numerical methods yielded very similar cross-sectionally averaged velocity and WSE values down the channel (Table I), with the 2D velocity values showing slightly greater longitudinal variation (Figure 3(A) and (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 (Figure 3(A)). This at-a-section lateral variability varied downstream in response to local flow convergence and divergence, as indicated by flow vectors (Figure 4(B)).

The hydraulic-variable profiles at $170 \text{ m}^3/\text{s}$ for numerical models in design 1 exhibited similar relative predictions as found at low discharge (Table II; Figure 3(C) and (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 WSEs 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 centre (Figure 5(B)). 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 $8.5 \text{ m}^3/\text{s}$ (Table III) revealed dramatic differences between analytical and numerical predictions. The high-relief riffle crest at 30 m downstream produced a strong backwater effect with higher WSEs and lower velocities in both numerical models (Figure 6(A) and (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 III). The 2D model showed greater hydraulic complexity and lateral variation in velocity in design 2 compared with design 1, which was caused by the TOR. This is exemplified by the presence of two distinct peak-velocity zones and two whirlpools (Figure 7(A) and (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 (Figure 7(B)).

For the high discharge test, the 1D analytical method was even worse off than at low discharge (Table IV; Figure 6(C) and (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 (Figure 8(A) and (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 help 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.

Table I. Cross-sectionally averaged values comparable across three test methods for design 1 at 8.5 m³/s

Channel feature	Variable	1D analytical	1D model	2D model*	2D model [†]
Broad flat riffle (middle) $S_G = 0.0025^\ddagger$	WSE (m)	560.30	560.35	560.36	
	U (m/s)	0.60	0.54	0.54 (± 0.13)	
	d mean (m)	0.37	0.42	0.44	
	τ^*	0.011	0.008	0.008 (± 0.003)	0.008
	Transport regime	Intermittent	None	None	None
	GHSI	0.84	0.92	0.84 (± 0.26)	0.92
Broad flat riffle (crest) $S_G = 0.0022$	Habitat quality	High	High	High	High
	WSE (m)	560.30	560.27	560.21	
	U (m/s)	0.57	0.68	0.77 (± 0.09)	
	d mean (m)	0.37	0.34	0.29	
	τ^*	0.009	0.015	0.020 (± 0.005)	0.021
	Transport regime	None	Intermittent	Intermittent	Intermittent
Pool 1 $S_G = 0.0014$	GHSI	0.88	0.73	0.56 (± 0.14)	0.58
	Habitat quality	High	High	Medium	Medium
	WSE (m)	559.71	560.01	560.01	
	U (m/s)	0.53	0.33	0.33 (± 0.05)	
	d mean (m)	0.48	0.73152	0.33	
	τ^*	0.007	0.002	0.003 (± 0.009)	0.004
L-shaped central bar (middle) $S_G = 0.002$	Transport regime	None	None	None	None
	GHSI	0.92	0.61	0.49 (± 0.51)	0.81
	Habitat quality	High	Medium	Medium	High
	WSE (m)	559.77	559.98	559.98	
	U (m/s)	0.54	0.34	0.29 (± 0.16)	
	d mean (m)	0.37	0.56	0.60	
L-shaped central bar (crest) $S_G = 0.0017$	τ^*	0.008	0.002	0.002 (± 0.003)	0.002
	Transport regime	None	None	None	None
	GHSI	0.91	0.80	0.61 (± 0.42)	0.69
	Habitat quality	High	High	Medium	Medium
	WSE (m)	559.86	559.80	559.80	
	U (m/s)	0.50	0.59	0.56 (± 0.20)	
Pool 2 $S_G = 0.001$	d mean (m)	0.37	0.32	0.34	
	τ^*	0.007	0.011	0.011 (± 0.004)	0.010
	Transport regime	None	Intermittent	Intermittent	None
	GHSI	0.95	0.82	0.78 (± 0.26)	0.87
	Habitat quality	High	High	High	High
	WSE (m)	559.34	559.61	559.61	
Pool 2 $S_G = 0.001$	U (m/s)	0.46	0.29	0.3 (± 0.23)	
	d mean (m)	0.50	0.30	0.30	
	τ^*	0.005	0.002	0.002 (± 0.001)	0.003
	Transport regime	None	None	None	None
	GHSI	0.96	0.60	0.46 (± 0.26)	0.73
	Habitat quality	High	Medium	Medium	High

*Parenthesis shows two standard deviations.

[†]Smoothed averaging method using mean hydraulic variables.

[‡]Geomorphic slope as defined in text.

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 analysed for design 1 at 8.5 m³/s, most Shields stress predictions were in the range of 0–0.01, corresponding with no transport (Table I, Figure 9(A)). For most channel units, the 1D

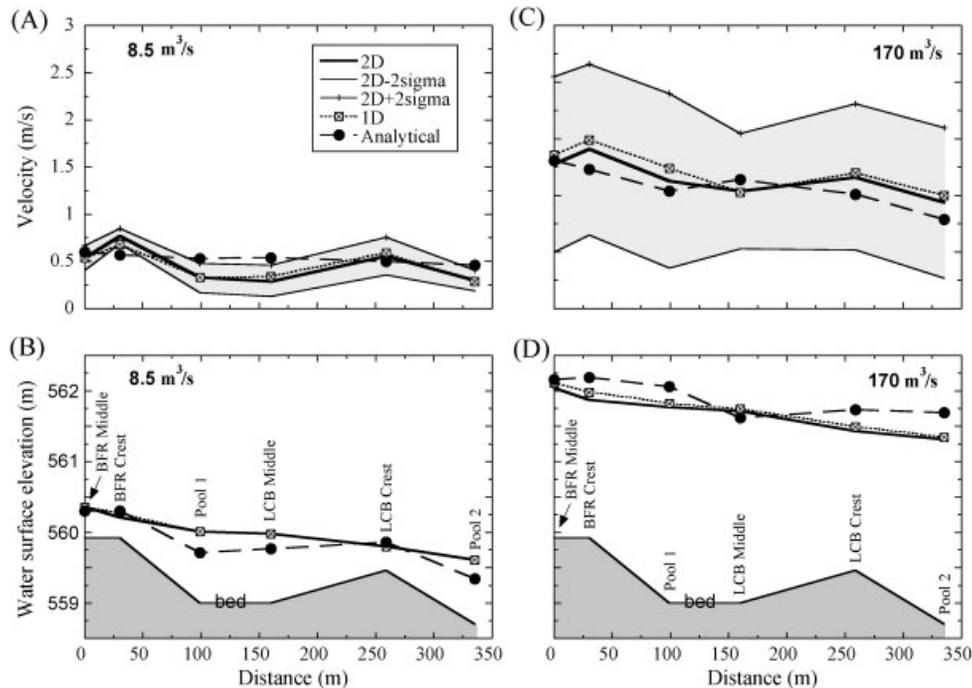


Figure 3. Design 1 comparison plots of (A) velocity and (B) water surface elevation at $8.5 \text{ m}^3/\text{s}$, (C) velocity and (D) water surface elevation at $170 \text{ m}^3/\text{s}$. The morphological unit labels refer to cross section locations where section-averaged values of depth, velocity,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

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 (Figure 4(C)) given the simple channel geometry.

At $170 \text{ m}^3/\text{s}$, maximum Shields stresses corresponding to a state of partial transport were predicted by all methods to occur over the BFR (Table II, Figure 9(B)). 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 centre of the channel was predicted to be in partial transport and the lateral margins in intermittent transport (Figure 5(C)).

Test design 2. For test design 2, the 1D analytical method performed very poorly at $8.5 \text{ m}^3/\text{s}$, predicting the wrong sediment transport regime at three of the four cross-sections, with the fourth one barely correct (Table III; Figure 10(A)). 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 (Figure 7(C)), 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.

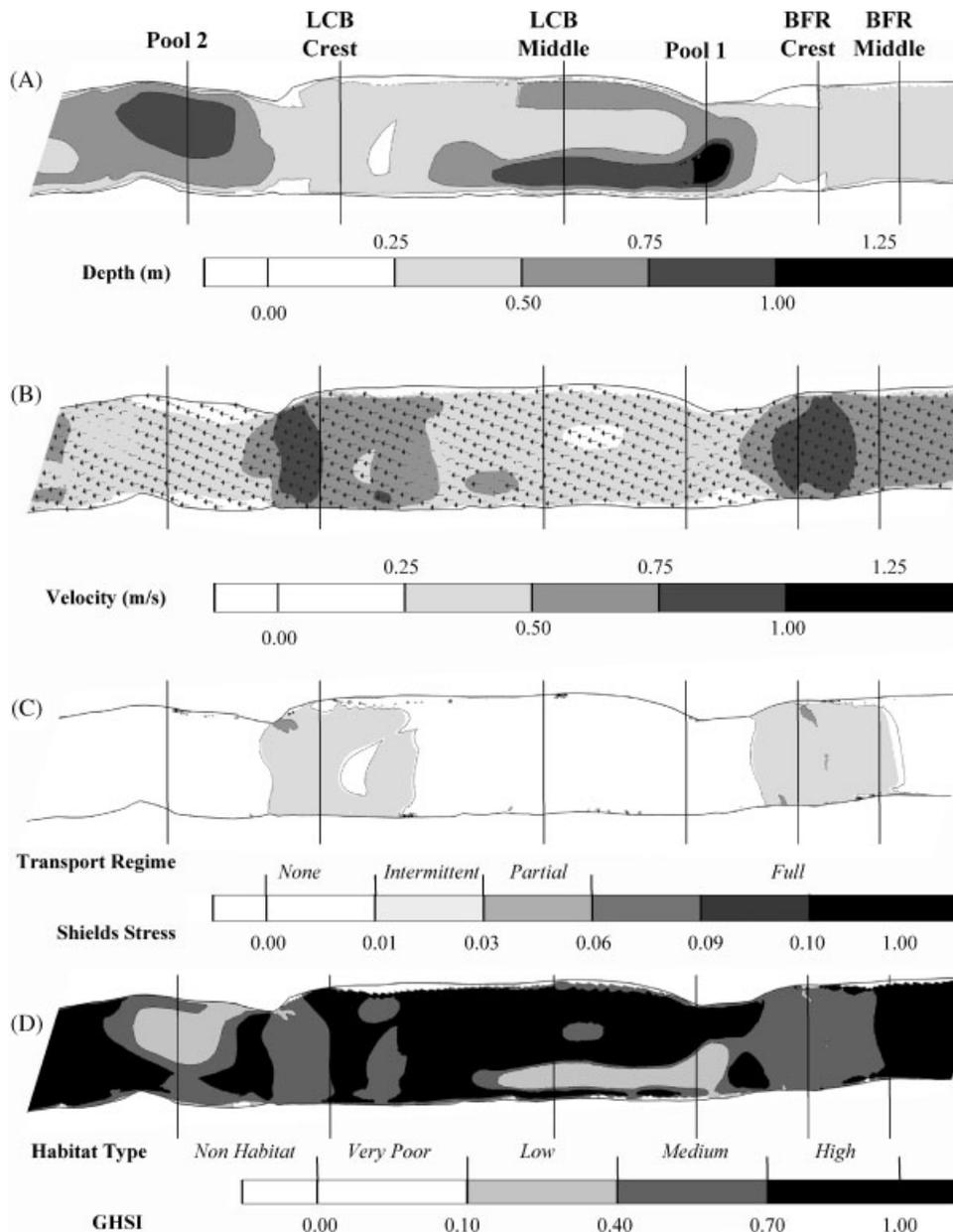


Figure 4. Design 1, 2D model plots of (A) depth, (B) velocity, (C) Shields stress and (D) GHSI for $8.5 \text{ m}^3/\text{s}$. The vertical lines refer to cross section locations where section-averaged values of depth, velocity, Shields stress and GHSI were compared

At $170 \text{ m}^3/\text{s}$, 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 1 (Table IV; Figure 10(B)). 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 centre and partial transport along the banks (Figure 8(C)).

Table II. Cross-sectionally averaged values comparable across three test methods for design 1 at 170 m³/s

Channel feature	Variable	1D analytical	1D model	2D model*	2D model [†]
Broad flat riffle (middle) $S_G = 0.0025$	WSE (m)	562.16	562.11	562.04	
	U (m/s)	1.81	1.86	1.78 (± 0.77)	
	d mean (m)	1.93	1.93	2.12	
	τ^*	0.037	0.039	0.040 (± 0.080)	0.034
	Transport Regime	Partial	Partial	Partial	Partial
Broad flat riffle (crest) $S_G = 0.0022$	WSE (m)	562.19	561.98	561.87	
	U (m/s)	1.73	1.99	1.91 (± 0.75)	
	d mean (m)	1.99	1.80	1.95	
	τ^*	0.033	0.046	0.046 (± 0.018)	0.041
	Transport regime	Partial	Partial	Partial	Partial
Pool 1 $S_G = 0.0014$	WSE (m)	562.06	561.82	561.77	
	U (m/s)	1.54	1.74	1.63 (± 0.77)	
	d mean (m)	2.34	2.20	1.63	
	τ^*	0.024	0.032	0.031 (± 0.015)	0.032
	Transport regime	Intermittent	Partial	Partial	Partial
L-shaped central bar (middle) $S_G = 0.002$	WSE (m)	561.62	561.74	561.71	
	U (m/s)	1.64	1.53	1.54 (± 0.51)	
	d mean (m)	1.98	2.10	2.33	
	τ^*	0.030	0.025	0.027 (± 0.012)	0.025
	Transport regime	Partial	Intermittent	Intermittent	Intermittent
L-shaped central bar (crest) $S_G = 0.0017$	WSE (m)	561.73	561.49	561.43	
	U (m/s)	1.51	1.70	1.66 (± 0.65)	
	d mean (m)	2.00	1.83	1.97	
	τ^*	0.025	0.034	0.034 (0.015)	0.031
	Transport regime	Intermittent	Partial	Partial	Partial
Pool 2 $S_G = 0.001$	WSE (m)	561.69	561.34	561.31	
	U (m/s)	1.29	1.50	1.44 (0.11)	
	d mean (m)	2.32	2.08	1.44	
	τ^*	0.017	0.025	0.023 (0.012)	0.027
	Transport regime	Intermittent	Intermittent	Intermittent	Intermittent

*Parenthesis shows two standard deviations.

[†]Smoothed-averaging method using mean hydraulic variables.

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 7 out of 10 locations misclassified by the 1D analytical method. In comparison, 3 out of 10 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.

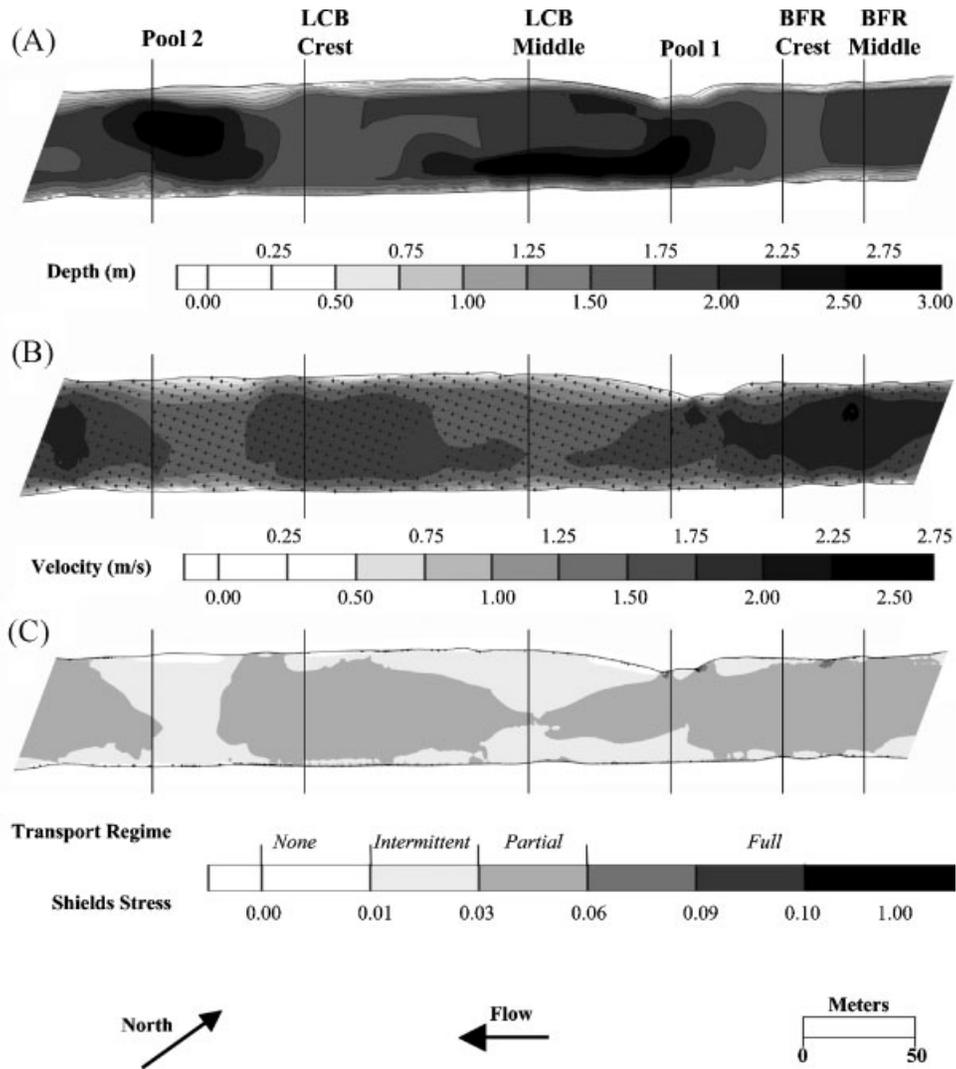


Figure 5. Design 1, 2D model plots of (A) depth, (B) velocity, (C) Shields stress for 170 m³/s. The vertical lines refer to cross section locations where section-averaged values of depth, velocity, Shields stress and GHSI were compared

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 I; Figure 11(A)). 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 1 and the LCB middle, the LCB crest, and the exit slope of the LCB chute (Figure 4(D)). 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 III; Figure 11(B)). 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

Table III. Cross-sectionally averaged values comparable across three test methods for design 2 at 8.5 m³/s

Channel feature	Variable	1D analytical	1D model	2D model*	2D model†
Pool 1 $S_G = 0.0033$	WSE (m)	559.57	560.21	560.28	
	U (m/s)	0.71	0.29	0.27 (± 1.32)	
	d mean (m)	0.39	0.86	0.87 (± 0.40)	
	τ^*	0.014	0.001	0.002 (± 0.004)	0.001
	Transport regime	Intermittent	None	None	None
	GHSI	0.71	0.42	0.16 (± 0.14)	0.38
Transverse oblique riffle (entrance) $S_G = 0.0025$	Habitat quality	High	High	Low	Medium
	WSE (m)	559.50	560.20	560.27	
	U (m/s)	0.84	0.29	0.38 (± 0.29)	
	d mean (m)	0.61	0.70	0.71	
	τ^*	0.015	0.002	0.005 (± 0.009)	0.003
	Transport regime	Intermittent	None	None	None
Transverse oblique riffle (exit) $S_G = 0.0022$	GHSI	0.49	0.59	0.51 (± 0.82)	0.71
	Habitat quality	Medium	Medium	Medium	High
	WSE (m)	560.13	560.08	560.06	
	U (m/s)	0.59	0.81	0.69 (± 0.46)	
	d mean (m)	0.39	0.31	0.31	
	τ^*	0.010	0.022	0.032 (± 0.051)	0.016
Pool 2 $S_G = 0.0019$	Transport regime	None	Intermittent	Partial	Intermittent
	GHSI	0.87	0.55	0.46 (± 0.56)	0.69
	Habitat quality	High	Medium	Medium	Medium
	WSE (m)	559.37	560.05	560.05	
	U (m/s)	0.62	0.22	0.27 (± 0.21)	
	d mean (m)	0.48	0.98	0.98	
$S_G = 0.0019$	τ^*	0.009	0.001	0.001 (± 0.001)	0.001
	Transport regime	None	None	None	None
	GHSI	0.83	0.24	0.16 (± 0.20)	0.29
	Habitat quality	High	Low	Low	Low

*Parenthesis shows two standard deviations.

†Smoothed averaging method using mean hydraulic variables.

design 2 showed a paucity of high quality habitat, except for the channel margin and the entrance and exit slopes of the TOR (Figure 7(D)). 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 centre 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

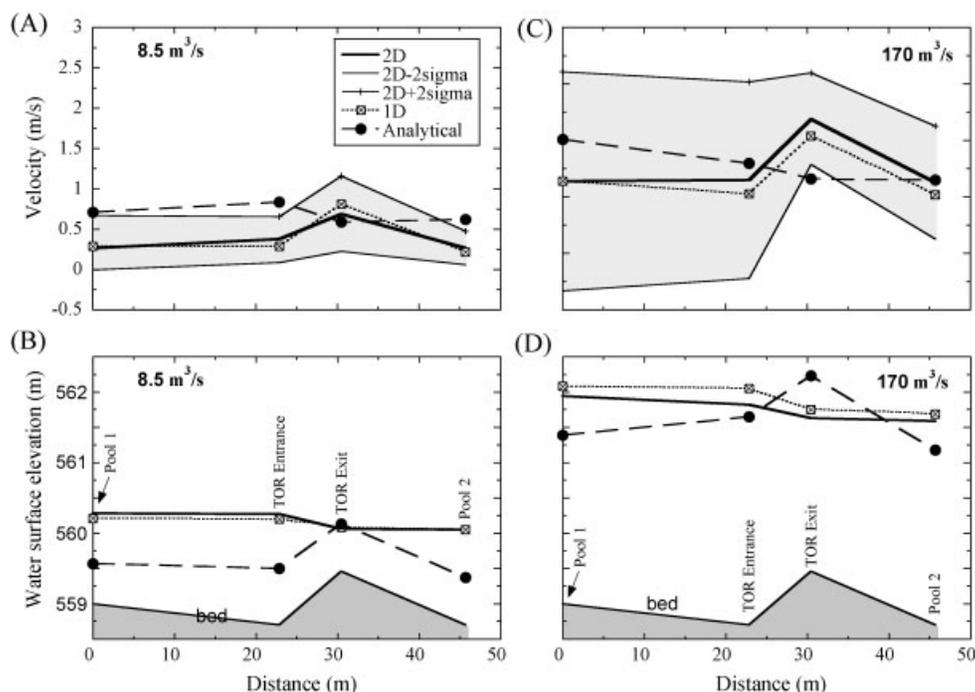


Figure 6. Design 2 comparison plots of (A) velocity and (B) water surface elevation at $8.5 \text{ m}^3/\text{s}$ (C) velocity and (D) water surface elevation at $170 \text{ m}^3/\text{s}$. The morphological unit labels refer to cross section locations where section-averaged values of depth, velocity,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

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

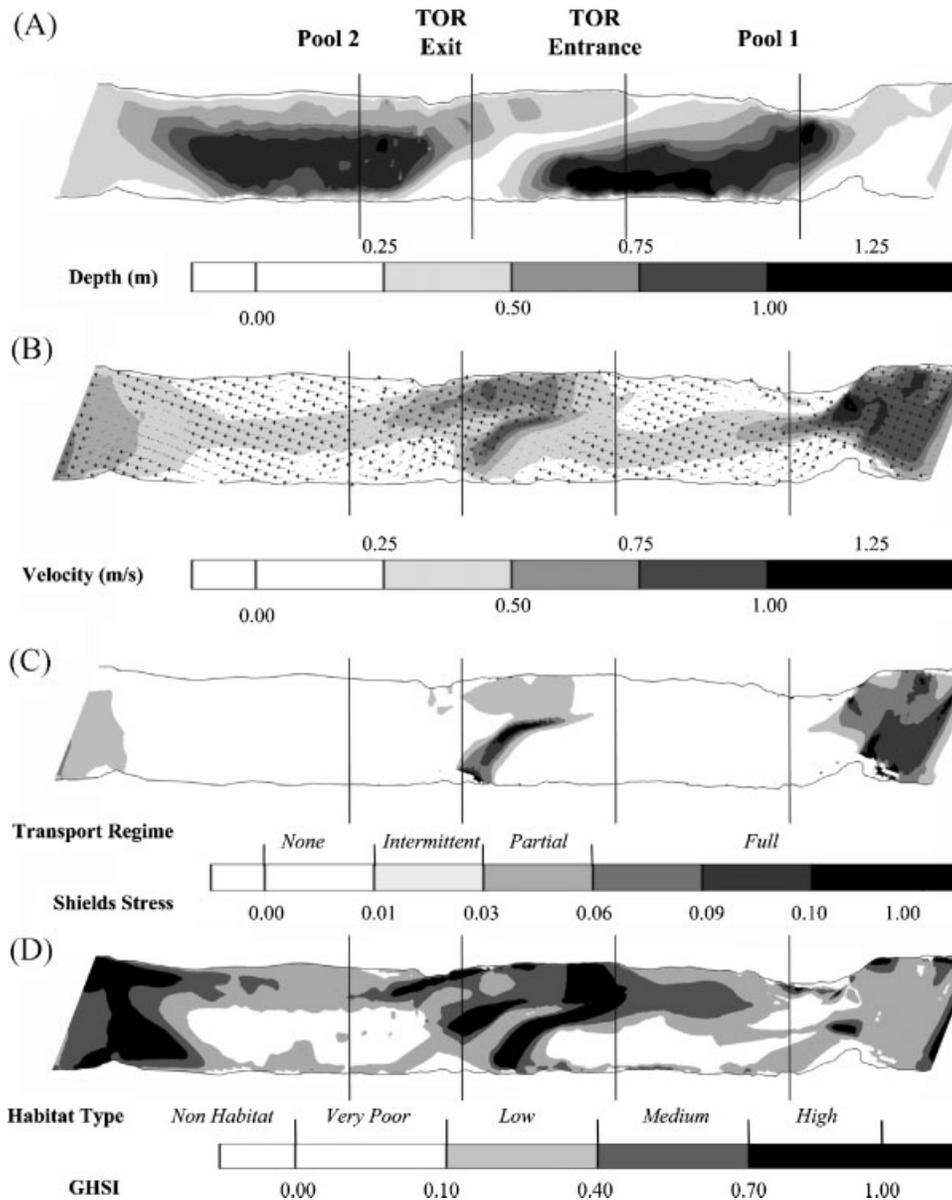


Figure 7. Design 2, 2D model plots of (A) depth, (B) velocity, (C) Shields stress and (D) GHSI for $8.5 \text{ m}^3/\text{s}$. The vertical lines refer to cross-section locations where section-averaged values of depth, velocity, Shields stress and GHSI were compared

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

Table IV. Cross-sectionally averaged values comparable across three test methods for design 2 at 170 m³/s

Channel feature	Variable	1D analytical	1D model	2D model*	2D model [†]
Pool 1 $S_G = 0.0033$	WSE (m)	561.39	562.08	561.94	
	U (m/s)	2.01	1.64	1.52 (± 1.02)	
	d mean (m)	1.84	2.22	2.16 (± 1.02)	
	τ^*	0.047	0.029	0.025 (± 0.025)	0.025
	Transport regime	Partial	Intermittent	Intermittent	Intermittent
Transverse oblique riffle (entrance) $S_G = 0.0025$	WSE (m)	561.65	562.05	561.82	
	U (m/s)	1.80	1.49	1.65 (± 0.87)	
	d mean (m)	1.91	2.27	2.12	
	τ^*	0.037	0.023	0.028 (± 0.017)	0.030
	Transport regime	Partial	Intermittent	Intermittent	Intermittent
Transverse oblique riffle (exit) $S_G = 0.0022$	WSE (m)	562.23	561.75	561.63	
	U (m/s)	1.66	2.04	2.19 (± 0.41)	
	d mean (m)	1.88	1.69	1.62	
	τ^*	0.032	0.050	0.057 (± 0.019)	0.059
	Transport regime	Partial	Partial	Partial	Partial
Pool 2 $S_G = 0.0019$	WSE (m)	561.18	561.69	561.59	
	U (m/s)	1.65	1.52	1.63 (± 0.50)	
	d mean (m)	2.10	2.29	2.29	
	τ^*	0.029	0.024	0.025 (± 0.011)	0.028
	Transport regime	Intermittent	Intermittent	Intermittent	Intermittent

*Parenthesis shows two standard deviations.

[†]Smoothed-averaging method using mean hydraulic variables.

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 (Figures 4(D) and 7(D)), 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.

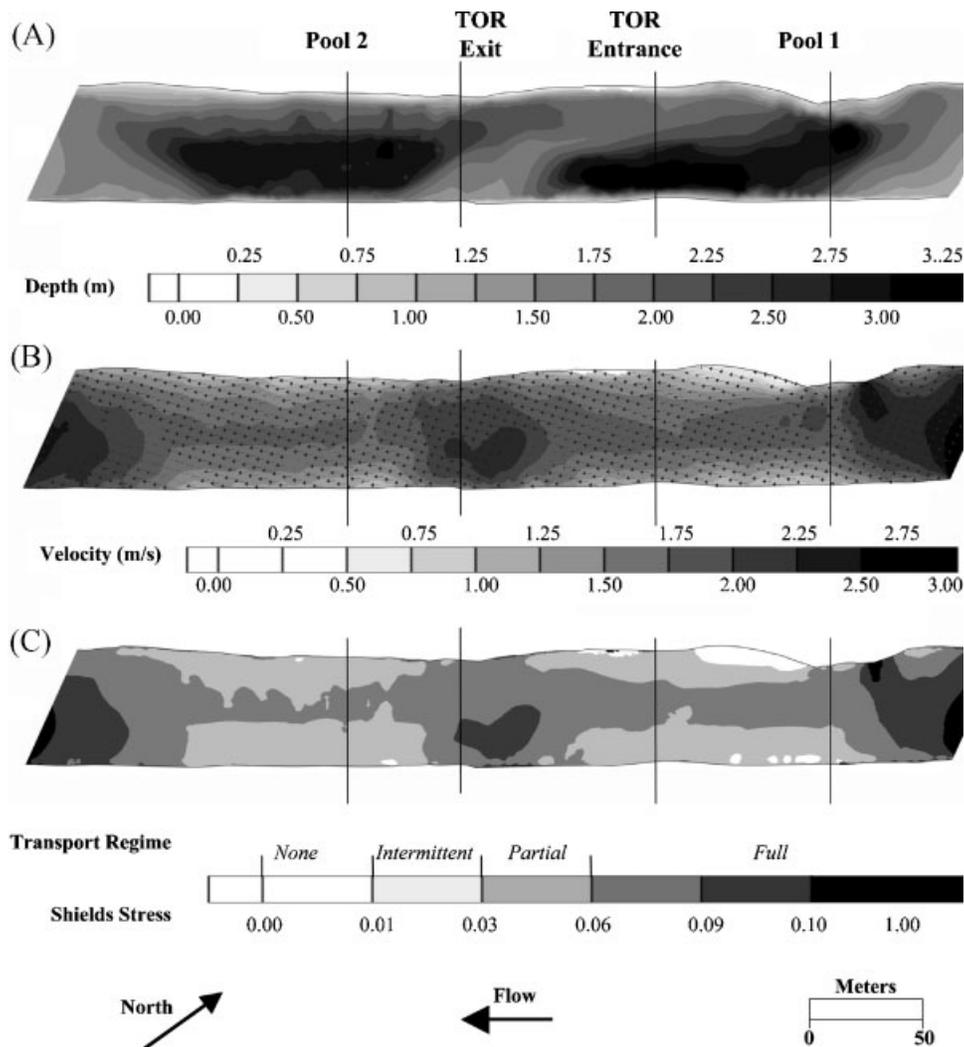


Figure 8. Design 2, 2D model plots of (A) depth, (B) velocity, (C) Shields stress for $170 \text{ m}^3/\text{s}$. The vertical lines refer to cross section locations where section-averaged values of depth, velocity, Shields stress and GHSI were compared

Broad flat riffles

The BFR, 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 BFRs 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 (Figure 1, first two cross sections). Both numerical models show the flow accelerating towards the crest, which the 1D analytical method does not (Figure 3(A)). 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 (Figure 9(B)). 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

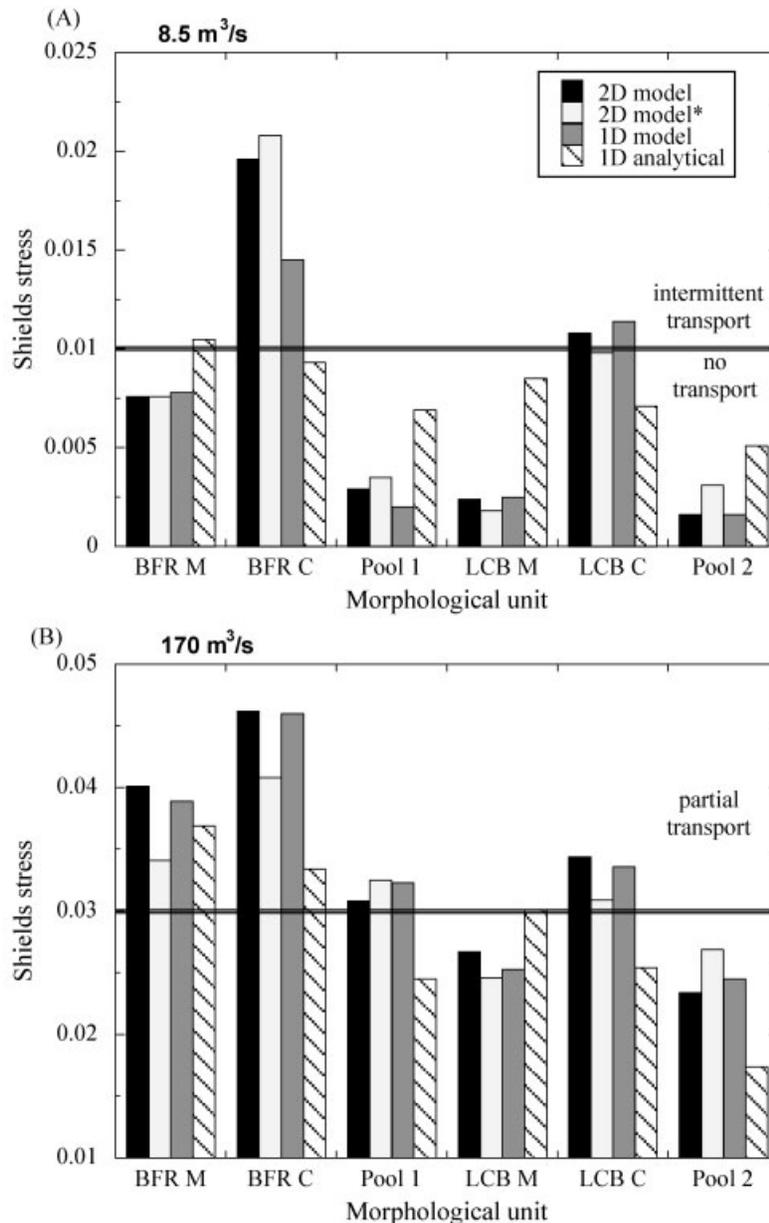


Figure 9. Design 1 comparison of Shields stress at (A) 8.5 and (B) 170 m³/s. The ** results were calculated using a smoothed averaging method based on mean depth and velocity as opposed to values obtained from nodal averaging

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 BFRs 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

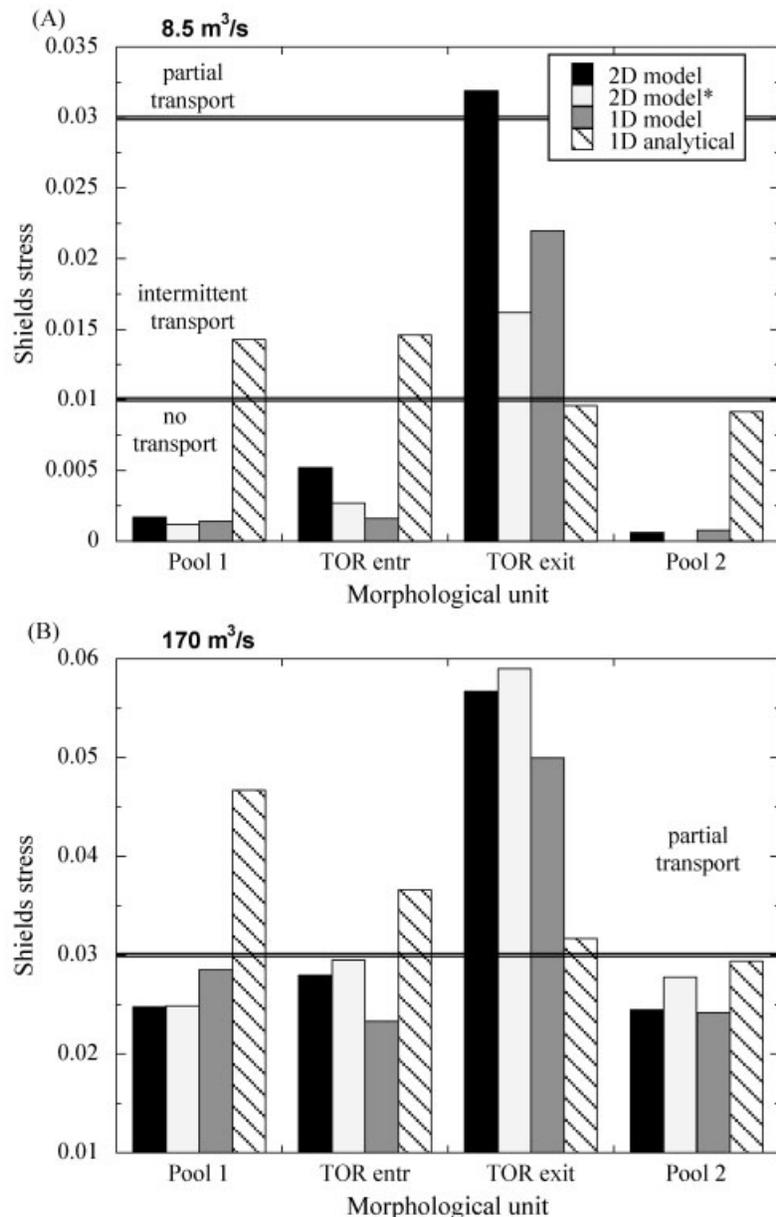


Figure 10. Design 2 comparison of Shields stress at (A) 8.5 and (B) 170 m³/s. The *** results were calculated using a smoothed averaging method based on mean depth and velocity as opposed to values obtained from nodal averaging

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 analysed 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

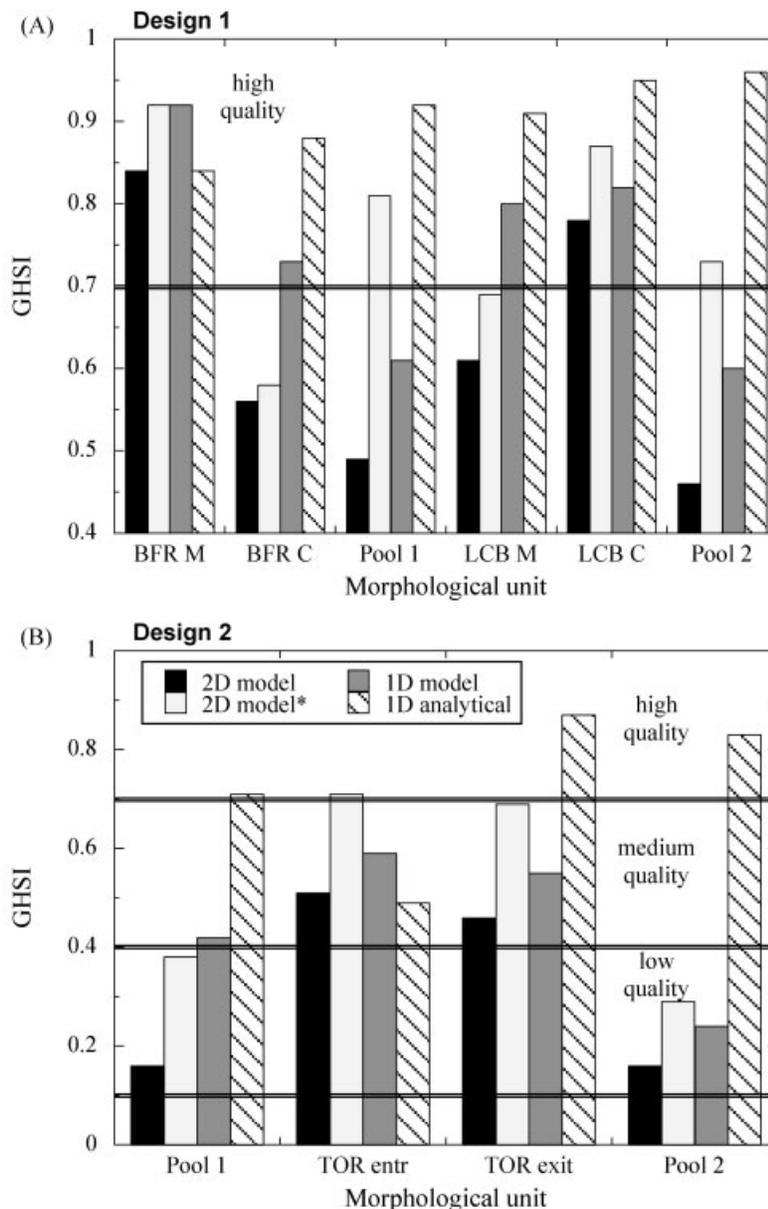


Figure 11. GHSI comparison of (A) design 1 and (B) design 2 at 8.5 m³/s. The “*” results were calculated using a smoothed averaging method based on mean depth and velocity as opposed to values obtained from nodal averaging

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 (MacWilliams *et al.*, 2006). No such reversal was evident in the test at 170 m³/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 by the 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 to 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.

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