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Title: Backwater Control on Riffle-Pool Hydraulics, Fish Habitat Quality, and Sediment Transport Regime in Gravel-Bed Rivers

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ABSTRACT

The importance of channel non-uniformity to natural hydrogeomorphic and ecological processes in gravel-bed rivers is becoming increasingly known, but its use in channel rehabilitation lags behind. Many projects still use methods that assume steady, uniform flow and simple channel geometries. One aspect of channel non-uniformity that has not been considered much is its role in controlling backwater conditions and thus potentially influencing patterns of physical habitat and channel stability in sequences of riffles and pools. In this study, 2D hydrodynamic models of two non-uniform pool–riffle–pool configurations were used to systematically explore the effects of four different downstream water surface elevations at three different discharges (24 total simulations) on riffle–pool ecohydraulics. Downstream water surface elevations tested included backwater, uniform, accelerating, and critical conditions, which are naturally set by downstream riffle-crest morphology but may also be re-engineered artificially. Discharges included a fish-spawning low flow, summer fish-attraction flow, and a peak snowmelt pulse. It was found that the occurrence of a significant area of high-quality fish spawning habitat at low flow depends on riffles being imposed upon by backwater conditions, which also delay the onset of full bed mobility on riffles during floods. The assumption of steady, uniform flow was found to be inappropriate for gravel-bed rivers, since their non-uniformity controls spatial patterns of habitat and sediment transport. Also, model results indicated that a ‘‘reverse domino’’ mechanism can explain catastrophic failure and reorganization of a sequence of riffles based on the water surface elevation response to scour on downstream riffles, which then increases scour on upstream riffles.

1. INTRODUCTION

River restoration is an established hydrological objective in the United States and worldwide (Bernhardt et al., 2005). In arid and semiarid regions where dams and channelization have altered fluvial processes in gravel-bed rivers (Williams and Wolman, 1984; Kondolf, 1997; Brandt, 2000), river restoration involves flow re-regulation to mimic the pre-dam hydrologic regime (Webb et al., 1999; Trush et al., 2000) and channel rehabilitation to naturalize hydraulic geometry and instream structures, such as riffles and pools (Wheaton et al., 2004a; Elkins et al., 2007). The central challenge in active river rehabilitation is to determine how to manipulate channel form to yield hydrogeomorphic processes that promote ecological functions. The goal of this study was to investigate interactions among discharge, channel form, and backwater hydraulics that control the instream physical and ecological outcomes of channel manipulations undertaken in rehabilitating regulated gravel-bed rivers.

Empirical relations between bankfull discharge and channel dimensions at the reach scale are commonly used to prescribe channel form at reach and smaller channel-unit scales, including the spacing of riffles and pools (e.g. Rosgen 1996; Brookes and Shields 1996; Shields et al. 2003). However, they neither account for sub-reach scale channel non-uniformity typical of riffles and pools nor explicitly include ecological variables. Conversely, indices of biological integrity diagnose “stream health” before and after projects based on ratings of richness and composition of species, trophic composition of the biotic community, and abundance and condition of the individuals (Karr 1991, Moyle and Randall 1998, Talmage et al. 2002), but do not account for governing hydrologic and geomorphic variables to make them predictive.

One approach that can explicitly link hydrogeomorphic and ecological predictions in the design phase of river rehabilitation is the coupling of two-dimensional (2D) hydrodynamic models with sediment transport regime equations for predicting scour potential and local habitat suitability curves for predicting physical habitat quality for organisms (Leclerc et al., 1995; Hardy, 1998; Pasternack et al., 2004; Wheaton et al., 2004b; Gard, 2006). Although these models have uncertainty and are not fully dynamic, Elkins et al. (2007) used a full-scale channel manipulation on the Mokelumne River, CA to show that this approach can successfully predict the ecological outcome of river rehabilitation for a pool-riffle-pool-rifle sequence. In comparison, one-dimensional models such as PHABSIM may be effective in assessing physical habitat conditions at the reach scale over a wide range of flows (e.g. Spence and Hickley, 2000; Booker and Dunbar, 2004; Moir et al; 2005), but they cannot be used to assess local habitat or sediment transport regime conditions and associated hydrogeomorphic processes in hydraulically complex streams (Gibbins et al., 2002). Rehabilitating channel complexity within and between channel units is often a project goal (Pasternack et al., 2004; Wheaton et al., 2004b; Elkins et al., 2007). At the other extreme, three-dimensional (3D) models have a more detailed representation of physics and are more accurate (Lane et al., 1999; Clifford et al., 2005; MacWilliams et al., 2006), but many important geomorphic and ecological functions critical to environmental management have not yet been related to 3D hydrodynamics.

Given the ability to couple hydrodynamic, geomorphic, and ecologic processes in a 2D model, opportunities exist to understand the riverine ecosystem better and improve applied river management of riffle-pool sequences. Riffle-pool sequences are the central geomorphic feature of many rehabilitation projects in gravel-bed rivers and they accommodate diverse organisms that fit different niches. Riffles and pools are a well-researched topic in fluvial geomorphology (Gilbert, 1914; Keller, 1971; Richards, 1976; Clifford and Richards, 1992; Sear, 1996;

Thompson et al., 1999) and aquatic ecology (Gorman and Karr, 1978; Brown and Brown, 1984; Giller and Malmqvist, 1998). Partly due to numerical modeling studies it is now understood that "self-maintenance" of the relief between riffle crests and pool troughs through time depends on two scales of channel non-uniformity that induce flow convergence routing (Carling, 1991; Booker et al., 2001; Cao et al., 2003; MacWilliams et al., 2006). During frequent low flows when discharge is less than bankfull, longitudinal variations in channel shape drive flow convergence over riffles causing gradual incision, armoring, and a decrease in riffle-pool relief (Brown and Pasternack, 2007). During infrequent overbank floods, lateral variations in channel and valley shape drive flow convergence over pools causing them to scour and thereby restoring riffle-pool relief. "Forced" pools associated with local, non-streamlined bank protrusions (e.g., bedrock, boulders, or wood) additionally experience vortex shedding that causes local scour (Thompson, 2006). Numerical models that assess the presence of flow convergence routing are now being used in gravel-bed river assessment (e.g. Brown and Pasternack, 2007; Moir and Pasternack; 2008) and rehabilitation (e.g. Wheaton et al., 2004b; Elkins et al., 2007).

One notable mechanism by which riffles affect pools and interact with each other is through the backwater condition that a riffle crest imposes on upstream channel units (Fig. 1). Recognizing that a riffle crest behaves like a man-made weir and backs water upstream (Clifford et al., 2005), some practitioners have long used weir equations to predict riffle depth for specified design discharges (Clifford and French, 1998). Wheaton et al. (2004a) explained and illustrated that it is possible to manipulate the crest elevation of a downstream riffle to affect the habitat conditions of the next upstream riffle. Elkins et al. (2007) tested that concept in a specific channel manipulation and documented how upstream riffle-pool hydrodynamics and physical habitat for fish spawning may be controlled. When the downstream riffle crest was at a low elevation and the upstream one was at a high elevation, the velocities on the next upstream riffle were high, erosion potential was very high, and physical habitat quality was low. After gravel was used to raise the downstream riffle crest, the velocities on the upstream riffle decreased significantly, causing a reduction in erosion potential and a dramatic improvement in physical habitat quality. These findings demonstrate the importance of backwater hydraulics on ecohydraulics and channel rehabilitation design. However, they are not a systematic exploration of the wide range of possible backwater conditions that might exist naturally or in association with channel rehabilitation. Consequently, it is hypothesized that hydrogeomorphic processes and ecological conditions in a sequence of riffles and pools may be highly sensitive to the hydrodynamic interaction between a riffle and the next one downstream.

The upstream hydraulic response to controlled manipulation of a downstream riffle crest suggests a natural analog associated with flood-induced channel change. Erosion of a downstream riffle crest is theorized to increase upstream velocities and erosion rates. One significance is that channel rehabilitation designs optimized for low-flow physical habitat area might increase the risk of riffle collapse during floods in the absence of an investigation of backwater hydraulics.

In this study numerical experimentation was undertaken to explore the significance of channel non-uniformity and discharge at characteristic pool-riffle-pool units on physical habitat conditions and sediment transport regimes associated with regulated gravel-bed streams. Such rivers typically have bed slopes of 0.001-0.01, width to depth ratios of 20-100, depth to median grain size ratios of 2-60, and a Shields stress incipient motion threshold of ~0.03. These non-dimensional values express the range of conditions for which this study has general scientific relevance. The objectives were to (1) assess the consequences of backwater, uniform, accelerating, and critical hydrodynamics on physical habitat and sediment transport regimes in the experimental scenarios, (2) assess how the consequences of these hydrodynamics vary as a function of discharge, and (3) assess how the consequences from objectives 1 and 2 vary between a typical transverse riffle with a notched crest and a steeper diagonal riffle (Table 1). To provide a scientifically rigorous and reductionistic approach with the simplest experimental design capable of answering the study's questions, the two channel configurations were limited to a single pool-riffle-pool unit. The importance of this basic research is that it demonstrates the primacy of channel non-uniformity in riffle-pool functionality, points out the ecological and geomorphic functionality of backwater conditions, and strongly questions the common practice of assuming uniform flow conditions in most gravel-bed river rehabilitation studies and basic scientific studies of sediment transport processes in gravel-bed rivers.

2. EXPERIMENTAL DESIGN

The overall approach used to assess pool-riffle-pool response to downstream water surface elevation (WSE) was to conduct 2D (depth-averaged) hydrodynamic modeling of two pool-riffle-pool configurations using four hydraulically significant WSEs and three ecologically significant discharges (Q) (Tables 1, 2). A real sequence of 4 riffle-pool units on the gravel-bed Trinity River below Lewiston Dam, CA (Fig. 1; 40°43'34"N, 122°47'48"W) was used as a reference reach to prepare and validate a 2D model suitable for a straight, gravel-bed, riffle-pool stream in a confined valley typical of where dams are located (USFWS, 1999; Brown and Pasternack, 2007). Then experimental pool-riffle-pool channel units were fabricated using AutoCAD Land Desktop to obtain digital elevation models that represent two specific pool-riffle-pool morphologies within the ranges of non-dimensional geomorphic variables stated one paragraph above, using the Trinity River's topography as a starting point for experimental design. The two fabricated riffle types included generic transverse and diagonal bars, which are both commonly found in straight reaches of confined gravel-bed rivers, not just on the Trinity River, providing broad scientific value. They are also common forms built in river rehabilitation projects in California on rivers such as the Sacramento, Mokelumne, Stanislas, and Merced Rivers. System response was evaluated in terms of flow pattern, fish habitat quality, and sediment transport regime. Specific methods were previously developed and validated using a similar shallow gravel-bed reach of the Mokelumne River, CA (Pasternack et al., 2004; Wheaton et al., 2004a, b; Elkins et al., 2007), but in those cases, multiple Q's and downstream WSEs were not evaluated. In particular, Pasternack et al. (2004) evaluated six different pool-riffle-pool channel morphologies, but only at a single Q and downstream WSE.

2.1 Experimental Channel Units

The first experimental pool-riffle-pool configuration consisted of a transverse riffle with a notched crest forming a chute (Fig. 2a). Chutes over riffles are natural thalweg features that are also useful in channel design for habitat heterogeneity and to bypass flow around the adjacent riffle crest (Elkins et al., 2007). The riffle crest and chute were 22 m long. The riffle entrance had an upslope of 0.0117. The riffle exit had a downslope of 0.0108, so the bar was fairly symmetrical. The maximum riffle-pool relief was 0.7 m and the overall bed slope was 0.0056, which are typical of good conditions for fish habitat associated with riffles (Elkins et al., 2007).

The second pool-riffle-pool configuration consisted of a slender, steep diagonal bar (Fig. 2b). Upstream pool, riffle crest, and downstream pool elevations were kept identical to those used in the notched riffle scenario, but the riffle entrance and exit slopes were steeper (0.0263 and 0.1407, respectively) and oriented to form a horseshoe-shaped drop on river left. The length of the diagonal bar was 15 and 57 m at the shortest and longest sections, respectively. The overall bed slope was very close to the notched riffle scenario (0.0059).

2.2 Numerical Model

A 2D hydrodynamic model, Finite Element Surface Water Modeling System 3.1.5 (FESWMS), was used to simulate the flow pattern and predict the fish habitat quality and sediment transport regime of the two test configurations. FESWMS solves the vertically integrated conservation of momentum and mass equations using a finite element method to acquire depth-averaged 2D velocity (U, V) and water depths (H) at each node in a finite element mesh. The model can simulate subcritical and supercritical flows. Hydrodynamic equations, discretization methods, and other details for solving the above equations using FESWMS were described by Froehlich (1989). This model has been heavily validated for use in shallow, regulated gravel-bed rivers (Pasternack et al., 2004; Wheaton et al., 2004b, Pasternack et al., 2006; Elkins et al., 2007; Moir and Pasternack, 2008). Brown and Pasternack (2007) developed, calibrated, and validated a FESWMS model of the reference reach of the Trinity River below Lewiston Dam used as the starting point for creating the channel configurations in this study. The calibration and validation of the Trinity model is summarized below to characterize the model's uncertainties in light of the inability to explicitly validate exploratory simulations.

FESWMS was implemented using the Surface Water Modeling System v. 8.1 (EMS-I, South Jordan, UT). Computational meshes for the channel scenarios had a typical internodal distance of 1.37 m, which was comparable to the spacing of the original topographic survey data from the reference reach (Brown and Pasternack, 2007). Meshes only covered the wetted channel, yielding slightly different final meshes for each discharge and riffle configuration.

To run FESWMS, Q at the upstream boundary and WSE at the downstream boundary are required. The flow regime for Lewiston Dam, typical of the regulated gravel-bed rivers in California at this time, was used to select ecologically significant Q's for the freshwater lifestage of anadromous Pacific salmon, including fish spawning in autumn (8.5 $m^3 s^{-1}$), fish attraction in summer (70.8 $m^3 s^{-1}$), and physical habitat rejuvenation during the highest release as of December 2004 (170 $m^3 s^{-1}$). Flow was assumed to be normal to the upstream boundary and it was distributed across the channel in proportion to the cross-sectional area of each boundary mesh element. These assumptions were validated by measuring H and U near the upstream boundary in the reference reach (Brown and Pasternack, 2007). WSEs at the downstream end of the reference reach were measured at Q's between 8.5-170 $m^3 s^{-1}$ using a total station to obtain a stage-discharge rating curve useful for simulating any flow in this range.

For the two fabricated channels, the model's downstream boundary was in a pool and corresponds with the level imposed by the next downstream riffle, which can be natural or re-engineered to any desired elevation (Elkins et al., 2007). The downstream WSE was varied to achieve backwater, uniform, accelerating (subcritical), and critical conditions. Even though shallow gravel-bed channels can naturally experience gradually and rapidly varied flows, it is common practice in channel design to assume uniform conditions. The backwater WSE was set the same for both riffle forms, and matched that imposed by a downstream riffle with a crest at 559.67 m. For both configurations, the downstream uniform-flow WSE was obtained using

$$Q = \frac{1.0}{n} A R_h^{2/3} S_0^{1/2} \quad (1)$$

where n is Manning's roughness, A is downstream cross-sectional area, R_h is hydraulic radius, and S_0 is channel slope. The defining equation for the Froude number (Fr) was used to determine critical depth and from that the critical WSE. A representative WSE for a subcritical accelerating flow was taken as the halfway WSE between those for uniform and critical flows.

The two primary model parameters in FESWMS are eddy viscosity (E) and bed roughness (n). E varied spatially in the model according to

$$E= c_o + 0.6 \cdot H \cdot u^* \tag{2}$$

where u^* is shear velocity and c_o is a minimized constant added for numerical stability (Fischer et al., 1979). Even with this variability, it is not enough to yield as rapid lateral variations in U as occurs in nature, presenting a fundamental limitation of FESWMS (MacWilliams et al., 2006). Roughness associated with resolved meter-scale bedform topography was explicitly represented in the detailed channel DEM. 2D models are highly sensitive to DEM inaccuracies (Bates et al., 1997; Hardy et al., 1999; Lane et al., 1999; Horritt et al., 2006). For unresolved roughness, a global n of 0.043 was used with all meshes (Pasternack et al., 2004, 2006; Elkins et al., 2007; Moir and Pasternack, 2008). This was not numerical calibrated. It was validated by comparing observed and predicted WSEs along the reference reach at different Q's as well as by comparing observed and predicted H and U values at cross-sections. Although one can vary n spatially in a 2D model to try to account for variable bed sediment facies, it is difficult to justify small (<0.005) local deviations relative to 2D-model and measurement accuracy in gravel-bed rivers. 2D models have been reported to be sensitive to large (>0.01) variations in n values (Bates et al., 1998; Lane and Richards, 1998; Nicholas and Mitchell, 2003), and the validation approach used here would reveal that scale of deficiency. Also, in typical projects the material placed on the bed has a set size distribution, is well mixed, and is not differentiated between riffles and pools.

2.3 Model Validation

In this study FESWMS was used for exploratory experimentation using fabricated, theoretical pool-riffle-pool units to improve the basic understanding of how flow, channel form, and fish habitat quality interrelate in shallow gravel-bed rivers. Acceptance of the numerical approach requires reasonable confidence in the predictive utility of FESWMS for the conditions explored in the study. As reported by Brown and Pasternack (2007), three different tests assessed model uncertainty for the Trinity River reference reach. First, the range of E values in model output was checked against field-based estimates calculated using the same equations with H and U measurements and taken in the real reach at the spawning discharge. Modeled and measured E values were found to be similar (~0.02-0.1 $m^2 s^{-1}$).

Second, recognizing that in a straight confined reach lateral and longitudinal variation in U in a river is highest at low Q (Clifford and French, 1998), detailed model validation of H and U on the Trinity River was performed at 12.9 $m^3 s^{-1}$. Predictions at two of the five cross-sections evaluated in detail by Brown and Pasternack (2007) show the typical results, with H accurately predicted and U predicted less well (Fig. 3). Spatial gradients in U were not predicted as strongly as observed, but at many spots U was very accurately predicted.

Third, a total station was used to measure the WSE at 14 locations at 170 $m^3 s^{-1}$ (vertical accuracy of <1 cm). These profiles were compared against modeled ones to test the selected Manning's n of 0.043. Modeled WSE was systematically slightly higher than observed, with the deviation averaging just 5% of mean cross-sectional depth at each observation location (standard deviation of 2.5%). Thus, n for this highest flow was slightly high, but not enough to warrant iterative calibration. Model validation of the reference reach once again showed that FESWMS is accurate enough to provide confidence that the reported spatial patterns in depth and velocity are real, but is not accurate enough to characterize regions with very strong lateral variation precisely, for which 3D numerical modeling would be better.

2.4 Fish Habitat Quality

Habitat quality predictions were made by extrapolating 2D model flow results through independent habitat suitability curves for H and U that were developed locally for the Trinity River. Although such empirical relations exist for many species, it was necessary to select specific examples for this study, so the ecological indicator species of anadromous Pacific salmon for the region- Chinook salmon, steelhead trout, and coho salmon- were used. Both spawning and rearing freshwater life-stages associated with riffles were assessed. The specific empirical habitat suitability curves used were obtained from previous research (USFWS 1999). To isolate the effect of hydraulics on habitat and simplify the experimental design, no substrate quality curve was used. A global habitat suitability index (GHSI) was calculated as the geometric mean of the H and U indices (Pasternack et al., 2004). To account for U uncertainty, GHSI values were lumped into broad classes, with GHSI = 0 as non habitat, $0 < \text{GHSI} < 0.1$ as very poor habitat, $0.1 < \text{GHSI} < 0.4$ as low quality, $0.4 < \text{GHSI} < 0.7$ as medium quality, and $0.7 < \text{GHSI} < 1.0$ as high quality (Leclerc et al., 1995). These broad classes reduce the impact of U prediction error, since they are largely insensitive to ~0-25 % U error. Elkins et al. (2007) tested whether model-estimated GHSI values for shallow gravel-bed streams obtained using FESWMS accurately predicted fish utilization patterns. They reported a strong, statistically significant fish preference for high quality habitat and an equally strong, statistically significant fish avoidance of non habitat and very poor quality habitat.

2.5 Sediment Transport Regime

Pasternack et al. (2006) validated the suitability of FESWMS for predicting bed shear stress in shallow gravel-bed rivers, finding that the model is as good as field estimation methods most of the time; the exception being in very shallow water (H ~ d_{90}, size that 90% of the bed material is smaller than). In this study, Shields stress was calculated at each mesh node to evaluate the sediment transport regime and channel stability under different flow conditions:

$$\tau^* = \frac{\tau_v^b}{(\gamma_s - \gamma_w) d_{50}} \tag{3}$$

$$u^* = \frac{U}{5.75 \log\left(\frac{12.2H}{2d_{90}}\right)} \text{ and } \tau^b_v = \rho_w u^{*2} \tag{4,5}$$

where τ^* is Shields stress, τ^b_v is bed shear stress in the direction of the velocity vector, d_{50} is median grain size, γ_s is sediment specific weight, γ_w is the water's specific weight, and ρ_w is water density. As with GHSI, τ^* was binned to account for H inaccuracy. Lisle et al. (2000) defined sediment transport regimes relative to τ^* as $\tau^* < 0.01$ is no transport; $0.01 < \tau^* < 0.03$ is intermittent entrainment; $0.03 < \tau^* < 0.06$ is Wilcock's (1996) "partial transport"; $0.06 < \tau^* < 0.10$ is full transport; and greater than 0.10 is a channel-altering condition.

3. RESULTS

The results are organized by test metric, with each subsection containing only an overview of the extensive results to conform to journal page requirements. A full detailed analyses by WSE, riffle configuration, and discharge is available upon request to the corresponding author. Overall, the simulations showed significant differences in patterns of hydrodynamics, spawning habitat quality, and Shields stress for the different flow conditions and topographies evaluated. The results for the critical WSE simulations were similar to those for the accelerating WSE simulations, so they are not illustrated. Similarly, steelhead spawning results mimicked those of Chinook, except that GHSI values were lower due to the preference of steelhead for lower velocities, so they are not shown. Little spawning habitat was found at the two higher Q's, so those GHSI results are not presented, but there is some discussion of it in section four. Fry habitat for all species was limited to channel margins that were always present and showed little interesting variation. The key finding is that different downstream WSEs controlled by the hypothetical crest elevation of the next downstream riffle yielded significantly different spawning habitat conditions and sediment transport regimes.

3.1 Downstream WSEs

Iterative calculations for downstream WSEs for uniform and accelerating flows differed greatly from those for the backwater flow (Table 2). For example, for the notched, transverse riffle at spawning Q, the estimated uniform downstream WSE was 0.42 m lower than that for the backwater WSE. The decrease in downstream WSE to get halfway to the critical value was only another 0.07 m. For the diagonal riffle, the corresponding values were 0.55 m and 0.06 m. At the highest Q, the difference increased to 0.76 m and 0.23 m for the notched, transverse riffle and 0.88 and 0.22 m for the diagonal riffle. The enhanced deviation from uniform flow at higher Q indicates that channel non-uniformities exert more backwater effect at the higher Q. Since the bed is already underwater, the observed backwater effect can be ascribed to channel constriction.

3.2 Physical Habitat

Corresponding with a decrease in downstream WSEs, the spatial distribution of medium and high quality spawning habitat for Chinook salmon changed significantly. Habitat quality deterioration mainly occurred downstream of the riffle crest, indicating that the crest elevation was controlling the hydrodynamics in the upstream pool, even with the backwater WSE imposed (Fig. 4). A similar response was observed in both riffle configurations, but with the notched, transverse riffle showing the more significant change. Overall, in the notched, transverse riffle configuration, the area of high- and medium-quality habitat decreased from 33 and 57 % of total area to 15 and 41 % of total area, respectively, as the flow conditions changed from backwater to uniform (Fig. 5). By further reducing the downstream WSE to yield accelerating flow, an additional 1.4 and 3.6 % decrease in high- and medium-quality habitat area was observed, respectively. In contrast, the diagonal riffle configuration had significantly different habitat distributions at the spawning Q. In this case, the transition from backwater to uniform flow yielded no change in the area of high (22 %) and medium (~50 %) quality habitat. There was a net decrease of 9 % in the area of medium-quality habitat when the downstream flow was accelerating. Although this change from uniform to accelerating flows was more significant than for the notched, transverse riffle configuration, the difference in spatial distribution was more similar for accelerating and uniform flows than when compared with backwater flow.

3.3 Channel Stability

Just as with habitat quality, the spatial τ^* distribution underwent major changes between backwater and uniform downstream WSEs, but only minor changes from uniform to accelerating downstream WSEs (Fig. 6). For both channel configurations, the backwater WSE yielded the most area of stable bed ($\tau^* < 0.03$). For example, at 8.5 $m^3 s^{-1}$, 62.5 % of the surface area of the notched, transverse riffle configuration had $\tau^* < 0.01$. This area was reduced by 42.6 or 43.7 % in total area when the downstream WSE changed from backwater to uniform or accelerating, respectively. Similarly, τ^* indicating partial transport ($0.03 < \tau^* < 0.06$) increased from 4.8 % in total area by 17.3 or 20.3 % for the shift from backwater to uniform or accelerating, respectively. In the diagonal-bar riffle configuration, the same pattern emerged, with the total area of $\tau^* < 0.01$ decreased from 73.6 % of total area by 34.4 or 33.2 % of total area for uniform or accelerating flow, respectively. In this scenario, the region of partial transport increased from 4.3 % of total area for the backwater condition to 0.7 or 3.6 % for uniform and accelerating conditions, respectively.

When the flow rate was 170 $m^3 s^{-1}$ with a backwater condition imposed, τ^* intensity for both riffle configurations increased mainly to the partial transport domain under backwater conditions (Fig. 6). When the downstream WSE was set to uniform, the region with τ^* indicating full bed mobility ($0.06 < \tau^* < 0.10$) increased sharply in total area by 56 %. Going from backwater to accelerating WSEs not only expanded the regional of full mobility, but also yielded $\tau^* > 0.1$ over 14.2 % of the total area. Similar to the notched, transverse riffle, under a backwater WSE the diagonal riffle maintained ~ 30 % of its total area with $\tau^* < 0.03$, but had ~60 % experiencing partial transport. When the downstream WSE was dropped to uniform in this case, regions of partial transport shifted to a full bed mobility regime (Fig. 6b).

For the notched, transverse riffle at 8.5 $m^3 s^{-1}$ and with the backwater WSE, the regions with the highest τ^* generally occurred over the riffle, which typically had the lowest depths and highest velocities (Fig. 7a). When compared to backwater conditions, uniform conditions were remarkably different over most of the river, except for the upstream pool (Fig. 7b). The intensity of τ^* was higher throughout the channel. Regions of partial transport included much of the riffle crest, the whole notch, the riffle tail, and the downstream pool entrance. Where there was a small rise in the bed of the pool on the river right, a zone of partial transport occurred. With the decrease in WSE from uniform to accelerating, minimal change was observed between the two.

The regions of highest stress remained the same for the diagonal bar riffle configuration, which had occurred over or just downstream of the riffle crest. For backwater flow conditions, the area of the upstream pool and channel margins had $\tau^* < 0.01$ (Fig. 7c). Unlike the notched, transverse riffle, the diagonal bar had supercritical flow over a portion of the crest, even with backwater conditions. A hydraulic jump was predicted at the toe of the riffle exit. The accuracy of the FESWMS model in the jump region is expected to be poor, though we have observed FESWMS to be accurate in standing waves on the Yuba River, CA. In uniform or accelerating conditions, major changes occurred over the lower half of the riffle and the second pool. Along the steep drop behind the riffle crest, supercritical flow expanded to cover the whole length of the bar, and it intensified τ^* (Fig. 7d). Channel-altering bed-load transport was predicted here. In the region where the dried out riffle crest created a stagnant pool, there was no transport predicted. At the base of the drop behind the bar, H increased and flow decelerated. The exception to this was in the horseshoe thalweg where flow convergence produced a narrow jet of high-velocity flow whose width expanded downstream. As it expanded, its sediment transport regime shifted from full bed mobility to partial transport, and then to only intermittent transport (Fig. 7d). The only difference evident under the accelerating downstream WSE condition was an increased region of the riffle crest that dried out.

At 70.8 $m^3 s^{-1}$ for both configurations with a backwater WSE, the channel had τ^* between 0.01-0.03 over the riffle tail, downstream pool, and part of the upstream pool for both riffle configurations. Partial transport occurred over the riffle entrances. Channel-altering transport conditions found at 8.5 m^3 s^{-1} for the diagonal bar riffle were not at the higher Q's, because the hydraulic jumps drowned out. Similar to the lower Q results, with a uniform WSE the channel was less stable. For both configurations, most of the channel away from the riffle and downstream boundary experienced partial transport. The peak transport regions, which shifted slightly downstream towards the exit of the riffle relative to the backwater simulation, had higher stresses ranging from partial to channel-altering transport, which occurred over the notched and diagonal bar riffle crests.

At 170 m^3 s^{-1} and with the backwater WSE, the stresses remained between 0.03-0.06 compared to 70.8 m^3 s^{-1} and expanded to include most of the channel for both riffle configurations (Fig. 8a,c). When the WSE decreased to uniform or accelerating, τ* intensified over the entire channel with stresses mostly between 0.06-0.10 (Fig. 8b,d). In addition, τ* between 0.10-1.0 increased significantly throughout the channel and were found near the riffle crest for the notched, transverse case and at the entrance of the diagonal bar for the other case. Also, for the diagonal bar case, there was another region with channel-altering conditions further downstream at the river-right bank. Channel-altering transport was also found in only accelerating flow along the downstream boundaries for both riffles too. Notably, neither riffle configuration showed a depth-averaged U or τ* "reversal" from low to high Q between riffles and pools. Peak τ* always occurred on the riffles, regardless of Q.

4. DISCUSSION

Two different pool-riffle-pool configurations were simulated using FESWMS for varying discharges and downstream WSE conditions. These 24 simulations provided detailed results to answer the three questions posed in this study (Table 1), even recognizing the uncertainty in simulation models.

4.1 Role of Downstream WSE

Downstream WSE is a primary control on flow pattern, spawning habitat quality, and sediment transport regime. Significant differences in channel functionality were predicted by the 2D model for the different downstream WSEs. The most important finding was that backwater conditions are necessary for a pool-riffle-pool unit to have the highest quality salmon-spawning habitat (Fig. 4). Riffle-pool hydrodynamics that yield backwater conditions also significantly enhance the morphological stability of high-quality habitat areas during all discharges (Fig. 5). During autumn low flows, scour does not naturally occur on non-uniform riffles and pools; hence Chinook salmon have evolved to establish egg pockets during that time. Even in subsequent months when Chinook embryos are incubating and Steelhead trout are spawning, flows are primarily low. Infrequent early winter storms when basins are already saturated yield punctuated moderate flows for short durations. Backwater conditions stemming from riffle-pool non-uniformity were found to result in only partial transport under such discharges. Thus, embryos buried deeper than d_{90} would survive such events.

The extent of natural gravel riffles with accelerating downstream WSE conditions is not known, but the interdependence between near-critical flow conditions, bed material size, and channel adjustment hypothesized by Grant (1997) ought to limit their persistence in the absence of other rejuvenating processes, such as flow convergence routing. One place where this condition has been observed is on the lower Yuba River (39°13'31"N, 121°19'39"W) below Englebright Dam, where the channel is incising into the remaining estimated 9-18 million m^3 of coarse sediment generated by hydraulic gold mining of hillside deposits fills the valley floor (Pasternack, unpublished data). In that reach, several riffle crests end in a steep knickpoint with accelerating to supercritical flow during the dry season. In contrast to natural riffles, the likelihood of producing accelerating conditions in construction of artificial riffles is apparently high, because narrow bars are a common bedform used in river rehabilitation (e.g. Fig. 1). Most projects are designed using analytical or 1D numerical models that bias managers toward uniform channel morphologies. In this study, it was found that a riffle built to yield uniform conditions would be a major hazard to the next upstream riffle. Even at the spawning discharge, the relative area of the channel above the critical threshold for initiation of sediment transport (τ^*~0.03) was estimated to increase by 250-520 % when a uniform WSE was imposed instead of the backwater WSE. Concomitant with this increased instability was a decrease in area of medium- and high-quality spawning habitat by 4-37 %. This decrease was significantly mitigated by the presence of another backwater condition imposed by the riffle in the middle of the study area, which acted as a weir maintaining higher depths and moderate velocities even as the downstream conditions deteriorated from a uniform to accelerating WSE.

4.2 Discharge Effects

Since most management schemes for regulated rivers call for low discharges during fish spawning periods, the effect of higher discharge on spawning was not focused on here. Analysis showed that a small amount of spawning habitat was present under the 70 $m^3 s^{-1}$ regime, but high depths and velocities were limiting. At 170 $m^3 s^{-1}$ there was virtually none present except along narrow channel margins. More importantly, the area of channel bed subjected to partial or full bed mobility significantly increased as a function of discharge, with a mitigating effect provided by backwater downstream WSE, as described above. As discharge increased, the flow pattern became more homogeneous, with higher velocities in the channel center and lower velocities along the margins. The consequence of a riffle acting as an upward bed step under subcritical flow conditions is that flow decreases in depth and accelerates over the non-uniformity (Fig. 1), focusing scour at the point of maximum acceleration beyond the riffle crest. Higher discharges yield stronger scour regimes. As long as the flow width is nearly constant, as it was in this study, the location of maximum scour remains just downstream of the riffle crest, at least until the crest is destroyed.

4.3 Channel Configuration Control

In this study, only two simple channel geometries were investigated to exemplify the riffle-pool dynamics associated with varying downstream WSE. The notched, transverse riffle with backwater flow conditions was found to produce the maximum quantity of high-quality habitat. Higher quality habitat was found in both riffle entrance and exit, as flow over the crest was too fast. However, whereas the notch in the transverse riffle allowed water to bypass the crest, the physical habitat in the diagonal riffle configuration proved more resistant to changing flow conditions because the even crest elevation produced a weir effect that backed water up providing high-quality habitat in the convective acceleration zone between the pool and the riffle. When the flow conditions were uniform or accelerating, the diagonal bar riffle configuration yielded more medium- and high-quality habitat.

At 8.5 $m^3 s^{-1}$, the notched, transverse riffle configuration was more stable than the diagonal bar riffle configuration. Since the diagonal bar's riffle exit was so steep, supercritical conditions were predicted to occur and cause some instability. Further, even though it could not be accurately modeled, a hydraulic jump was predicted to be present, and this would induce local scour and knickpoint migration, eating away at the bar. Scour would be severe if the downstream riffle yielded uniform or accelerating WSE conditions. Had the diagonal bar been designed with a more gently sloped riffle tail, the deleterious hydraulic jump could have been avoided in favor of undular jump conditions, so this lesson served to aid improved diagonal riffle designs.

Once discharge was >70 $m^3 s^{-1}$, the hydrodynamic and sediment-transport-regime differences between the two riffle configurations diminished. The water flowed much faster over the same central region at the high flow rates for both channel types. Scour remained focused on the riffle crest. Neither configuration yielded a velocity or shear stress “reversal”. The significance of this finding is that this study provides further confirmation that equalization or reversal of water surface slopes between riffles and pools is not the mechanism for riffle-pool self-maintenance as proposed by Keller (1971). Instead, pools must have a significantly lower expansion of cross-sectional area as a function of increasing discharge than riffles (Carling, 1991; MacWilliams et al., 2006). Such a difference results in flow acceleration and scour through pools and deceleration over riffles. In straight reaches below dams, the primary means for initiating this difference through rehabilitation is by building riffles that are significantly wider and shallower than pools at low discharge. This conjecture has been incorporated into the Spawning Habitat Integrated Rehabilitation Approach (Wheaton et al., 2004a,b).

4.4 At-a-station Design Analysis

Classic fluvial geomorphology and current river restoration practice place a primary focus on the role of a “dominant” discharge in the understanding and design of channel morphology (Rosgen, 1997). An important outcome of this study is that the functionality of a riffle-pool morphology is not determined by the local discharge, but instead is determined by the downstream water surface elevation dictated by the non-uniform hydrodynamics induced by the next downstream riffle. This result has profound implications for river restoration design. At least on par with evaluating the dominant discharge, restoration practitioners should perform at-a-station hydraulic geometry cross-comparisons in which the stage-discharge rating curves for the riffle crest and adjacent pools are obtained by observation, not computed falsely assuming uniform flow. The impact of a change to in-channel morphology on at-a-station hydraulics is central to understanding the functionality of the riffle-pool channel unit. 2D modeling is a useful tool for evaluating the functionality, but it may also be possible to finesse this through other means of at-a-station cross-comparison or using 1D modeling with many cross-sections.

4.5 Reverse Domino Conjecture

Given that the sediment transport regime of riffles evaluated individually in this study showed a high sensitivity to downstream WSE, it was impossible for an inquiring mind to not mentally extrapolate how variations in downstream WSE would affect channel morphodynamics over time, even though this was not explicitly modeled. Specifically, gravel-bed rivers are currently thought to re-organize their riffles and pools when sufficient flow is present to induce widespread Shields stress to partially suspend whole features, at which point channel maintenance stemming from shear stress “reversal” between riffles and pools no longer functions. However, a detailed mechanism of riffle failure, including the sequence by which riffles fail does not exist. Although the mechanism that follows is pure conjecture, it is rooted in the results of the study, and thus seems appropriate to expound upon.

A "reverse domino" mechanism is proposed in which downstream WSE plays the critical role in determining the timing and sequence of riffle-pool re-organization (Fig. 9). Specifically, if one riffle were to catastrophically fail (Fig. 9b) for whatever reason to be discussed shortly, the water surface elevation would drop, sending a wave of flow acceleration upstream to the next riffle. A sudden shift in riffle tail conditions involving a dramatically increased local water surface slope would create a jump in Shields stress that could then cause that riffle to fail (Fig. 9c), according to Grant's (1997) critical flow threshold conjecture. This failure would send a wave with even greater acceleration upstream, causing further riffle failures (Fig. 9d).

The results of this study lend strong support to the idea that a rapid change in downstream WSE would destablize a riffle and cause it to catastrophically fail. For both riffle configurations, a shift from backwater to lower-than-uniform WSE was observed to transform the channel from ~40% of its area not experiencing even partial transport to >65 % of its area experiencing full bed mobility. These results do not include the significant unsteady shear stress that would result from this failure scenario.

At the same time that a failed riffle would propagate a WSE depression upstream, it would also send increased discharge downstream. Under a competing conjecture, one might argue that this discharge could push the next downstream riffle beyond a key threshold and cause it to fail, yielding a downstream domino effect. A significant aid to such a mechanism would be a channel constriction at the riffle crest. However, the results of this study caution against this conjecture. The effect of increasing discharge on Shields stress is mitigated by riffle non-uniformity, such that each downstream riffle would work against the discharge pulse, slowing it down. This negative feedback contrasts with the positive feedback of an upstream propagating wave.

The primary question arises as to what causes the first riffle to fail in the first place. One possibility is that riffle failure occurs earlier at a particular site because that site has a valley constriction that is hydraulically activated at a threshold discharge governed by local at-a-station hydraulic geometry. The constriction would focus scour on the riffle and induce failure prior to failure at riffles lacking such a constriction. A second possibility is that large woody debris and hillslope-derived boulders that force riffles and pools (Thompson et al., 1999) either become emplaced or fail, thereby causing the associated riffle to fail. A third possibility is that a riffle composed of finer bed material catastrophically fails first. A fourth possibility is that a riffle already has a knickpoint with accelerating flow conditions, such as observed on the lower Yuba River, and thus may quickly migrate through the riffle crest more rapidly during the rising limb of a flood when the water surface slope is steepening.

Although this “reverse domino” mechanism for riffle-pool channel re-organization is pure conjecture and cannot be evaluated solely on the basis of this study, this idea is new and warrants consideration and testing. As more river projects are built assuming uniform flow conditions, the opportunity for observing how such poorly designed structure fail increases, which can be a benefit to advancing basic geomorphic theory. Determining the likely mechanism of riffle failure in a reach could significantly aid flow re-regulation experiments that are trying to change channel conditions downstream of dams without active channel manipulation.

5. CONCLUSIONS

This study evaluated the importance of considering the downstream water surface elevation to the functioning of riffle-pool units, whether natural or designed. In a pool-riffle-pool sequence, the influence of riffle crest elevation on flow patterns propagates upstream through the pool and to the next riffle. Sufficient backwater conditions are necessary to produce high-quality Chinook and steelhead spawning habitat. A higher backwater condition is needed for steelhead than for Chinook. Backwater conditions also help embryos survive moderate floods, by limiting mobility to partial transport, whereas uniform channel conditions would yield full bed mobility. A notched, transverse riffle was found to function better than a steep diagonal bar. From a design perspective, the downstream water surface elevation for a project site may be controlled by manipulating the crest of the next downstream riffle. One potential consequence of these results is that there may exist a "reverse domino" mechanism for the failure of a sequence of riffles and pools.

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Figure Captions

Figure 1. Artificial pool-riffle unit in the Lewiston Dam reach of the Trinity River, CA illustrating a backwater effect causing convective flow acceleration into a riffle. This is a common hydraulic structure built into gravel-bed rivers.

Figure 2. Oblique shaded visualizations of the non-uniform channel morphologies of A) a notched, transverse riffle (44 m wide by 101 m long) and B) a diagonal bar riffle (49 m wide by 93 m long).

Figure 3. Comparisons of observed versus predicted depths (A,B) and velocities (C,D) at 2 cross-sections in the Lewiston Dam Reach from a baseline modeling study performed prior to the numerical experiments reported in this study. Field observations were fit with a curve using the locally weighted Least Squared error method to reduce measurement noise.

Figure 4. Spatial pattern of Chinook salmon spawning habitat quality. Habitat quality is illustrated as white for non-habitat in dry areas and deep pools, light grey for very poor quality, medium grey for low quality, dark grey for medium quality, black for high quality.

Figure 5. Comparison of relative areas of Chinook salmon spawning habitat quality for the two riffle configurations in three downstream WSEs. Shading is identical to that in Figure 4.

Figure 6. Comparison of discharge and downstream WSEs for their impact on bed stability ($\tau^* < 0.03$) for A) a notched, transverse riffle and B) a diagonal bar riffle.

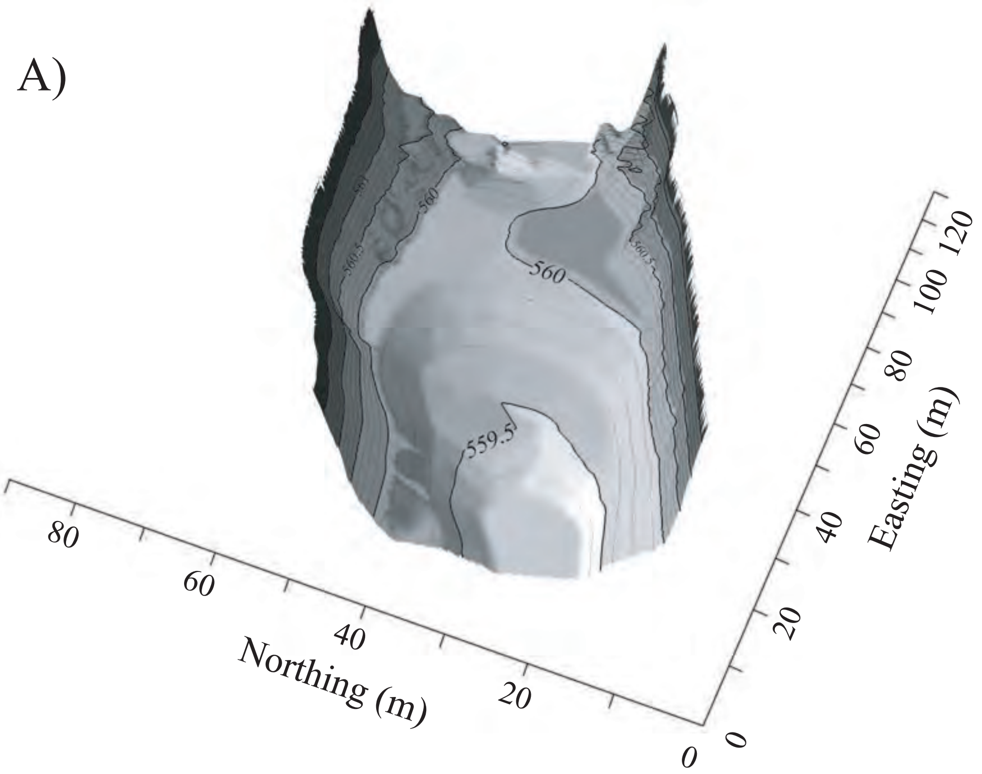
Figure 7. Spatial pattern of shields stress at 8.5 $m^3 s^{-1}$ with superposed velocity vectors. Color legend is white = 0; lightest grey = 0-0.01, light grey = 0.01-0.03, medium grey = 0.03-0.06 (partial transport), dark grey = 0.06-0.10 (full bed mobility), black = 0.10-1.0.

Figure 8. Spatial pattern of shields stress at 170 $m^3 s^{-1}$ with superposed velocity vectors. Color

legend same as used in Figure 7.

Figure 9. Conceptual illustration of the mechanism of riffle-pool degradation during a flood or sequence of floods as proposed in the reverse domino conjecture. Flow is from top to bottom, while sequential riffle scour is from bottom to top. Panel A) is the initial morphology of a sequence of riffles and pools. Subsequent panels show the change through time. Panel D) shows the eventual outcome of a single long glide lacking in morphologic diversity.

A)


561
560
560.5
560
560.5
559.5
80
60
40
Northing (m)
20
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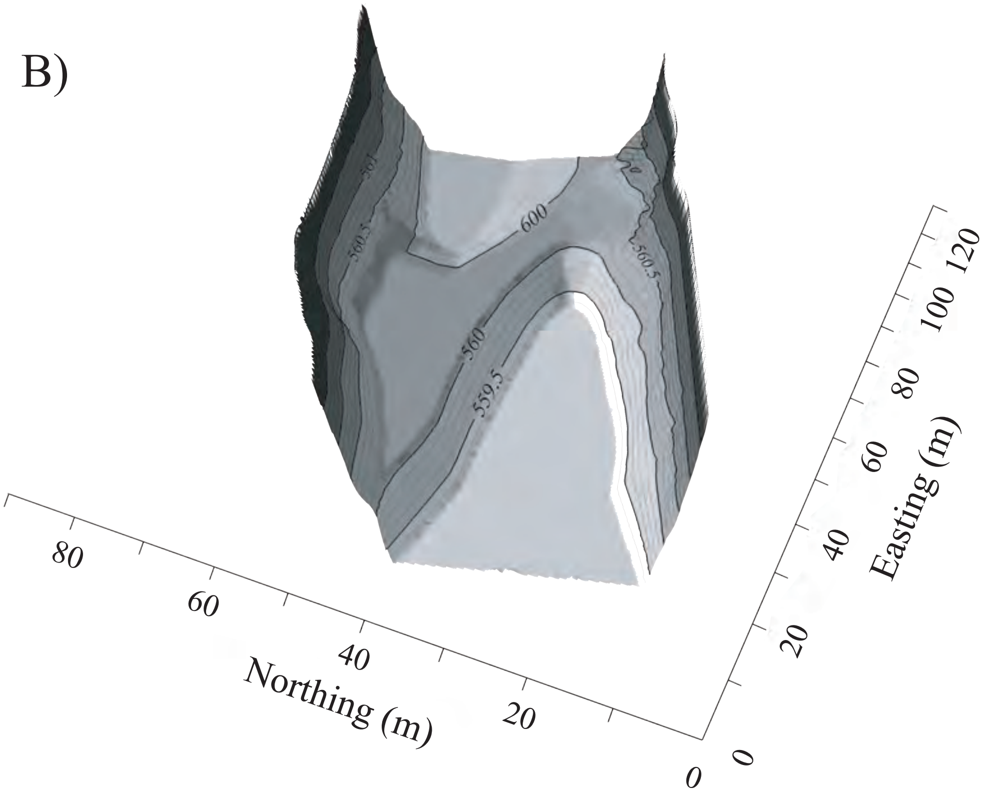
0
20
40
60
80
100
120
Easting (m)

B)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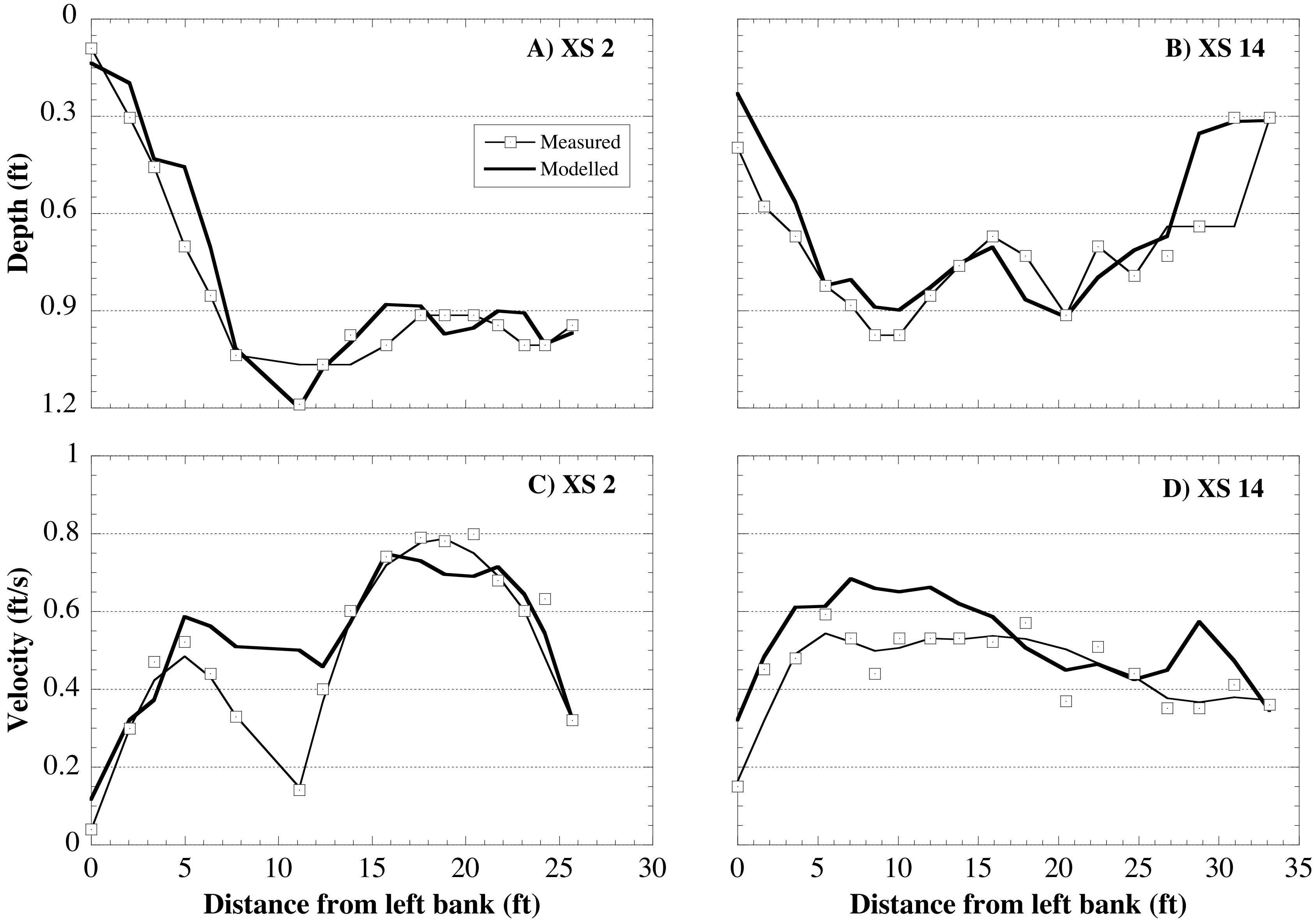
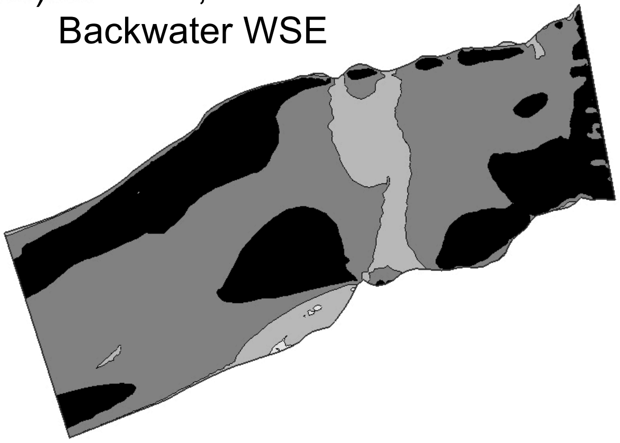
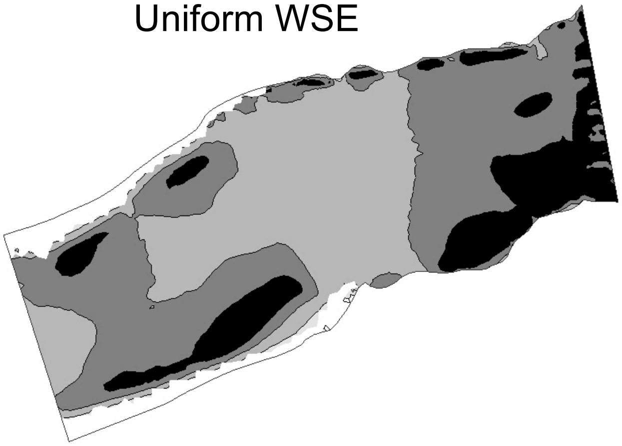
Easting (m)

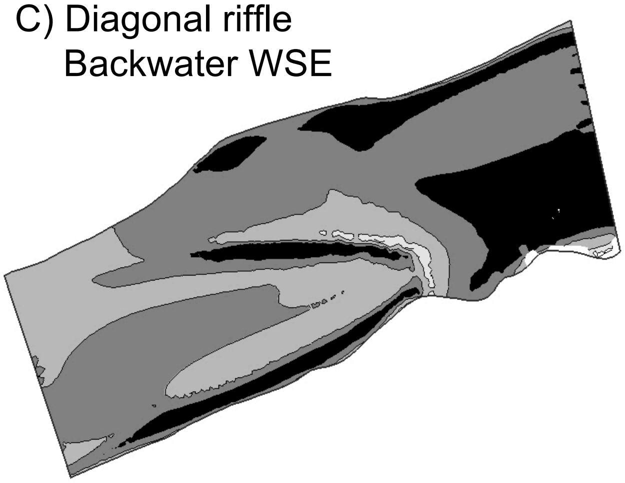

A) XS 2
B) XS 14
C) XS 2
D) XS 14
Measured
Modelled
Depth (ft)
0
0.3
0.6
0.9
1.2
Velocity (ft/s)
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
35
Distance from left bank (ft)
Distance from left bank (ft)



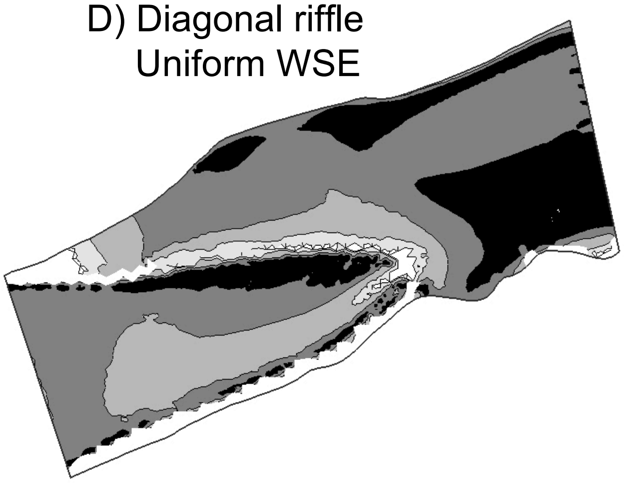
A) Notched, transverse riffle
Backwater WSE



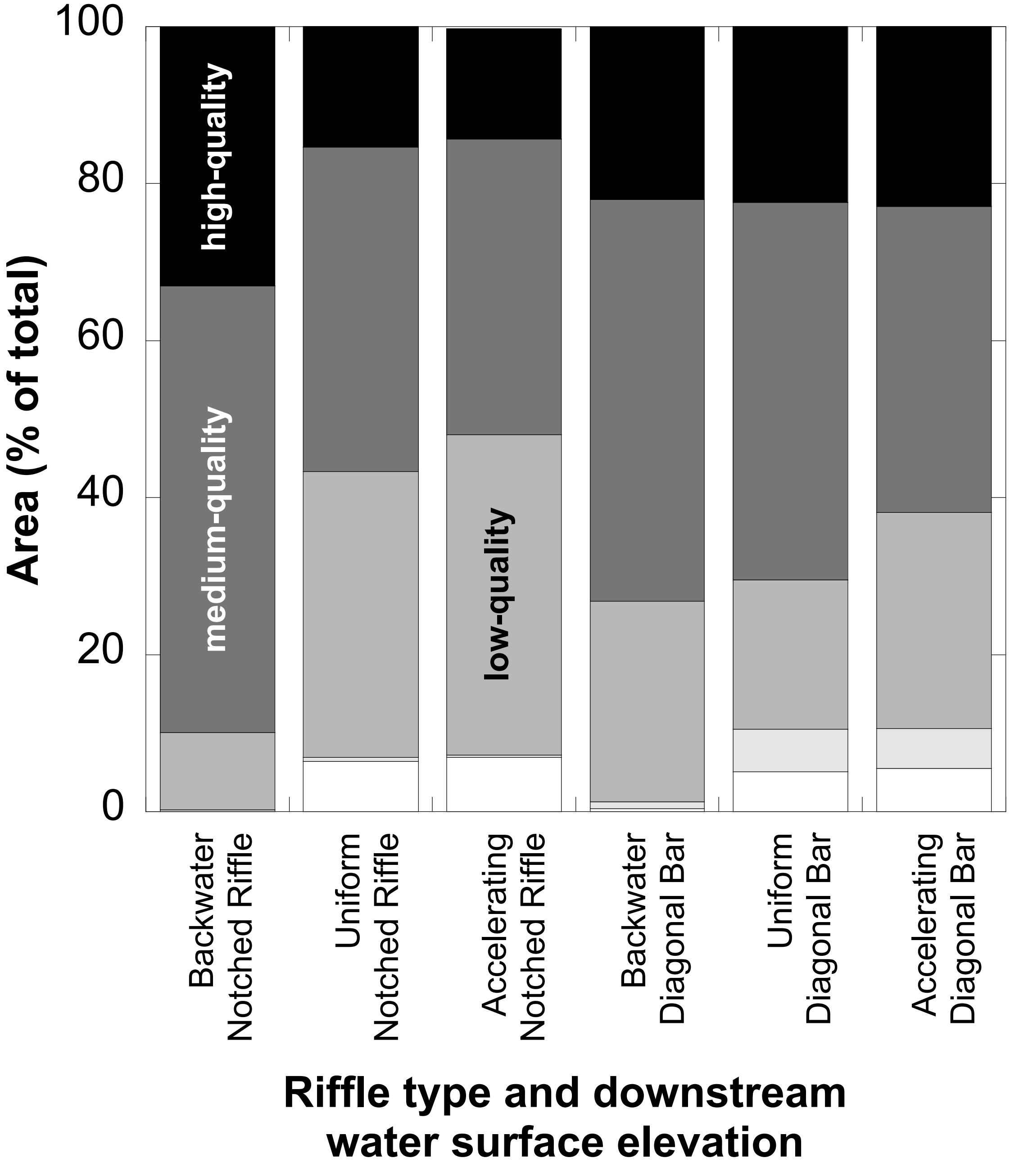
B) Notched, transverse riffle
Uniform WSE



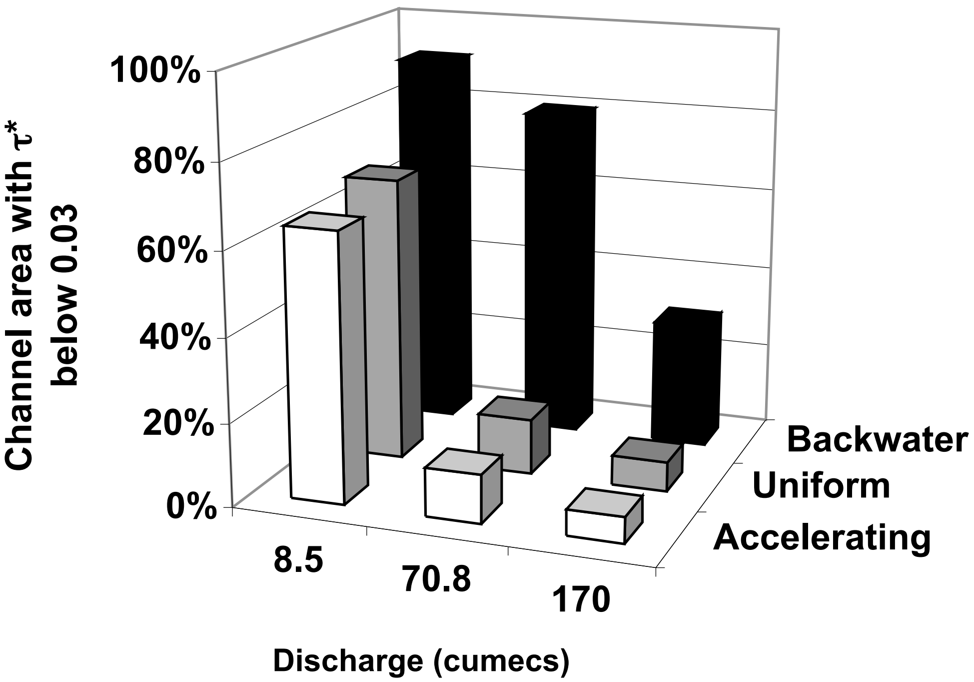
C) Diagonal riffle
Backwater WSE



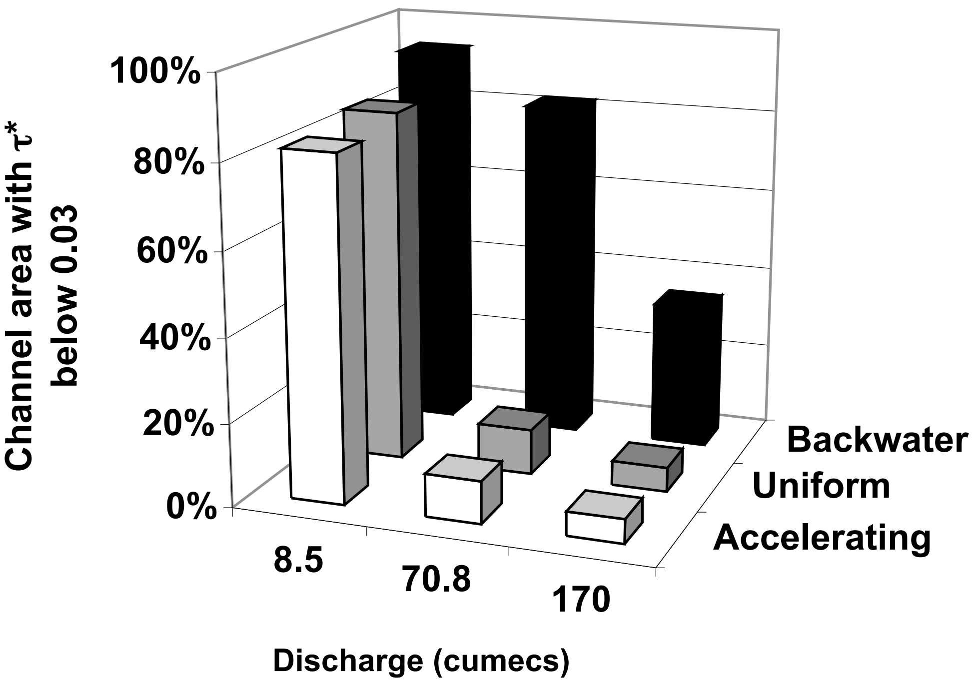
D) Diagonal riffle
Uniform WSE

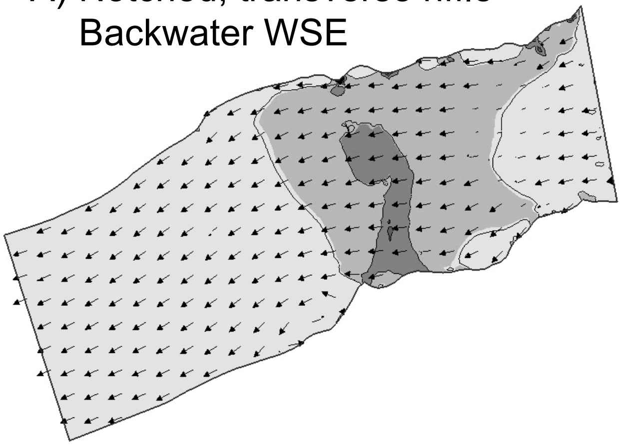

Area (% of total)
0
20
40
60
80
100
high-quality
medium-quality
low-quality
Backwater Notched Riffle
Uniform Notched Riffle
Accelerating Notched Riffle
Backwater Diagonal Bar
Uniform Diagonal Bar
Accelerating Diagonal Bar
Riffle type and downstream water surface elevation

A) Notched Riffle

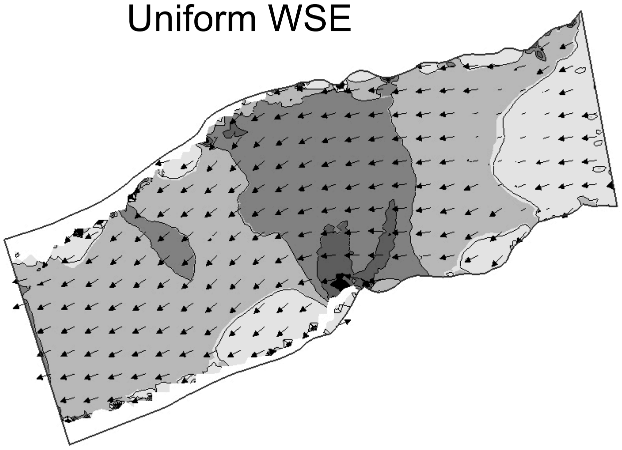


B) Diagonal Bar Riffle

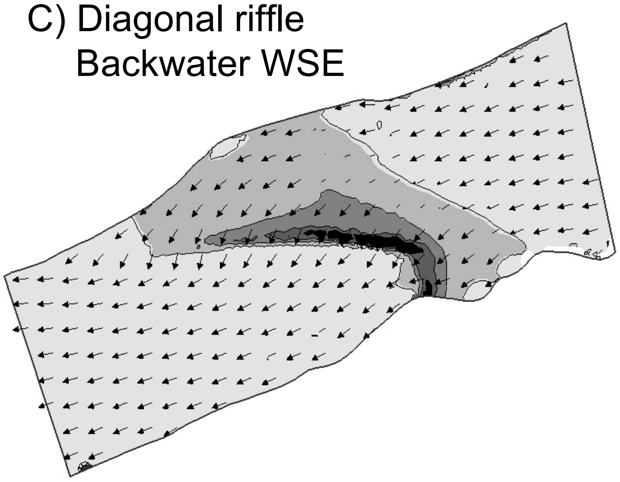




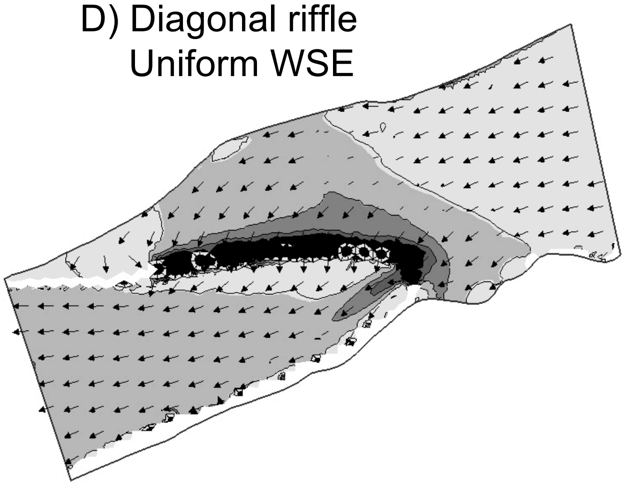
A) Notched, transverse riffle
Backwater WSE



B) Notched, transverse riffle
Uniform WSE

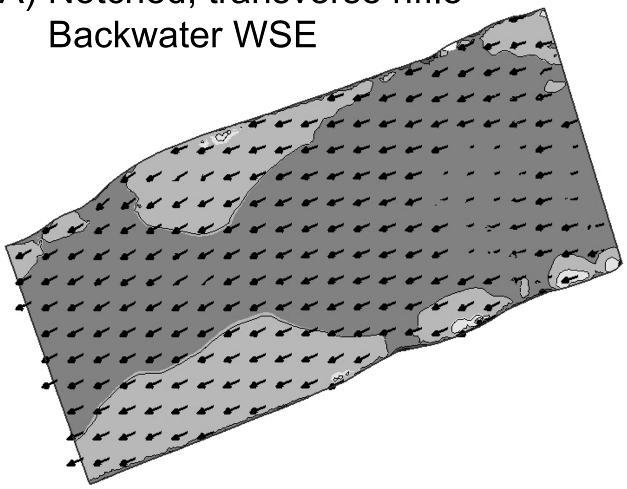


C) Diagonal riffle
Backwater WSE

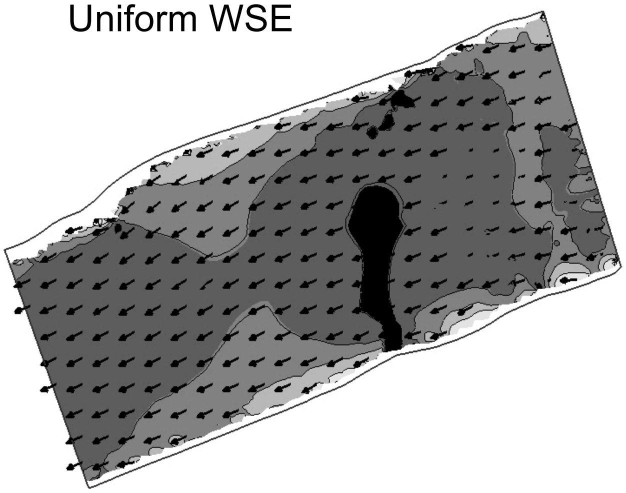


D) Diagonal riffle
Uniform WSE

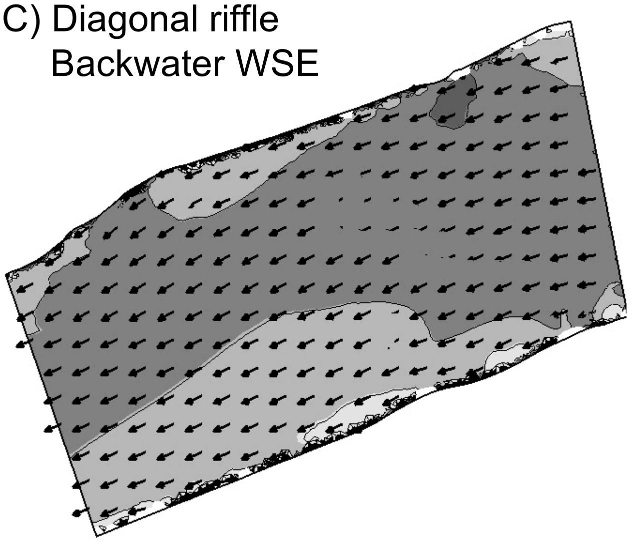
A) Notched, transverse riffle
Backwater WSE



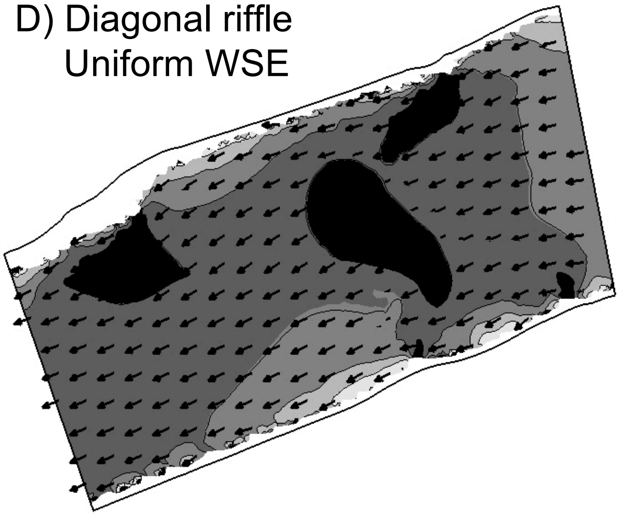
B) Notched, transverse riffle
Uniform WSE

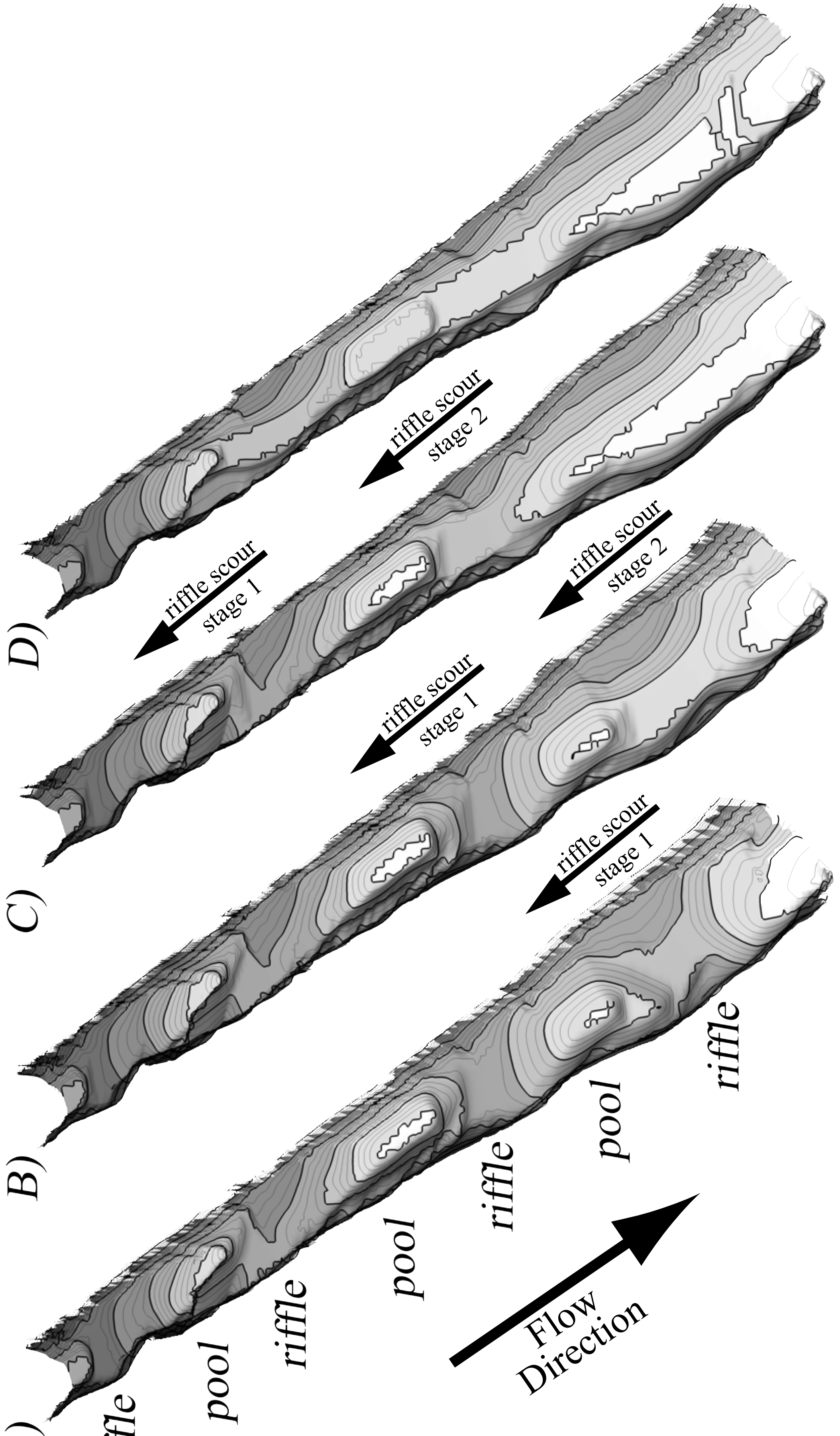


C) Diagonal riffle
Backwater WSE



D) Diagonal riffle
Uniform WSE




A)
B)
C)
D)
riffle
pool
riffle
pool
riffle
pool
riffle
Flow Direction
riffle scour stage 1
riffle scour stage 1
riffle scour stage 2
riffle scour stage 1
riffle scour stage 2