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Running Title: Ecohydraulic Design of Riffle-Pool Relief

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ABSTRACT

Riffle construction is a common practice in river engineering, but insufficient science exists to guide objective design of riffle-pool relief and the three-dimensional forms of features smaller than the scale of channel width. In this study, numerical experimentation with two-dimensional hydrodynamic modeling and ecohydraulic analysis was used to evaluate the performance of six different configurations of a sequence of riffle-pool units typical of shallow, regulated gravel-bed rivers, emphasizing a range of riffle-pool amplitudes (e.g., low, intermediate with hybrid features, and high). Twenty-two specific performance indicators (16 for physical habitat and six sediment-transport regime) were used to compare designs. It was found that low riffle-pool relief yielded the best performance for the majority of physical habitat indicators and all of the sediment transport regime indicators. The spatial patterns of test metrics revealed the mechanisms responsible for the statistical outcomes. Methodologically, two-dimensional modeling and ecohydraulic analysis are vital tools in project design along with previously accepted hydrologic, geomorphic, and engineering analyses. Scientifically, low-relief riffle-pool units are indicated as the normative condition in gravel-bed rivers where forcing elements driving deep scour are not systematically controlling morphology.

1. INTRODUCTION

Ecohydraulics is a rapidly emerging quantitative subdiscipline of river science with use in river engineering and rehabilitation in degraded landscapes (Nestler et al., 2008; Wheaton et al., 2011). Ecohydraulics links ecological functions and hydrodynamic patterns at each spatio-temporal scale (Pasternack, 2011). It is often used for baseline instream flow assessment emphasizing relations between species' physical habitat and discharge. The Instream Flow Incremental Methodology (IFIM) is a widely adopted tool for incorporating quantitative ecohydraulics into flow assessment (Bovee and Milhous, 1978; Bovee, 1982; Jowett, 1997), often facilitated using PHABSIM software (Waddle, 2001). Normally a statistical evaluation of flow and habitat is done, but now spatially explicit (2D) habitat modeling is practical (Ghanem et al., 1996; Pasternack, 2011). Studies have compared semi-analytical, 1D, and 2D ecohydraulic methods (Waddle et al., 2000; Brown and Pasternack, 2009). Many rivers exhibit a spatial anisotropy of channel geometry (Merwade, 2009) capable of steering flow, thereby violating 1D-model assumptions (Brown and Pasternack, 2009). In such cases, 2D modeling and GIS-based spatial analyses are necessary, and even for isotropic, orthogonal geometries they are preferential for evaluating mesohabitat structure (Hauer et al., 2011) as well as microhabitat heterogeneity. Use of 3D models is emerging, but suffers for lack of 3D ecological relations, the high cost and complexity of 3D validation, longer 3D numerical modeling time, and disproportionate GIS data volume and processing time.

In the practice of site- and reach-scale river rehabilitation, standard engineering and geomorphic methods have been highly criticized (Wissmar and Beschta, 1998; Simon et al., 2007; Lave et al., 2010), exacerbated by iconic failures against project goals (Kondolf and

Micheli, 1995; Doyle and Harbor, 2000). Statistical ecohydraulic methods such as IFIM that depend on static channel assumptions, direct observations of channel hydraulics, and static empirical parameters cannot yield predictions for alternative channel configurations, so they have limited ecohydraulic applicability as a tool for river engineering (as opposed to their strength in river assessment). Design methods that empirically mimic landforms (i.e. “natural channel design”) or hydrology (i.e. “natural flow regime”) are prescriptive and have no independent, quantitative design-testing scheme, yielding a high risk of failure when used alone.

The philosophy underlying *ecohydraulic design for river engineering* is that channel geometry is manipulated and then mechanistically tested until it achieves a flow-dependent hydraulic regime with a palette of homogeneity and heterogeneity at different spatial scales that is suitable for the breadth of geomorphic processes and ecosystem functions that are characteristic of a natural river of the type undergoing diagnosis and treatment. A key aspect of this design framework is that landforms designed at multiple spatial scales are not arbitrary, but are founded on scale-dependent physical mechanisms needed for morphologic resilience, such as stage-dependent flow convergence routing (MacWilliams et al., 2006; Sawyer et al., 2010) and pool maintenance by turbulent vortex shedding at forcing elements (Woodsmith and Hassan, 2005; Thompson, 2006). Ecohydraulic analysis of 2D hydrodynamic models is rooted in observation, but is structurally more universal than empirical, prescriptive geomorphic methods (Brown and Pasternack, 2009; Pasternack, 2011) and can cope with synthetic channel modifications (Pasternack et al., 2008; Oh et al., 2010). Ecohydraulic design has been tested in different applications and found useful as a tool for evaluating alternatives for channel reconfiguration, gravel injection, floodplain and side channel inundation, increasing habitat complexity, and spawning habitat rehabilitation (Elkins et al., 2007; Manwaring et al., 2009; Hoopa Valley Tribal Fisheries et al., 2011).

Now that the use of spatially explicit ecohydraulics in river engineering is established, there is an opportunity to generate design principles and project guidelines through scientific testing of diverse scenarios. Pasternack et al. (2004) tested the value of four channel patterns for yielding high-quality Chinook salmon spawning habitat on a regulated, degraded gravel-bed river, with two of those outperforming the *ad-hoc* project. Pasternack et al. (2008) used ecohydraulics to test riffle configurations, tailwater levels (imposed by the next downstream riffle that is not being altered), and discharge on physical habitat quality and morphological resilience. Instituting a backwater effect downstream of a design riffle aids both of those desired outcomes. Elkins et al. (2007) corroborated this in a real spawning habitat rehabilitation.

The goal of this study was to use ecohydraulic analysis of 2D model results in a numerical experiment to test the relative merits of building sequences of riffle-pool units in regulated gravel-bed rivers with different magnitudes of riffle-pool relief. 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 ~0.03-0.06. These dimensionless values express the range for which this study is relevant, except they ignore riffle-pool relief. While metrics for evaluating (let alone designing) riffle-pool relief are limited, alternative-design morphologies were compared using the slope-detrended relief indices of amplitude (A_{RP}), the difference between the maximum riffle crest elevation and the minimum pool trough on the slope-detrended river profile (Vetter, 2011), and asymmetry (A^*_{RP}), the ratio of the absolute values of slope-detrended riffle height and pool depth about the zero-crossing line (O'Neil and

Abraham, 1984; Rayburg and Neave, 2008). A high A^*_{RP} indicates a riffle crest sticking disproportionately high above the zero-crossing line.

Riffle-pool relief is an important yet untested metric for channel design, because it could play an important role in morphologic resilience during floods (Pasternack et al., 2008). There is no widely used dimensionless metric for riffle-pool relief design and there exist few pristine reference rivers free of anthropogenic influence to evaluate and mimic, especially for design of sub-width channel features. The studies mentioned above did not systematically assess the effect of riffle-pool relief on physical habitat quality and morphological-unit resilience against a range of flows. They also did not look at a sequence of units, just an individual pool-riffle-pool unit.

The specific objectives of this study were to assess the consequences of high versus low riffle-pool relief on (1) physical habitat quality for Chinook salmon and steelhead trout in their sensitive spawning and fry lifestages at the regulated discharge typical for the periods when those lifestages occur and (2) sediment transport regimes during two geomorphically and ecologically significant flows, as explained below. A third objective looked beyond relief to assess how the consequences from objectives one and two vary between different riffle-pool shapes. The discharges focused on were flows associated with bed occupation during the freshwater reproductive cycle (salmon spawning in autumn, embryo incubation in late autumn and early winter, and fry development in winter) (8.5 $m^3 s^{-1}$) and physical-habitat rejuvenation during prescribed spring snowmelt releases, using the highest regulated release as of December 2004 (169.9 $m^3 s^{-1}$).

2. EXPERIMENTAL DESIGN

The approach used to assess the effect of riffle-pool relief on river rehabilitation was to (a) design six synthetic river digital elevation models (DEMs) with different riffle-pool sequence configurations for a given testbed regulated river reach, (b) conduct 2D modeling of the synthetic designs at two key discharges, (c) extrapolate hydraulic predictions through physical-habitat curves and sediment transport regime equations, and (d) extract and compare performance indicators to determine designs' relative merits. Alternative designs were guided by the science about riffle-pool assemblages and the emerging knowledge of the structure, organization, and function of morphological units (e.g., Padmore et al, 1998; Fukushima, 2001). Previous research established performance indicators for physical habitat quality for indicator species' lifestages and sediment transport regimes (Elkins et al., 2007; Pasternack et al., 2008; Brown and Pasternack, 2008; Brown and Pasternack, 2009), as explained in sections 2.5-2.7 below.

A sequence of riffle-pool units on the gravel-bed Trinity River immediately below Lewiston Dam, California, USA (40°43'34"N, 122°47'48"W) was used as a reference assemblage (i.e. "pre-project" or "baseline" scenario) to prepare and validate a 2D model suitable for a straight, gravel-bed, riffle-pool stream in a confined valley (Brown and Pasternack, 2008). Then six experimental riffle-pool sequences were fabricated using AutoCAD Land Desktop® to obtain DEMs with different A_{RP} and A^*_{RP}, using the Trinity River's topography as a starting point for experimentation (Fig. 1). These alternatives were not scientific curiosities, but actual morphologies evaluated for construction below Lewiston Dam (Pasternack, 2004a); they were consistent with fluvial landforms in straight reaches of confined gravel-bed rivers that are common in Californian rivers (e.g., Manwaring et al., 2009; Sawyer et al., 2009; Cramer Fish Sciences, 2010).

System response was evaluated in terms of flow pattern, fish habitat quality, and sediment transport regime at two discharges within the regulated range permitted by operational rules at the time. Specific methods were previously developed and validated on the Trinity as well as on a similar shallow gravel-bed reach of the Mokelumne River (Pasternack et al., 2004; Wheaton et al., 2004a, b; Elkins et al., 2007). Unlike Pasternack et al., (2008), this study only evaluated a single tailwater water surface elevation for each discharge, using the real observed stage-discharge relation for the study reach as reported by Brown and Pasternack (2008).

2.1 Baseline Testbed Reach

Studies of hydrology, geomorphology, fisheries, and reach-scale ecohydraulics of the baseline study reach already exist for the Trinity River (USFWS, 1999, 2002; Brown and Pasternack, 2008; Gaeuman, 2008, 2011) and are briefly described here for context. The Trinity River above Lewiston Dam is an 1860-km^2 basin that is part of the Klamath Mountain Province in northwestern California. Damming barred access to ~160 km of upstream spawning grounds. Flow regulation and floodplain structures limit flushing of tributary-delivered sand and geomorphic processes that maintain alluvial spawning grounds, while enabling vegetation encroachment that degrades rearing habitat. Salmonid populations have dropped sharply and are the focus of habitat rehabilitation, though systemic factors are also addressed. Since 1972, projects have included gravel augmentation, channel reconfiguration, bank vegetation removal, and flow reregulation.

The 760-m Lewiston hatchery reach (LHR) that was the testbed for this study is located immediately downstream of Lewiston Dam and is the uppermost limit of salmonid spawning access. Previous work in the LHR determined that the existing artificial topography and substrates are controlled by anthropogenic and natural boundary and input controls that preclude natural geomorphic processes (Brown and Pasternack, 2008). Historically, the channel was wide with inset active alluvial gravel bars and a forested floodplain, but now it is narrow and straight. The river is confined on its south flank by a fish hatchery and on its north flank by bedrock. These forcings cause uniform high flow widths that preclude differential rates of sediment entrainment among morphological units at the 1-10 channel-width scale. The riverbed is armored by decades of flow and sediment regulation and it has coarse artificial riffle-steps (i.e., rock weirs) buttressed by boulders, which further degrades the topography for fish habitat. These structures do not have any of the geometric, hydraulic, or sedimentary attributes of riffles utilized by salmonids for spawning. The channel cannot adjust itself regardless of flow. These factors necessitate that channel rehabilitation is dependent on physical manipulation, which is limited by non-deformable boundary controls.

2.2 Design Concepts and Tools Used

Six channel configurations (Fig. 1) were developed within the real constraints imposed by site conditions, management objectives, laws and regulations, and other institutional factors. Research to date suggests that flow-dependent width variations between riffle and pool units is a prerequisite for sustainable (i.e., resilient during floods) riffle-pool units, assuming sediment supply is not limiting and in the absence of extreme bed-material grain-size differences between riffles and pools (Carling and Wood, 1994; MacWilliams et al., 2006; Wheaton et al., 2010; Thompson, 2011). Limited space for channel widening (or width undulation) constrained process-based design (Brown and Pasternack, 2008). Therefore, adding gravel/cobble fill and adjusting the amplitude and relief of morphologic units were the primary opportunities to enhance riffle-pool units. Although width undulation aids riffle-pool resilience (White et al., 2010), rivers below most large dams are channelized, constricted, and at least armored, if not scoured to bedrock. Also, flow regulation limits inundation of high-elevation valley wall oscillations. Furthermore, constructing channel designs with gravel/cobble using front loaders involves bulk placement of the sediment mixture (Sawyer et al., 2009); it is uncommon to design and install different surficial bed-material facies. Thus, evaluations of large width oscillations and differential bed texture were not considered.

The Spawning Habitat Integrated Rehabilitation Approach (SHIRA) for rehabilitating regulated gravel-bed rivers organized all phases of the project, including design development and final design selection aided by 2D modeling and ecohydraulic analysis (Wheaton et al., 2004a, b). A design objective is a specific goal that is aimed for when a project plan is implemented. To achieve the objective, it is turned into a design hypothesis, which is a mechanistic inference, formulated on the basis of scientific literature and available site-specific data, and thus is assumed true as a general scientific principle (Wheaton et al., 2004b). Next, specific morphological features are designed to work with the flow regime to yield the mechanism in the design hypothesis. Finally, a numerical test is formulated to determine whether the design hypothesis was appropriate for the project and the degree to which the design objective will be achieved.

The six alternative designs (Fig. 1) were created with diverse features that have many specific design hypotheses. The list of all design hypotheses is beyond the scope of this book chapter, but is available at the website Pasternack (2004b). A key aspect of the designs for the channel assemblages is that they span a range of different amplitudes of riffle-pool relief (Table 1; Fig. 2) and different planview patterns (Fig. 1). For each of these design elements, a suite of concepts and objective design tools aided the creative process of conceptualizing landforms and articulating their value toward hydraulic, geomorphic, and fisheries objectives in the form of design hypotheses. Riffle and bar analogs were generated by visualization from similar morphological-unit scale features in unregulated rivers. Next, these analogs were scaled and overlaid on the pre-project topography. The spacing and location of riffles were determined somewhat by existing locations and more so by fixed forcing elements, but this was varied between designs. Analytical and empirical design and testing of riffle crests was performed for low-flow conditions to determine if crests had gross hydraulic properties suitable with design objectives. The net volumetric fill (m^3) of gravel and cobble for each design was calculated by digital elevation model differencing in AutoCAD Land Desktop® between the baseline topography and that for each design. Finally, 2D modeling of design surfaces was used to evaluate each design with respect to performance indicators and spatial mechanisms.

For riffle-pool relief, some of the relevant design concerns included base flow riffle and pool habitat suitability and quality, stage-dependent riffle scour potential, knickpoint migration through riffles, and the resilience of riffle-pool relief. Initial riffle-crest sizing was done iteratively aided by depth and velocity estimates using the Cipoletti weir equation and mass conservation for specified discharges, because a crest functions like a weir to cause a backwater effect (USBR, 1953; Clifford et al., 2005). Hydraulic estimates for the regulated baseflow typically present during salmon spawning, embryo incubation, and fry development were used to check habitat quality and gravel scour potential at that flow. Riffle-pool relief metrics (A_{RP} and

A^*_{RP}) were computed for each individual pool-riffle pair in each design and averaged by design according to the method of Pasternack and Brown (2011).

For plan view morphology, design factors included the lateral distribution of mesohabitats, stage-dependent resilience of microhabitat patches, sediment routing through pools, knickpoint migration through riffle crests, the resilience of riffle-pool relief, and accessibility of pools preferred for recreation fishing. Some specific design morphometrics included degree of pool constriction for flow convergence, shape of riffle exit (e.g. horseshoe shaped, straight, or convex), crestline obliquity for flow divergence, partial riffle-crest notches/chutes for flow bypassing, and central bars for stage-dependent microhabitat resilience.

2.3 Experimental Riffle-Pool Assemblages

Due to page limits, readers are directed to Pasternack and Brown (2011) for thorough explanations of designs, with a brief overview here. Designs One, Two and Three involved high riffle-pool relief (aka "accentuated topography") and higher bed slope, while Designs Four, Five, and Six involved low riffle-pool relief (aka "blanket fill), lower bed slope, and ~3-m widening on river right (Table 1). The concept for Design One was to maintain the existing pattern of features, but accentuate them by building up riffles and increasing bed slope, yielding a high riffle-pool relief of 1.54 m (Fig. 2a). The three large riffles were conceived to provide for salmon spawning, the pools for adult holding, and the low-velocity bank fringe for fry habitat. Design Two had two large broad flat riffles with transverse orthogonal crests and accentuated pools, yielding a high riffle-pool relief of 1.58 m and a high asymmetry value of 2.57 (Fig. 2b). The central pool was designed to be large, channel-spanning, and have a lot of submerged features for juvenile rearing and adult holding. The large riffles were designed for Chinook and steelhead spawning. Using preliminary lessons learned from "stress testing" Designs One and Two with ecohydraulic analysis, Design Three was a modification of Design One that had a significantly lower slope, longer riffles, and smaller, narrower pools (Fig. 2c). It was conjectured that the central bar and flanking pools at the end of the design would provide adult holding habitat proximal to spawning habitat and habitat heterogeneity in the face of fluctuating spawning flows. Also, the two small pools might serve as sediment traps to retain sediment placed upstream in this key spawning reach over time. Design Four had a blanket fill with three riffles; the upper two had similar shapes as those in the previous designs with shallower intervening pools, while the third riffle was long and broken up with local crests and chutes (Fig. 2d). Even though riffle amplitude was very low, the fact that the bed undulation occurred on top of fill created a strong asymmetry for the last pool-to-riffle unit. This design sought to increase fluvial complexity, while maintaining low feature-to-feature slopes. A new feature for this design that was also used in Designs Five and Six was that the channel was widened three meters on river right to remove encroached vegetation and provide low-velocity, shallow habitat for fry. The biggest difference from the earlier designs was the presence of a long glide that featured a pair of tightly-spaced alternating bars at the end of the reach. Glides can serve for salmon spawning, especially for steelhead, so it was a worthwhile landform to evaluate. Design Five had a blanket fill with three simple riffle crests and a straight longitudinal bar (Fig. 2e). The goal for Design Five was to have the lowest change in riffle-pool relief to limit the amount of gravel fill, while still maintaining the same slope as in the baseline topography as well as to increase fluvial complexity and spawning habitat, while minimizing low-flow scour of that habitat. Design Six continued the evolution of the blanket-fill concept from Design Five by significantly increasing the sizes and amending the shapes of the second and third riffles, which resulted in a lower overall bed slope (Fig. 2f). It also used two longitudinal bars, each with a hook at the end to force flow divergence. The exit slope of the last riffle was graded convexly to cause flow divergence instead of convergence, and thus reduce scour on the riffle exit in the thalweg and shift scour energy to the rough banks where it would have little impact. Overall, the six designs use a lot of different specific elements, but share some commonality dictated by geomorphic and ecohydraulic knowledge. For comparison, the baseline real longitudinal profile is shown in Figure 2g. That profile shows little coherent landform organization, with just a few rock weirs peaking up above the slope-detrended median bed elevation.

2.4 2D Numerical Model

A 2D hydrodynamic model, Finite Element Surface Water Modeling System 3.1.5 (FESWMS), was used to simulate hydrodynamics for the baseline channel and the six alternative designs. FESWMS solves the vertically integrated conservation of momentum and mass equations using a finite element method to acquire depth-averaged 2D velocity components (U, V) and water depths (H) at each computational-mesh node. FESWMS simulates subcritical and supercritical flows. Froehlich (1989) described hydrodynamic equations, discretization and solution methods, and other FESWMS details. This model has been frequently 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; Manwaring et al., 2009; Sawyer et al., 2010). Brown and Pasternack (2008) developed, calibrated, and validated a

FESWMS model of the LDR baseline channel, which is summarized below to characterize the uncertainties that affect experimental simulations.

FESWMS was implemented using the Surface Water Modeling System v. 8.1 (Aquaveo, LLC). Computational design meshes 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, 2008). Based on past experience with evaluating numerical diffusion and numerical stability, the mesh resolution was high enough to avoid those problems for the finite element method. Meshes only covered the wetted channel and a few periphery dry cells, yielding slightly different final meshes for each discharge and channel configuration.

To run FESWMS in a single channel, inflowing discharge and the associated exit water surface elevation (WSE) are required. The ecologically significant discharges of 8.5 and 169.9 $m^3 s^{-1}$ were specified at the end of the introduction section. 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, 2008). WSEs at the downstream end of the reference reach were measured at Q's between 8.5-169.9 $m^3 s^{-1}$ using a total station to obtain a stage-discharge rating curve useful for simulating any flow in this range. For the six 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; Pasternack et al., 2008). Therefore, the designs upstream of the model exit had insignificant effect on the WSEs at the model's exit boundary.

The two primary model parameters in FESWMS are the eddy viscosity (E) and bed roughness (n). Pasternack and Brown (2011) explain how these were obtained. E was spatially distributed, but used a constant coefficient parameter value of 0.6. Roughness associated with resolved meter-scale bedform topography was explicitly represented in the detailed channel DEM. 2D models are highly sensitive to DEM inaccuracies (Horritt et al., 2006). For unresolved roughness, a global n of 0.043 was used with all meshes (Pasternack et al., 2004, 2006, 2008; Moir and Pasternack, 2008). This was not numerically 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. In gravel placement, added material is well mixed and not differentiated between riffles and pools, so uniform roughness is appropriate.

In this study FESWMS was used for exploratory experimentation using fabricated, theoretical channel configurations to improve ecohydraulic and geomorphic understanding of basic riffle-pool functioning as well as to improve the application of gravel-bed river design. Acceptance of the numerical approach requires reasonable confidence in FESWMS' predictions. Three different tests assessed model uncertainty for the LDR channel (Brown and Pasternack, 2008). First, the range of E values in model output was checked against field-based estimates and 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 velocity magnitude in a river is highest at low discharge (Clifford and French, 1998) and that 2D-model validation performance has been found to be insensitive to discharge (e.g., May et al., 2009; Pasternack and Senter, 2011), model validation of H and U was performed at 12.9 $m^3 s^{-1}$. Predictions evaluated in detail by Brown and Pasternack (2008) and also shown in Pasternack et al. (2008) yielded the typical results, with H accurately predicted and U adequately predicted. Abrupt lateral gradients in U were not predicted accurately, but at many points U was very accurately predicted.

Third, a total station was used to measure the WSE at 14 locations at 169.9 $m^3 s^{-1}$ (vertical accuracy of <1 cm). Modeled WSE was systematically slightly higher than observed (~5% of mean cross-sectional depth), but not enough to warrant iterative calibration of the n-value. Overall, validation analysis 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 poorly mapped regions with very strong lateral variation precisely, for which better mapping and 3D numerical modeling would be better. As this study used synthetic topography, map accuracy is irrelevant, while inadequate lateral velocity variation is an uncertainty.

2.5 Fish Habitat Quality

Physical habitat quality predictions were made by extrapolating 2D model depth and velocity predictions through local, independent habitat suitability curves (HSC) for H and U from USFWS (1999). Although many local HSC were used in the LDR rehabilitation design, this study focused on physical habitat metrics for spawning and fry rearing lifestages of anadromous Chinook salmon and steelhead trout (Fig. 3), which are particularly sensitive to flow and topography, as expressed in 2D hydraulic patterns. Because ideal substrates would be placed, no substrate HSC was needed to compare designs.

A global habitat suitability index (GHSI) was calculated at each computational node as the geometric mean of the H and U indices (Pasternack et al., 2004). To account for H and U uncertainty, GHSI values were binned with GHSI = 0 as non habitat, 0 < GHSI < 0.1 as very poor habitat, 0.1 < GHSI < 0.4 as low quality, 0.4 < GHSI < 0.7 as medium quality, and 0.7 < GHSI < 1.0 as high quality. These broad classes reduce the impact of H and U prediction error, since they are largely insensitive to ~0-25 % U error, unless a value is very close to a bin edge (Brown and Pasternack, 2009). Use of low-quality habitat depended on the degree of channel degradation and fish density. Elkins et al. (2007) reported a significant spawner preference for medium- and high-quality habitat (GHSI>0.4) and an equally strong, statistically significant fish avoidance of nonhabitat and very poor quality habitat (GHSI <0.1). Pasternack (2008) reported preference for GHSI>0.4 and avoidance for GHSI<0.4 for three tests at a highly utilized spawning site on the lower Yuba River. As a result of those findings, the terms "suitable habitat" and "preferred habitat" are used to refer to all areas with GHSI>0 and GHSI>0.4, respectively. Although no equivalent comparison was available for fry, regional expertise suggests that fry occur in suitable habitat of any quality, avoiding just nonhabitat areas (T.R. Payne, pers. comm., 2010). All performance indicators were checked for both species' lifestages, but a higher qualitative weighting was given to the habitat-suitability metric for fry and the habitat-preference metric for spawners.

2.6 Sediment Transport Regime

It is natural and unavoidable that in a regulated river with zero bedload influx, placed gravel/cobble will be entrained during floods, potentially degrading artificially contoured fluvial landforms (Merz et al., 2006). The use of concepts from fluvial geomorphology (e.g. Thompson, 2006; MacWilliams et al., 2006; Wilkinson et al., 2008; Caamaño et al., 2009; Sawyer et al., 2010) in the project aimed to focus scour in appropriate locations and yield downstream deposition beyond the project area, such that the overall integrity of gravel bars remains intact, even if sub-width features adjust. When coupled with a regular program of a suitable quantity of gravel injection at the entrance of the reach, it ought to be feasible to sustain the constructed topography (e.g. design hypothesis tests of Wheaton et al., 2004b; Wheaton et al., 2010). However, since the channel width was unavoidably constricted in the testbed reach, it was understood from the outset that flow-convergence routing was infeasible- scour would always be higher over riffles than pools in this area, tending toward diminished riffle-pool relief. Nonetheless, flow-dependent channel resilience could still vary significantly as a function of channel configuration, so that was an important basis for performance evaluation.

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:

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

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

where τ^* is Shields stress, τ^b_v is bed shear stress in the direction of the velocity vector, d_{50} is the median grain size, d_{90} is the size at the 90th percentile of the cumulative distribution function for bed material grain size distribution, 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 and U inaccuracy. Lisle et al. (2000) defined sediment transport regimes relative to τ^* as $\tau^* < 0.01$ represents no transport; $0.01 < \tau^* < 0.03$ represents probabilistically intermittent entrainment; $0.03 < \tau^* < 0.06$ represents the "partial transport" domain of Wilcock et al. (1996); $0.06 < \tau^* < 0.1$ represents full transport of a "carpet" of sediment 1-2·d_{90} thick, and $\tau^* > 0.1$ corresponds with potentially channel-altering conditions. These threshold delineations have uncertainty, but provide a reasonable basis for characterizing and comparing sediment transport conditions (Sawyer et al., 2010).

2.7 Test Analyses and Outcome Indicators

Tests evaluating physical habitat and sediment transport regime involved computing and comparing statistical distributions for the performance indicators for GHSI and Shields stress datasets as well as visual comparisons of the spatial patterns of GHSI and Shields stress to evaluate mechanisms. A summary table was produced in which the best performing design(s) were identified for each GHSI indicator, and then the best overall design was evident as the one with the most occurrences as the best performer across all the metrics. An identical analysis was done for Shields stress. Picking the best design was a necessary part of the real-world project, while the comparison alone is more interesting to appreciate the circumstances in which each landform sequence has value for different sets of project objectives. Therefore, design response according to different performance indicators was assessed relative to differences in A_{RP} and A^*_{RP}.

For physical habitat quality, the performance indicators were the percent distribution of GHSI bins, the habitat efficiency for habitat creation (defined below), the habitat efficiency for habitat improvement (defined below), and spatial pattern of GHSI. Each of these indicators was used for each species' lifestage. For the baseline channel and each alternative design, the percent of wetted area for each GHSI bin was plotted as a stacked column for each species' lifestages and the one with highest percentages of suitable and preferred habitat (as defined in section 2.5) were identified. Because each design has a different wetted area, care is required in cross-comparing this metric, as the design with the highest percent of something is not necessarily the one with the most area of it. Habitat efficiency is a cost/effectiveness metric where the cost is the amount of coarse sediment needed (in m^3, but could be expressed in dollars per m^3 of gravel placed) and the effectiveness is the amount of habitat, which can be expressed in different specific metrics as well. Habitat added means the net increase in suitable-habitat area (m^2) per m^3 of gravel added, while habitat improved means the net increase in preferred-habitat area (m^2) per m^3 of gravel added. Designs were directly compared for their performance in habitat efficiency. Habitat efficiency is a particularly useful metric when trying to prioritize among possible projects across many different sites of widely different morphologies. Assessing the relative merits of habitat efficiency in terms of addition of suitable habitat versus improvement of habitat to the preferred state involves more professional judgment, so both metrics are worth considering as performance indicators. As justified earlier, more weight was given to habitat improvement for spawning, while more weight was given to habitat addition for fry. These choices hinge on expert judgment or stakeholder consensus- the key is that this study shows the relative merits of different landforms with different types of riffle-pool relief. Finally, visual inspection of the spatial pattern of GHSI bins relative to the DEM for each design established the link between morphology and microhabitat pattern to explain the latter.

For sediment transport regime, three performance indicators were used. First, the % wetted area with $\tau^* > 0.06$ and that for $0.03 < \tau^* < 0.06$ for each scenario when discharge is 8.5 $m^3 s^{-1}$ were used to compare the risk of unacceptable ecological disturbance during the period of bed occupation by redds, embryos, and fry. Second, the % wetted area with $\tau^* > 0.06$ and that for $0.03 < \tau^* < 0.06$ for each scenario when discharge is 169.9 $m^3 s^{-1}$ were used to compare the potential of channel change for the ecological function of "bed preparation" (Escobar and Pasternack, 2010). Finally, the stage-dependent location of peak τ^* for each scenario was inspected for evidence of flow-convergence routing of sediment through pools as a performance indicator of the resilience of riffle-pool relief under existing reservoir operations.

3. Results

3.1. Physical Habitat

The statistical distribution of GHSI bins shows systematic differences in habitat benefits between designs using accentuated topography and those using blanket fills in terms of riffle-pool relief (Fig. 4). Depending on what the habitat goals of a rehabilitation project are aiming for, clear landform preferences are evident. Designs One and Two had the most accentuated topography and they yielded the largest percent areas of suitable and preferred Chinook fry habitat. A key result was found in comparing Chinook and steelhead fry performance in percent area of habitat. Because the steelhead-fry velocity HSC (Fig. 3b) has a broader range and a higher velocity of peak preference than that for Chinook fry, the blanket-fill designs yielded significantly higher percent areas of suitable habitat compared to the accentuated-topography ones. However, the accentuated-topography designs provided the highest percentages of preferred steelhead fry habitat. Designs Four, Five, and Six all yielded high-quality Chinook spawning habitat over >55% of the wetted area and medium-quality habitat over another 28-39% of it. Preferred steelhead spawning habitat was also present in high percentages for these blanket-fill designs. The accentuated topography designs provided improvements over the baseline in terms of percent area of suitable habitat, but did not necessary achieve that for preferred habitat, which is the more important metric for spawning habitat.

The habitat-efficiency performance indicators yielded similar outcomes as those using the GHSI bins for spawning, but were particularly helpful in distinguishing relative benefits within each riffle-pool relief grouping (Fig. 5). The habitat-addition and habitat-improvement efficiencies of Design One were more than double those of the next highest performer (Design Two) for Chinook fry. Also, while Design One had the least harmful effect on steelhead fry preferred-habitat loss, it caused the most loss of suitable habitat for steelhead fry. Design Six had the opposite outcome, yielding more than double the gain in suitable steelhead fry habitat compared to the next best performing designs (Four and Five). For both Chinook and steelhead spawning, the blanket-fill designs performed best across habitat efficiency metrics, and among those Design Six was the best. Across all eight habitat-efficiency metrics for all species' lifestages (Table 2, efficiency columns), Design Six was the best for five and the worst for only one (Chinook fry habitat-improvement efficiency).

The maps of the spatial patterns of GHSI bins (Fig. 6) provide insight about why the designs perform differently. For brevity and illustration purposes, only those for Chinook are shown and only for designs One and Six, since those show the sharpest contrast (and the rest for all species' lifestages are all available at the website provided in the introduction to section 2). For Design One, preferred spawning habitat is located in riffle entrances and to a much smaller extent on the periphery of channels, especially where there are lateral bars. Accentuating the topography created riffles that were too short, shallow, and fast to serve as spawning habitat. Since the pools are nonhabitat for spawning, then there is just too little area for spawning when topography is accentuated. An interesting nuance to that outcome is evident in the first riffle in Design Three, which had a small, high crest bounded by longer flat shelves of riffle entrance and exit. For that riffle, the crest was only low-quality habitat, but both shelves had medium-quality habitat with high-quality habitat along both banks. That suggests some benefits to having multiple elevation tiers to a riffle. Nevertheless, the really important result was the finding that Design Six yielded nearly ubiquitous high-quality Chinook spawning habitat and widespread preferred steelhead spawning habitat. Design Six had diverse landform features at multiple spatial scales and many of them had spawning value from a hydraulic perspective.

In terms of the fry lifestage, the GHSI maps show that the accentuated-topography designs yield significantly more preferred fry habitat, because they produce slackwater areas (sometimes large, slowly recirculating eddies) on the periphery behind each riffle crest. Abrupt bed-elevation increases caused flow to converge, yielding a narrower effective flow width bounded by slackwater or recirculating eddies. The higher the bed-elevation increase, the stronger the effects. This is the concept used in whitewater park design, where bed and width constrictions focus flow to produce standing waves for kayak stunts and intervening peripheral pools for kayakers waiting in line for their turn. Numerically, the blanket-fill designs performed poorly for Chinook fry habitat, because velocities were too fast, given an exponentially decreasing velocity HSC. The blanket-fill designs in this study yielded insufficient depth and width undulations to create the sheltering observed in the accentuated-topography designs. However, steelhead fry use the widespread, moderately higher velocities found in the blanket-fill designs, so the blanket fill is beneficial for them (Fig. 6).

3.2 Sediment Transport Regimes

The statistical distributions of Shields stress bins for $\tau^* > 0.06$ and $0.03 < \tau^* < 0.06$ indicated the relative resilience of each design across an order of magnitude of discharge (Fig. 7). At low discharge (8.5 $m^3 s^{-1}$) when embryos are at risk of being scoured out, < 5% of the wetted area was in the full transport regime for each design, with the highest values associated with the designs having the highest A_{RP} (One, Two, and Three). The partial-transport bin showed at-risk areas of < 9%, with the highest values associated with designs having the highest overall bed slope (One, Two, and Five). The τ^* maps helped explain the difference in response of these two metrics at low flow (Fig. 8a,b). Higher overall bed slope drives higher overall velocities, especially on riffles at within-bank flows, which is indicative of a higher area with $\tau^* > 0.03$. Higher A_{RP} is indicative of the presence of over-steepened riffle exits, which causes an abrupt local velocity increase capable of driving knickpoint migration.

At high discharge (169.9 $m^3 s^{-1}$), there is a marked difference in resilience between accentuated and blanket-fill topographies. Similar to low discharge, the designs with the highest A_{RP} (Designs One, Two, and Three) had the largest percent area of full bed mobility (4.4-21%). Meanwhile, the designs with the lowest slope had the highest percent areas of partial transport (60-76%). These patterns are explained using the τ^* maps (Fig. 8c,d) and Stewardson and McMahon's (2002) conceptual model of hydraulic variations within stream channels, as applied to the Trinity River by Brown and Pasternack (2008). According to this concept, there is a flow dependence to the transition of a river's hydraulic regime from one dominated by longitudinal velocity variation at low flow to one dominated by lateral velocity variation at high flow. As illustrated in this numerical experiment, the exact discharge required for the transition is dependent on riffle-pool relief. Specifically, for the accentuated-relief designs, the riffle crests are so high that even at 169.9 $m^3 s^{-1}$, there is a strong longitudinal velocity variation with high velocities and shear stresses focused on riffle crests and an abrupt increase in velocity at the oversteepened riffle exits (Fig. 8c). In contrast, this discharge is high enough for the blanket-fill channels to surpass the transition in hydraulic regime to lateral-variation dominance. As a result, these channels distribute velocity response to overall bed slope evenly along their length, avoiding focal points for scour (Fig. 8d). Design Three is a hybrid between the two in that its A_{RP} is just enough that the riffle crests peak up causing a longitudinal hydraulic variation at this flow and focusing scour at riffle exits somewhat.

Based on the six τ*-bin performance indicators, all the blanket-fill designs outperform the accentuated-topography designs, but among them there is not a universal standout (Table 3). Design Six is the best performer at low flow, because it exhibits the lowest percent area of partial transport, highest percent area of $\tau^* < 0.03$, and best pattern of τ* in terms of avoiding riffle-crest scour. The only problem with Design Six, which is very minor, is that the very end of the last riffle exit drops off enough to cause a sliver of partial transport, with a few spots experiencing full bed mobility. Design Four has a more gradual final riffle exist, so it avoids that problem, but does have larger zones of partial transport in other places on riffle crests. Design Five is the best performer at high flow, because its bar configuration helps to focus flow in the center where peak velocity is the most even along the channel among design and yielding the strongest lateral velocity variation. Design Six also has those bars and it has just enough lateral constriction after each riffle to help induce a similar centralized focusing of velocity and scour potential over pools. However, its long, shallow riffles do experience partial transport over nearly their full width.

4. Discussion and Conclusions

4.1 Lessons from Numerical Experimentation

Sequences of riffle-pool units designed with different riffle-pool relief attributes exhibit systematic and predictable variations in flow-dependent physical habitat patterns and geomorphic processes in a setting with a relatively uniform channel width. In general, this study found that modest riffle-pool amplitudes (<0.75 m; A_{RP}/D_{50}~10-12, where D_{50} is median bed-material particle size) from blanket-fill designs yielded the largest habitat addition and habitat improvement efficiencies, especially for salmon spawning. The Chinook fry lifestage was the exception, as high riffle-pool relief yielded large peripheral eddies in the lee of riffle crests (Fig. 6c). Similarly, analysis of patterns of sediment transport potential found that high-relief configurations had significantly more area of full bed mobility, regardless of flow. These configurations would be expected to fall apart quickly after construction as a result of knickpoint migration through riffle crests, due to oversteepened riffle exits.

For a given riffle-pool amplitude, differences in 3D bar morphology (including A^*_{RP}, but not well explained by it) yield significant differences in habitat and channel stability. For example, Designs Five and Six had ARP values of 0.75 and 0.74, respectively, but their performance indicators were significantly different. The use of longer riffle crests and curved tailouts in Design Six turned out to be important drivers of superior habitat performance. Meanwhile, the orthogonal bar forms and lower riffle exit slopes in Design Five helped avoid knickpoint migration, which is a risk in Design Six, especially at even higher flows that were not modeled in this study. Design Five had a small peak to its last riffle crest that was predicted to experience a higher velocity at the high flow, but it is still in the partial-transport regime, so it is resilient. Design Six had longer riffle-crest features to give them more resilience if knickpoint migration were to take place, but that evidently comes at the cost of increased knickpoint migration risk due to oversteepend riffle exits and the spreading of partial-transport across the full width of riffles. In evaluating these design alternatives, it was conjectured that at expected higher floods in the future, the last riffle crest in Design Five would likely transition into the full-mobility domain and not have enough crest area to absorb the erosion and avoid the “reverse domino” riffle sequence collapse mechanism described by Pasternack et al. (2008). In contrast it was conjectured that the evident lower-flow full mobility at the riffle exits in Design Six would simply lead to sloughing of material to naturally form a more gradual slope, because the length of full-mobility and the amount of bed-material cohesion are likely insufficient to sustain a migrating knickpoint. Therefore, it was deemed more valuable to have longer riffles more resilient to the largest flood releases than to have short riffles with certain resilience to the modeled flood release. Ultimately, the lack of feasibility of significant width increases at riffle crests fundamentally constrained instituting flow-convergence routing through this riffle-pool sequence, and that was repeatedly explained to project sponsors to ensure understanding of what Design Six would yield.

4.2 Merits of Iterative Design and Construction

Ecohydraulic river rehabilitation seeks to modify river geometry to achieve specific hydraulic and sedimentary characteristics for target aquatic organisms. In doing this, multiple topographic outcomes may be possible depending on site constraints. Iterative design is the process by which a single scenario is continually modified until ecohydraulic design criteria are satisfied. Iterative design is a key feature in the Spawning Habitat Integrated Rehabilitation Approach (Wheaton et al., 2004a; Elkins et al., 2007), and ought to be one in the more general practice of ecohydraulic design for river engineering. This study illustrates how iterative design can yield topographic surfaces that meet the needs of target organisms despite a wide range of potential scenarios. Without iterative design it would be difficult to determine the relationship between potential topographic manipulation and the optimal configuration of channel geometry.

Similarly, iterative construction that builds a design of a long sequence of riffles and pools over a period of years has several merits over attempting a single, massive project (Elkins et al., 2007). First, institutional barriers and regulatory hurdles seem to be lower for a series of smaller projects compared to a single massive one. Stakeholders perceive small projects to be "pilots" and are often willing to allow these with less scrutiny to see what happens, since the risks are low. Inevitable turnover in technical staff and stakeholder participants every few years often confounds large projects, whereas an incremental approach can be understood by neophytes with less effort, as they can focus on just understanding the current iteration first and learning the broader plan over time. Following the iterative approach, before people really grasp events, a significant overhaul in a river has been instituted on a transparent, scientific basis following the original plan. Second, for those who are closely monitoring and implementing the sequence of projects, iterative implementation allows for adaptive management to test design hypotheses for individual design elements and then adjust the overall design when performance indicators show that design hypotheses are not being corroborated. Finally, rivers degrade over decades, so it is sensible to rehabilitate them over a moderate duration, respecting the emerging status of the science and engineering underlying river rehabilitation as well as the unknowable uncertainty in predicting the future. No matter how critical river rehabilitation may be to avoid systemic ecological collapse, rushing large projects is most likely to yield further ecological disturbance rather than solve outstanding problems.

4.3 Actual Design Selection

In this study, Design Six was determined to be the best alternative, but at that point additional work is performed to fine-tune the design and generate multiple flow, habitat, and geomorphic predictions across a range of discharges for later evaluation. Small changes in the selected design often must be made to insure that all available gravels and boulders are used as well as to account for new constraints that emerge when the design is vetted among all stakeholders and the public. Further thought and testing may enhance even the best of the alternatives with subtle changes. It may be desired to add layers of complexity onto the basic topography using specific structures at the hydraulic-unit scale (~0.1-1 channel width), such as boulder clusters, riparian shade, and streamwood jams. Hydraulic effects of jams are extremely difficult to simulate, but boulder clusters are feasible. Because habitat quantity and quality is stage-dependent, a more comprehensive view of the final design is obtained by modeling as wide a range of flows as the original topographic and on-going monitoring data allow. The final project design is converted into an easily followed grading plan for use by the contracted front-loader operator.

4.4 Outlook for Ecohydraulics

Ecohydraulics is an emerging scientific subdiscipline and professional practice. Traditionally, use of heuristics in river assessments provided a deep understanding of habitat patterns and geomorphic processes, but lost favor for being opaque, non-reproducible, and dependent on “experts”. The rise of statistical analysis in ecology and geomorphology democratized river assessment and promoted greater transparency and quantification, but came at the cost of oversimplification of phenomena. Today, the combination of remote sensing, mechanistic modeling, and GIS-based analysis in “near-census” ecohydraulics (i.e. sampling at ~1-m resolution throughout long river segments) is poised to yield a decisive transformation in the practice of river science in which the best features of heuristics and statistics blend to yield deep and repeatable process-based, spatially explicit predictions of river behavior. New technologies will further enhance the capability, but the paradigm is now accessible for scientific exploration and professional practice (Pasternack, 2011).

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LIST OF FIGURES

Table 1. Riffle-pool relief metrics for each channel configuration.

Metric	Pre	Design Number					
		D1	**D2**	**D3**	**D4**	**D5**	**D6**
Bed slope (%)	0.22	0.23	0.20	0.18	0.17	0.22	0.17
Number of units	3	3	2	4	3	3	3
Average A_{RP}[1] (m)	0.78	1.54	1.58	0.88	0.58	0.75	0.74
Average A^*_{RP}[2] (m)	0.99	2.18	2.57	2.20	3.01	2.01	0.89
Design/pre A_{RP}		1.98	2.03	1.13	0.74	0.97	0.95
Design/pre A^*_{RP}		2.21	2.61	2.24	3.06	2.04	0.91
Net fill volume (m^3)		5505	8257	7493	6116	3440	3889

[1]Pool-to-riffle amplitude

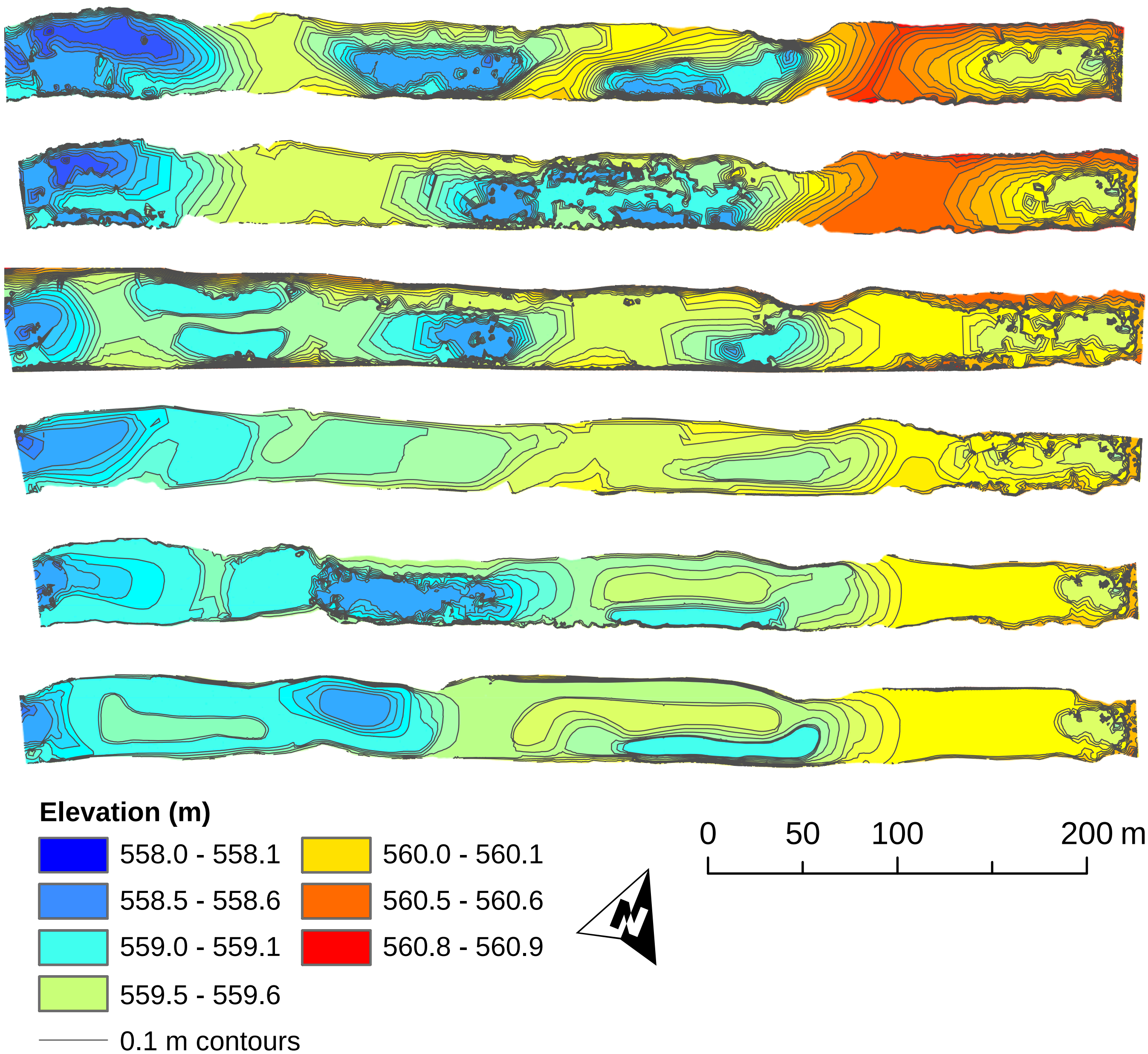
[2]Pool-to-riffle asymmetry

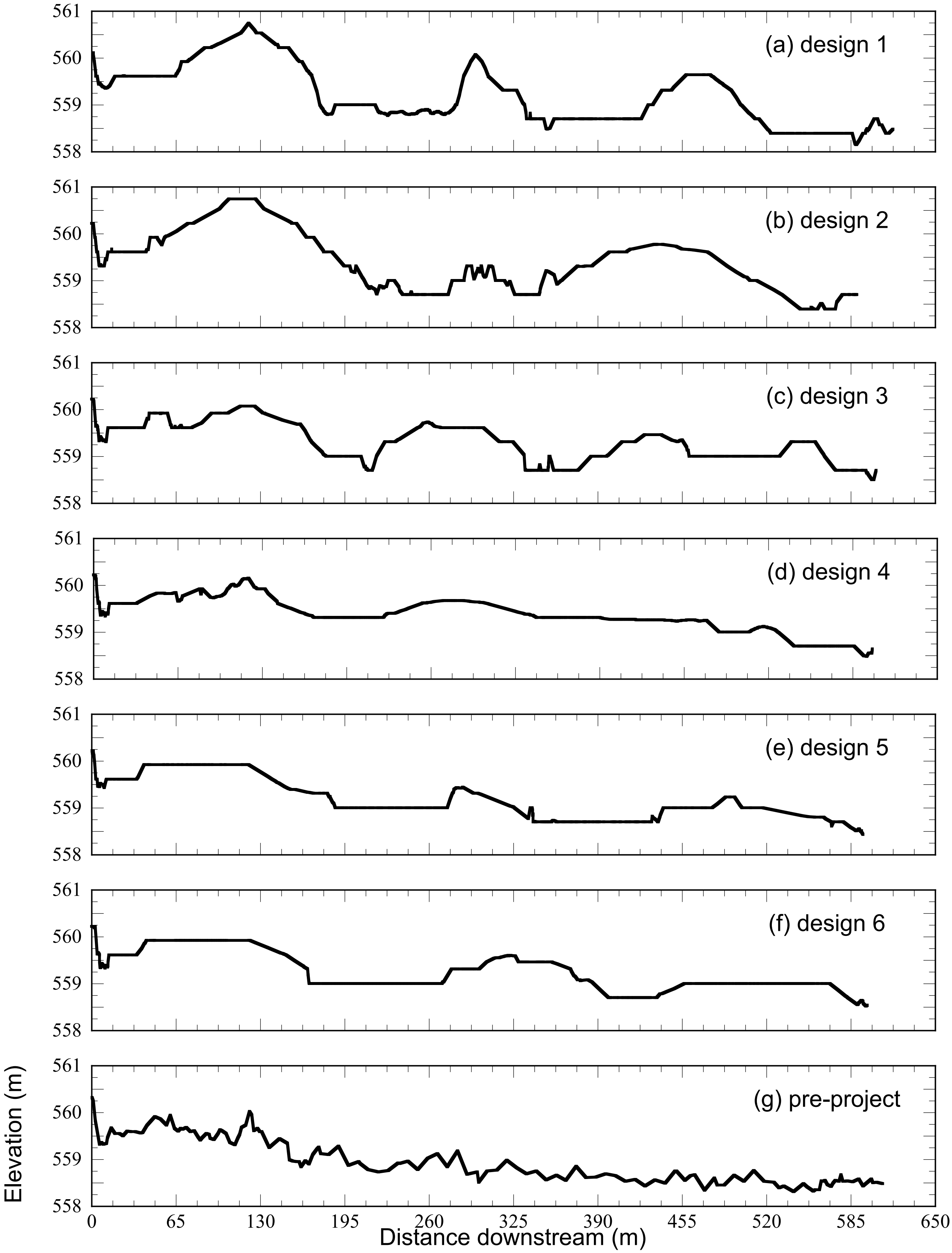
Table 2. Design number of the best performing design(s) for each indicator and the best design number overall.

	Design number				
Lifestage	GHSI bins	habitat addition efficiency	habitat improvement efficiency	GHSI spatial pattern	Best overall
Chinook fry	1-2	1	1	1	1
Steelhead fry	4-6	6	1	6	6
Chinook spawning	4-6	6	6	6	6
Steelhead spawning	4-6	5,6	6	6	6

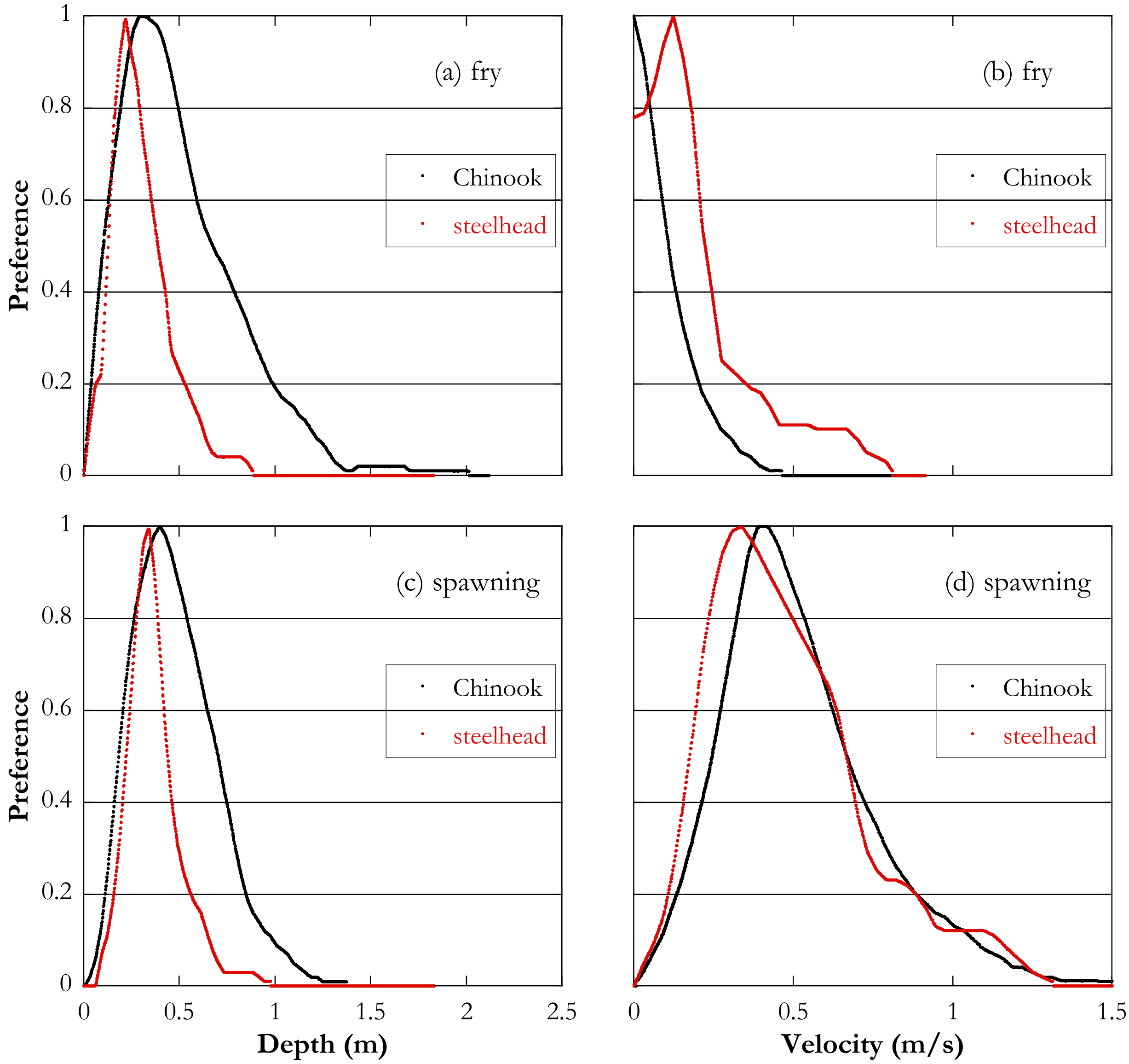
Table 3. Design number of the most resilient design(s) against scour and instability for each indicator and the best design number overall.

	Design number			
Discharge	full bed mobility	partial transport	τ* spatial pattern	best overall
low	4	6	6	6
high	5	5	5	5

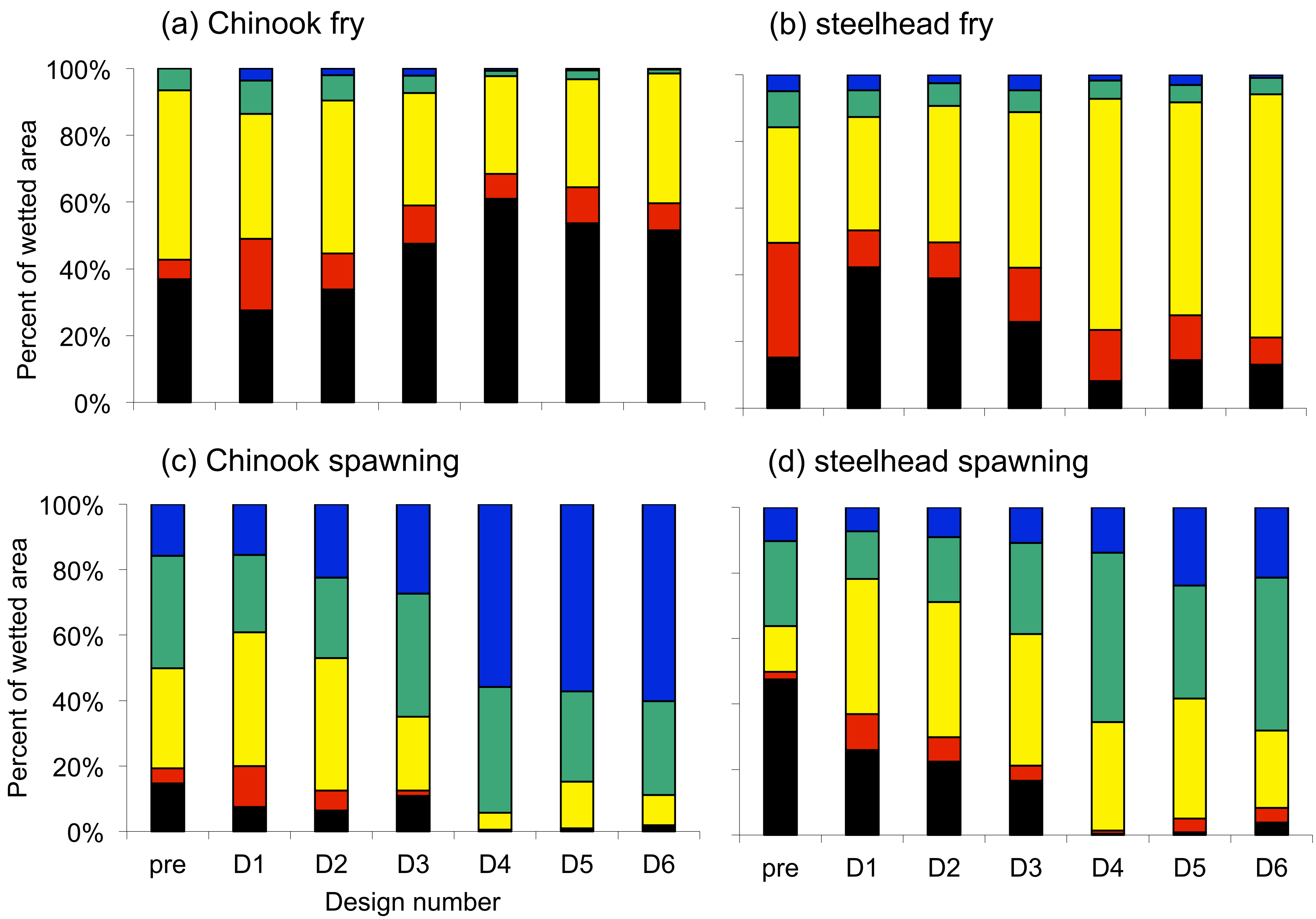

Elevation (m)
558.0 - 558.1
558.5 - 558.6
559.0 - 559.1
559.5 - 559.6
0.1 m contours
560.0 - 560.1
560.5 - 560.6
560.8 - 560.9
N
0
50
100
200 m



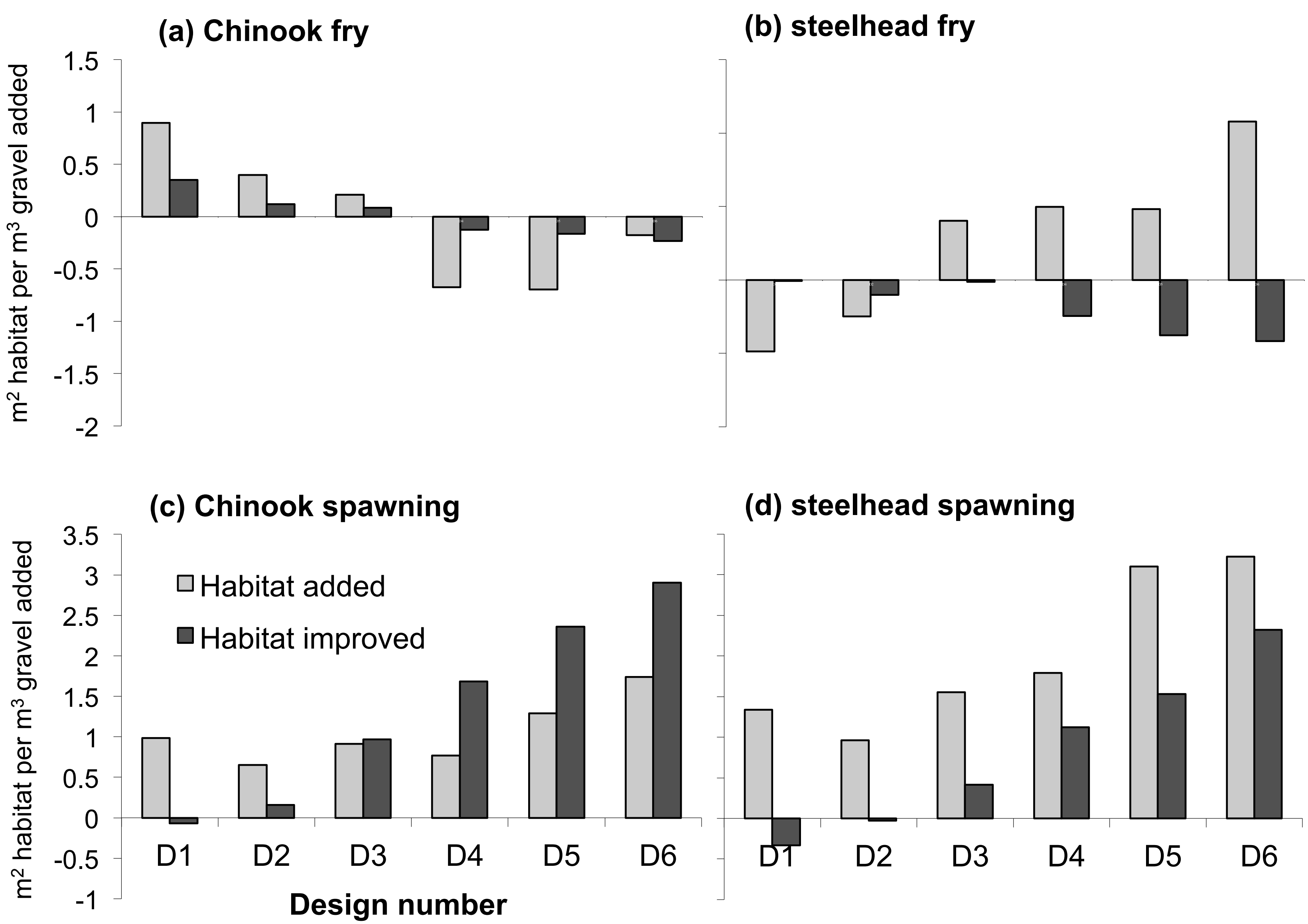
(a) design 1
(b) design 2
(c) design 3
(d) design 4
(e) design 5
(f) design 6
(g) pre-project
561
560
559
558
Elevation (m)
0
65
130
195
260
325
390
455
520
585
650
Distance downstream (m)



(a) fry
(b) fry
(c) spawning
(d) spawning
Chinook
steelhead
Preference
Depth (m)
Velocity (m/s)
0
0.2
0.4
0.6
0.8
1
0.5
1.5
2
2.5



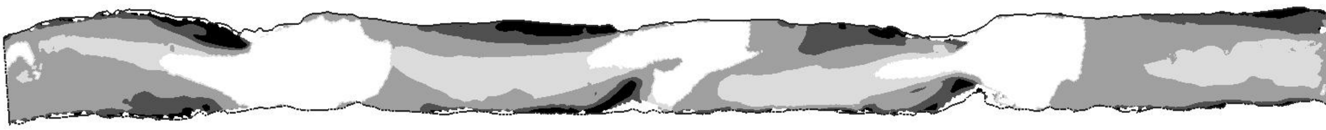
(a) Chinook fry
(b) steelhead fry
(c) Chinook spawning
(d) steelhead spawning
Percent of wetted area
100%
80%
60%
40%
20%
0%
pre
D1
D2
D3
D4
D5
D6
Design number


(a) Chinook fry
(b) steelhead fry
(c) Chinook spawning
(d) steelhead spawning
m² habitat per m³ gravel added
1.5
1
0.5
0
-0.5
-1
-1.5
-2
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
Habitat added
Habitat improved
D1
D2
D3
D4
D5
D6
Design number

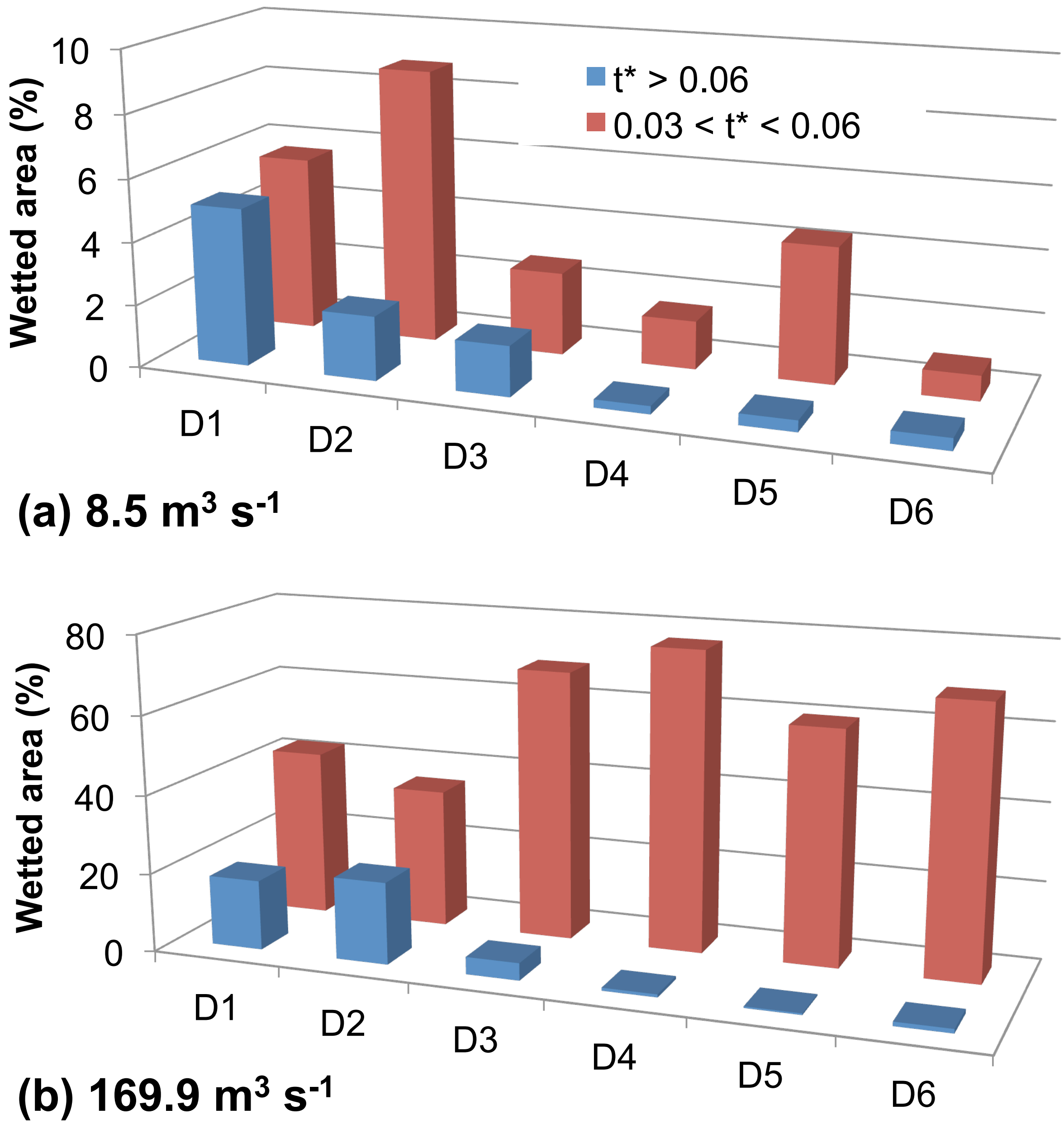
(a) design 1 Chinook spawning GHSI (8.5 m^3/s)

(b) design 6 Chinook spawning GHSI (8.5 m^3/s)

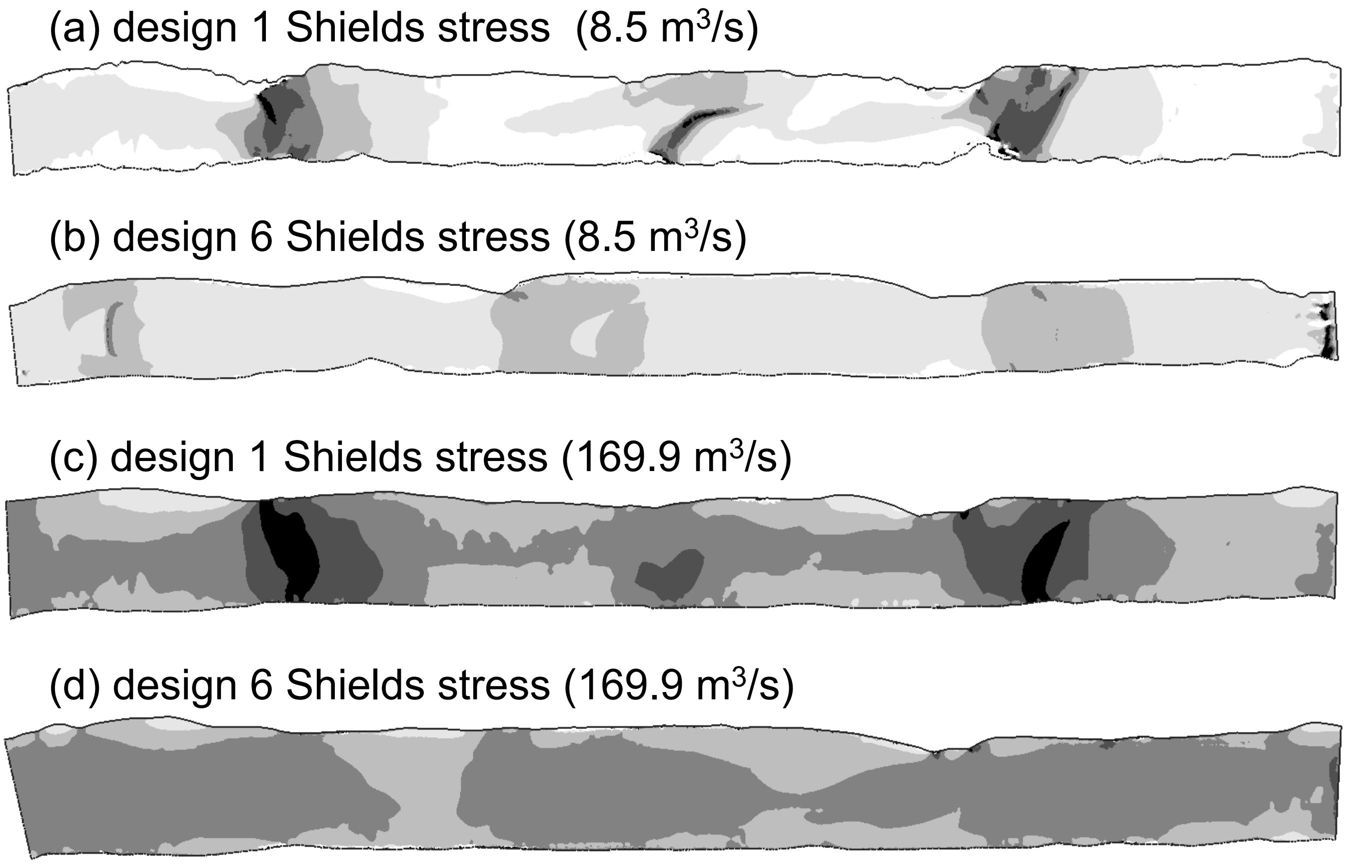
(c) design 1 Chinook fry GHSI (8.5 m^3/s)



(d) design 6 Chinook fry GHSI (8.5 m^3/s)



Wetted area (%)
10
8
6
4
2
0
t* > 0.06
0.03 < t* < 0.06
D1
D2
D3
D4
D5
D6
(a) 8.5 m3 s-1
Wetted area (%)
80
60
40
20
0
D1
D2
D3
D4
D5
D6
(b) 169.9 m3 s-1


(a) design 1 Shields stress (8.5 m3/s)
(b) design 6 Shields stress (8.5 m3/s)
(c) design 1 Shields stress (169.9 m3/s)
(d) design 6 Shields stress (169.9 m3/s)