1   Title: Ecohydraulic Design of Riffle-Pool Relief and Morphological-Unit Geometry in Support

2   of Regulated Gravel-Bed River Rehabilitation

3

4   Running Title: Ecohydraulic Design of Riffle-Pool Relief

5

6

7   Authors:

8

9   Gregory B. Pasternack and Rocko A. Brown

10

11

12

13   Department of Land, Air, and Water Resources, University of California, One Shields Avenue,

14   Davis, CA 95616, USA.

15

16

17   *Corresponding author. Tel.: +530-754-9243; E-mail: gpast@ucdavis.edu

18

19

20

21

22   ABSTRACT

23

24   Riffle construction is a common practice in river engineering, but insufficient science exists to

25   guide objective design of riffle-pool relief and the three-dimensional forms of features smaller

26   than the scale of channel width. In this study, numerical experimentation with two-dimensional

27   hydrodynamic modeling and ecohydraulic analysis was used to evaluate the performance of six

28   different configurations of a sequence of riffle-pool units typical of shallow, regulated gravel-bed

29   rivers, emphasizing a range of riffle-pool amplitudes (e.g., low, intermediate with hybrid

30   features, and high). Twenty-two specific performance indicators (16 for physical habitat and six

31   sediment-transport regime) were used to compare designs. It was found that low riffle-pool

32   relief yielded the best performance for the majority of physical habitat indicators and all of the

33   sediment transport regime indicators. The spatial patterns of test metrics revealed the

34   mechanisms responsible for the statistical outcomes. Methodologically, two-dimensional

35   modeling and ecohydraulic analysis are vital tools in project design along with previously

36   accepted hydrologic, geomorphic, and engineering analyses. Scientifically, low-relief riffle-pool

37   units are indicated as the normative condition in gravel-bed rivers where forcing elements

38   driving deep scour are not systematically controlling morphology.

39

40   1. INTRODUCTION

41

42   Ecohydraulics is a rapidly emerging quantitative subdiscipline of river science with use in

43   river engineering and rehabilitation in degraded landscapes (Nestler et al., 2008; Wheaton et al.,

44   2011). Ecohydraulics links ecological functions and hydrodynamic patterns at each spatio-

45   temporal scale (Pasternack, 2011). It is often used for baseline instream flow assessment

46   emphasizing relations between species' physical habitat and discharge. The Instream Flow

47   Incremental Methodology (IFIM) is a widely adopted tool for incorporating quantitative

48   ecohydraulics into flow assessment (Bovee and Milhous, 1978; Bovee, 1982; Jowett, 1997),

49   often facilitated using PHABSIM software (Waddle, 2001). Normally a statistical evaluation of

50   flow and habitat is done, but now spatially explicit (2D) habitat modeling is practical (Ghanem et

51   al., 1996; Pasternack, 2011). Studies have compared semi-analytical, 1D, and 2D ecohydraulic

52   methods (Waddle et al., 2000; Brown and Pasternack, 2009). Many rivers exhibit a spatial

53   anisotropy of channel geometry (Merwade, 2009) capable of steering flow, thereby violating 1D-

54   model assumptions (Brown and Pasternack, 2009). In such cases, 2D modeling and GIS-based

55   spatial analyses are necessary, and even for isotropic, orthogonal geometries they are preferential

56   for evaluating mesohabitat structure (Hauer et al., 2011) as well as microhabitat heterogeneity.

57   Use of 3D models is emerging, but suffers for lack of 3D ecological relations, the high cost and

58   complexity of 3D validation, longer 3D numerical modeling time, and disproportionate GIS data

59   volume and processing time.

60   In the practice of site- and reach-scale river rehabilitation, standard engineering and

61   geomorphic methods have been highly criticized (Wissmar and Beschta, 1998; Simon et al.,

62   2007; Lave et al., 2010), exacerbated by iconic failures against project goals (Kondolf and

63   Micheli, 1995; Doyle and Harbor, 2000). Statistical ecohydraulic methods such as IFIM that

64   depend on static channel assumptions, direct observations of channel hydraulics, and static

65   empirical parameters cannot yield predictions for alternative channel configurations, so they

66   have limited ecohydraulic applicability as a tool for river engineering (as opposed to their

67   strength in river assessment). Design methods that empirically mimic landforms (i.e. "natural

68   channel design") or hydrology (i.e. "natural flow regime") are prescriptive and have no

69   independent, quantitative design-testing scheme, yielding a high risk of failure when used alone.

70   The philosophy underlying *ecohydraulic design for river engineering* is that channel

71   geometry is manipulated and then mechanistically tested until it achieves a flow-dependent

72   hydraulic regime with a palette of homogeneity and heterogeneity at different spatial scales that

73   is suitable for the breadth of geomorphic processes and ecosystem functions that are

74   characteristic of a natural river of the type undergoing diagnosis and treatment. A key aspect of

75   this design framework is that landforms designed at multiple spatial scales are not arbitrary, but

76   are founded on scale-dependent physical mechanisms needed for morphologic resilience, such as

77   stage-dependent flow convergence routing (MacWilliams et al., 2006; Sawyer et al., 2010) and

78   pool maintenance by turbulent vortex shedding at forcing elements (Woodsmith and Hassan,

79   2005; Thompson, 2006). Ecohydraulic analysis of 2D hydrodynamic models is rooted in

80   observation, but is structurally more universal than empirical, prescriptive geomorphic methods

81   (Brown and Pasternack, 2009; Pasternack, 2011) and can cope with synthetic channel

82   modifications (Pasternack et al., 2008; Oh et al., 2010). Ecohydraulic design has been tested in

83   different applications and found useful as a tool for evaluating alternatives for channel

84   reconfiguration, gravel injection, floodplain and side channel inundation, increasing habitat

85   complexity, and spawning habitat rehabilitation (Elkins et al., 2007; Manwaring et al., 2009;

86   Hoopa Valley Tribal Fisheries et al., 2011).

87   Now that the use of spatially explicit ecohydraulics in river engineering is established,

88   there is an opportunity to generate design principles and project guidelines through scientific

89   testing of diverse scenarios. Pasternack et al. (2004) tested the value of four channel patterns for

90   yielding high-quality Chinook salmon spawning habitat on a regulated, degraded gravel-bed

91   river, with two of those outperforming the *ad-hoc* project. Pasternack et al. (2008) used

92   ecohydraulics to test riffle configurations, tailwater levels (imposed by the next downstream

93   riffle that is not being altered), and discharge on physical habitat quality and morphological

94   resilience. Instituting a backwater effect downstream of a design riffle aids both of those desired

95   outcomes. Elkins et al. (2007) corroborated this in a real spawning habitat rehabilitation.

96   The goal of this study was to use ecohydraulic analysis of 2D model results in a

97   numerical experiment to test the relative merits of building sequences of riffle-pool units in

98   regulated gravel-bed rivers with different magnitudes of riffle-pool relief. Such rivers typically

99   have bed slopes of 0.001-0.01, width to depth ratios of 20-100, depth to median grain size ratios

100   of 2-60, and a Shields stress incipient motion threshold of ~0.03-0.06. These dimensionless

101   values express the range for which this study is relevant, except they ignore riffle-pool relief.

102   While metrics for evaluating (let alone designing) riffle-pool relief are limited, alternative-design

103   morphologies were compared using the slope-detrended relief indices of amplitude (A_{RP}), the

104   difference between the maximum riffle crest elevation and the minimum pool trough on the

105   slope-detrended river profile (Vetter, 2011), and asymmetry ($A*_{RP}$), the ratio of the absolute

106   values of slope-detrended riffle height and pool depth about the zero-crossing line (O'Neil and

107 Abraham, 1984; Rayburg and Neave, 2008). A high $A*_{RP}$ indicates a riffle crest sticking

108 disproportionately high above the zero-crossing line.

109   Riffle-pool relief is an important yet untested metric for channel design, because it could

110 play an important role in morphologic resilience during floods (Pasternack et al., 2008). There is

111 no widely used dimensionless metric for riffle-pool relief design and there exist few pristine

112 reference rivers free of anthropogenic influence to evaluate and mimic, especially for design of

113 sub-width channel features. The studies mentioned above did not systematically assess the effect

114 of riffle-pool relief on physical habitat quality and morphological-unit resilience against a range

115 of flows. They also did not look at a sequence of units, just an individual pool-riffle-pool unit.

116   The specific objectives of this study were to assess the consequences of high versus low

117 riffle-pool relief on (1) physical habitat quality for Chinook salmon and steelhead trout in their

118 sensitive spawning and fry lifestages at the regulated discharge typical for the periods when

119 those lifestages occur and (2) sediment transport regimes during two geomorphically and

120 ecologically significant flows, as explained below. A third objective looked beyond relief to

121 assess how the consequences from objectives one and two vary between different riffle-pool

122 shapes. The discharges focused on were flows associated with bed occupation during the

123 freshwater reproductive cycle (salmon spawning in autumn, embryo incubation in late autumn

124 and early winter, and fry development in winter) ($8.5 \text{ m}^3 \text{ s}^{-1}$) and physical-habitat rejuvenation

125 during prescribed spring snowmelt releases, using the highest regulated release as of December

126 2004 ($169.9 \text{ m}^3 \text{ s}^{-1}$).

127

128 2. EXPERIMENTAL DESIGN

129

130   The approach used to assess the effect of riffle-pool relief on river rehabilitation was to

131   (a) design six synthetic river digital elevation models (DEMs) with different riffle-pool sequence

132   configurations for a given testbed regulated river reach, (b) conduct 2D modeling of the synthetic

133   designs at two key discharges, (c) extrapolate hydraulic predictions through physical-habitat

134   curves and sediment transport regime equations, and (d) extract and compare performance

135   indicators to determine designs' relative merits. Alternative designs were guided by the science

136   about riffle-pool assemblages and the emerging knowledge of the structure, organization, and

137   function of morphological units (e.g., Padmore et al, 1998; Fukushima, 2001). Previous research

138   established performance indicators for physical habitat quality for indicator species' lifestages

139   and sediment transport regimes (Elkins et al., 2007; Pasternack et al., 2008; Brown and

140   Pasternack, 2008; Brown and Pasternack, 2009), as explained in sections 2.5-2.7 below.

141   A sequence of riffle-pool units on the gravel-bed Trinity River immediately below

142   Lewiston Dam, California, USA (40°43'34"N, 122°47'48"W) was used as a reference

143   assemblage (i.e. "pre-project" or "baseline" scenario) to prepare and validate a 2D model

144   suitable for a straight, gravel-bed, riffle-pool stream in a confined valley (Brown and Pasternack,

145   2008). Then six experimental riffle-pool sequences were fabricated using AutoCAD Land

146   Desktop® to obtain DEMs with different A_{RP} and $A*_{RP}$, using the Trinity River's topography as

147   a starting point for experimentation (Fig. 1). These alternatives were not scientific curiosities,

148   but actual morphologies evaluated for construction below Lewiston Dam (Pasternack, 2004a);

149   they were consistent with fluvial landforms in straight reaches of confined gravel-bed rivers that

150   are common in Californian rivers (e.g., Manwaring et al., 2009; Sawyer et al., 2009; Cramer Fish

151   Sciences, 2010).

152   System response was evaluated in terms of flow pattern, fish habitat quality, and

153   sediment transport regime at two discharges within the regulated range permitted by operational

154   rules at the time. Specific methods were previously developed and validated on the Trinity as

155   well as on a similar shallow gravel-bed reach of the Mokelumne River (Pasternack et al., 2004;

156   Wheaton et al., 2004a, b; Elkins et al., 2007). Unlike Pasternack et al., (2008), this study only

157   evaluated a single tailwater water surface elevation for each discharge, using the real observed

158   stage-discharge relation for the study reach as reported by Brown and Pasternack (2008).

159

160   2.1 Baseline Testbed Reach

161

162   Studies of hydrology, geomorphology, fisheries, and reach-scale ecohydraulics of the

163   baseline study reach already exist for the Trinity River (USFWS, 1999, 2002; Brown and

164   Pasternack, 2008; Gaeuman, 2008, 2011) and are briefly described here for context. The Trinity

165   River above Lewiston Dam is an 1860-km^2 basin that is part of the Klamath Mountain Province

166   in northwestern California. Damming barred access to ~160 km of upstream spawning grounds.

167   Flow regulation and floodplain structures limit flushing of tributary-delivered sand and

168   geomorphic processes that maintain alluvial spawning grounds, while enabling vegetation

169   encroachment that degrades rearing habitat. Salmonid populations have dropped sharply and are

170   the focus of habitat rehabilitation, though systemic factors are also addressed. Since 1972,

171   projects have included gravel augmentation, channel reconfiguration, bank vegetation removal,

172   and flow reregulation.

173   The 760-m Lewiston hatchery reach (LHR) that was the testbed for this study is located

174   immediately downstream of Lewiston Dam and is the uppermost limit of salmonid spawning

175   access. Previous work in the LHR determined that the existing artificial topography and

176   substrates are controlled by anthropogenic and natural boundary and input controls that preclude

177   natural geomorphic processes (Brown and Pasternack, 2008). Historically, the channel was wide

178   with inset active alluvial gravel bars and a forested floodplain, but now it is narrow and straight.

179   The river is confined on its south flank by a fish hatchery and on its north flank by bedrock.

180   These forcings cause uniform high flow widths that preclude differential rates of sediment

181   entrainment among morphological units at the 1-10 channel-width scale. The riverbed is

182   armored by decades of flow and sediment regulation and it has coarse artificial riffle-steps (i.e.,

183   rock weirs) buttressed by boulders, which further degrades the topography for fish habitat.

184   These structures do not have any of the geometric, hydraulic, or sedimentary attributes of riffles

185   utilized by salmonids for spawning. The channel cannot adjust itself regardless of flow. These

186   factors necessitate that channel rehabilitation is dependent on physical manipulation, which is

187   limited by non-deformable boundary controls.

188

189   2.2 Design Concepts and Tools Used

190

191   Six channel configurations (Fig. 1) were developed within the real constraints imposed

192   by site conditions, management objectives, laws and regulations, and other institutional factors.

193   Research to date suggests that flow-dependent width variations between riffle and pool units is a

194   prerequisite for sustainable (i.e., resilient during floods) riffle-pool units, assuming sediment

195   supply is not limiting and in the absence of extreme bed-material grain-size differences between

196   riffles and pools (Carling and Wood, 1994; MacWilliams et al., 2006; Wheaton et al., 2010;

197   Thompson, 2011). Limited space for channel widening (or width undulation) constrained

198 process-based design (Brown and Pasternack, 2008). Therefore, adding gravel/cobble fill and

199 adjusting the amplitude and relief of morphologic units were the primary opportunities to

200 enhance riffle-pool units. Although width undulation aids riffle-pool resilience (White et al.,

201 2010), rivers below most large dams are channelized, constricted, and at least armored, if not

202 scoured to bedrock. Also, flow regulation limits inundation of high-elevation valley wall

203 oscillations. Furthermore, constructing channel designs with gravel/cobble using front loaders

204 involves bulk placement of the sediment mixture (Sawyer et al., 2009); it is uncommon to design

205 and install different surficial bed-material facies. Thus, evaluations of large width oscillations

206 and differential bed texture were not considered.

207 The Spawning Habitat Integrated Rehabilitation Approach (SHIRA) for rehabilitating

208 regulated gravel-bed rivers organized all phases of the project, including design development and

209 final design selection aided by 2D modeling and ecohydraulic analysis (Wheaton et al., 2004a,

210 b). A design objective is a specific goal that is aimed for when a project plan is implemented.

211 To achieve the objective, it is turned into a design hypothesis, which is a mechanistic inference,

212 formulated on the basis of scientific literature and available site-specific data, and thus is

213 assumed true as a general scientific principle (Wheaton et al., 2004b). Next, specific

214 morphological features are designed to work with the flow regime to yield the mechanism in the

215 design hypothesis. Finally, a numerical test is formulated to determine whether the design

216 hypothesis was appropriate for the project and the degree to which the design objective will be

217 achieved.

218 The six alternative designs (Fig. 1) were created with diverse features that have many

219 specific design hypotheses. The list of all design hypotheses is beyond the scope of this book

220 chapter, but is available at the website Pasternack (2004b). A key aspect of the designs for the

221   channel assemblages is that they span a range of different amplitudes of riffle-pool relief (Table

222   1; Fig. 2) and different planview patterns (Fig. 1). For each of these design elements, a suite of

223   concepts and objective design tools aided the creative process of conceptualizing landforms and

224   articulating their value toward hydraulic, geomorphic, and fisheries objectives in the form of

225   design hypotheses. Riffle and bar analogs were generated by visualization from similar

226   morphological-unit scale features in unregulated rivers. Next, these analogs were scaled and

227   overlaid on the pre-project topography. The spacing and location of riffles were determined

228   somewhat by existing locations and more so by fixed forcing elements, but this was varied

229   between designs. Analytical and empirical design and testing of riffle crests was performed for

230   low-flow conditions to determine if crests had gross hydraulic properties suitable with design

231   objectives. The net volumetric fill (m^3) of gravel and cobble for each design was calculated by

232   digital elevation model differencing in AutoCAD Land Desktop® between the baseline

233   topography and that for each design. Finally, 2D modeling of design surfaces was used to

234   evaluate each design with respect to performance indicators and spatial mechanisms.

235   For riffle-pool relief, some of the relevant design concerns included base flow riffle and

236   pool habitat suitability and quality, stage-dependent riffle scour potential, knickpoint migration

237   through riffles, and the resilience of riffle-pool relief. Initial riffle-crest sizing was done

238   iteratively aided by depth and velocity estimates using the Cipoletti weir equation and mass

239   conservation for specified discharges, because a crest functions like a weir to cause a backwater

240   effect (USBR, 1953; Clifford et al., 2005). Hydraulic estimates for the regulated baseflow

241   typically present during salmon spawning, embryo incubation, and fry development were used to

242   check habitat quality and gravel scour potential at that flow. Riffle-pool relief metrics (A_{RP} and

243   A*$_{RP}$) were computed for each individual pool-riffle pair in each design and averaged by design

244   according to the method of Pasternack and Brown (2011).

245   For plan view morphology, design factors included the lateral distribution of

246   mesohabitats, stage-dependent resilience of microhabitat patches, sediment routing through

247   pools, knickpoint migration through riffle crests, the resilience of riffle-pool relief, and

248   accessibility of pools preferred for recreation fishing. Some specific design morphometrics

249   included degree of pool constriction for flow convergence, shape of riffle exit (e.g. horseshoe

250   shaped, straight, or convex), crestline obliquity for flow divergence, partial riffle-crest

251   notches/chutes for flow bypassing, and central bars for stage-dependent microhabitat resilience.

252

253   2.3 Experimental Riffle-Pool Assemblages

254

255   Due to page limits, readers are directed to Pasternack and Brown (2011) for thorough

256   explanations of designs, with a brief overview here. Designs One, Two and Three involved high

257   riffle-pool relief (aka "accentuated topography") and higher bed slope, while Designs Four, Five,

258   and Six involved low riffle-pool relief (aka "blanket fill), lower bed slope, and ~3-m widening

259   on river right (Table 1). The concept for Design One was to maintain the existing pattern of

260   features, but accentuate them by building up riffles and increasing bed slope, yielding a high

261   riffle-pool relief of 1.54 m (Fig. 2a). The three large riffles were conceived to provide for

262   salmon spawning, the pools for adult holding, and the low-velocity bank fringe for fry habitat.

263   Design Two had two large broad flat riffles with transverse orthogonal crests and accentuated

264   pools, yielding a high riffle-pool relief of 1.58 m and a high asymmetry value of 2.57 (Fig. 2b).

265   The central pool was designed to be large, channel-spanning, and have a lot of submerged

266 features for juvenile rearing and adult holding. The large riffles were designed for Chinook and

267 steelhead spawning. Using preliminary lessons learned from "stress testing" Designs One and

268 Two with ecohydraulic analysis, Design Three was a modification of Design One that had a

269 significantly lower slope, longer riffles, and smaller, narrower pools (Fig. 2c). It was

270 conjectured that the central bar and flanking pools at the end of the design would provide adult

271 holding habitat proximal to spawning habitat and habitat heterogeneity in the face of fluctuating

272 spawning flows. Also, the two small pools might serve as sediment traps to retain sediment

273 placed upstream in this key spawning reach over time. Design Four had a blanket fill with three

274 riffles; the upper two had similar shapes as those in the previous designs with shallower

275 intervening pools, while the third riffle was long and broken up with local crests and chutes (Fig.

276 2d). Even though riffle amplitude was very low, the fact that the bed undulation occurred on top

277 of fill created a strong asymmetry for the last pool-to-riffle unit. This design sought to increase

278 fluvial complexity, while maintaining low feature-to-feature slopes. A new feature for this

279 design that was also used in Designs Five and Six was that the channel was widened three meters

280 on river right to remove encroached vegetation and provide low-velocity, shallow habitat for fry.

281 The biggest difference from the earlier designs was the presence of a long glide that featured a

282 pair of tightly-spaced alternating bars at the end of the reach. Glides can serve for salmon

283 spawning, especially for steelhead, so it was a worthwhile landform to evaluate. Design Five

284 had a blanket fill with three simple riffle crests and a straight longitudinal bar (Fig. 2e). The goal

285 for Design Five was to have the lowest change in riffle-pool relief to limit the amount of gravel

286 fill, while still maintaining the same slope as in the baseline topography as well as to increase

287 fluvial complexity and spawning habitat, while minimizing low-flow scour of that habitat.

288 Design Six continued the evolution of the blanket-fill concept from Design Five by significantly

289   increasing the sizes and amending the shapes of the second and third riffles, which resulted in a

290   lower overall bed slope (Fig. 2f). It also used two longitudinal bars, each with a hook at the end

291   to force flow divergence. The exit slope of the last riffle was graded convexly to cause flow

292   divergence instead of convergence, and thus reduce scour on the riffle exit in the thalweg and

293   shift scour energy to the rough banks where it would have little impact. Overall, the six designs

294   use a lot of different specific elements, but share some commonality dictated by geomorphic and

295   ecohydraulic knowledge. For comparison, the baseline real longitudinal profile is shown in

296   Figure 2g. That profile shows little coherent landform organization, with just a few rock weirs

297   peaking up above the slope-detrended median bed elevation.

298

299   2.4 2D Numerical Model

300

301   A 2D hydrodynamic model, Finite Element Surface Water Modeling System 3.1.5

302   (FESWMS), was used to simulate hydrodynamics for the baseline channel and the six alternative

303   designs. FESWMS solves the vertically integrated conservation of momentum and mass

304   equations using a finite element method to acquire depth-averaged 2D velocity components (U,

305   V) and water depths (H) at each computational-mesh node. FESWMS simulates subcritical and

306   supercritical flows. Froehlich (1989) described hydrodynamic equations, discretization and

307   solution methods, and other FESWMS details. This model has been frequently validated for use

308   in shallow, regulated gravel-bed rivers (Pasternack et al., 2004; Wheaton et al., 2004b,

309   Pasternack et al., 2006; Elkins et al., 2007; Moir and Pasternack, 2008; Manwaring et al., 2009;

310   Sawyer et al., 2010). Brown and Pasternack (2008) developed, calibrated, and validated a

311   FESWMS model of the LDR baseline channel, which is summarized below to characterize the

312   uncertainties that affect experimental simulations.

313   FESWMS was implemented using the Surface Water Modeling System v. 8.1 (Aquaveo,

314   LLC). Computational design meshes had a typical internodal distance of 1.37 m, which was

315   comparable to the spacing of the original topographic survey data from the reference reach

316   (Brown and Pasternack, 2008). Based on past experience with evaluating numerical diffusion

317   and numerical stability, the mesh resolution was high enough to avoid those problems for the

318   finite element method. Meshes only covered the wetted channel and a few periphery dry cells,

319   yielding slightly different final meshes for each discharge and channel configuration.

320   To run FESWMS in a single channel, inflowing discharge and the associated exit water

321   surface elevation (WSE) are required. The ecologically significant discharges of 8.5 and 169.9

322    $m^3 \, s^{-1}$ were specified at the end of the introduction section. Flow was assumed to be normal to

323   the upstream boundary and it was distributed across the channel in proportion to the cross-

324   sectional area of each boundary mesh element. These assumptions were validated by measuring

325   H and U near the upstream boundary in the reference reach (Brown and Pasternack, 2008).

326   WSEs at the downstream end of the reference reach were measured at Q's between 8.5-169.9 m^3

327   s^{-1} using a total station to obtain a stage-discharge rating curve useful for simulating any flow in

328   this range. For the six fabricated channels, the model's downstream boundary was in a pool and

329   corresponds with the level imposed by the next downstream riffle, which can be natural or re-

330   engineered to any desired elevation (Elkins et al., 2007; Pasternack et al., 2008). Therefore, the

331   designs upstream of the model exit had insignificant effect on the WSEs at the model's exit

332   boundary.

333   The two primary model parameters in FESWMS are the eddy viscosity (E) and bed

334   roughness (n). Pasternack and Brown (2011) explain how these were obtained. E was spatially

335   distributed, but used a constant coefficient parameter value of 0.6. Roughness associated with

336   resolved meter-scale bedform topography was explicitly represented in the detailed channel

337   DEM. 2D models are highly sensitive to DEM inaccuracies (Horritt et al., 2006). For

338   unresolved roughness, a global n of 0.043 was used with all meshes (Pasternack et al., 2004,

339   2006, 2008; Moir and Pasternack, 2008). This was not numerically calibrated; it was validated

340   by comparing observed and predicted WSEs along the reference reach at different Q's as well as

341   by comparing observed and predicted H and U values at cross-sections. In gravel placement,

342   added material is well mixed and not differentiated between riffles and pools, so uniform

343   roughness is appropriate.

344   In this study FESWMS was used for exploratory experimentation using fabricated,

345   theoretical channel configurations to improve ecohydraulic and geomorphic understanding of

346   basic riffle-pool functioning as well as to improve the application of gravel-bed river design.

347   Acceptance of the numerical approach requires reasonable confidence in FESWMS' predictions.

348   Three different tests assessed model uncertainty for the LDR channel (Brown and Pasternack,

349   2008). First, the range of E values in model output was checked against field-based estimates

350   and found to be similar (~0.02-0.1 $m^2 s^{-1}$).

351   Second, recognizing that in a straight confined reach lateral and longitudinal variation in

352   velocity magnitude in a river is highest at low discharge (Clifford and French, 1998) and that

353   2D-model validation performance has been found to be insensitive to discharge (e.g., May et al.,

354   2009; Pasternack and Senter, 2011), model validation of H and U was performed at 12.9 $m^3 s^{-1}$.

355   Predictions evaluated in detail by Brown and Pasternack (2008) and also shown in Pasternack et

356   al. (2008) yielded the typical results, with H accurately predicted and U adequately predicted.

357   Abrupt lateral gradients in U were not predicted accurately, but at many points U was very

358   accurately predicted.

359   Third, a total station was used to measure the WSE at 14 locations at 169.9 $m^3 s^{-1}$

360   (vertical accuracy of <1 cm). Modeled WSE was systematically slightly higher than observed

361   (~5% of mean cross-sectional depth), but not enough to warrant iterative calibration of the n-

362   value. Overall, validation analysis showed that FESWMS is accurate enough to provide

363   confidence that the reported spatial patterns in depth and velocity are real, but is not accurate

364   enough to characterize poorly mapped regions with very strong lateral variation precisely, for

365   which better mapping and 3D numerical modeling would be better. As this study used synthetic

366   topography, map accuracy is irrelevant, while inadequate lateral velocity variation is an

367   uncertainty.

368

369   2.5 Fish Habitat Quality

370

371   Physical habitat quality predictions were made by extrapolating 2D model depth and

372   velocity predictions through local, independent habitat suitability curves (HSC) for H and U

373   from USFWS (1999). Although many local HSC were used in the LDR rehabilitation design,

374   this study focused on physical habitat metrics for spawning and fry rearing lifestages of

375   anadromous Chinook salmon and steelhead trout (Fig. 3), which are particularly sensitive to flow

376   and topography, as expressed in 2D hydraulic patterns. Because ideal substrates would be placed,

377   no substrate HSC was needed to compare designs.

378   A global habitat suitability index (GHSI) was calculated at each computational node as

379 the geometric mean of the H and U indices (Pasternack et al., 2004). To account for H and U

380 uncertainty, GHSI values were binned with GHSI = 0 as non habitat, 0 < GHSI < 0.1 as very

381 poor habitat, 0.1 < GHSI < 0.4 as low quality, 0.4 < GHSI < 0.7 as medium quality, and 0.7 <

382 GHSI < 1.0 as high quality. These broad classes reduce the impact of H and U prediction error,

383 since they are largely insensitive to ~0-25 % U error, unless a value is very close to a bin edge

384 (Brown and Pasternack, 2009). Use of low-quality habitat depended on the degree of channel

385 degradation and fish density. Elkins et al. (2007) reported a significant spawner preference for

386 medium- and high-quality habitat (GHSI>0.4) and an equally strong, statistically significant fish

387 avoidance of nonhabitat and very poor quality habitat (GHSI <0.1). Pasternack (2008) reported

388 preference for GHSI>0.4 and avoidance for GHSI<0.4 for three tests at a highly utilized

389 spawning site on the lower Yuba River. As a result of those findings, the terms "suitable

390 habitat" and "preferred habitat" are used to refer to all areas with GHSI>0 and GHSI>0.4,

391 respectively. Although no equivalent comparison was available for fry, regional expertise

392 suggests that fry occur in suitable habitat of any quality, avoiding just nonhabitat areas (T.R.

393 Payne, pers. comm., 2010). All performance indicators were checked for both species'

394 lifestages, but a higher qualitative weighting was given to the habitat-suitability metric for fry

395 and the habitat-preference metric for spawners.

396

397 2.6 Sediment Transport Regime

398

399   It is natural and unavoidable that in a regulated river with zero bedload influx, placed

400 gravel/cobble will be entrained during floods, potentially degrading artificially contoured fluvial

401 landforms (Merz et al., 2006). The use of concepts from fluvial geomorphology (e.g. Thompson,

402 2006; MacWilliams et al., 2006; Wilkinson et al., 2008; Caamaño et al., 2009; Sawyer et al.,

403 2010) in the project aimed to focus scour in appropriate locations and yield downstream

404 deposition beyond the project area, such that the overall integrity of gravel bars remains intact,

405 even if sub-width features adjust. When coupled with a regular program of a suitable quantity of

406 gravel injection at the entrance of the reach, it ought to be feasible to sustain the constructed

407 topography (e.g. design hypothesis tests of Wheaton et al., 2004b; Wheaton et al., 2010).

408 However, since the channel width was unavoidably constricted in the testbed reach, it was

409 understood from the outset that flow-convergence routing was infeasible- scour would always be

410 higher over riffles than pools in this area, tending toward diminished riffle-pool relief.

411 Nonetheless, flow-dependent channel resilience could still vary significantly as a function of

412 channel configuration, so that was an important basis for performance evaluation.

413   Pasternack et al. (2006) validated the suitability of FESWMS for predicting bed shear

414 stress in shallow gravel-bed rivers, finding that the model is as good as field estimation methods

415 most of the time; the exception being in very shallow water ($H \sim d_{90}$, size that 90% of the bed

416 material is smaller than). In this study, Shields stress was calculated at each mesh node to

417 evaluate the sediment transport regime and channel stability under different flow conditions:

418
$$\tau^* = \frac{\tau_v^b}{(\gamma_s - \gamma_w)d_{50}} \tag{3}$$

419
$$u^* = \frac{U}{5.75\log\left(\frac{12.2H}{2d_{90}}\right)} \text{ and } \tau_v^b = \rho_w u^{*2} \tag{4,5}$$

420 where τ^* is Shields stress, τ_v^b is bed shear stress in the direction of the velocity vector, d_{50} is the

421 median grain size, d_{90} is the size at the 90th percentile of the cumulative distribution function for

422 bed material grain size distribution, γ_s is sediment specific weight, γ_w is the water's specific

423   weight, and ρ_w is water density. As with GHSI, $\tau*$ was binned to account for H and U

424   inaccuracy. Lisle et al. (2000) defined sediment transport regimes relative to $\tau*$ as $\tau* < 0.01$

425   represents no transport; $0.01 < \tau* < 0.03$ represents probabilistically intermittent entrainment;

426    $0.03 < \tau* < 0.06$ represents the "partial transport" domain of Wilcock et al. (1996); $0.06 < \tau* <$

427   0.1 represents full transport of a "carpet" of sediment $1\text{-}2\cdot d_{90}$ thick, and $\tau* > 0.1$ corresponds

428   with potentially channel-altering conditions. These threshold delineations have uncertainty, but

429   provide a reasonable basis for characterizing and comparing sediment transport conditions

430   (Sawyer et al., 2010).

431

432   2.7 Test Analyses and Outcome Indicators

433

434   Tests evaluating physical habitat and sediment transport regime involved computing and

435   comparing statistical distributions for the performance indicators for GHSI and Shields stress

436   datasets as well as visual comparisons of the spatial patterns of GHSI and Shields stress to

437   evaluate mechanisms. A summary table was produced in which the best performing design(s)

438   were identified for each GHSI indicator, and then the best overall design was evident as the one

439   with the most occurrences as the best performer across all the metrics. An identical analysis was

440   done for Shields stress. Picking the best design was a necessary part of the real-world project,

441   while the comparison alone is more interesting to appreciate the circumstances in which each

442   landform sequence has value for different sets of project objectives. Therefore, design response

443   according to different performance indicators was assessed relative to differences in A_{RP} and

444    $A*_{RP}$.

445   For physical habitat quality, the performance indicators were the percent distribution of

446   GHSI bins, the habitat efficiency for habitat creation (defined below), the habitat efficiency for

447   habitat improvement (defined below), and spatial pattern of GHSI. Each of these indicators was

448   used for each species' lifestage. For the baseline channel and each alternative design, the percent

449   of wetted area for each GHSI bin was plotted as a stacked column for each species' lifestages

450   and the one with highest percentages of suitable and preferred habitat (as defined in section 2.5)

451   were identified. Because each design has a different wetted area, care is required in cross-

452   comparing this metric, as the design with the highest percent of something is not necessarily the

453   one with the most area of it. Habitat efficiency is a cost/effectiveness metric where the cost is

454   the amount of coarse sediment needed (in m^3, but could be expressed in dollars per m^3 of gravel

455   placed) and the effectiveness is the amount of habitat, which can be expressed in different

456   specific metrics as well. Habitat added means the net increase in suitable-habitat area (m^2) per

457   m^3 of gravel added, while habitat improved means the net increase in preferred-habitat area (m^2)

458   per m^3 of gravel added. Designs were directly compared for their performance in habitat

459   efficiency. Habitat efficiency is a particularly useful metric when trying to prioritize among

460   possible projects across many different sites of widely different morphologies. Assessing the

461   relative merits of habitat efficiency in terms of addition of suitable habitat versus improvement

462   of habitat to the preferred state involves more professional judgment, so both metrics are worth

463   considering as performance indicators. As justified earlier, more weight was given to habitat

464   improvement for spawning, while more weight was given to habitat addition for fry. These

465   choices hinge on expert judgment or stakeholder consensus- the key is that this study shows the

466   relative merits of different landforms with different types of riffle-pool relief. Finally, visual

467   inspection of the spatial pattern of GHSI bins relative to the DEM for each design established the

468   link between morphology and microhabitat pattern to explain the latter.

469   For sediment transport regime, three performance indicators were used. First, the %

470   wetted area with $\tau^* > 0.06$ and that for $0.03 < \tau^* < 0.06$ for each scenario when discharge is 8.5

471    $m^3 s^{-1}$ were used to compare the risk of unacceptable ecological disturbance during the period of

472   bed occupation by redds, embryos, and fry. Second, the % wetted area with $\tau^* > 0.06$ and that

473   for $0.03 < \tau^* < 0.06$ for each scenario when discharge is 169.9 $m^3 s^{-1}$ were used to compare the

474   potential of channel change for the ecological function of "bed preparation" (Escobar and

475   Pasternack, 2010). Finally, the stage-dependent location of peak τ^* for each scenario was

476   inspected for evidence of flow-convergence routing of sediment through pools as a performance

477   indicator of the resilience of riffle-pool relief under existing reservoir operations.

478

479   3. Results

480

481   3.1. Physical Habitat

482   The statistical distribution of GHSI bins shows systematic differences in habitat benefits

483   between designs using accentuated topography and those using blanket fills in terms of riffle-

484   pool relief (Fig. 4). Depending on what the habitat goals of a rehabilitation project are aiming

485   for, clear landform preferences are evident. Designs One and Two had the most accentuated

486   topography and they yielded the largest percent areas of suitable and preferred Chinook fry

487   habitat. A key result was found in comparing Chinook and steelhead fry performance in percent

488   area of habitat. Because the steelhead-fry velocity HSC (Fig. 3b) has a broader range and a

489   higher velocity of peak preference than that for Chinook fry, the blanket-fill designs yielded

490   significantly higher percent areas of suitable habitat compared to the accentuated-topography

491   ones. However, the accentuated-topography designs provided the highest percentages of

492   preferred steelhead fry habitat. Designs Four, Five, and Six all yielded high-quality Chinook

493   spawning habitat over >55% of the wetted area and medium-quality habitat over another 28-39%

494   of it. Preferred steelhead spawning habitat was also present in high percentages for these

495   blanket-fill designs. The accentuated topography designs provided improvements over the

496   baseline in terms of percent area of suitable habitat, but did not necessary achieve that for

497   preferred habitat, which is the more important metric for spawning habitat.

498   The habitat-efficiency performance indicators yielded similar outcomes as those using the

499   GHSI bins for spawning, but were particularly helpful in distinguishing relative benefits within

500   each riffle-pool relief grouping (Fig. 5). The habitat-addition and habitat-improvement

501   efficiencies of Design One were more than double those of the next highest performer (Design

502   Two) for Chinook fry. Also, while Design One had the least harmful effect on steelhead fry

503   preferred-habitat loss, it caused the most loss of suitable habitat for steelhead fry. Design Six

504   had the opposite outcome, yielding more than double the gain in suitable steelhead fry habitat

505   compared to the next best performing designs (Four and Five). For both Chinook and steelhead

506   spawning, the blanket-fill designs performed best across habitat efficiency metrics, and among

507   those Design Six was the best. Across all eight habitat-efficiency metrics for all species'

508   lifestages (Table 2, efficiency columns), Design Six was the best for five and the worst for only

509   one (Chinook fry habitat-improvement efficiency).

510   The maps of the spatial patterns of GHSI bins (Fig. 6) provide insight about why the

511   designs perform differently. For brevity and illustration purposes, only those for Chinook are

512   shown and only for designs One and Six, since those show the sharpest contrast (and the rest for

513   all species' lifestages are all available at the website provided in the introduction to section 2).

514   For Design One, preferred spawning habitat is located in riffle entrances and to a much smaller

515   extent on the periphery of channels, especially where there are lateral bars. Accentuating the

516   topography created riffles that were too short, shallow, and fast to serve as spawning habitat.

517   Since the pools are nonhabitat for spawning, then there is just too little area for spawning when

518   topography is accentuated. An interesting nuance to that outcome is evident in the first riffle in

519   Design Three, which had a small, high crest bounded by longer flat shelves of riffle entrance and

520   exit. For that riffle, the crest was only low-quality habitat, but both shelves had medium-quality

521   habitat with high-quality habitat along both banks. That suggests some benefits to having

522   multiple elevation tiers to a riffle. Nevertheless, the really important result was the finding that

523   Design Six yielded nearly ubiquitous high-quality Chinook spawning habitat and widespread

524   preferred steelhead spawning habitat. Design Six had diverse landform features at multiple

525   spatial scales and many of them had spawning value from a hydraulic perspective.

526   In terms of the fry lifestage, the GHSI maps show that the accentuated-topography

527   designs yield significantly more preferred fry habitat, because they produce slackwater areas

528   (sometimes large, slowly recirculating eddies) on the periphery behind each riffle crest. Abrupt

529   bed-elevation increases caused flow to converge, yielding a narrower effective flow width

530   bounded by slackwater or recirculating eddies. The higher the bed-elevation increase, the

531   stronger the effects. This is the concept used in whitewater park design, where bed and width

532   constrictions focus flow to produce standing waves for kayak stunts and intervening peripheral

533   pools for kayakers waiting in line for their turn. Numerically, the blanket-fill designs performed

534   poorly for Chinook fry habitat, because velocities were too fast, given an exponentially

535   decreasing velocity HSC. The blanket-fill designs in this study yielded insufficient depth and

536   width undulations to create the sheltering observed in the accentuated-topography designs.

537   However, steelhead fry use the widespread, moderately higher velocities found in the blanket-fill

538   designs, so the blanket fill is beneficial for them (Fig. 6).

539

540   3.2 Sediment Transport Regimes

541

542   The statistical distributions of Shields stress bins for $\tau^* > 0.06$ and $0.03 < \tau^* < 0.06$

543   indicated the relative resilience of each design across an order of magnitude of discharge (Fig.

544   7). At low discharge ($8.5 \text{ m}^3 \text{ s}^{-1}$) when embryos are at risk of being scoured out, $< 5\%$ of the

545   wetted area was in the full transport regime for each design, with the highest values associated

546   with the designs having the highest A_{RP} (One, Two, and Three). The partial-transport bin

547   showed at-risk areas of $< 9\%$, with the highest values associated with designs having the highest

548   overall bed slope (One, Two, and Five). The τ^* maps helped explain the difference in response

549   of these two metrics at low flow (Fig. 8a,b). Higher overall bed slope drives higher overall

550   velocities, especially on riffles at within-bank flows, which is indicative of a higher area with τ^*

551   > 0.03. Higher A_{RP} is indicative of the presence of over-steepened riffle exits, which causes an

552   abrupt local velocity increase capable of driving knickpoint migration.

553   At high discharge ($169.9 \text{ m}^3 \text{ s}^{-1}$), there is a marked difference in resilience between

554   accentuated and blanket-fill topographies. Similar to low discharge, the designs with the highest

555   A_{RP} (Designs One, Two, and Three) had the largest percent area of full bed mobility (4.4-21%).

556   Meanwhile, the designs with the lowest slope had the highest percent areas of partial transport

557   (60-76%). These patterns are explained using the τ^* maps (Fig. 8c,d) and Stewardson and

558   McMahon's (2002) conceptual model of hydraulic variations within stream channels, as applied

559   to the Trinity River by Brown and Pasternack (2008). According to this concept, there is a flow

560   dependence to the transition of a river's hydraulic regime from one dominated by longitudinal

561   velocity variation at low flow to one dominated by lateral velocity variation at high flow. As

562   illustrated in this numerical experiment, the exact discharge required for the transition is

563   dependent on riffle-pool relief. Specifically, for the accentuated-relief designs, the riffle crests

564   are so high that even at 169.9 m^3 s^{-1}, there is a strong longitudinal velocity variation with high

565   velocities and shear stresses focused on riffle crests and an abrupt increase in velocity at the

566   oversteepened riffle exits (Fig. 8c). In contrast, this discharge is high enough for the blanket-fill

567   channels to surpass the transition in hydraulic regime to lateral-variation dominance. As a result,

568   these channels distribute velocity response to overall bed slope evenly along their length,

569   avoiding focal points for scour (Fig. 8d). Design Three is a hybrid between the two in that its

570   A_{RP} is just enough that the riffle crests peak up causing a longitudinal hydraulic variation at this

571   flow and focusing scour at riffle exits somewhat.

572   Based on the six τ^*-bin performance indicators, all the blanket-fill designs outperform

573   the accentuated-topography designs, but among them there is not a universal standout (Table 3).

574   Design Six is the best performer at low flow, because it exhibits the lowest percent area of partial

575   transport, highest percent area of $\tau^* < 0.03$, and best pattern of τ^* in terms of avoiding riffle-

576   crest scour. The only problem with Design Six, which is very minor, is that the very end of the

577   last riffle exit drops off enough to cause a sliver of partial transport, with a few spots

578   experiencing full bed mobility. Design Four has a more gradual final riffle exist, so it avoids that

579   problem, but does have larger zones of partial transport in other places on riffle crests. Design

580   Five is the best performer at high flow, because its bar configuration helps to focus flow in the

581   center where peak velocity is the most even along the channel among design and yielding the

582   strongest lateral velocity variation. Design Six also has those bars and it has just enough lateral

583   constriction after each riffle to help induce a similar centralized focusing of velocity and scour

584   potential over pools. However, its long, shallow riffles do experience partial transport over

585   nearly their full width.

586

587   4. Discussion and Conclusions

588

589   4.1 Lessons from Numerical Experimentation

590

591   Sequences of riffle-pool units designed with different riffle-pool relief attributes exhibit

592   systematic and predictable variations in flow-dependent physical habitat patterns and

593   geomorphic processes in a setting with a relatively uniform channel width. In general, this study

594   found that modest riffle-pool amplitudes (<0.75 m; A_{RP}/D_{50}~10-12, where D_{50} is median bed-

595   material particle size) from blanket-fill designs yielded the largest habitat addition and habitat

596   improvement efficiencies, especially for salmon spawning. The Chinook fry lifestage was the

597   exception, as high riffle-pool relief yielded large peripheral eddies in the lee of riffle crests (Fig.

598   6c). Similarly, analysis of patterns of sediment transport potential found that high-relief

599   configurations had significantly more area of full bed mobility, regardless of flow. These

600   configurations would be expected to fall apart quickly after construction as a result of knickpoint

601   migration through riffle crests, due to oversteepened riffle exits.

602   For a given riffle-pool amplitude, differences in 3D bar morphology (including A^*_{RP}, but

603   not well explained by it) yield significant differences in habitat and channel stability. For

604   example, Designs Five and Six had ARP values of 0.75 and 0.74, respectively, but their

605 performance indicators were significantly different. The use of longer riffle crests and curved

606 tailouts in Design Six turned out to be important drivers of superior habitat performance.

607 Meanwhile, the orthogonal bar forms and lower riffle exit slopes in Design Five helped avoid

608 knickpoint migration, which is a risk in Design Six, especially at even higher flows that were not

609 modeled in this study. Design Five had a small peak to its last riffle crest that was predicted to

610 experience a higher velocity at the high flow, but it is still in the partial-transport regime, so it is

611 resilient. Design Six had longer riffle-crest features to give them more resilience if knickpoint

612 migration were to take place, but that evidently comes at the cost of increased knickpoint

613 migration risk due to oversteepend riffle exits and the spreading of partial-transport across the

614 full width of riffles. In evaluating these design alternatives, it was conjectured that at expected

615 higher floods in the future, the last riffle crest in Design Five would likely transition into the full-

616 mobility domain and not have enough crest area to absorb the erosion and avoid the "reverse

617 domino" riffle sequence collapse mechanism described by Pasternack et al. (2008). In contrast it

618 was conjectured that the evident lower-flow full mobility at the riffle exits in Design Six would

619 simply lead to sloughing of material to naturally form a more gradual slope, because the length

620 of full-mobility and the amount of bed-material cohesion are likely insufficient to sustain a

621 migrating knickpoint. Therefore, it was deemed more valuable to have longer riffles more

622 resilient to the largest flood releases than to have short riffles with certain resilience to the

623 modeled flood release. Ultimately, the lack of feasibility of significant width increases at riffle

624 crests fundamentally constrained instituting flow-convergence routing through this riffle-pool

625 sequence, and that was repeatedly explained to project sponsors to ensure understanding of what

626 Design Six would yield.

627

628   4.2 Merits of Iterative Design and Construction

629

630   Ecohydraulic river rehabilitation seeks to modify river geometry to achieve specific

631   hydraulic and sedimentary characteristics for target aquatic organisms. In doing this, multiple

632   topographic outcomes may be possible depending on site constraints. Iterative design is the

633   process by which a single scenario is continually modified until ecohydraulic design criteria are

634   satisfied. Iterative design is a key feature in the Spawning Habitat Integrated Rehabilitation

635   Approach (Wheaton et al., 2004a; Elkins et al., 2007), and ought to be one in the more general

636   practice of ecohydraulic design for river engineering. This study illustrates how iterative design

637   can yield topographic surfaces that meet the needs of target organisms despite a wide range of

638   potential scenarios. Without iterative design it would be difficult to determine the relationship

639   between potential topographic manipulation and the optimal configuration of channel geometry.

640   Similarly, iterative construction that builds a design of a long sequence of riffles and

641   pools over a period of years has several merits over attempting a single, massive project (Elkins

642   et al., 2007). First, institutional barriers and regulatory hurdles seem to be lower for a series of

643   smaller projects compared to a single massive one. Stakeholders perceive small projects to be

644   "pilots" and are often willing to allow these with less scrutiny to see what happens, since the

645   risks are low. Inevitable turnover in technical staff and stakeholder participants every few years

646   often confounds large projects, whereas an incremental approach can be understood by

647   neophytes with less effort, as they can focus on just understanding the current iteration first and

648   learning the broader plan over time. Following the iterative approach, before people really grasp

649   events, a significant overhaul in a river has been instituted on a transparent, scientific basis

650   following the original plan. Second, for those who are closely monitoring and implementing the

651   sequence of projects, iterative implementation allows for adaptive management to test design

652   hypotheses for individual design elements and then adjust the overall design when performance

653   indicators show that design hypotheses are not being corroborated. Finally, rivers degrade over

654   decades, so it is sensible to rehabilitate them over a moderate duration, respecting the emerging

655   status of the science and engineering underlying river rehabilitation as well as the unknowable

656   uncertainty in predicting the future. No matter how critical river rehabilitation may be to avoid

657   systemic ecological collapse, rushing large projects is most likely to yield further ecological

658   disturbance rather than solve outstanding problems.

659

660   4.3 Actual Design Selection

661

662   In this study, Design Six was determined to be the best alternative, but at that point

663   additional work is performed to fine-tune the design and generate multiple flow, habitat, and

664   geomorphic predictions across a range of discharges for later evaluation. Small changes in the

665   selected design often must be made to insure that all available gravels and boulders are used as

666   well as to account for new constraints that emerge when the design is vetted among all

667   stakeholders and the public. Further thought and testing may enhance even the best of the

668   alternatives with subtle changes. It may be desired to add layers of complexity onto the basic

669   topography using specific structures at the hydraulic-unit scale (~0.1-1 channel width), such as

670   boulder clusters, riparian shade, and streamwood jams. Hydraulic effects of jams are extremely

671   difficult to simulate, but boulder clusters are feasible. Because habitat quantity and quality is

672   stage-dependent, a more comprehensive view of the final design is obtained by modeling as wide

673   a range of flows as the original topographic and on-going monitoring data allow. The final

674 project design is converted into an easily followed grading plan for use by the contracted front-

675 loader operator.

676

677 4.4 Outlook for Ecohydraulics

678

679   Ecohydraulics is an emerging scientific subdiscipline and professional practice.

680 Traditionally, use of heuristics in river assessments provided a deep understanding of habitat

681 patterns and geomorphic processes, but lost favor for being opaque, non-reproducible, and

682 dependent on "experts". The rise of statistical analysis in ecology and geomorphology

683 democratized river assessment and promoted greater transparency and quantification, but came at

684 the cost of oversimplification of phenomena. Today, the combination of remote sensing,

685 mechanistic modeling, and GIS-based analysis in "near-census" ecohydraulics (i.e. sampling at

686 ~1-m resolution throughout long river segments) is poised to yield a decisive transformation in

687 the practice of river science in which the best features of heuristics and statistics blend to yield

688 deep and repeatable process-based, spatially explicit predictions of river behavior. New

689 technologies will further enhance the capability, but the paradigm is now accessible for scientific

690 exploration and professional practice (Pasternack, 2011).

691

692 ACKNOWLEDGEMENTS

693

696   Bounrisavong and Kaushal Parikh for their help with performing and analyzing all of the 2D

697   model runs.

698

699   REFERENCES

700

701   Bovee, K.D. and Milhous R. 1978. 'Hydraulic simulation in instream flow studies: theory and

702   techniques', *US Fish and Wildlife Service Biological Services Program*, FWS/OBS-78/33.

703   Bovee, K.D. 1982. 'A guide to stream habitat analysis using the instream flow incremental

704   methodology', *US Fish and Wildlife Service Biological Services Program*, FWS/OBS-

705   82/26.

706   Brown, R.A., Pasternack, G.B. 2008. Engineered channel controls limiting spawning habitat

707   rehabilitation success on regulated gravel-bed rivers. Geomorphology 97:631-654.

708   Brown, R.A., Pasternack, G.B. 2009. Comparison of methods for analyzing salmon habitat

709   rehabilitation designs for regulated rivers. River Research and Applications 25:745-772.

710   Caamaño, D., Goodwin, P., Buffington, J.M., Liou, J.C.P., Daley-Laursen, S. 2009. Unifying

711   Criterion for the Velocity Reversal Hypothesis in Gravel-Bed Rivers. Journal of Hydraulic

712   Engineering 135 (1): 66-70.

713   Carling, P.A. and Wood, N., 1994. Simulation of Flow over Pool-Riffle Topography - a

714   Consideration of the Velocity Reversal Hypothesis. Earth Surface Processes and Landforms,

715   19(4): 319-332

716   Clifford, N.J., French, J.R., 1998. Restoration of channel physical environment in smaller,

717   moderate gradient rivers: geomorphological bases for design criteria. In: Bailey, R.G., Jose,

718   P.V., Sherwood, B.R. (Eds.), United Kingdom Floodplains. Westbury Academic & Scientific

719   Publishing, Westbury, pp. 72–76.

720   Clifford, N.J., Soar, P.J., Harmar, O.P., Gurnell, A.M., Petts, G.E., Emery, J.C. 2005.

721   Assessment of hydrodynamic simulation results for eco-hydrological and eco-hydraulic

722   applications: a spatial semivariance approach. Hydrological Processes, 19: 3631-3648.

723   Cramer Fish Sciences. 2010. Evaluation of the 2008 and 2009 Sailor Bar gravel placements on

724   the Lower American River, California. Cramer Fish Sciences, Gresham, OR.

725   Doyle, M.W., Harbor, J.M., 2000. Evaluation of Rosgen's streambank erosion potential

726   assessment in northeast Oklahoma. Journal of the American Water Resources Association,

727   36 (5): 113-121.

728   Elkins, E. E., Pasternack, G. B., and Merz, J. E. 2007. The Use of Slope Creation for

729   Rehabilitating Incised, Regulated, Gravel-Bed Rivers. Water Resources Research 43,

730   W05432, doi:10.1029/2006WR005159.

731   Escobar, M. I. and Pasternack, G. B. 2010. A Hydrogeomorphic Dynamics Approach to Assess

732   In-Stream Ecological Functionality Using the Functional Flows Model, Part 1 - Model

733   Characteristics . River Research and Applications, doi: 10.1002/rra.1316.

734   Froehlich DC. 1989. Finite Element Surface-Water Modeling System: Two-dimensional Flow in

735   a Horizontal Plane User's Manual. US Department of Transportation, Publication #FHWA-

736   RD-88-177.

737   Fukushima, M., 2001. Salmonid habitat–geomorphology relationships in low gradient streams.

738   Ecology 82: 1238–1246.

739 Fulton, A. A. 2008. Gravel for Salmon in Bedrock Channels: Elucidating Mitigation Efficacy

740 Through Site Characterization, 2D-Modeling, and Comparison Along the Yuba River, CA.

741 University of California.

742 Gaeuman, D. 2008. Recommended quantities and gradation for long-term coarse sediment

743 augmentation downstream from Lewiston Dam. Trinity River Restoration Program,

744 Technical Monograph TM-TRRP-2008-2.

745 Gaeuman, D. 2011. Water year 2010 implementation monitoring report. Trinity River

746 Restoration Program, Technical Monograph TM-TRRP-2011-1.

747 Ghanem, A., Steffler, P., Hicks, F. and Katapodis, C. 1996. Two-Dimensional Hydraulic

748 Simulation of Physical Habitat Conditions in Flowing Streams, Journal of Regulated Rivers:

749 Research and Management, 12: 185-200.

750 Hanrahan, T.P., 2007. Bedform morphology of salmon spawning areas in a large gravel-bed

751 river. Geomorphology 86: 529–536.

752 Hauer, C., Unfer, G., Tritthart, M., Formann, E., Habersack, H. 2011. Variability of mesohabitat

753 characteristics in riffle-pool reaches: testing an integrative evaluation concept (FGC) for

754 MEM-application. River Research and Applications, 27 (4): 403-430.

755 Hoopa Valley Tribal Fisheries, McBain & Trush, Inc., Northern Hydrology and Engineering.

756 2001. Preliminary demonstration of the capabilities of a 2D model to assess and improve

757 Trinity River rehabilitation designs. McBain & Trush Technical Memorandum, Arcata, CA.

758 Horritt, M.S., Bates, P.D., Mattinson, M.J. 2006. Effects of mesh resolution and topographic

759 representation in 2D finite volume models of shallow water fluvial flow. Journal of

760 Hydrology 329: 306-314.

761 Jowett, I.G. 1997. Instream flow methods: a comparison of approaches. Regulated Rivers:

762   Research & Management 13: 115-127.

763 Kondolf, G.M., Micheli, E.M. 1995. Evaluating stream restoration projects. Environmental

764   Management, 19: 1-15.

765 Lave, R., Doyle, M., Robertson, M. 2010. Privatizing stream restoration in the US. Social

766   Studies of Science 40:677-703.

767 Lisle, T.E., Nelson, J.M., Pitlick, J., Madej, M.A., Barkett, B.L. 2000. Variability of bed mobility

768   in natural, gravel-bed channels and adjustments to sediment load at the reach and local

769   scales. Water Resources Research, 36 (12): 3743-3755.

770 MacWilliams, M. L. Jar., Wheaton, J.M., Pasternack, G.B., Street, R. L. and Kitanidis, P. K. ,

771   2006. Flow convergence and routing hypothesis for pool-riffle maintenance in alluvial rivers,

772   Water Resources Research, 42, W10427.

773 Manwaring, M., Cepello, S., Kennedy, S., Pasternack, G.B. 2009. Spawning Riffle Gravel

774   Supplementation for Anadromous Spring-Run Chinook Salmon and Steelhead. Waterpower

775   XVI, July 27-30, Spokane. p. 1-18.

776 May, C.L., Pryor, B.S., T. Lisle, Lang, M. 2009. Coupling hydrodynamic modeling and

777   empirical measures of bed mobility to predict the risk of scour and fill of salmon redds in a

778   large regulated river. Water Resources Research, 45, W05402, doi:10.1029/2007WR006498.

779 McKean, J.A., Isaak, D.J., Wright, C.W. 2008. Geomorphic controls on salmon nesting patterns

780   described by a new, narrow-beam terrestrial-aquatic lidar. Frontiers in Ecology and the

781   Environment, 6 (3): 125-130.

782 Merwade, V. 2009. Effect of spatial trends on interpolation of river bathymetry. Journal of

783   Hydrology, 371 (1-4): 169-181.

784   Merz, J.E., L.K. Ochikubo Chan. 2005. Effects of gravel augmentation on macroinvertebrate

785   assemblages in a regulated California river. River Research and Applications, 21: 61-74.

786   Merz, J. E., Pasternack, G. B., Wheaton, J. M. 2006. Sediment Budget for Salmonid Spawning

787   Habitat Rehabilitation in the Mokelumne River. Geomorphology, 76 (1-2): 207-228.

788   Merz, J. E., Setka, J., Pasternack, G. B., Wheaton, J. M. 2004. Predicting benefits of spawning

789   habitat rehabilitation to salmonid fry production in a regulated California river. Canadian

790   Journal of Fisheries and Aquatic Science, 61: 1433-1446.

791   Moir, H. J., Pasternack, G. B. 2008. Relationships between mesoscale morphological units,

792   stream hydraulics and Chinook salmon (Oncorhynchus tshawytscha) spawning habitat on the

793   Lower Yuba River, California. Geomorphology 100:527-548.

794   Nestler, J. M., R. A. Goodwin, D. L. Smith, and J. J. Anderson. 2008. A Mathematical and

795   Conceptual Framework for Ecohydraulics. In Wood, P. J., D. M. Hannah, and J. P. Sadler,

796   eds, Hydroecology and Ecohydrology: Past, Present, and Future, John Wiley & Sons, Ltd.

797   Oh, K., Lee, J., Rubio, C.J., Jeong, S. 2010. Assessment of aquatic habitat effect by artificial

798   change of streambed topography. Water Science Technology, 62 (12): 2872-2879.

799   O'Neill, M. P., and A. D. Abrahams. 1984. Objective Identification of Pools and Riffles, Water

800   Resour. Res., 20(7): 921–926, doi:10.1029/WR020i007p00921.

801   Padmore, C. L., Newson, M. D., Charlton, M. E. 1998. Instream habitat in gravel bed rivers:

802   identification and characterisation of biotopes. In: Klingeman, P. C., Beschta, R. L., Komar,

803   P. D., Bradley, J. B. (Eds.), Gravel bed rivers in the environment. Water Resources

804   Publications, Highlands Ranch, Colorado, pp. 345‒364.

805   Pasternack, G. B. 2004a. http://shira.lawr.ucdavis.edu/trinity.htm

806   Pasternack, G. B. 2004b. http://shira.lawr.ucdavis.edu/trinity_designconcepts.htm

807   Pasternack, G. B. 2006. Demonstration project to test a new interdisciplinary approach to

808   rehabilitating salmon spawning habitat in the central valley. CALFED Cooperative

809   Agreement DCN#113322G003 Final Report, University of California at Davis, Davis, CA,

810   299pp.

811   Pasternack, G. B. 2008a. Spawning habitat rehabilitation: advances in analysis tools. In (D.A.

812   Sear, P. DeVries, S. Greig, Eds) Salmonid spawning habitat in rivers: physical controls,

813   biological responses, and approaches to remediation. Symposium 65, American Fisheries

814   Society, Bethesda, MD.

815   Pasternack, G. B. 2008b. SHIRA-Based River analysis and field-based manipulative sediment

816   transport experiments to balance habitat and geomorphic goals on the lower Yuba River.

817   Cooperative Ecosystems Studies Unit (CESU) 81332 6 J002 Final Report, University of

818   California at Davis, Davis, CA, 569pp.

819   Pasternack. G. B. 2011. 2D Modeling and Ecohydraulic Analysis. Createspace: Seattle, WA.

820   Pasternack, G. B. in press. Geomorphologist's guide to participating in river rehabilitation. In:

821   Shroder, J., Jr., Wohl, E.(Eds.), Treatise on Geomorphology. Academic Press, San Diego,

822   CA, v. 9. 18pp.

823   Pasternack, G. B., Senter, A.E. 2011. 21st Century instream flow assessment framework for

824   mountain streams. California Energy Commission, Public Interest Energy Research.

825   Pasternack, G.B., Brown, R.A. 2011. Ecohydraulic Design of Gravel-Bed River Rehabilitation in

826   the Lewiston Dam Reach of the Trinity River, CA. University of California at Davis, Davis,

827   CA.

828   Pasternack, G.B., Bounrisavong, M.K., Parikh, K.K. 2008. Backwater control on riffle-pool

829   hydraulics, fish habitat quality, and sediment transport regime in gravel-bed rivers. Journal of

830   Hydrology, 357 (1-2): 125-139.

831   Pasternack, G.B., Wang, C.L., and Merz, J. 2004. Application of a 2D hydrodynamic model to

832   reach-scale spawning gravel replenishment on the lower Mokelumne River, California. River

833   Research and Applications, 20 (2): 205-225.

834   Pasternack, G.B., Gilbert, A.T., Wheaton, J.M., Buckland, E.M. 2006. Error Propagation for

835   Velocity and Shear Stress Prediction Using 2D Models For Environmental Management.

836   Journal of Hydrology, 328: 227-241.

837   Pate, W. D. and Rohleder, W. J. 2007. Cradle of Invention. Civil Engineering, 77 (3): 36-43.

838   Payne, T.R. (2010) Personal Communication. Thomas R. Payne & Associates. California, USA.

839   Rayburg, S., Neave, M., 2008. Assessing morphologic complexity and diversity in river systems

840   using three-dimensional asymmetry indices for bed elements, bedforms and bar units. River

841   Research and Applications, 24: 1343-1361.

842   Redd, R., and Horner, T.C. 2008. Physical and geochemical characteristics of the 2008 Sailor

843   Bar gravel addition. Report to the U.S. Bureau of Reclamation, Sacramento office, 75pp.

844   Redd, R., and Horner T.C. 2010. Physical and geochemical characteristics of the 2009 Sailor Bar

845   gravel addition. Report to the U.S. Bureau of Reclamation, Sacramento office, 77pp.

846   Richards, K. S. 1976a, The morphology of riffle-pool sequences. Earth Surface Processes, 1: 71-

847   88, doi: 10.1002/esp.3290010108.

848   Richards, K. S. 1976b. Channel width and the riffle-pool sequence. GSA Bulletin, 87 (6): 883-

849   890.

850 Sarkisian, M., Mathias, N., Mazeika, A. 2007. Suspending the limits. Civil Engineering, 77 (11):

851   36-45.

852 Sawyer, A. M., Pasternack, G. B., Merz, J. E., Escobar, M., Senter, A. E. 2009. Construction

853   constraints on geomorphic-unit rehabilitation on regulated gravel-bed rivers. River Research

854   and Applications, 25: 416-437.

855 Sawyer, A. M., Pasternack, G. B., Moir, H. J., Fulton, A. A. 2010. Riffle-Pool Maintenance and

856   Flow Convergence Routing Confirmed on a Large Gravel Bed River. Geomorphology, 114:

857   143-160.

858 Senter, A. E. and Pasternack, G. B. 2010. Large wood aids spawning Chinook salmon

859   (Oncorhynchus tshawytscha) in marginal habitat on a regulated river in California. River

860   Research and Applications, DOI: 10.1002/rra.1388.

861 Simon, A., Doyle, M., Kondolf, G.M., Shields Jr., F.D., Rhoads, B., McPhillips, M., 2007.

862   Critical evaluation of how the Rosgen classification and associated "natural channel design"

863   methods fail to integrate and quantify fluvial processes and channel responses. Journal of the

864   American Water Resources Association, 43 (5): 1117-1131.

865 Stewardson, M.J., McMahon, T.A., 2002. A stochastic model of hydraulic variations within

866   stream channels. Water Resources Research 38 (1), doi:10.1029/2000WR000014.

867 Thompson, D.M., 2006. The role of vortex shedding in the scour of pools. Advances in Water

868   Resources, 29: 121–129.

869 Thompson, D. 2011. The velocity-reversal hypothesis revisited. Progress in Physical

870   Geography, 35 (1): 123-132

871 USACE. 2010. Lower Yuba River Gravel Augmentation Final EA. Univted States Army Corps

872   of Engineers, Sacramento, CA.

873   USBR. 1953. Water Measurement Manual. United States Bureau of Reclamation, Washington,

874   DC.

875   USFWS. 1999. Trinity River Flow Evaluation. United States Fish and Wildlife Service,

876   Washington, DC.

877   USFWS. 2002. Mainstem Trinity River Chinook salmon spawning survey year 2000 and 2001.

878   United States Fish and Wildlife Service, Washington, DC.

879   Vetter, T. 2011. Riffle-pool morphometry and stage-dependant morphodynamics of a large

880   floodplain river (Vereinigte Mulde, Sachsen-Anhalt, Germany). Earth Surface Processes and

881   Landforms, 36 (12): 1647-1657.

882   Waddle, T.J. 2001. PHABSIM for Windows User′s Manual and Exercises. United States

883   Geological Survey, Fort Collins, CO.

884   Waddle, T.J., Steffler, P., Ghanem, A., Katopodis, C., Locke, A. 2000. Comparison of one and

885   two‑dimensional open channel flow models for a small habitat stream. Rivers, 7 (3):

886   205‑220.

887   Watry, C., Merz, J.E. 2009. Evaluation of the 2008 Sailor Bar Gravel placement on the Lower

888   American River, California. Cramer Fish Sciences, Gresham, OR.

889   Wheaton, J. M., Pasternack, G. B., and Merz, J. E. 2004a. Spawning Habitat Rehabilitation - 1.

890   Conceptual Approach & Methods. International Journal of River Basin Management, 2 (1):

891   3-20.

892   Wheaton, J. M., Pasternack, G. B., and Merz, J. E. 2004b. Spawning Habitat Rehabilitation - 2.

893   Using hypothesis development and testing in design, Mokelumne River, California, U.S.A.

894   International Journal of River Basin Management, 2 (1): 21-37.

895   Wheaton, J. M., Brasington, J., Darby, S., Merz, J. E., Pasternack, G. B., Sear, D. A., Vericat, D.

896   2010. Linking geomorphic changes to salmonid habitat at a scale relevant to fish. River

897   Research and Applications, 26: 469-486.

898   Wheaton JM, Gibbins C, Wainwright J, Larsen L and McElroy B. 2011. Preface: Multiscale

899   Feedbacks in Ecogeomorphology. Geomorphology, 126 (3-4): 265-268, DOI:

900   10.1016/j.geomorph.2011.01.002.

901   White, J. Q., Pasternack, G. B., and Moir, H. J. 2010. Valley width variation influences riffle-

902   pool location and persistence on a rapidly incising gravel-bed river. Geomorphology 121:

903   206-221.

904   Wilcock, P.R., Barta, A.F., Shea, C.C., Kondolf, G.M., Matthews, W.V.G., Pitlick, J.C. 1996.

905   Observations of flow and sediment entrainment on a large gravel-bed river. Water Resources

906   Research, 32: 2897-2909.

907   Wilkinson, S.N., Rutherfurd, I.D., Keller, R.J., 2008. An experimental test of whether bar

908   instability contributes to the formation, periodicity and maintenance of pool–riffle sequences.

909   Earth Surface Processes and Landforms, 33 (11): 1742–1756.

910   Wissmar, R.C., Beschta, R.L., 1998. Restoration and management of riparian ecosystems: a

911   catchment perspective. Freshwater Biology, 40: 571-585.

912   Woodsmith, R.D., Hassan, M.A., 2005. Maintenance of an obstruction-forced pool in a gravel-

913   bed channel: stream flow, channel morphology, and sediment transport. Catchment

914   Dynamics and River Processes: Mediterranean and Other Climate Regions, 10: 69–196.

915

916

917   LIST OF FIGURES

918

919   Figure 1. Topographic maps of the alternative design scenarios with 0.1-m contours.

920   Figure 2. Longitudinal profiles of the alternative design scenarios and the baseline real channel.

921   Figure 3. Chinook salmon and steelhead trout habitat suitability curves for sensitive fry and

922   spawning lifestages on the Trinity River. Data from USFWS (1999).

923   Figure 4. Stacked column plot comparing the percent wetted area of each GHSI bin for each

924   species' lifestage at 8.5 m^3 s^{-1} among the different designs and the baseline reach. Total area

925   varies somewhat between designs. The color legend for physical habitat quality is as follows:

926   black is high, dark gray is medium, medium gray is low, and light gray is very poor quality.

927   white is non habitat.

928   Figure 5. Habitat efficiency metrics comparing the designs at 8.5 m^3 s^{-1} for four different

929   species' lifestages. Higher bars are better.

930   Figure 6. Examples of GHSI maps for two designs showing the spatial pattern of habitat quality

931   for two different species' lifestages at 8.5 m^3 s^{-1}. The color legend is the same as in Figure 4.

932   Figure 7. Sediment transport regime metrics comparing the designs at two discharges. Black

933   bars show the area of full mobility and gray bars show the area of partial transport. Lower

934   black bars are better.

935   Figure 8. Examples of Shields stress maps at two discharges for two designs. The color legend is

936   as follows: white and light grey are no transport, medium grey is probabilistically

937   intermittent entrainment, darker medium gray is partial transport, dark grey is full mobility,

938   and black is potentially channel-altering conditions.

939

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.

Discharge	Design number			
	full bed mobility	partial transport	τ^* spatial pattern	best overall
low	4	6	6	6
high	5	5	5	5
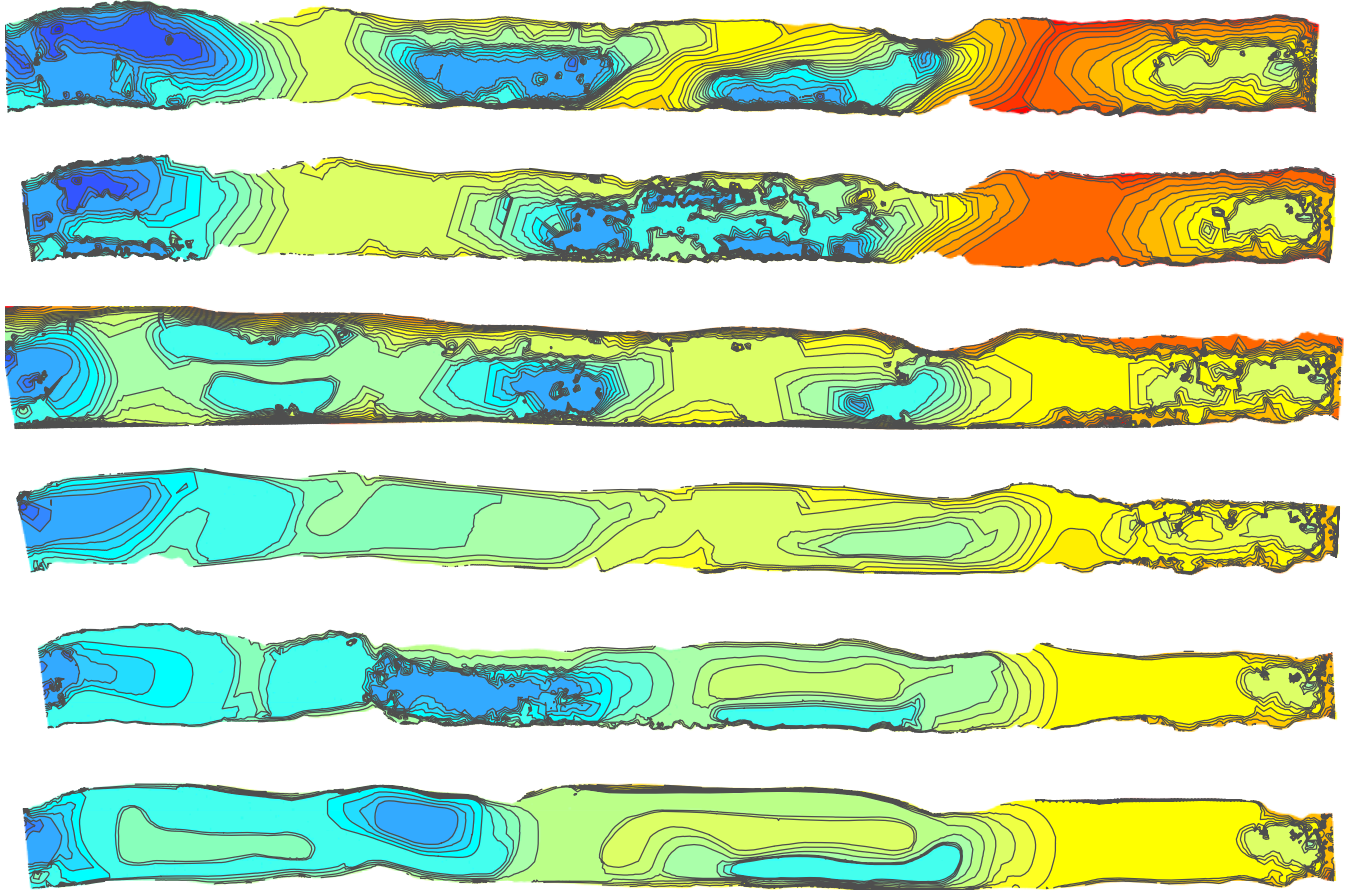
Elevation (m)

558.0 - 558.1	560.0 - 560.1
558.5 - 558.6	560.5 - 560.6
559.0 - 559.1	560.8 - 560.9
559.5 - 559.6	

—— 0.1 m contours

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

Elevation (m)

Distance downstream (m)

(a) Chinook fry

(b) steelhead fry

(c) Chinook spawning

(d) steelhead spawning

(a) Chinook fry

(b) steelhead fry

(c) Chinook spawning

(d) steelhead spawning

Habitat added

Habitat improved

Design number

m² habitat per m³ gravel added
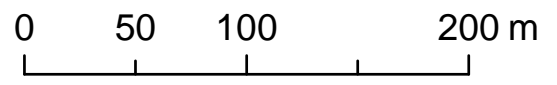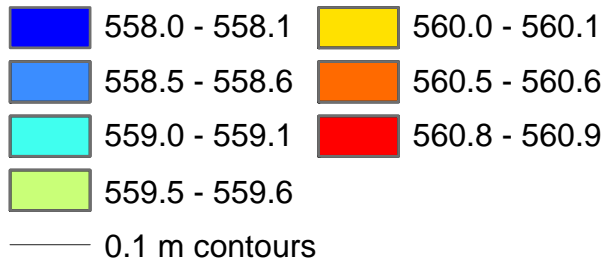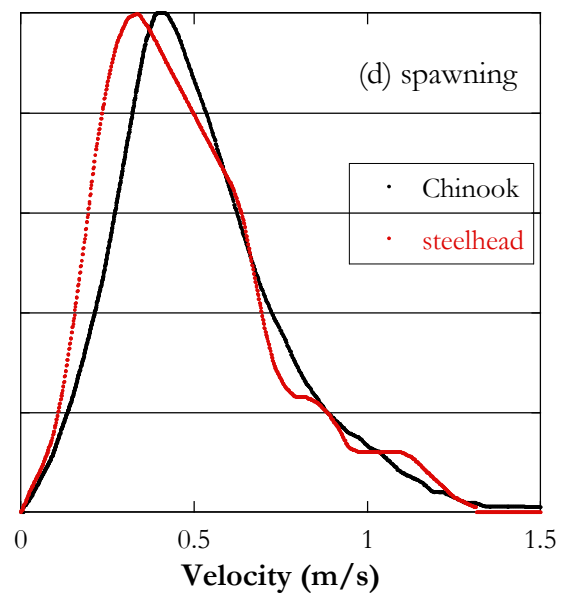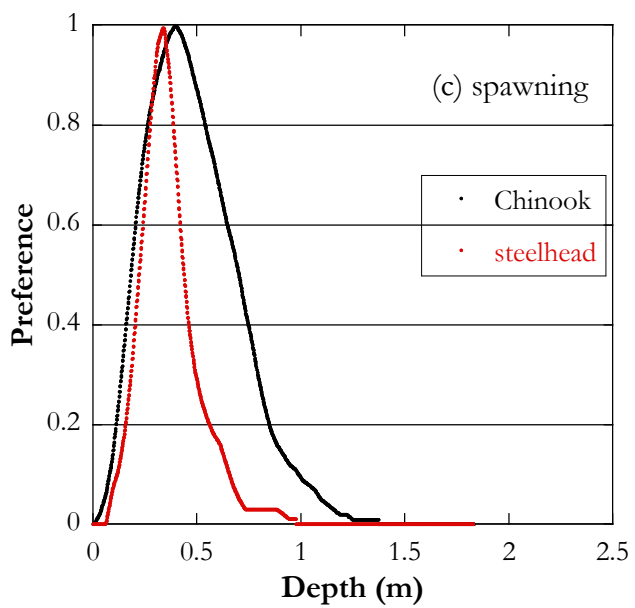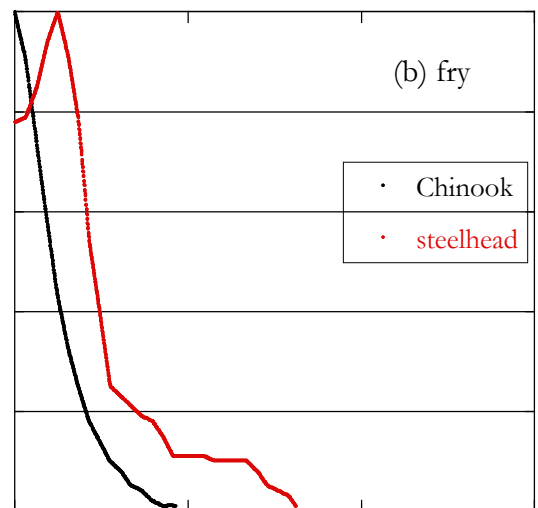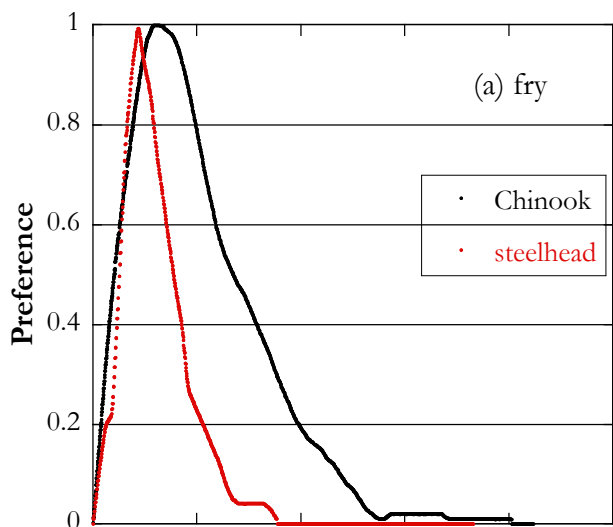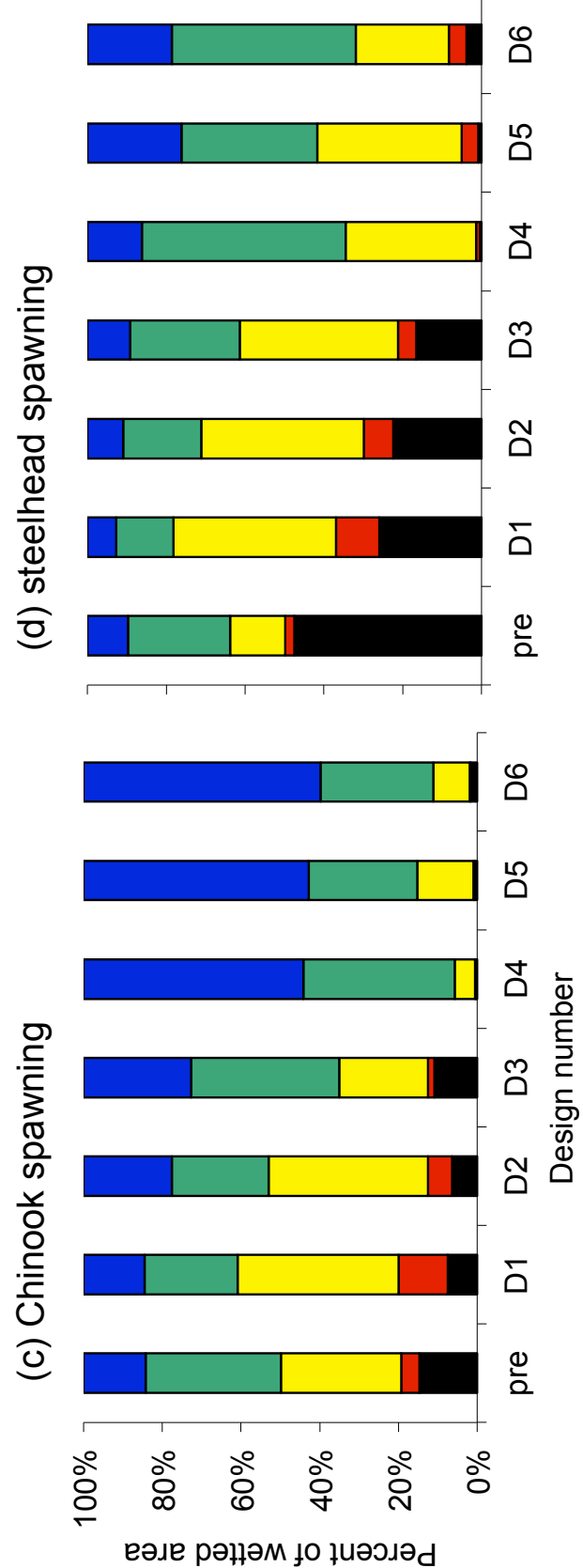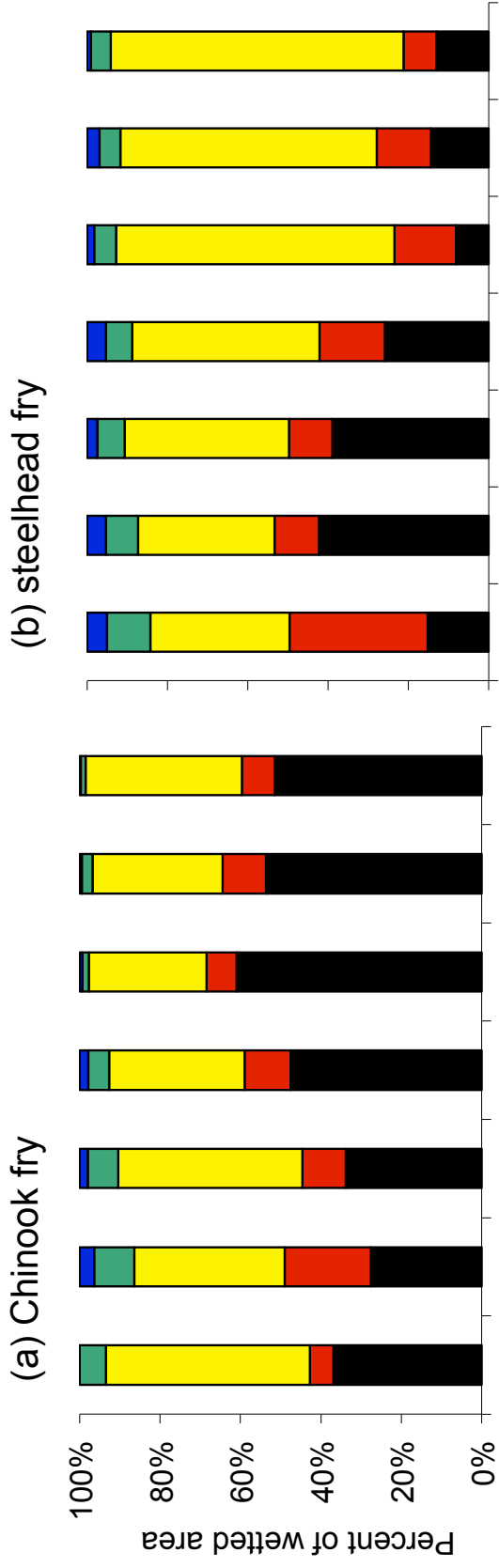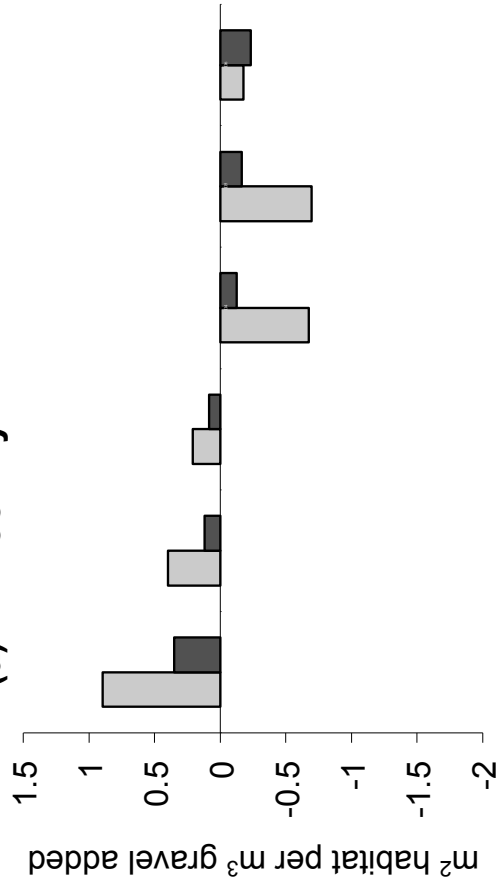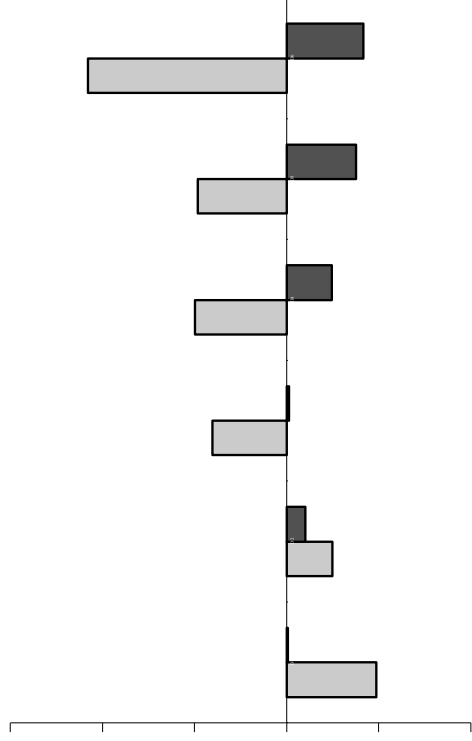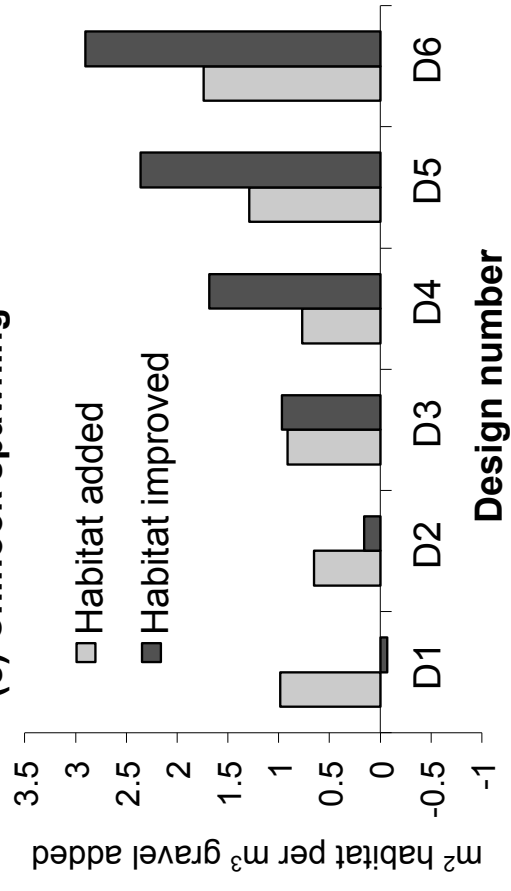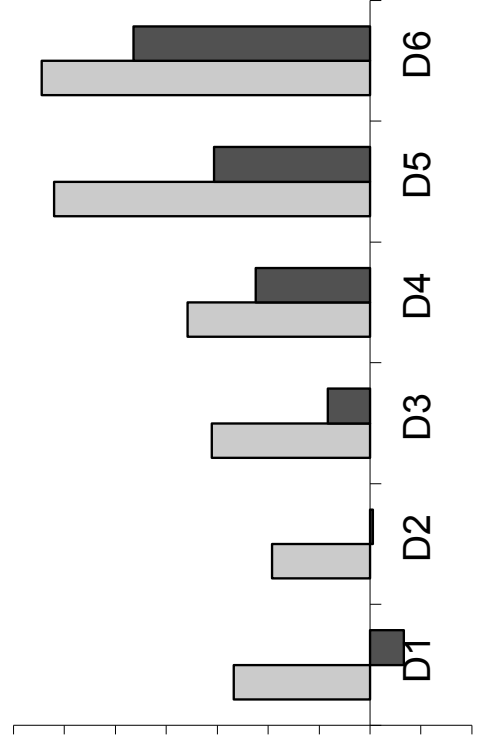
(a) design 1 Chinook spawning GHSI (8.5 m^3/s)

(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)
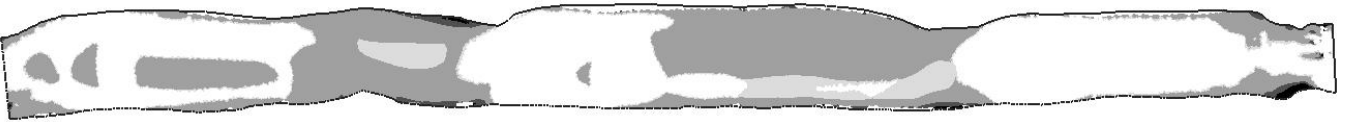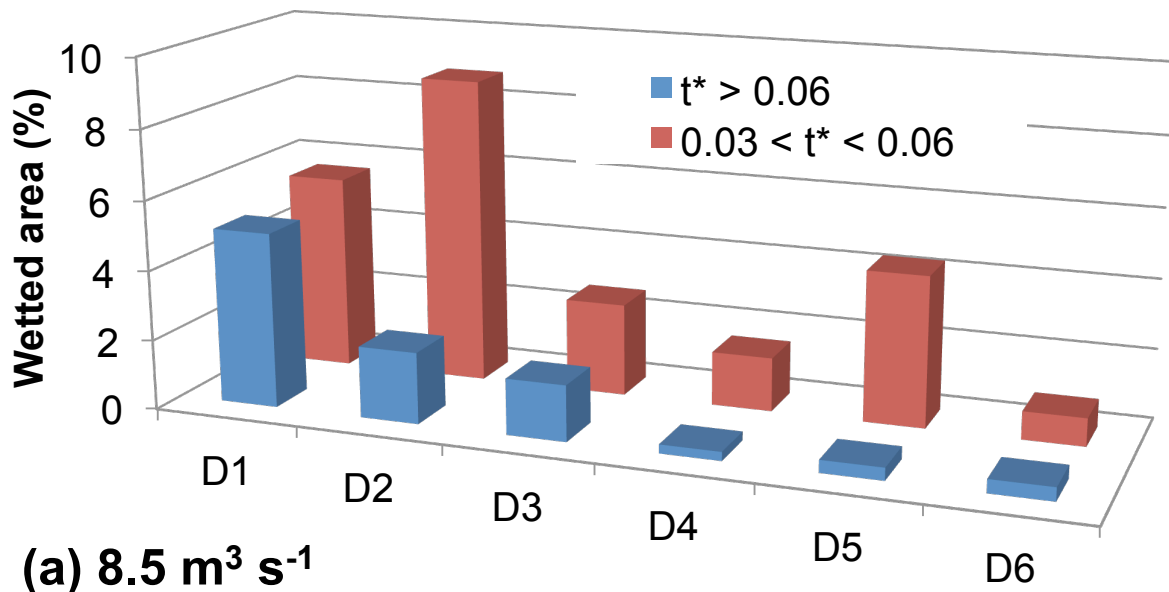
(a) 8.5 m³ s⁻¹
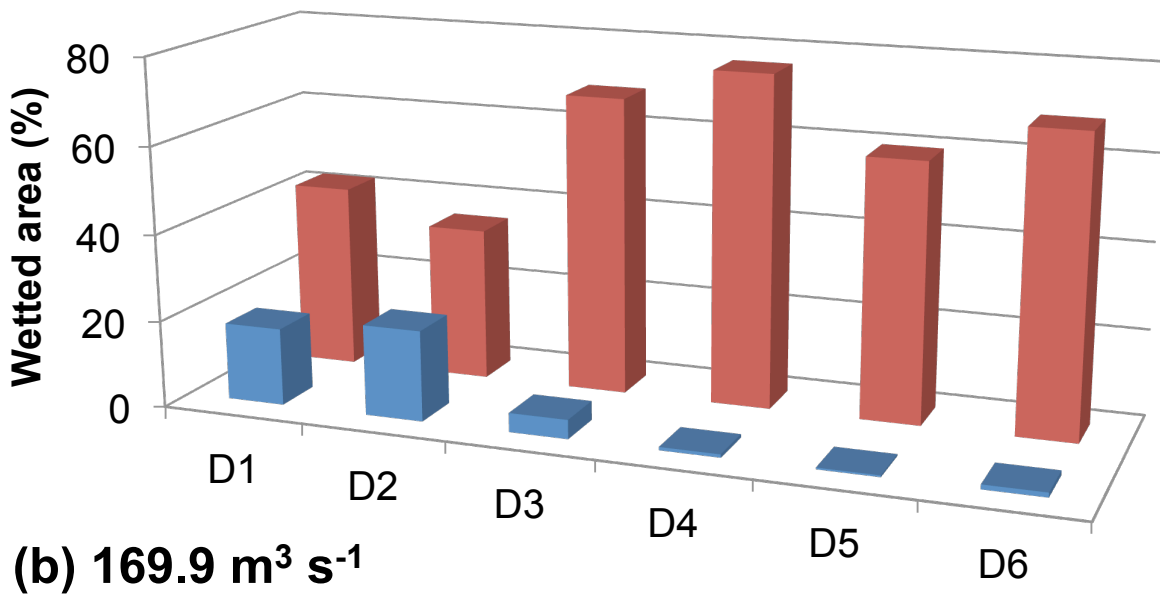
(b) 169.9 m³ s⁻¹

(a) design 1 Shields stress (8.5 m^3/s)
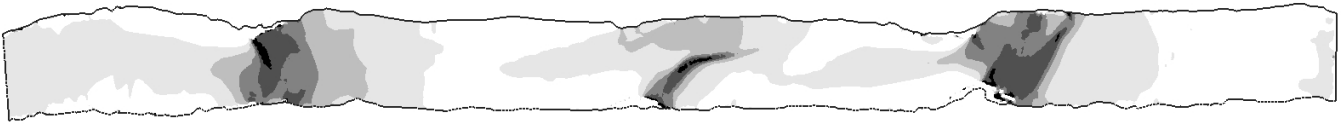
(b) design 6 Shields stress (8.5 m^3/s)

(c) design 1 Shields stress (169.9 m^3/s)

(d) design 6 Shields stress (169.9 m^3/s)