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Engineered channel controls limiting spawning habitat rehabilitation success on regulated gravel-bed rivers

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Abstract

In efforts to rehabilitate regulated rivers for ecological benefits, the flow regime has been one of the primary focal points of management strategies. However, channel engineering can impact channel geometry such that hydraulic and geomorphic responses to flow reregulation do not yield the sought for benefits. To illustrate and assess the impacts of structural channel controls and flow reregulation on channel processes and fish habitat quality in multiple life stages, a highly detailed digital elevation model was collected and analyzed for a river reach right below a dam using a suite of hydrologic, hydraulic, geomorphic, and ecological methods. Results showed that, despite flow reregulation to produce a scaled-down natural hydrograph, anthropogenic boundary controls have severely altered geomorphic processes associated with geomorphic self-sustainability and instream habitat availability in the case study. Given the similarity of this stream to many others, we concluded that the potential utility of natural flow regime reinstatement in regulated gravel-bed rivers is conditional on concomitant channel rehabilitation.

Keywords: river restoration; fluvial geomorphology; flow reregulation; two-dimensional modeling; salmonid habitat

1. Introduction

Alluvial rivers consist of a geometric channel with bank and bed boundaries over which the inputs of water and sediment pass creating a suite of physical processes (Leopold et al., 1964). Thus, the physical controls for a river may be distinguished as boundary or input related (Table 1). Each of these can be further subdivided into natural or anthropogenic in origin, and each has a spatiotemporal range of influence. Most research on the effects of dams and on methods for restoring regulated rivers have emphasized manipulation of the input regime, with the assumption that boundary changes will follow from reregulation, just as natural channel change stems from natural input changes (Graf, 1996; Poff et al., 1997). However, in natural systems, no anthropogenic boundary controls exist, so the flow regime is effective at achieving channel change (Parker et al., 2003). The overall goal of this study was to evaluate the constraints imposed by anthropogenic boundary controls on the potential benefits of flow reregulation for rehabilitating a regulated river in a typical constrained reach below a major dam. Flow reregulation is defined as increases in the magnitude and duration of water releases below dams timed to achieve key ecological and geomorphic functions, such as promoting successful anadromous fish spawning and rejuvenating gravel-bed features during spring flow pulses. Impacts are defined in terms of the regulated channel's hydraulic, sediment transport, and physical habitat regimes at the hydraulic unit and geomorphic unit spatial scales, as defined next. The significance of this study is that it illustrates how existing physical constraints can limit the potential for flow reregulation to promote river rehabilitation.

1.1. Physical controls

Input controls are those that affect the river's flow and sediment supply regimes. Natural "genetic" controls include topography, geology, climate, soils, and vegetation, with the topographic variables of upslope contributing area and local slope providing a particularly strong influence on landscape processes (Montgomery 1999; Montgomery and Buffington, 1997; Montgomery et al., 1996). Anthropogenic input controls include land use, dams, and diversions. Land use affects the gross supply of water and sediment to streams (Bosch and Hewlett, 1982; Jacobson, 1995; Pasternack et al., 2001; Constantine et al., 2005), whereas dams and diversions determine the timing, magnitude, frequency, and rate of change of delivery of inputs to downstream areas (Williams and Wolman, 1984; Kondolf, 1997; Grant et al., 2003).

Boundary controls primarily affect fluvial processes at the hydraulic unit (10^{-1}-10^{0} channel widths) and geomorphic unit (10^{1} channel widths) scales and are typically limited to the reach (10^{2}-10^{3} channel widths) in which they occur. Boundary controls affect channel structure and mediate the response of the channel to flow regime impacts by directing or restricting channel change (Lisle, 1986; Abbe and Montgomery, 1996; Thompson et al., 1998; USFWS, 1999). As a boundary control, valley confinement and valley width variation affects many gravel-bed rivers (Jacobson and Gran, 1999; Coulombe-Pontbriand and Lapointe, 2004). Compared to unconfined channels, the hydraulics of valley-confined channels tend to concentrate flow and bed shear stress in a channel's center with increasing discharge, creating reaches with high transport capacity (Leopold et al., 1964; McBain and Trush, 2000; Constantine et al., 2003). The persistence of pool and riffle sequences has also been related to boundary controls such as bedrock outcroppings, bar features, logjams, and valley geometry (Lisle, 1986; Thompson et al., 1998; MacWilliams et al., 2006). Large changes in relative cross-sectional area between pools and riffles as a function of discharge yield hydraulic "reversals" in which velocity and bed shear stress are greater for riffles than pools at low discharge, but then are greater for pools than riffles at high discharge (Keller, 1971; Carling, 1991; Thompson et al., 1998; MacWilliams et al., 2006).

Anthropogenic boundary controls occur at subreach spatial scales and involve direct channel interventions (Table 1). Because anthropogenic boundary controls generally constrict channels and reduce their roughness (Erskine, 1992; Surian and Rinaldi, 2003), they increase transport capacity and decrease physical-habitat diversity, reducing ecological productivity and diversity (Negishi et al., 2002; Merz et al., 2004; Merz and Ochikubo Chan, 2005). Bed armoring, vegetation encroachment, and levee formation can indirectly result from flow regulation (Williams and Wolman, 1984; Kondolf, 1997; USFWS, 1999). Although such input alterations cause these boundary controls, the effect of these boundary controls is on the boundary and thus its designation as an anthropogenic boundary control. Bank stabilization is used to prevent channel migration and reduce bank erosion that produces sand, silt, and clay (Chang, 1988). Engineered in-stream structures also exist to constrain or aid channel dynamics in association with dams, check dams, bed sills, artificial riffles, boulder clusters, and wood (Abbe et al., 2003; Cederholm et al., 1997; Newbury et al., 1997; Thompson and Stull, 2002). In-stream structures may be used to promote fluvial diversity in support of ecological health (Hunter, 1991; Thompson and Stull, 2002; Wheaton et al., 2004c, Elkins et al., 2007). Artificial riffles are frequently prescribed for slope control and consist of weir like arrangements of large boulders (0.5-2.0 metric ton) that are often cabled (Thompson, 2002; Saldi-Caromile et al., 2004).

1.2. Study objectives

While there is literature discussing flow reregulation for improving streams (e.g., Poff et al., 1997; Webb et al., 1999; Galat and Lipkin, 2000), the consequence of not addressing anthropogenic boundary controls when considering flow reregulation has not been carefully weighed. This research examines the potential for salmonid habitat rehabilitation by flow reregulation alone for a reach directly below a dam on a midsized regulated gravel-bed river that has experienced numerous channel engineering measures. Two types of boundary controls (anthropogenic valley confinement and artificial riffles) are examined to determine their affect on channel response to increased discharge with respect to hydraulic variables (i.e., depth and velocity), sediment transport regime, and physical habitat of salmonids. The impacts associated with these specific controls are important because they are frequently prescribed and implemented in channel engineering and restoration efforts.

2. Study site

2.1. Trinity River basin

The Trinity River above Lewiston, CA, is a 1860-km^2 basin (Fig. 1) that is part of the Klamath Mountain Province in northwestern California. It has a high point of over 2700 m, and the terrain is steep with deep gorges. The basin is far enough inland to have extreme weather variations, with winter snows and hot, dry summers. Average annual precipitation ranges from 90-190 cm. Natural streamflow is governed by large winter storms (October to March) and moderate spring snowmelt.

The Trinity Dam was built in 1962, with Lewiston Dam built shortly after and 13 km downstream the valley. Peak flows at the Lewiston Dam site reached as high as 2100 m^3/s prior to damming (Fig. 2). From 1962-1979, up to 90% of the total inflow was diverted to the Sacramento River basin. From 1979-2004, diversions were reduced to 75%. Recent legislation has now restricted total diversions to 53%.

Damming of the Trinity River altered channel morphology in several ways. The reduction in coarse sediment has lead to monotypic morphologies characterized by glides with high velocities (USFWS, 1999). The reduction in both the frequency and magnitude of floods has allowed riparian vegetation to encroach channel margins, creating riparian berms and fossilizing gravel bars. This confinement increases bed shear stress through the channel centerline with increasing discharge. Over time, this has led most reaches to develop a symmetric, trapezoidal cross section. Loss of asymmetry has decreased habitat diversity, such that shallow water habitat occurs only on channel margins and is eliminated at intermediate discharges between 11-57 m^3/s (USFWS, 1999).

The Trinity River supports 18 fish species, including eight anadromous ones: chinook salmon, chum salmon, coho salmon, steelhead trout, American shad, green sturgeon, speckled dace, and Pacific lamprey. Damming has affected fisheries habitats on the Trinity River by blocking over 160 km of upstream spawning grounds and by reducing instream flows necessary to flush sand and drive geomorphic processes that maintain alluvial spawning grounds. The culmination of dam effects on anadromous fish has been devastating, resulting in 80-90% loss of salmonid habitat by 1980 (USFWS, 1999). Chinook and coho salmon as well as steelhead trout have experienced losses of 67, 96, and 53% of pre-dam averages, respectively, and consequently these species are the focus of restoration efforts. Historically, an average of 66,000 chinook, 10,000 steelhead, and 5,000 coho adults migrated past Lewiston each year. Spawning between the three species was distributed with channel gradient, with coho and steelhead spawning in upper headwaters and chinook spawning in the mainstem and tributaries. Superposition of redds is now more common as all three species reach the Lewiston dam with little available space for spawning. The target for a fall-run chinook salmon population is 62,000 (nonhatchery fish). Most spawning occurs in a 3.3-km reach below the Lewiston Dam (USFWS, 2002). Fisheries populations are enhanced by hatchery fish that supplement post-dam in-river escapement of fall-run chinook, spring-run chinook, coho, and fall-run steelhead by 56, 68, 97, and 30% respectively. River rehabilitation activities on the Trinity River include gravel augmentation, channel reconfiguration, bank vegetation removal, and flow reregulation below Lewiston Dam (USFWS, 1999).

2.2. Lewiston hatchery reach

The 760-m Lewiston hatchery reach (LHR) is located immediately downstream of Lewiston Dam (Fig. 2; 40°43'34"N, 122°47'48"W) and is the uppermost limit of spawning access on the Trinity River. Historically, the reach was characterized by a wide channel with inset active alluvial gravel bars and a wide forested floodplain (Fig. 3A). Valley walls on river right served as a limiting boundary control on channel adjustment. Channel width was otherwise free to adjust to changes in discharge and sediment supply. A deep constricted pool is evident in the photo followed by a diverging alluvial transverse bar feature. The alluvial transverse bar most likely provided hydraulic diversity that provided habitat for a multitude of species and life stages of salmonids. This large riffle feature began at a bedrock-induced constriction. As sediment was routed through the deep and constricted upstream pool, the expansion following the bedrock outcrop likely reduced velocities and promoted settling of entrained sediments.

Currently, the LHR has three types of boundary controls: armoring induced by the dam, anthropogenic valley confinement, and artificial riffles that cannot be self-adjusted under the current flow regime. The reach is artificially straight confined on the river left by the Lewiston Hatchery on the river right by the valley walls (Figs. 2B, 4A). The left bank is confined by floodplain infill placed during construction of the Lewiston Hatchery and are sloped approximately uniform at 45° and consist of 1 to 2 metric-ton rocks. In comparing the present conditions with a 1939 United States Geological Survey topographic map (1:31680 scale with a contour interval of 6.1 m contour), channel width has been decreased by as much as 40%. Channel width ranges from 24-46 m at 8.5 m^3/s (the regulated spawning-period discharge). The right bank is confined by the valley wall with steep banks, > 10%, composed of bedrock outcrop, thin soils, and sparse vegetation. Because of its position in the basin and associated high rate of bed material export, the LHR has been a primary location for gravel augmentation (USFWS, 1999; Kondolf and Minear, 2004; Wilcock, 2004). Since 1972, there have been numerous gravel enhancement projects below Lewiston Dam resulting in the addition of over 27,370 m^3 of gravel and large boulders (Kondolf and Minear, 2004). Within the LHR, there are four riffles, three of which are artificial, "rock-weir" riffles composed of coarse cobbles and boulders remaining from past gravel augmentation and slope control projects (Figs. 2B, 4B). Riffles 1, 2, and 4 were constructed in 1976. They were built to stabilize the existing longitudinal profile. In 1983, 4,128 m^3 were added to riffle 3. The only "natural" riffle is located near a fishing access point. This one may be self-formed, because there are no records of gravel placement at this location. Also, a bedrock outcrop between riffles 2 and 3 induces a visible flow convergence at 8.5 m^3/s. As a consequence of relatively frequent construction activities, all artificial riffles have compacted gravel protrusions into the channel. These constrictions, along with the valley and hatchery confinement, effectively have made the riffles narrower than the pools, thereby likely focusing high velocities and scour at those locations. Three outfall pipes from the adjacent hatchery are within the study reach. These outfall pipes have created highly localized scour holes, but do not produce significant discharge relative to the dam releases. Each of the anthropogenic boundary controls acts hierarchically on different spatial scales. The rocky banks of the Lewiston Hatchery, moderate bed slope, and narrow V-shaped valley are the primary reach-scale controls. Geomorphic unit controls consist of fixed rocky banks, artificially cabled rock riffles, and a bedrock constriction. Hydraulic unit controls include the outfalls from the hatchery, the rock-weir riffles, gravel augmentation deposits, and the hatchery terrace confinement.

3. Methods

To evaluate the effectiveness of flow reregulation in the LHR a combination of empirical, analytical, and numerical methods were used to determine the impact of anthropogenic boundary controls on salmonid rehabilitation. The impact of anthropogenic boundary controls on reach and geomorphic unit scale hydraulic and geomorphic processes was evaluated by using longitudinal profile and hydraulic-geometry analyses. Long-profile analysis can allow determination of dominating factors controlling slope distribution. Cross-sectional hydraulic geometry can be used to analyze channel response to flow reregulation over a wide range of discharges beyond that observed during the study period. Geomorphic unit self-sustainability of the riffles and pools present in the LHR was evaluated by comparing log-log plots of velocity versus discharge for riffle and pool sections to discern the presence of a hydraulic reversal mechanism in the reach associated with relative cross-sectional area (Keller, 1971; MacWilliams et al., 2006).

Two-dimensional (2D) depth-averaged computational modeling was done to estimate channel hydrodynamics, sediment transport regime (defined in terms of a range of Shields stress values), and anadromous fish habitat patterns at the 1-m spatial scale relevant to key geomorphic and ecologic functions of the channel. Quantitative analyses necessitated development of a high-resolution digital elevation model (DEM) as well as gathering hydraulic and bed material data. The 2D model node values of depth and velocity for each discharge evaluated were plotted to analyze trends in hydraulic distribution with increasing stage. The flow release regime for Lewiston Dam was used to select appropriate discharges for assessing the impact of boundary controls on key ecological and geomorphic processes. The discharges studied were the autumnal anadromous fish spawning flow (8.5 m^3/s), late summer adult fish holding flow (13 m^3/s), early summer anadromous fish attraction flow (70.8 m^3/s), and the peak dam release during the study (170 m^3/s). These flows are re-regulated releases from Lewiston Dam associated with the effort to provide a more natural flow regime. Floodplain structures and bridges prevent any substantially higher peak releases from occurring in the near future.

3.1. Field methods

A detailed topographic survey was conducted using a Topcon GTS-802A robotic total station in summer 2003 yielding 15,284 points from the bed, boulders, edge of water, and water surface elevation within the 13 m^3/s channel. A standard feature-based surveying method was used (Wheaton et al., 2004b) yielding a sampling density of 1.3 pts/m^2. Water surface elevations along the study reach were measured at 8.5, 13, 127.4, and 170 m^3/s relative to the NAVD88 vertical datum. Geomorphic features within the study reach were identified, surveyed, and incorporated into the DTM.

Fourteen cross sections were selected to characterize the geomorphic unit variations in the LHR (Fig. 5). Wolman pebble counts (Wolman, 1954) were performed on cross sections 1, 2, 3, 4, 10, 11, 13, and 14. Grain size distributions were calculated for each cross section and averaged for the project reach. Velocity validation measurements were recorded at cross sections 1, 2, 3, 13, and 14 at a discharge of 13 m^3/s. Flow conditions were too dangerous to obtain velocity data at the highest discharges. Cross section endpins were surveyed with the Topcon GTS-802A so that field data could be compared to model predictions for the same location. Depth and velocity were measured at 1.5 m intervals between surveyed endpins. A Marsh-McBirney Flo-mate (±33 mm/s) mounted to a depth setting wading rod was used to estimate average velocity as the point velocity at 0.6·depth, because the water was shallow (Pasternack et al., 2006). Positional accuracy and observation resolution was much finer than the scale of bed features (5-10 m) and similar to 2D model node spacing.

3.2. Digital elevation model

A DEM of the study reach was constructed using the surveyed topographic points in Autodesk, Land Desktop 3. The four iterative stages of DEM development as described by French and Clifford (2000) were implemented: interpolation, visualization, editing, and augmentation. First, survey data were interpolated and a surface defined respecting breaklines. Next, the surface was visualized as a map and edited to remove obvious interpolation errors. The revised surface was visually verified in the field to check for poorly represented areas in the DEM. Further iteration was done as needed. All 14 cross sections and a thalweg profile were extracted from the DEM using Land Desktop. At each cross section, mean depth, top width of flow, width-to-depth ratio, wetted perimeter, hydraulic radius, and area were calculated at 0.3-m intervals from the 8.5 m^3/s water surface elevation to a water surface elevation 4 m above.

3.3. Hydraulic geometry analysis

Boundary controls have been noted to have an impact on hydraulic geometry relations in cases where channel width is constrained (Singh, 2003). Holding one variable relatively constant (for example, channel width), the hydraulic response will be largely dictated by changes in nonstatic variables such as depth and velocity, which may have an impact on geomorphic processes such as riffle and pool sustainability, and thus spatial nested geomorphic features necessary for salmonid fisheries. *Ceteris paribus*, unforced riffles and pools are considered geomorphically self-sustainable over time if the local bed shear stress over pools exceeds that over riffles at some discharge above bankfull so that the existing topographic variation is maintained as long as sediment is supplied to the riffle-pool sequence (Keller, 1971; Carling, 1991; Clifford and Richards, 1992; Booker et al., 2001; MacWilliams et al., 2006). Cross-sectional analyses of riffle-pool sustainability have yielded somewhat contrasting results depending on the resolution of the tools used to study the phenomenon. If a hydraulic reversal is present in mean flow variables, then it will also be present in local ones, though the converse is not true (McWilliams et al., 2006). Thus, analysis of mean flow conditions is a conservative predictor of riffle-pool sustainability. Cross sections were analyzed to estimate the effect of increasing discharge and channel geometry on hydraulics and riffle-pool self-sustainability. At-a-station hydraulic geometry equations (Leopold and Maddock, 1953) were used to develop relationships between width, depth, and velocity as a function of discharge:

$$w = aQ^b, \quad \overline{H} = cQ^f, \quad \overline{U} = kQ^m \qquad (1,2,3)$$

where w is top width (m), $\overline{H}$ is cross-sectionally averaged depth (m); $\overline{U}$ is cross-sectionally averaged velocity (m/s); a, c, and k are regression coefficients; and b, f, and m are regression exponents. Steady, uniform flow was assumed for calculating mean velocity. Manning's equation was coupled with the continuity equations to predict depth and velocity:

$$\overline{U} = \left(\frac{1}{n}\right) R^{2/3} S^{1/2} \text{ and } Q = \overline{U} A \qquad (4,5)$$

where R is hydraulic radius, A is cross-sectional area, n is Manning's roughness coefficient, and S is slope. Manning's n was approximated as 0.043 based on roughness tables for a straight, coarse gravel channel with no vegetation (McCuen, 1989) and past studies in this channel type (Pasternack et al., 2004, 2006; Wheaton et al., 2004b). For each cross section, w, $\overline{H}$, A, and R were obtained in AutoCad as described in the above section. A ternary diagram was constructed to compare the width, depth, and velocity exponent values (b, f, and m). To test for riffle and pool sustainability via a hydraulic reversal, log-log plots of velocity versus discharge were constructed and compared for all riffle and pool units. Also, the velocity results from the 2D model were examined for the existence of velocity reversals, as reported later.

3.4. 2D Trinity model

Two-dimensional hydrodynamic models have existed for decades and have been used to study a variety of hydrogeomorphic processes (Bates et al., 1992; Leclerc et al., 1995; Miller and

Cluer, 1998; Cao et al., 2003). Recently, they have been evaluated for use in regulated river rehabilitation emphasizing spawning habitat rehabilitation by gravel placement (Pasternack et al. 2004, 2006; Wheaton et al. 2004b; Elkins et al., 2007). In this study, the long-established 2D model known as Finite Element Surface Water Modeling System 3.1.5 (FESWMS) was used to simulate hydraulics and predict anadromous fish habitat quality and sediment transport regime. FESWMS solves the vertically integrated conservation of momentum and mass equations using a finite element method to acquire depth-averaged 2D velocity vectors and water depths at each node in a finite element mesh. The model is capable of simulating both steady and unsteady 2D flow as well as subcritical and supercritical flows. The basic governing equations for vertically integrated momentum in the *x*- and *y*- directions under the hydrostatic assumption are given by

$$\frac{\partial}{\partial t}(HU)+\frac{\partial}{\partial x}(\beta_{uu}HUU)+\frac{\partial}{\partial y}(\beta_{uv}HUV)+gH\frac{\partial z_b}{\partial x}+\frac{1}{2}g\frac{\partial H^2}{\partial x} + \frac{1}{\rho_w}[\tau_x^b-\frac{\partial}{\partial x}(H\tau_{xx})-\frac{\partial}{\partial y}(H\tau_{xy})]=0 \quad (6a)$$

and

$$\frac{\partial}{\partial t}(HV)+\frac{\partial}{\partial x}(\beta_{vu}HVU)+\frac{\partial}{\partial y}(\beta_{vv}HVV)+gH\frac{\partial z_b}{\partial y}+\frac{1}{2}g\frac{\partial H^2}{\partial y} + \frac{1}{\rho_w}[\tau_y^b-\frac{\partial}{\partial x}(H\tau_{yx})-\frac{\partial}{\partial y}(H\tau_{yy})]=0 \quad (6b)$$

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

$$\frac{\partial H}{\partial t} + \frac{\partial}{\partial x}(HU) + \frac{\partial}{\partial y}(HV) = 0 \quad (7)$$

In this study, FESWMS was used for exploratory numerical experimentation to obtain a conceptual understanding of the potential value of flow reregulation in a constrained regulated gravel-bed river. FESWMS was implemented using the Surface Water Modeling System v. 8.1 graphical user interface (EMS-I, South Jordan, UT). The boundary conditions required to run FESWMS are the input hydrograph, the exit water surface elevation, and high-resolution channel topography. In addition, model parameters are needed to describe channel roughness and provide turbulence closure. Values for all boundary conditions and parameters were selected to be physically realistic and were not numerically calibrated. As previously stated, the discharges used were steady values of 8.5 m^3/s, 13 m^3/s, 70.8 m^3/s, and 170 m^3/s. Corresponding water surface elevations at the end of the reach were directly observed with a Topcon 802A total station, except for the value associated with 70.8 m^3/s, which was obtained using a stage-discharge rating curve.

DEM $\{x,y,z\}$ contour and grid points were imported from AutoCAD into SMS where they were used to interpolate the elevations of the nodes in a finite element mesh consisting of triangular and quadrangular elements. A unique mesh was generated for each discharge to maintain a similar number of computational nodes (~43,000) given that the inundated area increased with discharge and to enable increased resolution of key features relevant to each flow (e.g. steep banks, boulder clusters, riffle crests, and recirculating eddies). Internodal spacing ranged from 0.2-1.0 m for each mesh. To reduce model instability associated with mesh-element wetting and drying at a threshold of 9-cm depth (~D_{90}), meshes were iteratively trimmed to exclude dry areas.

The effect of channel roughness on flow was addressed two ways in the model. Roughness associated with resolved bedform topography (e.g. rock riffles, boulders, gravel bars, etc) was explicitly represented in the detailed channel DEM. 2D model predictions are highly sensitive to DEM inaccuracies (Bates et al., 1997; Hardy et al., 1999; Lane et al., 1999; Horritt et al., 2006), which is why such a highly detailed topographic mapping campaign was done in this study. For unresolved roughness, a global Manning's coefficient of 0.043 was used with all meshes based on previous work in similar conditions (Pasternack et al., 2004, 2006; Elkins et al., 2007). This value was not obtained by numerical calibration. It was carefully checked in the validation effort by comparing observed and predicted water surface elevations along the reach at the different discharges as well as by comparing observed and predicted depths and velocities at cross-sections. Although it is possible to vary the bed-roughness parameter spatially in a 2D model to try to account for variable bed sediment facies, it is difficult to justify small (<0.005) local deviations relative to 2D-model and measurement accuracy in gravel bed rivers. 2D models have been reported to be sensitive to large (>0.01) variations in n values (Bates et al., 1998; Lane and Richards, 1998; Nicholas and Mitchell, 2003), and the validation approach used here would reveal that scale of deficiency.

In a study of 2D model sensitivity for a bedrock channel, Miller and Cluer (1998) showed that 2D models are particularly sensitive to the eddy viscosity parameterization used to cope with turbulence. In the model used in this study, eddy viscosity (E) was a variable in the system of model equations, and it was computed as

$$E = c_o + 0.6 \cdot H \cdot u^* \qquad (8)$$

where u^* is shear velocity and c_o is a minimized constant added for numerical stability (Fischer et al., 1979). This equation was implemented in FESWMS to allow eddy viscosity to vary throughout the channel, which yields more accurate transverse velocity gradients. However, a comparison of 2D and 3D models for a shallow gravel-bed river demonstrated that even with this spatial variation, it is not enough to yield as rapid lateral variations in velocity as occurs in natural channels, presenting a fundamental limitation of 2D models like FESWMS (MacWilliams et al., 2006).

3.4.1. 2D model validation

Recognizing that 2D models, like all models, have inherent strengths and weaknesses, some amount of uncertainty in model results must be understood and accepted (Van Asselt and Rotmans, 2002). Past studies using FESWMS for similar shallow gravel-bed rivers like the Trinity River have validated the model for this application and provide a basis for appreciating model utility and uncertainty (Pasternack et al., 2004, 2006; Wheaton et al., 2004b; MacWilliams et al., 2006; Elkins et al., 2007). In addition to that past work on similar rivers, a new analysis of model uncertainty was done for the LHR on the Trinity River. Since the model parameters were set to physically realistic values and not numerically calibrated to match observations, comparisons of predicted and observed conditions provide a meaningful assessment of model uncertainty.

Three different types of validation testing were done to evaluate model performance. First, to validate model performance with regard to the key model parameter of eddy viscosity, the range of E values in model output was checked against field-based estimates at 8.5 m^3/s calculated using Eq. (8) with observed depth and velocity measurements at the study's cross-sections. Modeled and measured E values were found to be similar (~0.02-0.1 m^2/s).

Second, a Topcon total station was used to measure the longitudinal water surface elevation along the reach at 8.5, 13, and 171 m^3/s. These profiles were compared against model-produced WSE profiles to test the suitability of the selected Manning's n value of 0.043. The results are reported later for each cross-section at 13 m^3/s. For 171 m^3/s, modeled WSE was systematically slightly higher than the observed WSE, with the deviation averaging just 5% of mean cross-sectional depth at each observation location (standard deviation of 2.5%). Thus, the prescribed Manning's n value for this highest flow was slightly high, but not enough to warrant iterative calibration.

Third, recognizing that lateral and longitudinal variation in velocity in a river is highest at low discharge and low during large floods (Clifford and French, 1998), detailed model validation of depth and velocity on the Trinity River was performed at a low discharge of 13 m^3/s using observed depths and velocities from cross sections 1, 2, 3, 13, and 14 (Fig. 5). All cross sections were taken a year after topographic surveying because of time constrains and regulatory flow releases, so the few significant differences in bed topography are attributable to real changes from bed scour, notably at cross section 13. The detailed findings of this aspect of model validation are reported in the results section. Models such as FESWMS are best viewed as uncertain conceptual guides of likely outcomes, rather than literal truth, and that is how it has been used here to yield a balanced array of exploratory numerical modeling and field-based empirical studies to seek the most thorough process-based understanding.

3.4.2. Sediment transport regime model

Shields stress (τ^*) is a variable that characterizes the state of sediment transport in a stream and is defined as

$$\tau^* = \frac{\tau_0}{(\rho_s - \rho_w) g D_{50}} \quad (9)$$

where τ_o is bed shear stress, ρ_s is sediment grain density, and D_{50} is median grain size (Lisle et al., 2000). Using the results of the 2D model, τ_o was first calculated on a nodal basis using Einstein's log-velocity equation for turbulent flows over rough beds:

$$\tau_0 = \rho_w \left(U \Big/ \left(5.75 \cdot \log\left(\frac{12.2 \cdot H}{4.5 \cdot D_{50}} \right) \right) \right)^2 \quad (10)$$

where the value of D_{50} used at each node was the reach-average value. It was infeasible to measure D_{50} in detail through the reach. The Nikuradse roughness size was taken as $k_s = 4.5 * D_{50}$ after Thompson and Campbell (1979). Equation (10) was then nondimensionalized using Eq. (9) with the reach-average D_{50} to yield nodal τ^*.

The sediment transport regime was characterized by the range of values that τ^* falls into, as defined by Lisle et al. (2000): values of $0.00 < \tau^* < 0.01$ correspond with no transport; $0.01 < \tau^* < 0.03$ indicates intermittent, localized transport in response to infrequent turbulent bursts and/or bed vibrations; $0.03 < \tau^* < 0.06$ corresponds with Wilcock et al.'s (1996) domain of "partial transport" in which grains move in proportion to their relative exposure on the bed surface; $0.06 < \tau^* < 0.1$ represents full transport of a "carpet" of sediment 1-2·D_{90} thick; and $\tau^* > 0.1$ corresponds with channel-altering conditions. The use of these regime classes helps reduce the impact of propagation of errors in hydrodynamic prediction, as the classes are much broader than the precision and accuracy of the predictions (see Pasternack et al., 2006, for evaluation of such propagation errors and validation of 2D shear stress predictions for shallow gravel-bed rivers). These thresholds are likely to shift down for very loose gravel beds and up for highly compacted and structured gravel beds.

3.4.3. Physical habitat quality model

The physical habitat for coho, chinook, and steelhead spawning, fry, and juvenile life stages as well as the steelhead adult life stage were modeled at 8.5, 13, and 71 m^3/s respectively to understand how the anthropogenic boundary controls in the LHR affect the quantity and quality of available habitat as a function of discharge. Fisheries habitat conditions are highly specific to species and life stage (USFWS, 1999; Moyle and Cech, 2003; Hardy and Addley, 2001) and are the result of complex chemical, biological, and physical interactions (Stalnaker, 1979; Jowett, 1997). Although diverse variables such as temperature, bioenergetics, competition, predation, hyporheic flow, and water quality are known to influence fish behavior, the physical variables of water depth, velocity, and channel-bottom substrate conditions are highly predictive of physical habitat in shallow gravel-bed rivers (Leclerc et al., 1995; Ghanem et al., 1996).

By combining the 2D model predictions of depth and velocity with field observations of channel substrates and independently obtained local habitat suitability curves for these three physical variables for each species in each life stage (USFWS, 1999), it was possible to predict the spatial pattern of physical habitat quality (method detailed in Pasternack et al., 2004). The result of this integration was a depth, velocity, and substrate habitat suitability index value (DHSI, VHSI, and SHSI, respectively) at each model node for chinook spawning, fry, and juvenile habitat; steelhead spawning, fry, juvenile and adult habitat; and coho spawning, fry and juvenile habitat. Because nonspawning life stages are much less dependent on substrate quality, a global habitat suitability index (GHSI) was calculated as the geometric mean using GHSI = $DHSI^{0.5}$ x $VHSI^{0.5}$ for those cases, giving depth and velocity equal weighting (e.g. Leclerc et al., 1995; Cavallo et. al., 2003; Elkins et al., 2007). Similarly, GHSI values for spawning habitat were calculated as the geometric mean using GHSI = $DHSI^{0.3}$ x $VHSI^{0.3}$ x $SHSI^{0.3}$, giving depth, velocity, and substrate equal weighting (e. g. Gard, 2006). GHSI was calculated on a nodal basis and classed as poor (0-0.1), low (0.1-0.4), medium (0.4-0.7), and high (0.7-1.0) quality habitat adopting the system of Leclerc et al., (1995). This grouping helps account for 2D model and HSI uncertainty by averaging over a range of GHSI values, as there is no ecological basis for distinguishing GHSI at a finer resolution at this time. The effect of flow reregulation on the amount of physical habitat was evaluated by comparing the amount of medium- and high-quality habitat (GHSI > 0.4) for all species and life stages for the three modeled discharges. For brevity and illustrative purposes, detailed spatial patterns of habitat quality are presented for chinook only, with results for the other species and life stages summarized in a single figure. Full details for the other species and life stages are available on-line at the address provided in the results section.

4. Results

Empirical and numerical results both show that anthropogenic boundary controls in LHR significantly impact hydrogeomorphic processes key to river rehabilitation, including the recovery of physical habitat for anadromous fish. Key metrics from the detailed analyses performed are reported below. Full simulation results are available to the public from the U.S. Bureau of Reclamation or the corresponding author upon request.

4.1. Empirical metrics of channel conditions

The cumulative frequency distributions of bed material grain size shows that the bed is very coarse (Fig. 6). The median particle size (D_{50}) of the LHR is 61.1 mm with a standard deviation of 27 mm. Cross sections 2 and 3 are located in the pool after riffle 1; and they have significantly finer bed material, with D_{50} of 32.1 and 38.2 mm, respectively. Cross sections 4 and 10 illustrate armoring of artificial riffles, with D_{50} of 120.7 and 72.6 mm, respectively (not counting the large, placed boulders). Along with these geomorphic unit differences in grain size, facies mapping revealed that there are local lateral variations caused by anthropogenic activities. These include finer particle sizes occupying the hatchery outfall scour pools (Fig. 5) as well as 16-32 mm gravels on a relic gravel-injection bar near the end of the reach.

The distribution of slope within the LHR is directly related to anthropogenic boundary controls. The long profile has an overall slope of 0.0022, with significantly higher slopes occurring over rock-riffles (Fig. 7). Although the thalweg bed profile shows a lot of variability, the water surface profiles for 8.5 and 13 m^3/s clearly identify the artificial riffles located at 0, 125, 270, and 450 m as slope control structures. The profile begins at riffle 1and slopes to riffle 2 at 0.0017. From riffle 2 to the downstream pool located at a bedrock constriction (Figs. 3,5), the channel slope increases to 0.0298. The slope from riffle 3 to 4 is 0.052. The distribution of slope over the rock-riffles is not distributed evenly. The majority of the slope in the LHR is lost over riffle 2. This slope is associated with the dense cluster of wired, 1.25-m-diameter boulders that help hold the smaller cobbles and boulders comprising the feature.

The average hydraulic geometry exponents (b, f, m) for the LHR cross sections are 0.17, 0.50, and 0.33, respectively (Table 2). These suggest that depth responds most strongly to changes in discharge. Excluding cross section 14, which is not as confined on the river right, the standard deviation of the width exponent is 0.04, so the variation is 15% of the mean value. Comparing pools and riffles, the average hydraulic geometry exponents for the former are 0.19, 0.49, and 0.32, with standard deviations of 0.14, 0.09, and 0.05, while those for the latter are 0.16, 0.51, and 0.34 with standard deviations of 0.05, 0.03, and 0.02. The significance of this close similarity is that there is no reversal expected for any of these variables as discharge increases. For example, for discharges ranging from 8.5-285 m^3/s, riffles always have a greater velocity and bed shear stress than pools (Fig. 8).

4.2. 2D Model predictions

To address the key questions of this study the 2D model results were divided into sections evaluating hydraulics, sediment transport, and physical habitat. For each of these regimes anthropogenic boundary controls were found to have a dominating influence over the spatial distribution of all metrics of hydrogeomorphic and ecological functionality assessed.

4.2.1. 2D Model Validation

The primary validation of model-predicted depths and velocities was performed at 13 m^3/s, which is representative of the July through March low-flow conditions. Lateral patterns of depth predicted by the 2D model at this flow for the five test cross sections closely match those observed, except for cross section 13 that likely experienced scour during the period between topographic surveying and model-validation data collection (Fig. 9). The similarity in predicted and observed depths suggests that the topographic survey and associated DEM were of sufficient resolution to capture bed features. It also demonstrates that the physically realistic bed-roughness parameter (Mannings n) used globally was well estimated. In contrast, 2D-model velocity predictions show more scatter relative to observed values, with deviations typically 15-30%. At some points, velocity error is very high. The lateral pattern of velocity magnitude successfully mimics observed conditions, but as is commonly seen with 2D models, smoothing is excessive. This is attributable to inadequate variation in eddy viscosity that cannot be further improved with these models (Pasternack et al., 2006). Using too high of an eddy viscosity value enables greater transference of momentum, hence the smoothing (MacWilliams et al., 2006). A comparison of observed versus model-predicted water surface slopes for 171 m^3/s found that the model matched observed conditions very well. Although it would be ideal to have velocity validation for all flows, the pattern of the velocity field is much more uniform at higher flows, and thus the model can be expected to perform better at higher discharges.

Model validation of the LHR on the Trinity River once again revealed the strengths and limitations of 2D modeling of shallow gravel-bed rivers along lines previously reported (Lane et al., 1999; Pasternack et al., 2004, 2006; Wheaton et al., 2004b; MacWilliams et al., 2006; Elkins et al., 2007). The 2D model is accurate enough to provide confidence that the reported spatial patterns in depth and velocity are real, but is not accurate enough to precisely characterize regions with very strong lateral variation, for which 3D numerical modeling would be necessary. In the spirit of scientific exploration, we think the value of 2D modeling in this study outweighs the inherent uncertainty associated with modeling.

4.2.2. Hydraulic spatial patterns

The distribution of depth and velocity in the LHR is controlled by anthropogenic boundary controls regardless of discharge. From 8.5 m^3/s to 170 m^3/s, hydraulic conditions become more uniform, as the spatial patterns of depth and velocity become less influenced by local topography and the artificial riffles, and are governed to a great degree by the channel banks. At 8.5 m^3/s, local topography controls the distribution of depth and velocity and is disrupted at the four artificial riffles (Figs 10A, 11A). Each riffle creates an area of peak velocities and non-uniform flow patterns. Immediately downstream of each riffle eddies and complex flow patterns are present. Between riffles velocity vectors follow local topography, with the bedrock outcropping between riffles *2* and *3* and the gravel injection bar having the greatest affect on flow direction. At 13 m^3/s, hydraulic conditions change very little, except that riffles 3 and 4 have velocity and depth patterns that deviate less from the surrounding upstream and downstream areas between riffles (Figs. 10B, 11B). At 71 m^3/s the channel boundaries become more uniform and the valley walls on the river right and the hatchery walls on the river left govern the velocity vectors. (Figs. 10C, 11C). Velocity and depth are comparatively more uniform than lower discharges from riffle 1 to 2. The bedrock constriction after riffle two provides the only area of flow convergence in the channel. Flow direction and magnitude vary little after the bedrock constriction to the end of the model despite differences in depth from local topography. The highest peak flow release from the Lewiston Dam during the study was 170 m^3/s. Velocity vectors were omitted for clarity and follow a similar distribution to 71 m^3/s (Fig. 11C), being almost perfectly parallel to the channel banks. Peak velocity zones in the channel did not migrate upstream or downstream, but became more uniform with discharge. There was not a velocity reversal in the channel at 170 m^3/s (Fig. 11).

4.2.3. Depth-velocity joint distribution

The combination of depth and velocity values in a fluvial geomorphic unit has long been used as an indicator of the meso-scale habitat present (Coarer, 2007). Stewardson and McMahon

(2002) showed that depth and depth-averaged velocity are codependent variables, because channel hydraulics exhibit spatial organization. Besides showing how to obtain independent variables, they also used the joint probability distribution of the two codependent variables to show that it is possible to distinguish between two types of channels (i.e. two hydraulic signatures)- one in which velocity and depth are inversely related and one in which they are directly related. The former relation occurs when the channel has a much stronger longitudinal variation in depth than a lateral variation, and vice versa for the latter relation. Whereas Stewardson and McMahon (2002) focus on how these hydraulic signatures can be explained by different channel morphologies, the results of this study demonstrate that the same channel morphology can shift its hydraulic signature as discharge increases (Fig. 12). This effect of decreasing relative roughness and increasing prismatic channel conditions on hydraulic signature as discharge increases is known (e.g. Clifford and French, 1998), but its significance for geomorphic and ecological applications has not been sufficiently explored.

The effects of artificial riffles and channel confinement imposed by the hatchery terrace on hydraulic behavior in the LHR are evident in the shifting pattern of the joint distribution of local depth and local velocity as a function of discharge (Figs. 12B,C). For discharges <13 m/s^3, velocity decreases as depth increases. At these discharges, the hydraulic regime is characterized by a wide range of velocities (0-5 m/s) when depth is < 0.5 m and a narrow range of low velocities when depth > 0.5 m. For these discharges, local velocity is controlled by local topographic perturbations that yield pronounced local convective accelerations. Over the artificial riffles, flow is supercritical, so shallow depths have very high velocities; while along rough channel margins, velocities are stagnant. At 71 m^3/s, small local topographic perturbations associated with depths < 0.5 m no longer controlled the hydraulic regime (Fig. 12C). At 170

m^3/s, valley confinement by the hatchery terrace yields an essentially prismatic channel with a parabolic lateral velocity distribution, thereby yielding the highest velocities in the deepest part of the channel (Fig. 12D). Two hydraulic regimes are evident in the channel from these analyses. The first regime is a decreasing velocity with increasing depth associated with convective accelerations over and around larger bed perturbations, such as the artificial "rock-weir" riffles, large individual boulders, and boulder clusters submerged to a depth of 0.5-1.25 m. The less submerged these features are, the more the flow approaches and exceeds the critical threshold. The second regime, which occurred at and above 71 m^3/s is the valley confinement hydraulic regime in which velocity increases as depth increases, indicating uniform flow conditions.

4.2.4. Sediment transport

Boundary controls were observed to influence the distribution of Shields stress in the LHR. Regardless of discharge, Shields stress peaks over the rock riffles in bands perpendicular to the channel edge (Fig. 13). At successively higher discharges, confinement causes longitudinal growth of areas of mobility. At 8.5 m^3/s, 90% of the channel is predicted to experience no transport, while 6% of the channel is expected to experience selective transport, 2% experiences partial transport, and 2% experiences full transport conditions (Fig. 14). Riffles 1 and 2 have exhibit areas of full mobility associated with the tops of boulders in the riffles. Past riffle 2 at the bedrock constriction, an area of selective transport is evident. Riffles 3 and 4 are predicted to experience select transport. At 13 m^3/s, patterns of selective transport at the rock riffles and bedrock constriction expand in the downstream direction. Three distinct shear zones are also evident over three boulders past riffle 1 on the river right that have adjacent selective transport patches on the left. Riffle 2 shows two bands of selective transport extending downstream ~ 40 m from the riffle crest. Selective transport is predicted over 11% of the channel, while 2% of the channel is predicted to experience partial transport, and 2% experiences full transport conditions. Areas of selective transport increase to 74% of the channel and extend from rock riffle to rock riffle at 71 m^3/s (Fig. 14). Partial transport is limited to 11% of the channel over the rock riffles, the bedrock constriction, and in several lateral bands between riffles 1 and 2. At 170 m^3/s, 64% of the channel is in at least partial transport in a longitudinal band in the center of the channel that begins at riffle 1 and extends downstream. The channel edges experience selective transport at this discharge.

4.2.5. Physical habitat

For brevity, detailed illustration of the spatial distribution of physical habitat is limited to only one species in one life stage (Fig. 15) with the analyses of all others summarized in Fig.14. All detailed habitat-quality maps for the Trinity River may be viewed at http://shira.lawr.ucdavis.edu. The spatial pattern of fall-run chinook spawning habitat quality was predicted with and without consideration of substrate quality. When substrate is not considered, spawning habitat is predicted to be very abundant in the LHR with 77% being at least medium quality at 8.5 m^3/s (Fig. 16A). However, when the SHSI is utilized the 2D model predicted chinook spawning habitat decreases to 36% of the total area (Fig. 16b). The reason for this is that the bed is heavily armored, with just a few locations with the desirable size range of gravels and cobbles. Regardless of whether or not an SHSI was utilized, little to no chinook spawning habitat was predicted within 15 m of the artificial riffles, indicating that these structures are heavily armored and flow over them is too fast.

The spatial distribution of chinook juvenile and fry rearing habitat are controlled by lateral bars, artificial riffles, and historical gravel injection sites (Figs. 15C,D). Chinook fry prefer very shallow and slow-moving channel margins. The majority of the channel is predicted to be either low or very poor quality rearing habitat for chinook fry, as the channel is relatively prismatic. However, the 2D model turns off any element with < 9 cm depth, because that is close to D_{90} and causes model instability. Thus, the model may be under representing the available fry habitat for a thin strip of sheet flow along each bank. This represents an important limitation for the use of 2D models in habitat evaluation.

Chinook juvenile rearing habitat follows a similar spatial distribution as that of chinook fry, but with a shift in habitat preference to deeper areas with low velocities. The central third of the channel is predicted to range from low to medium quality because the velocity is too high. High quality habitat is present on lateral bars, including remnant gravel deposits at historical gravel injection sites, with the largest being on river left at the end of the reach.

Steelhead, chinook, and coho spawning and fry habitat quality spatial patterns at 8.5 m^3/s are relatively similar in reflecting hydrodynamics, but with different percentages of habitat quality classes (Fig. 16). Coho and steelhead spawning habitat are both more abundant than chinook spawning habitat. In contrast, the limited amount of chinook juvenile rearing habitat, for steelhead is much more ubiquitous throughout the reach, along with steelhead adult holding habitat, because steelhead juveniles (and adults) prefer 1-3 times higher velocities than chinook juveniles. Whereas steelhead juveniles prefer higher velocities than chinook juveniles, coho juveniles prefer significantly lower velocities, and thus their rearing habitat availability in the reach is greatly reduced. Thus, during fall and winter low flows, this upstream-most reach has a reasonable abundance of steelhead and chinook juvenile rearing and adult holding habitat, but a significant lack of steelhead and chinook spawning habitat. Availability of all coho life stage habitats is inadequate, but that species is not primarily managed for in this reach

A central aim of this study is to quantify the response of physical habitat quantity to changes in discharge, which is a very important component of evaluating the potential effectiveness of flow reregulation on fisheries restoration. A near doubling of the low-flow release is predicted to cause dramatic decreases in the percent of medium and high quality physical habitat for most species' life stages within the LHR (Fig. 16). The change from 8.5 to 13 m^3/s substantially reduces the percent of at least medium quality of the physical habitat for all three species' life stages except chinook and steelhead juvenile habitat, steelhead adult habitat, and chinook and coho fry habitat, with these last two already near zero. Only 0-3% of the channel is predicted to be at least medium quality fry habitat at 8.5 m^3/s, and this increases by 3% for chinook fry and 1% for coho fry at 13 m^3/s. Medium plus high quality habitat for steelhead adult and juveniles increases by 3 and 1%, respectively; while chinook juvenile habitat of this quality decreases by 13% from 8.5 to 13 m^3/s. Spawning habitat for steelhead, chinook, and coho decreases by 37, 22, and 43%, respectively, from 8.5 to 13 m^3/s.

When flow is increased from 13 to 71 m^3/s the percent of the channel that is at least medium quality habitat decreases sharply for all species' life stages to below 5% of channel area, except steelhead adult habitat (Fig. 16), which still was present in medium or high quality over 27% of the channel. Medium and high quality coho fry rearing habitat showed an insignificant increase in habitat area with this change, but remained below 5%. Further flow increases assessed for Shields stresses were not evaluated for habitat quality, as the channel was too deep and fast to have any significant fish habitat.

5. Discussion

5.1. Effect of anthropogenic valley confinement

Anthropogenic valley confinement in the LHR through construction of the Lewiston Hatchery has had the commonly observed effect on geomorphology, hydraulics, and fisheries for alluvial rivers (Bowen et al., 2003; Jacobson and Galat, 2006). Variations in channel width has in many ways been linked to hydraulic conditions that contribute to geomorphic and ecological variability (Coulombe-Pontbriand and Lapointe, 2004). In reaches where channel width is constant, such as the study reach, hydraulic conditions are promoted that lead to monotony in geomorphic form and in resultant ecological habitat. In this study, empirical and numerical tests for the study reach both came to the same conclusion that a confined and restricted width affects existing and potential fisheries restoration. The lack of variation in channel width between riffle and pool sections, coupled with the cross section averaged velocity being always faster over riffles than pools, limits the potential for geomorphic sustainability in the LHR, as no hydraulic reversals in mean conditions were empirically detected. Hydraulic geometry analysis results are reinforced by 2D model results for depth, velocity, and their joint distribution. For flows < 13 m^3/s, local topographic features control the distribution of depth and velocity between riffles, and channel width displays moderate control on flow vectors. However, at 71 m^3/s channel width becomes very uniform and 2D model results show that hydraulic variables display less variability and uniform, subcritical flow conditions dominate. The 2D model did not detect any velocity reversals for the reach. The distribution of Shields stress is controlled by local topography and the riffles below 13 m^3/s. Increases in discharge cause the distribution of Shields stress to grow from transverse bands associated with the artificial riffles to longitudinal tubes down the central third of the channel, especially at 170 m^3/s. Such a distribution of Shields stress shows that the channel banks exhibit a fundamental control on sediment transport and bed morphology in the study reach. The lateral bars between riffles provide the majority of the physical habitat for all lifestages in the LHR, but have unsuitable depths at 71 m^3/s. The net effect of valley confinement on physical habitat in the LHR is that shallow water habitat is nonexistent for flows >71 m^3/s.

5.2. Effect of artificial riffles

Artificial riffles fix the bed slope of the LHR and create local zones of high bed slope, velocity, and Shields stress. The riffle-pool units in the LHR do not appear to be sustainable, as log-log plots of velocity versus depth for riffle-pool sections as well as 2D model results for velocity and Shields stress indicate that riffles are always faster than pools. These results do not account for forced pools associated with vortex shedding and convective acceleration, but flow reregulation would not induce such forced pools anyway. The artificial riffles are also predicted to experience a "full transport" sediment-transport regime with regards to the median particle size of the reach at all discharges modeled. This instability is verified as riffles 1, 2, and 3 that are heavily armored, implying that smaller gravels have a low probability of occurrence from hydraulic forces. Gravel instability at artificial riffles during flow < 13 m^3/s has led to infilling of downstream pools, decreasing bed relief and forming monotonous runs. Median particle sizes on some parts of the riffles are adequate for Chinook spawning, but velocities are still too high. Thus, most spawning is predicted and has been independently observed by the authors to occur on lateral bars in the study area between the riffles. Also, Elkins et al. (2007) experimentally created a chute with lateral bars in a different regulated gravel bed river and observed that the fish shifted their spawning pattern to line up on those bars adjacent to the high-velocity chute. These peripheral locations may have poor hyporheic water quality and low embryo survival to the fry life stage.

5.3. The potential for salmonid habitat restoration in the LHR by flow reregulation

Existing physical habitat in the reach is of relatively poor quality and diminishes quickly as flow increases. Spawning habitat is not associated with riffles, but rather with lateral bars between the rock riffles. Potentially these areas experience little upwelling and hyporheic flows possibly affecting embryo mortality rates. Riffle velocities are too fast and substrate too coarse for spawning.

River rehabilitation for salmonids requires that suitable habitat be available for all lifestages. At the spawning discharge of 8.5 m^3/s, the amount of available medium and high quality spawning habitat as a percentage of the total area is 36% for chinook, 50% for coho, and 44% for steelhead, including significant overlap on the same lateral bar morphologic units. These values drop significantly for even a modest flow increase to 13 m^3/s and are virtually nonexistent by 71 m^3/s. These decreases are linked to the hydraulic response of the channel from unnatural confinement and from the focusing of energy dissipation at oversteepened rock riffles, whereby increases in discharge concentrate velocity and Shields stress on riffles at low flows and in the central thalweg at high flows.

In contrast to the current condition in which flow reregulation would not improve salmonid habitat, the historical channel configuration (Fig. 2) lacked confinement and bed steps. An increase in discharge under historical morphological conditions would have activated secondary and tertiary channels across a wide active gravel valley bottom, creating more areas of shallow water with low to moderate velocities that match the conditions desired for fish spawning and rearing identified by USFWS (1999). That would provide ample physical habitat at all flows up to the threshold for filling the valley completely. Jacobson and Galat (2006) performed a numerical experiment comparing historical and modern shallow water habitat for a similarly confined river and reported this type of outcome. Thus, the benefits of a natural flow regime are dependent on the presence of a wide and connected channel-floodplain system.

In determining adequate flows for instream fisheries needs, many have relied on statistical methods that relate fish escapement to frequency of flow occurrence (Jowett, 1997; Maddock, 1999). This approach yields the recommendation of instituting a "scaled down" hydrograph in which the natural timing and duration of discharge fluctuations are mimicked with flow releases by the dam, but at a reduced flow magnitude. However, little or no consideration has been given of geometric constraints that control flow and sediment transport responses to discharge at the hydraulic and geomorphic unit scales. Channel geometry varies significantly along alluvial rivers depending on the local balance of transport capacity versus sediment supply (Leopold et al., 1964; Lisle et al., 2000). This study adds to a growing body of work (Bowen et al., 2003; Jacobson and Galat, 2006) that suggests that consideration of channel geometry, and subsequent controls on its adjustment, need be considered along with flow reregulation as human and biological activities during interim flow regulation can impact channel geometry and thus hydraulic and geomorphic processes that drive physical habitat.

While past studies detail constraints on sediment transport and physical habitat in regulated reaches (Bowen et al., 2003; Jacobson and Galat, 2006), few explicitly define causal mechanisms associated with geomorphic processes at the hydraulic unit and geomorphic unit scales with implications to flow-based restoration strategies. Two fundamental processes will likely govern bed-morphology evolution and thus the abundance of physical habitat in the LHR. At flows < 13 m^3/s, an unarmored bed will be unstable at step-like riffle units. Any loose particles available for transport will be hydraulically sorted between riffles. At flows > 170 m^3/s, the partial transport over riffles gives way to a continuous thalweg experiencing partial transport. The presence of lateral gravel bars is morphological evidence that this pattern of thalweg scour is occurring in the LHR. The implication is that natural development of riffle-pool differentiation and habitat heterogeneity is inhibited at low flow by the artificial riffles and at high flow by anthropogenic valley confinement. As physical habitat in alluvial rivers is considered to be heavily dependent on spatially nested morphologic features, anthropogenic boundary controls that limit or prohibit bedform development can ultimately serve as a limiting factor in salmonid habitat restoration.

6. Conclusion

In this study, we found that anthropogenic boundary controls in the LHR have disrupted the natural linkages between hydrologic, geomorphic, and ecological processes independently of the changes in the natural flow regime associated with flow regulation. Rock riffles controlling energy slope at discharges < 71 m^3/s have fixed channel morphology and hydraulics, preventing any dynamic equilibrium between flow, sediment, and hydraulic geometry. Moreover, riffle exit slopes create areas of high shear stress that prohibit both stability of spawning-sized gravels and spawning activity. The fish hatchery adjacent to the straight channel acts as a lateral boundary control prohibiting any channel migration and overbank dynamics, prohibiting self-development of riffle-pool units under the commonly understood mechanisms for their formation and self-maintenance. Because of vertical and lateral boundary controls, we concluded that reregulation of flow would do little for improving salmonid habitat in the LHR where large numbers of anadromous fish come to spawn.

Beyond serving as a specific example of conditions on a local reach on a regulated gravel-bed river, this study illustrates how geomorphic and 2D hydrodynamic tools may be integrated to identify specific mechanisms underlying complex river management problems. Also, it shows that for sediment starved reaches experiencing confinement that a distinct pattern of velocity, depth, and shear stress will develop with implications to the distribution of physical habitat of salmonids. Substrate suitability should be accounted for in heavily armored sites to more accurately predict physical habitat. Moreover, it shows that from an evaluation perspective artificial riffles that function as rock-weirs to limit channel incision can prohibit morphologic adjustment and create hydraulic conditions unsuitable for fisheries use.

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10. List of Figures

Figure 15. 2D model GHSI results for chinook salmon life stages. (A) spawning without SHSI, (B) spawning with SHSI, (C) juvenile, and (D) fry. Darker shading indicates higher quality habitat.

Figure 16. Relation between the percent of channel predicted to be at least “medium” quality habitat (GHSI > 0.4) and discharge.

Figure 1

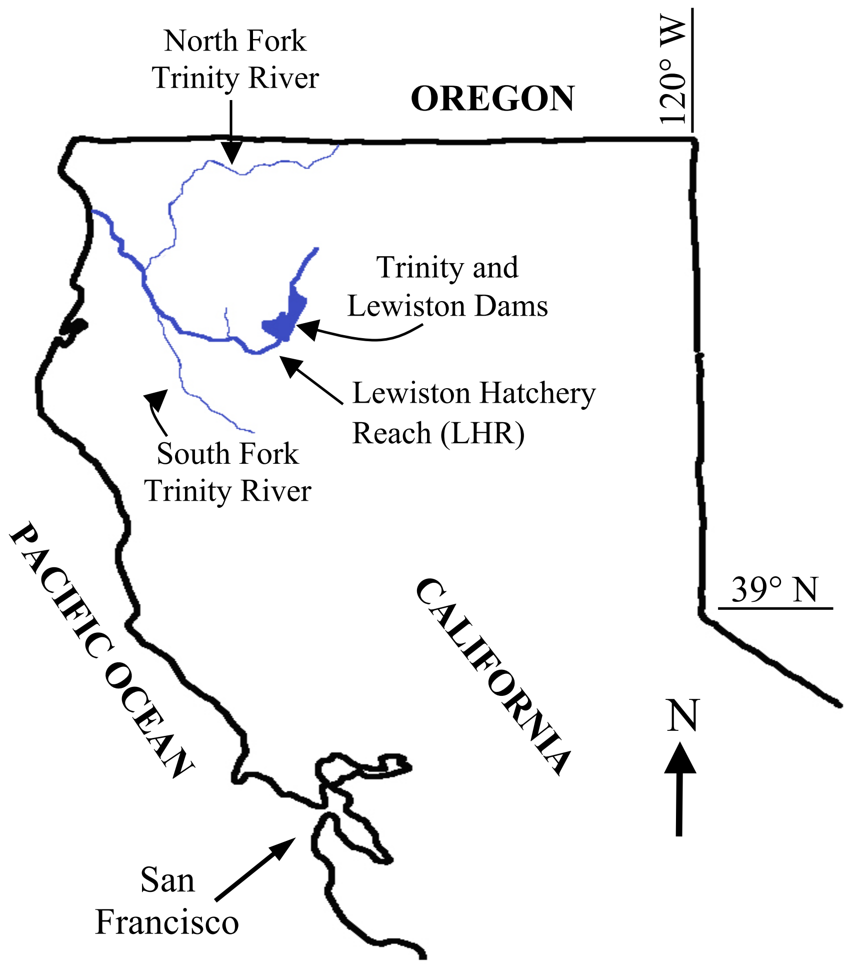
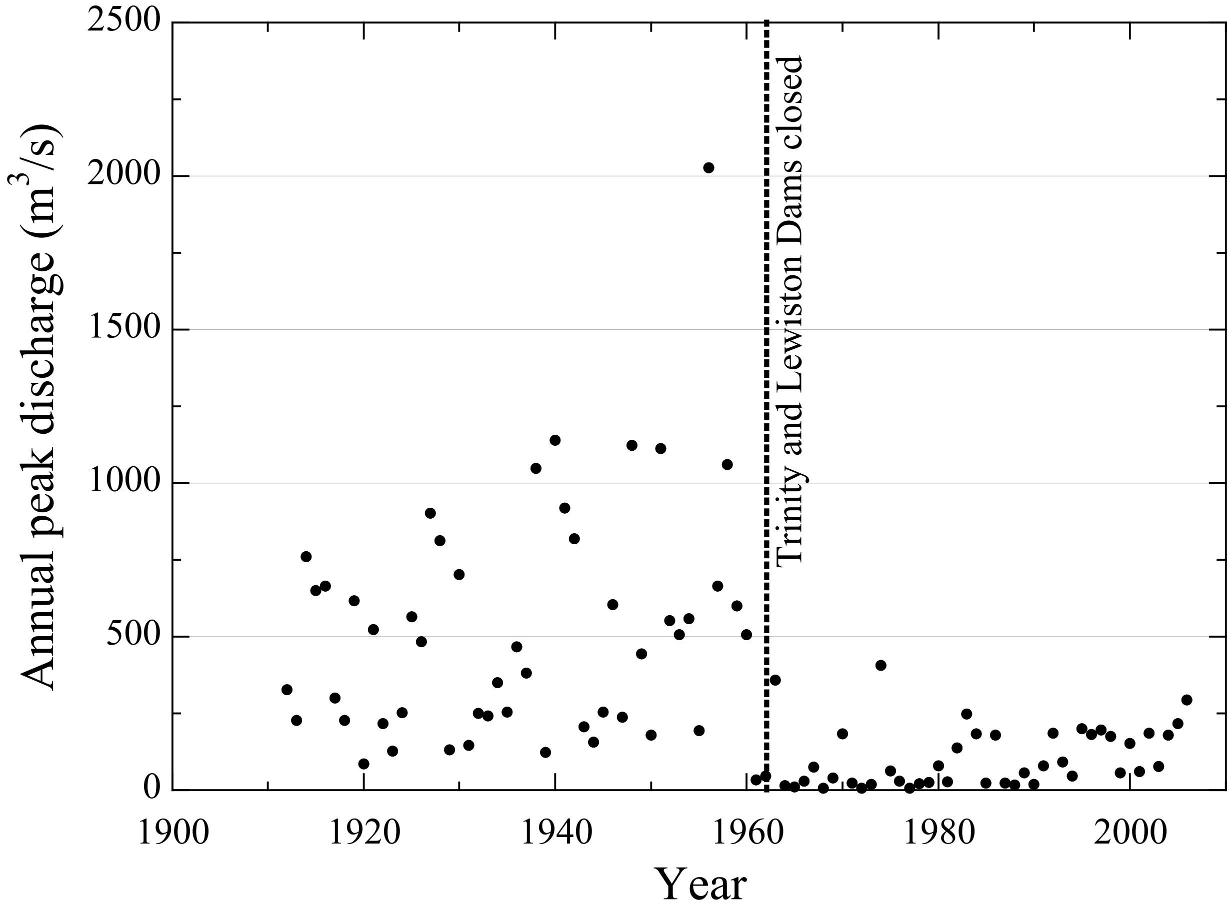
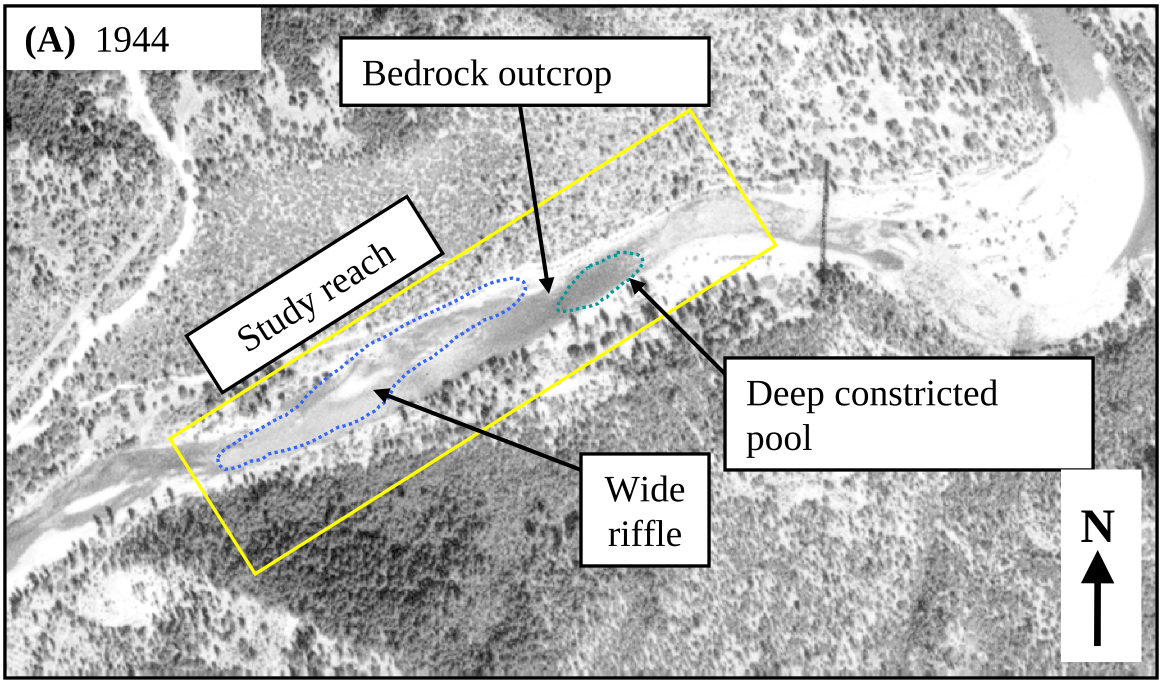

North Fork
Trinity River
OREGON
120° W
Trinity and
Lewiston Dams
Lewiston Hatchery
Reach (LHR)
South Fork
Trinity River
PACIFIC OCEAN
CALIFORNIA
39° N
N
San
Francisco

Figure 2



2500
2000
1500
1000
500
0
1900
1920
1940
1960
1980
2000
Year
Annual peak discharge (m^3/s)
Trinity and Lewiston Dams closed


(A) 1944
Bedrock outcrop
Study reach
Deep constricted pool
Wide riffle
N

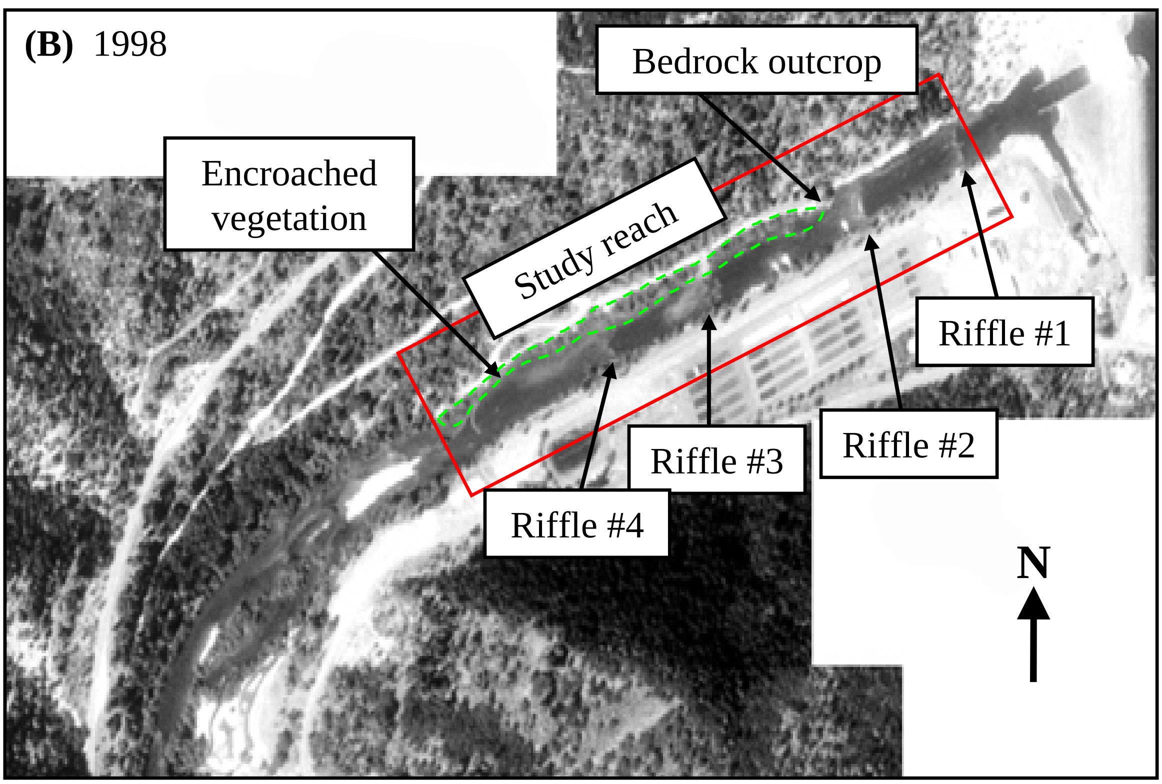

(B) 1998
Bedrock outcrop
Encroached vegetation
Study reach
Riffle #1
Riffle #2
Riffle #3
Riffle #4
N

Figure 4

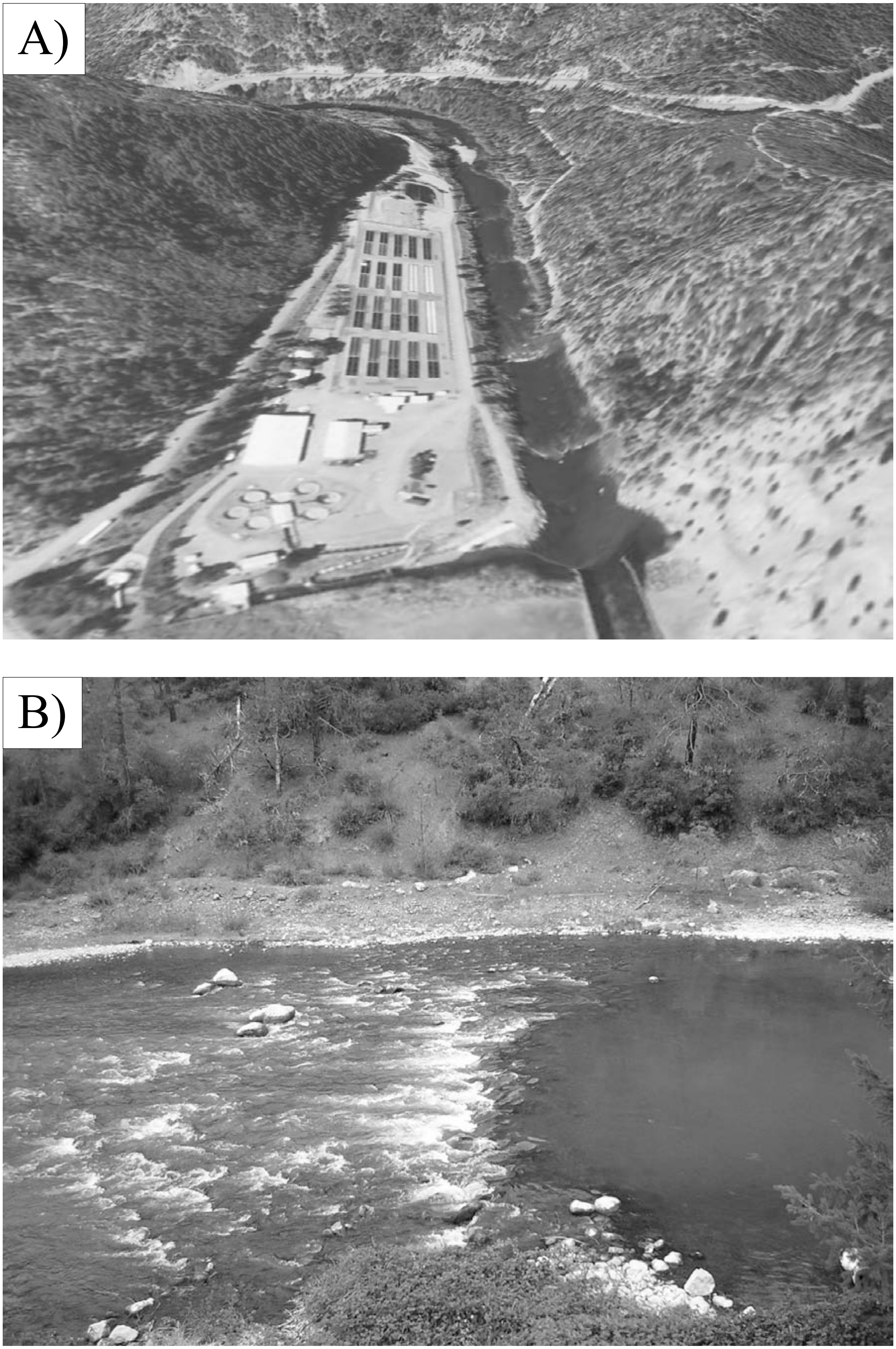


Figure 5

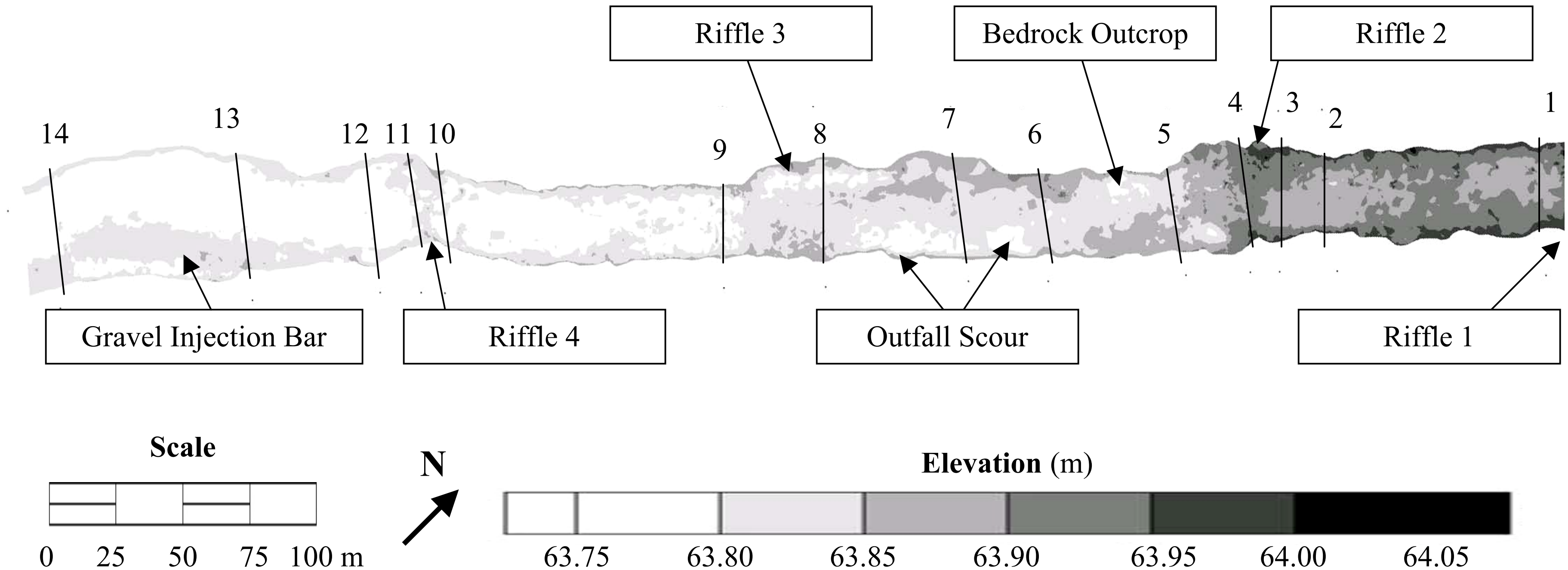
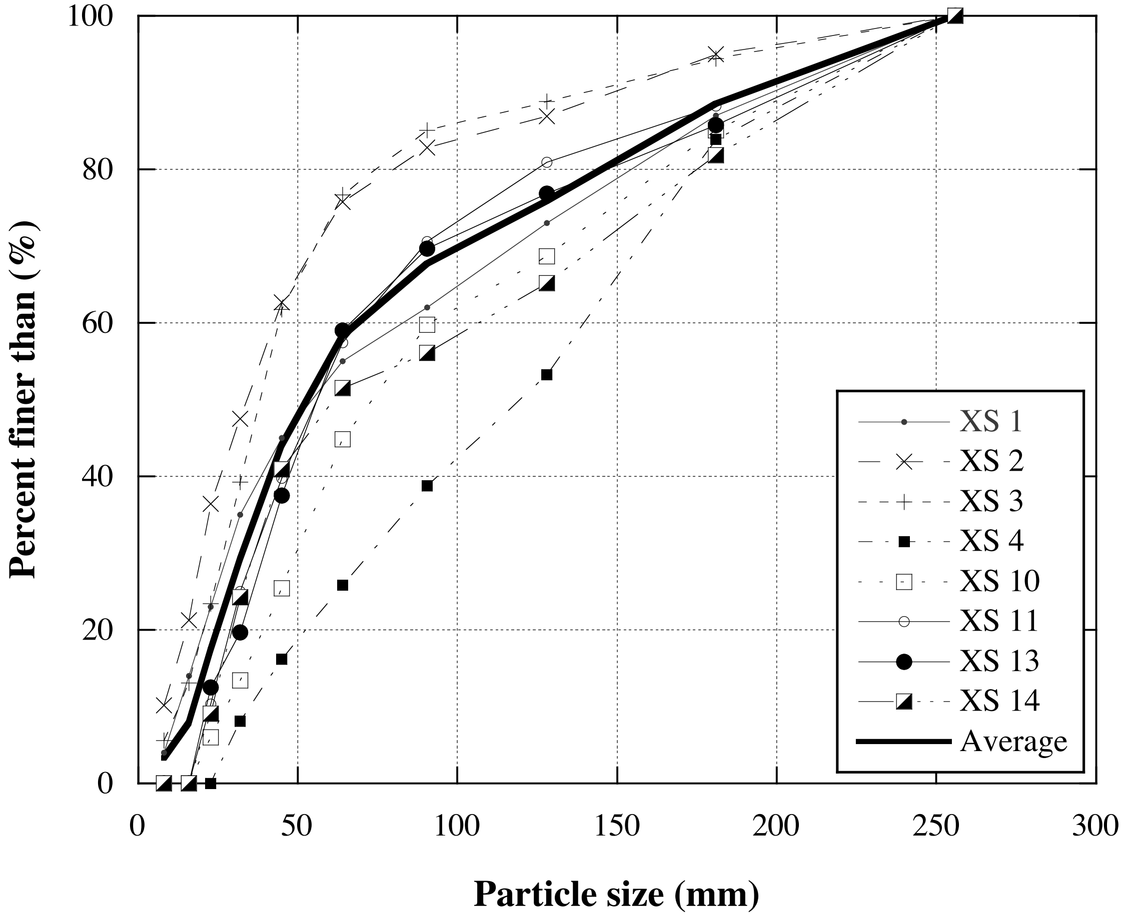
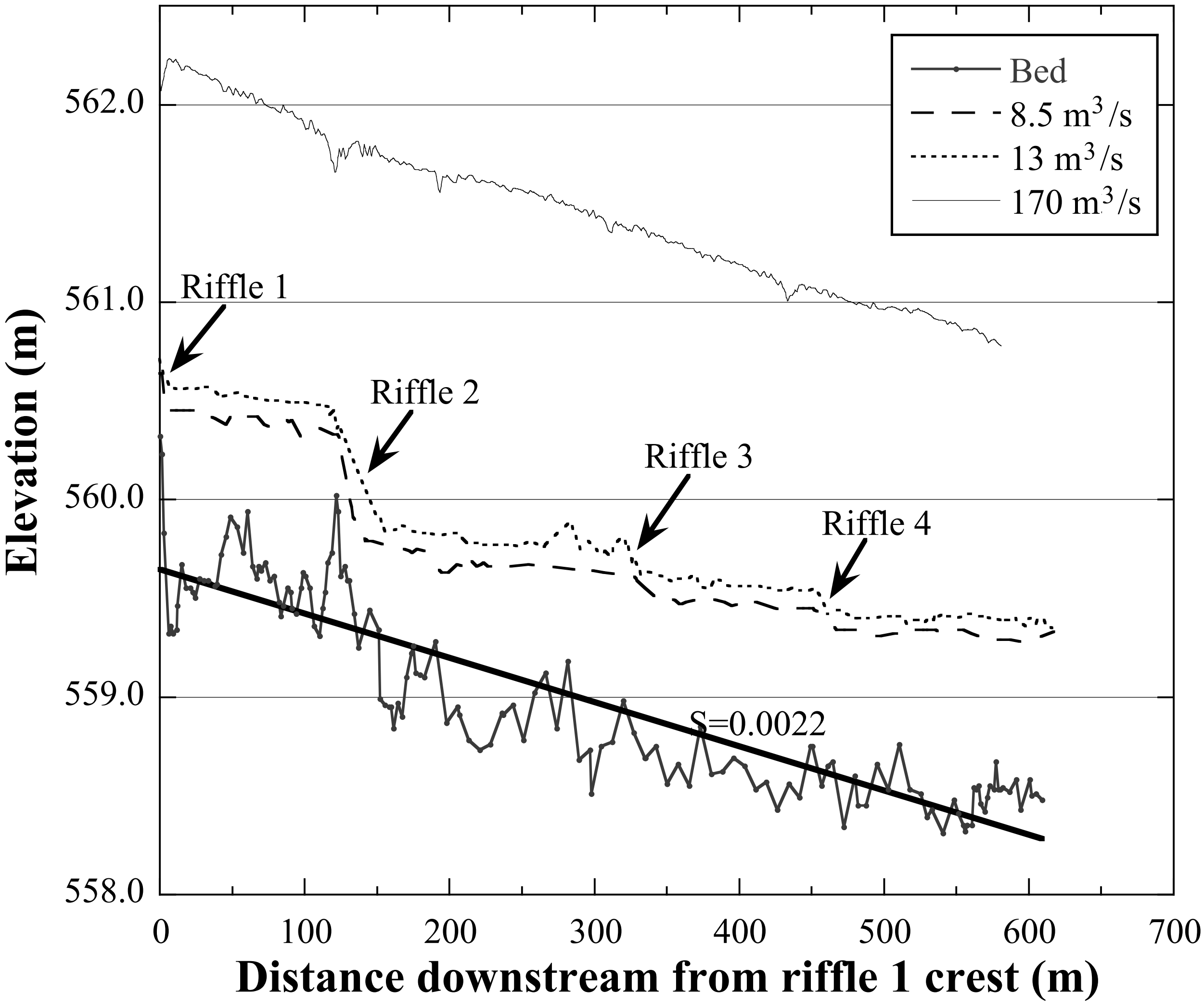

Riffle 3
Bedrock Outcrop
Riffle 2
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Gravel Injection Bar
Riffle 4
Outfall Scour
Riffle 1
Scale
0
25
50
75
100 m
N
Elevation (m)
63.75
63.80
63.85
63.90
63.95
64.00
64.05

Figure 6



100
80
60
40
20
0
0
50
100
150
200
250
300
Percent finer than (%)
Particle size (mm)
XS 1
XS 2
XS 3
XS 4
XS 10
XS 11
XS 13
XS 14
Average

Figure 7



Bed
8.5 m3/s
13 m3/s
170 m3/s
Riffle 1
Riffle 2
Riffle 3
Riffle 4
S=0.0022
Elevation (m)
562.0
561.0
560.0
559.0
558.0
0
100
200
300
400
500
600
700
Distance downstream from riffle 1 crest (m)

Figure 8

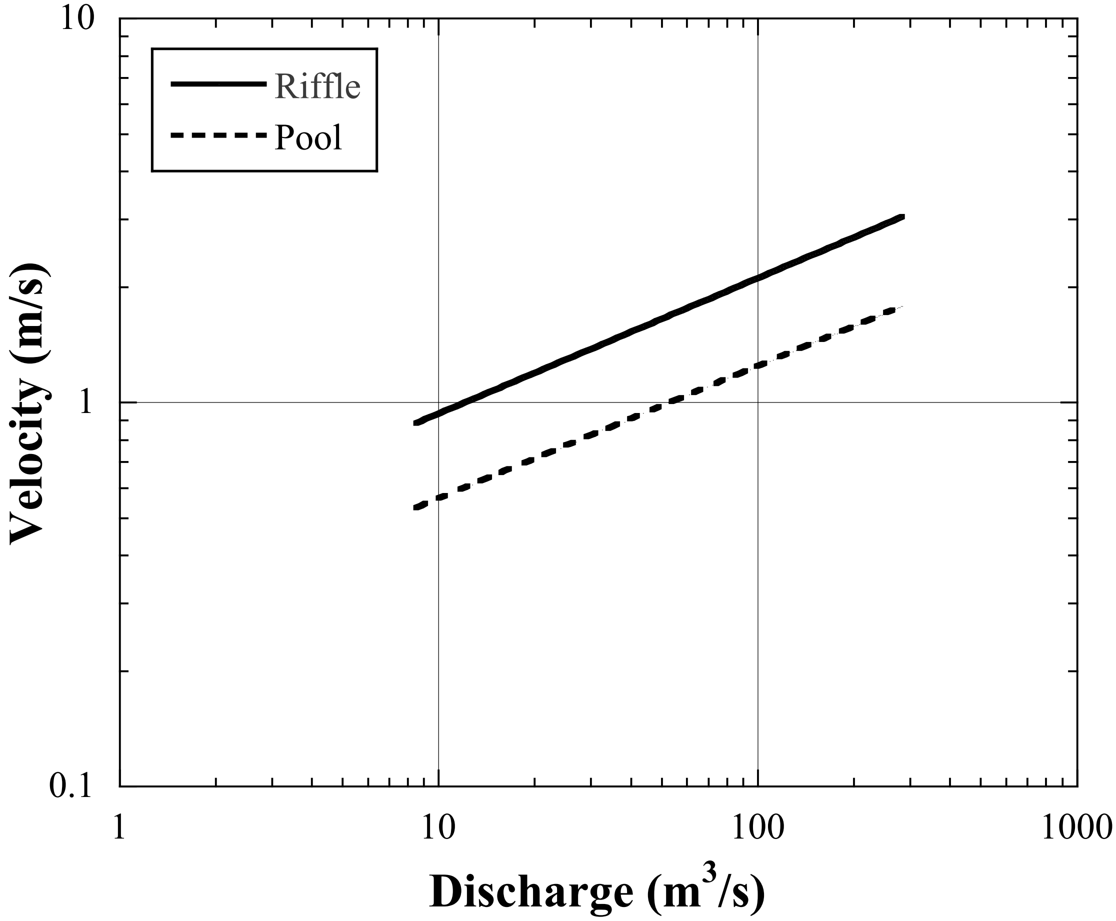
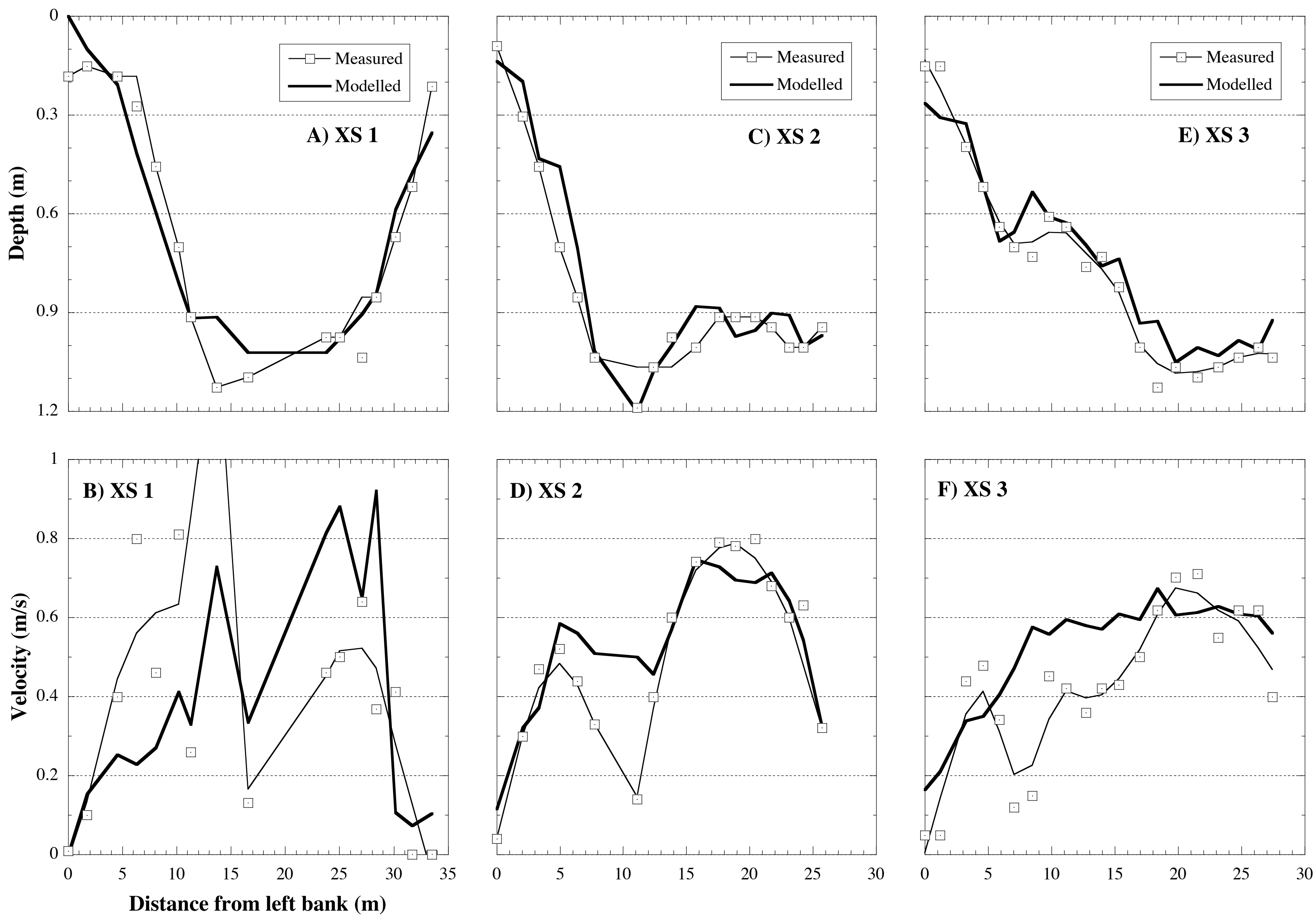


Figure 9



Measured
Modelled
A) XS 1
C) XS 2
E) XS 3
B) XS 1
D) XS 2
F) XS 3
Depth (m)
Velocity (m/s)
Distance from left bank (m)
0
0.3
0.6
0.9
1.2
0
0.2
0.4
0.6
0.8
1
0
5
10
15
20
25
30
35

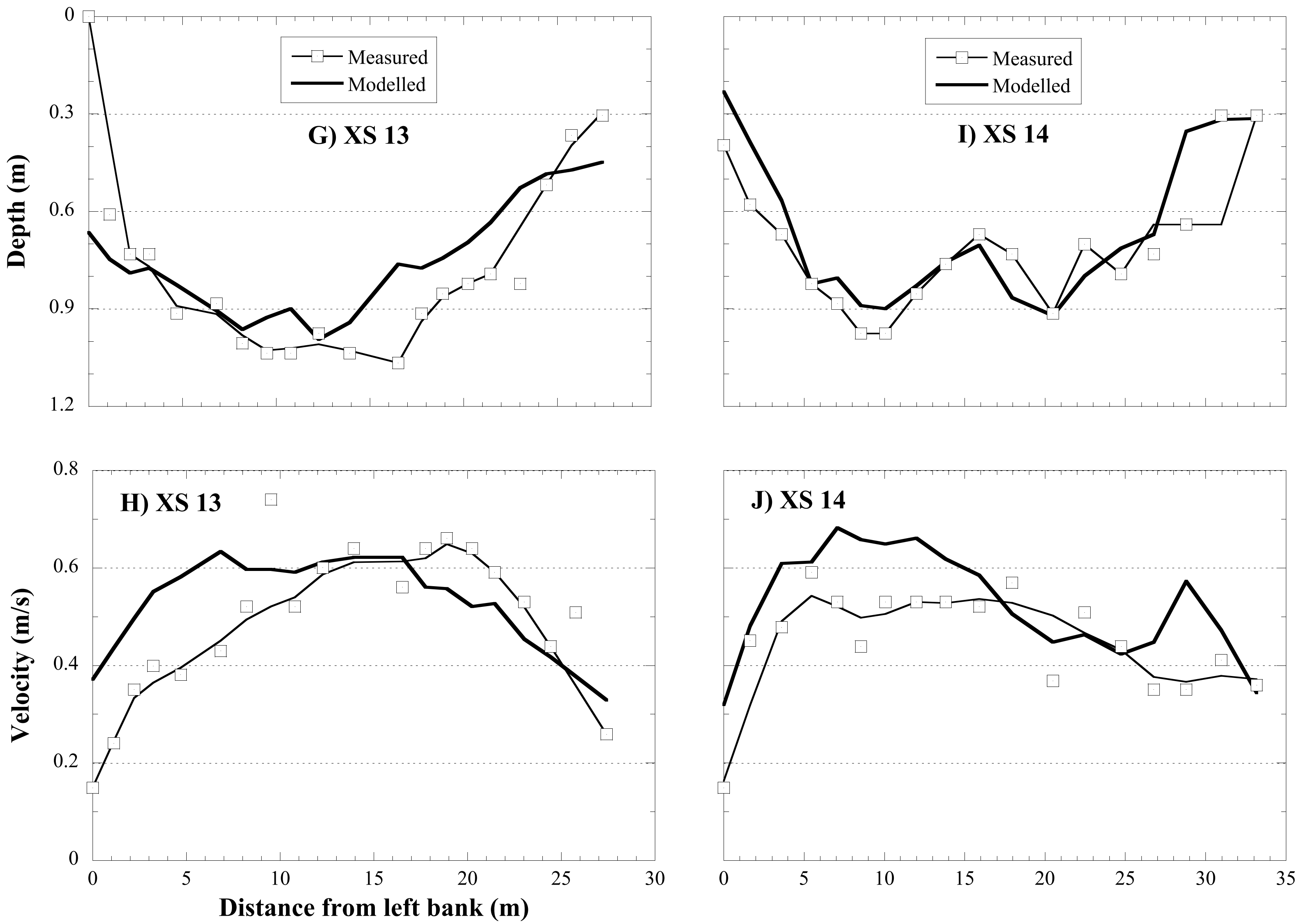

G) XS 13
I) XS 14
H) XS 13
J) XS 14
Measured
Modelled
Depth (m)
Velocity (m/s)
Distance from left bank (m)
0
0.3
0.6
0.9
1.2
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
35

Figure 10

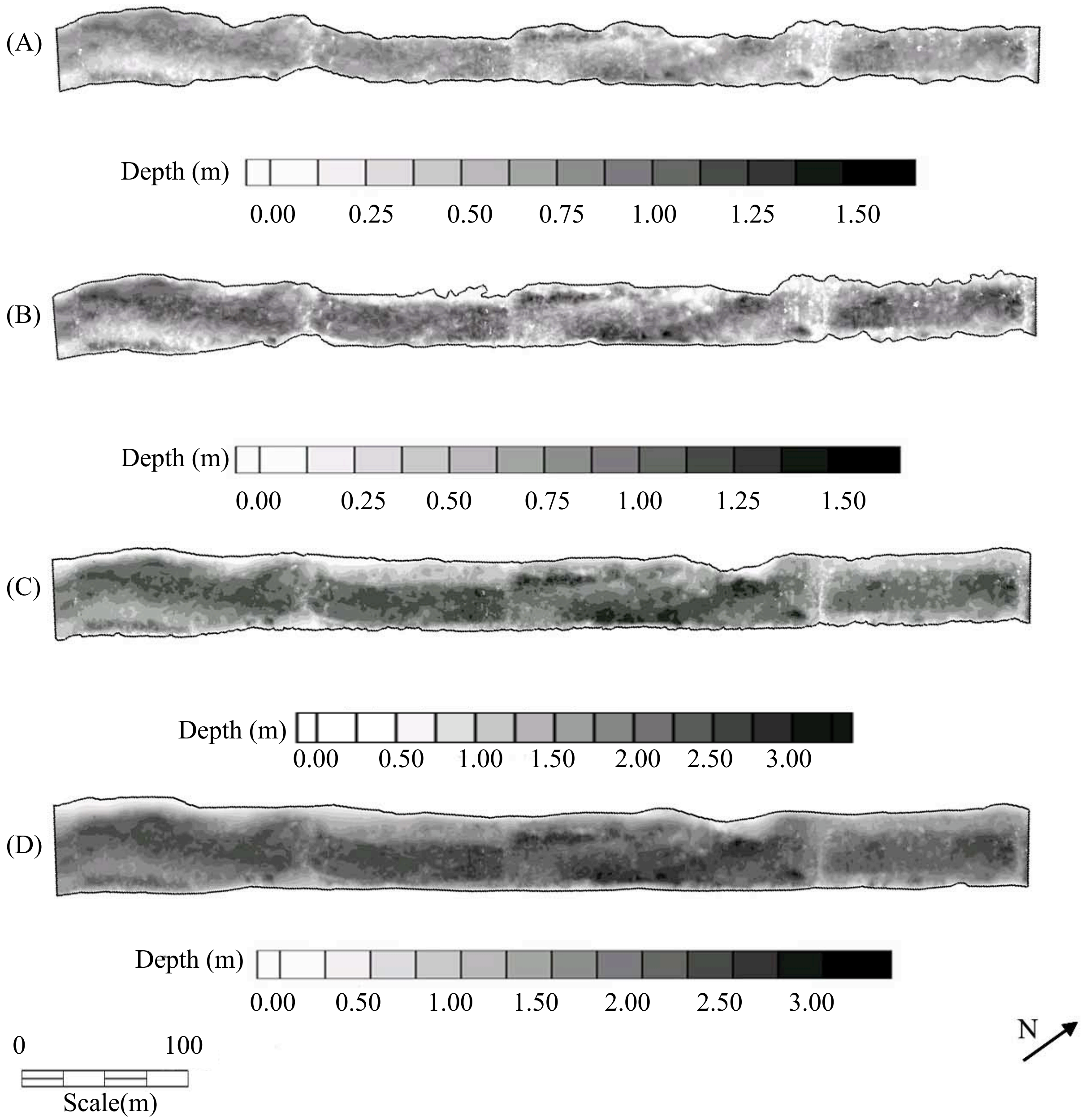
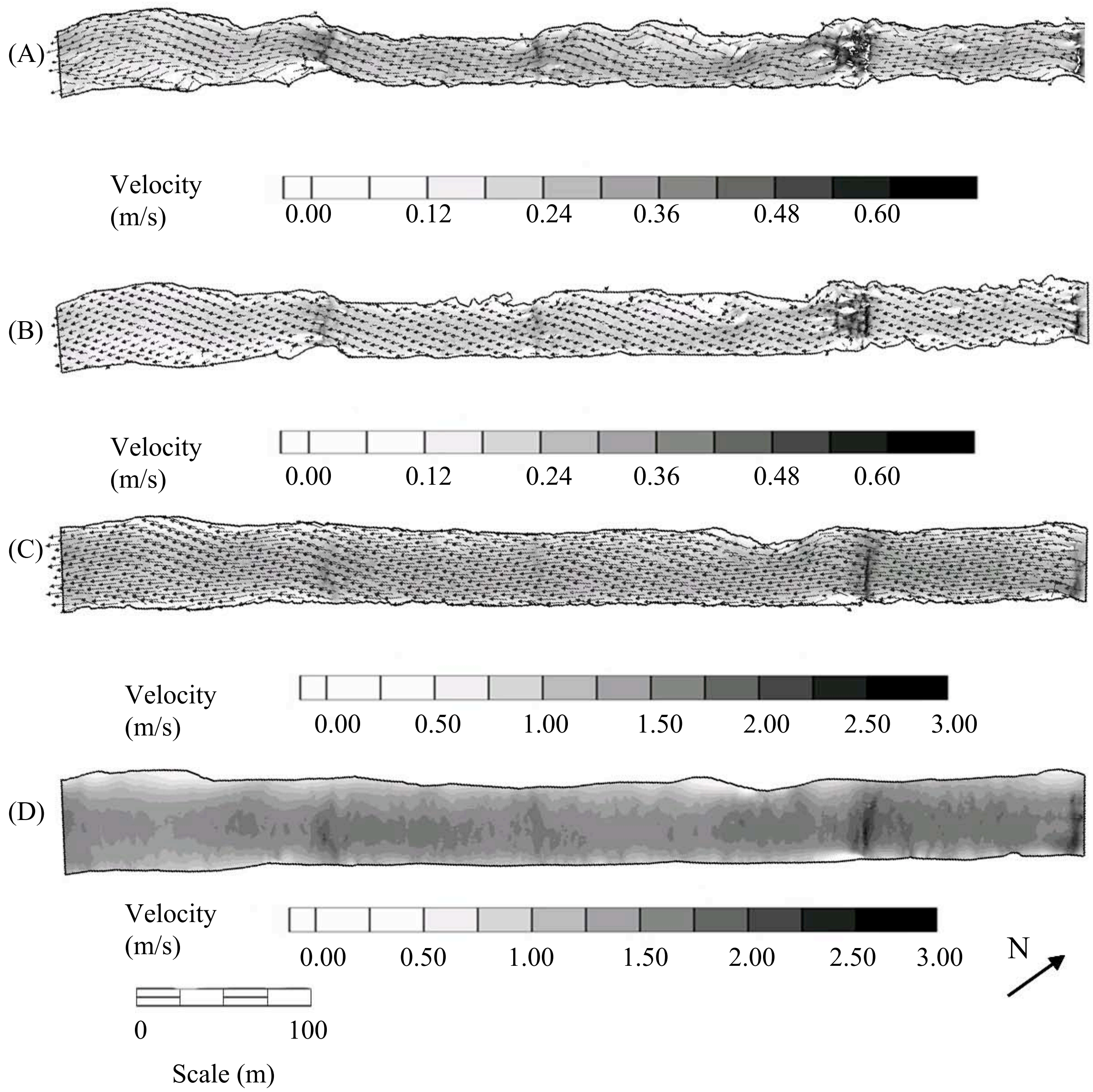
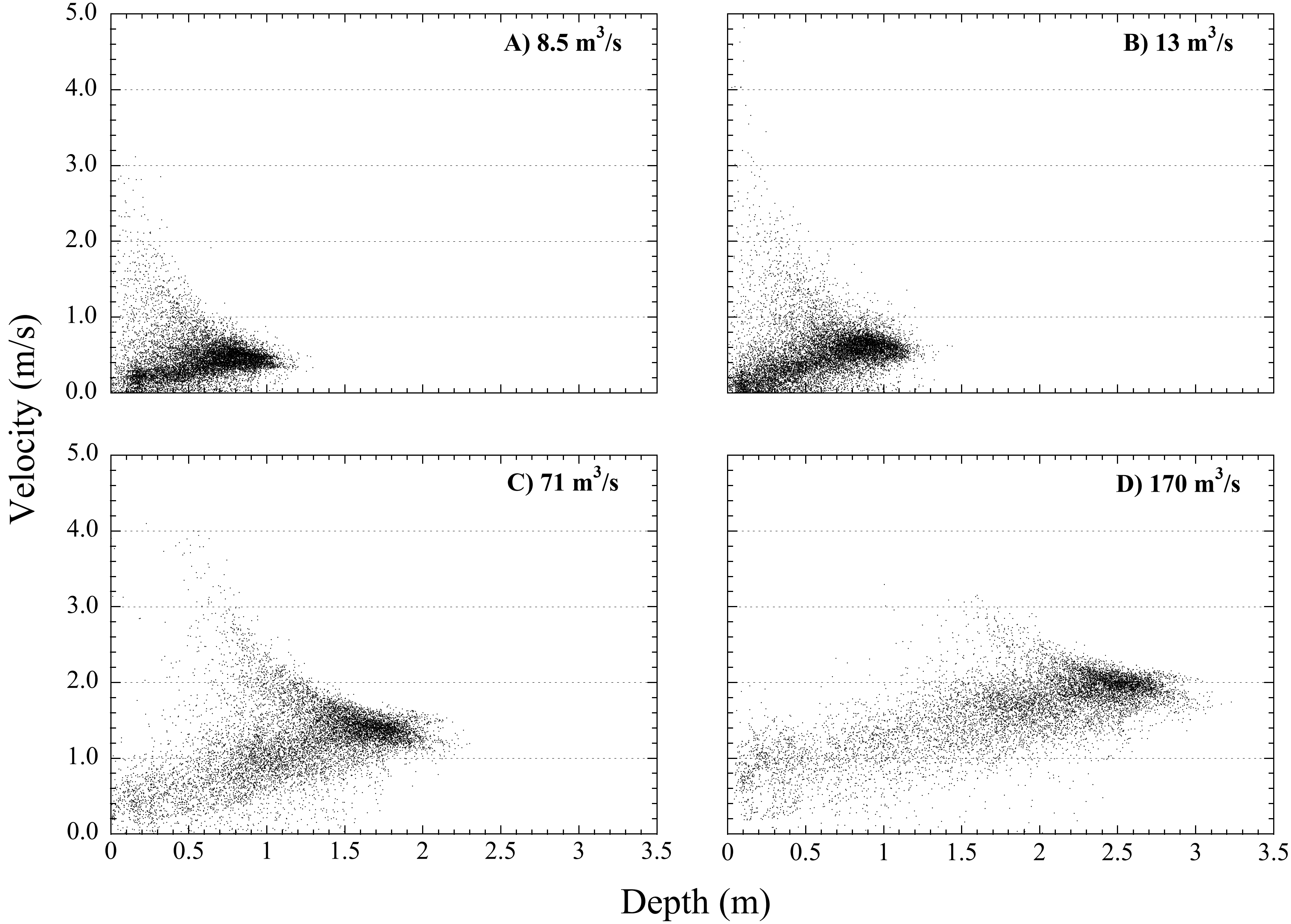

(A)
Depth (m)
0.00 0.25 0.50 0.75 1.00 1.25 1.50
(B)
Depth (m)
0.00 0.25 0.50 0.75 1.00 1.25 1.50
(C)
Depth (m)
0.00 0.50 1.00 1.50 2.00 2.50 3.00
(D)
Depth (m)
0.00 0.50 1.00 1.50 2.00 2.50 3.00
0 100
Scale(m)
N

Figure 11


(A)
Velocity
(m/s)
0.00 0.12 0.24 0.36 0.48 0.60
(B)
Velocity
(m/s)
0.00 0.12 0.24 0.36 0.48 0.60
(C)
Velocity
(m/s)
0.00 0.50 1.00 1.50 2.00 2.50 3.00
(D)
Velocity
(m/s)
0.00 0.50 1.00 1.50 2.00 2.50 3.00
N
0 100
Scale (m)



A) 8.5 m3/s
B) 13 m3/s
C) 71 m3/s
D) 170 m3/s
Velocity (m/s)
Depth (m)
0.0
1.0
2.0
3.0
4.0
5.0
0
0.5
1
1.5
2
2.5
3
3.5

Figure 13

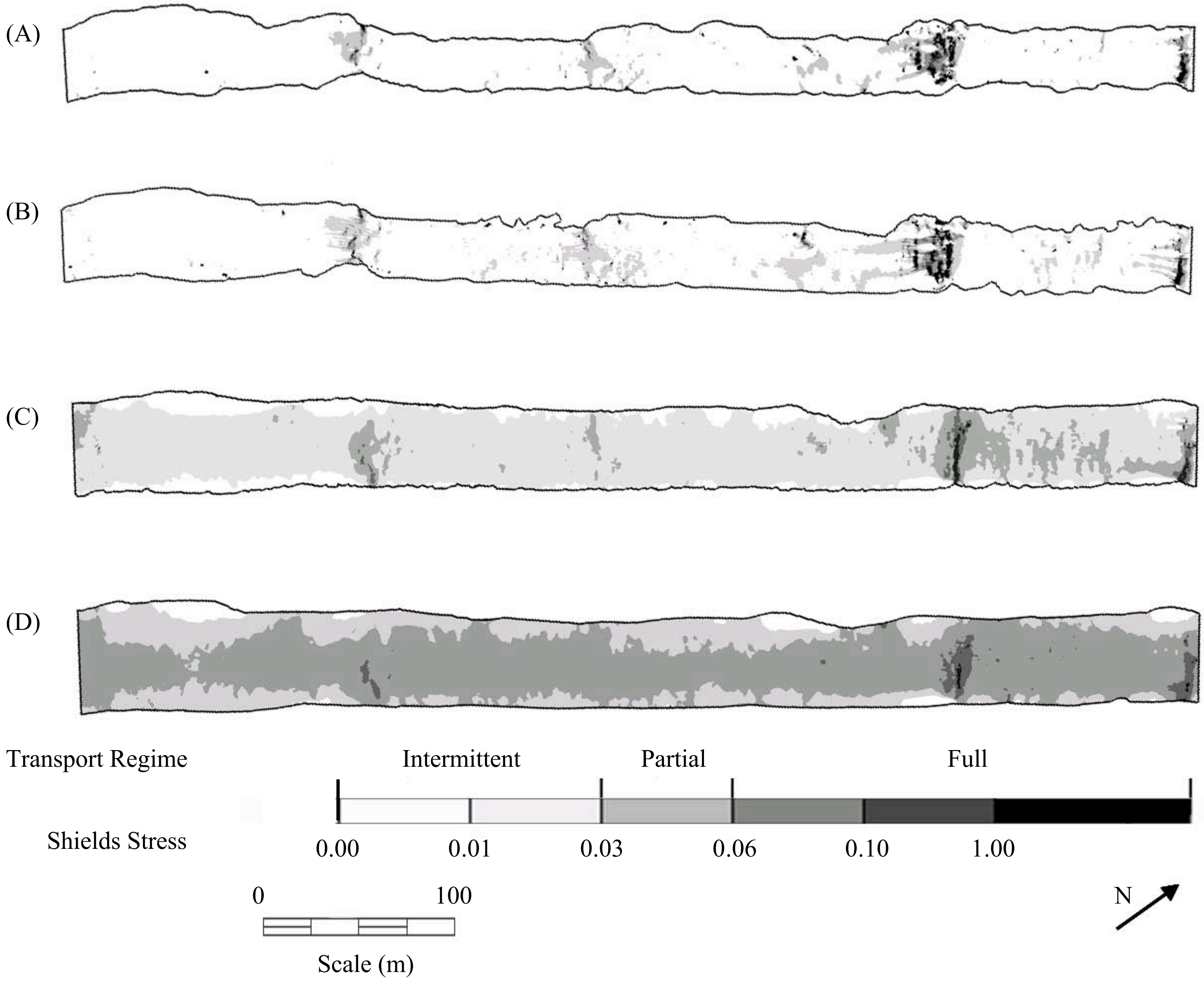

(A)
(B)
(C)
(D)
Transport Regime
Intermittent
Partial
Full
Shields Stress
0.00
0.01
0.03
0.06
0.10
1.00
0
100
Scale (m)
N

Figure 14

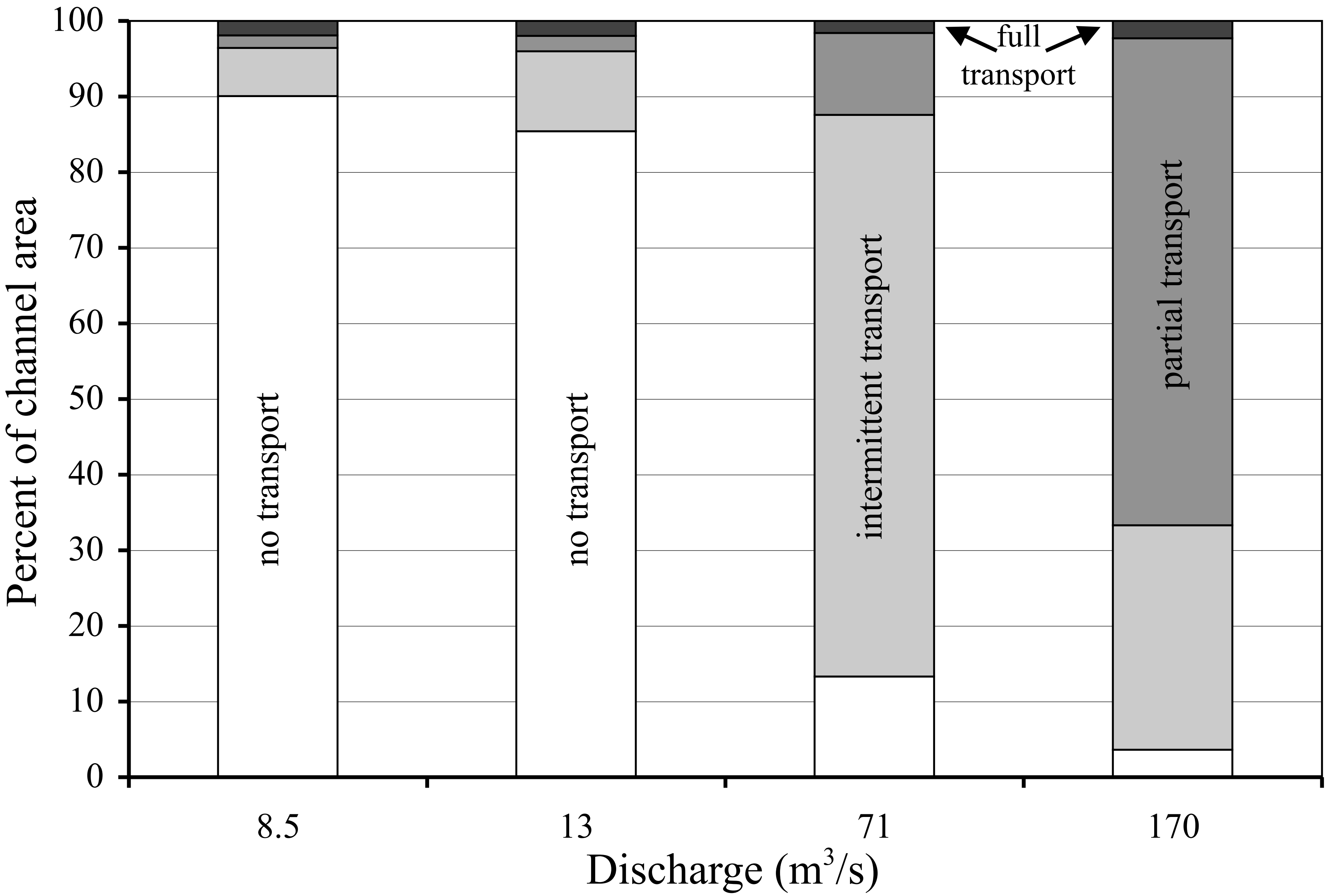

Percent of channel area
100
90
80
70
60
50
40
30
20
10
0
no transport
no transport
intermittent transport
full transport
partial transport
8.5
13
71
170
Discharge (m3/s)

Figure 15

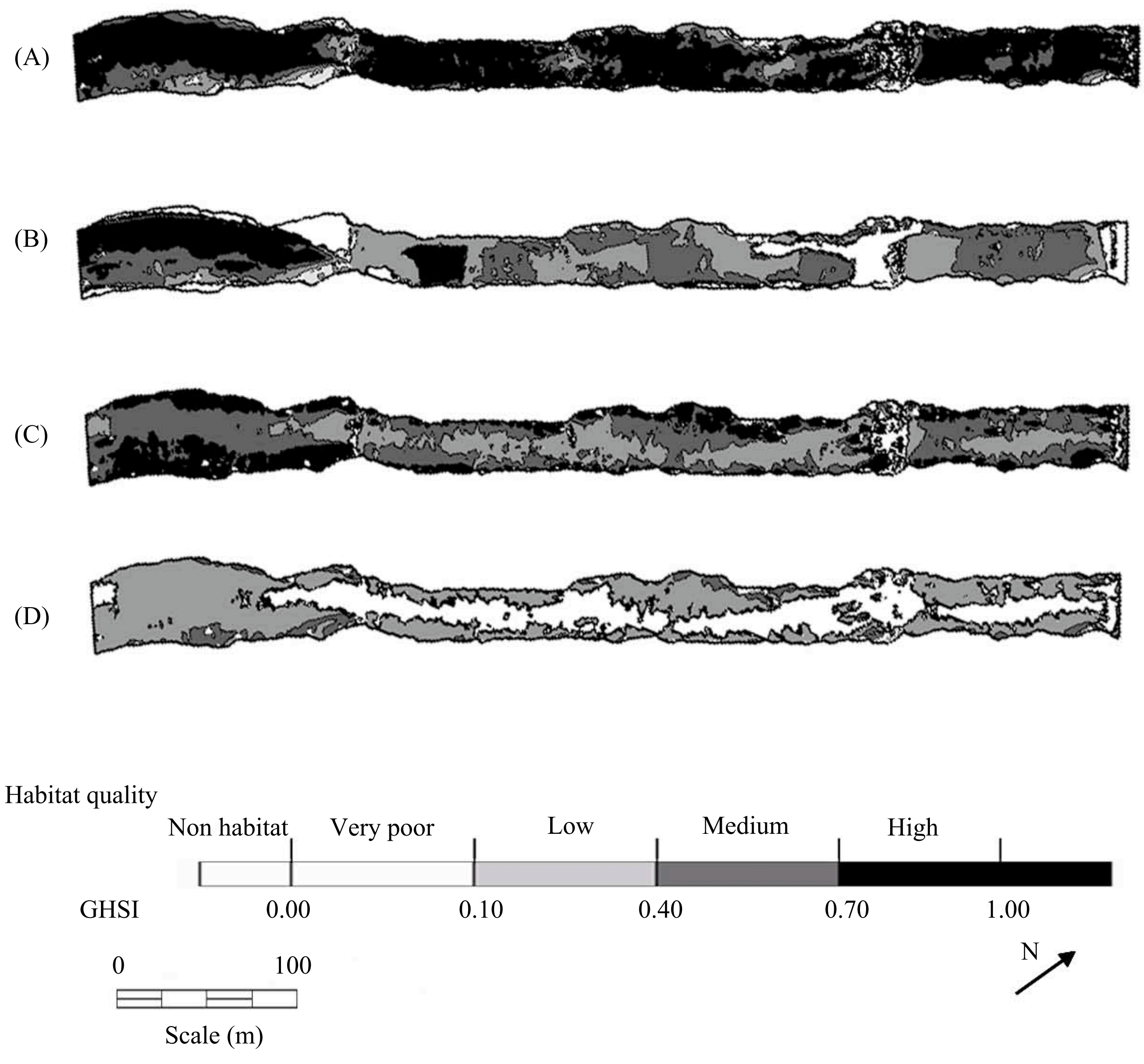

(A)
(B)
(C)
(D)
Habitat quality
Non habitat
Very poor
Low
Medium
High
GHSI
0.00
0.10
0.40
0.70
1.00
0
100
Scale (m)
N

Figure 16

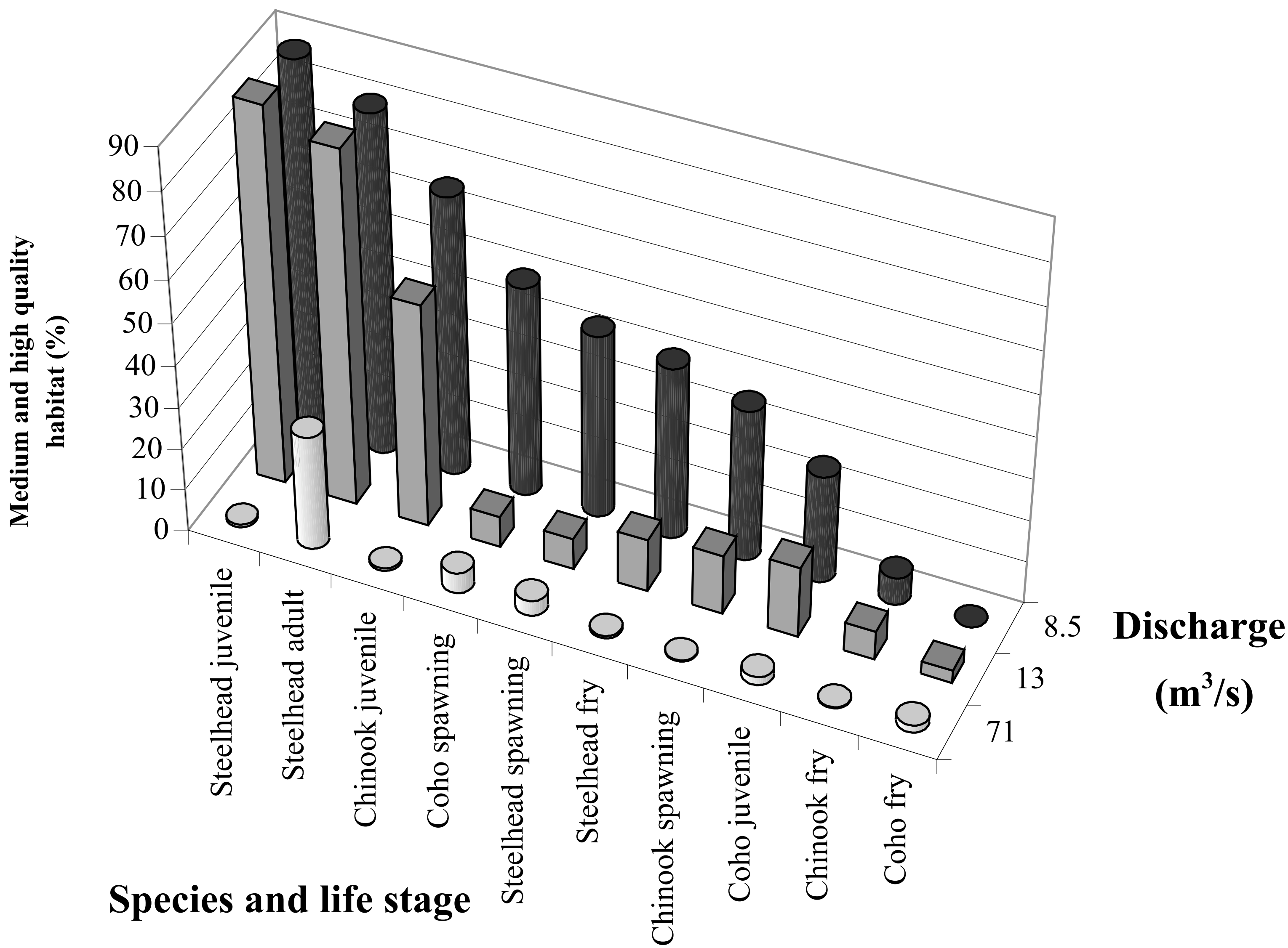

Medium and high quality habitat (%)
90
80
70
60
50
40
30
20
10
0
Steelhead juvenile
Steelhead adult
Chinook juvenile
Coho spawning
Steelhead spawning
Steelhead fry
Chinook spawning
Coho juvenile
Chinook fry
Coho fry
Species and life stage
8.5
13
71
Discharge (m^3/s)

Table 1
Characterization of Physical Controls on Fluvial Environments

	Natural	Anthropogenic
Boundary Controls	Valley confinement (H, G, R)	Bank stabilization (H, G, R)
	Bedrock outcroppings (H,G, R)	Armoring (G)
	Boulders (H,G)	Levees (G, R)
	Large woody debris (H, G)	In-stream habitat improvement (H, G)
	Bed material size (H, G)	Woody debris removal (H, G)
	Dense vegetation (H, G, R)	
Input Controls	Geology/soils (B)	Land use (R, B)
	Climate (B)	Dams (R, B)
	Topography (B)	Diversions (R, B)
	Land cover (R, B)	

Letters denote spatial scales: H is Hydraulic Unit (0.1-1 channel widths), G is Geomorphic Unit (10 channel widths), R is Reach Unit (100-1000 channel widths), B is Basin.

Table 2
Hydraulic geometry exponent values associated with eqs. 1-3.

Cross section	Geomorphic unit	b	f	m
1	Riffle Exit	0.13	0.52	0.36
2	Pool	0.11	0.54	0.35
3	Pool Exit	0.11	0.55	0.34
4	Riffle	0.08	0.55	0.37
5	Riffle Exit	0.18	0.49	0.33
6	Pool	0.11	0.53	0.35
7	Pool	0.17	0.50	0.33
8	Pool Exit	0.16	0.50	0.33
9	Riffle Exit	0.20	0.48	0.32
10	Riffle	0.17	0.50	0.33
11	Riffle	0.12	0.53	0.35
12	Riffle Exit	0.22	0.47	0.31
13	Pool	0.17	0.49	0.34
14	Pool exit	0.51	0.28	0.21
	Average	0.17	0.50	0.33
	Standard Deviation	0.10	0.07	0.04