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Spawning habitat rehabilitation – II. Using hypothesis development and testing in design, Mokelumne River, California, U.S.A.

JOSEPH M. WHEATON, *Department of Land, Air, and Water Resources, University of California at Davis, One Shields Avenue, Davis, CA 95616*
Corresponding Author: School of Geography, University of Southampton, Highfield, Southampton SO17 1BJ
E-mail: Joe.Wheaton@soton.ac.uk

GREGORY B. PASTERNACK, *Department of Land, Air, and Water Resources, University of California at Davis, One Shields Avenue, Davis, CA 95616*

JOSEPH E. MERZ, *East Bay Municipal Utility District, 1 Winemasters Way, Lodi, CA 95240; Department of Wildlife, Fish and Conservation Biology, University of California at Davis, One Shields Avenue, Davis, CA 95616*

ABSTRACT
Rehabilitation of salmonid spawning habitat in regulated rivers through spawning bed enhancement is commonly used to mitigate altered sediment and flow regimes and associated declines in salmonid communities. Partial design-phase predictive results are reported from the application of SHIRA (Spawning Habitat Integrated Rehabilitation Approach) on the lower Mokelumne River, California. The primary management goal of the project was to improve habitat for spawning and incubation life stages of fall-run chinook salmon (*Oncorhynchus tshawytscha*). In the summer of 2001, we conducted a pre-project appraisal followed by development and testing of 12 design scenarios. A subsample of eight design hypotheses, used in three of the design scenarios, is presented. Hydrodynamic, habitat suitability and sediment entrainment model results were used to test five of the eight design hypotheses. Two of the three hypotheses not tested were due to inadequate data on flow boundary conditions at high discharges. In September 2001, the project was constructed in a 152 m reach of the LMR from a final design based on all eight of the design hypotheses presented. Transparent hypothesis development and testing in design is emphasized as opposed to declaring success or failure from an ongoing long-term monitoring campaign of the case study presented.

Keywords: river restoration design; gravel augmentation; spawning gravels; habitat enhancement; Mokelumne River; fall-run chinook salmon (*Oncorhynchus tshawytscha*).

1 Introduction

In the Central Valley of California, U.S.A., rivers that once sustained robust runs of chinook salmon (*Oncorhynchus tshawytscha*) are now regulated or otherwise impacted by dams, diversions, chanelisation and instream gravel mining (Yoshiyama *et al.*, 1998). The decline of salmonids in regulated rivers has been linked to many perturbations including over-harvest and the deterioration, inaccessibility and reduction of spawning habitat for these fish (Maddock, 1999; Moyle and Randall, 1998; Nehlsen *et al.*, 1991). In an inventory of gravel injection projects within California's Central Valley from 1976 to 1999, Lutrick and Kondolf (p. comm.) identified 73 spawning habitat rehabilitation (SHR) projects, on 19 different rivers, totalling over 45 US$ million, and involving the addition of over 1.2 million m^3 (1.8 million metric tons) of gravel. Wheaton *et al.* (2004) segregate SHR projects into three categories: (1) gravel augmentation, (2) hydraulic structure placement and (3) spawning bed enhancement. The two most dominant forms of SHR in California are gravel augmentation and spawning bed enhancement and most have not included a detailed design process but instead relied on prescriptive treatments (Kondolf, 2000b). SHR as a type of river restoration is an indicator-species-centred endeavour that focuses on a specific ecological function connected to and indicative of other functions in an effort to promote broader ecosystem recovery. Benefits to a diverse range of other ecological functions, dependent on hydrogeomorphic processes across a range of spatiotemporal scales, are presumed to follow (Maddock, 1999).

Despite the popularity of SHR in practice, it has received little attention in the peer-reviewed literature (Wheaton *et al.*, 2004). Kondolf *et al.* (1996) reviewed a case study of a riffle construction (spawning bed enhancement) on the Merced River, California; and found geomorphic considerations to be lacking. Kondolf (2000b) offered suggestions for SHR, emphasizing the importance of geomorphic assessment across multiple spatiotemporal scales. Merz and Setka (in press) outlined several techniques they used to evaluate and monitor a spawning bed enhancement project constructed in 2000 on the Mokelumne River, California and

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implemented without a design approach. In a separate spawning bed enhancement project constructed in 1999 on the Mokelumne River, California, Pasternack *et al.* (in press) established that more efficient use of gravel and spawning habitat could have been achieved had 2D hydrodynamic and habitat suitability models been used to develop design alternatives. Measurement of habitat enhancement success has been variable with little work assessing design, implementation or longevity of projects. Despite numerous sources of uncertainty in the restoration process, which make developing specific or appropriate performance measures difficult, methods to cope with uncertainty in restoration are almost non-existent in the literature.

In a companion paper (Wheaton *et al.*, 2004) we reviewed the application of a variety of existing science-based tools and concepts to design and analyze SHR projects in regulated rivers and suggested the SHIRA (Spawning Habitat Integrated Rehabilitation Approach) framework to be employed with those tools. Ideally, the utility of this approach might be tested by monitoring fish populations at experimental rehabilitation sites. In practice, such trends are strongly influenced by many external factors and internal intermediate mechanisms related to flow and sediment dynamics, run-size and timing, changes in harvest regulations, and ocean harvesting and predation (Yoshiyama *et al.*, 1998). Thus, comprehensive post project appraisal evaluating specific mechanistic links among hydrodynamics, geomorphology, and ecology is an important aspect of river restoration (Downs and Kondolf, 2002). This topic has been investigated repeatedly in the peer reviewed literature, though the degree of practicality implementing post project appraisal remains uncertain.

Rather than providing the story of a rehabilitation project through post project appraisal, the aim of this paper is to illustrate the utility of hypothesis development and testing during design. The river restoration literature is rich with case-by-case criticism but lacks detailed SHR design advice for practitioners (Wilcock, 1997). Traditional scientific hypothesis testing takes many forms (after Schumm, 1991):

- Falsification – trying to disprove a hypotheses (Popper, 1968)
- Statistical Inference – deduce statistical hypotheses (H_0 & H_A) and iteratively refine a scientific hypothesis based on inference and rejection of null hypothesis (Anderson, 1998)
- Ruling hypothesis – induction of a single hypothesis (Beveridge, 1980)
- Multiple working hypothesis (Chamberlin, 1890) – formulation of as many sequential, parallel or composite hypotheses as possible (Schumm, 1991)

Design hypothesis testing, as presented here, differs from traditional scientific hypothesis testing. The latter aims to universally corroborate or disprove a tentative explanation based on observed evidence. In contrast, a design hypothesis is a mechanistic inference, formulated on the basis of scientific literature review, and thus is assumed true as a general scientific principle. Hence, design hypothesis testing examines for presence of generally accepted functional or process attributes inherent in a design hypothesis in the specific, relevant setting. Design hypothesis testing does not test the overall validity of the scientific principle.

Design hypothesis falsification of a specific site design could be a highly useful and cost-effective tool. Under some circumstances, such falsification may also provide insight and testing of underlying scientific principles that would be of great value to the larger scientific community as well (Cao and Carling, 2002). Selected results from the design phase of a spawning bed enhancement project implemented with SHIRA on the lower Mokelumne River, California are used as to demonstrate the utility of design hypothesis testing (see Wheaton, 2003 for details).

2 Study reach

The Mokelumne River of central California drains a 1700 km^2 catchment westward to the Sacramento-San Joaquin Delta (see also Merz, 2001a). Sixteen major dams or diversions, including the 0.24 km^3 Pardee and the 0.51 km^3 Camanche reservoirs, have dramatically altered the Lower Mokelumne River's (LMR) flow regime (Pasternack *et al.*, in press). A flood frequency analysis using a Log Pearson III distribution reveals a dramatic reduction in discharge after the construction of Pardee and Camanche Reservoirs. The two, five, ten and one hundred year recurrence interval flows were reduced from pre Camanche dam levels by 67%, 59%, 73% and 75% respectively. The fragmentation of the Mokelumne River basin via damming has completely altered the hydrology, and disconnected the flux of sediment from the upper basin to the LMR. Hence, spawning gravels have not been replenished from the upper basin since the construction of Pardee Reservoir in 1929. Excluding enhancement, all sediment now supplied in the LMR is derived from erosion of existing relic deposits, its own bed and fine-grained sediment primarily from agricultural runoff. In basins like the Mokelumne where dam removal is not under consideration, SHR is a compromise to provide some ecological function in a new downscaled system positioned downstream of a major dam (Trush *et al.*, 2000).

The LMR spans 72 km from the Delta to Camanche Dam, which has a chinook salmon and steelhead (*O. mykiss*) fish hatchery but no fish ladder (Figure 1A). The majority of salmonid spawning now takes place in a 14-km reach between Camanche Dam and Elliot Road (Merz and Setka, in press). In addition to native anadromous steelhead and fall-run chinook salmon, at least 34 other fish species occur in the LMR (Merz, 2001a). Slopes throughout the current spawning reaches are low (ranging from 0.0005 to 0.002). The study reach begins 580 m downstream of Camanche Dam and 76 m downstream of the confluence of Murphy Creek (a 13.4 km^2 subbasin). From June to July of 2001, the pre project phase was carried out within the 272 m long study reach (Figure 1B). From early July to mid August the design phases detailed in this paper were conducted on 152 m reach contained within the study reach.

3 Methods

3.1 Specific application of SHIRA to lower Mokelumne River

As detailed in the companion paper (Wheaton *et al.*, 2004), SHIRA is organized into a set of science-based tools, termed

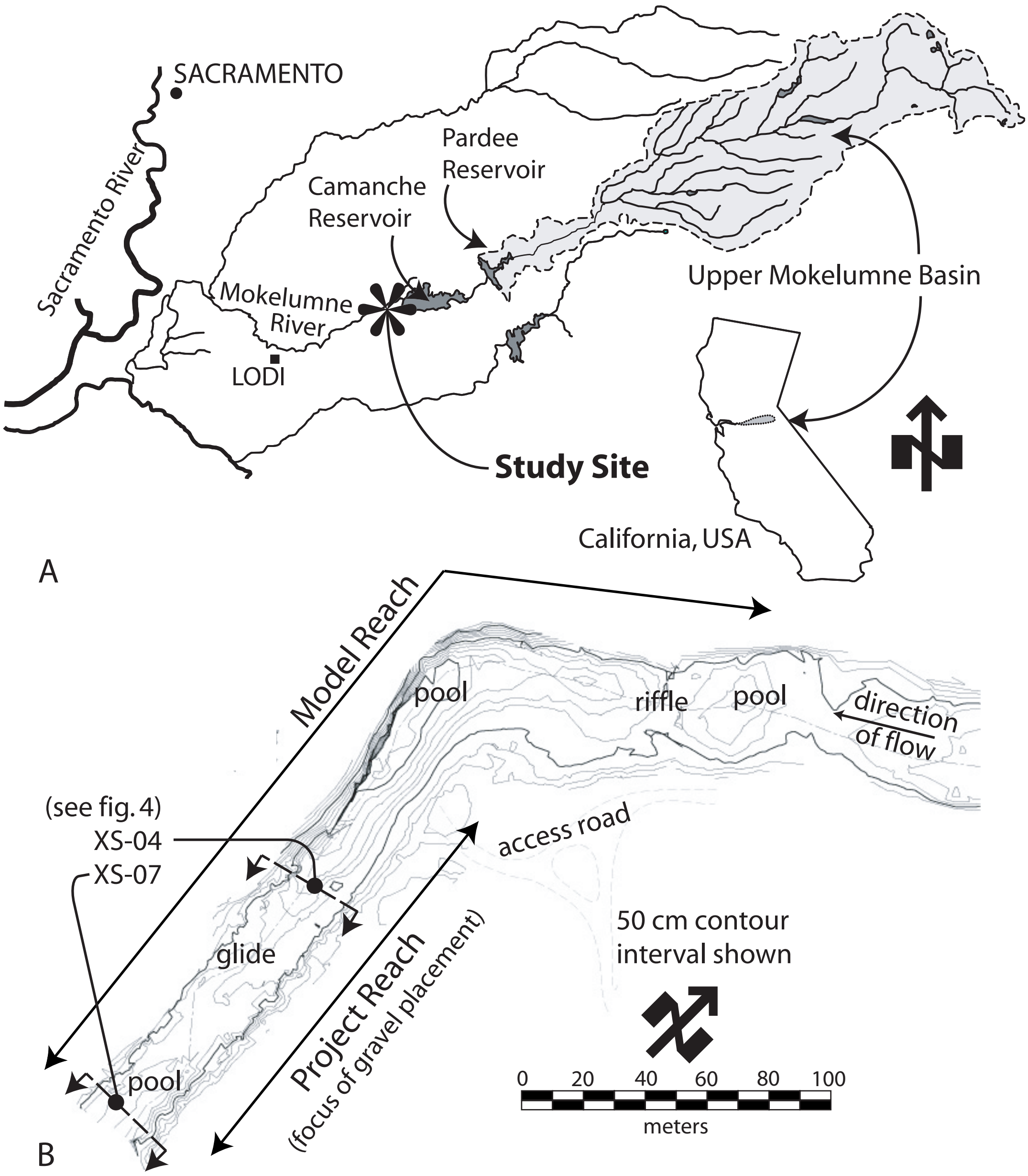

Figure 1 Study site maps. (A) Mokelumne River catchment location map. (B) Topographic survey of study reach showing extent of model domain versus project domain.

modes, used throughout a sequence of project phases. In the methods here, we explain only how specific SHIRA modes were used during the design phase for a specific LMR study. SHIRA is not a prescriptive, cookbook approach and the details of its application will vary from river to river.

On the LMR, a handful of assumptions guided the choices made during data collection, modelling and conceptualization modes. Fall-run chinook salmon are the focus of management efforts on the LMR (FERC, 1998). Reduced quantity and quality of spawning habitat on the LMR was identified by FERC (1993) as the second most important factor restricting population goals. The 2001 experiment site was located just downstream of a major dam incapable of passing coarse-grained sediment. Due to flow reductions, the LMR is largely disconnected from its floodplain and once-active alluvial deposits are now armoured with vegetation (Edwards, 2001). As such, it was assumed that the sediment supply from upstream was negligible and recruitment of gravels in floodplain storage unlikely. Grain size distributions for placed gravels (supplied from a LMR floodplain quarry) were determined from a mix of fork length data for LMR adult female fall-run chinook salmon (Miyamoto, 2001) and related envelope curves reported in the literature (Kondolf and Wolman, 1993). Spawning habitat suitability models were built using only depth and velocity habitat suitability curves (HSC). Grain-size HSCs were not used because source gravels from a local quarry have shown little variability in projects dating back to 1991. Thus, during design inclusion of grain-size HSC acts as a constant and only further emphasizes the poor quality habitat of pre-project conditions. All designs were based on an assumed 1150 m^3 of gravel available for construction (768 m^3 from a quarry and 382 m^3 from retired hatchery spawning beds). This volume was dictated by available funds for the project as opposed to being derived from sediment budget calculations, which suggest a bedload deficit of $\sim$40,000 to 47, 000 m^3 accruing since the construction of Pardee reservoir in 1929. The flow regime of the LMR is heavily regulated with a maximum Camanche release of 141 cumecs, a minimum mandated fish flow of 4.25 cumecs and spawning flows typically between 5.7 (exceeded 80% of time) and 14.2 cumecs (exceeded 45% of time) depending on water deliveries to downstream users (for detailed hydrologic analysis: Pasternack *et al.*, in press). Due to the absence of project site rating curves, lack of availability of vegetated floodplain topographic data, and lack of high flows during the 2001 water year, hydrodynamic modelling was primarily conducted at an 11.46 cumecs spawning flow, for which validation data was collected. The 11.46 cumecs flow is exceeded 54% of the time under the current flow regime (1963–2003). The above assumptions and limitations helped determine the specific methods and metrics used in the data collection mode (Table 1). Although not included explicitly in this study, monitoring of previous enhancement sites since 1991 has involved macroinvertebrate, fish community, alevin egg tube survival and water quality studies (Merz, 2001a,b; Merz, 2002; Merz and Setka, in press). This biological foundation strongly influenced the assumptions described above.

3.2 *Incorporating established concepts into designs*

Drawing on SHIRA's Conceptualization Mode, key concepts from the literature were documented, including related processes, the geomorphic forms thought to promote and interact with those processes and the presumed ecological benefits. In the development of designs, we took several design objectives and established design hypotheses for them (Table 2). These concepts were then incorporated into 12 competing design scenarios. We report how some of the concepts led to conceptual designs for three of twelve scenarios: Design Five – Flat Riffle, Design Six – Constricted Pools, and Design Twelve – Central Bar Complex. For each design, form-process sketches and finished grading plans

Table 1 Data collection mode. Description of purpose, methods and metrics for various data collection mode components for project.

Data collection component	Purpose	Method	Metric: pre	Metric: Design
Topographic Reach Survey	Build Digital Elevation Models	Total station w/true datum and coordinate system; feature-based irregular surveying (high density around topographically complex areas; low density on floodplains)	1886 points; Avg. density: 0.17 pt./m^2; 1.09 ha; Surface complexity: 1.05	NA (grading plans used to create DEMs)
Flow/ Hydrodynamics	Rating curves; Hydrodynamic Model Validation; Model boundary condition specifications; eddy viscosity estimation from theory and velocity measurements	Depth-averaged estimates (0.6 depth if <0.75 m; average of 0.2 and 0.8 depth if >0.75 m): Wadable cross sections: Marsh McBirney Electromagnetic current meter and top setting rod. Non-wadable cross sections: Flat bottom boat and Price AA current meter	Seven cross sections (4 wadable; 3 non-wadable); 219 points	No validation possible (Pre-project boundary conditions used)
Geomorphic Analysis	Characterize active and inactive geomorphic processes and limitations	Hydraulic geometry analysis, channel classification, geomorphic process inventory, rough bedload sediment budget using ACRONYM	Seven cross sections, field reconnaissance and 59 years of flow record	NA
Flow Regime Analysis	Identify timing, duration and intensity of peak flows, spawning flows and various recurrence interval flows	Pre dam USGS daily records (1904–1963); Post dam EBMUD daily records (1964–2001); Log Pearson III flood frequency analysis	59 years of pre dam records; 37 years of post dam records	NA (same used)
Spawning Habitat Characterization	Quantify hydrodynamic characteristics of spawning habitat; habitat typing; redd utilization	Velocity and depth habitat suitability curves from (CDFG, 1991); River styles characterization; weekly redd surveys (1994–2001) (Merz and Setka, in prep.)	Velocity and depth HSC; *Redd surveys* (*1994–2000*): Total LMR: 6483 redds (≈926/year) Project reach: 55 redds (≈7/year)	Same velocity and depth HSC used;
Substrate Characterization	Quantify surface grain size distributions; Estimate model roughness parameters	Wolman Pebble Counts; Roughness estimation (Manning's n)	3 transects (100 samples each); $n = 0.043$	Quarry specified distribution; $n = 0.043$

Table 2 Some examples of design concepts used. The table illustrates how to start with basic design objectives, develop specific design hypotheses, incorporate the hypotheses into channel design and test them.

Design objective	Possible design hypothesis	How to include hypothesis in design	How to test design hypothesis
1. Provide higher quantity of higher quality spawning habitat.	1A. Spawning habitat should be provided that is as close to GHSI defined high quality habitat as possible.	Design features that will promote shallower water depths, swifter velocities and locally steepened water surface slopes (e.g. riffles; transverse bars, ribs; point bars; longitudinal bars).	Use GHSI models of designs at spawning flows to predict habitat quality of modeled design scenarios.
2. Spawning habitat should be geomorphically sustainable.	2A. Pool riffle sequences should be self-maintaining when provided with an upstream gravel supply if at high flows an entrainment reversal promotes net deposition over riffles and net scour within pools.	Place riffles where flow width expansions are permissible and place pools where flow width constrictions may be used at pool heads.	Model velocity, shear stress, and sediment entrainment over range of flows and look for entrainment reversal at high flows.*
	2B. Deposition of coarse bedload at high flows should be encouraged over spawning habitat (e.g. riffles and bars) and scour should be promoted in pools.	Design bed morphology and channel width variations over a range of flows to encourage convergent flow paths in pools and divergent flow paths over spawning habitat.	Use 2D hydrodynamic model flow vector solution to test for presence of convergent and divergent flow paths at high flows.*
	2C. Although active scour and deposition is presumed to take place at higher flows, there should not be significant erosion of spawning habitat during spawning flows.	Design spawning habitat to be stable at spawning flows by not using channel narrowing or excessively steep water surface and/or bed slopes in spawning habitat zones.	Model sediment entrainment at spawning flows and check that entrainment of spawning habitat not occurring.
3. Provide intergravel conditions to support higher alevin survival rates.	3A. Higher rates of hyporheic exchange (e.g. upwelling or downwelling through gravels) should be promoted to maintain connectivity of intergravel pore space, maintain high levels of dissolved oxygen and promote flushing of fines and metabolic wastes.	Include broad bowl-shaped pool-exit slopes at pool-riffle transitions (tend to increase hydraulic head gradient rapidly and induce downwelling).	Use a hyporheic flow model to test for downwelling; OR calculate hydraulic head gradients (based on some major assumptions) and test for downwelling.**
4. Provide refugia in close proximity to spawning habitat.	4A. Structural refugia in close proximity to spawning habitat should provide resting zones for adult spawners, protection from predation and holding areas for juveniles.	Place spawning habitat in close (>5 m) proximity to pools; overhanging cover, boulder complexes, and LWD.	Measure distance from medium and high GHSI quality habitats to structural refugia and check to see that most spawning habitat is within reasonable proximity.
	4B. Shear zone refugia (characterized by two distinct blocks of flow moving in opposite directions; e.g. eddies) in close proximity to spawning habitat should provide resting zones for adult spawners and drift feeding opportunities for juveniles and macroinvertebrates.	Through design of bed features, irregular shaped banks, channel width variations, LWD or boulder complexes, promote shear zones in close (>5 m) proximity to spawning habitat.	Look for presence of shear zones in hydrodynamic model results at spawning flows and measure distances from high and medium GHSI quality habitats to check for reasonable proximity.
5. Providing morphological diversity should support biological diversity.	5A. Designs should promote habitat heterogeneity to provide a mix of habitat patches that serve multiple species and lifestages.	Avoid GHSI optimization of excessively large contiguous areas of habitat; design for functional mosaic of geomorphic forms and habitat.	Large (>2 to 4 channel widths) patches of homogenized flow conditions in hydrodynamic model and homogenized habitat quality in GHSI model results should not be present at spawning flows.

*Due to inadequate data on high flows, these hypotheses were only partially tested at spawning flows and it was presumed that desired patterns would be preserved at high flows.
**Not tested in this study.

depict the utility of SHIRA's conceptualization mode at creatively incorporating scientific concepts into designs (Wheaton, 2003).

Finished grading plans were drawn in AutoCAD and TIN-based digital elevation models (DEMs) were created in AutoDesk's Land Desktop R3. A finished grading plan specifies finished grade elevations in reference to a pre-project DEM. A pre-project DEM was made from detailed topographic surveys. Design DEMs combined the pre-project DEM with grading plans for hypothetical designs (Table 1). DEMs were each iteratively developed using (1) visualization, (2) editing, (3) data augmentation and (4) interpolation stages. Point data augmentation was used to improve pre-project DEM representation of areas with lower point resolution or inadequate data (typically deep pools). Three types of point augmentation were used: (1) additional field surveys, (2) interpolation between known points and (3) user-specified spacing along contours. When iterative DEM development finally yielded realistic terrain representation, refined point and breakline data were extrapolated from Land Desktop for later use in hydrodynamic model mesh characterization.

3.3 Numerical models for process predictions

SHIRA's Modelling Mode was used to create hydrodynamic, sediment entrainment and spawning habitat models that in turn were used to test specific design hypotheses (Table 2). Model results are presented for the pre-project (for validation and comparison) and three design scenarios. Emphasis is placed on the ability or inability of these models to test the design hypotheses made. The models used are reviewed briefly below (see also Pasternack *et al.*, in press).

The 2D Finite Element Surface Water Modelling System (FESWMS) and Surfacewater Modelling System graphical interface were used to analyze steady state hydrodynamics. The boundary conditions required to run FESWMS are: (1) a discharge at the upstream boundary, (2) a corresponding water surface elevation at the downstream boundary and (3) channel topography. Due to inadequate flow variation during the 2001 water year, lack of forested floodplain topographic data, and lack of historical rating curves for the reach, discharge and water surface boundary conditions were identified only for spawning flows (11.46 cumecs). Refined DEM data were used to discretize channel topography to a finite element model mesh at an approximately uniform node spacing (~45 cm apart). This resulted in model meshes with between 49,000 and 53,000 computational nodes comprising between 15,000 and 16,500 quadrilateral and triangular elements. The most noteworthy model parameters include Manning's roughness and Boussinesq's eddy viscosity coefficient for turbulence closure. Manning's roughness (n) was estimated as 0.043 for entire study site using a McCuen summation method (McCuen, 1989). This was used instead of a spatially explicit application of Strickler's equation for roughness based on substrate size variations, because in this instance there was a narrow and homogenized range of gravel substrate sizes. Eddy viscosity is a fourth-order tensor (33 terms), which describes the property of the flow and arises from the closure problem when averaging the velocity terms in the Navier-Stokes equations. We used Boussinesq's analogy to parameterize eddy viscosity, which crudely approximates eddy viscosity as an isotropic scalar. Doing so allows a theoretical estimate of eddy viscosity as 60 percent of the product of shear-velocity (u*) and depth (Froehlich, 1989). Pasternack *et al.* (in press) were unable to achieve model stability for a reach with a shallow riffle and a relatively deep, in-channel mining pit using a single constant eddy viscosity value estimated from field measured depth and velocity data with a mesh built on unrefined DEM data at a study site located 220 m upstream. In fact, model stability was only achieved when the constant eddy viscosity was kept above $0.065\,\mathrm{m}^2/\mathrm{sec}$. During a flow of 11.46 cumecs at the study site reported here, an average eddy viscosity of $0.017\,\mathrm{m}^2/\mathrm{sec}$ was calculated from 219 velocity and depth measurements. Due to significantly less topographic variation as well as higher mesh and DEM quality in this study, model stability and convergence was achieved even using the actual calculated eddy viscosity value of $0.017\,\mathrm{m}^2/\mathrm{sec}$. No model calibration was performed as all model parameters were specified with actual measured or theoretically calculated values. Pre project model results (velocity and depth) were compared against measured values at five cross sections for validation.

Habitat suitability curves for fall-run chinook on the LMR were used to develop a global habitat suitability index (GHSI) for spawning (Wheaton *et al.*, 2004). In principle, this is similar to PHABSIM habitat simulations with the major exception that a 2D instead of 1D hydrodynamic model is used (Leclerc *et al.*, 1995). The index yields spatial predictions of spawning habitat suitability based on 2D hydrodynamic model results (Pasternack *et al.*, in press). Whereas the hydrodynamic model results can be used to test specific hydrodynamic process predictions and make ecological function inferences, the habitat suitability model tests the claim that specific forms will produce preferable spawning habitat conditions.

A sediment entrainment sub-model based on hydrodynamic model results and representative grain sizes (d_{16}, d_{50} and d_{84}) was used to test for potential scour at spawning flows. A common approach to modelling sediment entrainment using Shields' incipient motion criterion (Garde and Raju, 1985), and Einstein's log velocity profile equation was employed (Wheaton *et al.*, 2004). The theoretical HSC and entrainment functions were analyzed by plotting them as a third dimension on velocity versus depth plots. Actual measured hydraulic conditions (velocity and depth) could then be overlaid on the same plot to assess both habitat suitability and sediment entrainment thresholds. Sediment entrainment model results were used to test for erosion at low spawning flows, but could not be used to test hypothesized erosion processes at higher flows due to lack of adequate rating curve data coupled with an un-surveyed, wide, and complex vegetated floodplain.

4 Results

4.1 Incorporating established concepts into designs

The pre-project topographic survey and geomorphic habitat classification revealed a pre-project reach-averaged slope of

Table 3 Summary grading statistics.

Design	Volume of gravel used (m^3)	Gravel placement footprint (m^2)	Maximum fill depth (m)	Bed elevation at riffle crest (m)	Local slope
Pre	NA	NA	NA	26.90	0.0011
Five	961	2225	1.5	27.66	0.0080
Six	956	2457	1.4	27.51	0.0049
Twelve	1146	2402	1.5	27.44*	0.0020

*Upper riffle reported (central bar raised from 27.02 to 27.75 and lower riffle raised from 26.66 m to 27.44 m).

0.0011 and a pool-glide morphology dominating the project area (Figure 1B). Excessive depths on the LMR are attributed to a history of instream gravel mining and channel re-alignment. All designs were intended to improve spawning habitat within the glide portion of the uniform and homogenized reach (Figure 1B). Design alternatives included: tight alternate bars, constricted riffle, broad flat riffle, constricted pools, braided and complex channel geometries. Only three of the twelve design scenarios, which illustrate a range of different concepts, are reported below. Summary earthwork statistics are provided in Table 3.

The conceptual design formulation for Scenario Five was based primarily on optimizing the area of GHSI-defined high quality spawning habitat with a pool-riffle unit (hypothesis 1A of Table 3). A broad flat riffle with a slope of 0.008 was specified across the entire width of the channel and extended longitudinally roughly 60 m (Figure 2A). The upstream portion of the project was to transition out of an existing confined pool onto a broad pool-exit slope. Pool-exit slopes are bedforms at the pool-riffle transition that we hypothesized (hypothesis 3A) would promote hyporheic exchange or downwelling of water due to an increased hydraulic head gradient and vertically contracting streamlines (Kondolf, 2000a). The inferred ecological benefits of hyporheic exchange for salmonids are realized during egg-incubation through potential flushing of metabolic wastes, maintenance of interstitial voids and elevated dissolved oxygen levels, all of which could promote higher alevin survival rates (Chapman, 1988). Furthermore, chinook salmon have been found to preferentially spawn where downwelling occurs (Geist, 2000; Vronskiy, 1972). The broad flat riffle was to provide a large area of contiguous high quality spawning habitat. It was hypothesized that the riffle would decrease water depths, increase water surface slope and increase velocities to those optimal for spawning (hypothesis 1A). Modelling of earlier design scenarios (e.g. constricted riffle) suggested scour even at spawning flows and this design was modified to discourage scour during spawning and incubation flows (hypothesis 2C in Table 2). Finally, the large flat riffle was a simple design commonly used in spawning bed enhancement projects and a good benchmark for comparison.

The conceptual design formulation for Scenario Six also specified a broad riffle (hypothesis 1A in Table 2), but used some of the design volume of gravel to further constrict flow width through pools both upstream and downstream of the riffle (hypothesis 2A) using two submerged bars (Figure 2B). The bars were designed roughly four channel widths apart (consistent with empirical observations (e.g. Brookes and Sear, 1996). Pool constriction was sought (hypothesis 2B) to promote convergent flow and focus scour in pools at higher flows based on mass conservation (Carling, 1991) and convective acceleration force mechanisms for pool maintenance (Dietrich and Whiting, 1989). Divergent flow over the riffle was intended to promote gravel deposition on the riffle at higher flow as suggested by Booker *et al.* (2001) and Thompson *et al.* (1999). It was hypothesized that the bar pattern would encourage the flow thalweg to switch from river right to river left as it diverges across the riffle and further concentrate flow in the downstream pool (hypothesis 2B). This was intended to compliment the transitional classification of the channel between a straight and meandering river and work in harmony with the existing upstream meander bend hydraulics. Whereas in design scenario five the majority of gravel was used to create contiguous spawning habitat, here a significant portion of the gravel was used to achieve geomorphic goals thought to promote sustaining fluvial processes.

In Design Scenario Twelve, two flat riffle areas with finish grades at an elevation slightly lower than the single riffle in previous designs (limiting backwater impact on an upstream riffle with riffle crest elevation of 27.55 m) were bridged by a central longitudinal bar (Figure 2C). The central bar has multiple hypothesized functions. First, it yields flow divergence across both flat riffle areas (promoting gravel deposition there) and flow convergence over adjacent pools (reducing gravel deposition there; hypothesis 2B). Booker *et al.* (2001) found that grains seeded in riffles in a channel with a small width to depth ratio were routed and deposited around the perimeters of pools. Second, it provides needed construction access for the downstream riffle area. Third, Pasternack *et al.* (in press) previously found central bars to be highly gravel-efficient and yield large contiguous areas of high quality habitat (hypothesis 1A). Existing deeper areas along both sides of the central bar were maintained as small pools, and like the central bar, they too serve several hypothesized purposes. First, recirculating eddies induced by the constriction of flow through the pools could lead to aggradation of gravels on pool exit slopes or along the central bar (hypothesis 2A). Second, designs with only one riffle introduce only one pool-exit slope. Thus, by incorporating two small pools into the design, a total of three pool-exit slopes were present (hypothesis 3A). Third, the sloping bed around the small pools provides habitat heterogeneity (hypothesis 5A). Fourth, the small pools provide adult holding areas proximal to spawning habitat (hypothesis 4A). Finally, the existing banks on both sides of the bar were highly irregular due to tree roots and overhanging cover. Maintaing pools on both sides of the bars was hoped to preserve existing shear zones along these irregular banks; thus providing shear zone refugia (hypothesis 4B).

4.2 Numerical models for process predictions

4.2.1 Comparison with pre project

Pre-project hydrodynamic model results at a representative spawning flow of 11.46 cumecs highlight several interesting flow

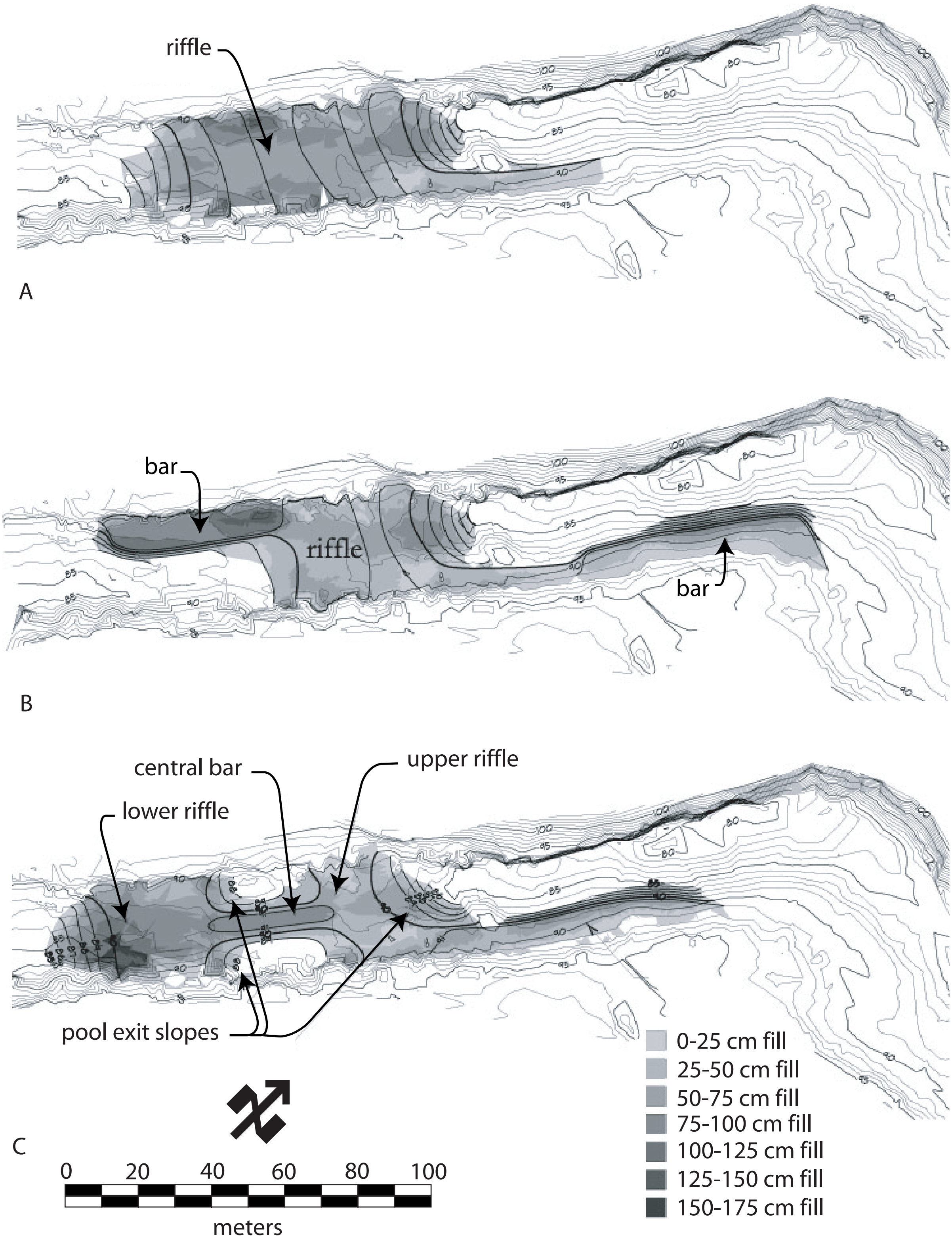

Figure 2 Conceptual designs and grading plans for selected design scenarios. (A) Design scenario 5 (flat riffle). (B) Design scenario 6 (constricted pools). (C) Design scenario 12 (final design – complex channel geometry). Shaded areas represent depth of design specified gravel placement; whereas faded contours represent pre project topography.

features (Figure 3A). Pronounced eddies on the inside bend of the river and downstream of irregularities that protrude into the channel along the banks are correctly captured in model results and qualitatively verifiable in the field. The pre-project model results highlight the swifter velocities over an existing riffle upstream of the bend, the concentration of flow through the deep pool on the outside bend, and the rather homogenous flow patterns and sluggish velocities through the glide where gravel addition is proposed.

Pre-project flow data collection and model validation at five cross sections (Figure 4), during an 11.46 cumecs discharge, show a generally good agreement between field data and model

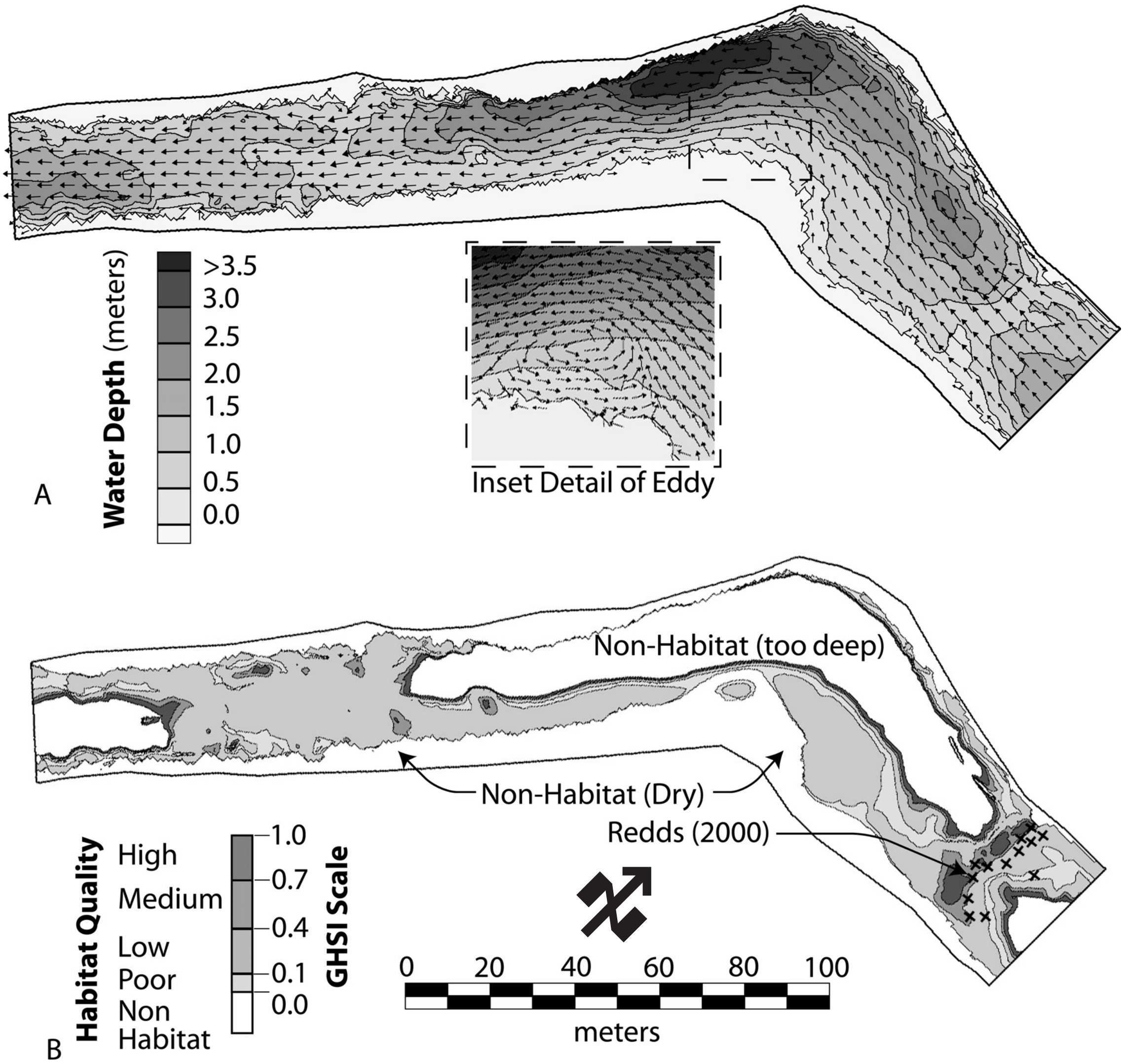

Figure 3 Pre-project Model Results at 11.46 cumecs for comparison. (A) Hydrodynamic Model Results. Shading corresponds to depth solutions and arrows correspond to velocity vectors (scaled to magnitude). (B) Spawning habitat suitability model (GHSI) results w/2000 redd survey results overlaid (redds delineated by black x's).

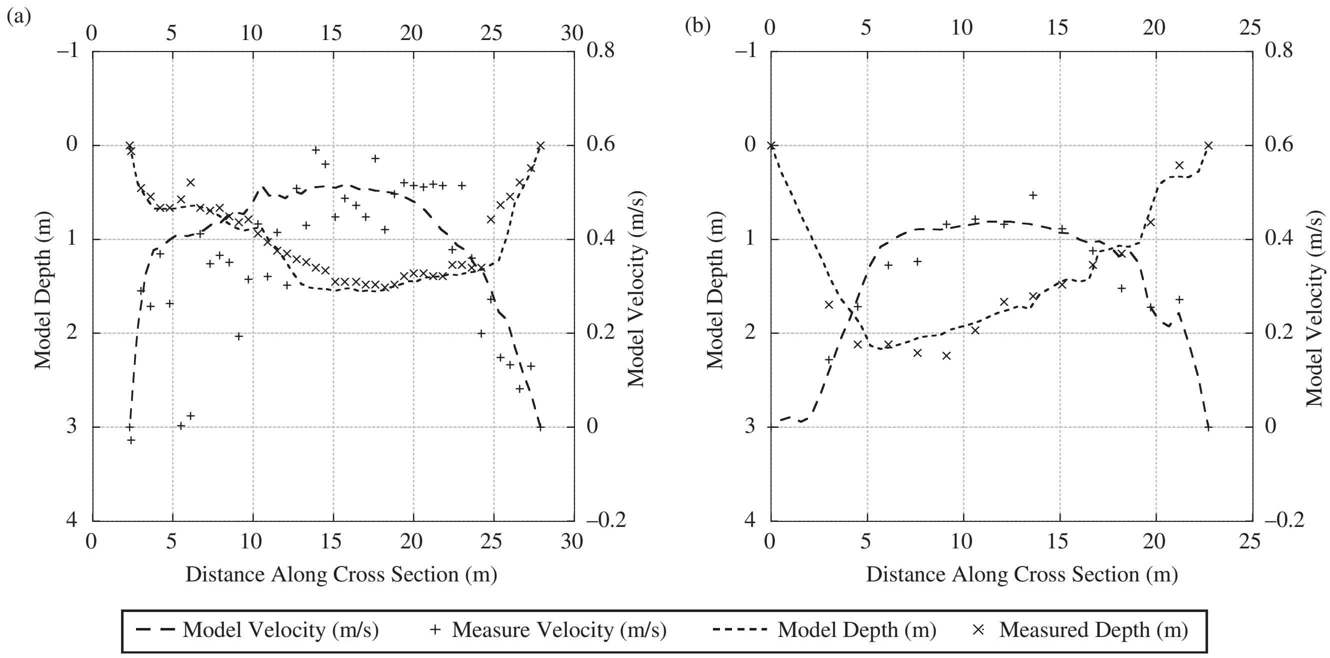

Figure 4 Examples of Pre-project Model validation at two cross sections. (A) Cross section four. (B) Cross section seven. (See Figure 1 for cross section locations.) Generally, poor velocity validation is attributed to areas of poor topographic quality (indicated by errors in measured and predicted depth) and to a lesser extent local-scale measured velocity fluctuations are muted by the model.

predictions (see Wheaton 2003 for full results). The largest errors in velocity predictions are where model bathymetry inaccurately describes the bed. The use of an intermediate AutoCAD-driven DEM process in this study represented a significant advance in model prediction compared to an earlier study (Pasternack *et al.*, in press) in which raw survey data were directly interpolated to yield the model mesh.

For comparison, pre-project GHSI modelling results confirm the lack of substantial areas of high or medium quality spawning habitat within the proposed enhancement area (Figure 3B).

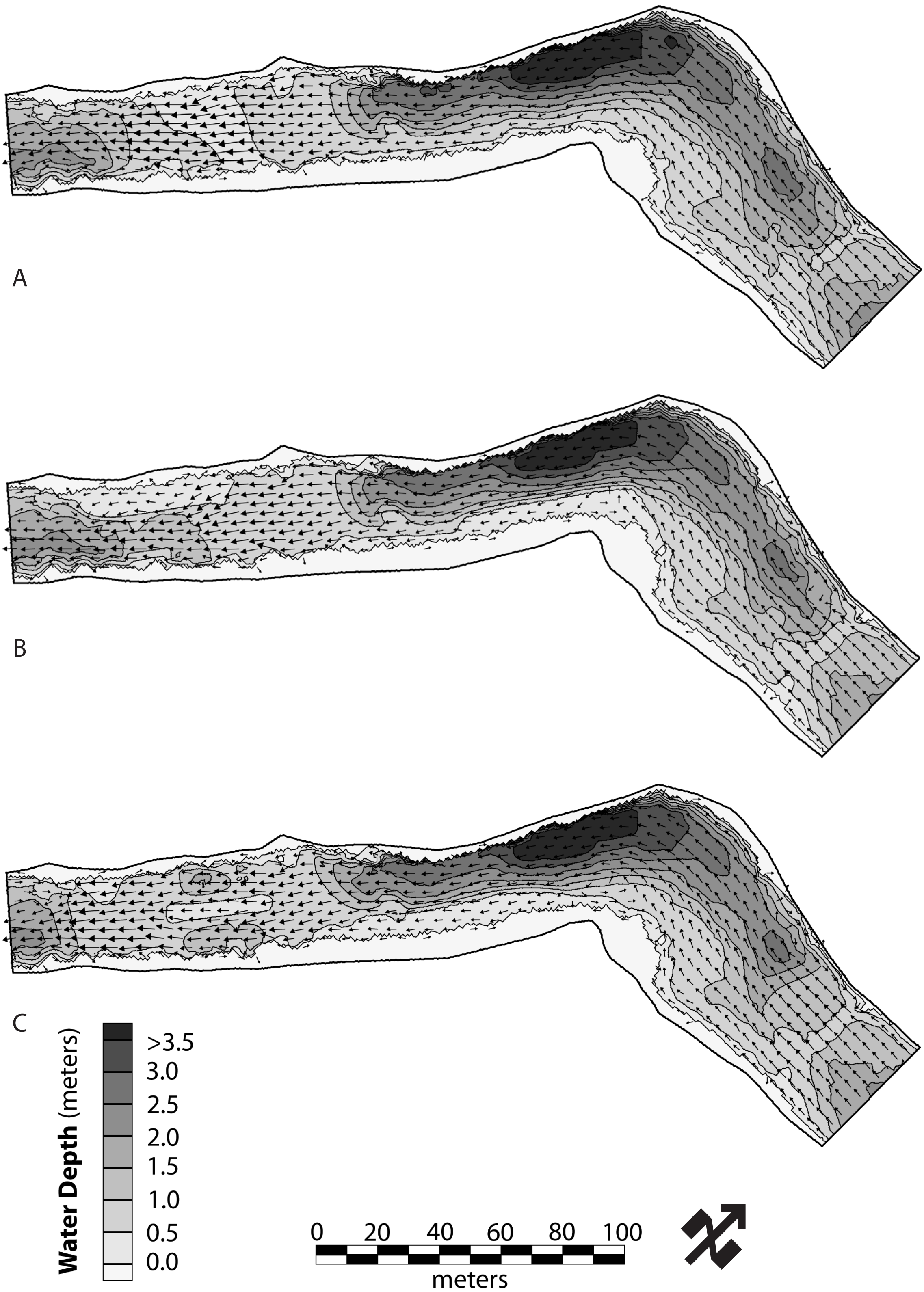

Figure 5 Design Phase Hydrodynamic Model Results at 11.46 cumecs. Shading corresponds to depth solutions and arrows correspond to velocity vectors (scaled to magnitude). (A) Design scenario 5 (flat riffle). (B) Design scenario 6 (constricted pools). (C) Design scenario 12 (final design – complex channel geometry).

Conversely, the best suited spawning habitat is highlighted in an existing riffle upstream of the project area (at the top of the model reach) and the locations of redds from the year 2000 survey (x's in Figure 3B) illustrate these preferences. Note that no redds were located in the project area in 2000. However, the thirteen redds located on the riffle upstream of the bend show good agreement with GHSI predictions and reveal clustering at a pool exit slope (hypothesis 3A). Roughly 56% of the model reach was found to be non-spawning habitat. Of the 44% considered potential spawning habitat, only 2.8% was found to be of high quality, 7.5% was of medium quality, 23.1% was of low quality and 67.6% was of poor quality.

4.2.2 Comparison of three designs

The hydrodynamic model results at an 11.46 cumec discharge are depicted in Figure 5 for all three designs and can be directly compared with the pre project results in Figure 3A. Table 4 shows the results of hypothesis testing inferred from hydrodynamic, habitat suitability (GHSI) and sediment entrainment modelling results. Figure 6 shows a direct comparison of GHSI habitat suitability predictions for the three designs and can be compared directly with pre project results in Figure 3B. Figure 7A shows a summary evaluation of the respective percentages of GHSI spawning habitat and non-habitat throughout the entire modelled reach for the three designs and pre project. Much of modelled area received no gravel by design, since it is necessary to model a larger reach than just the project site. Figure 7B recasts the GHSI results in terms of three different metrics of gravel efficiency (based on volume of gravel used in Table 3).

Figure 8 synthesizes the hydrodynamic, habitat suitability and sediment entrainment model results into a single graph. The plots of Figure 8 depict both the depth and velocity distributions as small black points for the pre project (8A) and all three designs (8B–8D). Each point represents a velocity and depth prediction at one of over 50,000 nodes. Overlaid behind these distributions are the GHSI habitat suitability predictions (same shading scheme as

Table 4 Hypothesis testing results summarized.

Design hypothesis used (refer to Table 2)	Hypothesis tested?	Results of hypothesis testing or reason for not testing
Design Five		
1A – Optimize HSC habitat	Yes	Ranks 4th in terms of new habitat created (Figure 7A), 1st in terms of high quality habitat production efficiency (Figure 7B), and provides a large contiguous area of high quality spawning habitat.
2C – No scour during spawning	Yes	Sediment entrainment model showed no prediction of scour at spawning flows (Figure 8B).
3A – Pool exit slopes	No	No hyporheic exchange model. One pool exit slope provided based on empirical evidence of habitat utilization (e.g. Figure 3B).
Design Six		
1A – Optimize HSC habitat	Yes	Ranks 3rd in terms of new habitat created (Figure 7A), 2nd in terms of high quality habitat production efficiency (Figure 7B), and provides a large contiguous area of high quality spawning habitat.
2A – Pool-riffle maintenance	No	No data for specifying hydrodynamic and sediment entrainment model boundary conditions at high flows.
2B – Flow paths for maintenance	No	(see 2A above)
2C – No scour during spawning	Yes	Sediment entrainment model showed no prediction of scour at spawning flows (Figure 8C).
3A – Pool exit slopes	No	No hyporheic exchange model. One pool exit slope provided based on empirical evidence of habitat utilization (e.g. Figure 3B).
Design Twelve		
1A – Optimize HSC habitat	Yes	Ranks 1st in terms of new habitat created (Figure 7A), 4th in terms of high quality habitat production efficiency (Figure 7B), yet provides less contiguous or homogenized areas of high quality spawning habitat.
2A – Pool-riffle maintenance	No	(see 2A above)
2B – Flow paths for maintenance	No	(see 2A above)
2C – No scour during spawning	Yes	Sediment entrainment model showed no prediction of scour at spawning flows (Figure 8D).
3A – Pool exit slopes	No	No hyporheic exchange model. Three pool exit slopes provided based on empirical evidence of habitat utilization (e.g. Figure 3B).
4A – Structural refugia	Yes	All GHSI high and medium quality habitat found in close proximity to pools.
4B – Shear zone refugia	Yes	All GHSI high and medium quality habitat found in close proximity to shear zones at bank edges.
5A – Habitat Heterogeneity	Yes	More fluvial complexity apparent in hydrodynamic model predictions and GHSI habitat is more heterogeneous than previous designs.

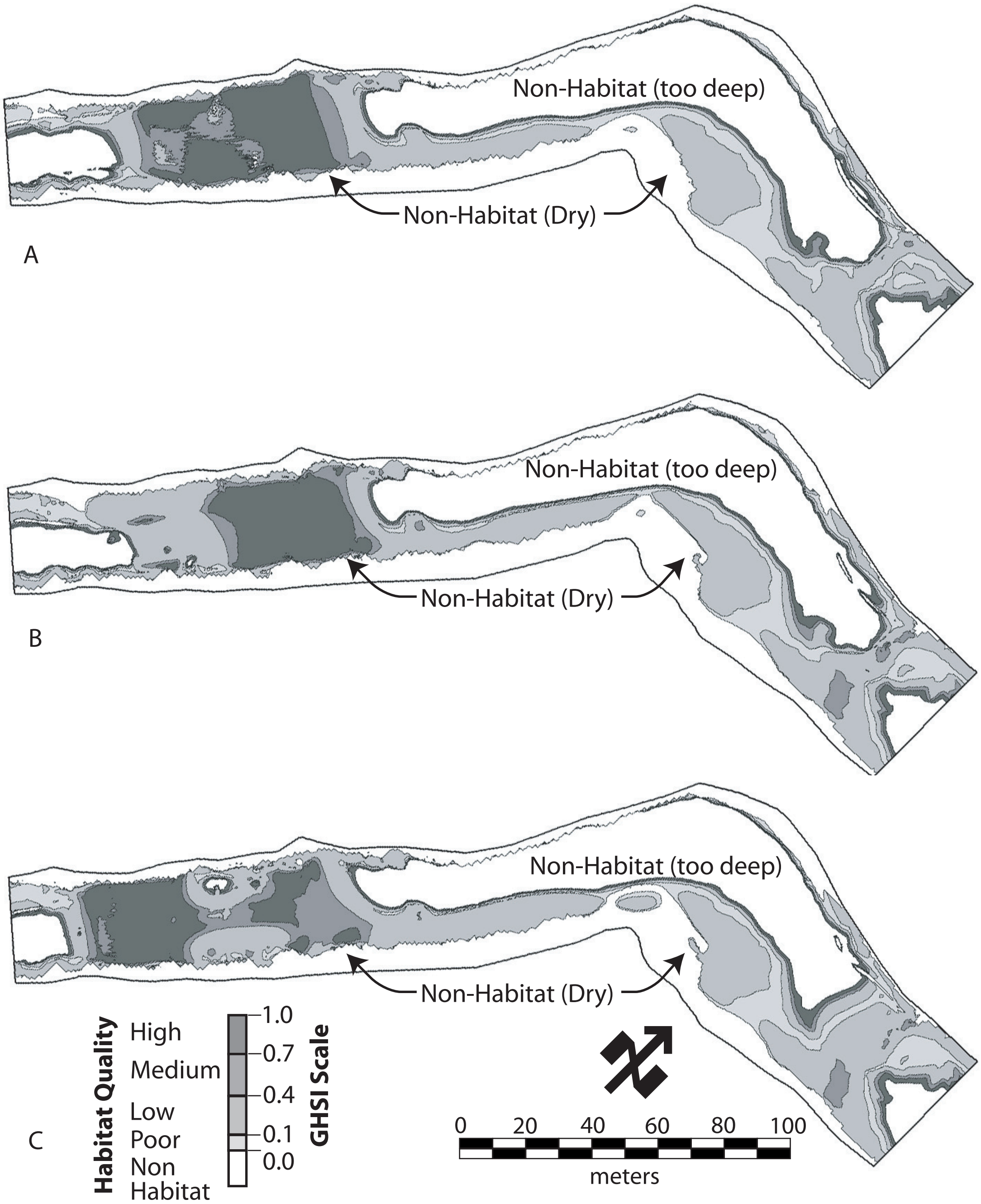

Figure 6 Design Phase Spawning Habitat Suitability Model (GHSI) results at 11.46 cumecs. (A) Design scenario 5 (flat riffle). (B) Design scenario 6 (constricted pools). (C) Design scenario 12 (final design – complex channel geometry).

Figure 6) and sediment entrainment thresholds for four different grain sizes. In general, the pre project distribution (8A) occupies the lower velocity region of the graph which corresponds to generally poorer spawning habitat. All of the plots show more variability in depth (spread horizontally) than velocity (compacted vertically). However, the three designs shift portions of these distributions to lower depth (i.e. gravel placement) higher velocity regions that correspond with higher quality spawning habitat. The darkened vertical streaks of the distributions found in the three designs represent areas graded to a consistent depth but that yield significant variations in velocity. Notice that the homogenized flat riffle of Design Five (8B) has only one vertical streak, whereas the more heterogeneous Design Twelve (8D) has four vertical streaks. Finally, as the distributions are all for an 11.46 cumecs spawning discharge, none of the distributions exceed any of the thresholds for sediment entrainment.

This paper focused on the utility of hypothesis testing in design development of SHIRA, and as such does not report the results of construction, post project appraisal or long-term monitoring. Incidentally, design scenario twelve was chosen as the final design because it showed the best mix of model-defined spawning habitat and conceptually identified important features (Table 4). Construction was carried out in September of 2001 based on this design and the first spawning activity was recorded later that year (see Wheaton, 2003 for full results). From 1991 to 2001 East Bay Municipal Utility District placed over 8500 m^3

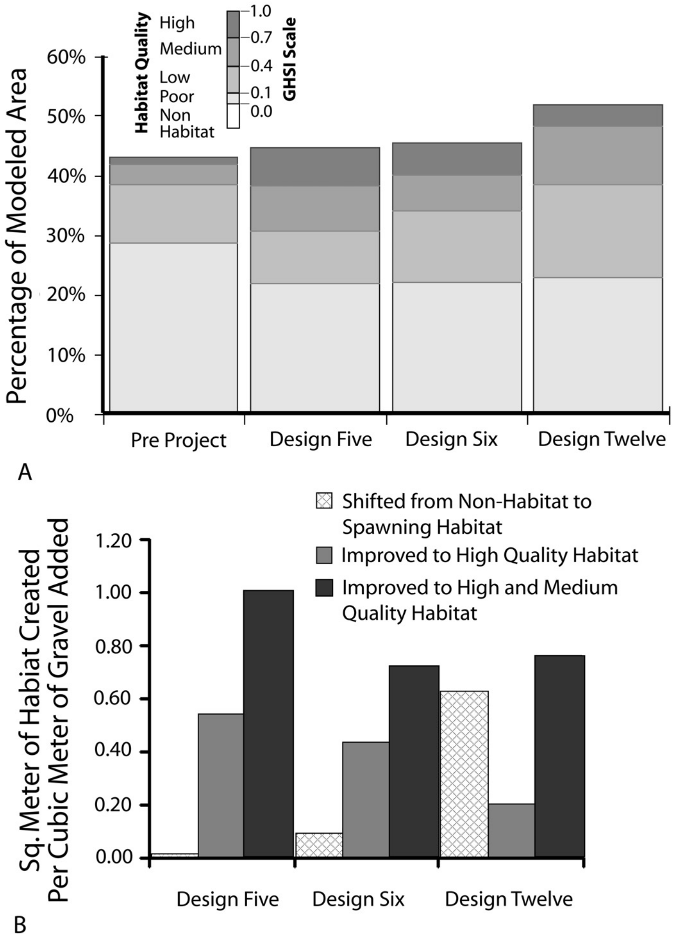

Figure 7 Design Phase Spawning Habitat Suitability Model comparisons. (A) In terms of percentage of total model domain. Notice that a large percentage (48 to 57%) of the model domain is not spawning habitat (i.e. pools comprise a large portion of the model reach) and that a significant portion (22 to 28%) remains as poor quality spawning habitat. Such areas provide important adult holding and refugia as well as juvenile rearing habitat. (B) In terms of three different gravel efficiency measures.

of gravel at 12 spawning habitat enhancement sites along the LMR and has a geomorphic and biological monitoring program encompassing all of these projects extending at least to 2009.

5 Discussion

5.1 Active versus passive … form-based or process-based?

In river restoration practice, designs are most often developed on the basis of form mimicry. In other words, designs are produced by imitating the attributes of either a present day or a historical 'natural' analogue. As form and process are intimately linked (Ritter *et al.*, 1995), form-based restoration sometimes works (Annable 1999). In many cases, 'form-based' templates digress towards a prescriptive specification of structures and treatments thought to improve a site (e.g. placement of groins, LWD, riffles without careful consideration). Although concepts drawn from scientific research may well enlighten a form-based design process, what often lacks is a systematic consideration of the interaction between geomorphic processes and ecologic functions (Annable, 1999). Wilcock (1997) suggests basing design goals on general physical principles instead of empirical relations between channel geometry and flow frequency. For example, what hydrologic and geomorphic processes are necessary to provide a specific ecological function? What form will produce those processes under various flow and sediment regimes? Given the water and sediment supply, how will those forms adjust? Such questions point towards a 'process-based' approach mindful of processes ranging from the grain scale to the catchment scale.

Most investigators of river restoration are comfortable claiming 'process-based' rehabilitation is better than 'form-based' rehabilitation (Wheaton *et al.*, 2004). In the case of 'passive approaches' to restoration (e.g. pulse flows, changes in basin landuse), using a 'process-based' approach makes intuitive sense. For example, providing flow releases from a reservoir to mimic a natural hydrograph and encourage mobilization and reorganization of sediments, may restore the processes that 'allow the river to do the work' (Stanford *et al.*, 1996; Trush *et al.*, 2000). Yet 'active approaches' are chosen in place of 'passive approaches' when river managers decide that a 'passive approach' will take an unacceptably long amount of time (Montgomery and Bolton, 2003). The FERC dam re-licensing agreement for Camanche Reservoir (FERC, 1998), which requires that EBMUD provide SHR on the LMR, is an example of an 'active approach' chosen because a 'passive approach' was deemed too slow.

'Active approaches', by definition, involve direct manipulation of channel structure or form (Montgomery and Bolton, 2003). But does this mean they are 'form-based' rehabilitation? In 'active' SHR channel design, you can not consider process without considering form, but it is quite easy and tempting to base "active" channel design on form without considering process. We argue that explicit development of design hypotheses, which articulate processes and functions expected from placed forms, allows one to undertake a 'process-based' active approach. Using accepted scientific hypotheses found in the peer reviewed literature to drive conceptual design development is not necessarily new or novel. With three design scenario examples, we demonstrated the incorporation of ecological function and geomorphic process concepts to produce conceptual designs and detailed finished grading plans.

5.2 Numerical models to test design hypothesis

Neither modelling nor conceptualization alone can constrain the potential uncertainties arising from design decision making. At a minimum, conceptual consideration of uncertainties in restoration design can yield more realistic expectations of restoration outcomes. Modelling can not definitively prove design hypotheses correct or incorrect because of inherent model uncertainties (Cardwell and Ellis, 1996). For example, design decisions based solely on GHSI defined velocity and depth criteria will neglect potentially important characteristics such as proximity to refugia (Quinn and Kwak, 2000). Conversely, employing a conceptual design (e.g. "build a riffle") without testing for desired hydraulic and flow conditions could easily lead to construction

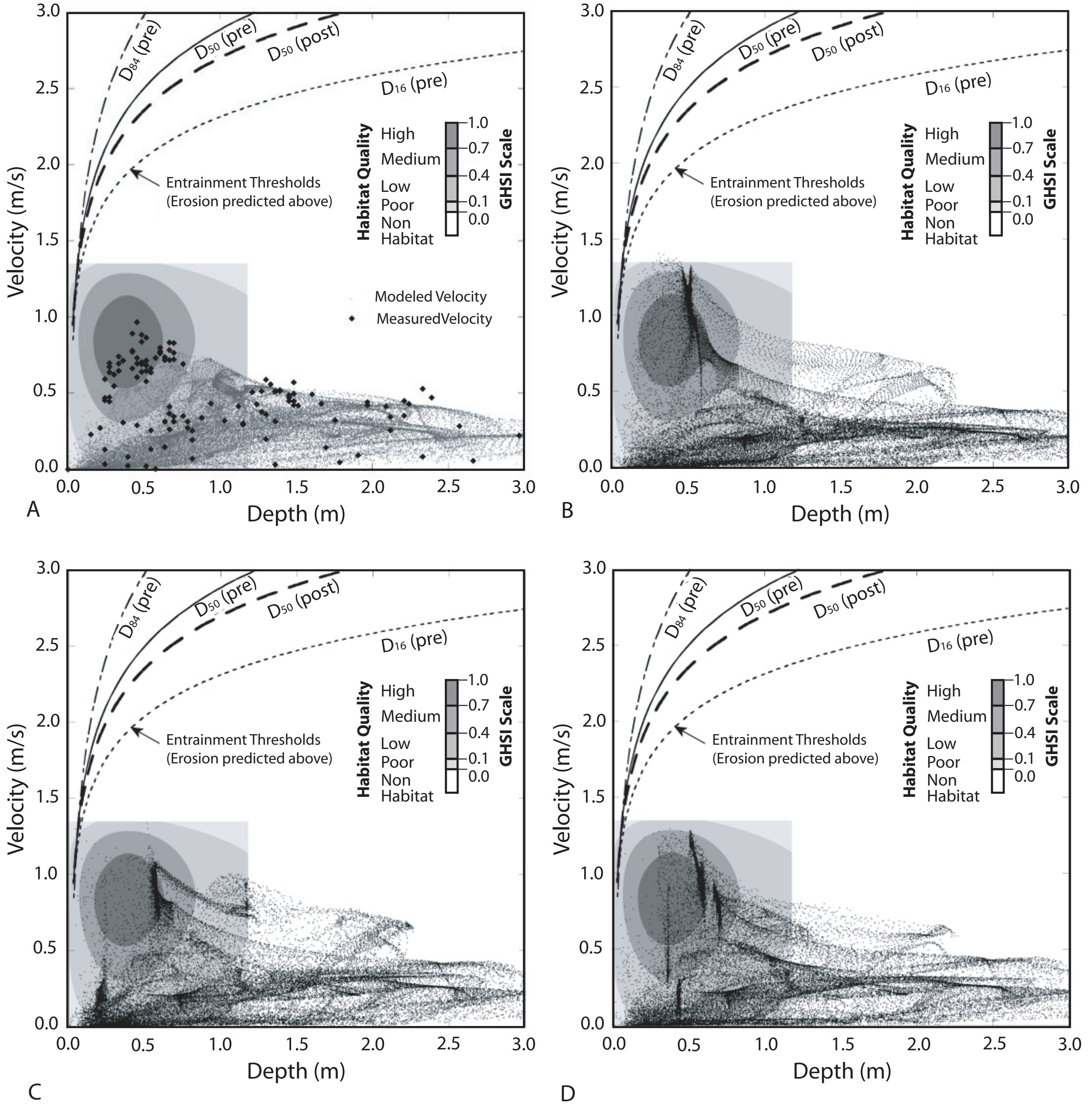

Figure 8 Design phase velocity vs. depth plots at 11.46 cumecs. (A) Pre project. (B) Design scenario 5 (flat riffle). (C) Design scenario 6 (constricted pools). (D) Design scenario 12 (complex channel geometry).

of a feature which does not provide the crucial characteristics. However, conceptual design development in conjunction with modelling can be viewed as a reasonable decision support system to make the restoration design process more transparent (Clark and Richards, 2002).

In this project, design hypotheses were tested systematically with off-the-shelf numerical models before project construction (Tables 2 and 3). We were forced to accept a higher degree of uncertainty in implementing a design scenario (design 12) based partially on untested design hypotheses. Proceeding on the best available information is a central tenant of adaptive management (Clark, 2002) and the precautionary principle (deFur and Kaszuba, 2002). Ideally, design scenarios would have been modelled over a range of flows to test stage dependence of conceptual design hypotheses. For example, habitat suitability should be analyzed over a range of spawning flows, whereas sediment entrainment should be analyzed at spawning flows and geomorphically relevant high flows. Of the three design hypotheses we were unable to test, two were due to inadequate model boundary conditions for high flows (hypotheses 2A and 2B). The lack of stage data from higher flows was due to a flat-lined low flow regime over a relatively dry study period, absence of a DEM for the floodplain, and inadequacy of artificially constructed rating curves (Wheaton, 2003). Partial data has subsequently been collected during a prescribed pulse flow and was used in design of a project built in 2003. A vegetated floodplain DEM is under production now.

Although ecological function inferences and hypotheses reported were largely limited to spawning and incubation life stages of a single species, it is easy to include conceptual ideas that benefit other life stages (e.g. rearing, out-migration), other organisms (e.g. steelhead and macroinvertebrates), food webs or energy budgets. Additional models beyond those used in this study, including those that model water quality, 1D sediment transport, fine sediment deposition, alevin survival, hyporheic exchange, habitat suitability for other fish species, lifestages and/or macroinvertebrates are available and could be incorporated into other applications of the SHIRA framework. Final designs can be chosen with the help of these analyses, but in balance with conceptual ideas that are not necessarily easy to analyze quantitatively.

5.3 Does hypothesis testing insure success?

As in any hypothesis testing, supportive results do not prove a project (even if constructed exactly as designed) will respond as hypothesized. In the earth sciences especially, Schumm (1991) suggests that convergence (when different processes produce similar effects) and divergence (when similar processes produce different effects) complicate drawing simple conclusions from hypothesis testing. For example, we relied on two hypotheses from the recent literature (hypotheses 2A and 2B) for the maintenance of pool riffle sequences. Neither has been proven and both are based on limited empirical evidence from a handful of sites (Booker *et al.*, 2001; Thompson *et al.*, 1999). However, a major advantage of using and testing transparent design hypotheses emerges during the post project appraisal and long term monitoring phases. Consider a design hypothesis that was accepted based on design testing and a project then constructed based on that evidence. Perhaps long term monitoring data then suggests that the scientific hypothesis was incomplete or false for a particular application. Such a scenario provides the perfect setting to use SHIRA's 'Scientific Exploration Mode' and the results then feed back through adaptive management (Walters, 1997). The conceptual models that drive the development of the design hypothesis and/or the numerical models used to test it may then be revised based on a more complete understanding of their limitations.

Alternatively, unforeseen problems not considered during design may arise. An example currently under consideration on the LMR has emerged from monitoring habitat utilization through redd surveys and substrate composition through time (Merz *et al.*, in press). In brief, habitat utilization and substrate quality are quite high in the first few years following rehabilitation. Yet under a homogenized low-flow regime, substrate quality drops due to establishment of aquatic vegetation and colmation of fines normally mobilized by higher flows (Brunke, 1999). Preliminarily, the corresponding ecologic response appears to be at least a temporary drop in habitat utilization. For this example, the conceptual model of spawning habitat (Figure 3 in Wheaton *et al.*, 2004) can be used to explain the observed declines in substrate quality and habitat utilization. One working hypothesis emerging from these observations could be that regular substrate mobilization is necessary to maintain habitat quality so long as it does not coincide with the incubation period (Montgomery *et al.*, 1999; Montgomery *et al.*, 1996). Although, sediment mobility models could be used to test what flows entrainment is likely to occur, better testing is likely to come out of experimental pulse flows and continued long term monitoring of substrate conditions and habitat utilization.

6 Conclusion

This paper presents partial results of hypothesis development and testing as used in the design phases of a spawning habitat bed enhancement project on the Lower Mokelumne River implemented using SHIRA. We developed multiple conceptual designs based on specific design hypotheses and used modelling analyses to test hypotheses where possible. Even though hypothesis testing does not insure project success, it provides mechanistic understanding and predictive capability to restoration practitioners; as well as experimental opportunities to test how underlying scientific concepts fare at a local site. This arguably constrains uncertainties in project outcomes and fosters more realistic expectations.

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