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Use of slope creation for rehabilitating incised, regulated, gravel bed rivers

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[1] Gravel-bedded channels often become incised and degraded below dams. Gravel can be added to the channel to rehabilitate hydrogeomorphic conditions, including those promoting salmon spawning. When implemented without increasing bed slope, gravel addition at downstream riffles back floods upstream riffles. A 2-year gravel augmentation project was done to test the efficacy of a new method for "slope creation." Riffle-to-riffle slope was raised from 0.002 to 0.008 by adding gravel to the most upstream riffle. When gravel was added to the next downstream riffle a year later, riffle-to-riffle slope decreased to the sought after 0.004. After the study, the area of high-quality Chinook salmon spawning habitat increased 471%. The number of redds observed went from 62 to 161 during the study despite a 50% decline of in-river spawners. This eliminates variations in migrant population size and hatchery take as alternative explanations. Slope creation can be a useful aid for rehabilitating regulated rivers.

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1. Introduction

[2] Dams alter a stream's hydrologic and geomorphic regimes leading to channel narrowing, incision, armoring, increased stability, and decreased slope [*Ligon et al.*, 1995; *Lisle and Church*, 2002; *Williams and Wolman*, 1984]. Physical habitat quality is the degree of suitability of local depth, velocity and river bed substrate size in a stream to support a particular ecological function. Together with other stressors, dam-related degradation of physical habitat quality for salmonid spawning is responsible for interdecadal declines in anadromous populations [*Moyle*, 1994; *Moyle and Randall*, 1998; *Nehlsen et al.*, 1991; *Yoshiyama et al.*, 2000].

[3] To mitigate the ecological impacts of river regulation, "gravel augmentation," defined as adding washed gravel and cobble to a stream, is widely performed in California. This is done to reduce bed armoring, improve river bed substrate quality, increase flow velocity, reduce water depth, increase habitat heterogeneity, and increase hyporheic exchange [*Department of Water Resources* (*DWR*), 2000, 2001; *Kondolf et al.*, 1996, 2001; *Kondolf and Minear*, 2004; *McBain et al.*, 2000; *Wheaton et al.*, 2004a]. Such projects often emphasize rehabilitation of spawning habitat for key salmon species whose status strongly indicates that of the aquatic ecosystem [*Merz et al.*, 2004; *Merz and Ochikubo Chan*, 2005].

[4] Because regulated streams are often incised, the benefits of in-channel gravel augmentation may be limited by the maximum riffle crest elevation achievable. As gravel is added at one degraded riffle the next upstream riffle may be flooded out and lose its functionality. This backwater effect may diminish the gains of a project or make conditions worse overall [*Sear and Newson*, 2004; *Wheaton et al.*, 2004a]. To address this problem, gravel can be added at the base of a dam to increase the local bed elevation, and then a steeper slope can be built down the reach (Figure 1). We term this artificial increase in riffle-to-riffle bed slope "slope creation." This is conjectured to improve hydrogeomorphic conditions, including those comprising the physical habitat quality preferred for native Chinook salmon (*Oncorhynchus tschawytscha*) spawning.

[5] Although river rehabilitation that enhances in-river fish production will aid spawning fish of both wild and hatchery origins, the consensus of the scientific [*Botsford and Brittnacher*, 1998; *Marchetti and Moyle*, 2001] and policy [*Flosi et al.*, 1995; U.S. Fish and Wildlife Service (*USFWS*), 2001; *DWR*, 1994; *Comprehensive Monitoring, Assessment and Research Program*, 1999] communities in California is that in-channel habitat restoration is a necessary component of species recovery. According to *Marchetti et al.* [2004, p. 1522], "the restoration of natural processes in aquatic systems can be expected to minimize the establishment of alien fishes while helping to maintain native fish populations." This wide consensus is reflected in the millions of dollars being spent at this time to rehabilitate most Central Valley streams. The more spawning that can be achieved in-stream, the more hatchery production may be reduced.

[6] This study investigated the short-term hydrodynamic, physical habitat, and sediment transport regime responses of a degraded river reach to slope creation. Channel manipulation, defined as recontouring a river's topography with the aid of washed coarse sediment brought in from a nearby quarry, was done to increase the riffle-to-riffle slope from 0.002 to 0.004 immediately below a dam. Although a single carefully monitored and modeled channel manipulation

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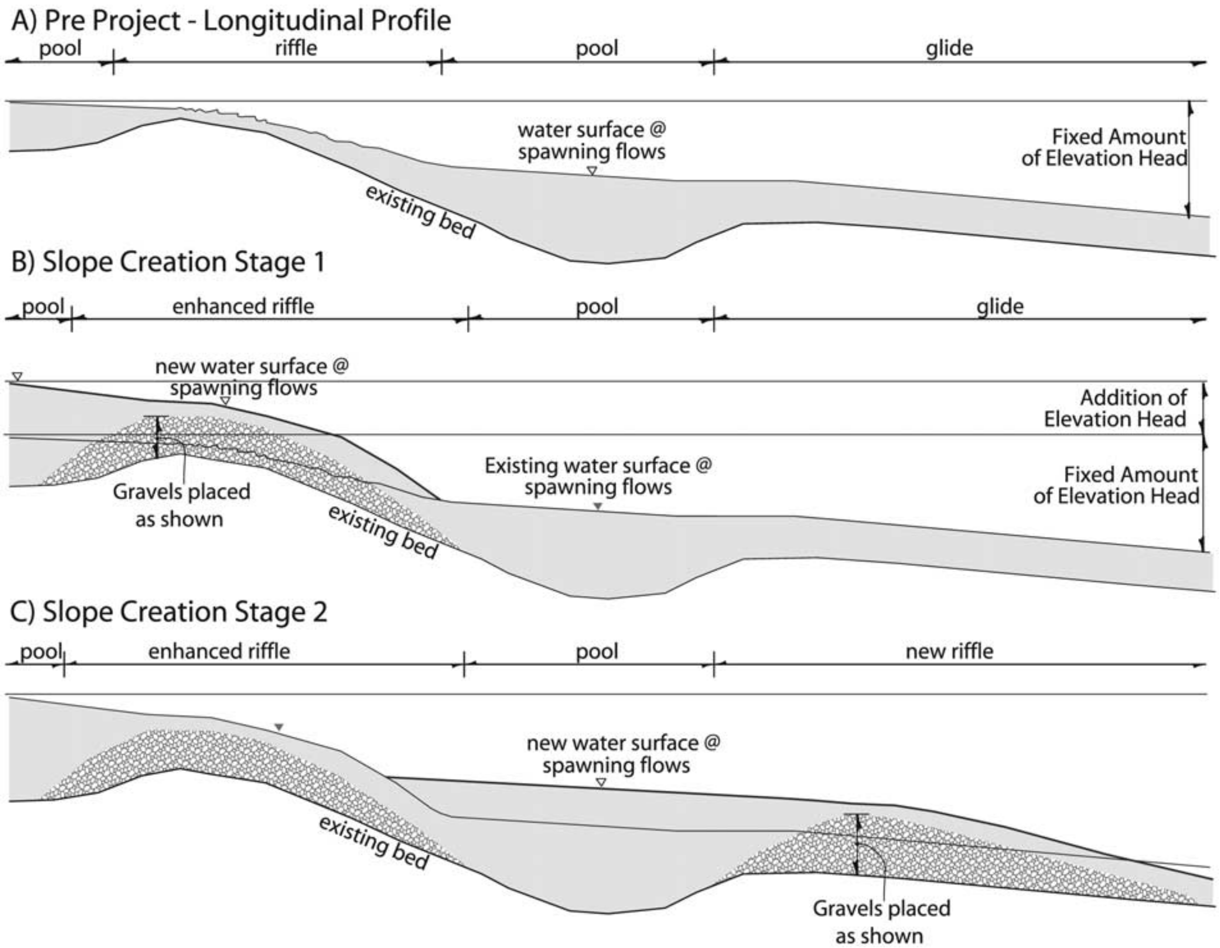

Figure 1. Longitudinal profile of a stream illustrating a two-stage addition of gravel for "slope creation," such as performed in this study. After the first stage, riffle-to-riffle slope is steeper than desired, but that is resolved in the second stage.

cannot fully corroborate the slope creation procedure, specific predictions (formally defined later) were evaluated to better understand the role of slope in regulated streams: (1) slope creation improves salmon spawning habitat quality, (2) spawning salmon prefer areas predicted in advance to be high-quality habitat, and (3) slope creation can provide a sediment transport regime that keeps high-quality habitat stable during spawning and incubation life stages. These predictions were tested by analyzing patterns of flow, scour potential, and spawning habitat quality at a site on the Mokelumne River in northern California prior to (preproject), after the first (midproject) and after the second (postproject) channel manipulation. Observed counts of up-migrating fish, hatchery take, and redds for each spawning season were also used to test predictions and assess the slope creation approach. The significance of this study is that specific predictions regarding hydrogeomorphic and fish response to slope creation were tested to reveal mechanisms underlying complex linkages among flow, morphology, and habitat regimes.

2. Slope Creation

[7] When examining geomorphic units at a subreach scale, slope and discharge control in-channel hydraulics and morphodynamic change [*Knighton*, 1998]. In regulated reaches where channel slope has declined slowly over decades, depth is increased, velocity is decreased, and substrates become clogged, yielding poor habitat quality (Figure 1a). Bed relief typically yielding riffles and pools decreases to produce a single long glide. Moreover, in most cases reinstatement of the historic (or a "naturalized") flow regime is politically infeasible. Thus raising slope back to its predam state can quickly undo decades of degradation. Not only might this improve physical habitat quality, but it is hypothesized to restore many key geomorphic processes that maintain high-quality habitat.

[8] To address this complex water resources issue a slope creation approach was developed, implemented, and assessed. Slope creation involves adding coarse sediment to the channel below a dam in a staged manner (Figures 1b and 1c) heavily relying on iterative design development, design evaluation, and adaptive monitoring over many years (Figure 2). It was conceived of in response to observations of detrimental backwater effects at 4 previous isolated gravel augmentation projects [*Wheaton et al.*, 2004a]. It was also added onto the previously reported SHIRA gravel augmentation framework [*Wheaton et al.*, 2004a, 2004b]. Because it is often unaffordable or infeasible to undo decades of degradation in a single, 1-year project, the slope

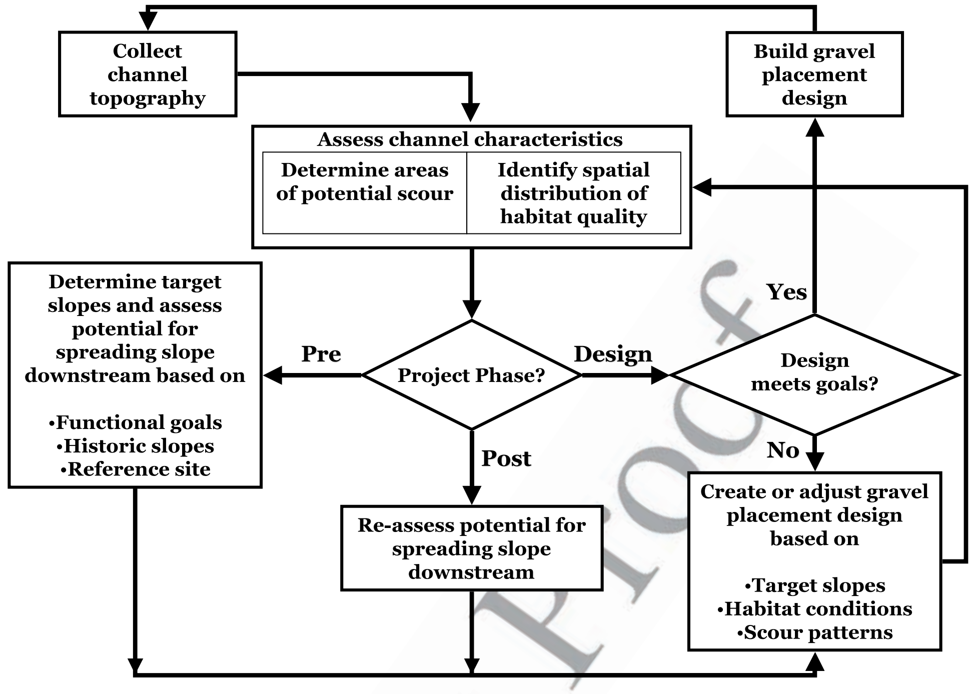

Figure 2. Conceptual model describing slope creation methodology used in this study for Chinook salmon spawning habitat rehabilitation. Before using tfhis, preliminary planning including goal setting should be performed, such as described by *Wheaton et al.* [2004a].

creation approach was designed to be implemented in small stages over many years.

[9] The ultimate length of reach whose longitudinal profile may be restored using this approach depends on the magnitude of slope change needed, the history of incision, and the total elevation gain permitted at the base of a dam in light of dam operations. *Williams and Wolman* [1984] reported examples of meters of channel incision as far as 60 km downstream of dams. Any depth of bed incised in the past may be recreated using slope creation. Restoring each increment of 0.1% slope to the uppermost 1-km reach below a dam requires 1 m of elevation gain. Because the critical region of habitat-limited fish spawning at the base of a dam may be <1 km in length, much steeper slopes may be achieved over shorter distances in this critical zone for the same amount of elevation gain. If a longer regulated reach was historically used for spawning, then restoring the bed elevation at the base of the dam to its predam elevation and distributing the predam slope downstream should yield the desired hydrogeomorphic conditions over the total length of the historical spawning reach.

[10] Several limitation of slope creation must be considered. The most important is that as long as a dam remains, constructed channel features and the rehabilitated slope must be maintained with periodic gravel injections below the dam to sustain short-term gains. Longer-term issues associated with this maintenance regime are not addressed in this study, but are covered in an investigation of longer-lived rehabilitation sites [*Merz et al.*, 2006]. In addition, slope creation only deals with structural enhancement; the minimum requirements for water quality parameters such as temperature and dissolved oxygen are assumed to be within an acceptable range [*Merz and Setka*, 2004] and are not addressed in this approach. Finally, the maximum slope that should be built is constrained by the unnatural and undesirable onset of bed material transport of the added gravels during spawning or early incubation, times when flow is normally low and abnormally high transport would destroy fish embryos.

3. Study Area

[11] The snow-fed Mokelumne River drains 1624 km^2 of the central Sierra Nevada (Figure 3). It has 16 major water impoundments, including Salt Springs (175 million m^3), Pardee (259 million m^3) and Camanche (531 million m^3) reservoirs. Prior to Camanche Dam, annual peak flows 1904–1963 exceeded 200 m^3/s for 21 of 57 years. Since 1964, releases are capped at 142 m^3/s. Predam, the annual hydrograph was snowmelt-dominated, with highest flow in May–June, well after peak precipitation. Postdam, snowmelt runoff is greatly reduced. Flood frequency analysis revealed a dramatic reduction in flow magnitude for all recurrence intervals [*Pasternack et al.*, 2004]. From May 2000 to the completion of this study, flow was near the 4.25 m^3/s minimum prescribed in relicensing [*Federal Energy Regulatory Commission* (*FERC*), 1998].

[12] The lower Mokelumne River has been impacted by direct anthropogenic intervention and slow, long-term morphologic degradation. Hydraulic mining, gravel extraction, dam construction, water diversion, altered flow regimes, deforestation, artificial bank protection, channelization and levee construction have resulted in depleted, degraded and otherwise, inaccessible gravel beds within the river. The first 750 m of channel below Camanche Dam was reengineered to accommodate sluicing, power generation, and hatchery operations. Also, reduced flood peaks and durations stabilized formerly active gravel deposits and permit-

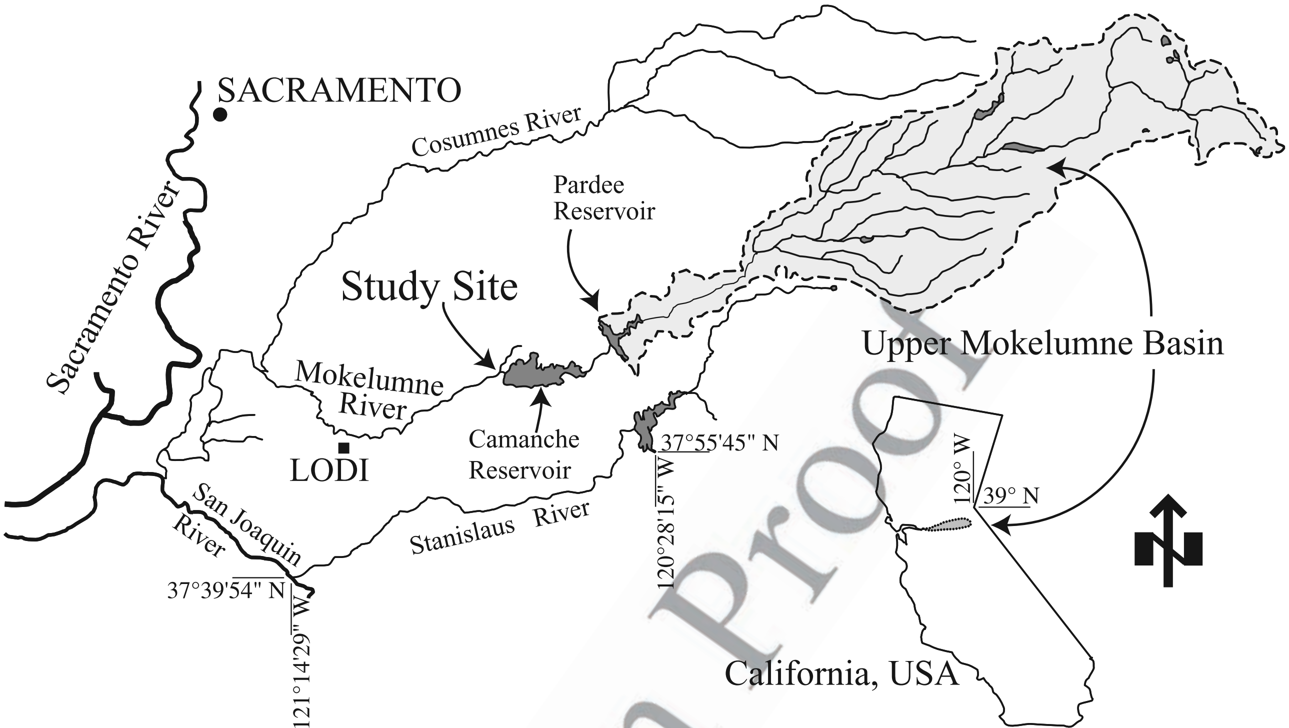

Figure 3. Map of the Mokelumne River basin showing locations of Camanche and Pardee Reservoirs. The study site was located immediately downstream of the tail pool at the base of Camanche Dam.

ted encroachment of vegetation into the channel [*FERC*, 1998]. Presently, the lower Mokelumne River between Camanche Dam and Highway I-5 has a low slope (0.0002–0.002 instead of 0.001–0.006), narrow width (19–43 m instead of 40–90 m), and poor salmonid spawning bed substrates (compacted coarse sediment partially overgrown with aquatic vegetation and organic-rich mud instead of clean, loose gravel and cobble).

[13] For the 19-year period before Camanche Reservoir was impounded, runs averaged 3,300 spawners, though spawning areas were estimated to accommodate ~15,000 adult Chinook salmon [*California Department of Fish and Game* (*CDFG*), 1959]. Presently, average annual lower Mokelumne River Chinook escapement averages 5500 [*Workman*, 2003]. Between 1994 and 2002, the percent of length of the upper 1-km of channel observed to have redds varied between 19 and 34%, with high densities focused at a few riffles. The Mokelumne River Fish Hatchery uses the majority of up-migrating fish to produce 3–9 million juvenile Chinook salmon. *USFWS* [1997] called for a fall run Chinook salmon population target of 9,300.

4. Methods

4.1. Channel Manipulation

[14] To evaluate slope creation, a channel manipulation was performed 2003–2004 on the lower Mokelumne River in the top 300-m reach downstream of Camanche Dam (Figure 3) located at the coordinates 38°13′3″ N, 121°1′43″ W. This is the farthest upstream migratory point accessible to spawners. The SHIRA framework [*Wheaton et al.*, 2004a] was used to study the baseline condition of the river, design and implement a 2–year slope creation project, evaluate the viability of iterative slope creation, and perform as-built, postspawning, and interannual assessments. A detailed map (~1 pt/m^2) of channel topography was surveyed. Surveying accuracy was assessed using control network checks and was found to average ±0.35 cm horizontal and ±0.39 cm vertical. Topographic data were imported into Autodesk Land Desktop 3 to create a digital elevation model for each year (Figure 4a).

[15] Several slope creation designs were developed, iteratively refined, and reduced to a final selection in spring 2003. Local expert experience and diverse concepts regarding Chinook salmon habitat requirements [*Healey*, 1991; *Geist and Dauble*, 1998], habitat heterogeneity [*Gibbins and Acornley*, 2000; *Brooks et al.*, 2004; *Wheaton et al.*, 2004c], pool-riffle maintenance [e.g., *Carling*, 1991; *MacWilliams et al.*, 2006], and effects of dams [*Grant et al.*, 2003] guided design development. Also, design elements related to other life stages were utilized, such as submerged wood and boulder clusters [*Abbe and Montgomery*, 1996; *Inoue and Nakano*, 1998; *Urabe and Nakano*, 1998; *Merz*, 2001] as well as hyporheic flow [*Geist and Dauble*, 1998; *Baxter and Hauer*, 2000; *Gayraud et al.*, 2002]. These have been shown to correlate with higher redd and fish densities [*Zalewski et al.*, 1998; *Horan et al.*, 2000; *Gibson*, 2002; *Brooks et al.*, 2004]. Shaded, deep, cool pools were enhanced to provide adult holding habitat [*Nielsen and Lisle*, 1994], while slow and backwater areas were incorporated to provide rearing and juvenile habitat [*Bozek and Rahel*, 1991]. Spawning habitat quality and scour patterns predicted by 2-D model simulations aided design evaluation and improvement.

[16] The use of these design elements would appear to diminish the ability to attribute study outcomes solely to slope creation. However, one of the riffles manipulated in

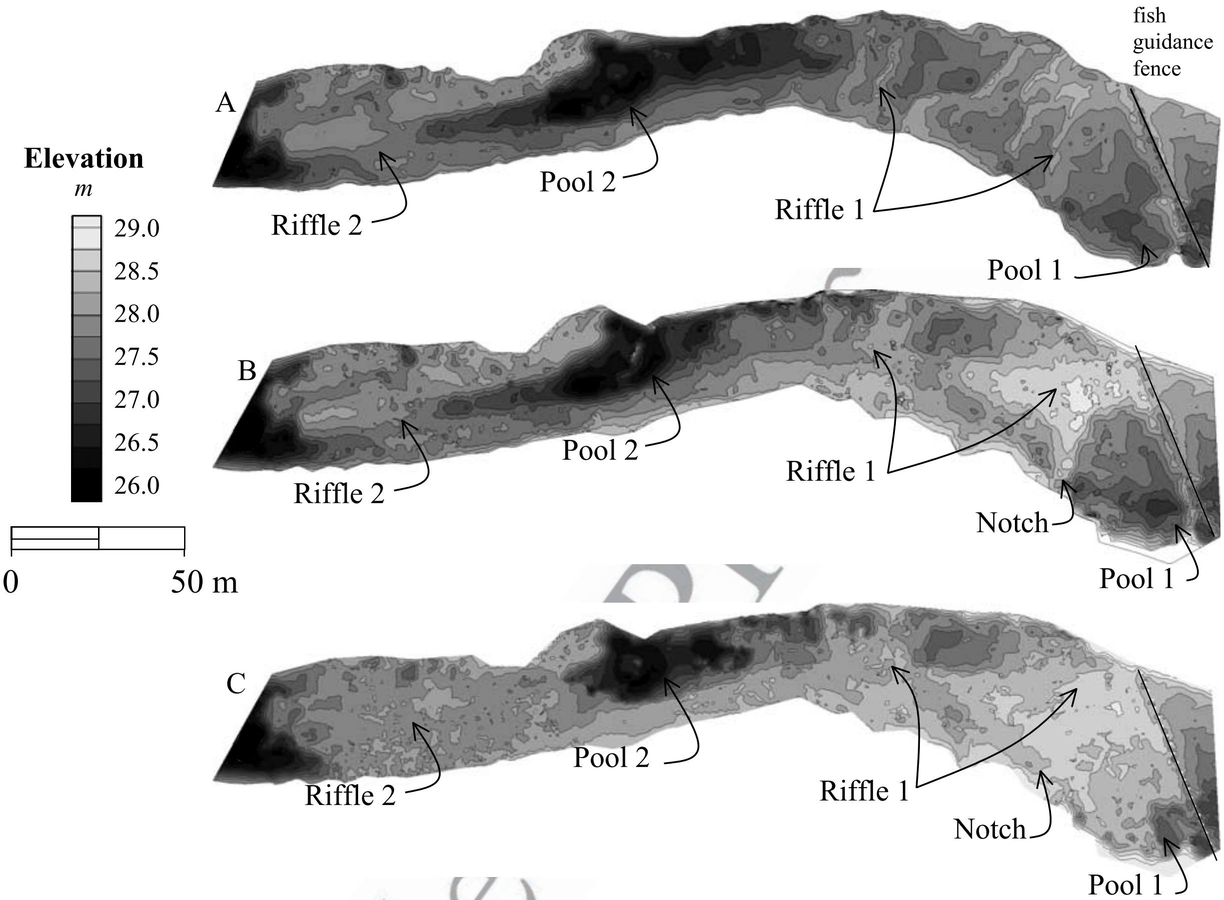

Figure 4. Digital elevation models of the study site during (a) premanipulation, (b) midmanipulation, and (c) postmanipulation stages. Darker shading equals lower elevation.

this study (riffle 2) was previously enhanced in 1999 with all of the above features ad hoc without considering slope creation, SHIRA, or 2-D modeling [*Pasternack et al.*, 2004]. No spawners utilized the site in the first season after enhancement in 1999. The hatchery took 60% of the run that year. Between 2000–2003 its habitat quality degraded sharply, as detailed later [*Merz et al.*, 2006]. Thus use of slope creation, SHIRA, and 2-D modeling at this site provides a direct test of riffle rehabilitation with versus without slope creation at the same spawning discharge of ~8.5 m^3/s.

[17] The final design for 2003 incorporated a 0.5-m fill depth at the riffle crest, a large riffle, a peripheral chute, and a small secondary riffle crest (Figure 4b). Fill depth was limited by the maximum sustainable increase in slope and riffle entrance/exit slopes of 0.005–0.01. The length of the project was constrained by the target slope and the 3217 metric tons of coarse sediment available. The design was constructed in summer 2003.

[18] On the basis of midproject observations and modeling, the design goal for the second phase of slope creation was to raise the elevation of riffle 2, thereby creating new high-quality habitat there and imposing a backwater effect on riffle 1 (Figure 1c). In this case a backwater effect would be beneficial, because the first phase of slope creation maximized the local elevation gain to sustain several years of downstream slope redistribution. This came at the cost of excessively high local velocities and shallow depths (Figure 1b), partially mitigated against in the first year using the peripheral chute. The second-phase, final design raised riffle 2 by 0.5 m resulting in a broad, relatively flat riffle. It also called for the crest of riffle 1 to be lowered by 0.2 m and the peripheral chute to be partially filled in (Figure 4c). In summer 2004, 3,012 metric tons of coarse sediment were used to construct the design.

4.2. The 2-D Mokelumne Model

[19] Finite Element Surface Water Modeling System 3.0 (FESWMS) was used to simulate and compare depth-averaged 2-D flow hydrodynamics, spawning habitat quality, and sediment transport regime. FESWMS solves the vertically integrated conservation of momentum and mass equations using a finite element method to acquire local water depth and depth-averaged 2-D velocity vectors at each node in a computational mesh [*Froehlich*, 1989]. Application of FESWMS to gravel bed rivers has been extensively validated on the Lower Mokelumne River using observed velocity and depth at 35 cross sections, indicating good predictions for the gravel bed and poor predictions around large woody debris or complex banks [*Pasternack et al.*, 2004; *Wheaton et al.*, 2004b; *Pasternack et al.*, 2006]. *Pasternack et al.* [2006] reported details regarding FESWMS model uncertainty. They found that FESWMS could predict local shear stress over gravel bed riffles as accurately as 5 common field estimation methods.

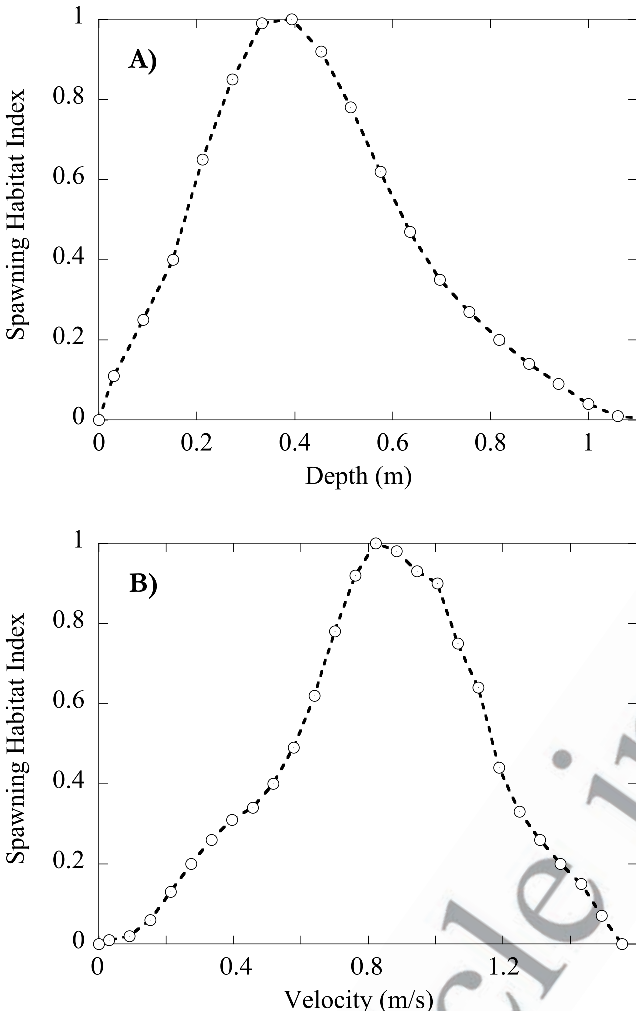

Figure 5. Habitat suitability curves developed for the Mokelumne River by *CDFG* [1991]. Curves predict habitat quality based on flow depth, velocity, and substrate type.

MacWilliams et al. [2006] compared FESWMS with 1D and 3D models of gravel bed river hydrodynamic and found that the 2-D model was capable of simulating key stage-dependent processes responsible for riffle-pool maintenance. FESWMS is a long-established model best viewed as a conceptual guide of likely outcomes, rather than literal truth. In this study, validation is taken further by directly testing habitat quality model predictions against salmon-spawning observations.

[20] FESWMS was implemented using Surface Water Modeling System v. 8.1 graphical user interface (EMS-I, South Jordan, UT). Discharge and downstream boundary water surface elevation were obtained from flow records and by surveying the water surface at the desired flow conditions, respectively. A constant Manning's n of 0.043 was estimated for placed gravel features [*Pasternack et al.*, 2004]. A constant eddy viscosity of 0.028 m^2/s was used. Digital elevation model data were interpolated to the mesh with a typical internodal spacing of 1.2 m.

[21] Local habitat suitability curves for depth and velocity based on observations in the lower Mokelumne River [*CDFG*, 1991; *Pasternack et al.*, 2004] were used to make habitat quality predictions (Figure 5). Since placed gravel was specified to meet spawning requirements, grain size suitability curves were not needed. During extended years of below average flow, aquatic vegetation is observed in low-gradient geomorphic units on the lower Mokelumne River [*Smith et al.*, 2004]. Minimal vegetation existed on steeper riffles that were rehabilitated in 2000 and 2002. Lacking direct literature on the habitat suitability of vegetated gravels, this uncertainty was addressed by recognizing that salmonids generally do not spawn in reaches covered in aquatic vegetation, because it slows velocities, stabilizes substrates, and accumulates sand, mud, and organic muck [*Sand-Jensen*, 1998; *Madsen et al.*, 2001]. On the lower Mokelumne, there is no significant source of sand or mud in the study area, but organic fines grow and accumulate in situ as long as flow remains very low and steady. Thus, where aquatic vegetation was present, it was considered a complete deterrent to spawning and spawning habitat quality was assigned a value of 0. Where aquatic vegetation was not present, a global habitat suitability index (GHSI) for spawning was calculated at each mesh node as the geometric mean of the depth and velocity suitability. GHSI values of 0, 0–0.1, 0.1–0.4,0.4–0.7, and 0.7–1.0 were interpreted as predicting nonhabitat, very poor habitat, low-quality habitat, medium-quality habitat, and high-quality habitat, respectively [*Leclerc et al.*, 1995]. This classification was independently validated using observed fish utilization data. GHSI does not directly account for the value of aggregate habitat heterogeneity features or hyporheic water quality [*Geist*, 2000].

[22] To evaluate coarse sediment entrainment risk at the flow during which spawning and embryo incubation occur, Shields stress was calculated at each node in the model as described in *Pasternack et al.* [2006]. Wolman pebble counts [*Kondolf and Li*, 1992] were completed preproject, midproject, and postproject for Shields stress calculations. Shields stress values were categorized based on transport regimes defined by *Lisle et al.* [2000] where values of $\tau^* < 0.01$ correspond to no transport, $0.01 < \tau^* < 0.03$ correspond to intermittent entrainment, $0.03 < \tau^* < 0.06$ corresponds to "partial transport," and $\tau^* > 0.06$ corresponds to full transport.

4.3. Model Validation

[23] To validate 2-D depth and velocity predictions, cross-sectional hydraulic data were collected along multiple transects using the methods of *Pasternack et al.* [2004, 2006] before and after each channel manipulation. Field observations along each cross section were fit with a curve using the locally weighted Least Squared error method to reduce measurement noise. A 2-D model simulation was performed for the corresponding flows that were observed. Modeled and measured curves were compared for cross-channel patterns.

[24] To assess fish utilization of manipulated riffles and validate spawning habitat quality predictions, redd surveys were conducted by wading and canoeing. Redd locations were recorded using a Trimble Pro XR Global Positioning System and a laser range finder (Atlanta Advantage) [*Merz and Setka*, 2004] resulting in a horizontal accuracy of ±1 m. A 2-D model simulation was performed for the corresponding average autumn spawning flows that occurred preproject, midproject, and postproject (6.0, 9.5, and 6.0 m^3/s). The predicted GHSI for each redd location was extracted

from the 2-D model. Because of the hatchery take, 73–91% of up-migrating Chinook salmon during this study, density dependency in spawning location selection was significantly reduced. Minimal redd superposition was observed, so redd location is a good indicator of physical habitat preference.

5. Prediction Testing

[25] A prediction is a statement that is testable by observation. Predictions about specific outcomes of the channel manipulation in the study area were developed to test key issues, such as whether spawning improved and whether slope creation was responsible for it. Prediction testing involved comparing field observations against model predictions for each project stage and cross comparing 2-D model simulations among the different stages. For 2-D model cross comparison, it was necessary to simulate a common flow, which was chosen as 11.33 m^3/s, a typical spawning discharge for the lower Mokelumne River.

5.1. Prediction 1: Habitat Quality Will Improve

[26] To determine whether the quantity of high-quality and medium-quality habitat increased the spatial distribution of predicted habitat quality was compared for the preproject, midproject, and postproject scenarios at 11.33 m^3/s. Arc GIS 9 was used to determine and compare the predicted area of each type of habitat quality. An increase in habitat quality would corroborate the prediction and support the use of slope creation to improve spawning habitat quality. Comparison of spawning at riffle 2 in 1999 and 2004 provided a direct test of the efficacy of slope creation relative to other rehabilitation measures.

5.2. Prediction 2: Spawners Will Preferentially Utilize High-Quality Habitat

[27] To determine whether predicted high-quality habitat was preferentially used by spawning fall run Chinook salmon, preproject, midproject, and postproject, GHSI predictions were validated against redd observations. Percent habitat availability (%A_i) and percent utilization (%U_i) for each habitat quality class (*i*) defined earlier were solved for premanipulation, midmanipulation, and postmanipulation scenarios using

$$\%A_i = 100 \times \frac{\text{bed area}_i}{\text{total area}} \quad (1)$$

$$\%U_i = 100 \times \frac{\#\ \text{redds}_i}{\text{total}\ \#\ \text{redds}}. \quad (2)$$

To determine whether salmon preferred certain predicted habitat types as opposed to randomly selecting available habitat, habitat quality preference was calculated using Strauss' linear index (L) as described in the work of *Lechowicz* [1982]. L is calculated by subtracting $\%U_i$ from $\%A_i$. This index yields values that range from −1 (avoidance) to 1 (preference). A value of 0 indicates a random selection. As an additional test, an analysis of variance (ANOVA) was used to compare the spawning preference index to the habitat quality index. These analyses test whether spawners prefer model-predicted high-quality habitat. If the tests corroborate the prediction, then that also validates the conclusions from the first prediction, showing not only that slope creation improved 2-D model predicted habitat quality, but also that it improved it in reality.

[28] An analysis was performed to account for fluctuations in the number of fish returning from the ocean to the lower Mokelumne River as well as fluctuations in hatchery take on variations in observed numbers of redds. The number of spawners was counted using a video recorder that images up-migrating fish at Woodbridge Dam (located downstream of any spawning habitat). A few fish may sneak past the video system or be missed in the count due to human error [*Workman*, 2006]. The number of fish taken into the hatchery was obtained from a manual hatchery count. These data were used to calculate the actual number of spawners in the river relative to the number of redds observed in the study area. If the number of in-river spawners decreased during each stage of slope creation, but the number of observed redds increased in the study area, then that would eliminate variation in migrant population size and hatchery take as possible explanations for increases in redds.

[29] To assess the utilization of the rehabilitated sites relative to the utilization of the much larger area of non-rehabilitated sites, the redds observed at the study site each year was divided by the total number of redds observed throughout the river. An increase in fraction of redds at the study site relative to the rest of the river over the course of the study would demonstrate that the fish were preferentially selecting the rehabilitated sites.

5.3. Prediction 3: Riffles Will Not Scour During Spawning Flows

[30] To determine whether detrimental scour at spawning flows is inevitable when implementing slope creation, model-predicted Shields stresses were compared preproject, midproject, and postproject at 11.33 m^3/s. Evidence of full transport in the midproject and postproject would refute the prediction and indicate the inevitability of scour when implementing a staged slope creation project, regardless of the lack of a flood regime. Modeling higher flows would be useful for examining sustainability of observed improvements and maintenance mechanisms but necessary floodplain topography and roughness data as well as a stage-discharge rating curve for >22.65 m^3/s does not exist. Bed scour at high flows is both expected and ideal for gravel maintenance.

6. Results

[31] To aid the presentation and evaluation of study results, the 2-D model predictions for preproject, midproject, and postproject are first described. Hydrodynamic validation at the 9 new cross sections measured in 2003 and 2004 showed similar results to previous validations reported for the lower Mokelumne River [*Pasternack et al.*, 2004; *Wheaton et al.*, 2004b; *Pasternack et al.*, 2006]. Depth was predicted with high accuracy (Figures 6a and 6b), except near submerged wood (Figure 6c). Lateral velocity patterns were mimicked by the model, but showed smoothing (Figures 6d–6f).

[32] Prior to construction, the study reach consisted of three deep pools alternating with two riffles degraded into glides (Figures 4a and 7a). The reach was relatively homogeneous and lacking hydraulic variability (Figure 8a). Riffle 1

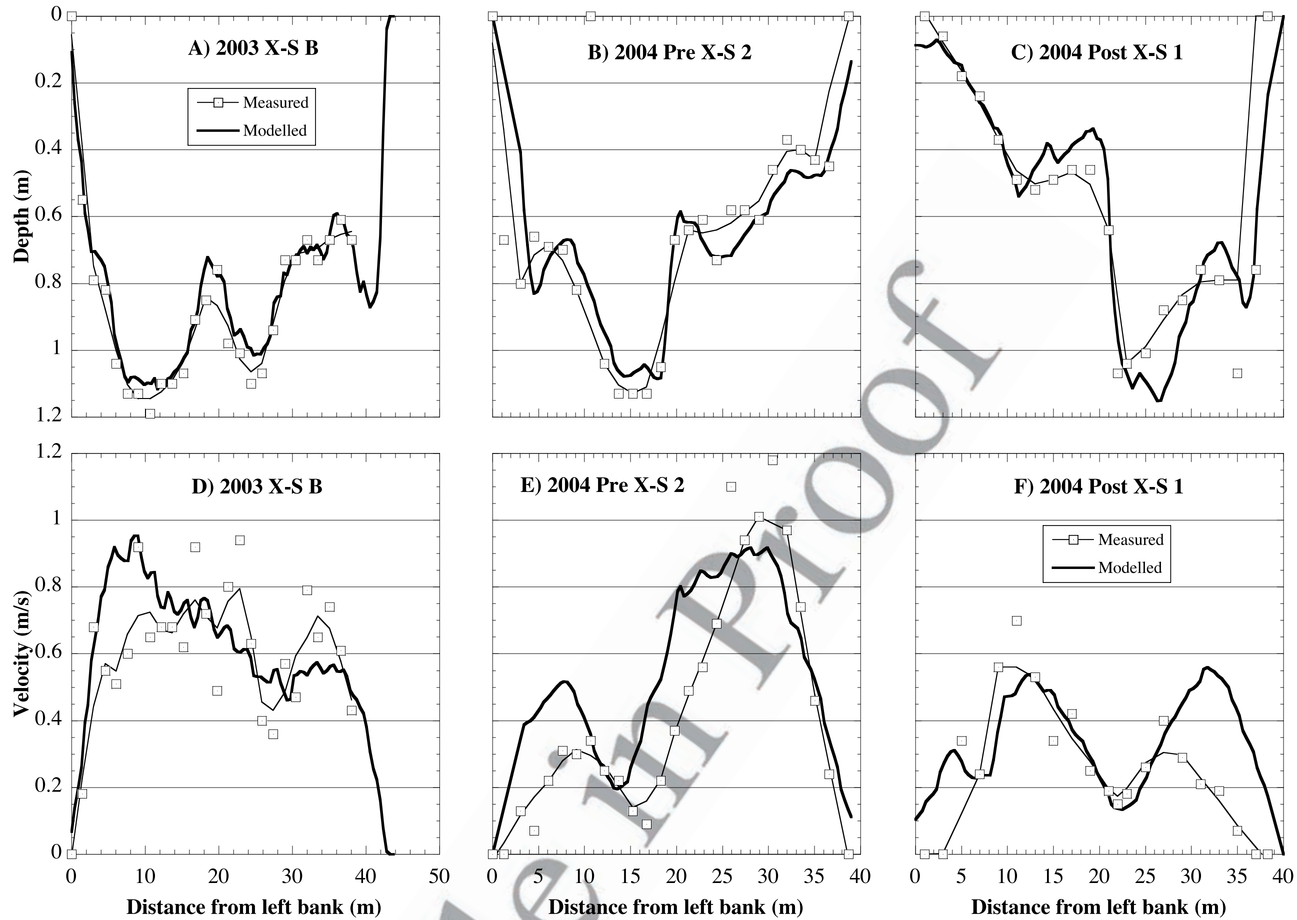

Figure 6. Comparisons of observed versus predicted depths and velocities at a representative cross section for the (a, d) preproject, (b, e) midproject, and (c, f) postproject stages. Field observations were fit with a curve using the locally weighted least squares error method to reduce measurement noise.

consisted of low-relief transverse ridges formed by the tail spills of redds constructed in previous spawning seasons. Velocity was locally accelerated over the ridges. The remaining areas consisted of several deep, low-velocity pools and a long uniform glide at "riffle" 2. Mean depth and velocity for each riffle and the study area are given in Table 1.

[33] After the first manipulation, riffle-to-riffle slope was increased from 0.0022 in 2002 to 0.0084 in 2003 (Figures 4b and 7b). Riffle entrance and exit slopes ranged from 0.002 to 0.060 with the steepest slopes over the study area terminus. According to the midproject longitudinal profile, after the first stage of gravel augmentation, water backed up into pool 1 with the water surface rising approximately 0.5 m, equivalent to the increase in riffle 1 crest elevation. Flow accelerated through the chute, completely bypassing the crest of riffle 1, making flow very shallow on the crest of riffle 1 (Figure 8b). Flow was sent obliquely across the riffle over the secondary crest of riffle 1 with accelerating velocities at the project's terminus. Mean depth on riffle 1 was reduced and mean velocity was increased and more variable (Table 1). No changes were made to riffle 2.

[34] During the second manipulation the increase in riffle 2 elevation created a backwater effect, raising depths upstream on riffle 1 and resulting in a final slope of 0.0039 (Figures 4c and 7c). The crest elevation of riffle 1 was slightly lowered and a backwater condition was imposed by the increase in elevation on riffle 2. This eliminated overly fast and excessively shallow areas for spawning on riffle 1 that resulted from the first phase (Figure 8c). The post-project condition on riffle 1 maintained the same mean depth, increased the mean velocity and reduced the range of both. On riffle 2 depths were reduced and velocities increased (Table 1).

6.1. Prediction 1: Habitat Quality Will Improve

[35] Prior to construction the high-quality habitat was arranged in transverse bars along the ridges in riffle 1. There was a large area unsuitable for spawning in pools 1 and 2 (Figure 9a). High- and medium-quality habitat made up 20% of the study reach. Very little spawning habitat was predicted on riffle 2 as it was covered with aquatic vegetation.

[36] Following the first manipulation, high-quality habitat was rearranged into longitudinal patches that bordered the chute and the riffle crest (Figure 9b). The total area of nonhabitat for spawning was increased by 1517 m^2 (Table 2). The increase in the crest of riffle 1 induced a backwater effect in pool 1 converting very poor and low quality habitat into nonhabitat for spawning. The high velocities and shallow depths on riffle 1 caused a 149 m^2 loss in medium quality habitat providing less than ideal spawning habitat. Regardless, there was a 109 m^2 increase in high-quality

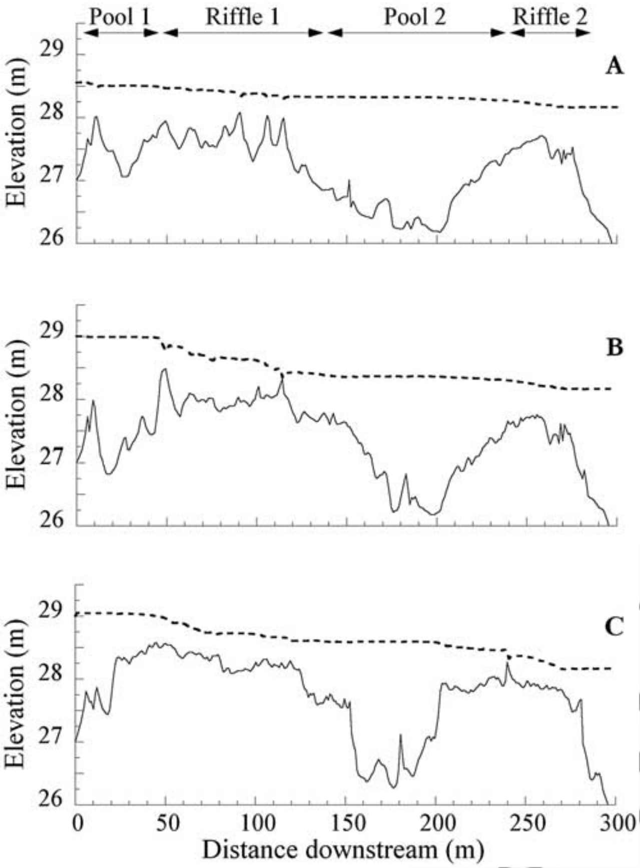

Figure 7. Longitudinal profiles showing change in thalweg elevation (solid line) and water surface elevation (dashed line) for the (a) premanipulation, (b) midmanipulation, and (c) postmanipulation stages of the study.

habitat mostly bordering the crest of riffle 1 and the chute. Much of the altered channel was on the verge of being too steep and shallow for spawning. The changes in the upstream conditions had no significant effect on habitat quality for unmodified riffle 2.

[37] After the second manipulation, habitat quality was significantly improved across riffle 1, in the chute, and across riffle 2 (Figure 9c). The nonhabitat area was reduced by 3870 m^2 as large portions of the deeper areas were filled in with gravel (Table 2). There was a dramatic increase (876 m^2) in medium-quality and high-quality habitat (2540 m^2) relative to the initial condition. The combined two stages of slope creation resulted in a 471% increase in high-quality habitat. This predicted increase in habitat quality corroborates prediction 1, if the model's predictions are accurate, as assessed next.

6.2. Prediction 2: Spawners Will Preferentially Utilize High-Quality Habitat

[38] The numbers of fish migrating upstream past Woodbridge Dam preproject, midproject, and postproject were 10,752, 10,266, and 11,416, respectively. Hatchery take during those three seasons was 7929 (74%), 8117 (79%), and 10,355 (91%), respectively. Thus the number of spawners actually in the river declined from 2833 preproject to 2149 midproject, and then plummeted down to 1061 postproject.

[39] The number of redds observed preproject, midproject, and postproject were 62, 79, and 161, respectively. Thus the number of redds in the manipulated study area increased steadily, even while in-river spawners declined. From 2003 to 2004, the number of spawners dropped by 51%, but the number of redds in the study area increased by 104%. These numbers eliminate variation in migrant population size and hatchery take as possible explanations for observed increases in numbers of redds in the study area.

[40] The redds observed in the study area during the three seasons equaled 7, 11, and 20% of all redds recorded river-wide, chronologically. These relative increases occurred despite the fact that the study area made up only ~2% of lower Mokelumne River's total spawning reach, fish could freely move in and out of the study area, the number of total spawners in the river decreased sharply in 2004, and the area should already have been highly preferred prior to rehabilitation, because it is located at the upstream limit of fish migration. Thus not only were there more fish spawning in the study area with each successive manipulation, but the percent of the total spawners river-wide choosing this reach increased as well.

[41] Analysis of the observed spatial distribution of redds validated the habitat quality predictive capability of the 2-D model. Using ANOVA, there was a highly significant positive relationship between GHSI and the actual spawning preference index ($p = 0.0004$). This statically validated model predictions. When utilization was adjusted by availability (equations (1) and (2)), high-quality habitat was strongly preferred all years, while no- and low-quality habitats were avoided (Figure 10), providing an independent validation of model predictions. Thus both predictions 1 and 2 were corroborated in the study.

[42] Even though predicted high-quality habitat was highly preferred and non habitat avoided in all years, fish preferences shifted noticeably throughout the study as the sites were manipulated (Figure 10). Over the study, the percents of redds constructed in model-predicted medium- and high-quality habitat at spawning flows trended upward from 48% preproject to 58% midproject to 88% postproject. Very poor quality habitat and nonhabitat were avoided during all stages, even though the number of spawners increased appreciably after the final stage, again indicating a lack of density dependence.

6.3. Prediction 3: Riffles Will Not Scour During Spawning Flows

[43] Prior to manipulation intermittent entrainment of the median bed surface particle size, D_{50} (40.8 mm), was predicted along the crest of the transverse bars on riffle 1 at the spawning flow (Figure 11a). Following the first manipulation intermittent entrainment and partial transport was predicted for the D_{50} (50.4 m) in the chute, across the crest of riffle 1 and at the tail spill at the end of riffle 1 (Figure 11b). This indicates that the elevation gain is close to the maximum possible without initiating significant scour during spawning and incubation periods. There was no change in grain size with the second manipulation, as the same size and range of gravel was added to the site (Table 3). After the second manipulation areas of partial transport at the spawning flow were almost completely eliminated, with a few small areas of intermittent entrainment predicted over the crest of riffle 1 and along the end of

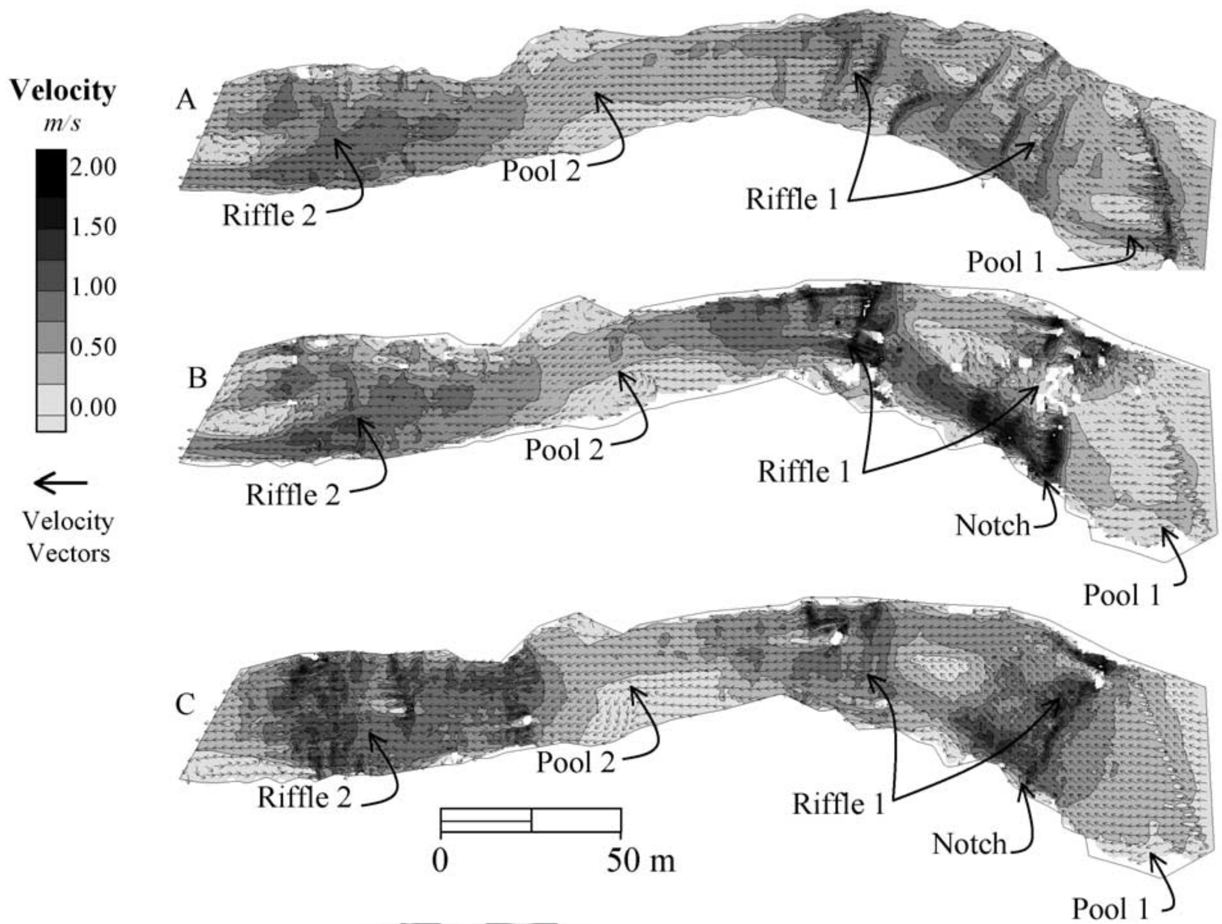

Figure 8. Two-dimensional model velocity predictions at 11.33 m^3/s for the (a) premanipulation, (b) midmanipulation, and (c) postmanipulation stages. Arrows indicate velocity direction, while darker shading equals higher velocity.

riffle 2 (Figure 11c). This indicates that raising riffle 2 stabilized riffle 1, enabling future rounds of slope creation once this initial effort is extended as far downstream as possible.

7. Discussion

7.1. Ecological Assessment

[44] Widespread changes in channel hydrodynamics and spawner utilization occurred during a 2-year controlled manipulation of a regulated, gravel bed river channel. Hydrodynamic and spawning habitat preference predictions made with a 2-D model were accurate enough to be statistically validated using observed redd counts. Controlled channel manipulations resulted in a 471 % increase in high-quality Chinook salmon spawning habitat area and more than a doubling in spawner utilization of the study reach, even after the number of in-river spawners dropped by half.

[45] An important outcome of the study was that changing two riffle-pool units had an impact on the population-scale abundance of redds. Even as the river-spawning population declined steady over the study, the number of redds in the study area increased steadily. The study area makes up only ∼2% of lower Mokelumne River's spawning reach, but prior to the project, 7% of the population used the site, with this overrepresentation likely due to the site's location at the head of the reach and its proximity to the hatchery. After enhancement, the proportion of the total run spawning at this site tripled, with 20% of the total population using the study area in 2004.

[46] With this population-scale shift toward using rehabilitated sites preferentially, *Merz and Setka* [2004] and *Merz et al.* [2004] showed that spawners on those sites are accessing clean porous gravel, large areas of ideal depth and velocity, complex flow patterns and boulder clusters combining to create some of the most desirable habitat on the

Table 1. Mean ±1 Standard Deviation of Depth and Velocity Modeled at 11.33 m^3/s in the Project Reach on Riffles 1 and 2

Location	Preproject	Midproject	Postproject
		Depth, m	
Study Area	0.76 ± 0.45	0.68 ± 0.51	0.68 ± 0.50
Riffle 1	0.63 ± 0.29	0.45 ± 0.34	0.45 ± 0.23
Riffle 2	0.59 ± 0.29	0.60 ± 0.30	0.44 ± 0.15
		Velocity, m s^{-1}	
Study Area	0.45 ± 0.24	0.47 ± 0.38	0.52 ± 0.35
Riffle 1	0.51 ± 0.21	0.63 ± 0.46	0.68 ± 0.29
Riffle 2	0.62 ± 0.19	0.65 ± 0.26	0.85 ± 0.26

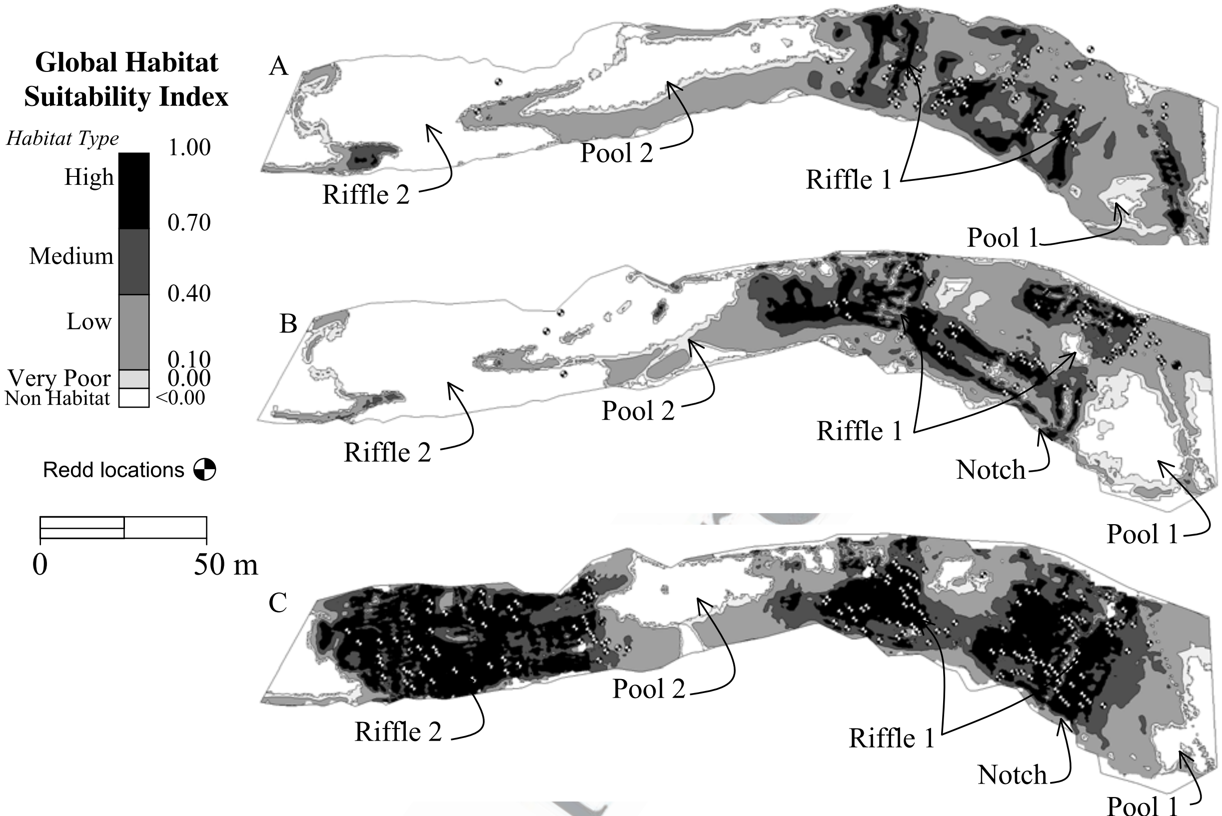

Figure 9. Two-dimensioanl model habitat quality predictions at 11.33 m^3/s showing the global habitat suitability index (GHSI) at the (a) premanipulation, (b) midmanipulation, and (c) postmanipulation stages. Validation is provided by comparison against actual redd locations for each stage, shown as targeted disks.

lower Mokelumne River. Sites that have been enhanced have shown as high as a 35% increase in survival of incubating embryos to the fry stage as compared to unenhanced sites [*Merz et al.*, 2004]. If 20% of the fish are spawning in areas where there is a 35% increase in fry production, then this manipulation will have a highly beneficial impact on river production of Mokelumne Chinook salmon.

[47] Throughout the study, spawning Chinook salmon preferentially used areas predicted by the 2-D model to be medium- and high-quality spawning habitat while avoiding areas predicted to be very poor quality and non spawning habitat. Despite the general validation of prediction 2, the assumptions made about substrate quality may mask the effect of various factors. Qualitative evidence suggests vegetation plays a key role in the choice of spawning location and thus should be incorporated into habitat quality predictions, as done in this study. A more detailed substrate suitability curve incorporating dominant and subdominant sediment size as well as organic mud and live aquatic vegetation ought to provide more accurate substrate suitability predictions. The lack of vegetation growing on riffles 1 and 2 during 2003–2006 as well as the ongoing lack of vegetation over several more years on the 2000 and 2002 sites rehabilitated with steeper slopes shows that increasing riffle slope and providing periodic spring flow releases of >55 m^3/s effectively eliminates the previous problem observed in ad hoc gravel augmentation at the 1999 and 2001 sites on the lower Mokelumne River. The 1999 site was built ad hoc and 30% less gravel arrived for construction of the 2001 site relative to the design specification [*Wheaton et al.*, 2004b]. Both of these projects were limited by the upstream backwater effect they created. These factors explain the differences in outcome observed at different riffles after ~5 years.

[48] Spawner utilization of habitat changed as channel conditions improved (Figure 10). On the basis of the

Table 2. Channel Area in Each Spawning Habitat Quality Category Modeled at 11.33 m^3/s

			Habitat Quality				
Project Stage	Metric	Non	Very Poor	Low	Medium	High	Total Habitat Area,[a] m^2
Preproject	area (m^2)	4173	444	4204	1433	539	6619
Preproject	area (%)	-	7	64	22	8	100
Midproject	area (m^2)	5690	901	2595	1284	648	5427
Midproject	area (%)	-	17	48	24	12	100
Prechange to Midchange	area (m^2)	1517	457	−1609	−149	109	−1192
Postproject	area (m^2)	1819	782	3128	2308	3079	9297
Postproject	area (%)	-	8	34	25	33	100
Midchange to postchange	area (m^2)	−3870	−119	533	1025	2431	3870

[a]Excludes nonhabitat.

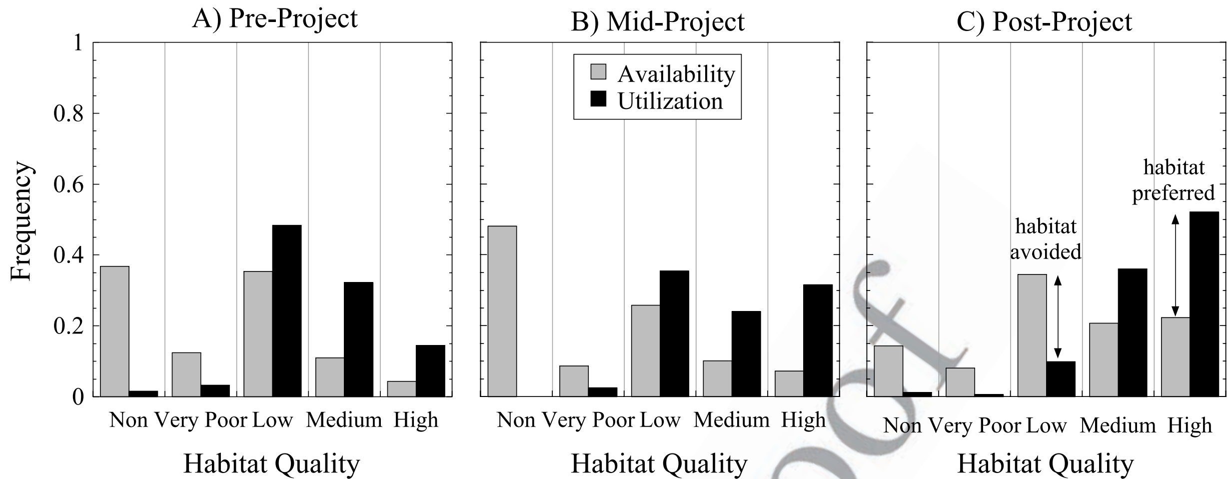

Figure 10. Utilization and availability of spawning habitat as predicted for the (a) premanipulation, (b) midmanipulation, and (c) postmanipulation stages using the three analysis methods. Utilization values larger than availability indicate a preference, while availability larger than utilization indicates avoidance.

sequence of utilization over the course of the study, spawners have more relaxed hydraulic criteria for choosing redd locations when a river is degraded. It is likely that under such degraded conditions, surface hydraulics are not adequately indicative of hyporheic water quality, and that fish are choosing sites based on their assessment of hyporheic conditions. Nevertheless, after rehabilitation improved hydraulic conditions, increased hyporheic exchange, and added new heterogeneous habitat features, spawners became more discerning, with more utilizing high-quality physical habitat in the final state relative to the initial and midstudy states (Figure 10).

[49] It seems reasonable to conclude that lack of available high-quality habitat forced fish to spawn in lower quality habitat areas initially, but the habitat quality maps show there is available, unused, good habitat in 2002. The fish packed more tightly into the high-quality habitat in 2003 and 2004, indicating something must be turning fish away

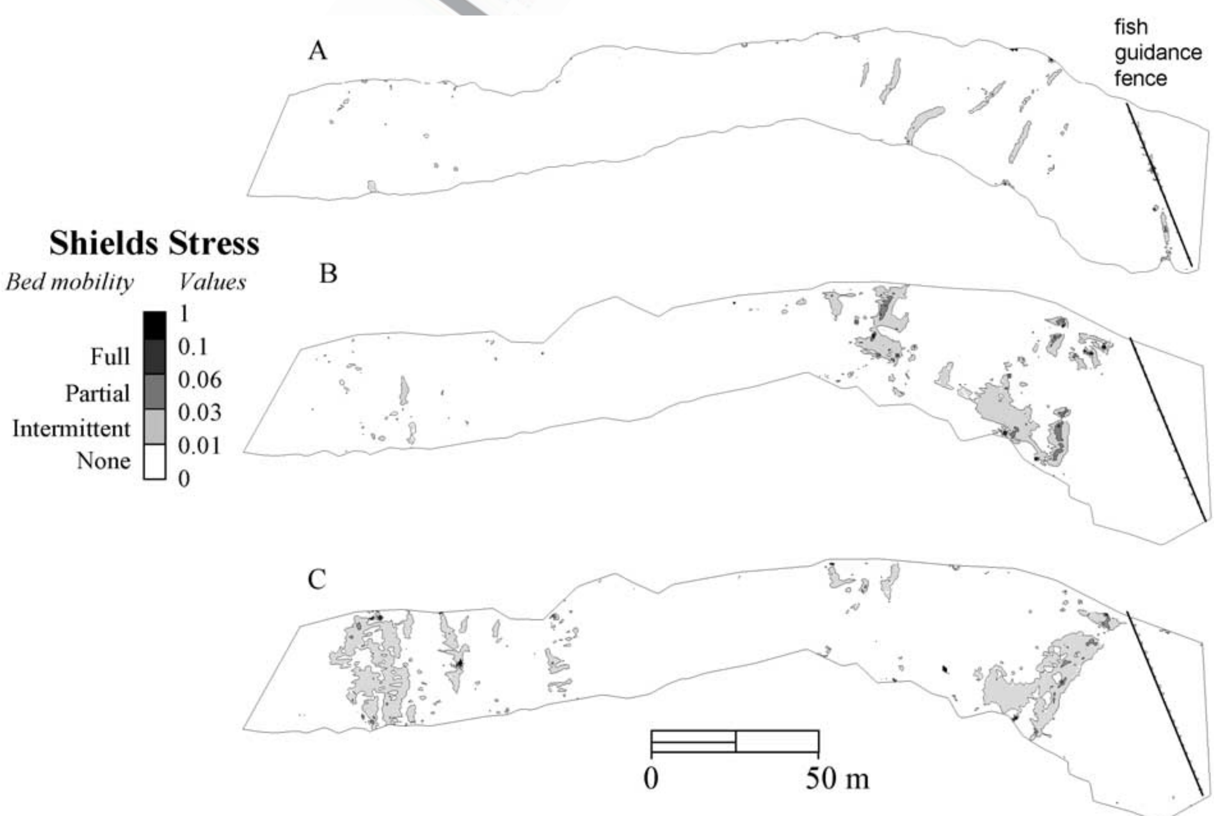

Figure 11. Two-dimensional model predictions of Shield stress at 11.33 m^3/s for the (a) premanipulation, (b) midmanipulation, and (c) postmanipulation stages of the study.

Table 3. Measured Low, Median, and High Surface Grain Sizes for Each Stage of the Study[a]

Size Parameter[b]	Preproject	Midproject	Postproject
D_{16}	22.8	32.5	32.5
D_{50}	40.8	50.4	50.4
D_{90}	69.6	85.1	85.1

[a]Values are in mm.
[b]Subscript denotes percent of particles smaller.

from the relatively better habitat in 2002. This could be due to the model's inability to capture the effect of intraspecies and interspecies interactions and/or the effect of complex flow structures and hyporheic flow on the choice of redd location. An example of the former is when early spawners choose a site, and then subsequent spawners use the same locations. This may be because the gravel is loosened, and cleaned improving substrate quality, hydraulic conditions and making redd construction easier [*Essington et al.*, 1998]. It may be a mechanism to outcompete the early spawners [*Ferguson and Rice*, 1980] or it may simply be one fish following the lead of another. Regardless this phenomenon would be more evident in the preproject stage when the gravel has yet to be worked over. Early redd construction will improve substrate quality dramatically in a degraded channel, but after clean gravel is added during channel manipulation, all the placed substrates would be loose, clean and easy to move. In this state, the work of early spawners would have less beneficial impact on hyporheic flow and substrate quality. Additionally, most redds are clustered near specific channel features; channel margins, boulder clusters, and along the upstream edge of riffle crests (Figure 9). Clear patterns of clustering around boulder clusters, riffle crests, and large wood have been observed throughout past Mokelumne augmentation projects [*Merz*, 2001; *Wheaton et al.*, 2004c] and elsewhere [*Piegay et al.*, 2000; *Rosenfeld et al.*, 2000; *Roni and Quinn*, 2001]. Boulder clusters and large woody debris have been shown to improve spawning habitat by increasing eddies and shear zones [*Abbe and Montgomery*, 1996; *Bouckaert and Davis*, 1998] and providing resting habitat and cover from predators. Redd clustering evident throughout this study (Figure 9) illustrates the necessity for developing designs not only based on habitat suitability curves and 2-D models but on a wider range of qualitative information and established concepts regarding ideal salmon spawning habitat.

7.2. Isolating Impact of Slope Creation

[50] By introducing slope directly below the dam the driving force required to raise the flow velocity and lower flow depth was restored, allowing for the introduction of complex flow patterns, improving spawning habitat quality and corroborating prediction 1. Even though fish migration size and hatchery take were eliminated as factors explaining observed increases in redd numbers, a complication arises in attributing the improvements to slope creation as opposed to ancillary improvements associated with gravel placement, including substrate quality improvement, addition of habitat heterogeneity, improved hyporheic flow, flushing of fines and nutrients, etc. For example, major improvements in spawning conditions were observed at riffle 2, but the cause cannot be isolated by this manipulation alone due to the presence of aquatic vegetation and other degraded conditions during the preproject phase. However, the cause for the improvement can be isolated by comparing the outcome of this manipulation with a previous ad hoc non-SHIRA project done at riffle 2 in 1999 [*Pasternack et al.*, 2004; *Merz et al.*, 2006]. That effort used a comparable amount of gravel at the same location, but was built with no design process or consideration of slope. The upstream riffle remained unaltered while the project on riffle 2 improved substrate quality, used habitat heterogeneity, decreased the cross-sectional area, increased velocity, decreased depth, and flushed fines and nutrients. Despite those changes, no spawners used the site in the first season immediately following construction when substrate quality was highest. In contrast, the same metric after SHIRA-based slope creation in 2004 showed 65 redds. Discharge was ~8.5 m^3/s in both years. Thus the immediate utilization differences between 1999 and 2004 can be directly attributed to the use of SHIRA and slope creation.

[51] Subsequent utilization of riffle 2 has differed markedly after slope creation in comparison to previous enhancement without it. During 2000–2003, when no manipulations were made to riffle 2, there were 30, 5, 2, and 6 redds present, respectively [*Merz et al.*, 2006]. Inadequate slope and low winter flow releases during this sequence of dry years explain why this site had poor substrate quality and vegetation growth. In contrast, in the second spawning season after the 2004 slope creation, 187 redds were observed on riffle 2 alone. As of October 2006, the study area was clear of vegetation and substrate quality was high. It remains to be seen what future utilization of the site will be, but this comparison of rehabilitation with versus without slope creation at the same location and using the same material strongly suggests that slope creation was primarily responsible for the dramatic gains in redd abundance.

[52] Slope creation effectively provided the opportunity to improve the spawning habitat in the entire reach without drowning upstream riffles. Because slope creation was implemented below a dam and staged over a 2-year period, detrimental backwater effects were avoided. This was only possible because the 2-D model proved to be accurate enough for this purpose.

7.3. Hydrogeomorphic Assessment

[53] Bed scour during low flows associated with spawning and incubation periods can have a significant influence on salmonid embryo survival [*Lisle and Lewis*, 1992]. Artificially cleaned material may exacerbate the potential for scour mortality [*Nawa and Frissell*, 1993]. Consequently, it was important to assess the potential for localized scour in the study area. Little to no intermittent or partial sediment transport was predicted throughout this study at spawning flows, indicating slope creation can be implemented in a staged manner without unwanted scour and sediment transport during the sensitive periods of spawning and embryo incubation. This corroborates prediction 3. No scour was observed between stages. The peak winter flows (42.7 m^3/s) caused no measurable difference in digital elevation model elevations, even in the chute, predicted to exhibit subcritical intermittent sediment transport. This indicates the need for higher flushing flows to be released from the dam in order to maintain the short-term benefits of slope creation over the

longer term. Regardless of the features created, coarse sediments at past Mokelumne rehabilitation projects have accumulated organic fines that may degrade hyporheic water quality. Organic fines build up over years and promote vegetation growth. However, with average to above average water years in 2005 and 2006, transport of placed gravels did take place during late winter and spring after the incubation period. This well-timed runoff was observed to dislodge organic fines, remove vegetation from spots that had it, and redistribute gravel among channel features. Annual injection of 500 tons of gravel upstream of riffle 1 has been implemented to sustain the observed sediment budget in light of the active transport regime that is developing [*Merz et al.*, 2006].

[54] During this study it became apparent that an understanding of the interplay between riffles is critical to managing regulated riffle-pool streams. A single riffle cannot be rehabilitated without considering the impact on upstream riffles. When gravel augmentation is implemented below a dam there is no upstream riffle affected in the first stage but in the second stage the relationship between riffle 1 and 2 became evident and essential to manage. The increase in elevation at riffle 2 did create a backwater effect in the second stage but turned out to be critical to improving conditions on riffle 1. As more riffles crests are rehabilitated downstream, the interplay becomes more complex, and interdependent. This is metaphorically termed a ‘‘reverse domino’’ effect, with upstream crests dependent on the functioning of downstream crests, just as an individual domino placed in a series depends upon the stability of those around it.

[55] Although not quantified in this study, subsequent gravel augmentations in 2005 and 2006 have been able to distribute this initial elevation gain downstream by an additional 230 m. In part, this has been possible because the next 2 riffle-pool units had such a large cross-sectional area due to historic in-channel gravel mining that filling them in yielded substantial increases in velocity associated with depth constriction without having to raise the slope much. Filling in the channel has also reduced the flow necessary for bankfull discharge, providing a longer duration of floodplain inundation. Changing the channel’s width:depth ratio has promoted bank scour, increasing the width of the active channel. As long as active management continues, this positive trajectory should continue.

8. Conclusions

[56] A channel manipulation was performed to test aspects of a newly proposed slope creation methodology. Results indicated (1) habitat quality was maintained in the first stage while providing the opportunity to significantly improve habitat quality in the second stage, (2) spawning Chinook salmon preferentially used 2-D model predicted high-quality habitat, and (3) detrimental sediment entrainment at spawning and embryo incubation flows was avoided. Alternate explanations for observed increases in numbers of redds in the study area, including fish migration size, hatchery take, and substrate quality improvement were disproved through careful analysis. The results of this study demonstrated the utility of slope creation as a methodology for salmon spawning habitat restoration implemented below dams.

[57] **Acknowledgments.** This project relied heavily on previous research completed on the Mokelumne River in collaboration with Chein Wang, Joe Wheaton, Jose Setka, and Jim Smith. Financial support for this work was provided by East Bay Municipal Utility District (Research Agreement OOK6046), the University of California, and U.S. Fish and Wildlife Service (contracting entity for CALFED Bay-Delta Ecosystem Restoration Program: Cooperative Agreement DCN 113322G003). We acknowledge Marisa Escobar, Rocko Brown, Hamish Moir, Peng Gao, and Jeff Mount for their critical input and support. Ellen Mantalica and Diana Cummings at the UC Davis Center for Watershed Sciences provided valuable administrative support. We thank Warren Jung, Russ Taylor, and other East Bay Municipal Utility District staff, who were instrumental in assisting with field work and data collection. We thank the undergraduate students Andy Tranmer, April Sawyer, Carlos Alvarado, Dave Van Herrick, Evan Buckland, Kashaul Parikh, Mike Bezemek, and Mike Bounrisavong for help with field work, modeling, and data analysis.

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