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Sediment budget for salmonid spawning habitat rehabilitation in a regulated river

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Abstract

Bed elevation, feature adjustments, and spawning use were monitored at three Chinook salmon (*Oncorhynchus tschawytscha*) spawning habitat rehabilitation sites to measure project longevity in a regulated river. Sites enhanced with 649–1323 m^3 of gravel lost from 3–20% of remaining gravel volume annually during controlled flows of 8–70 m^3/s and 2.6–4.6% of placed material during a short-duration (19 days) release of 57 m^3/s. The oldest site lost ~50% of enhancement volume over 4 years. Of the mechanisms monitored, gravel deflation was the greatest contributor to volumetric reductions, followed by hydraulic scour. Spawning, local scour around placed features, and oversteepened slopes contributed to volumetric changes. As sites matured, volumetric reductions decreased. Sites captured as much large woody debris as was lost. While complexity is an extremely important aspect of ecological function, artificial production of highly diverse and complex habitat features may lead to limited longevity without natural rejuvenation.

Keywords: Salmonid; Spawning habitat; Rehabilitation; Restoration; Morphometric budgets; Digital elevation model differencing

1. Introduction

A sediment budget quantifies sediment fluxes and storage in a designated area over a specific time period. Budgets can be performed for whole basins (Dietrich et al., 1982; Reid and Dunne, 1996) or individual channel reaches (Fuller et al., 2003). The morphometric sediment budget approach quantifies erosion and deposition volumetrically by differencing observed topographic changes (Brasington et al., 2003; Lane and Chandler, 2003). Morphometric sediment budgets largely reflect changes from bedload transport (Fuller et al., 2003). In regulated rivers, bedload is rarely transported past large dams, hence virtually eliminating the (volumetric) input term of the sediment budget from upstream (Vaithiyanathan et al., 1992). In these areas, sediment-starved flow may erode the channel bed and banks, producing channel incision, bed material coarsening, and gravel loss (Waldichuk, 1993; Gilvear and Bradley, 1997; Kondolf, 1997; Shields et al., 2000). Such changes typically result in habitat modifications for numerous aquatic organisms, including anadromous salmonids (Osmundson et al., 2002).

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Sediment budgets provide a record of relative channel stability and thus a means of assessing physical habitat change. For instance, because of declining salmonid populations (Yoshiyama et al., 1998), coarse sediment and physical structures [such as large woody debris (LWD), boulder complexes, and groins] are being added to streams to augment deficiencies, create meandering channels, and enhance spawning riffles (Scheeler, 1990; Chapman, 1995). Reviews of such spawning habitat rehabilitation (SHR) projects are detailed elsewhere (e.g., Kondolf, 2000; Wheaton et al., 2004c). While SHR projects appear to attract spawning fish and may increase embryo survival and fry production (Merz and Setka, 2004; Merz et al., 2004), numerous failures have also been documented (Frissell and Nawa, 1992; Avery, 1996). Expectations of stability are one of the greatest inadequacies associated with SHR (Wheaton et al., 2004c). Even with low flows, without further sediment input, natural and placed gravels eventually scour (Paintal, 1971). While the placement of structures (such as boulders and woody debris) is designed to improve habitat for fish, it can also accelerate scour locally (Kuhnle et al., 2002). For placed gravel, scour has been viewed as a failure (Kondolf et al., 1996); whereas the failure may not be scour itself, but rather the expectation that it should stay there. A site-scale sediment budget to estimate residence times of placed gravels and requirements for habitat maintenance might produce more reasonable expectations.

In this study, sediment budgets were used to track the fate of gravel, boulders, and LWD placed according to complex SHR designs and to identify mechanisms controlling project longevity. Site-scale (i.e. ~10^1 channel widths) sediment budgets were calculated for three spawning bed enhancement projects in a low-slope regulated river impacted by in-stream mining. Sediment input (from construction), change in storage, and gravel loss were measured volumetrically at each site and compared with process-based analyses of compaction, slope failure, and entrainment potential to assess specific mechanisms of morphological change after gravel placement. This study is significant for its insight into the relative roles of mechanisms for gravel-bed change under low flow, low-slope conditions, with lessons for future gravel placement design and monitoring strategies.

1.1. Site-scale sediment budget

A volumetric sediment budget for an SHR project on a regulated river at the typical site-scale of ~10^1 to 10^2 channel widths should account for all gravel sources and losses associated with project implementation and subsequent changes (Fig. 1). Because SHR projects involve gravel placement in a generally gravel-deficient setting, we emphasize the volumetric loss components.

1.1.1. Sources for gravel placement

Gravel for SHR is typically purchased from floodplain quarries or in-channel mining sources (Kondolf, 2000). In California, the cost for each metric ton of concrete-grade aggregate ranges from USD 7–20 at the mine, plus USD 0.06–0.10 km^{-1} for site transportation. On the Mokelumne River, cost for in-basin river gravel (including triple-washing and transport) was USD 22.90 m^{-3} total. The cost for gravel placement equipment and labor was an additional USD 0.47 m^{-3}. As gravel is sold by weight, some volumetric change may be due to overestimates in mass to volume conversions.

1.1.2. Fluvial sediment recruitment

Fluvial sediment recruitment refers to the local sediment supply via fluvial erosion of upstream sources. Localized bank sloughing, tributaries, and upstream augmentation are potential sediment sources. Hydraulic structures are often intended to encourage gravel deposition (FISRWG, 1998). Depending on trap efficiency, reservoirs may pass sand at a reduced rate (Brune, 1953), detrimentally affecting developing salmonid embryos within the substrate (Kondolf, 1997). However, sand does not comprise a significant volumetric component of the sediment budget for a placement project.

1.1.3. Gravel losses before placement: operational losses

Depending on how gravel is imported to a site, staged at the site, and positioned in the stream, some material is lost prior to placement (Fig. 1). The larger the site and number of staging areas used, the greater the gravel loss from floodplain and channel bank imbedding. Overhandling during construction can cause gravel breakage and spawnable-material loss. Misconfiguration and loss from spillage during transport and placement may further decrease final volume. Unforeseen problems, such as loose banks or pools too deep to operate equipment, may require operators to use a gravel portion to create access.

1.1.4. Gravel losses after placement: fluvial erosion

The volume of the final configuration can be deflated by several mechanisms. Hydraulic drag and lift forces are foremost in conventional thinking (Paintal, 1971). Particle entrainment is generally assumed to be estimated by shear stress (Nelson et al., 2000). Lacking direct

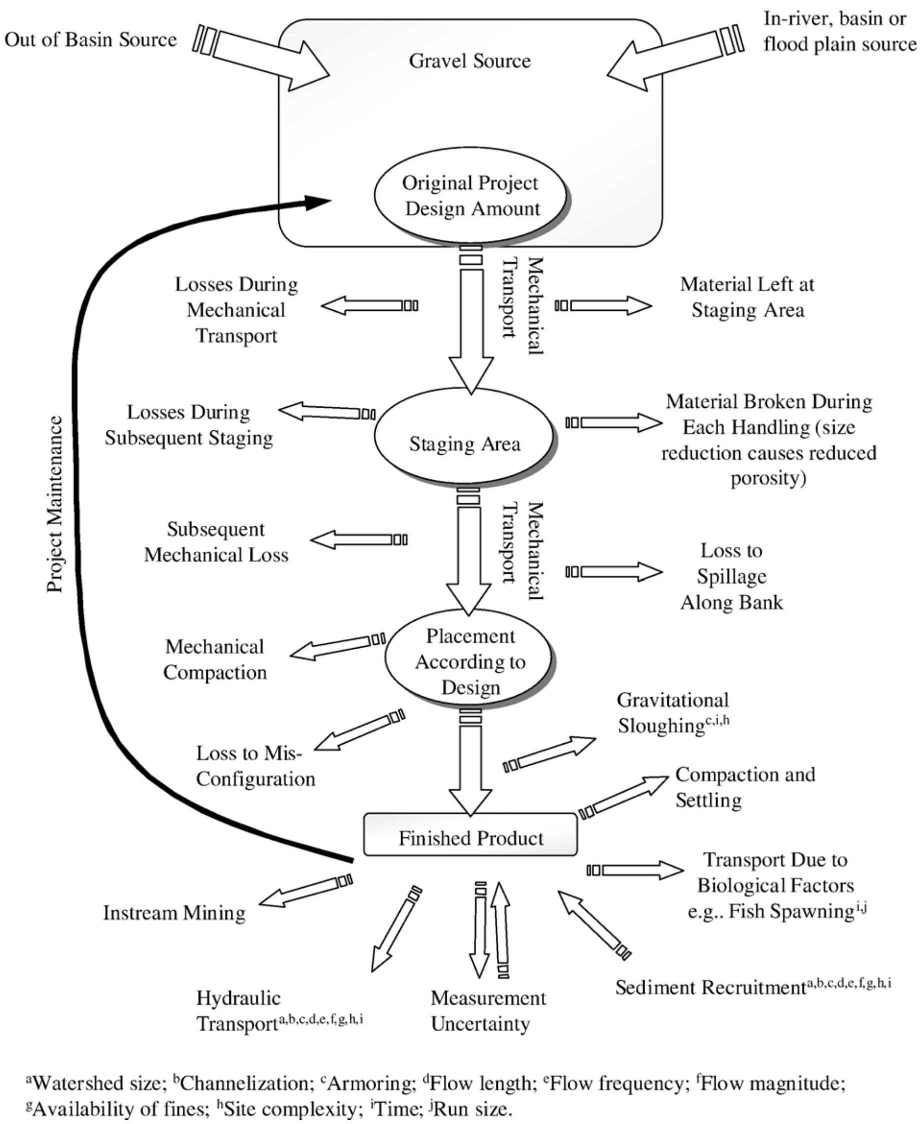

Fig. 1. Factors influencing volumetric sediment budgets for salmonid spawning gravel enhancement. Arrows indicate direction and relative amount of gravel. Major effects on each mechanism for sediment loss[a–j].

measurements, shear stress is widely estimated based on flow field knowledge (Wilcock, 1996; Biron, 2004). Critical shear stress for sediment entrainment with particle diameter d_i can be estimated using the Shields (1936) equation:

$$\tau_c = \tau_c^*(\gamma_s - \gamma_f)d_i \tag{1}$$

where τ_c is critical shear stress (N/m^2), τ_c^* is dimensionless critical shear stress, γ_s is specific sediment weight (assumed to be 25 990 N/m^3), γ_f is specific water weight (9807 N/m^3), and d_i is the sediment size (m) of interest. Because placed gravel is well-mixed, an initially high relative exposure of smaller particles is likely, yielding a risk of partial transport of the finer fraction leaving behind the coarser fraction (Wilcock, 1997).

To estimate whether an individual grain is mobilized by flow, critical shear stress may be compared to shear stress induced by the flow (e.g., Pasternack et al., 2004). An individual grain's entrainment depends on its relative projection above the mean bed, its exposure relative to upstream grains, its shape, and its friction angle (Kirchner et al., 1990). Placed boulders, LWD, and man-made structures (such as deflector weirs) create local convective accelerations and secondary currents in the form of vortices that intermittently raise near-bed velocities, potentially increasing local scour (Smith and Beschta, 1994).

1.1.5. Gravel losses after placement: settling and compaction

In consideration of volumetric losses of placed gravels, erosion is not the only potential mechanism. Hole (1961) defined nine categories of pedoturbation, with faunal pedoturbation, gravipedoturbation (mixing by noncatastrophic mass-wasting), and seismipedoturbation (mixing by vibrations) applicable to aquatic volumetric changes. Fish, people, and wildlife can briefly increase local drag and lift, inducing local scour. Over time, this might add up to significant change where flow regulation precludes floods.

Unconsolidated materials that exhibit steep surface slopes are inherently unstable. Placed gravels will adjust oversteepend slopes through small, localized slope failures and in situ settling to achieve more stable configurations. These processes can be magnified when gravel piles are placed at steep angles (Buffington et al., 1992). Gravitational force and friction are in balance at the angle of repose, 23° for dry glass beads (Barabási et al., 1999). However, water lubricates grain motion, reducing intergranular friction and hence friction angles (Ingles and Grant, 1975). In practice, gravel injection along riverbanks yields steep-sided piles, that often mobilize easily. For in-stream placement, avoiding steep slopes may be limited by bathymetry and placement method—a front loader cannot construct a gentle riffle entrance or exit where the depth could flood it.

Deposit volume may change through time from natural settling and repacking enhanced by gravel vibration. Placed gravel may compact and subside preexisting substrate. Gravel can also spread laterally into the underlying alluvium. As gravel fill depths increase, so too does deposit mass and therefore its confining pressure. Similarly, the more equipment drives over the deposit, the more compaction. Finally, turbulent flow fluctuations exert forces causing settling and compaction. During low flows, a riffle is subjected to chaotic, turbulent flows that cause in situ particle vibration and sporadic particle motion (Sear, 1996).

Estimates of spherical packing density have been well discussed in the literature (Gauss, 1831; Rogers, 1958; Goldberg, 1971; Steinhaus, 1999). While the densest packing for uniform spheres is 77.836% of total volume (Muder, 1993), one must take into account shape/size variability and additional complications associated with natural stream sediments (Ingles and Grant, 1975). Measuring sediment packing directly over time as part of a sediment budget would help in understanding its contribution to the volumetric budget. Particle packing can significantly affect bulk density and natural particle assemblages are seldom unisized. Packing becomes denser with wider particle-size distribution, especially if the deposit becomes compacted. Packing can be described by calculating material bulk density or porosity. Bulk density (P_b) is calculated as

$$P_b = M_b / V_b \tag{2}$$

where M_b is bulk material weight and V_b is bulk volume (Bunte and Abt, 2001). Milhous (2001) observed bulk densities of 1.70–2.60 (g/cm^3) and porosities of 0.02–0.36 in several gravel-bed rivers. While it has not received significant study, grain-packing configuration and gravel-bar compaction could significantly impact site design, longevity, and future function of spawning gravel augmentation projects.

1.1.6. Detection uncertainties

Regardless of measurement technique, topographic surveying and DEM differencing contain uncertainties (Brasington et al., 2004; Holmes et al., 2000). In this study, we assume that detection uncertainties have equal influence on volumetric loss and gain and subsequently cancel each other out. These detection uncertainties are currently under further investigation to explore the validity of this assumption (Brasington et al., 2004; Wheaton et al., 2004a).

2. Regional setting

The snow-fed Mokelumne River, in California drains ~1624 km^2 of the central Sierra Nevada (Fig. 2). It presently has 16 major water impoundments, including Salt Springs (175 032 089 m^3), Pardee (258,909,341 m^3) and Camanche reservoirs (531,387,061 m^3), which have dramatically altered the late spring snowmelt flow regime (see Pasternack et al., 2004; Wheaton, 2003) (Fig. 3). The LMR bed slope ranges from 0.10% near Camanche Dam to 0.02% near the Cosumnes River confluence, with the active channel now half its former width (present average 30 m; range of 19–43 m) and overdeepened. In the upper ~9.5–14.5 km below Camanche Dam, the channel bed has limited amounts of compacted gravels and cobbles associated with higher bed slope and shallow riffle-run hydraulics. Camanche Dam blocks gravel delivery from upstream. Murphy Creek, a small tributary close to the dam, potentially contributes a small amount of gravel. Historic mining operations depleted instream gravel storage and yielded deep pits that are sediment transport barriers. Although isolated by berms and levees, mine tailings exist along the upper third of the LMR. Channel

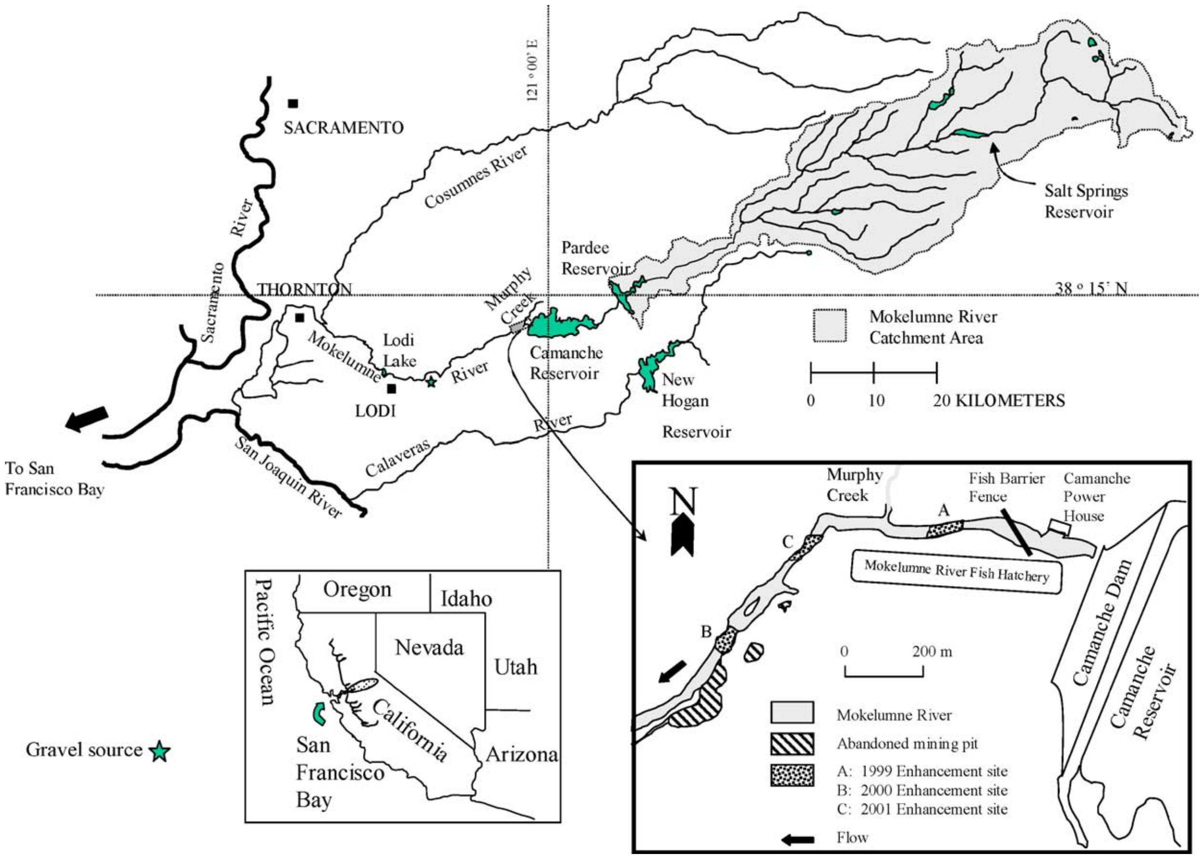

Fig. 2. Study location in relation to the Mokelumne River drainage, Sacramento–San Joaquin River system and the Southwestern United States.

and banks show little instability that could lead to gravel recruitment with a thin ribbon of riparian vegetation remaining along most of the stream, providing vegetative armoring of the bank. Presently, the LMR supports over 35 native and non-native fish species including native Chinook salmon (*Oncorhynchus tschawytscha*) and steelhead (*O. mykiss*) (Merz et al., 2004; Workman, 2003).

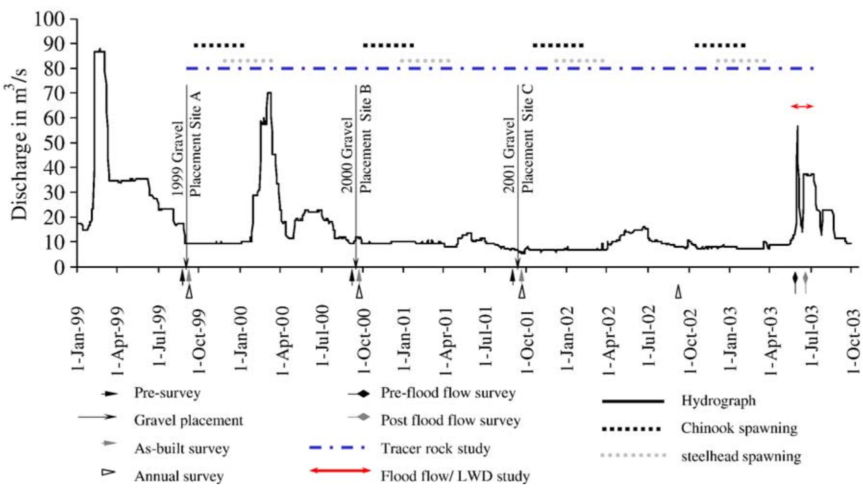

Fig. 3. Hydrograph of the lower Mokelumne River immediately below Camanche Dam, 1 January 1999 through 30 September 2003. Flood flow surveys not performed at site B. Only site B surveyed on 23 September 2003.

3. Material and methods

3.1. Site selection, enhancement procedures, and gravel input

The purpose of LMR SHR is to replenish suitable-sized gravel within the spawning reach (Fig. 2), provide immediate salmonid spawning habitat (recognizing that placed gravels will not be static), and serve as a controlled field experiment for river research.

In August of 1999, 2000 and 2001, three sites were augmented (Figs. 2–6; sites A–C). Degraded sites were selected based on depth and equipment access. Historic aerial photographs (1933–1963) were used to select sites of previously shallow gravel depths that had been mined between 1952 and 1964, and recent Chinook salmon and steelhead redd (nest) surveys to identify appropriate locations (Figs. 4–6) (Setka, 2002).

An estimated 1659, 1200, and 794 m^3 (sites A, B and C, respectively) of clean 25–150 mm diameter river gravel (CDFG, 1991; Kondolf and Wolman, 1993) from an open floodplain quarry located 0.5 km from the active channel (Fig. 2) was transported by dump truck and contoured by rubber-tire loader in berm, riffle, and staggered bar configurations. Configurations intended to enhance Chinook salmon and steelhead spawning conditions by reducing depth, increasing velocities, providing structure, and promoting exchanges of water between the stream and gravel interstices (Vronskiy, 1972; Chapman, 1988).

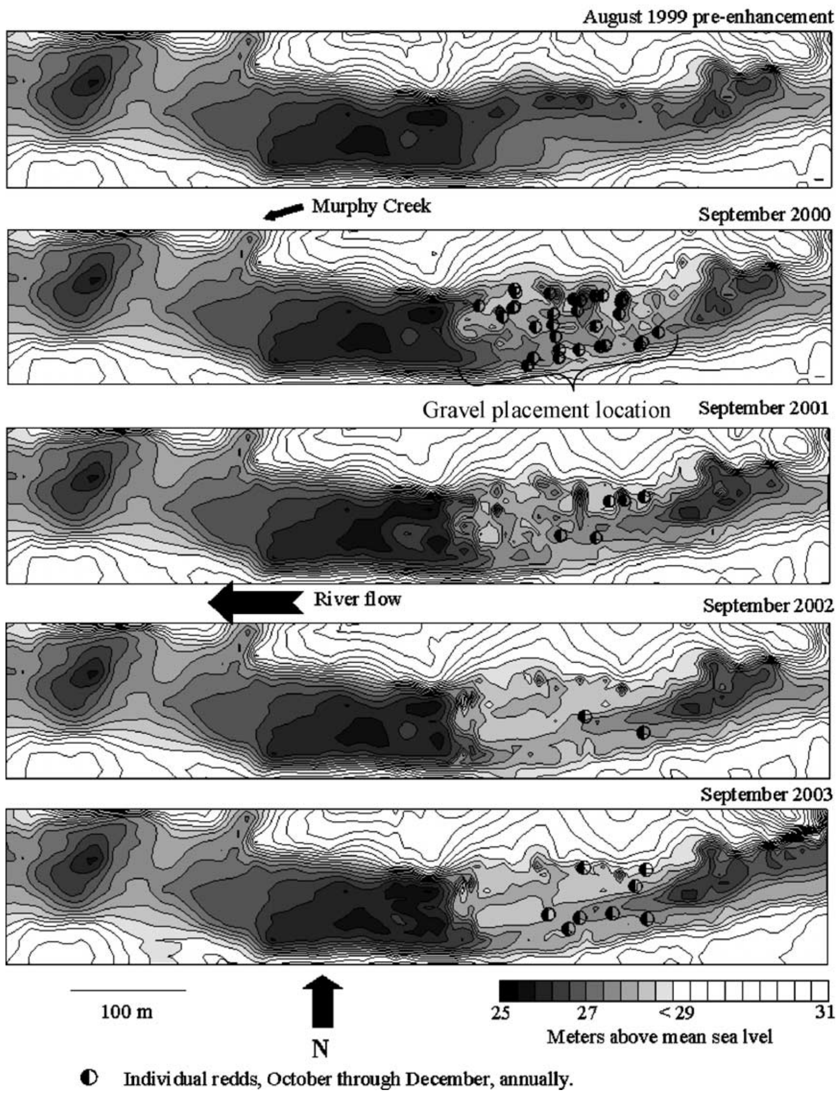

Fig. 4. Contour maps depicting streambed elevation before and after gravel placement at site A, lower Mokelumne River California.

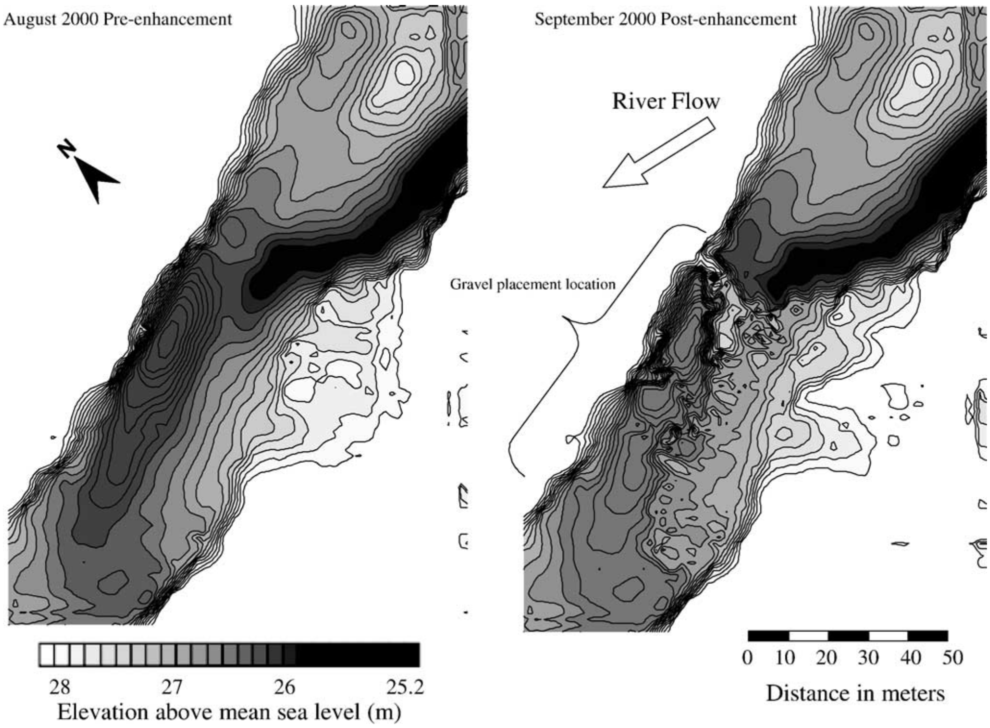

Fig. 5. Contour maps depicting streambed elevation before and after gravel placement at site B, lower Mokelumne River, California.

Boulders (0.6–1.2 m diameter) and LWD (trunks up to 0.6 m diameter) were placed throughout the sites to increase downwelling, channel complexity, and cover for spawning salmonids (House, 1996; Geist and Dauble, 1998; Merz, 2001). Gravel was placed under various configurations built on numerous modeling designs (Spawning Habitat Integrated Rehabilitation Approach–Adaptive Management Phase 5; see Wheaton et al. (2004b,c). Final design selection was based on model results, consideration of project constraints, and revisiting conceptual models (viewable on the web:http://www.shira.lawr.ucdavis.edu).

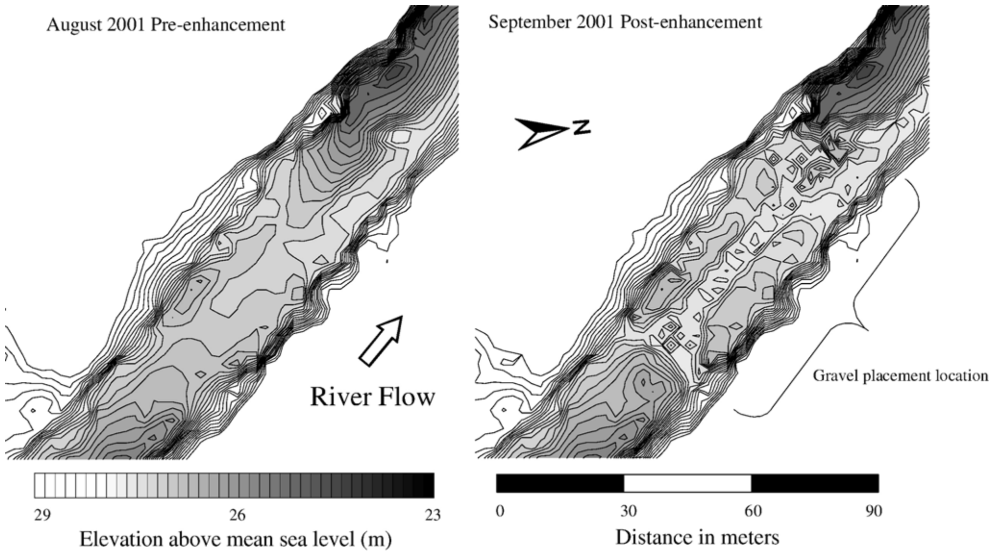

Fig. 6. Contour maps depicting streambed elevation before and after gravel placement at site C, lower Mokelumne River, California.

3.2. Sediment budget

3.2.1. Timing of monitoring program

Repeat surveys tracked morphometric change (Brasington et al., 2003) over two temporal scales: (i) annually with surveys each summer during low flows and (ii) event-based in response to a controlled flood release. Annual surveys were typically repeated during the first week of September (Fig. 3). This yielded six time steps during which surveys were conducted and five appraisal periods over which changes were analyzed.

3.2.2. Topographic channel surveys and DEM differencing

A Topcon GTS-802A total station (1 s angular accuracy) was used to record 1200–3400 bed points for each survey. Average point densities across all three sites (21 surveys) were 0.78 m^{-2} (min: 0.39; max: 2.41; SD: 0.32). This variation reflects higher density in complex areas and low point density in flat areas (Fuller et al., 2003).

Surfer® (Golden Software, Inc.) was used to build triangulated irregular networks (TINS) and interpolate survey data to 1.1-m resolution DEMs. Blanking files ensured that elevation and volumetric changes were only assessed where gravel, LWD, and boulders were specifically placed. Placed gravel volume and net cut/fill after specific time periods and flow events were calculated at each site using the Surfer Grid Volume Report (Golden Software Inc., 1999). Downstream tracking of exported sediment was not done; whereas placed gravels created easily discernable, localized features: exported grains may be only 1–2 D_{90} thick and spread over a large area, being impractical to resolve. Because of regulated flows, stable banks, and proximity to Camanche Dam, natural gravel recruitment was assumed negligible.

To estimate potential error from mapping and DEM analysis, two areas (13.28 and 8.55 m^2) were surveyed three times each, within a 15-min timespan (as to insure volumetric change was negligible) with a mean point density: 5.9 m^{-2} and analyzed as described above. Mean DEM error calculations were +0.01955 m^3/m^2 surveyed within the LMR channel.

3.2.3. Techniques to assess processes responsible for observed volumetric changes

3.2.3.1. Fluvial erosion estimates. Fluvial erosion potential based on recorded flows was estimated using the Shields (1936) equation for site-specific and 1-Φ grain sizes and for τ_c* of 0.03 and 0.045 (Table 1). The flow duration above each threshold was then calculated by comparing threshold values to actual Camanche Dam flow record. Spatially explicit predictions of mobilization at the 0.1–2 m scale for sites A and C pre- and post-project were previously published (Pasternack et al., 2004; Wheaton, 2003). As an alternative to process-based predictions, flow-based scour was also evaluated using statistical regressions between gravel volume changes and measures of flow magnitude and duration.

3.2.3.2. Fluvial erosion verification—tracer rocks. Bed material scour was verified with tracer rocks. Quarry stones (800 and 500 at sites A and B, respectively) were washed and painted for use as scour indicators and pathway tracers. Tracer rocks were clustered by grain size using a gravel template with 22, 32, 44, 64, and 89 mm round openings. One group of 100 sorted tracers was piled on the bed at a randomly located point along each of eight evenly spaced transects at site A (September 1999) and five at site B. A measuring tape was used to measure the distance each tracer had moved downstream of its release site, and grain size was measured using the template. This was repeated again 12 months later. Individual points were also recorded during channel bathymetry surveys for release and recovered tracer rock locations at site A on 8 September 1999 and 10 June 2003. The JMP linear regression model function with an analysis of variance (ANOVA) was used to compare distances tracer rocks moved with stream velocity at initial placement (Sall et al., 2001).

3.2.3.3. In situ slope settling. Slope analyses of as-built DEMs explored the influence of oversteepened (>23°) gravel piles on site adjustment. The terrain module of Land Desktop R3 was used to calculate the slope of each TIN triangular plane and add its area to predefined slope range bins. Although friction angles have been reported to vary from 10–110° in gravel streambeds (Kirchner et al., 1990; Buffington et al., 1992), Barabási et al. (1999) suggested that critical slope for stability is ~23° for spherical particles and Handin (1966) suggested 25–40° for filling angles of rock and sand. A maximum hypothetical gravel volume loss attributed to oversteep bedslopes was calculated by multiplying the area over 23° by the maximum observed scour depths. This yielded a conservative estimate of the maximum volume reasonably attributed to readjustment for these slopes.

3.2.3.4. Gravel porosity and potential compaction estimates. To assess possible volumetric change from compaction, dry bulk gravel density (kg/m^3) was measured prior to placement (six quarry samples collected in a 0.020-m^3 bucket) and empirically estimated after-

Table 1
Calculations for theoretical entrainment of site-specific grain sizes at three spawning gravel enhancement sites on the lower Mokelumne River, California

Variable	Values for site-specific grain sizes			Values for 1-Φ grain sizes					Values for site-specific grain sizes			Values for 1-Φ grain sizes					Units
	D_{10}	D_{50}	D_{90}	8 mm	16 mm	32 mm	64 mm	128 mm	D_{10}	D_{50}	D_{90}	8 mm	16 mm	32 mm	64 mm	128 mm	
$\gamma_{sediment}$	25945	25945	25945	25945	25945	25945	25945	25945	25945	25945	25945	25945	25945	25945	25945	25945	N m^{-3}
γ_{water}	9790	9790	9790	9790	9790	9790	9790	9790	9790	9790	9790	9790	9790	9790	9790	9790	N m^{-3}
f(Re)	0.045	0.045	0.03	0.045	0.045	0.045	0.045	0.045	0.03	0.03	0.03	0.03	0.03	0.03	0.03		
n	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043		
Site A (1999)																	
D_s	24.9	48.0	80.6	8.0	16.0	32.0	64.0	128.0	24.9	48.0	80.6	8.0	16.0	32.0	64.0	128.0	mm
D_s	0.025	0.048	0.081	0.008	0.016	0.032	0.064	0.128	0.025	0.048	0.081	0.008	0.016	0.032	0.064	0.128	m
Q_crit	18.09	34.89	58.60	5.82	11.63	23.26	46.52	93.05	12.06	23.26	39.07	3.88	7.75	15.51	31.02	62.03	N m^{-2}
S	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	
R	1.124	2.169	3.644	0.362	0.723	1.446	2.893	5.785	0.750	1.446	2.429	0.241	0.482	0.964	1.928	3.857	m
V_crit	1.02	1.58	2.23	0.48	0.76	1.21	1.91	3.04	0.78	1.21	1.70	0.37	0.58	0.92	1.46	2.32	m/s
W	46	46	46	46	46	46	46	46	46	46	46	46	46	46	46	46	m
Q_crit	52.7	157.6	374.1	8.0	25.3	80.2	254.6	808.4	26.8	80.2	190.3	4.0	12.9	40.8	129.5	411.3	m^3/s
Site B (2000)																	
D_s	7.5	39.4	106.4	8.0	16.0	32.0	64.0	128.0	7.5	39.4	106.4	8.0	16.0	32.0	64.0	128.0	mm
D_s	0.007	0.039	0.106	0.008	0.016	0.032	0.064	0.128	0.007	0.039	0.106	0.008	0.016	0.032	0.064	0.128	m
Q_crit	5.45	28.66	77.31	5.82	11.63	23.26	46.52	93.05	3.63	19.11	51.54	3.88	7.75	15.51	31.02	62.03	N m^{-2}
S	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	
R	0.093	0.488	1.316	0.099	0.198	0.396	0.792	1.584	0.062	0.325	0.877	0.066	0.132	0.264	0.528	1.056	m
V_crit	0.37	1.12	2.16	0.39	0.61	0.97	1.54	2.45	0.28	0.85	1.65	0.29	0.47	0.74	1.18	1.87	m/s
W	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	m
Q_crit	1.4	22.3	116.7	1.6	5.0	15.8	50.1	159.0	0.7	11.4	59.4	0.8	2.5	8.0	25.5	80.9	m^3/s
Site C (2001)																	
D_s	26.4	40.5	60.0	8.0	16.0	32.0	64.0	128.0	26.4	40.5	60.0	8.0	16.0	32.0	64.0	128.0	mm
D_s	0.026	0.041	0.060	0.008	0.016	0.032	0.064	0.128	0.026	0.041	0.060	0.008	0.016	0.032	0.064	0.128	m
τ_crit	19.19	29.44	43.64	5.82	11.63	23.26	46.52	93.05	12.79	19.63	29.09	3.88	7.75	15.51	31.02	62.03	N m^{-2}
S	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	0.0013	
R	1.470	2.256	3.344	0.446	0.891	1.782	3.565	7.130	0.980	1.504	2.229	0.297	0.594	1.188	2.377	4.753	m
V_crit	1.10	1.46	1.90	0.50	0.79	1.25	1.98	3.15	0.84	1.11	1.45	0.38	0.60	0.95	1.51	2.40	m/s
W	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	m
Q_crit	43.6	89.0	171.4	6.0	18.9	60.1	190.7	605.5	22.2	45.3	87.2	3.0	9.6	30.6	97.0	308.0	m^3/s

wards. Porosity of placed gravels was estimated with the Winterkorn formula ($\Phi = 0.385 - 0.08_{\log 10} d_{max} / d_{min}$), where d_{min} and d_{max} represent the smallest and largest particle sizes present, respectively (Ingles and Grant, 1975). The minimum and maximum porosity observed by Milhous (2001) in gravel and cobble rivers were used to calculate gravel porosity from the three SHR sites to estimate potential substrate deflation at various gravel placement depths.

3.2.3.5. Scour at boulders and LWD. In order to assess the extent to which structures placed to promote habitat heterogeneity caused local scour, the vicinity of such features was repeatedly surveyed. Placed boulder diameters, weights, and volumes ranged from 60–120 cm, 250–500 kg, and 0.01–0.25 m^3, respectively. Methods used to quantify boulder redistribution are described in Merz (2004). Briefly, sites A, B, and C boulders over the previously defined timesteps were surveyed by averaging ~20 elevation measurements on top of each boulder. We used a one-tailed t-test (Zar, 1996) to compare average boulder elevations at initial stream channel placement to elevations after selected time periods (e.g. every 12 months) and compared stream channel depth to boulders depth at each site after given time periods (typical time between surveys was 3–12 months).

During SHR site bathymetry surveys, at least 3 individual points were recorded on each piece of LWD to track its fate. After 12 months, points were recorded again to compare location and numerical change for LWD. High-density point surveys (8–14.3 points m^{-2}) were recorded around nine pieces of LWD at site A after initial construction (August 1999). These surveys were repeated in August 2000 to estimate scour volume using the Surfer Grid Volume Report.

3.2.3.6. Salmon pedoturbation. To measure Chinook salmon spawning effect on bed volume, bathymetry surveys were made to estimate channel morphology change caused by seven individual redds. Average point density per redd was 89.79 m^{-2} (min: 36.16; max: 132.45; SD: 39.60). Estimated volume differences were compared to estimated redd volumes calculated by lengths, widths, and depths of 98 Chinook salmon redds randomly measured between 1996 and 2002 to calculate an average volume of mobilized substrate by spawning salmon. Average estimated volumes were then multiplied by the number of redds observed each season to estimate total volume of bed material redistributed annually by spawning Chinook salmon at each enhancement site. Too few steelhead redds were observed during this study to provide an estimate.

4. Results

The LMR flow was largely unchanged at 10 m^3/s for most of the study period (Figs. 3 and 7). During its first snowmelt season, site A was subjected to a 77-day flow release with a peak of 70 m^3/s lasting 8 days. The peak flow corresponded to a 1.29-year event pre dam or a 2.5-year event post dam. In June 2003, all sites were

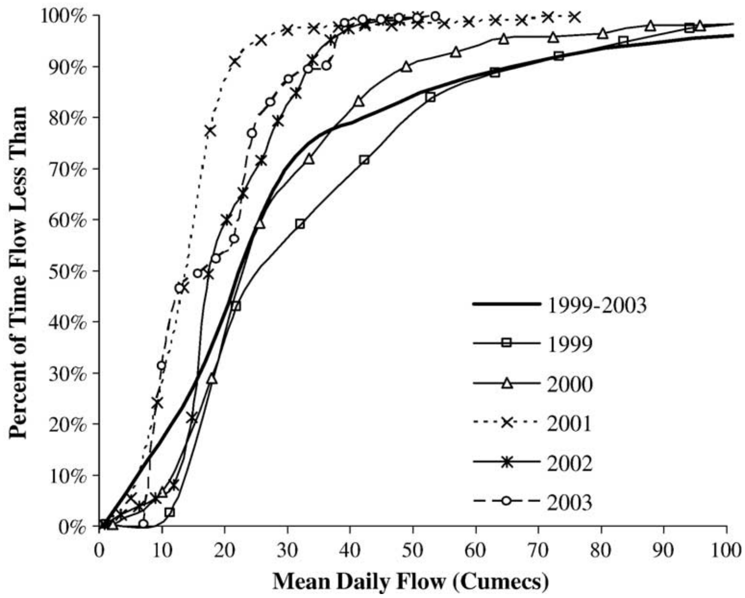

Fig. 7. Flow duration curves for the lower Mokelumne River, 1 January 1999 through 31 December 2003.

Table 2

Time periods, river discharge rates and gravel volumne calculations made at 3 spawning gravel enhancement sites on the lower Mokelumne River, California, 1 September 1999 through 23 September 2003

Flow period	Time period	Number of days	Site	River discharge rates									Gravel measurements				
				Total volume ($m^3 \times 10^5$)	Ave daily volume ($m^3 \times 10^5$)	Peak flow (m^3 s^{-1})	f(Re) = 0.045 Number of days ≥ Q_crit for			f(Re) = 0.03 Number of days ≥ Q_crit for			Volume remaining (m^3)	Volume lost (m^3)	Ave daily volume lost (m^3)	From previous period	
							D_{10}	D_{50}	D_{90}	D_{10}	D_{50}	D_{90}				Total percent lost	Daily percent lost
Flood release	23 May 2003 to 10 June 2003	19	1999 (A)	432.3	22.8	56.7	1 (5%)	0	0	8 (42%)	0	0	663.1	17.44	0.92	0.03	0.0013
4	1 Sept 2002 to 23 May 2003	266	1999 (A)	1841.8	6.9	12.5	0	0	0	22 (8%)	0	0	680.5	87.58	0.33	0.11	0.0004
3	1 Sept 2001 to 30 Aug 2002	364	1999 (A)	2751.1	7.5	15.9	1 (>1%)	0	0	92 (25%)	0	0	768.1	83.24	0.23	0.10	0.0003
2	1 Sept 2000 to 30 Aug 2001	364	1999 (A)	2990.3	8.1	13.4	6 (2%)	0	0	13 (4%)	0	0	851.4	207.00	0.56	0.20	0.0005
1	1 Sept 1999 to 30 Aug. 2000	364	1999 (A)	5830.9	16.0	70.0	30 (8%)	0	0	139 (38%)	126 (35%)	0	1058.4	264.90	0.73	0.20	0.0005
5	1 Sept 2002 to 23 Sept 2003	388	2000 (B)	4048.1	11.0	12.5	388 (100%)	127 (33%)	0	388 (100%)	282 (73%)	0	870.2	48.90	0.13	0.05	0.0001
3	1 Sept 2001 to 30 Aug 2002	364	2000 (B)	2751.1	7.5	15.9	362 (99%)	131 (36%)	0	364 (100%)	291 (80%)	0	919.1	56.54	0.15	0.06	0.0002
2	1 Sept 2000 to 30 Aug 2001	364	2000 (B)	2990.3	8.1	13.4	362 (99%)	26 (7%)	0	364 (100%)	268 (74%)	5 (1%)	947.6	224.00	0.61	0.19	0.0005
Flood release	23 May 2003 to 10 June 2003	19	2001 (C)	432.3	22.8	56.7	3 (16%)	0	0	9 (47%)	3 (16%)	0	524.9	13.75	0.72	0.03	0.0014
4	1 Sept 2002 to 23 May 2003	266	2001 (C)	1841.8	6.9	12.5	0	0	0	61 (23%)	0	0	538.6	17.57	0.07	0.03	0.0001
3	1 Sept 2001 to 30 Aug 2002	364	2001 (C)	2751.1	7.5	15.9	5 (1%)	0	0	135 (37%)	131 (36%)	0	556.2	93.21	0.25	0.14	0.0004

Flows are measured in m^3 /s and gravel volumes in m^3.

subjected to an 8-day release of 65 m^3/s, specifically designed for environmental purposes.

4.1. Volumetric budget results

DEM differencing of the 11 surveys performed over 4 years showed an overall decrease in placed gravel volume at all sites (Table 2). The total bed volume of 2948 m^3 created in the river among all sites was reduced by 28% by study end. Average site bed elevation change was 0.153 mm day^{-1} (range of 0.022–0.323 mm day^{-1}). Site A experienced a 50% volume reduction over the initial 45 months (September 1999 to June 2003). Site B experienced a 30% decrease over its initial 37 months, while site C experienced a 20% decrease over its initial 20 months.

Among annual surveys, normalized volumetric decreases ranged from 0.07–0.73 m^3/day (26–266 m^3/year) and trended downward over time (Table 2). For all three sites, the largest annual decreases occurred during the first year after placement. Site A showed gradual decreases in change rate until period 4, when it showed an increase. Sites B and C showed strong drops in change rate after the first year.

Sites A and C had higher event-based volumetric decreases than those observed on an annual basis. For site A, the 266-day period prior to the designed release had a 0.33 volumetric change. During the release, it increased to 0.92. For site C, the same numbers were 0.07 and 0.72, respectively. These changes are threefold and tenfold increases for sites A and C, respectively.

4.2. Fluvial erosion estimates

Based on predicted entrainment thresholds (Table 1), strong differences in flow-based scour were evident between sites and between periods (Table 2). Site B has ~4.5 times higher channel slope than either sites A or C, thus requiring a much lower sediment mobility discharge. The greatest overall flow-based scour was predicted at site B. Period 1 had the longest high flow durations, yielding the greatest overall potential for scour. This could only affect site A, as sites B and C were not yet built.

In terms of grain-size specific mobility, large particles were predicted to have rarely moved, while movement of smaller gravels was highly site and period dependent. For the substrate framework D_{90} particles, flows were never high enough to entrain them using $t_c^*=0.045$ for any site (just 5 days at site B for $t_c^*=0.03$). For the median substrate size (D_{50}), sites A and C were not predicted to ever experience scour using $t_c^*=0.045$; but for $t_c^*=0.03$ they would have both scoured ~35% of the time during the first year post-placement, though not in any subsequent periods. Median-sized material at site B was predicted to mobilize for a significant portion of time. Finally, for smaller bed particles (D_{10}), sites A and C were predicted to experience some mobility some of the time, while those at site B should have been susceptible to mobility all of the time.

From an empirical perspective, percent daily bed sediment volume cut was significantly related to average daily discharge (Fig. 8A) and total water volume released from Camanche Dam (Fig. 8B). SHR sites lost 0.05% of remaining material daily (range of 0.01–0.14%). We measured 17.4 m^3 of cut from site A during the 19-day flood increase.

4.3. Fluvial erosion verification—tracer rocks

Of the 800 tracer rocks released at site A in August 1999, 245 were recovered in August 2000 (31%). Of

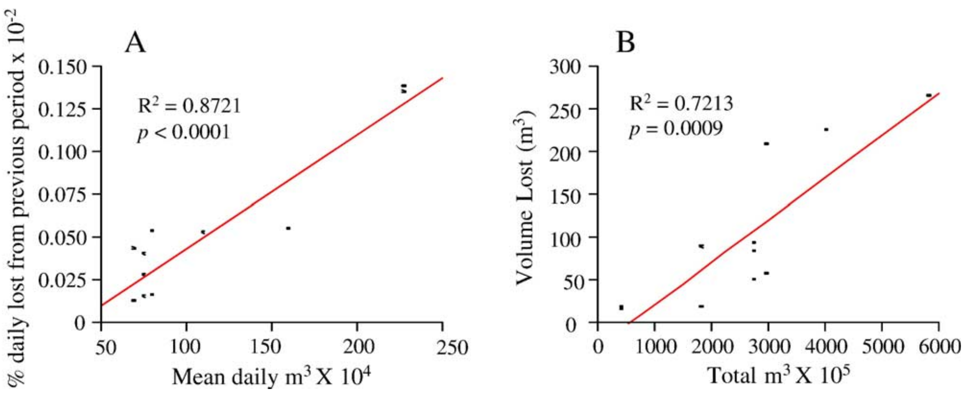

Fig. 8. Comparison of bed cut, as indicated by volume and percent, to river flow at 3 gravel enhancement sites over 5 various time periods, lower Mokelumne River, California. A: Percent daily gravel volume lost from previous period by mean daily m^3 of water released from Camanche Dam; B: Total gravel volume lost (m^3) by total m^3 of water released from Camanche Dam.

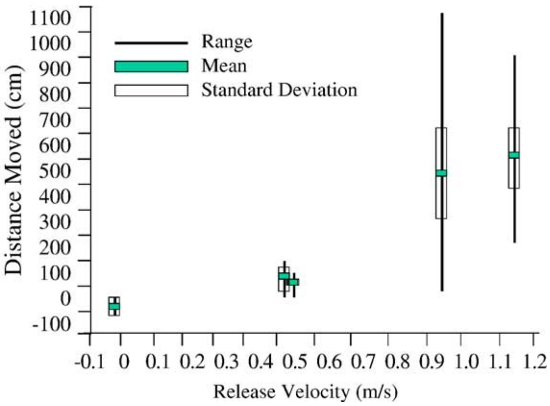

Fig. 9. Distance downstream tracer rocks were recorded after 12 months, compared to velocities recorded at initial release, site A, lower Mokelumne River, California.

those recovered 86% (211) did not move from initial placement locations. The mean distance downstream rocks were recovered after 12 months was 1.64 m (range of −0.38 to 25.81 m) (Fig. 9). Of those recovered that moved, four (12%) left the site. Piles 2, 6, 7, and 8 were completely scoured or buried by 10 June 2003 (Fig. 10). No tracers were recovered from these piles. Twenty-two (22%) of tracer rocks at release location 1 were mobilized upstream. Similarly, of the 500 tracer rocks released at site B in August 2000, 124 (20%) were recovered the following year. Three (2% of recovered, mobilized tracers) were recovered downstream of the site. Site B tracer rocks were disturbed by local visitors to the adjacent public park the following year and no further monitoring was performed. Tracer rocks had a higher propensity to move when placed in areas of higher velocities at low flow, typically near the channel center (Fig. 10). This was also observed for LWD (Fig. 11). By June 2003, four of the original eight tracer rock piles were completely scoured from site A. Maximum distance tracer rocks were recovered from original release locations was 121.9 m downstream in site A, 4 years after original placement.

4.4. In situ slope settling

Overall, as-built project areas with slopes over 23% were between 6 and 12% with the highest at site C (Fig. 12). This equates to 1405, 1393, and 2057 m^2 of area susceptible to slope failure at sites A–C, respectively, and expands to potentially 130, 26 and 19 m^3 of gravel scour at sites A–C, respectively. Greatest reduction in overall site slope (increase in area of slope 0–10°)

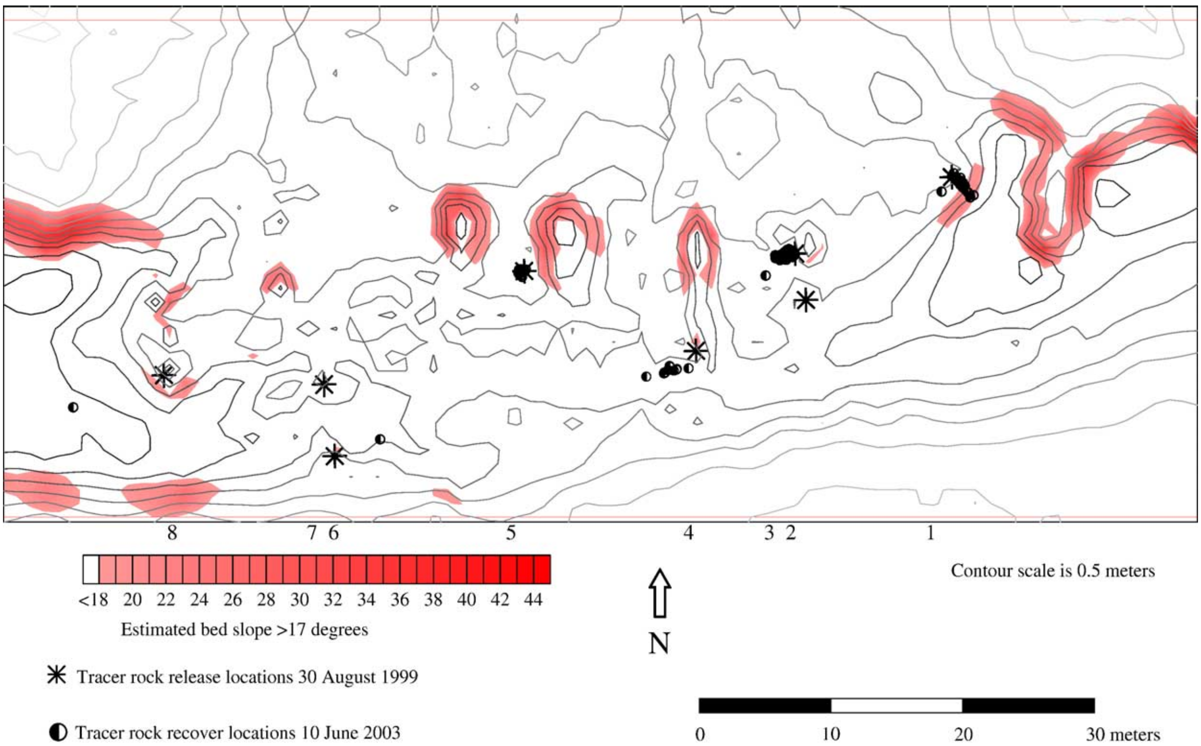

Fig. 10. Tracer rock release and recovery locations in relation to estimated bed areas where slope meets or exceeds the angle of repose. Base map is of as-built contours of site A, 30 August 1999. Numbers indicate tracer rock release pile designation.

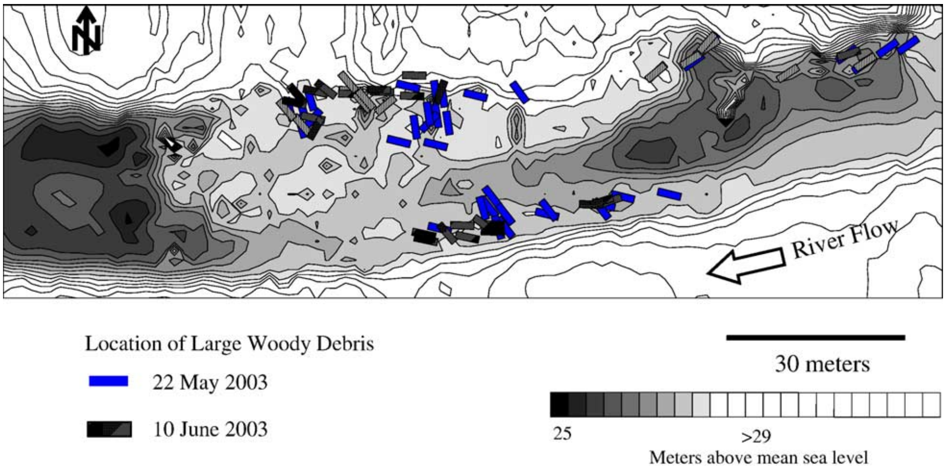

Fig. 11. Location of large woody debris before and after a 19-day flow increase at site A, lower Mokelumne River, California.

occurred after the first year at each site. Predicted areas of high failure potential corresponded well with tracer rock results (Fig. 9).

4.5. Gravel porosity and potential compaction

Estimated bulk density from our six enhancement gravel samples was 1.644 g cm^{-3} (SD: 0.054). Mean estimated gravel porosity was 0.281 (Tables 3 and 4). Likely porosity changes for sites A–C are 0.059, 0.107, and 0.072, respectively, with maximum plausible porosity change of 0.34 for all three sites. Based on porosity calculations, we estimate 28 to 41% of observed gravel volume reduction can be explained by deflation alone (max: 130–190%) (Table 4).

4.6. Scour at boulders and LWD

Site bed elevations lowered 0.022 to 0.323 mm day^{-1} (mean: 0.153). Mean boulder elevation change was 0.588 mm day^{-1} (range −0.053 to 2.054 mm day^{-1}). Average boulder elevational changes were significantly higher than average channel bed elevation between each monitoring period ($t = -1.825$; df = 16; $p = 0.043$).

SHR sites contained from 0.5 to 6.0 pieces of LWD/1000 m^2 of channel bed. While LWD was not captured in site C, we observed nearly a 300% LWD increase at sites A and B over a 4-year period. Some LWD was mobilized during the study, with individual pieces moving completely out of SHR sites within a year of placement. Distinct clumping and mobilization patterns were observed during a short-duration flow increase (Fig. 11). Seven of nine LWD pieces used in the high-density surveys were still intact in August 2000. Average cut around LWD was 0.58 m^3 (SD = 0.231).

4.7. Salmon pedoturbation

Chinook salmon spawning use of three SHR sites was highly variable over several seasons (Table 5; Fig. 4). All three of the SHR sites had no documented spawning previous to gravel placement, although site C had an initial placement of gravel in 1996. Average substrate volume excavated during redd construction was 2.26 m^3 (min: 0; max: 10.37; SD: 2.16). Estimated annual bed material mobilization by spawning salmon within each site was 2.26–65.5 m^3 (mean: 19.13 m^3).

Estimated mean volume loss from mechanisms quantified in this study account for 86 to 113% of volume reductions observed with gravel deflation, faunal pedoturbation (salmon spawning), and surface scour explaining most of this loss (Fig. 13; Table 6).

5. Discussion

Our data show that SHR sites of 649–1323 m^3 of gravel lost from 11–24% of remaining volume annually during controlled flows of 8–70 m^3/s and 2.6% of placed material during short-duration (19 days) flow releases of 57 m^3/s. Site A lost 50% of gravel volume in a 4-year period. By using mean volume loss estimates from mechanisms quantified in this study, we can account for 86 to 113% of volume reductions observed. Overall, deflation appears to have the greatest influence, followed by spawning activity and surface scour. This is not surprising because of restricted flows in the system (Gilvear et al., 2002).

We observed significant bed material volume reductions (up to 20%) during the first year after gravel placement at all sites. Bement and Selby (1997) showed that although it took many minutes to fully reduce gran-

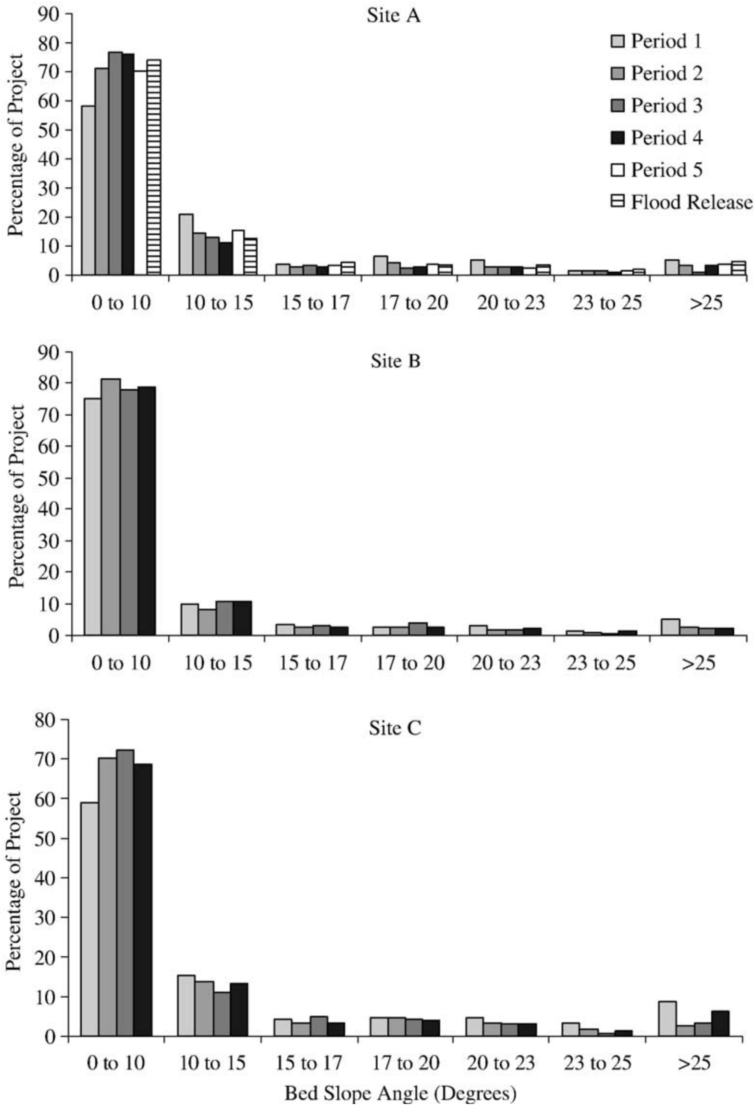

Fig. 12. Slope analysis distribution for sites A–C. Flow Period duration and magnitude are provided in Fig. 3 and Table 2.

ular soil volumes during a vibration test early response was more rapid. Similarly, we observed greater volumetric reduction in placed materials during the earliest surveys of individual sites. Because of selective screening and cleaning of placement gravels, porosity was higher and density was lower within placed gravels than what is typically observed in natural streambed conditions (Bunte and Abt, 2001). This suggests cleaned, placed material has a higher settling propensity. However, because in situ bed porosity and bulk density were not measured through time, we cannot quantify what proportion of volumetric change predicted by DEM differencing is due to settling. Measurement error must also be taken into consideration (Fuller et al., 2003).

Table 3
Estimated porosity compared to volume change of placed gravels at three spawning enhancement sites in the lower Mokelumne River, California

Site	D_{min}	D_{max}	Estimated Porosity (Φ)	Estimated percent volume lost 1st year	Total time monitored	Overall percent volume lost	Estimated percent volume lost day^{-1}
1999 (A)	16	178	0.301	25	1385	50	0.0360
2000 (B)	4	178	0.253	24	1104	25	0.0226
2001 (C)	8	127	0.289	17	651	18	0.0270

Table 4
Estimated gravel deflation at three spawning enhancement sites due porosity

Period	Volume loss (m^3)	Likely deflation		Plausible deflation	
		Volume (m^3)	Proportion	Volume (m^3)	Proportion
Site A:		Porosity: 0.301			
Calculated fill: 1323 m^3					
1	264.9	184.6	0.7	1063.5	4.0
2	207	184.6	0.9	1063.5	5.1
3	83.2	184.6	2.2	1063.5	12.8
4	87.6	184.6	2.1	1063.5	12.1
Flood flow	17.4	184.6	10.6	1063.5	61.0
Total lost:	660.2	184.6	0.3	1063.5	1.6
Site B		Porosity: 0.253			
Calculated fill: 1147 m^3					
2	224	136.6	0.6	434.2	1.9
3	56.5	136.6	2.4	434.2	7.7
5	48.9	136.6	2.8	434.2	8.9
Total Lost:	329.4	136.6	0.4	434.2	1.3
Site C		Porosity: 0.288			
Calculated fill: 649 m^3					
3	93.2	50.9	0.5	240.4	2.6
4	17.6	50.9	2.9	240.4	13.7
Flood flow	13.7	50.9	3.7	240.4	17.5
Total lost:	124.5	50.9	0.4	240.4	1.9

While our entrainment and compaction estimates indicate site B should have the highest volume loss potential, several site-specific aspects may explain why this did not occur. Because of a channel bend, site B was the only site receiving flow somewhat diagonally across the placed gravel, from the SE to the NW portion of the site. Flow actually cut into the site's north bank. Slower flow on the south bank, further protected by trees, actually settled fines (<8 mm diameter) out. These fines reduced the overall D_{10}–D_{90} of the site, yet were protected from the main force of channel flow.

According to Konrad et al. (2002), the probability of bed material transport is approximately uniform over a gravel bar during a flood, provided the bar has uniform sedimentologic and hydraulic conditions. Within our SHR sites, shallow berms, LWD, and boulders are used to attract spawning Chinook salmon. Such features specifically alter uniform gravel beds, adding complexity. Our data suggest that these features increase gravel scour within SHR sites, supported by Rosenfeld and Huato (1993).

LWD can also affect secondary morphological structures within a channel (Mutz, 2000). Over the monitoring period, we observed no net LWD loss. Surprisingly, all three sites entrained as much LWD as was lost over the study period even as close as they were to Camanche Dam, which does not pass upstream LWD. This suggests that adjacent riparian vegetation is gen-

Table 5
Number of Chinook salmon redds observed at each of three spawning gravel enhancment sites (A, B and C) in the lower Mokelumne River, California

Year	A				B				C			
	Number	Percent total[a]	Volume (m^3)[b]	Percent mobilized[c]	Number	Percent total	Volume (m^3)	Percent mobilized[c]	Number	Percent total	Volume (m^3)	Percent mobilized[c]
1999	1	0.2	2.3	0.2	0	0.0	0.0	0.0	3	0.5	6.8	1.0
2000	29	2.9	65.3	4.9	18	1.8	40.5	3.2	1	0.1	2.3	0.3
2001	5	0.6	11.3	0.1	11	1.3	24.8	1.9	7	0.8	15.8	2.2
2002	2	0.2	4.5	0.3	16	1.9	36.0	2.8	5	0.6	11.3	1.6
2003	8	1.1	18.0	1.4	17	2.1	38.3	3.0	4	0.5	9.0	1.3

[a] Percent of total lower Mokelumne River Chinook salmon redds observed at each site.
[b] Estimated total volume of gravel mobilized by spawning Chinook salmon.
[c] Percent volume of total placed gravel mobilized by spawning Chinook salmon.

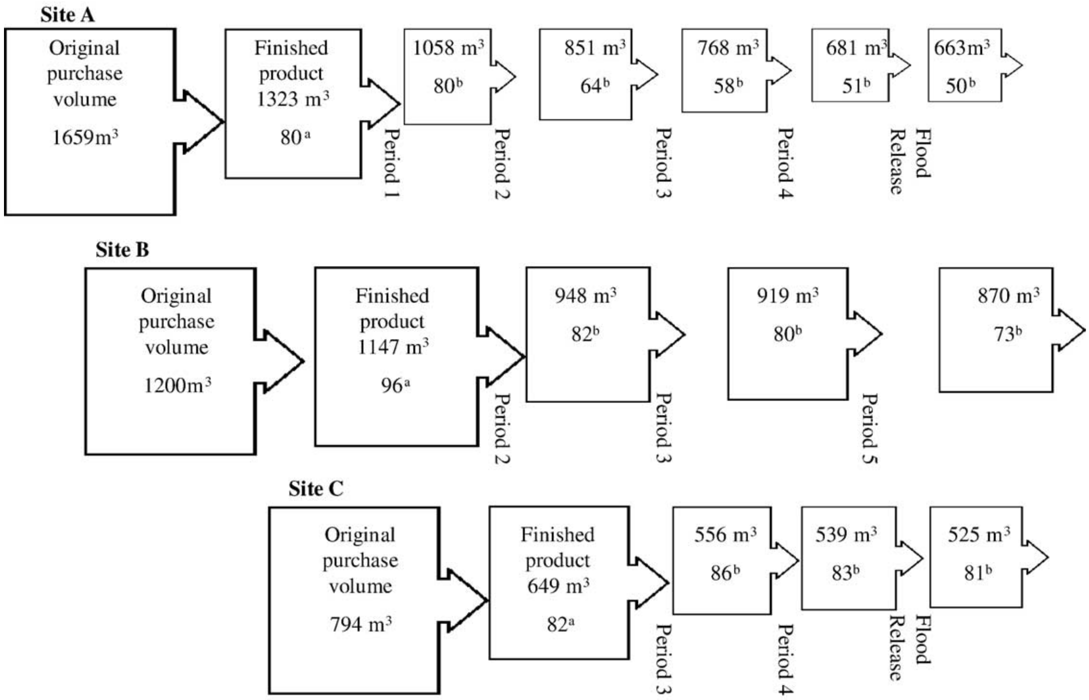

Fig. 13. Volumetric gravel budget for three Chinook salmon spawning enhancement projects in the lower Mokelumne River, California. Time periods are provided in Fig. 3 and Table 2.

erating enough material to compensate annual loss, at least during a period of relatively low and stable flows. LWD collected on the constructed gravel berms for periods of <12 months to >4 years. Merz (2001) concluded that such debris is important to spawning salmon, and these observations suggest that captured LWD may further benefit constructed spawning habitat. LWD budgets have been calculated for several northwestern coastal streams of the U.S. (Martin and Benda, 2001; Benda and Sias, 2003). The importance of this debris has been associated with maintenance of riverine gravel bars and structures (Everest and Meehan, 1981; Sedell et al., 1983). Surprisingly, we were not able to substantiate any LWD budget estimates for California Central Valley streams within the literature. To further benefit SHR sites, an LWD budget (including riparian woody vegetation regeneration) should be addressed (Gippel et al., 1996).

According to Gottesfeld et al. (2004), spawning salmon likely play an integral role in the sediment transport dynamics and annual sediment budget of stream reaches. Using tracer recovery experiments, they found that spawning salmon mobilized sediment only for short distances but were able to mobilize similar depths of bed material as annual floods did. This influence on sediment residence time and turnover frequency has important implications on the quality of the intra-gravel environment and subsequent survival of salmon embryos (Merz et al., 2004). Visible tailspill lengths for Chinook salmon redds in the LMR are typically 1 to 1.5 m in length, although tailspills have been reported as long as 6 m (Merz, unpublished data). This too suggests that while salmon may not necessarily mobilize material completely out of a site, they can have a significant impact on sediment turnover and potentially site morphology. It is possible for a site to have regular turnover and/or throughput of sediment while maintaining a consistent morphology. From a habitat sustainability perspective, the key is that some level of geomorphic dynamism is in place—not necessarily a static morphological habitat feature.

Considering the average gravel placement volume at each site was 1217 m^3, an average female Chinook salmon could rework ~0.2% of an LMR enhancement project. Therefore, 538 spawning female Chinook salmon could potentially rework an entire enhancement site. On average, annual construction at these SHR sites has been 11 redds. Assuming these averages persist, fall-run Chinook salmon might mobilize an entire enhancement site in about 49 years. Changes to the number of naturally spawning LMR salmonids may significantly affect this period. While over the short-term increased

Table 6
Observations of volumetric changes to the channel bed at three spawning gravel enhancment sites in the lower Mokelumne River, California

Site		Original purchase volume (m^3)	DEM error (m^3)	Operational losses (m^3)	Finished product		Duration of monitoring (Days)	Total volume loss	DEM error (m^3)	Mechanisms	Mechanism portion of total volume loss	Remaining volume (m^3)	DEM error (m^3)
					Volume (m^3)	DEM error (m^3)							
A	Actual	1659	±31.52	300 to 363	1323	±25.1	1380	659.9	±12.52			663.1	±12.6
	Percent									Deflation	30% to 160%		
			1.9%	18.1–21.9%	80%	1.9%		49%	2%	Faunal pedoturbation	0% to 15%	51%	1.9%
										Surface scour	8% to 33%		
										Local scour	1.5% to 3.5%		
										Slope angle (slippage)	3.1% to 9.8%		
										Total percent of observed volume loss:	42.1% to 221.3%		
B	Actual	1200	±22.8	25 to 71	1147	±21.79	1118	247.8	±4.71			870.2	±16.5
	Percent		1.9%	2.1–5.9%		1.9%		25%	1.90%	Faunal pedoturbation	0% to 42%	76%	1.9%
										Surface scour	4.5% to 27%		
										Local scour	0.8% to 2.0%		
										Slope angle (slippage)	0.4% to 2.3%		
										Total percent of observed volume loss:	45.7% to 203.3%		
C	Actual	794	±15.1	128 to 158	649	±12.33	650	125.1	±2.38			524.9	±9.9
	Percent									Deflation	40% to 190%		
			1.9%	16.1–19.9%		1.9%		19%	1.90%	Faunal pedoturbation	0% to 36%	81%	1.9%
										Surface scour	5.4% to 32.5%		
										Local scour	0.4% to 0.8%		
										Slope angle (slippage)	0.9% to 2.9%		
										Total percent of observed volume loss:	46.7% to 262.2%		

complexity attracts more spawning fish, shortened habitat lifespan from other forms of site degradation, lack of turnover and/or gravel loss may offset the relative importance of volumetric losses from spawners; may require some balancing between site attractiveness and longevity. In this context, if increased and continued salmon spawning is the goal of a specific spawning gravel enhancement project, is it better to have high spawning activity for a short period of time with short site longevity or low levels of spawning activity over a longer time period with long site longevity? Such a myopic management goal may be inappropriate, and ill-suited to providing habitat sustainability via geomorphic dynamism.

5.1. Management implications

While complexity is an extremely important aspect of ecological function, production of highly diverse and complex habitat features appears to come at a cost to site longevity. River restoration projects tend to provide little (if any) short-term monitoring and then declare success (Wheaton et al., 2004e). Particularly in the regulated river setting, the notion of self-sustainability may have little utility. Sustainability concepts would suggest that building and maintaining specific substrate features are less important than providing environmental processes necessary to rejuvenate new features as older features are destroyed. This includes insuring that mobilized enhancement gravels have the potential to be deposited to form future spawning sites instead of filling large gravel-mining pits downstream.

In highly managed systems with little natural coarse sediment recruitment, complex sites constructed with edges, high velocity chutes, and obstructions such as LWD and boulders will become less complex through time (scour, sinking of boulders, and even salmon erode and simplify site complexity) (Frissell and Nawa, 1992). Practically speaking, without disturbance, complex, organized systems tend to become simple and unorganized. Such disturbance, typically in the form of flood events, is receiving increasing attention as a mechanism for maintaining habitat and biota diversity in large, temperate streams (Huston, 1996; Townsend et al., 1997; Sparks and Spink, 1998). Our observations of tracer rock mobilization, channel cut at placed boulders, and constructed areas of high velocity suggest that complexity may actually reduce life-expectancy of a given enhancement site unless energy (in the form of additional gravel) is added to the site to maintain its complexity. While not a component of this study, Smith et al. (2004) observed an increase in rooted aquatic vegetation at sites A and C during the relatively stable flows of 2001 and 2002. This appeared to reduce spawning activity (Fig. 4). The 2003 study release removed a significant amount of rooted vegetation within the spawning gravel, which appeared to positively correlate with increased spawning use. In regulated systems with flow regimes incapable of supporting geomorphic dynamism, artificial intervention (e.g. gravel augmentation, SHR) may be necessary to prevent sites from returning to simple, degraded habitats over time (Wheaton et al., 2004b).

Numerous authors discuss the importance of habitat heterogeneity to restoration (Harper et al., 1999; Jungwirth et al., 1995). According to Ward and Tockner (2001), re-establishing functional diversity (e.g., hydrologic and successional processes) across the active corridor could serve as the focus of river conservation initiatives. Once functional processes have been reconstituted, habitat heterogeneity will increase, followed by corresponding increased diversity of aquatic and riparian species. Merz and Setka (2004) inferred that the addition of complexity to restoration sites within a highly regulated stream attracted spawning salmon to those sites. Wheaton et al. (2004d) proposed several habitat heterogeneity metrics relevant to spawning salmonids, which seemed to explain the utilization of heterogeneity elements by spawning salmonids. Increased benthic macroinvertebrate production and increased survival of Chinook salmon and steelhead embryos have also been observed (Merz et al., 2004; Merz and Chan, 2005). However, increased heterogeneity, especially in the way of structure and edge, increases erosive power within the site, not only through geomorphological principals (Buffington et al., 2002) but through increased substrate mobilization by increased numbers of spawning fish. For instance, our tracer rock and channel DEM modeling shows increased erosive force where greatest velocities are created or large structures have been placed.

This then begs the question as to whether form or function is the ultimate SHR goal. Unfortunately, creation or enhancement of specific habitats, such as spawning beds, has been interwoven into the false perception that natural aquatic systems are stable entities (Middleton, 1999). This misperception, coupled with the concept that habitat longevity equates to restoration success, may doom many projects to perceived failure. Restoration objectives are commonly based on value-laden societal choices (Davis and Slobodkin, 2004). Thus, if restoration science suggests that continued intervention is the cost of maintaining spawning habitat in a regulated river setting, is society willing to pay the price?

According to Middleton (1999), the perception of natural systems as stable entities may be rooted in human memory and cultural background. Importance of long-term maintenance of stream ecosystem processes should not be misconstrued as longevity of specific channel features, such as gravel berms and bars. In fact, Beechie and Bolton (1999) argued that attempts to build stable habitats may interrupt long-term processes that maintain habitat diversity. Our observations suggest that stable features in such regulated streams as the LMR may actually become less attractive and functional to spawning salmonids over time.

While this study provides some insight into the volumetric budget for site-specific spawning enhancement projects within the LMR spawning reach, it is important to note that our present method does not take into account the sediment deficit from historic mining and channel aggradation caused by flow regulation. Nor does it specifically take scale into account for DEM uncertainties (Wheaton et al., 2004a). According to Kondolf (1998), if changes in dammed rivers because of altered flow and sediment transport are not recognized, restoration designs are likely to be ineffective or inappropriate. Therefore, restoration may be driven by the desire to return to a historical condition, but it should be designed with contemporary processes and realities in mind. Perhaps then, this budget should be supplemented with an appropriate volume of material to restore acceptable channel geometry and to reduce the size and number of abandoned mining pits to satisfactory levels (Kondolf, 1997). This amount of material may be constrained more by fiscal budgets, gravel available, and the societal decisions of what is satisfactory than by geomorphic and hydrologic science. Once these factors are addressed, this volumetric budget might become a more meaningful component of a long-term restoration and management plan.

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