Spawning Habitat Enhancement For Pacific Salmon (*Oncorhynchus spp.*) In A Regulated River

By

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Abstract- Large, temperate rivers (LTR) throughout the northern hemisphere have undergone dramatic and long-term anthropogenic changes. Such impacts have altered the hydrologic, sediment, temperature and flow regime of these systems and have had negative impacts on their native flora and fauna. Numerous projects have been undertaken to counteract these impacts in the past three decades. Unfortunately, a strong tendency has emerged to focus river conservation, restoration and monitoring on charismatic or economically important fauna without thorough consideration of watershed attributes and processes of the watershed that control biodiversity and production. Furthermore, uncertainty as to how well restoration projects actually work demonstrates the critical need for research to evaluate how habitat manipulations directly influence aquatic resources. Confounding our understanding of how to restore riverine function is the fact that most LTR have been under some state of impairment long before any attempt was made to study them, making evaluation even more difficult.

In this study, I examined the effects of chinook salmon (*Oncorhynchus tschawytscha*) and steelhead (*O. mykiss*) spawning habitat enhancement on specific parameters associated with the spawning environment in the Mokelumne River, a regulated stream in California’s Central Valley. Specifically, I assessed:

1. effectiveness of a project to enhance spawning habitat for chinook salmon;
2. benefits of gravel enhancement to the development and survival of native chinook salmon and steelhead embryos;
3. effects of gravel enhancement on the benthic macroinvertebrate community associated with these spawning habitat enhancement sites and;
4. prospects of estimating an appropriate bed sediment budget for these projects.
Results from specific assessments are as follows:

Physical measurements taken before and after gravel placements show that spawning gravel enhancement sites significantly increased channel water velocities, intergravel permeability and dissolved oxygen, reduced channel depths and equilibrated intergravel and ambient river temperatures. These positive benefits remained throughout a 30-month monitoring period. Adult chinook salmon began spawning at previously unused sites within 2 months after gravel placement and continued to use sites for the length of the study period. Topographical channel surveys provided a useful tool for monitoring bed material transport and layering redd locations on contour maps.

Spawning bed enhancement increased survival of chinook salmon embryos in a regulated California stream with a gravel deficit. Eyed chinook salmon eggs planted in enhancement gravels had higher survival to swim-up stage than did eggs planted in unenhanced spawning gravels, although no significant difference in growth was observed. Intergravel temperatures and substrate size within spawning sites were highly correlated with distance downstream from the lowest non-passable dam. Strong correlations were also observed between intergravel turbidity and total suspended and total volatile solids. Four multiple regression models built with a combination of physical parameter measurements performed well in predicting survival and length of chinook salmon and steelhead embryos under various conditions. Survival models accounted for 87% of the variation around the mean for chinook salmon and over 82% for steelhead. Growth models accounted for 95% of the variation around the mean for chinook salmon and 89% for steelhead. These findings suggest that spawning bed enhancement can improve survival of salmonid embryos in degraded habitat.
Additionally, measuring a suite of physical parameters before and after spawning bed manipulation can accurately predict benefits to target management species. Gravel enhancement can be an effective means for improving salmon spawning habitat in rivers with low gravel recruitment because of upstream dams.

In spawning enhancement projects, benthic organisms colonized new gravels quickly, equaling densities and biomass of unenhanced spawning sites within 4 weeks. Macroinvertebrate species richness equaled that of unenhanced sites within 4 weeks and diversity within 2 weeks. Standing crop, as indicated by densities and dry biomass, was significantly higher in enhancement sites after 12 weeks and remained so over the following 10 weeks. Although mobile collector/browsers initially dominated new gravels, sedentary collectors were the most common feeding category after 4 weeks, similar to unenhanced sites. These data suggest that cleaned gravels from adjacent floodplain materials, used to enhance salmonid spawning sites, are quickly incorporated into the stream ecosystem, benefiting benthic macroinvertebrate densities and dry biomass.

Finally, short-term bed elevation and feature adjustments were monitored over 36 months at three Chinook salmon (*Oncorhynchus tschawytscha*) spawning bed enhancement sites in the regulated lower Mokelumne River, California. Our data show that spawning bed sites containing 794 – 1323 m³ of enhancement gravel lost from 3-20% of remaining gravel volume annually during controlled flows of 8 – 70 m³ sec⁻¹ and 2.6 – 4.6% of placed material during short-duration (19 days) flow releases of 57 m³ sec⁻¹. The oldest site lost ~50% of placed material over the four-year monitoring period. Of the mechanisms monitored, gravel deflation was the greatest contributor to volumetric
reductions, followed by surface scour. Salmon spawning, scour around placed features and over-steepened slopes also contributed to volumetric reductions. As sites matured, reductions were less pronounced. Sites entrained as much large woody debris as was lost over the study and large woody debris settled on constructed gravel berms for periods of <12 months to >4 years. While complexity is an extremely important aspect of ecological function, production of highly diverse and complex habitat features appears to come at a cost. Placement of features such as gravel berms, boulders and large woody debris, to attract spawning Chinook salmon, increased gravel cut within enhancement sites. Furthermore, increased spawning activity can reduce the longevity of enhancement sites.
CHAPTER ONE
HUMAN DISTURBANCE AND TEMPERATE RIVERS

Many of the world’s temperate rivers have been altered in function and carrying capacity due to human disturbances (Fischetti 2001, Voeroesmarty and Sahagian 2000). Amongst these disturbances are dams, levees, mining, and overall watershed degradation, including increased pollution, road construction, and watershed vegetation changes (Dynesius and Nilsson 1994, Shiemer et al. 1999, Baras and Lucas 2001). All of these impacts alter the composition and delivery of sediments to and through river systems. For instance, dams typically reduce bed material production and transport and increase channel scour, degrading the historic channel, while passing fines that can armor the channel and reduce interactions between the river and the hyporheic environment (Stanford et al. 1996). Leveed and armored banks reduce lateral channel movement and expansion to the historic floodplain, exacerbating these problems further. Mining pits, often incorporated into the remaining river channel, act as bed material traps, cutting the continuity of sediment transport in the remaining contiguous channel (Kondolf 1997).

ANADROMOUS SALMONIDS

Many organisms rely on healthy exchanges between the hyporheic and stream environment, including plants, microbes, benthic macroinvertebrates and fish species for all or a portion of their life histories (Mahoney and Rood 1998, Rubin 1998, Brunke 1999, Ward and Tockner 2001). Around the Northern Hemisphere, anadromous salmonid fish species have seen dramatic declines over the past 150 years. Many declines have been tied to over-harvest and the impacts mentioned above (Zeh and Donni
1994, Brown et al. 1994, Yoshiyama et al. 1998, Ingendahl 2001). While anadromous salmonids spend a large portion of their juvenile and/or adult lives within the marine environment, most require cool, clear, gravel streams with the appropriate physical parameters for each species for spawning and egg incubation. Much of the historical habitat required for this portion of their lives is now behind or beneath large barriers or is otherwise inaccessible to migrating adults and much of the remaining available habitat has been degraded (Yoshiyama et al. 1998). Compounding impacts to temperate rivers are the introduction of numerous alien species (Gehrke and Harris 2001) further impacting native communities already stressed by habitat modification (Meffe 1985, Moyle and Williams 1990, Brown and Moyle 1991, Muzika and Liebhold 1997, Hill et al. 1998, Arndt et al. 2000).

In the past 3 decades, numerous projects have been undertaken to counteract these impacts. Such projects include manipulation and augmentation of stream flow and spawning gravels, reduction or removal of fine sediment sources within watersheds, revegetation of riparian corridors to reduce water temperatures, reconnection of floodplain water bodies and main channels, removal of instream impoundments to increase spawning sediment quality and quantity and to facilitate fish migration, and control of non-native populations by aggressive harvest (Grift et al. 2001, Marchetti and Moyle 2001, Kondolf 2000, Tyus and Saunders 2000, Nakamura 1999, Stanford et al. 1996). Unfortunately, a strong tendency has emerged to focus river conservation, restoration, and monitoring on charismatic or economically important fauna without thorough consideration of the attributes and processes of the watershed that control biodiversity and production (Stanford et al. 1996, Sparks 1995). An example can be seen in the state
of California, where salmonid spawning gravel augmentation was taking place on more than 13 dammed Sierra Nevada rivers beginning as early as 1979 (Kondolf and Mathews 1993). While little work has been done to assess whether gravel augmentation actually improves salmonid spawning habitat, even less study has involved effects of gravel augmentation on associated organisms (Kondolf et al. 1996, Kondolf 1998). For instance, many lotic macroinvertebrate species are found in the same habitat utilized by anadromous salmonid species for spawning (Platts et al., 1983, Mangum, 1986, Groot and Margolis, 1991), are important to the ecology of lotic systems (Gore, 1985, Hershey et al., 1993, Hamilton and Barclay, 1998, Hocking et al., 2002) and can be significantly impacted by river regulation (Blinn et al. 1995, Dessaix et al. 1995, Cortes et al. 2002). Yet, no published literature exists, to date, on the effects of salmonid spawning gravel augmentation on benthic macroinvertebrate communities. This demonstrates the critical need for researchers to evaluate how substrate, water quality, and hydrologic manipulations directly influence aquatic assemblages (Walters et al. 2001, Kondolf 2000, Lisle and Lewis 1992). Confounding our understanding of how to restore riverine function is the fact that most LTR have been under some state of impairment long before any attempt was made to study them (Hudson 1997, Ward et al. 2001).

In this study, I evaluate salmonid spawning gravel enhancement on the lower Mokelumne River, California. Specifically, I assess the effectiveness of a project to enhance spawning habitat for chinook salmon; the benefits of gravel enhancement to the development and survival of native chinook salmon (*Oncorhynchus tschawytscha*) and steelhead (*O. mykiss*) embryos; the effects of gravel enhancement on the associated benthic macroinvertebrate community; and the prospect of estimating an appropriate bed
sediment budget for these projects. The ultimate goal of this study is to understand how to best rejuvenate benthic processes within the spawning reaches of temperate rivers to return them to a reasonable state of ecosystem function.

THE MOKELOMNE RIVER- A CASE STUDY

The Mokelumne River is a snow-fed system that drains approximately 1,624 km$^2$ of the central Sierra Nevada. Its headwaters begin in the Eldorado National Forest, some 65 km south of Lake Tahoe, at approximately 3,050 m above mean sea level. A major tributary of the Sacramento-San Joaquin River system, it enters the Sacramento-San Joaquin Delta ~ 48 km southeast of Sacramento. The Mokelumne River 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$^3$).

The lower Mokelumne River (LMR) ranges in elevation from approximately 28 m at Camanche Dam, the lowest non-passable barrier to anadromous fish, to sea level at Thornton (Fig. 1). The gradient of this section of river ranges from 0.10% near Camanche Dam to 0.02% near the Cosumnes River confluence. Tidal influences are observed as high as RKM 45 near the town of Thornton. Similar to many other tributaries of the system, hydraulic mining, gravel extraction, dam construction, water diversions, altered flow regimes, deforestation, artificial bank protection, channelization and levee construction have resulted in depleted, degraded and otherwise, inaccessible gravel beds within the river.

Channel widths of the LMR range from 19 to 43 m with a mean of 30 m. The river tends to be wider in the first 9.5 km below Camanche Dam and, with the exception
of Lodi Lake, generally narrower downstream to the tidal reach. Much of the narrowing of the channel downstream can be attributed to flood control levees built to protect homes and farmland on the historical floodplains of the river. There are approximately 64 km of levee constructed on the LMR between Camanche Dam and tidal influence.

The LMR flows through floodplains and alluvial fan deposit soils of the Valdez-Columbia and Hanford-Greenfield associations which are both sandy-loams with good to poor drainage characteristics (Weir 1952, USSCS 1967). Tailings from continuing and abandoned gravel mining operations are apparent along the upper third of the LMR. These tailings are isolated from the river by berms and levees although several mining pits are now incorporated into the present river channel. Geologic formations associated
with the river include the Mehrten Formation consisting of Andesitic conglomerates, sandstone, and breccia near Camanche Dam, and mostly alluvium, levee and channel deposits (sand and mud) downstream to the Delta region.

Substrates within the LMR channel include limited amounts of gravels and cobbles for about 9.5-14.5 km below Camanche Dam and sand, mud, sandstone or highly compacted alluvium down the remainder of the river. Substrate types are associated with channel width, river gradient and hydraulic conditions. The gravel-cobble substrates are mostly associated with the broader river channels and higher gradients with fast, shallow riffle-run hydraulics. Substrates of narrower, deep channels with pools and slow runs are mostly sand and mud. Sand and mud substrates are dominant along the extensive low gradient of the river as it flows through low-lying floodplain below Camanche Dam.

Recruitment of suitable spawning gravels below Camanche Dam is minimal. The dam blocks gravel movement from upstream and immediately below the dam there is no source of replacement gravels. Murphy Creek, a small tributary that enters on the north bank at RKM 101.7, contributes only a small amount of gravel to the river. Otherwise, the LMR receives little drainage and coarse sediment. Also, several historic gravel and gold mining operations along the river significantly reduced the quantity of gravel in the river, although all gravel mining activities are currently off-channel behind levees. Channel and banks show little evidence of instability that could lead to gravel recruitment.

According to Pasternack et al. (2003), the active channel below Camanche Dam is now half its former width and incised. Hydrologic analysis of pre-dam (1904–1963) and post-dam (1964–1999) annual peak flows below the dam (USGS ID 11323500) shows
the impact. Prior to Camanche Dam, annual peaks exceeded 200 m$^3$• sec$^{-1}$ for 21 of 57 years. Since 1964, annual peaks have never exceeded 200 m$^3$• sec$^{-1}$. Pre-dam mean monthly flow had a typical snow-melt hydrograph, with highest flow during May and June, well after peak precipitation. The post-dam hydrograph shows a significant reduction in late spring snowmelt runoff below the dam. A flood frequency analysis using annual extreme pre- and post-dam data shows a dramatic reduction in flow for all recurrence intervals after the dam was built. Estimated using Log Pearson III distributions, Q$_2$, Q$_5$, Q$_{10}$, and Q$_{100}$ decreased by 67, 59, 73, and 75%, respectively (Wang et al. 2001). The statistical bankfull discharge (Q$_{1.5}$) prior to Camanche was 120 cm, which is now released only about every five years. Flow out of Camanche has a step hydrograph, with lows near the minimum (4.25 cm) prescribed in the Joint Settlement Agreement for relicensing (Federal Energy Regulatory Commission (FERC), 1998).

Average annual discharge for the Mokelumne River before Camanche Dam (period 1905 – 1963) was 26.3 m$^3$• sec$^{-1}$ (min 0; max 761.7) at the town of Clements (Fig. 1). Post dam average daily flow (period 1964 – 2000) is 22.6 m$^3$• sec$^{-1}$ (min: 0.7; max: 162.8) with US Army Corps of Engineers flood flows set at 142 m$^3$• sec$^{-1}$.

Presently, the LMR floodplain is dominated by agriculture, including walnut and winegrape production, livestock grazing and an increasing number of single-family dwellings. Riverbanks are characterized by 50 to 100-m sections of broken concrete and stone riprap with a thin ribbon of Fremont cottonwood (Populus fremontii), valley oak (Quercus lobata), willow (Salix spp.), and red alder (Alnus rubra). Numerous non-native trees and shrubs such as black locust (Robinia pseudo-acacia), Himalayan blackberry (Rubus discolor), and Giant Reed (Arundo donax) are also common.
The LMR supports over 35 native and non-native fish species. These fish include five anadromous species: Fall-run chinook salmon, winter steelhead trout, American shad \textit{(Alosa sapidissima)}, striped bass \textit{(Morone saxatilis)} and Pacific lamprey \textit{(Lampetra tridentata)}. Native chinook salmon and steelhead trout populations are supplemented by fish production at the Mokelumne River Fish Hatchery located at the base of Camanche Dam. Between 1990 and 2002, chinook salmon runs into the LMR have ranged from 410 to 10752 (average: 5,506) with ~40 to 80 percent of returning fish entering the MRFH. Adult steelhead have averaged less than 100 individuals annually with most hatchery production imported from the Feather River or American River (Nimbus) hatcheries. 

Further information on LMR chinook salmon and steelhead is provided in Merz and Setka (2004). Introduced American shad and striped bass have not been documented above the Woodbridge Irrigation District Dam, which creates Lake Lodi (Fig. 1). The most abundant native fish species, in addition to chinook salmon and steelhead trout, are prickly sculpin \textit{(Cottus asper)}, Sacramento sucker \textit{(Catostomus occidentalis)}, and hitch \textit{(Lavinia exilicauda)} (Merz 2002). Abundant nonnative fishes include western mosquitofish \textit{(Gambusia affinis)}, largemouth bass \textit{(Micropterus salmoides)}, spotted bass \textit{(M. punctulatus)}, and golden shiner \textit{(Notemigonus crysoleucas)}.

In 1990, East Bay Municipal Utility District (EBMUD) initiated an experimental chinook salmon spawning gravel project by placing approximately 382 m$^3$ sec$^{-1}$ of suitable-sized gravel in the LMR just below the fish diversion fence below Camanche Dam (Figure 1). The objective was to enhance existing spawning areas as a means of increasing reproductive success of fall-run chinook salmon. The project was continued over the next 7 years (except 1995) in cooperation with the California Department of Fish
and Game (CDFG) and Department of Parks and Recreation and typically consisted of placing washed river gravel in known spawning areas.

In August 1998 EBMUD, CDFG, and United States Fish and Wildlife Service (USFWS) began implementation of the Mokelumne River Gravel Enhancement Project (FWS Agreement #113328J200). The spawning gravel replenishment and rehabilitation were intended to increase available and usable spawning habitat, improve intergravel permeability and ultimately increase production of fall-run chinook salmon and steelhead. While initial studies suggest that such projects improve environmental variables associated with and attraction of spawning adult salmon (Merz 1997), little work has been done to evaluate direct benefits of such gravel augmentation projects. This dissertation is an attempt to fill some of that gap.

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CHAPTER TWO
EVALUATION OF A SPAWNING HABITAT ENHANCEMENT SITE FOR
CHINOOK SALMON IN A REGULATED CALIFORNIA RIVER

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Abstract.—An evaluation was conducted of the effectiveness of a project to enhance spawning habitat for chinook salmon in the Mokelumne River, a regulated stream in California’s Central Valley. Approximately 976 m$^3$ of clean river gravel (25 – 150mm) was placed in berm and gravel bar configurations, along the 45-m enhancement site. Physical measurements taken before and after gravel placement indicate the project significantly increased channel water velocities, intergravel permeability, and dissolved oxygen, reduced channel depths and equilibrated intergravel and ambient river temperatures. These positive benefits remained throughout the 30-month monitoring period. Adult chinook salmon began spawning at the previously unused site within 2 months after gravel placement and continued to use the site for the length of the study period (three spawning seasons). Bed material movement was documented by channel bathymetry surveys over two water years. Topographical channel surveys proved to be a useful tool for monitoring bed material transport and layering redd locations on contour maps. Gravel enhancement can be an effective means for improving salmon spawning habitat in rivers with low gravel recruitment because of upstream dams, although their usefulness in restoring salmon populations is poorly understood.

INTRODUCTION

Throughout the Pacific Northwest, spawning habitats of anadromous salmonids have been significantly degraded through dam and levee construction, water diversion, bank armoring, mining, and widespread changes to surrounding watersheds. These alterations have had significant impacts on native salmonid populations (Yoshiyama et al.
Riverine salmonids typically spawn in cool, clear, well-oxygenated streams with suitable depth, water velocity, and gravel size for each species (Bjorn and Reiser 1991). Dams and other fish migration barriers have made spawning reaches of many streams inaccessible and remaining habitat degraded or depleted. Disruption of sediment transport, removal of gravel by mining, and poor management of remaining bed material below these barriers continue to degrade remaining spawning habitats (Nelson et al. 1987; Sear 1993; Kondolf 1997; Hancock 2002). While attempts have been made to mitigate for habitat loss through hatchery propagation, there is a growing concern about reliance on hatchery production and increased interest in enhancing and maintaining viable salmonid populations through restoration and maintenance of remaining accessible habitat (White 1996; Knudsen et al. 2001; Levine et al. 2001).

One of the principal means proposed for salmonid restoration in regulated streams is establishing a “natural” flow regime (Poff et al. 1997) including periods of high flow for maintaining a dynamic river channel. Implementation of channel maintenance flows is often viewed as necessary to achieve desired stream character and enhance aquatic and riparian habitat (Andrews and Nankervis 1995). However, in streams with bed material deficits such flows may exacerbate already scoured or degraded stream channel problems. Furthermore, increasing human encroachment on the historic floodplain greatly limits the size and extent of high management flows. As a result, gravel augmentation has received increasing attention as a restoration tool for flow-limited streams to reduce channel incision, enhance capture of organic detritus, and rehabilitate degraded salmonid spawning habitat (Kuhl 1992; Kondolf et al. 1996; Scruton et al. 1998; Levin and Tolimieri 2001).
1997; Gore et al. 1998). Unfortunately, little work has been done to evaluate direct
benefits of gravel augmentation projects and in some instances, restoration projects have
actually further degraded habitats (Kondolf 1997; Bash and Ryan 2002; Roni et al. 2002).
Furthermore, although spawning gravels provide incubation habitat for developing
salmonid embryos for several weeks after spawning, we have found no documentation as
to how gravel augmentation influences the physical parameters associated with survival
of these early lifestages. Our objective in this study was to test the hypothesis that gravel
augmentation would improve habitat physical characteristics, specifically, depths,
velocities and intergravel water quality and would subsequently attract spawning chinook
salmon Oncorhynchus tschawytscha.

**Study Area**

The Mokelumne River is a modified system that drains approximately 1,700 km²
of the Central Sierra-Nevada. Similar to many other Central Valley river systems, the
Mokelumne River has been affected by numerous human influences, including 16 major
water projects and instream gravel and gold mining (CDC 1988). Camanche Dam,
completed in 1964, is the lowest non-passable dam to migratory fishes and was
constructed for flood control and river regulation. The subsequent altered flow regime
stabilized active sediment and enabled in-channel vegetation survival. According to
Pasternack et al. (In press), changes are documented in historical aerial photos with the
active channel now half its former width and overdeepend. Prior to Camanche Dam,
annual peaks exceeded 200 m³ • s⁻¹ for 21 of 57 years. Since 1964, annual peaks have
never exceeded 200 m³ • s⁻¹. Pre-dam mean monthly flow had a typical snowmelt
hydrograph with highest flow May to June, after the peak in precipitation. The post-dam hydrograph shows significant reduction in late spring snowmelt runoff below the dam. A flood frequency analysis using annual extreme pre- and post-dam data shows a dramatic reduction in flow for all recurrence intervals after the dam was built. Estimated Q2, Q5, Q10, and Q100 decreased by 67, 59, 73, and 75 %, respectively. The statistical bankful discharge (Q1.5) prior to Camanche was 120 m$^3$ • s$^{-1}$, which is now only released every ~5 years (Pasternack et al. In Press). Flow out of Camanche has a step hydrograph, with lows near the minimum (4.25 m$^3$ • s$^{-1}$) prescribed in the Joint Settlement Agreement for re-licensing (FERC, 1998). The lower Mokelumne River (LMR) is an approximately 54-km reach of regulated stream between Camanche Dam, the downstream-most non-passable barrier to anadromous fish, and its confluence with the Sacramento-San Joaquin Delta (Figure 1). The river between Camanche Dam and Lake Lodi, a seasonal reservoir with a fish passage facility at Woodbridge Irrigation District Dam (WIDD), is characterized by alternating bar complex and flatwater habitats with a gradient of 0.0017. The LMR flows through floodplains and alluvial fan deposit soils of the Valdez-Columbia and Hanford-Greenfield associations, which are both sandy-loams with good to poor drainage characteristics. Tailings from abandoned gravel mining operations are frequent along the upper one-third of the LMR. While many of the tailings are isolated from the river by berms and levees, several large pits are now incorporated into the main river channel. The LMR floodplain is dominated by agriculture, including walnut and winegrape production, livestock grazing and an increasing number of single-family dwellings. Riverbanks are characterized by 50 to 100-m sections of broken concrete and stone riprap with a thin ribbon of Fremont cottonwood *Populus fremontii*, valley oak
Quercus lobata, willow Salix spp., and red alder Alnus rubra. Numerous non-native trees and shrubs such as black locust Robinia pseudo-acacia, Himalayan blackberry Rubus discolor, and Giant Reed Arundo donax are also common. At least 35 fish species occur in the LMR including prickly sculpin Cottus asper, Sacramento sucker Catostomus occidentalis, and two anadromous salmonids, steelhead O. mykiss, and fall-run chinook salmon (Merz 2001). Both salmonid populations are supplemented by fish reared in the Mokelumne River Hatchery or imported from the Feather River and Nimbus hatcheries (American River) (Figure1). Abundant non-native fish species include western mosquitofish Gambusia affinis, golden shiner Notemigonus crysoleucas, and spotted bass Micropterus punctulatus.

Figure 1. Map of the Mokelumne River and gravel augmentation site. American River (1). Feather River (2).
Records of historical Mokelumne River chinook salmon runs are incomplete and conflicting (Clark 1929; Reynolds et al. 1990). Winery, cannery and mining pollution, along with water diversions and habitat blockage periodically eliminated all LMR fish life, including whole year classes of salmon (CDFG 1959; Finlayson and Rectenwald 1978). From 1980 to 1988, over 90 percent of Mokelumne River Hatchery production originated from imported eggs and fry, all suggesting a run of questionable origin (Jewett 1982; Meyer 1982; Estey 1989). At present, Mokelumne River fall-run chinook salmon are an ocean race; they typically emigrate to the ocean in the spring of their first year and spend two to four years in the ocean before returning to their natal stream to spawn (Healy 1991). Before completion of Camanche Dam, fall-run chinook salmon spawned primarily between the town of Clements and an unnamed canyon about 4 km below Pardee Dam. Few fish spawned upstream of the canyon or downstream of Clements. The California Department of Fish and Game estimated that the river downstream of Pardee was capable of sustaining annual runs of 15,000 adult chinook salmon (CDFG 1959). However, runs for the 19-year period of record before Camanche Reservoir was impounded averaged 3,300 spawners, a period when instream mining was widespread.

The majority of salmon spawning now takes place in the 16-km reach between Camanche Dam (RKM 102.2) and Clements (RKM 86.9). The Revised Draft Restoration Plan for the Anadromous Fish Restoration Program (USFWS 1997) calls for a fall-run chinook salmon production target of 9,300 for the Mokelumne River. Recent escapement in the Mokelumne River, based on counts at the WIDD, has ranged from 410 in 1991 to over 10,000 in 1997. The annual fall-run chinook salmon migration in the Mokelumne River begins in September, peaks in November and tapers off in December.
and early January. Spawning generally occurs shortly after migration, primarily in late October through January. Fry emergence typically begins in late December and continues to the beginning of April.

FERC (1993) ranked the various factors limiting the production of chinook salmon in the LMR and determined that spawning habitat (quality and quantity) was the second-most important factor. Ocean harvest, which can account for 75-85% of adult chinook salmon mortality, was identified as the most severe constraint on escapement of adults to the spawning grounds. From 1990 to 2000, East Bay Municipal Utility District (EBMUD), owner and operator of Camanche Dam, performed annual chinook salmon spawning habitat enhancement projects in the LMR. While the goal of the enhancement projects was to improve existing marginal habitat, a secondary goal was to increase total available spawning habitat. These projects typically consisted of placing approximately 500–1,500 yd$^3$ (382-1,147 m$^3$) of washed river rock (25 – 150 mm diameter) in berms and staggered bar configurations as a means to increase natural reproduction of these fish. Sites were typically 30 to 100 m long, spanning the river channel, with an average depth of 0.4 m for placed gravels. Cleaned gravel materials were purchased from an open floodplain quarry approximately 0.5 km from the river channel. The site discussed in this study had no recorded chinook salmon spawning activity from 1990 until the site enhancement took place. Mean annual discharge to the LMR for the 5 years prior to this study was 28.3 m$^3$ • s$^{-1}$, while maximum discharge over the 24-month study period was 69.9 m$^3$ s$^{-1}$. The maximum flood release rate, set by the Army Corp of Engineers, for Camanche Dam is 142 m$^3$ • s$^{-1}$ (FERC 1993).
METHODS

*Site selection and gravel placement.*—The study site is located in the Mokelumne River Day-Use Area approximately 1km downstream of Camanche Dam and the Mokelumne River Fish Hatchery (Figure 1). The site was selected because of its location within the spawning reach of fall-run chinook salmon and because of its easy access by roads for gravel-placing equipment. We used historic aerial photographs (1933 – 1963) to select a site of previously shallow gravel that had been mined for gold or gravel between 1952 and 1964. Approximately 976 m$^3$ of clean river gravel (25–150 mm) was placed by dump truck and rubber-tire loader in berm and staggered toe-bar configurations along the 45-m enhancement site. The configuration was chosen as a means to enhance chinook salmon spawning conditions by reducing depth, increasing velocities, and promoting exchanges of water between the stream and the interstices of the gravel (Vronskiy 1972, Chapman 1988).

*Topographic channel surveys.*—Surveys were made with a Trimble 4000 GPS receiver, Leica T-1600 Theodolite, DI-1600 electronic distance meter, and NA-2002 electronic level to record 2,000–2,800 individual reference points (latitude, longitude, elevation). Point spacing was quasi-systematic and stratified by grade-breaks and channel topography as opposed to a uniform grid (Brasington et al. 2000). Survey data were downloaded to an American Standard Code for Information Interchange (ASCII) file and translated to the grid-based graphics program, Surfer® (Golden Software, Inc.). Reference points were used to construct a digital terrain model and contour map of the site (Figure 2). Volume of gravel material placed at the site and net cut of gravel after 12 and 24 months was calculated using the Grid Volume Report within the Surfer program,
which computes net, cut and fill volumes between two grid files (Golden Software Inc. 1999).

**Pebble counts.**—Pebble counts were conducted at four randomly selected transects (~100 samples per transect) at each site prior to gravel enhancement and immediately following gravel enhancement using methods similar to those of Bauer and Burton (1993). Four 30-m longitudinal transects were randomly placed at each site. Surveyors collected substrate samples by hand every 0.3m along the transect and used a template to measure size. Substrate from pebble counts were categorized into 12 sizes: <0.80, 0.80, 1.60, 2.22, 3.18, 4.45, 6.35, 8.90, 12.70, 17.78, 25.40, and >25.40 cm. The categorization was based on the largest slot (round hole with specified diameter) through which an individual pebble could not be passed. Measurements were repeated 12 months after gravel placement.

**Hydrologic Data.**—Velocities and depths were measured every 0.6 m along 5 evenly-spaced cross-sections over the site with a Marsh-McBirney Flo-Mate Model 2000 flowmeter and a depth-setting wading rod, immediately before and after gravel placement (Camanche release rate: 7.0 m³/s⁻¹). Intergravel water quality measurements were taken at three random stations (3 replicates/sample) within the enhancement site and an adjacent reference site prior to, immediately following, and 12 and 24 months after gravel placement. A modified Terhune Mark VI standpipe was driven into the gravel to measure gravel permeability, dissolved oxygen (DO) and temperature following the methodologies noted by Barnard and McBain (1994). A vacuum hand pump apparatus was used to collect water samples from the standpipe for 20 s and volumes were measured (Saiki and Martin 1996). Samples were taken at depths of 15, 30, and 45 cm to
evaluate stratification of compaction and sedimentation within the known range of depths of chinook salmon spawning (Chapman 1988, Bjornn and Reiser 1991). Approximately 200 mL of water was collected from each sample and transported to lab to measure turbidity (NTU) and Total Suspended Solids (TSS). Turbidity was measured with a Hach 2100P Turbidimeter. TSS samples were filtered through a 50-micron sieve, then passed through a pre-combusted gas fiber filter, dried to 60°C, and weighed (APHA et al. 1995). Ambient DO and stream temperature (15 cm below the water surface) as well as intergravel DO and water temperature were recorded with a YSI 55® dissolved oxygen meter.

**Redd surveys.**—During September-January each year, salmonid spawning surveys were conducted weekly along the 16-km reach, including all available spawning habitat below Camanche Dam. Three surveyors canoed and walked downstream searching for signs of redd construction. Redd locations were recorded using a hand-held Global Positioning System (GPS) unit (Trimble Pro XR) and a laser range finder (Atlanta Advantage). Location of each redd was downloaded from the GPS unit into an ArcView (ESRI) coverage. Data were saved into an ASCII file and translated to the grid-based graphics program mentioned above. In addition to being mapped, individual redds were marked with a 115-mm plastic tag. Tags were numbered and anchored to the substrate at the peak of each redd tailspill with a 216mm steel bolt with a 40 mm drywall toggle wing anchor to differentiate old redds from new during subsequent surveys and monitor scour of individual redds. Tags were recovered the first week of the following annual redd survey.
Analysis.— A paired $t$-test (Zar 1996) was used to compare mean depth and velocities along 5 transects immediately before and after gravel placement and to
compare intergravel water quality data from enhanced and unenhanced bed material. We tested the hypothesis that the amount of bed material ≤ 8 mm was not related to whether new gravel was placed at the site using likelihood ratio chi-square (Sall et al. 2001).

RESULTS

Stream channel

The channel bed of the site was covered with up to 2.1 m of new gravel, significantly increasing the average bed elevation over the 5 transects by 0.12 m ($t = 5.51, \text{ df} = 203, P < 0.001$). Gravel was applied to the shallow edge of the channel (south bank) with two lateral bars across the nose and tail of a scoured pool (Figure 2). The upstream bar directed a portion of the flow across the new gravel berms along the south bank, significantly increasing average velocities throughout the entire site by 0.24 m/s ($t = 14.22; \text{ df} = 203; P < 0.001$). After 12 months, increased velocities created scour along the north bank (Figure 2).

Bed material

Overall amount of fines within surface bed material (≤8 mm) was significantly related to gravel placement at the site ($G^2 = 56.827; \text{ df} = 703; P < 0.001$; Figure 3). Enhanced gravels were significantly more permeable than adjacent unenhanced bed material ($t = -9.698; \text{ df} = 8; P < 0.001$) and pre-enhancement gravels ($t = -2.086; \text{ df} = 8; P = 0.035$; Table 1). After 12 months, fines remained lower in enhanced surface material than unenhanced areas (Table 1). Enhanced gravel remained significantly more permeable than unenhanced gravel ($t = 2.81; \text{ df} = 8; P = 0.011$). After 24 months, mobilized enhanced gravels covered the adjacent unenhanced bed material, ending
comparative assessment. However, enhanced gravels remained significantly more permeable than pre-enhancement material ($t = -4.101; df = 8; P = 0.002$).

![Grain-size distributions for surface pebble counts taken before, immediately after, and 12 months after gravel placement along the chinook salmon spawning reach of the lower Mokelumne River California.](image)

**Hyporheic environment**

Intergravel water temperature was significantly cooler in enhanced gravel (Table 1; $t = -7.23; df = 8; P < 0.001$) and DO was significantly higher in enhanced gravel ($t = 2.07; df = 8; P = 0.036$) immediately after placement. Total suspended solids (mg/l) and measured turbidity (NTU) within water samples collected from enhanced gravels were significantly lower than samples from unenhanced gravels immediately after gravel placement ($t = -3.03; df = 8; P = 0.008; t = -3.90; df = 8; P = 0.002$). After 12 months, intergravel water temperature within enhancement gravels remained significantly cooler ($t = -3.66, df = 8, P = 0.003$) and DO within the enhancement gravel remained significantly higher ($t = 2.08, df = 8, P = 0.036$) than unenhanced gravels.
turbidity and TSS remained significantly lower in enhancement bed materials ($t = -3.63$, df = 8, $P = 0.003$; $t = -3.03$, df = 8, $P = 0.008$).
Table 1. Physical parameters recorded at a chinook salmon spawning gravel enhancement site in the lower Mokelumne River, including intergravel permeability, temperature, dissolved oxygen, turbidity, and total suspended solids. Mean measurements and (1 standard deviation) are provided for each depth.

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<td>Unenhanced</td>
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<td>Depth below gravel surface (cm)</td>
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<td>66 (16.4)</td>
<td>79.1 (13.7)</td>
<td>124.5 (44.3)</td>
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Channel Adjustment

Contour maps show relatively little change in the bathymetry (topography) from the enhancement site over the monitoring period (Figure 2). However, localized patterns of fill and re-scour were observed within the site and are captured in the topographic
surveys. A total estimated deficit of 216 m$^3$ and 303 m$^3$ of placed gravel was observed after 12 and 24 months respectively (22 and 31% of total placement).

*Spawning use*

Chinook salmon began spawning at the enhancement site within 2 months of gravel placement. The site supported 1.8 % of total natural Mokelumne River spawning the first spawning season, 1.3 % the second and 1.9 % the third spawning season after gravel placement (Figure 2). Total number of chinook salmon redds observed in the Mokelumne River each season of the study period were: 987, 843 and 844 respectively. All numbered redd tags were recovered after each monitoring period indicating scour did not damage redds constructed within the enhancement site.

**DISCUSSION**

Gravel placement provided a veneer of clean, loosely packed gravel 0.1 to 2.1 m deep over large portions of the enhancement area. Parameters known to influence habitat suitability for chinook salmon spawning were all affected positively and included increases in stream velocity, gravel permeability and dissolved oxygen, and decreases in depths, intergravel water temperature, turbidity and TSS. Chinook salmon responded immediately to the improvement in conditions and chose the site for spawning. The improved conditions lasted at least 24 months.

Numerous studies have concluded that physical parameters such as intergravel DO, temperature and permeability can have profound effects on developing eggs and embryos of salmonids (Coble 1961, Phillips et al. 1961, Beachham and Murray 1990,
Heming 1992). The fertilized egg to alevin stage of salmonids is a very dynamic period that can be disproportionately influenced by environmental parameters when compared to other life stages. One cause for the increased impacts due to less than optimal parameters is the limited ability alevin have to escape unfavorable conditions. Some studies have indicated that salmonid alevin can move within the interstitial spaces of the gravel, but the distances involved are less than 1 m (Dill 1967). However, the most important factor in susceptibility of early lifestage salmonids to poor environmental conditions involves the sensitive nature of embryonic development. Egg cleavage and differentiation of tissues occur at specific times and sequences (Greely 2002). The events and sequences involved in development are species specific and can be altered by environmental conditions. In some cases sexual differentiation can be altered or interrupted by temperature or pressure extremes (Thorgaard 1983). In this study, we observed significant beneficial changes to the hyporheic environment for chinook salmon spawning and incubation at the enhancement site.

In addition to interrupting developmental sequences, poor environmental conditions can affect metabolic rates and somatic growth of early lifestage salmonids. Time to emergence varies significantly with water temperatures, but for chinook salmon it takes approximately 40 to 60 days for temperatures of 10° C and 14° respectively (Piper et al. 2001). In salmonids, emergence generally occurs when the alevin has used up a majority of the yolk reserve and is ready to begin exogenous feeding. Increased temperatures above optimal levels can lead to alterations in metabolic rates through decreasing the yolk to tissue conversion efficiency (Hemming 1982). The ultimate result of increased temperatures beyond this threshold is decreased survival due to smaller size
at emergence decreasing overall fitness and possibly increasing predation risk. In the study site, intergravel and ambient river temperatures equilibrated due to the enhancement project.

Outward physical characteristics have been used to classify the suitability of riverine habitat for salmonid spawning (Bjorn and Reiser 1991). However, the environment within the hyporheic zone also influences the suitability of spawning habitat (Geist et al. 2002). At a site in the Columbia River, differences related to upwelling and downwelling currents were found in spawning area selection between chum salmon *O. nerka* and chinook salmon. Chinook salmon were attracted to areas where there was downwelling and temperatures within the gravel were equal to surrounding river temperatures, whereas chum salmon were attracted to areas of upwelling with intergravel temperatures warmer than surrounding river temperatures. Our results suggest that the enhancement was successful in terms of improving inter-connected pore spaces to allow downwelling and equalizing temperatures between the hyporheic zone and the surrounding water, attracting spawning chinook salmon.

Gravel permeability is a proxy for hyporheic flow, which can influence redd temperature, DO, and the removal of metabolic wastes and is directly related to fine sediments within the interstitial spaces of the gravel. Depending on the particle size, fines can have deleterious effects on developing salmonid eggs (Reiser and White 1980; Sowden and Power 1985; Platts et al 1989). It has been generally shown that fines less than 0.85mm in diameter can affect embryo survival. As the amount of fines increases, interchange between intergravel and surface waters is reduced, essentially suffocating embryos (Olsson and Persson 1988). Increases of particles as large as 4-12mm can also
have deleterious effects on salmonid survival, either through suffocation, or reduced emergence success (Chapman 1988). Additionally, sedimentation can alter the vectors of flow within the gravel and ultimately affect site suitability. Fine clay and silt particles suspended within the water column are often measured as total suspended solids (TSS) or turbidity. High concentrations of TSS can adversely affect aquatic biota by smothering benthic organisms and consuming oxygen as organic solids degrade. Suspended sediments can also adsorb pollutants such as heavy metals and hydrocarbons. These sediments can often harm incubating fish eggs and fry and reduce the abundance of insect larvae, an important food source for juvenile fish (Hynes 1973; Cederholm et al. 1982). The significant increase in permeability and decrease in turbidity and TSS immediately after gravel placement further suggest incubation parameters within the site were improved. We hypothesize that solar radiation will warm the substrate in water shallow enough for light to reach the substrate. By increasing substrate permeability, residence time of hyporheic water may be reduced, providing a mechanism to remove stored heat energy. This should be evaluated further. While spawning bed enhancements can provide immediate physical improvements to specific sites, their longevity and impacts to the entire system are unknown. It is quite apparent that these enhancements may alleviate problems associated with bed material deficits in anadromous salmonid streams where damming, mining and channelization have taken place. However, many questions remain. For instance, how much and how often should such augmentation take place? What is the longevity of these sites and what flows are appropriate for bed material maintenance? Although we observed a distinct reduction in gravel volume after 12 and 24 months, it is unclear what percent of total loss is due to actual transport from the site
as compared to settling or packing of the new gravels in place. Both processes appear to have occurred and volumetric changes of bed material, documented by our surveys, suggest that such measurements may greatly benefit the calculation of bed sediment budgets for regulated streams. Estimates from direct observation of the site and the fact that no redd tags were dislodged during all three spawning and incubation periods indicate minimal bed material movement (<5m) downstream. However, Harvey and Lisle (1999) showed that fall-spawning chinook salmon redds constructed in mine tailings had a higher propensity to scour than those constructed on natural substrate. This suggests newly placed gravels, especially in streams with a high potential for scour, deserve special attention. Complementary monitoring techniques, such as tracer rocks and scour chains in conjunction with topographic surveys and redd tags, may better assess the degree of sediment travel and the potential for redd scour (Nawa and Frissell 1993).

Although spawning adult chinook salmon are using our enhancement gravels and preliminary data from this study suggest that the intergravel environment is significantly improved for developing embryos, these improvements must be fully quantified to assess the true benefits of gravel augmentation. Furthermore, gravel-enhanced streambeds may have significant impacts on numerous other organisms, including other fish and benthic macroinvertebrates and this should be fully appraised.

While physical assessments of this and other projects are key to evaluating their success (Stanford et al. 1996), other factors can confound the desired outcome of successful enhancement, increased salmon production. For example, since the inception of our enhancement monitoring program in 1999, major sport harvest regulation changes
have taken place. These include changes in take limits and minimum size of kept fish. Further, annual variation in other impacts to salmon yield, including precipitation and runoff, ocean conditions, water diversion rates, and predation rates can all greatly influence salmon numbers. While site-specific augmentation appears promising, it is important to note that the lower Mokelumne River is a relatively low gradient stream with a highly regulated flow. Expanding the use of the monitoring tools presented here to other river systems will reveal their true range of capabilities.

ACKNOWLEDGMENTS

We thank Leigh Chan, James Jones, Warren Jung, Bert Mulchaey, Russ Taylor, Richard Walker, Michelle Workman and all field staff who collected data for this study. We also thank Randy Dahlgren and Erwin Van Nieuwenhuyse, who provided TSS analysis of our water samples. Peter Moyle, Greg Pasternack and Joe Wheaton contributed valuable comments on the manuscript. Joseph Cech and James Smith also made helpful suggestions on subsequent drafts. Support from the United States Fish and Wildlife Service through the Central Valley Project Improvement Act Restoration Funds and EBMUD are gratefully acknowledged.

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CHAPTER THREE

Predicting benefits of spawning habitat rehabilitation for production of salmonid (Oncorhynchus spp.) fry in a regulated California river

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Abstract

We tested the hypothesis that spawning bed enhancement increases survival and growth of chinook salmon (*Oncorhynchus tschawytscha*) embryos in a regulated California stream with a gravel deficit. We also examined how 12 physical parameters correlated within spawning sites and how well they predicted survival and growth of chinook salmon and steelhead (*O. mykiss*) embryos. Salmon embryos planted in enhanced gravels had higher survival to swim-up stage than embryos planted in unenhanced spawning gravels. No significant increase in growth was observed. Intergravel temperature and substrate size were strongly correlated to distance downstream from the lowest non-passable dam to anadromous fish. Intergravel turbidity and total suspended and volatile solids were also strongly correlated. Multiple regression models were built with a combination of physical measurements to predict survival and length of chinook salmon and steelhead embryos. Survival models accounted for 87% of the variation around the mean for salmon and 82% for steelhead. Growth models accounted for 95% of the variation around the mean for salmon and 89% for steelhead. These findings suggest that spawning bed enhancement can improve embryo survival in degraded habitat. Additionally, measuring a suite of physical parameters before and after spawning bed manipulation can accurately predict benefits to target species.

Key words: salmonid; spawning; habitat enhancement; multiple regression; survival
INTRODUCTION

Salmonids have specific substrate and water quality requirements for successful spawning, incubation and embryo development. Riverine salmonids typically spawn in cool, clear, well-oxygenated streams with distinct depth, current velocity and gravel size for each species (Bjorn and Reiser 1991; Groot and Margolis 1991). Salmonid eggs and embryos remain in the gravel for a relatively long time, ranging between roughly 2 and 8 months. The length of time between egg deposition and alevin emergence depends on species, redd location and numerous physical parameters (DeVries 1997). Timing of spawning, egg burial depth and embryo development are tied to the dynamic hydrologic regime of a river, including disturbances such as streambed scour (Montgomery et al. 1999).

Interannual mobilization of channel bed sediment provides renewal of substrate conditions and infrequent large floods reset spatially complex channel morphology (Trush et al. 2000). Alteration of flow, sediment transport and continuity of river systems by dams, water diversions, levees, armored banks and mining may have deleterious affects on these processes, impacting one or more salmonid life stages (Nelson et al. 1987; Heaney et al. 2001; Soulsby et al. 2001). Elimination of a natural flow and sediment transport regime causes channel stabilization and narrowing, reduced formation of point gravel bars and secondary channels, accumulation of finer sediment in gravels and reduced water quality (Poff et al. 1997). These physical degradations contribute to decreased substrate permeability and dissolved oxygen (DO) content. Impaired water quality is presumed to cause decreased health and survival of developing salmonid
embryos within the substrate (Olsson and Persson 1988; Reiser and White 1988; Beacham and Murray 1990).

Concerns over the fate of California Central Valley steelhead (Oncorhynchus mykiss) and several runs of chinook salmon (O. tschawytscha) resulted in the NOAA Fisheries listing of these populations as threatened or endangered under the Endangered Species Act (NOAA 1994 and NOAA 1998). Salmonid spawning habitat rehabilitation within California has received increasing attention as a tool to enhance these dwindling populations (Buer et al. 1981, Kondolf and Mathews 1993, CDWR 2002). In the Central Valley of California, 73 spawning habitat rehabilitation projects, on 19 different rivers occurred between 1976 and 1999 with variable success (Kondolf et al. 1996; Wheaton 2003). Wheaton (2003) developed a systematic approach to designing salmon spawning habitat rehabilitation projects using spawning bed enhancement. While gravel augmentation typically entails dumping of appropriate materials in or near the channel to allow distribution via stream flow, spawning bed enhancement involves placement of gravel as specific bed features (typically riffles or bars), potentially providing immediate spawning habitat. Merz and Setka (2004) showed that spawning bed enhancement not only attracted spawning salmon to previously unused areas, but improved intergravel physical parameters associated with spawning and embryo development. Spawning bed enhancement has been shown to benefit non-target aquatic fauna as well (Merz and Chan 2004). Yet there is much uncertainty as to how well projects mitigate for degraded spawning habitat or improve survival of developing embryos (Roni et al. 2002). Additional research is needed to evaluate how substrate and associated hyporheic environment directly influence embryo survival (Kondolf et al. 1996; Merz and Setka
In this paper, results from two embryo survival experiments are reported. In the first experiment, we test the hypothesis that spawning bed enhancement increases survival and growth of riverine chinook salmon embryos to the swim-up stage. In the second experiment, we propose embryo survival and growth models based on measurable physical parameters. We then test the validity of four multiple regression models to predict the benefits of spawning habitat enhancement on developing chinook salmon and steelhead embryos in a regulated California river.

Materials and methods

Study site

The Mokelumne River, California, drains approximately 1624 km$^2$ of the central Sierra Nevada. Sixteen major dams or diversions, including the 0.24 km$^3$ Pardee and the 0.51 km$^3$ Camanche reservoirs, have dramatically altered the lower Mokelumne River’s flow regime (Pasternack et al. 2003). Prior to Camanche Dam completion in 1964, annual peaks exceeded 200 m$^3$•s$^{-1}$ for 21 of 57 years. Since 1964, annual peaks have never exceeded 200 m$^3$•s$^{-1}$, with the discharges associated with the 2-year, 5-year, 10-year, and 100-year recurrence intervals decreased by 67, 59, 73, and 75%, respectively.

The lower Mokelumne River (LMR) is approximately 54 km of regulated river between Camanche Dam, a non-passable barrier to anadromous fish, and its confluence with the Sacramento-San Joaquin Delta. The river between Camanche Dam and Lake Lodi (Fig. 1), is characterized by alternating bar complex and flatwater habitats, and is above tidal influence, with a gradient of approximately 0.00017. The drainage consists of 87 km$^2$ of mostly agricultural and urbanized land. Several small streams and storm
drains enter the lower river. At least 35 fish species occur in the LMR including two native anadromous salmonids, fall-run chinook salmon and winter steelhead (Merz 2001). Both populations are supplemented by Mokelumne River Fish Hatchery (MRFH) production and fish imported from the Feather River and Nimbus (American River) hatcheries. The majority of chinook salmon and steelhead spawning on the LMR now takes place in the 14-km reach immediately below Camanche Dam.

Figure 1. Ten egg tube study sites within the lower Mokelumne River, California. Circles are egg tube locations; C = Mokelumne River Hatchery (Control); E = enhanced; U = unenhanced; F = Feather River; A = American River; M = Lower Mokelumne River.

Compared to other major barriers on Sierra rivers, Camanche Dam is positioned in an area of relatively low elevation and relief. Accordingly, slopes throughout the spawning reaches remain low (ranging from 0.0005 to 0.0020). Tailings from abandoned gravel mining operations are frequent along the upper 11 km of the LMR. While many
of the tailings are isolated from the river by berms and levees, several large pits are now incorporated into the main river channel. It has been estimated that approximately 80% of historic spawning habitat is now inaccessible due to construction of Camanche Dam and remaining habitat quality is a limiting factor to Mokelumne River salmonid production, second only to ocean harvest (Menchen 1961; FERC 1993). East Bay Municipal Utility District, owner and operator of Camanche Dam, has placed over 11000 m³ of gravel at 12 spawning bed enhancement sites along the LMR since 1991 and has a monitoring program encompassing all of these projects that will extend at least to 2009 (Pasternack et al. 2003). The projects consist of placing approximately 350-1200 m³ of washed river rock in berms, staggered bar, riffle or complex channel geometry configurations to improve spawning habitat. Chinook salmon and steelhead typically begin spawning in the new gravels within 3-24 months of gravel placement. For this study, ten sites were evaluated based on access and how many could be assessed within a single day. The sites are spread out within the upper 11.3 km of the LMR, four of which are spawning bed enhancement sites (Fig. 1).

Egg incubation tubes

The focus of the first experiment was to compare survival and growth of chinook salmon embryos in enhanced and unenhanced spawning gravel sites. The second experiment was conducted to develop a predictive model of chinook salmon and steelhead survival and growth using associated physical parameters within spawning beds. Both experiments used egg incubation tubes buried in gravels to test survival and growth of fertilized eggs and embryos.
Egg tubes were constructed of SDR 35-Polyvinyl Chloride (PVC) pipe with two PVC caps used to close tube ends (Fig. 2). Eighteen-19 mm evenly spaced holes were drilled into each tube. The tube inner surface was covered with a 0.35-mesh/mm plastic screen typically used for steelhead and chinook salmon hatchery egg incubation (Leitritz and Lewis 1980). An artificial “redd” was constructed at each site for egg tube placement. A series of depressions was made in the gravel streambed by hand for each set of egg tubes (Fig. 2). Pockets were constructed in an upstream progression, following the description of DeVries (1997). At each study site, egg incubation tubes were buried horizontally and perpendicular to stream flow at 22 cm deep, the approximate depth of egg pockets in chinook salmon and steelhead redds according to Healey (1991) and Montgomery et al. (1999). Bed material from subsequent pockets was used to cover each egg tube.

Figure 2. Diagram of constructed “redd” with egg tubes, stand pipe and temperature logger (top view). Figure not to scale.
Experiment one: survival and growth in enhanced versus unenhanced Sites

To compare survival of chinook salmon embryos in enhanced and unenhanced gravel sites, egg tubes were buried at four enhanced substrate locations (constructed between 1994 and 2001) and six unenhanced substrate locations within the LMR (Fig. 1). Unenhanced sites were selected based on consistent spawning use by chinook salmon and accessibility. Ten tubes with approximately 200 chinook salmon eggs each from the MRFH were buried at each site. A control group of 2000 eggs was placed in incubation tubes (200 eggs each) at the MRFH to monitor embryo development. Eggs were then taken from approximately 22 female chinook salmon at the MRFH on 21 November 2001. Fertilized eggs were “eyed” and 18 days old (average hatchery water temperature = 12.3 °C) when placed in the egg tubes and buried within the gravel. MRFH water is sand-filtered and piped from Camanche Reservoir.

Experiment two: predictive models of survival and growth

To test predictive models of chinook salmon and steelhead embryo survival and growth from associated physical measurements, approximately 20,000 chinook salmon and steelhead embryos were buried in egg tubes at various spawning habitats located throughout the LMR (see habitat selection and evaluation below). Five tubes with approximately 200 eyed chinook salmon embryos and five tubes with approximately 200 eyed steelhead embryos were buried at each site. A control group of five chinook salmon egg tubes and five steelhead egg tubes (200 embryos each) was placed in rearing troughs at the MRFH to monitor egg development and survival. Chinook salmon eggs were
taken from 15 female salmon spawned on 23 December 2001 at the MRFH. Fertilized embryos were “eyed” and 18 days old (average hatchery water temperature = 10.12 °C) when placed in egg tubes and buried within the gravel on 9 January 2002. An insufficient number of steelhead was spawned at the MRFH to provide embryos for this study. Therefore, eggs were taken from 12 female steelhead spawned on 18 December 2001 at the Feather River Hatchery, California. Fertilized steelhead eggs were approximately 22 days old when placed in the egg tubes and buried in the gravel on 9 January 2002 (average hatchery water temperature = 10.3 °C).

**Habitat selection and evaluation**

Ten sites were selected for Experiment 2 within the upper 11.3 km of the LMR based on historical spawning use and enhancement activities (Fig. 1). Although, the sites were located within the vicinity of Experiment 1 sites, the sites did not overlap and were not selected on the basis of enhanced versus unenhanced gravels. The ten sites each consisted of similar riffle morphologies with comparable substrate composition ($D_{50} \approx 150$-450 mm gravels), channel slopes (0.002 to 0.006) and hydraulic conditions (shallow ($< 0.36$ m) and swift current ($>0.6$ m•s$^{-1}$). Hydraulics of each site were crudely characterized from one point measurement of depth and velocity positioned between the egg tube placement locations (at standpipe location; Fig. 2)). This measurement was performed on 9 December 2001 during a discharge of 6.5 m$^3$•s$^{-1}$, which was representative of hydraulics experienced throughout the incubation period. Depth was recorded from a top-setting velocity rod and depth averaged velocity was approximated
by assuming a logarithmic velocity profile and taking a measurement at 60 percent of the depth with an electromagnetic Marsh McBirney Flo-Mate velocimeter.

**Substrate evaluation**

Both surface and subsurface grain size distributions were used to characterize the substrate during the post-study period (post-egg-tube removal) at each site. Grain size distributions were assumed not to have changed from pre- to post-analysis based on previous studies (Merz and Setka 2004). Subsurface samples were collected at the location of the standpipe at each site using a McNiel core sampler (St-Hilaire et al. 1997). Samples were placed in sealed containers and transported to the laboratory for analysis. Substrate was sieved through screens of the following sizes: 0.5 mm; 1.0 mm; 2.4 mm; 4.7 mm; 9.5 mm; 12.7 mm; 15.9 mm; 22.2 mm; 31.8 mm; 44.5 mm; 63.5 mm; 88.9 mm; 127.0 mm; 177.8 mm; 254.0 mm. Each size-class was weighed and recorded. Residual water and associated suspended sediment was poured through 15 cm #595 filter paper. The paper and sediment residual was dried at 70 °C for 24 h, weighed and recorded. Surface samples were collected by pebble count at three randomly selected transects (~100 samples per transect) at each site using methods similar to those of Bauer and Burton (1993). Three 30-m longitudinal transects were randomly placed at each site. Surveyors collected substrate samples by hand every 0.3 m along the transect and used a round-holed template to measure size. Substrate from pebble counts were categorized into 12 sizes: < 8.0, 8.0, 16.0, 22.2, 31.8, 44.5, 63.5, 89.0, 127.0, 177.8, 254.0, and > 254.0 mm. The categorization was based on the largest slot (round hole with specified diameter) through which an individual pebble could not be passed.
Intergravel permeability, dissolved oxygen content, temperature, and turbidity

Intergravel water quality measurements were taken at each site prior to egg tube placement and immediately after egg tube removal. A modified Terhune Mark VI standpipe was driven into the gravel to measure gravel permeability, DO and water temperature following Barnard and McBain (1994). We collected water samples from the standpipe with a vacuum hand pump apparatus (Saiki and Martin 1996). Samples were taken at depths of 15, 30 and 45 cm to evaluate stratification of compaction and sedimentation within the known depth ranges of chinook salmon and steelhead spawning (Vronskiy 1972; Chapman 1988; Bjornn and Reiser 1991). Approximately 200 mL of water was collected from each sample and transported to lab to measure turbidity in Nephelometric Turbidity Units (NTU), Total Suspended Solids (TSS) and Volatile Suspended Solids (VSS). Turbidity was measured with a Hach 2100P Turbidimeter. TSS samples were filtered through a 50-micron sieve, then passed through a pre-combusted gas fiber filter, dried to 60 °C, and weighed (APHA et al. 1995). Ambient DO and stream temperature (15 cm below the water surface) as well as intergravel DO and water temperature were recorded with a YSI 55 dissolved oxygen meter. An Onset StowAway TidbiT temperature logger (-4 °C to +37 °C) was buried with the eighth tube (starting with top left tube #1) at each monitoring location (Fig. 2). Loggers recorded water temperature within the gravel every 60 minutes for the duration of the monitoring period (approximately 26 days). Hourly temperature data was totaled to calculate temperature hours for each site.
**Survival, Development and General Condition**

Based on observation of the hatchery control group, egg tubes were removed from the gravel when embryos reached the alevin stage and at least 10% showed capabilities of self-orientation in water current, typical of the swim-up stage. Live alevins were counted, measured by Total Length (TL) and assessed for anomalies (such as disease or deformities). Alevin mortalities and un-hatched embryos were enumerated and recorded.

**Data analyses**

We used a one-way t-test to compare mean survival and length of chinook salmon alevins buried in enhanced and unenhanced gravel (Zar 1999). To build a survival and growth model for chinook salmon and steelhead embryos, principal components analysis (PCA) was used to reduce the number of physical condition variables in the data set. This analysis was performed with Statistical Programs for the Social Sciences, Version 10 software. We used the B4 selection method, as described in Joliffe (1972) and prescribed by Talmage et al. (2002), to select representative environmental variables indicated by the first four axes. We used multiple linear regression to build preliminary models with these independent variables to predict mean survival and mean TL of chinook salmon and steelhead alevins using the JMP linear regression model function, which performs an analysis of variance (ANOVA) (Sall et al. 2001). Alternate variables were then exchanged to strengthen the models. We also used ANOVA to compare the independent variables to alevin survival and TL. A significance level of 0.05 was used in statistical tests.
RESULTS

Experiment 1. Chinook salmon embryo survival and growth in enhanced and unenhanced spawning gravel

Chinook salmon embryos used to compare enhanced and unenhanced gravels were recovered on 8 January 2002, 28 days after tube placement. Survival of chinook salmon embryos was highly variable. Chinook salmon embryo survival ranged from 0% in several unenhanced gravel tubes to over 63% in tubes used as controls within the MRFH (Table 1).

Growth of chinook salmon was also variable. Chinook salmon embryos ranged from 11 – 31 mm TL in tubes incubated at the MRFH, while embryos incubated in river gravel tubes ranged from 13mm TL (Site 3) to 30 mm TL (Sites 4 and 5). Survival of chinook salmon alevins was significantly higher in enhancement gravel than unenhanced gravel (Table 1; \( t = 2.022; \) df = 8; \( P < 0.039 \)). No significant difference was observed for growth in enhanced and unenhanced gravel (\( t = 0.038; \) df = 8; \( P = 0.485 \)).

<table>
<thead>
<tr>
<th>Experiment/Group</th>
<th>Species</th>
<th>Mean survival</th>
<th>Standard error*</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
<th>Mean TL (mm)</th>
<th>Standard error*</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hatchery</td>
<td>Chinook salmon</td>
<td>60%</td>
<td>0.05</td>
<td>0.50</td>
<td>0.70</td>
<td>26.9</td>
<td>0.38</td>
<td>26.19</td>
<td>27.68</td>
</tr>
<tr>
<td>River - Enhanced</td>
<td>Chinook salmon</td>
<td>29%</td>
<td>0.03</td>
<td>0.24</td>
<td>0.35</td>
<td>25.2</td>
<td>0.12</td>
<td>24.77</td>
<td>25.55</td>
</tr>
<tr>
<td>River - Unenhanced</td>
<td>Chinook salmon</td>
<td>22%</td>
<td>0.02</td>
<td>0.18</td>
<td>0.26</td>
<td>25.1</td>
<td>0.02</td>
<td>24.81</td>
<td>25.43</td>
</tr>
<tr>
<td>Hatchery</td>
<td>Chinook salmon</td>
<td>88%</td>
<td>0.04</td>
<td>0.76</td>
<td>1.00</td>
<td>22.6</td>
<td>0.44</td>
<td>21.32</td>
<td>23.78</td>
</tr>
<tr>
<td>Hatchery</td>
<td>Steelhead</td>
<td>84%</td>
<td>0.08</td>
<td>0.62</td>
<td>1.00</td>
<td>22.2</td>
<td>0.19</td>
<td>21.69</td>
<td>22.73</td>
</tr>
<tr>
<td>River gravel</td>
<td>Chinook salmon</td>
<td>58%</td>
<td>0.04</td>
<td>0.50</td>
<td>0.65</td>
<td>18.5</td>
<td>0.84</td>
<td>16.81</td>
<td>20.21</td>
</tr>
<tr>
<td>River gravel</td>
<td>Steelhead</td>
<td>61%</td>
<td>0.03</td>
<td>0.54</td>
<td>0.68</td>
<td>19.0</td>
<td>0.89</td>
<td>17.20</td>
<td>20.79</td>
</tr>
</tbody>
</table>

* A pooled estimate of error variance was used.
Experiment 2. Physical parameters associated with 10 spawning sites and their predictive power for salmonid survival and growth

Camanche Dam releases to the LMR ranged from 6.6 m$^3$•s$^{-1}$ on 1 December 2001 to 6.8 m$^3$•s$^{-1}$ on 31 January 2002 with a peak of 8.1 m$^3$•s$^{-1}$ on 2 January 2002 (Fig. 3). Physical parameters associated with the spawning sites are provided (Table 2). Average daily temperature varied within the constructed redds. Although temperatures were somewhat consistent during Experiment 1, during Experiment 2, mean gravel temperature was inversely correlated with distance downstream of Camanche Dam (Fig. 4). Moreover, daily temperature variation was also greater downstream. Intergravel DO ranged from 6.1 mg•L$^{-1}$ at 45 cm below the gravel surface to 10.11 mg•L$^{-1}$ at 15 cm below gravel surface. Intergravel permeability ranged from 1.2 mL•s$^{-1}$ at 30 cm beneath the Site 9 gravel surface to 48 mL•s$^{-1}$ at 15 cm beneath the surface at the same site. We were able to draft 63 mL•s$^{-1}$ through the standpipe in filtered hatchery water.

![Figure 3. Mean daily discharge and water temperature released from Camanche Dam into the lower Mokelumne River from 1 November 2001 to 31 January 2002. Dashed line indicates Camanche Dam release temperature. Solid line indicates Camanche Dam release.](image-url)
Spatial (i.e., distance from Camanche Dam) trends were observed in the variables collected (Table 3). As distance from Camanche Dam increased, average temperature within the gravels decreased and diurnal temperature fluctuations increased (Fig. 4). Surface substrate sizes, as indicated by pebble count $d_{50}$ ($Pd_{50}$) and general bed material size, as indicated by core $d_{50}$ ($Cd_{50}$), decreased as samples were taken further from the dam. Correlations between turbidity, total suspended solids and total volatile solids were strong as were $Cd_{50}$ and $Pd_{50}$ measurements.

Figure 4. Temperature recorded at 15 cm below gravel surface at 10 spawning sites and 15 cm below water surface within the Mokelumne River Fish Hatchery. Figure shows average, minimum and maximum temperature. Squares indicate 12 December 2001 through 8 January 2002 (Experiment 1). Diamonds indicate 9 January through 31 January 2002 (Experiment 2).
Chinook salmon and steelhead embryos used for the survival and growth models were recovered on 31 January 2002, 22 days after tube placement. Chinook salmon survival ranged from 0% to 100% in river gravel and 74% to 98% within the MRFH. Similarly, steelhead survival ranged from 15% to 100% within river gravel and 56% to 97% within the MRFH. Chinook salmon lengths ranged from 14mm TL at Site 5 to 25 mm TL within the tubes incubated at the MRFH. Steelhead lengths ranged from 13mm TL Site 3 to 24 mm TL at all but two of the river sites. Chinook salmon and steelhead embryos ended to grow more slowly further downstream from Camanche Dam, as indicated by average embryo size (Table 3).

Table 3. Principal component correlations among dependent and independent variables for chinook salmon and steelhead embryos developing in spawning gravel of the lower Mokelumne River, 9 January - 31 January 2002. Bold font indicates correlations greater than 0.7.

<table>
<thead>
<tr>
<th>Physical Variables</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DFCD</td>
</tr>
<tr>
<td>CSSurvival</td>
<td>-0.273</td>
</tr>
<tr>
<td>CSAS</td>
<td>-0.721</td>
</tr>
<tr>
<td>CSSM</td>
<td>-0.661</td>
</tr>
<tr>
<td>CSSMX</td>
<td>-0.600</td>
</tr>
<tr>
<td>STHSurvival</td>
<td>0.108</td>
</tr>
<tr>
<td>STHAS</td>
<td>-0.710</td>
</tr>
<tr>
<td>STHSM</td>
<td>0.381</td>
</tr>
<tr>
<td>STHMX</td>
<td>-0.535</td>
</tr>
<tr>
<td>WD</td>
<td>0.651</td>
</tr>
<tr>
<td>SV</td>
<td>0.423</td>
</tr>
<tr>
<td>TH</td>
<td>-0.753</td>
</tr>
<tr>
<td>TA</td>
<td>-0.883</td>
</tr>
<tr>
<td>PA</td>
<td>-0.103</td>
</tr>
<tr>
<td>DOA</td>
<td>-0.410</td>
</tr>
<tr>
<td>TURA</td>
<td>-0.122</td>
</tr>
<tr>
<td>TSSA</td>
<td>0.132</td>
</tr>
<tr>
<td>VSSA</td>
<td>-0.360</td>
</tr>
<tr>
<td>PD50</td>
<td>-0.863</td>
</tr>
<tr>
<td>CD50</td>
<td>-0.724</td>
</tr>
</tbody>
</table>

Abbreviation Key
CSSurvival = Average chinook salmon survival; CSAS = Chinook salmon average size; CSSM = Chinook salmon minimum size; CSSMX = Chinook salmon maximum size; STHSurvival = Average steelhead survival; STHAS = Steelhead average size; STHSM = Steelhead minimum size; STHMX = Steelhead maximum size; WD = Water depth; SV = Stream velocity; DFCD = Distance from Camanche Dam; TH = Temperature hours; TA = Average temperature within gravel; PA = Average gravel permeability; DOA = Average dissolved oxygen within gravel; TURA = Average water turbidity within gravel; TSSA = Average total suspended solids within gravel; VSSA = Average total volatile suspended solids within gravel; PD50 = Pebble count D50; CD50 = Core sample D50
While \( C_d_{50} \) and water depth appeared to have the strongest correlation with average survival of chinook and steelhead embryos, respectively, no single physical parameter influenced both species strongly. The first four PCA axes explained over 87% of the total variance in physical conditions associated with the spawning locations (Table 4). The variables with the greatest loadings on each axis were distance from Camanche Dam, average volatile suspended solids (VSS), and stream velocity.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Axis 1</th>
<th>Axis 2</th>
<th>Axis 3</th>
<th>Axis 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from Camanche</td>
<td>-0.9280</td>
<td>-0.1830</td>
<td>-0.0372</td>
<td>0.0344</td>
</tr>
<tr>
<td>Average ambient temperature</td>
<td>0.8790</td>
<td>-0.2220</td>
<td>0.0037</td>
<td>-0.2330</td>
</tr>
<tr>
<td>Temperature hours</td>
<td>0.8780</td>
<td>-0.2210</td>
<td>0.0093</td>
<td>-0.2340</td>
</tr>
<tr>
<td>CORE ( D_{50} )</td>
<td>0.8110</td>
<td>0.1470</td>
<td>0.4170</td>
<td>0.1830</td>
</tr>
<tr>
<td>Pebble Count ( D_{50} )</td>
<td>0.7950</td>
<td>0.3620</td>
<td>0.3660</td>
<td>0.2090</td>
</tr>
<tr>
<td>Average dissolved oxygen</td>
<td>0.6190</td>
<td>-0.1980</td>
<td>-0.3420</td>
<td>0.4270</td>
</tr>
<tr>
<td>Water depth</td>
<td>-0.5930</td>
<td>-0.4490</td>
<td>0.3800</td>
<td>-0.2980</td>
</tr>
<tr>
<td>Average volatile suspended solids</td>
<td>-0.1180</td>
<td>0.9490</td>
<td>-0.0025</td>
<td>-0.0313</td>
</tr>
<tr>
<td>Average total suspended solids</td>
<td>-0.3020</td>
<td>0.9060</td>
<td>0.0128</td>
<td>0.1710</td>
</tr>
<tr>
<td>Average turbidity</td>
<td>-0.0134</td>
<td>0.9030</td>
<td>-0.3450</td>
<td>0.0386</td>
</tr>
<tr>
<td>Average permeability</td>
<td>-0.0040</td>
<td>0.6330</td>
<td>0.4700</td>
<td>-0.4860</td>
</tr>
<tr>
<td>Stream velocity</td>
<td>-0.4250</td>
<td>-0.1610</td>
<td>0.5580</td>
<td>0.6270</td>
</tr>
<tr>
<td>% Total variance explained</td>
<td>39.3</td>
<td>29.05</td>
<td>10.19</td>
<td>9.33</td>
</tr>
</tbody>
</table>

**Survival models**

We used \( C_d50 \), average VSS and total temperature hours as predictors of chinook salmon survival (Table 5). The F ratio in the analysis of variance for the overall model was significant at an \( F_{\text{prob}} < 0.01 \) and the model accounted for 87% of the variation around the mean. We used average DO, temperature hours and average turbidity as predictors of steelhead survival. The F ratio in the analysis of variance for the overall
model was significant at an $F_{\text{prob}} < 0.05$ and the model accounted for over 82% of the variation around the mean.

Table 5. Statistics and associated multiple regression results for 2 models used to predict chinook salmon and steelhead embryo survival in Mokelumne River spawning gravel.

### Chinook salmon

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>$F$ ratio</th>
<th>Prob &gt; $F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>3</td>
<td>0.2503</td>
<td>0.0834</td>
<td>12.8116</td>
<td>0.0051</td>
</tr>
<tr>
<td>Error</td>
<td>6</td>
<td>0.0391</td>
<td>0.0065</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. Total</td>
<td>9</td>
<td>0.2893</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Steelhead

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>$F$ ratio</th>
<th>Prob &gt; $F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>4</td>
<td>0.1195809</td>
<td>0.029895</td>
<td>5.8201</td>
<td>0.0402</td>
</tr>
<tr>
<td>Error</td>
<td>5</td>
<td>0.0256829</td>
<td>0.005137</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. Total</td>
<td>9</td>
<td>0.1452638</td>
<td></td>
<td></td>
<td></td>
</tr>
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</table>

**Growth models**

We used temperature hours, average permeability, average DO and $Cd_{50}$ as the independent variables to predict chinook salmon length at the time of egg tube removal.
The growth model accounted for 95% of the variation around the mean with a significant F ratio for the analysis of variance. We used $Cd_{50}$, average permeability, redd depth and stream velocity as independent variables to predict steelhead length at the time of egg tube removal. The growth model accounted for 89% of the variation around the mean with a significant F ratio for the analysis of variance.

Table 6. Statistics and associated multiple regression results for 2 models used to predict chinook salmon and steelhead growth in Mokelumne River spawning gravel.

**Chinook salmon**

<table>
<thead>
<tr>
<th>Summary of Fit</th>
<th>$R^2$</th>
<th>$R^2_{Adj}$</th>
<th>Root mean square error</th>
<th>Mean of response</th>
<th>Sum of weights</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.9472</td>
<td>0.9050</td>
<td>0.3162</td>
<td>20.6088</td>
<td>10</td>
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<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
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<th>Mean square</th>
<th>$F$ ratio</th>
<th>Prob &gt; $F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
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<td>8.9686</td>
<td>2.2422</td>
<td>22.4320</td>
<td>0.0022</td>
</tr>
<tr>
<td>Error</td>
<td>5</td>
<td>0.4998</td>
<td>0.1000</td>
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</tr>
<tr>
<td>C. Total</td>
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<td>9.4684</td>
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<th>df</th>
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</thead>
<tbody>
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<td>Temperature hours</td>
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<td>1</td>
<td>0.6773</td>
<td>6.7766</td>
<td>0.0481</td>
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<tr>
<td>Average permeability</td>
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<td>1</td>
<td>3.2321</td>
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</tr>
<tr>
<td>Average dissolved oxygen</td>
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<td>1</td>
<td>0.3008</td>
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<td>0.1433</td>
</tr>
<tr>
<td>Core $d_{50}$</td>
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<td>1</td>
<td>2.7874</td>
<td>27.8869</td>
<td>0.0032</td>
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</table>

**Steelhead**

<table>
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<tr>
<th>Summary of Fit</th>
<th>$R^2$</th>
<th>$R^2_{Adj}$</th>
<th>Root mean square error</th>
<th>Mean of response</th>
<th>Sum of weights</th>
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<tr>
<td></td>
<td>0.8857</td>
<td>0.7943</td>
<td>0.1825</td>
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<tbody>
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<tr>
<td>Error</td>
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<td>0.1665</td>
<td>0.0333</td>
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<td>C. Total</td>
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<th>Sum of squares</th>
<th>$F$ ratio</th>
<th>Prob &gt; $F$</th>
</tr>
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<td>Core $d_{50}$</td>
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<td>1</td>
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<td>0.0098</td>
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<tr>
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<td>0.1379</td>
<td>4.1391</td>
<td>0.0976</td>
</tr>
<tr>
<td>Depth</td>
<td>1</td>
<td>1</td>
<td>0.0859</td>
<td>2.5776</td>
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</tr>
<tr>
<td>Velocity</td>
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<td>1</td>
<td>0.0294</td>
<td>0.8815</td>
<td>0.3909</td>
</tr>
</tbody>
</table>
Discussion

Growth and survival

Benefits documented for spawning salmonids and their developing embryos by enhancement projects have been anecdotal, and typically inferred from measurements of physical habitat characteristics and observations of spawning activity (Zeh and Donni 1994; Van-Zyll-De-Jong et al. 1997). Our results indicate LMR spawning gravel enhancements significantly increased chinook salmon embryo survival to swim-up stage up to 5 years after placement. Survival of salmonid embryos has been tied to DO (Coble 1961), temperature (Heming 1982), percent fines (Sear 1993) and permeability (Kondou et al. 2001) within spawning gravels. Merz and Setka (2004) showed that strategically placed gravel within the LMR significantly increased velocities and permeability, and decreased depths and fines, equilibrating the hyporheic and water column environments, which supports our findings in this study. However, short-term benefits of spawning gravel enhancements may diminish through time if inter-annual bed mobilization from high flows are not provided (Wheaton 2003).

Although we observed no significant increase in embryonic growth in enhancement gravels during Experiment 1, our preliminary egg tube test showed a 24% average increase in survival and 11% increase in growth of chinook salmon embryos placed in two enhanced sites when compared to two unenhanced spawning sites in December 2000 (unpublished data). Embryo quality may have been a significant factor in the reduced benefits to growth observed in this study considering we observed 65-100% survival in enhancement gravels in tubes buried for four weeks during our preliminary test and only 1-67% within enhancement gravels during this study. Similar
rates of survival were also observed by hatchery staff monitoring the same egg lots incubated in the MRFH.

Physical correlations

The principal component correlations (Table 3) explain a few trends with respect to median grain sizes that are consistent with conventional geomorphic theory. First, surface bed material was consistently coarser than subsurface material. In gravel bed streams, this is known as paving or armouring (Parker et al. 1982) and is thought to arise from differential erosion of coarse and fine grains in heterogeneous bed mixtures. Briefly, finer grains require less energy to erode than coarser grains due primarily to their differences in mass. For example, a prolonged intermediate flow event may produce hydraulic forces competent to erode fine and medium grained particles from the surface of a heterogeneous gravel bed, but not strong enough to erode the coarser grain particles. This in turn, can lead to an armoured layer comprised of a higher percentage of coarse grains as compared to a subsurface layer, which is not subjected to hydraulic forces adequate to winnow finer material away. In regulated rivers like the LMR, Kondolf (1997) explains that surface armouring is often accentuated due to flow regulation conditions because larger particles that lag behind are less easily mobilized by hungry water below dams. Furthermore, dams block the passage of gravels and once finer material (including spawning gravels) has winnowed away it is not replenished. Although the subsurface layers may provide a source of appropriately sized spawning gravels, they can become inaccessible or erodible under the protection of a coarse armour veneer.

The second trend apparent in the principal component correlations is a reduction in grain size with distance downstream from Camanche Dam (fining). This fining of bed
material is evident in both the surface median grain size and to a lesser extent the subsurface, consistent with the literature (e.g., Ashworth and Ferguson, 1989, Schumm and Stevens, 1973). Constantine et al. (2003) documented downstream fining in the gravel bed reaches of the neighboring Cosumnes River, but also noted the presence of a confined, gravel-bed reach where downstream fining was not evident. They attributed the lack of decreased grain size in that discrete reach to equal mobility of bed material and incised channel morphologies that limit the freedom of the channel to migrate laterally. Given the incised nature of the LMR channel and the artificial reset of grain sizes at enhancement sites located throughout the LMR, one might suspect that the downstream fining trend would not persist in similarity to the Cosumnes River. However, the rather small percentage of the entire spawning reach actually covered by enhancement gravels (< 2%) may prevent a noticeable influence on the general fining trend (Merz and Setka 2004). Furthermore, the equal mobility of all grain sizes observed in the Cosumnes River is in response to a non-regulated natural flow regime with no major dams blocking the replenishment of sediment. Thus, the armoured surface substrates of the LMR may exhibit downstream fining through the coarse relic deposits left behind from the pre-regulation flow and sediment regime.

We also observed a strong correlation between water temperature and distance downstream from Camanche Dam, evident in both average temperature and temperature hours. Preece and Jones (2002) observed a three-week lag in and 5.0 °C reduction of annual maximum daily temperature on Australia's Namoi River after a dam construction. Similarly, Camanche Reservoir acts as an insulator, cooling water within the spawning
reaches of the LMR during summer and fall. However, this pattern is reversed during the winter period with temperatures actually cooling further downstream from the dam.

**Correlations between physical and biological parameters**

Substrate size $Cd_{50}$ was significantly correlated with chinook salmon survival and, along with temperature hours and VSS, explained 86% of the variability in predicted survival. Likewise, growth regression equations for both chinook and steelhead included $Cd_{50}$. The mechanistic pathway of the $Cd_{50}$ effect likely involved a relationship with permeability (Sowden and Power 1985). Interestingly, while we observed strong correlations between $Cd_{50}$ chinook alevin survival and growth, $Cd_{50}$ only appeared strongly correlated to steelhead growth, not survival. According to Chapman (1988), mean particle size was not as good an indicator of steelhead survival as for other salmonid species. Usefulness of mean particle size may be limited because gravel mixtures with the same geometric mean can have different size compositions. While our study design focused on survival of salmonid embryos within the hyporheic environment, the placement of embryos into a tube provided protection from physical impacts from all but the smallest substrates ($< 2.9$ mm diameter). It is expected that $Cd_{50}$ would have a direct egg-size dependent effect on survival of embryos deposited directly in substrate. Likely, direct impacts related to substrate size include physical abrasion and crushing in the case of smaller sized gravel and interstitial space or, in the case of larger interstitial space, increased trauma due to currents and decreased cushioning. In a similar vein, egg size varies between salmonid species and even within species. Fecundity and egg size are inversely related in Pacific salmon and vary over latitudinal clines with northernmost populations producing more, but smaller eggs (Flemming and Gross 1990). Quinn et al.
(1995) showed that there was a correlation between egg and substrate size for sockeye salmon, implying a selective effect of gravel size on egg size. Natural selection effects on salmonid egg size can occur over decades and may be influenced by hatchery production (Kinnison et al. 1998). Independent of body size, there is little variation in egg size within populations of salmonids and we assumed that the egg sizes in our study were similar for each species for each experiment (Flemming and Gross 1990).

Developmental rates in sockeye (O. nerka) and chinook salmon embryos are optimized for thermal regimes present within a given population’s home spawning area suggesting a genetic component that may vary between populations (Hendry et al. 1998; Kinnison et al. 1998). Although we used Feather River steelhead eggs, we assume there is little difference between these present populations considering the high egg importation rate by hatcheries that has occurred over the past 4 decades (Bryant 2000). Even so, genetic influence on developmental rates should be considered when compiling information on restoration techniques and resulting salmonid physiological performance (growth, behavior, mortality).

Intra-watershed variation must also be considered. For instance, the thermal shift in the LMR below Camanche Dam appears to affect embryo survival and growth. We observed both slower growth with cooling downstream of the dam late in the season and increased growth with warming earlier in the season (unpublished data). The reservoir insulating effect (i.e., warming water in winter and cooling water in summer and fall) will affect oxygen saturation levels as well.

Numerous studies have documented correlations between individual physical parameters and embryo survival (Coble 1961; Heming 1982; Sear 1993). However, a
specific action, such as increasing substrate permeability may also influence temperature, DO or even predator access to developing embryos. Shepherd et al. (1986) showed that the thermal mass of the substrate in Pacific Northwest coastal streams caused parallel but lagged and buffered heating and cooling trends in infiltration-source intergravel water compared with surface water. Similarly, this study and other work performed on LMR spawning gravel enhancement demonstrated that during the early portion of the fall-run chinook salmon spawning season (October through early November), intergravel water temperature may be as much as 2.3 °C warmer than surface water, potentially influencing growth and development within the different embryo life-stages. Salmonid egg to fry development is generally partitioned into three phases: pre-hatch, post-hatch and terminal phase. During the post-hatch phase, yolk utilization increases markedly concurrent with increased somatic growth and organogenesis. The terminal phase is when the fish begins the transfer to exogenous feeding. It is during the terminal phase that sub-optimal environmental conditions effects are manifested in either reduced physiological performance or increased mortality. Prior to the terminal phase sub-optimal conditions generally affect growth rates and yolk utilization efficiencies, whereas sub-lethal or critical conditions lead to developmental arrest and death. Progression of embryonic development is affected by extraneous factors such as temperature and DO, both of which are correlated with hyporheic flow (Chapman 1988). During the study period intergravel temperatures ranged from 7.6 °C to 12.8 °C, well within the optimal incubation range for chinook salmon and steelhead (Bjornn and Reiser 1991). Results from Experiment 2 indicate that, as expected, temperature affected the growth and presumably yolk utilization efficiency of the embryos, but had no significant impact on survival.
However, this study was performed during the middle of the LMR redd incubation period (October through April) and results could be different at either end of this period.

Use of several physical parameter measurements to construct a predictive model of chinook salmon and steelhead survival and growth worked well. In addition to the parameters discussed above, VSS, DO, permeability, depth and water velocities were all used in regression equations to predict growth and survival. While literature and previous work on the LMR support the fact that each of the parameters listed can influence salmonid physiology, their inclusion in our predictive model is not necessarily indicative of a significant effect individually (Garric et al. 1990). In our analysis we found that there were significant differences in the predictive power of regression equations based on what combination of parameters were used. While individually some parameters, such as average temperature, had a higher correlation with average steelhead size, when included in a suite of parameters it was not as useful as stream velocity in maximizing the predictive power of the regression equation. While the bulk of variation in growth and survival is explained by 2 to 3 parameters, the inclusion of minimally correlated measures may act to fine tune equations to particular sites or systems.

Leftwich et al. (1997) compared the predictive power of local and regional habitat models for the tangerine darter (*Percina aurantiaca*). Their results indicate significant differences in the relative importance of limiting factors between habitats, which limited the transferability of local habitat models. It is likely that the influence of non-limiting parameters in predictive models would also vary geographically, emphasizing the importance of collecting a full suite of data when evaluating restoration projects. (Koslow et al. 2002).
Management implications

It is important to note that the earliest development period for steelhead and chinook salmon eggs was not exposed to the test environment. Even so, our results suggest that survival and development effects from manipulation of the spawning and incubation environment can be accurately measured. By increasing substrate porosity, hyporheic and surface water quality can be equilibrated. However, these synergistic effects greatly complicate evaluation of enhancement benefits, especially when parameters are assessed individually. These effects may explain documented low correlations between alevin survival and substrate permeability measurements.

The simple test between embryo survival in enhanced and unenhanced gravels performed here provides an explanation as to why spawning habitat rehabilitation has biological benefits. From a subset of the 12 parameters, we were able to develop predictive multiple regression models for chinook salmon and steelhead embryo survival and growth, suggesting benefits from gravel augmentation can be predicted and measured. However, this is not to suggest that all forms of spawning habitat rehabilitation will yield similar improvements in embryo survival. Instead, differences between substrate conditions in enhanced and unenhanced gravels can explain the observed differences in survivability. The four spawning bed enhancement sites consisted of riffles constructed between 1994 and 2001. Unlike gravel augmentation or hydraulic structure placement forms of rehabilitation, these projects involve the direct placement of clean, optimally-sized spawning gravels to form immediate spawning habitat (Wheaton 2003). On the LMR, typical fill depths of these projects is greater than
that of egg-burial depths (> 25 cm). Merz and Setka (2004) showed significant reductions in channel depth, sediment fines and intergravel temperature and significant increases in stream velocities, intergravel permeability and DO. Therefore, strategic gravel placement equilibrated the hyporheic and water column environments and related positively to embryo survival rates. As Pasternack et al. (2003) point out, ad hoc implementation (as done on the LMR from 1991-2000) of spawning bed enhancement projects without a systematic design process (e.g., Wheaton 2003) can lead to less effective gravel placement. To better gauge the benefits of such projects to the effort applied, we suggest appropriate cost benefit analysis of material and effort to actual embryo or fry production. Furthermore, while site specific augmentation appears promising, it is important to note that the LMR is a relatively low gradient stream with a highly regulated flow. Using the methods presented here in other river systems, should increase our understanding of how gravel enhancement projects work in different situations. This understanding, in turn, can be linked to the establishment of healthy ecosystem, hydrologic and geomorphic processes.

ACKNOWLEDGEMENTS

We wish to thank James Smith, Michelle Workman, Leigh Chan, Dr. Peter Moyle and Dr. Joseph Cech for their contributions to this project. We are also grateful to Dillon Collins, Dr. Randy Dahlgren, Leslie Ferguson, Liz Gordon, James Jones, Nina Kogut, Gina Ladd, Donna Maniscalco, Bert Mulchaey, Audrey Peller, Kent Reeves, Matt Saldate, Jason Shillam, John Strelka and Dr. Erwin Van Nieuwenhuyse who assisted at various times with field and lab work. Finally, we wish to thank the Mokelumne River
and Feather River hatchery staff of the California Department of Fish and Game for providing chinook salmon and steelhead eggs for this project. Support from the United States Fish and Wildlife Service through the Central Valley Project Improvement Act Restoration Funds, California State Park Funding, and East Bay Municipal Utility District are gratefully acknowledged.

References


CHAPTER FOUR

Full Title: Effects of Gravel Augmentation on Macroinvertebrate Assemblages in a Regulated California River.

Short title: Gravel Augmentation Effects on Aquatic Macroinvertebrates

Authors:

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Sponsored by East Bay Municipal Utility District and the United States Fish and Wildlife Service through the Central Valley Project Improvement Act Restoration Funds

Key words: river enhancement, macroinvertebrates, salmon, spawning, gravel, biomass, species diversity, physical habitat
Abstract

Enhancement projects within anadromous salmonid rivers of California have increased in recent years. Much of this work is intended as mitigation in regulated streams where salmon and steelhead spawning habitat is inaccessible or degraded due to dams, water diversions and channelization. Little research has been done to assess the benefits of spawning habitat enhancement to stream organisms other than salmon. We monitored benthic macroinvertebrates at 7 spawning gravel augmentation sites in the lower Mokelumne River, a regulated stream in the Central Valley of California. Placement of cleaned floodplain gravel decreased depths and increased stream velocities. Benthic organisms colonized new gravels quickly, equaling densities and biomass of unenhanced spawning sites within 4 weeks. Macroinvertebrate species richness equaled that of unenhanced sites within 4 weeks and diversity within 2 weeks. Standing crop, as indicated by densities and dry biomass, was significantly higher in enhancement sites after 12 weeks than in unenhanced sites and remained so over the following 10 weeks. Although mobile collector/browsers initially dominated new gravels, sedentary collectors were the most common feeding category after 4 weeks, similar to unenhanced sites. These data suggest that cleaned gravels from adjacent floodplain materials, used to enhance salmonid spawning sites, are quickly incorporated into the stream ecosystem, benefiting benthic macroinvertebrate densities and dry biomass.

1. Introduction

Alluvial streams in semi-arid climates may transport large amounts of bed material, especially during rain and snowmelt pulses (Andrews and Nankervis, 1995).
Adaptations of biota to these “pulses” include the regeneration of riparian plant species (Mahoney and Rood, 1998), seasonal migrations and life stages of numerous native fish species (Sommer et al., 2001; Bennett et al., 2002) and diversity and development of benthic macroinvertebrate communities (Townsend et al., 1997).

Damming, regulation, levee construction, water diversion and mining have disrupted natural sediment transport mechanisms, including timing, frequency, agitation and cleansing, processes important to the flora and fauna of riverine systems (Collins and Dunne, 1989; Kondolf, 1997). Sediment-starved rivers are prone to channel bed and bank erosion, channel incision, coarsening bed material and reduced habitat heterogeneity (Brooks and Boulton, 1991; Kondolf, 1997). Stream channelization may further exacerbate these problems, decreasing abundance and diversity of riverine species (Negishi et al., 2002).

2. Restoration efforts in sediment-starved systems

Numerous techniques have been used in restoration and enhancement projects in an attempt to ameliorate these impacts. Wheaton et al. (In Review) segregate improvement projects into three sometimes-overlapping categories: 1) gravel augmentation, 2) structural improvements and 3) habitat enhancement. The most common improvement projects in North America have been structural, including current deflectors, overpour structures, bank cover and boulder placements (Gore et al., 1998). These projects can be successful. For example, Fuselier and Edds (1995) showed that an artificial riffle constructed in an area of previously dredged gravel, improved habitat for the Neosho madtom (Noturus placidus). The artificial riffle had similar fish species
diversity and richness to natural riffles in the Cottonwood River, Kansas after 1 year. Gravel augmentation has received increasing attention as a restoration tool to improve salmonid spawning habitat in sediment-starved systems, especially on regulated systems (Scrutin et al., 1997; Nakamura, 1999). In California alone, gravel augmentation was taking place on more than 13 dammed Sierra Nevada rivers beginning as early as 1979 (Kondolf and Mathews, 1993). Little work has been done to assess whether gravel augmentation actually improves salmonid spawning habitat and even less study has centered on the effects of gravel augmentation on associated organisms. For instance, many lotic macroinvertebrate species are found in riffle areas with streambed substrate of gravel or rubble which is the same habitat utilized by many anadromous salmonid species for spawning (Platts et al., 1983; Mangum, 1986; Groot and Margolis, 1991). This is surprising considering the importance of benthic macroinvertebrates to the ecology of lotic systems (Gore, 1985; Hershey et al., 1993; Hamilton and Barclay, 1998; Hocking et al., 2002) and the significant impacts river regulation has on these communities.

The use of benthic macroinvertebrates to assess enhancement or restoration projects is relatively new (Ebrahimnezhad and Harper, 1997; Gørtz, 1998; Muotka et al., 2002). Results of such studies have been variable due to study length and project size (Tikkanen et al., 1994; Laasonen et al., 1998). Aquatic macroinvertebrates, especially insects, are often used in water quality assessment due to their ubiquity, sedentary nature and length of life cycles. These traits make them useful indicators of temporal and spatial changes in aquatic habitats (Rosenberg and Resh, 1993; 1996). Furthermore, Colonization rates and eventual macroinvertebrate community structure on new substrate may demonstrate how well “rehabilitated” sites are incorporated into the river system.
Macroinvertebrate colonization of artificial substrates in lentic and lotic environments has been well discussed in the literature (Lake and Doeg, 1985; Brooks and Boulton, 1991; Benoit et al., 1998; Quinn et al., 1998). Mackay (1992) describes processes and patterns of lotic macroinvertebrate colonization, and Ebrahimnezhad and Harper (1997) have assessed the biological effectiveness of riffle construction for the benthic community in an artificial channel. Assessment of habitat improvement projects implies that we know what should be measured to evaluate success. According to Palmer et al. (1997), from a community ecology perspective, appropriate structural endpoints include measuring species richness of focal groups or entire assemblages. Functional restoration endpoints, in the strictest sense, refers to process measurements such as primary or secondary production, and the measurement of trophic levels and their connectiveness, functional groups, desired community structure and careful consideration of community level attributes, not just a focus on single species or clusters of “desirable” species (Palmer et al., 1997; Maddock, 1999). Colonization of enhanced or restored stream channels by aquatic communities has not been well documented nor are the patterns of colonization well understood.

This paper examines the influence of salmonid spawning gravel augmentation on colonization and development of the benthic macroinvertebrate community of a regulated California Central Valley river. Specifically, we test the hypothesis that gravel augmentation will influence the density, biomass, species richness, diversity and evenness of benthic macroinvertebrates within the chinook salmon spawning reaches of the regulated lower Mokelumne River.
3. Study Site

3.1 Mokelumne River System

The Mokelumne River, California, drains approximately 1,624 km$^2$ of the central Sierra Nevada. The lower Mokelumne River (LMR) includes approximately 54 km of regulated river between Camanche Dam, a complete barrier to anadromous fish, and the Sacramento-San Joaquin Delta (Figure 1). The river between Camanche Dam and Lake Lodi, a seasonal reservoir with a fish passage facility, is characterized by alternating bar complex and flatwater habitats, with a gradient of approximately 0.17 m/km. Similar to many other Central Valley rivers, the Mokelumne River has been affected by numerous human influences including 16 major water projects and instream gravel and gold mining (CDC, 1988; Kattelmann, 1996). Tailings from abandoned gold dredging operations are frequent along the upper one-third of the LMR. While many of the tailings are isolated from the river by berms and levees, several large pits from gold and gravel dredging are now incorporated into the main river channel. Leveed banks and regulated flow greatly reduce lateral scour within this section of river, further impacting bedload recruitment.

At least 35 fish species occur in the LMR including two native anadromous salmonids, steelhead (*Oncorhynchus mykiss*) and fall-run chinook salmon (*O. tschawytscha*) (Merz, 2002). It has been estimated that approximately 80% of historical Mokelumne River anadromous salmonid spawning habitat is now inaccessible due to construction of Camanche Dam. The quantity and quality of remaining habitat limits salmonid production (Menchen, 1961; FERC, 1998). Natural salmon and steelhead spawning now occurs within the upper 16 km of the LMR between Camanche Dam and Elliott Road (Figure 1). Both populations are supplemented with fish from the
Mokelumne River Hatchery (local fish), the Feather River Hatchery and Nimbus Hatchery (American River). Mean annual discharge for the 25 years prior to this study was 20.3 m$^3$ s$^{-1}$ (Minimum: 0.7 m$^3$ s$^{-1}$; Maximum: 162.8 m$^3$ s$^{-1}$). Detailed information on the lower Mokelumne River and its salmonid populations is also provided in Pasternack et al. (2003) and Merz and Setka (In press).

3.2 Gravel augmentation

Since 1990, East Bay Municipal Utility District, owner and operator of Camanche Dam, has performed annual chinook salmon spawning enhancement projects in the LMR, including gravel augmentation to improve spawning habitat. These projects typically consist of placing approximately 380-1,200 m$^3$ of washed river rock (25-150 mm...
diameter) in berms and staggered gravel bar configurations. Sites locations are selected within the spawning reach of fall-run chinook salmon with easy access by roads for gravel-placing equipment. According to Merz and Setka (In Press) historic aerial photographs (1933 – 1963) are used to select sites of previously shallow gravel that have been mined for gold or gravel between 1952 and 1964. Clean river gravel is placed by dump truck and rubber-tire loader in berm and staggered toe-bar configurations along each enhancement site. Configurations are chosen as a means to enhance chinook salmon spawning conditions by reducing depth, increasing velocities, and promoting exchanges of water between the stream and the interstices of the gravel. Gravel placement is carried out between 15 August and 15 September of each year to avoid impacts on fish migration and spawning. Sites are typically 30 m wide by 65 m long (each site corresponds in size to 1-2% of remaining chinook salmon spawning habitat) with an average depth of 0.4 m for placed gravels. Chinook salmon typically begin spawning in the new gravels within 3 months of gravel placement (Figure 2). Steelhead are uncommon. Preliminary assessment of these sites indicates that the projects increase intergravel permeability and dissolved oxygen and decrease intergravel temperatures in most situations (Merz and Setka, In press). Up to 49% of in-river chinook salmon spawning now occurs within LMR enhancement sites (Setka, 2001).

4. Methods

4.1 Channel topography and physical measurements

Topographic channel surveys of the enhancement sites before and after gravel placement were made with a Trimble 4000 GPS receiver, Leica T-1600 Theodolite, DI-
1600 electronic distance meter, and NA-2002 electronic level to record 2000–2800 individual reference points (latitude, longitude, elevation). Point spacing was quasi-systematic and stratified by grade-breaks and channel topography as opposed to a uniform grid (Brasington et al., 2000). Surveys were performed in early August, before gravel placement and again in late September, after gravel placement.

Depth (D) and water velocity (at 0.6 x D) were measured prior to and immediately after gravel placement using a Marsh-McBirney, Inc. Flo-Mate Model 2000 Portable Flowmeter. Measurements were recorded every 60 cm at 5 evenly spaced transects within each site.
During September-January each year, salmonid spawning surveys were conducted weekly along the 16-km spawning reach below Camanche Dam. Redd locations were recorded using a hand-held Global Positioning System (GPS) unit (Trimble Pro XR) and a laser range finder (Atlanta Advantage). Survey data were downloaded to an American Standard Code for Information Interchange (ASCII) file and translated to the grid-based graphics program, Surfer® (Golden Software, Inc.). Reference points were used to construct digital terrain models and contour maps of sites before and after gravel placement with an overlay of salmon redds (Figure 2).

4.2 Substrate size

Newly placed gravel came from an open pit, dry quarry approximately 0.4 km south of the river channel. Therefore, new gravel was void of benthic organisms at time of placement (Week 0). Wolman pebble counts were conducted at three randomly selected transects (100 samples per transect) at each site prior to and immediately after gravel placement following the methods of Bauer and Burton (1993). Substrate from pebble counts was categorized into twelve sizes: <0.80, 0.80, 1.60, 2.22, 3.18, 4.45, 6.35, 8.90, 12.70, 17.78, 25.40, and >25.40 cm (Pasternack et al. 2003). Cumulative percentages of each class were calculated.

4.3 Macroinvertebrate collection

Benthic macroinvertebrate collection was performed at 7 spawning gravel enhancement sites along the LMR from 1996 through 2000. Benthic macroinvertebrates were collected with a 330 mm ID x 400 mm high, stainless steel 363 µm Nitex Hess
Stream Sampler (bottom open area = 0.086 m²) with an attached 368 µm dolphin bucket. Samples were taken to an approximate 15 cm depth within the substrate. Macroinvertebrates were collected both prior to and following gravel enhancement at all 7 sites. Collections of benthic macroinvertebrates were made at 4 random points within a site in both pre- or unenhanced gravel and enhanced gravel areas. Pre-enhancement macroinvertebrate collection (Week 0) occurred approximately one week prior to gravel placement. Collected samples were placed in 500 mL Nalgene bottles in 95% ethyl alcohol. In order to maximize sampling efficiency, all samples were taken in riffle/run habitats with substrates dominated by gravel, in depths less than 60 cm and velocities between 0.25 and 1.00 m s⁻¹, typical of chinook salmon spawning ranges (Healey, 1991; Allen and Hassler, 1986).

Following gravel placement, macroinvertebrate samples were collected every 2 weeks to assess rates of colonization and changes in biomass and community structure based on colonization rates of previous studies (Waters, 1964; Shaw and Minshall, 1980). Samples were collected until flows became too high to wade the channel (typically late mid-January through July). In several instances, unenhanced substrate was slowly covered by scoured new material, ending comparative assessment. Dates of completed gravel placement and benthic sampling are provided in Table I.

Samples were transported to the laboratory and hand sorted using a 60x dissecting scope. When possible, organisms were identified to species. If taxa could not be identified to species, they were differentiated into apparent morphospecies. Size class (<2, 2-7, 8-13, 14-20, >20 mm) and life stage (larva/nymph, pupa and adult) were
determined for each individual. Organisms were grouped into functional feeding categories following Merritt and Cummins (1996), Wiggins (1998), and Pennak (1989).

Dry biomass of samples was determined by oven drying samples of each taxonomic group (order or family) in representative life stage and size classes at 70° C for 24 hours to constant weight (Bowen 1983). Samples were then weighed to the nearest 0.0001 gram. For extremely small organisms (i.e. <0.0001 g), groups of up to 20 individuals of the same life stage and size class were combined, and an average dry weight for that organism was calculated (Merz, 2002). The resulting average weights were multiplied by the count of that particular taxon present in a given sample to obtain a dry biomass measurement.

### 4.4 Data analyses

Structure and function of the benthic communities at each site were evaluated using density (No · m$^{-2}$), dry biomass (g · density), taxa richness, Shannon’s diversity (H) and evenness (J) and relative proportion of functional feeding guilds. We used Morisita’s index (C) as described by Horn (1966) to analyze similarity of benthic communities from enhanced and unenhanced gravel sites, where a value of 0 indicates no species in

<table>
<thead>
<tr>
<th>Site</th>
<th>Completed Gravel Placement Date</th>
<th>Date of first paired benthic sample (Week 2)</th>
<th>Date of last paired benthic sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>02-September-1996</td>
<td>16-September-1996</td>
<td>03-February-1997</td>
</tr>
</tbody>
</table>
common and a value of 1.0 indicates identical populations. We used a paired t-test to compare depths and velocities of each site before and after gravel placement. Differences in macroinvertebrate densities, dry biomass, species richness, diversity and evenness between enhanced and unenhanced gravel were examined using repeated measures ANOVA. We compared functional feeding categories between enhanced and unenhanced gravels by chi-square.

5. Results

5.1 Habitat Configurations- channel depths, velocities and cumulative grain size distribution

A portion of the channel bed of 7 sites was covered with up to 2.1 m of clean, quarry gravel, significantly increasing average bed elevation over each site by 0.17 m (t = -1.90, df = 317, p < 0.001). Gravel was typically applied in shallow bars, perpendicular to channel flow, providing a series of gravel deflectors throughout each site (e.g., Figure 2). These bars directed portions of the flow across veneers of new gravel, significantly increasing velocities throughout each site (t = -10.98; df = 103; p < 0.001). All 7 sites attracted spawning chinook salmon (Figure 2). Overall surface bed material had fewer fines (<8 mm) after gravel placement at each site (Figure 3).

5.2 Community Structure

A total of 59677 individuals representing 58 taxa was collected over the 5-year period. Colonization of new gravel gradually occurred over several weeks (Figure 4). There were no differences between mean macroinvertebrate densities on enhanced and unenhanced gravel from all 7 sites by Week 6 (F = 0.536; df = 10; p = 0.481) and
significantly greater densities on enhanced gravel by Week 10 \((F = 5.137; \text{df} = 13; p = 0.041)\). Densities peaked at Week 6 and again at Week 18 in the enhancement gravels. Patterns for dry biomass were similar with average dry biomass significantly higher on the new gravel after Week 6 \((F = 6.940; \text{df} = 10; p = 0.025)\). Peak biomass occurred at Week 12 in the enhancement gravels.

![Figure 3](image-url)

Figure 3. Cumulative grain-size distributions for surface pebble counts taken before and after gravel augmentation at 7 chinook salmon spawning habitat enhancement sites in the lower Mokelumne River, California (1996-2000). Bars indicate 1 standard deviation.

Taxa richness increased on the enhancement gravel gradually over the first 6 weeks with greatest change between the first and second week (Figure 5). Species richness on enhancement gravel peaked at Week 6 and again during Week 18. Overall species richness on enhancement gravel was not significantly different from unenhanced gravel by Week 6 \((F = 1.576; \text{df} = 10; p = 0.238)\) and remained similar over the following 16 weeks \((p > 0.333)\).
Shannon Diversity (H) and Shannon Evenness (J) in enhancement gravel both increased rapidly over the first 2 weeks (Figure 6). Enhanced and unenhanced gravel were not significantly different by Week 2 for both diversity ($F = 0.041; \text{df} = 12; p = 0.843$) and evenness ($F = 0.582; \text{df} = 12; p = 0.460$). Greatest eveness was observed in enhancement gravels at Week 2. Overlap in species composition of enhanced and unenhanced gravel was greatest during Week 16.

We found significant differences in mean densities of 5 of the 10 most abundant taxa in the new gravel by Week 12 (Figure 7). Greatest differences were observed for *Baetis tricaudata* and *Hydropsyche californica.*

![Graph showing total density and dry biomass of macroinvertebrates](image-url)
Figure 5. Total number of macroinvertebrate orders, families, and species per sampling period at 7 chinook salmon spawning gravel enhancement sites.
Figure 6. Mean (± 1 SE) benthic macroinvertebrate diversity, evenness and species overlap for 7 Chinook salmon spawning gravel enhancement sites.
5.3 Functional Feeding Groups

Unenhanced gravels were dominated by sedentary collector/filterers, predominately *H. californica*, *Simulium* sp. and *Cricotopus* sp. (35–52%) (Figure 8). Mobile collector/browsers, primarily *B. tricaudatus* and *Acentrella insignificans*, were the most
common invertebrates in enhanced gravels during the first sampling period (Week 2; 37%). Feeding category distribution was different between enhanced and unenhanced at this time ($G^2 = 27.4; \text{df} = 6; P < 0.001$). However, feeding categories were independent of gravel enhancement by Week 4 ($G^2 = 5.9; \text{df} = 6; P < 0.430$). Sedentary collector/filterers were established as the dominant feeding category in enhancement gravel and remained so throughout the remaining sampling periods (42-66%).

![Figure 8](image-url)  
Figure 8. Mean relative abundance of functional feeding categories in unenhanced and enhanced gravels within Chinook salmon spawning habitat.
6. Discussion

As in other studies, macroinvertebrates colonized new substrate rather quickly after initial placement (Wise and Molles, 1979; Boulton et al., 1988; Quinn et al., 1998; McCabe and Gotelli, 2000; Zuellig et al., 2002). Benthic macroinvertebrate densities and dry biomass was similar to that of undisturbed gravels within 6 weeks of gravel placement and remained significantly higher in enhancement gravels to the end of the monitoring period (except Week 18; up to Week 22).

We speculate the higher densities and biomass observed was likely the result of four factors, in probable order of importance: (1) reduction of fines in enhancement gravel, (2) increase in habitat for collectors in enhancement gravels, (3) reduction of large predators, and (4) presence of nutrients in the new gravel. The increase in invertebrate production in stream enhancement sites has not been recorded in the literature, to our knowledge, although substrate particle size and permeability can have a significant effect on faunal distribution (Brusven and Prather, 1974; Marchant et al., 1985; Beisel et al., 1998). Overall surface bed material had fewer fines (<8 mm) after gravel placement and enhanced gravels were significantly more permeable than adjacent unenhanced bed material, suggesting possible benefits for invertebrate production (Merz and Setka, In press). Some studies discuss increasing aquatic system productivity through manipulation of nutrients, such as phosphorus (e.g., Perkins and Underwood, 2002). Sugunan (2000) suggests that increased productivity is observed in new reservoirs immediately after inundation due to phosphorus released from newly inundated soils. It is quite possible that increases in macroinvertebrate standing crop in new gravels may partially be explained by remnant soils from newly mined material providing some
nutrient “kick-start” for newly established organisms. Another important aspect is that the greatest number and biomass of benthic organisms within spawning habitat of the LMR is filter-feeding collectors. By increasing average water velocity within the sites, this feeding strategy may benefit by exploiting sites of increased food delivery (Smith-Cuffney and Wallace, 1987; Wetmore et al. 1990). Shurin et al. (2002) compared indirect effects of predators on plants via herbivores (trophic cascades) in a wide variety of food webs. They found that in lotic studies, primary consumers had a positive response to predator removal. Although predatory macroinvertebrates were observed within the first sampling period of our study, prickly sculpin Cottus asper, the most common benthic predatory fish in LMR riffle habitat (Merz, 2002), were not collected in benthic samples until Week 6. Predatory fish can have a significant affect on local density of stream insects (Forrester, 1994). It is quite possible that all four mechanisms increased macroinvertebrate density and biomass within enhancement sites.

An interesting finding of this study is that macroinvertebrate density and biomass peaked in new gravels 6-12 weeks after placement (15 October – 30 November), roughly the same time length for chinook salmon hatching and emergence (a 6-12 week period sometime between 15 December and 30 March) within the temperature regime of the lower Mokelumne River (Healy, 1991; Piper et al., 1982). This suggests that appropriately timed gravel augmentation (approximately 1 November) may benefit juvenile salmonid production 3-fold: by increasing spawning habitat, improving incubation parameters and increasing food availability for newly emerged fish.

We observed significantly lower species richness and diversity in the enhancement gravels only for the first sampling period after gravel placement. By Week
4, and subsequent sampling periods, we observed no significant difference between enhanced and unenhanced gravel species richness or diversity. McCabe and Gotelli (2000) argue that because disturbance lowers abundance, fewer species per unit area in disturbed areas should be expected. However, even after macroinvertebrate densities equaled or surpassed those of unenhanced areas, we observed no significant change in the diversity or evenness of the benthic community. It is important to note, however, that species richness of the macroinvertebrate assemblage in the lower Mokelumne River is low. For example, although we have infrequently observed 4 plecopteran families in various monitoring efforts within the LMR, only 5 individual specimens (all Perlodidae) were observed during this monitoring project (< 0.01% of total). Furthermore, one species of Tricoptera (*H. californica*) and two species of mayflies (*B. tricaudata* and *A. insignificans*) made up over 61% of total organisms sampled during this study. Influences of tailwater habitat, such as an altered sediment regime, changes to natural seasonality and variability of flow regimes (duration, extent and rate), and modified temperature range, may simply overshadow positive effects of small-scale gravel augmentation to invertebrate production, limiting potential improvements to the benthic macroinvertebrate community (Vannote and Sweeney, 1980; De Jalon et al., 1994; Hawkins et al., 1997). The lack of a source of diverse immigrants in areas upstream may also be an important limiting factor (MacArthur and Wilson, 1967, Simberloff and Wilson, 1969). Considering the impaired state of virtually all Central Valley streams at this elevation (Brown 2000; Anonymous 1995; Moyle 1995), even if this habitat was improved to the point that it could support less tolerant species, source populations may simply not be available. Furthermore, even if they were available, 5 years may not be
enough to allow for immigration and establishment of less tolerant organisms to enhanced sites (Muotka et al., 2002).

We observed two distinct mechanisms for new gravel colonization over the five-year study period. During 1996 and 1998, we observed flow fluctuations immediately after gravel placement (41-85% flow reduction). Mats of filamentous algae and aquatic plants (primarily Egeria densa, Elodea canadensis and Rorippa nasturtium-aquaticum) were observed floating into new gravel areas and taking root. Floating plants provided a seeding mechanism for Daphnia pulex, cyclopoid copepods, early instars of B. tricaudata, A. insignificans, H. californica and numerous small chironomids in the new gravel. Furthermore, we have observed an adult female chinook salmon dislodging aquatic vegetation upstream of an enhancement site during spawning activity and this material floated into the new gravel. During enhancement year 2000, no flow fluctuations were observed. Within 2 hours of gravel piling along the river’s edge, larvae of Glossosoma sp. appeared on new gravel, and were observed crawling in from adjacent undisturbed material.

Our study demonstrates that cleaned gravels from adjacent floodplain materials can be quickly incorporated into the stream ecosystem. Benthic macroinvertebrate assemblages on salmonid spawning enhancement materials, as indicated by species richness, diversity and evenness, is similar to adjacent unenhanced spawning areas within 4 weeks of augmentation and can support higher benthic density and dry biomass for up to 22 weeks after placement. While increases in macroinvertebrate diversity were not apparent from such small-scale projects, colonization occurred rapidly and standing crop was increased indicating such projects provide benefits beyond initial target species.
Observation of scour and fill of new gravels in this and other studies (Merz and Setka, In press; Kondolf et al., 1996) and the transient nature of alluvial systems suggests that these enhancement sites are transitory as are the site-specific benefits described here. Appropriate sediment budgets, flow regimes and reconnection of these processes with the flora and fauna of entire regulated streams must be incorporated into such enhancement work to realize longer term benefits.

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CHAPTER FIVE

Sediment Budget of Spawning Bed Enhancement Projects In A Regulated Salmonid Stream

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Abstract: Short-term bed elevation and feature adjustments were monitored over 36 months at three Chinook salmon (*Oncorhynchus tschawytscha*) spawning bed enhancement sites in the regulated lower Mokelumne River, California. Our data show that spawning bed sites containing 794 – 1323 m$^3$ of enhancement gravel lost from 3-20% of remaining gravel volume annually during controlled flows of 8 – 70 m$^3$ sec$^{-1}$ and 2.6 – 4.6% of placed material during short-duration (19 days) flow releases of 57 m$^3$ sec$^{-1}$. The oldest site lost ~50% of placed material over the four-year monitoring period. Of the mechanisms monitored, gravel deflation was the greatest contributor to volumetric reductions, followed by surface scour. Salmon spawning, scour around placed features and over-steepened slopes also contributed to volumetric reductions. As sites matured, reductions were less pronounced. Sites entrained as much large woody debris as was lost over the study and large woody debris settled on constructed gravel berms for periods of <12 months to >4 years. While complexity is an extremely important aspect of ecological function, production of highly diverse and complex habitat features appears to come at a cost. Placement of features such as gravel berms, boulders and large woody debris, to attract spawning Chinook salmon, increased gravel cut within enhancement sites. Furthermore, increased spawning activity can reduce the longevity of enhancement sites.

INTRODUCTION

A sediment budget quantifies the amount of size-specified material that moves through and is stored in a designated area over a specific time period. Typical budgets are performed for whole basins (Reid and Dunne 1996; Dietrich et al. 1982) or individual
channel reaches (Fuller et al. 2003; McLean and Church 1999). Monitoring changes in channel morphology and quantifying the mechanisms for the observed change is one approach by which a volumetric sediment budget may be estimated (Ashmore and Church 1998; Dunne 1998; Davies 1987).

The proportion of coarse sediment within a given section of stream has a strong influence on scour, affecting channel shape and stability and is an important habitat component for the stream’s biota (Osmundson et al. 2002; Church et al. 1998). Watershed size, gradient, precipitation characteristics, and faunal pedoturbation (sediment mixing by animals) are examples of natural processes that affect the coarse sediment budget (Hole 1961). However, anthropogenic disturbances, such as dam construction and mining can interrupt the continuity of coarse sediment transport. Other factors affecting bedload include engineered or armored banks and construction of overly narrow and high channel constrictions to promote water conveyance and reduce channel shifts.

In regulated rivers, coarse sediment load past large dams or sequences of dams is negligible, simplifying sediment budgets downstream (Vaithiyanathan et al. 1992). For instance, on the Merced River, California, a 3,305-km² drainage of the central Sierra Nevada Range, Kondolf et al. (1996) report the cumulative bedload deficit to the river below Exchequer Dam (346 608 10³m³) was 2245-4490 metric tons year⁻¹. Mining deficits were between 6.8 and 14 million metric tons for a 27 km section of the same river. In such situations, sediment–starved flow may erode the channel bed and banks, producing channel incision, coarsening of bed material, and loss of spawning gravels for
many fish species (Waldichuk 1993; Shields et al. 2000; Gilvear and Bradley 1997; Kondolf 1997).

Because of declining salmonid populations (detailed below), coarse sediment and physical structure, such as gabions, weirs and large woody debris (LWD) are being added to streams to augment deficient budgets, create meandering channels, and enhance existing individual geomorphic units, such as riffles used by salmon spawners (Scheeler 1990; Chapman 1995; Schmetterling and Pierce 1999). While such 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). One of the greatest inadequacies associated with spawning habitat rehabilitation has been manager and external reviewer expectations of stability or instability. Without sediment input, all natural and artificial gravels eventually scour (Paintal 1971). The rate of scour is often accelerated when micro-habitat structures are utilized (Kuhnle et al. 2002). For placed gravel, scour has been viewed as failure (Kondolf et al. 1996), whereas the failure may not be the scour itself, but rather the lack of a site-scale sediment budget to estimate required inputs to maintain the habitat.

In this paper we posit that a site-scale (i.e. \( \sim 10^1 \) channel widths) sediment budget provides a foundation for planning interannual gravel augmentation to sustain rehabilitation sites on regulated rivers severely impacted by in-stream mining and to incorporate rehabilitation projects into overall basin management schemes. To evaluate this concept, we propose a site-scale sediment budget for rehabilitation projects and test it using data from 3 sizable (i.e. \( 10^2 \)-\( 10^3 \) metric tons) gravel placement experiments on the
Mokelumne River, California. Sediment input, change in storage, and gravel loss are quantified volumetrically at each site and compared with process-based predictions of the potential for compaction and entrainment to assess specific mechanisms of morphological change after gravel placement. Activities include calculation of site-scale sediment budgets from digital elevation model (DEM) differencing at single flood-event and annual time scales to yield within-site spatio-temporal patterns of channel change, monitoring of bed change localized in proximity to LWD and boulders that provide habitat heterogeneity, tracking of tracer rocks to isolate the role of flow-induced gravel mobilization, and assessment of salmon-induced gravel redistribution.

Within the sediment-budget framework, the following specific questions about individual mechanisms of sediment flux and volumetric change are addressed.

1. What is the relation between flow regime and gravel volume loss, including the relative significance of infrequent above-bankfull flows versus sustained durations of below-bankfull flow?
2. What morphologic variables, such as maximum fill-depth, fill-depth at the riffle crest, and bed slope, facilitate more rapid morphologic change?
3. Does placed gravel settle and compact over time?
4. What is the fate of micro-habitat hydraulic structures composed of boulders or LWD?
5. To what extent does improved spawning attractiveness promote bed volume changes due to bed manipulation by spawning salmon?
SITE SCALE SEDIMENT BUDGET

A sediment budget for a gravel placement project at the typical site scale of $\sim 10^1$ channel widths needs to account for all sources and losses of gravel associated with project implementation and subsequent changes (Figure 1). All potential fluxes are described below for completeness. Equations for predicting key components are also presented.

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Figure 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:

- Watershed size
- Channelization
- Armoring
- Flow length
- Flow frequency
- Flow magnitude
- Availability of fines
- Site complexity
- Time
- Run size

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Sources for Gravel Placement

Material is typically purchased from floodplain quarries or in-channel mining (Kondolf 2000). Ideally, a source exists within the basin, but gravel may often only be available from other basins, posing ethical questions. In California, the cost for each metric ton of concrete-grade aggregate can range from USD $7 to 20 at the mine, plus an additional USD $0.06 to $0.10 km$^{-1}$ transported from mine to site. On the Mokelumne River, the cost of in-basin river gravel and cobble including the cost of triple-washing and transport to the site was USD $22.90 m$^{-3}$ total. The cost for the gravel placement equipment and labor was an additional USD $0.47 m$^{-3}$, which is just 2% of the cost of purchase and transport.

Natural Sediment Recruitment

Sediment recruitment is also important within the enhancement reach. Depending on their trap efficiency reservoirs may pass fines at a reduced rate (Brune 1953). Fine recruitment within the bedload of an enhancement site may significantly degrade potential spawning habitat by filling pore spaces of coarse bed material, reducing permeability and compaction potential, as well as cementing gravels and cobbles (Kondolf 1997). While coarse sediment load is typically limited within the regulated stream, bank sloughing, tributary sources as well as augmentation upstream of a given site are potential sources of bed recruitment and are typically the aim of projects that incorporate the placement of weirs, gabions and wingdams, to collect potential “spawning-sized” material (FISRWG 2001).
**Gravel Losses Before Placement – Operational Losses**

Depending on how gravel is imported to a site, staged at the site and/or positioned in the stream, some of the material is lost prior to placement (Figure 1). The longer the distance traveled to import sediment and the more material brought in, the larger the staging area needed and hence the greater risk of losses. In staging, most losses are due to gravel becoming imbedded into the floodplain and channel bank. Unless the floodplain is newly created as well, the space available for staging can be limiting. Poor pre-project planning can increase material loss at staging areas and over-handling, increasing gravel breakage. Mis-configuration and loss due to spillage during transport and placement may further decrease final volume. Unforeseen problems, such as loose banks or pools too deep to operate equipment in may require operators to use a portion of the gravel to create access. Finally, error from various measurements and DEM use and can further affect an estimate of gravel volume (Holmes *et al.* 2000).

**Gravel Losses After Placement**

Of the gravel that actually ends up in the channel, there are three possible changes that can occur: surface scour, local landsliding, and *in situ* settling. First, gravel at the bed surface may be mobilized (e.g. by flow, fish, or people) and either redistributed locally within the site or exported out of the site. Normally, one expects gravel mobilization to be induced by drag and lift imposed by overflowing water (Paintal 1971). Given the grain size distribution of the placed gravel, the critical shear stress for entrainment of the sediment median particle size can be estimated using the Shields (1936) equation:
\[ \tau_c = \tau^* c (\gamma_s - \gamma_f) d_i \]  

(1)

where \(\tau_c\) is the critical shear stress (N/m\(^2\)), \(\tau^* c\) is the dimensionless critical shear stress, \(\gamma_s\) is the specific weight of sediment (assumed to be 25,990 N/m\(^3\)), \(\gamma_f\) is the specific weight of water (9,807 N/m\(^3\)), and \(d_i\) is the sediment size (m) of interest. Because placed gravel is well-mixed, there is likely a high relative exposure of smaller particles, yielding a risk of Wilcock’s “partial transport” mechanism (Wilcock 1997).

To determine whether placed gravel is mobilized by flow, the critical shear stress may be compared to the actual shear stress over the site (Wheaton et al. 2004a). The latter can be computed on a cross-section or at-a-point basis, depending on available field data or model output. For a cross-section experiencing steady, uniform flow, the total shear stress is given by

\[ \tau = \gamma_f R S \]  

(2)

where \(R\) is hydraulic radius and \(S\) is channel slope. Equations 1 and 2 may be re-stated in terms of discharge by combining with the following equations:

\[ Q = WHV \text{ and } V = n^{-1} R^{0.67} S^{0.5} \]  

(3-4)

where \(W\) is channel width (m), \(H\) is flow depth, \(V\) is cross-sectionally averaged water velocity (m/s), and \(n\) is Manning’s coefficient.

For a single point, shear stress may be computed either using the drag force equation:

\[ \tau = 0.5 \rho_f V_b^2 \]  

(5)

where \(\rho_f\) is water density and \(V_b\) is near-bed water velocity or through the log-velocity equation for turbulent flows over rough beds (Garde and Rana Raju 1985):
Where \( u_* \) is shear velocity (m/s), \( U \) is depth-averaged water velocity (m/s), and \( z_0 \) is bed roughness height (m).

Beyond these equations, erodability can be influenced by grain-scale variables and by the use of microhabitat structures. 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 manmade structures such as deflector weirs create local convective accelerations and secondary currents in the form of vortices that intermittently raise near-bed velocities, causing local scour (Smith and Beschta 1994). LWD can make up a significant portion of a section of stream channel and depending on size, completeness (e.g. rootwad attached) and percent of burial into the substrate, can either be highly mobile or stationary over a variety of flows and timescales, further affecting sediment transport (Naiman et al. 1992; Wallerstein 2002).

Hole (1961) has defined nine categories of pedoturbation (soil mixing) which he considers to be a “special case of erosion”. Of these, faunal pedoturbation (mentioned above), gravipedoturbation (mixing by non-catastrophic mass-wasting), and seismipedoturbation (mixing by vibrations) appear to be most applicable to volumetric changes within the augmented gravel locations and may influence the budgetary outcomes mentioned above. Gravel transport due to biological factors such as fish spawning, may be influenced by run size and time.

Second, piles of gravel may be unstable if they are placed at steep angles that exceed a threshold (Buffington et al. 1992). The forces of gravity and friction are in
balance at the angle of repose, which is the maximum slope angle that unconsolidated materials can maintain. For dry glass beads, the maximum angle of repose is 23° (Barabási et al. 1999). However, within the aquatic environment, water may lubricate the motion of grains over one another, reducing intergranular friction and hence friction angles of water-worked grains (Ingles and Grant 1975). In practice, gravel injection along river banks yields steep-sided piles that are meant to be moved easily. For gravel placed into streams, the ability to avoid steep slopes may be limited by site bathymetry and method of placement. For example, a rubber-tire front loader cannot construct a low gradient transition from a riffle to a pool if the depth could flood the cab and engine.

Third, the deposit volume may change through time due to natural settling and repacking processes enhanced by gravel vibration due to flow turbulence and other bed disturbances. The interaction between primary flow and secondary circulation patterns can greatly influence shear stress distribution at a given discharge (Bathurst 1979). Primary flow can interact with channel pattern and bedforms such as riffles and pools to create regions of high and low velocity, and flow acceleration and deceleration (Bathurst 1979). Secondary circulation currents, particularly at moderate flows, can also be a local source of shear stress variability. According to Sear (1996), during low magnitude, high frequency flows, the riffle surface is subjected to chaotic, turbulent flows that develop structure through in-situ particle vibration and sporadic particle motion. The bed surface becomes tightly packed and interlocked.

Gravel compaction has been of major concern to scientists and managers dealing with salmonid spawning habitat quality primarily because of the influence that porosity has on the bulk permeability of spawning gravels and in turn, its influence on the survival
of salmonid embryos (Ingles and Grant 1975; Gustafson-Greenwood and Moring 1991). However, while it has not received significant study, grain packing configuration and gravel bar compaction can have a potentially profound effect on volumetric gravel budget estimation, site design and future function of spawning gravel augmentation projects worldwide.

One can consider grain packing configuration and resulting porosity on purely theoretical terms and the estimate of spherical packing density has been well discussed in the literature (Gauss 1831; Rogers 1958; Goldberg 1971; Steinhaus 1999). While the densest packing for uniform spheres to date has been estimated at 0.77836 of total volume (Muder 1988), one must take into account the shape and size variability and additional complications associated with natural stream sediments (Ingles and Grant 1975). Measuring sediment packing over time is essential to estimate sediment budgets for spawning gravel enhancement projects.

Particle packing can significantly affect bulk density and assemblages of natural particles are seldom uni-sized. Thus, small particles fit between the voids left by the larger particles, and the packing becomes denser the wider the particle-size distribution. Packing also becomes denser as the deposit becomes more compacted due to pressure and shockwaves. Packing can be described either by calculating the density or porosity of a given material. Bulk density ($P_b$) is defined as the ratio of the weight of a bulk material ($M_b$) that is contained in a specific bulk volume ($V_b$) (Bunte and Abt 2001):

$$P_b = \frac{M_b}{V_b}$$  \hspace{1cm} (8)
Porosity is defined as the ratio of the space taken up by voids to the total volume of sediment. Milhouse (2001), as reported in Bunte and Abt (2001), observed bulk densities of 1.70-2.60 (g/cm³) and porosities of 0.02-0.36 in several gravel-bed rivers.

**STUDY SITE**

**River Rehabilitation Motivation**

Many anadromous salmonids spend a large portion of their adult lives at sea, but all must return to freshwater to spawn in cool, clear streams and lakes with appropriate substrate to support successful spawning, embryo development and fry emergence (Groot and Margolis 1991). Much of this habitat is now inaccessible due to barriers or change in stream hydrographs and degradation of remaining habitat (Yoshiyama et al. 1998; Regetz 2003). Spawning habitat degradation can often be tied to two sediment-related problems. The first problem is fine-grain sediment intrusion (Newcombe et al. 1991), which can lead to lower embryo survival, but is not the emphasis of this study (see Sear 1993; Merz and Setka 2004). The second is the lack of spawning gravels. Lack of spawning gravels can be attributed to four factors: bed sediment starvation and armoring due to dams (Ligon et al. 1995; McBain and Trush 1997; Nakamura 2001; Sear 1995); instream gravel and gold mining and associated borrow-pits; reduced channel lateral migration due to bank armoring, levee construction and altered hydrograph; and the homogenization of spawning habitat (Nelsen et al. 1987; Kondolf 1997; Wyga 1998; Kondolf et al. 2001).

Ecologic, economic, and societal factors have promoted strong interest in restoring salmonid habitat in much of its historic range (Groot and Margolis 1991, Helfield and Naiman 2001). In California, the two dominant forms of habitat
rehabilitation have been gravel augmentation and spawning bed enhancement (Wheaton et al. 2004b). Between 1976 and 1999, Kondolf (pers. comm.) identified 73 spawning habitat rehabilitation projects on 19 different rivers. These projects added 1.2 million m$^3$ of gravel at a cost of over US$ 45 million.

Merz and Setka (2004) showed that spawning bed enhancement in the lower Mokelumne River, California significantly reduced water depths and decreased fines, thereby significantly increasing stream velocity and substrate permeability, equilibrating the hyporheic and water column environments. Spawning salmon began using the previously un-used sites within 3 months of gravel placement and these qualities remained for at least 3 spawning seasons. Merz et al. (2004) showed spawning gravel enhancement significantly increased survival of Chinook salmon (Oncorhynchus tshawytscha) and steelhead (O. mykiss) embryos and that collecting a suite of physical parameters within specific sites would allow prediction of at least short-term survival benefits from spawning bed enhancement projects.

Despite these biological benefits, serious geomorphic flaws have been documented with past projects. Thompson (2002) documented the long-term failure of several instream habitat enhancement structures placed in the Blackledge and Salmon rivers, Connecticut. Scour of reconstructed riffles on the Merced River, California led Kondolf et al. (1996) and Kondolf (2000) to recommend that project planning and design consider geomorphic context at multiple scales, acknowledge project maintenance, and incorporate monitoring and evaluation.

**Mokelumne River Setting**
The Mokelumne River is snow-fed and drains ~1624 km² of the central Sierra Nevada. It presently has 16 major water impoundments, including Salt Springs (175 032 089 m³), Pardee (258 909 341 m³) and Camanche reservoirs (531 387 061 m³) (Figure 2). Comparison of annual peak flows pre- (1904–1963) and post- (1964–1999) Camanche shows the hydrologic impact. Prior to Camanche Dam, annual peaks exceeded 200 m³ sec⁻¹ for 21 of 57 years. Since 1964, US Army Corps of Engineers flood flows are set to a maximum of 142 m³ sec⁻¹. Pre-dam mean monthly flow had a typical snowmelt hydrograph, with highest flow during May and June, well after peak precipitation. The post-dam hydrograph shows a significant reduction in late spring snowmelt runoff. Flood frequency analysis revealed a dramatic reduction in flow for all recurrence intervals (Pasternack et al. 2004). At present, Camanche outflow has a step hydrograph, with prolonged lows near the minimum (4.25 m³ sec⁻¹) prescribed in the Joint Settlement Agreement for relicensing (Federal Energy Regulatory Commission (FERC), 1998) (Figure 3).

In terms of geomorphology, the lower Mokelumne River (LMR) from Camanche Dam down to Thornton has a low slope, constrained width, and poor substrates. The LMR bed slope ranges from 0.10% near Camanche Dam to 0.02% near the Cosumnes River confluence. The active channel of the LMR is now half its former width (present average of 30 m; range of 19-43 m) and over-deepened. The first 9.5 km below Camanche Dam are wider, while the river downstream of that is narrower due to flood control levees protecting land use on historic floodplains. LMR substrate types are associated with channel width, river bed slope and hydraulic conditions. For the broader channel 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, shallow riffle-run hydraulics. Downstream substrates of narrower, deep channels with pools and slow runs are mostly sand and mud. Further details including LMR geologic formations and floodplain characteristics can be found in Pasternack et al. (2004) and Merz and Setka (2004).

Figure 2. Study location in relation to the Mokelumne River drainage, Sacramento-San Joaquin River system and the Southwestern United States. Star = Gravel source; NFMR = North Fork Mokelumne River; MFMR = Middle Fork Mokelumne River; SFMR = South Fork Mokelumne River; SSR = Salt Springs Reservoir.

Hydraulic mining, gravel extraction, dam construction, water diversions, altered flow regimes, deforestation, artificial bank protection, channelization and levee construction have resulted in depleted, degraded and otherwise, inaccessible gravel beds within the river. Camanche Dam blocks gravel delivery from upstream. Murphy Creek, a small tributary close to the dam, contributes a small amount of gravel. Several historic
gravel mining operations depleted the instream gravel storage and yielded deep pits that are barriers to sediment transport. Although mine tailings exist along the upper third of the LMR, these are isolated by berms and levees. Channel and banks show little evidence of instability that could lead to gravel recruitment.

Presently, the LMR supports over 35 native and non-native fish species. These fish include five anadromous species: fall-run Chinook salmon, winter steelhead trout, American shad (Alosa sapidissima), striped bass (Morone saxatilis) and Pacific lamprey (Lampetra tridentata). Native Chinook salmon and steelhead trout populations are supplemented by fish production at the Mokelumne River Fish Hatchery located at the base of Camanche Dam. Average annual Chinook salmon escapement to the LMR since video monitoring at Woodbridge Dam (Figure 2) began (1990 – 2002) is 5506 (min:280;
max:10757) and steelhead escapement is typically less than 100 individuals (Workman 2003). Further information on LMR Chinook salmon and steelhead is provided in Merz and Setka (2004).

METHODS

Site selection, enhancement procedures, and gravel input

Prior to the onset of the spawning season, in August of 1999, 2000 and 2001 respectively, three enhancement sites within the LMR (122 m x 46 m, 70 m x 41m and 76 m x 27 m, respectively) were constructed as part of an ongoing fall-run Chinook salmon spawning bed enhancement project (Figures 2, 4, 5 and 6; Sites A-C). Degraded sites were selected based on depth within the spawning reach of Chinook salmon and steelhead and access by roads for gravel-placing equipment. We used historic aerial photographs (1933 – 1963) to select sites and 6) of previously shallow gravel depths that had been mined for gold or gravel between 1952 and 1964, and recent Chinook salmon and steelhead redd surveys to identify appropriate locations (Figures 4-6) (Setka 2002). The purpose of the spawning habitat rehabilitation program has been to replenish suitable-sized gravel in the spawning reach of the LMR (Figure 2) and provide immediate spawning habitat for Chinook salmon and steelhead, recognizing that placed gravels would not remain static over time.

An estimated 1659, 1200 and 794 m³ (Site A, B and C respectively) of clean 25-150 mm diameter river gravel (CDFG 1991; Kondolf and Wohlman 1993) was purchased from an open, floodplain dry quarry located 0.5 km from the active channel (Figure 2). A single placement of gravel was made at each site (A-C), equating to 1323, 1147 and 649
m³ of finished project volume respectively. Gravel was transported by dump truck and contoured by rubber-tire loader in berm, riffle and staggered bar configurations. Configurations were 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 the interstices of the gravel (Vronskiy 1972, Chapman 1988). Boulders (0.6 – 1.2 m diameter) and woody debris (trunks up to 0.6 m diameter) were strategically placed throughout the sites and intended to increase downwelling, channel complexity and cover for spawning salmonids (House and Boehne 1986; Geist and Dauble 1998; Merz 2001a). In 1999 and 2000, these configurations were constructed based on the ad hoc direction of a fisheries biologist in the field (a very common approach). In 2001, the configuration was designed using the science-based SHIRA-AMP5 (Spawning Habitat Rehabilitation Approach-Adaptive Management Phase 5; see Wheaton et al. 2004a; Wheaton et al. 2004b for details on SHIRA-AMP5). Briefly, numerous designs were systematically developed based on a variety of hydrogeomorphic and biological concepts and then tested with 2D hydrodynamic, habitat suitability and sediment entrainment models. Final design selection was based on analysis of model results and consideration of project constraints and revisiting of conceptual models.

**Gravel Placement Monitoring**

Monitoring of the three study sites and eight other sites has been in place since 1991 and is planned through at least 2009. Monitoring of macroinvertebrates, fish community, weekly redd surveys, alevin survival, water quality, aquatic vegetation, discharge and stage-specific hydrodynamics have been part of this program (Merz 2001a;
Merz 2001b; Merz 2002; Merz et al. 2004). Sediment budget monitoring has included repeat surveys of channel topography at each site, surface and subsurface grain size characterization, gravel tracer studies, large woody debris (LWD) and boulder surveys. The repeat surveys tracked morphometric change over two temporal scales: 1) annually with surveys each summer during low flows and 2) event based in response to a controlled flood release in June 2003. Annual surveys of each site were typically repeated during the first week of September each year (Figure 3). This yielded six time steps during which surveys were conducted and five appraisal periods over which changes were analyzed, which we will refer to throughout the remainder of the paper.

**Sediment Budget Measurement Methods**

**Gravel Storage Measurement**

The single most important and largest component of the site-scale sediment budgets after placement was the gravel storage volume. To quantify the volume and assess its change, channel bathymetry was mapped annually as well as before and after a higher controlled flow release. A Topcon GTS-800 total station, with an angular accuracy of 1 second, was used to record 1,200-3400 bed points for each of 21 topographic surveys. Average point densities across all three sites (21 surveys) was 0.78 m\(^2\) (min: 0.39; max: 2.41; std: 0.32). This variation reflects areas of higher sampling density in topographically complex areas and quite low point density in flat channel or floodplain areas (Fuller et. al. 2003). A coordinate system based on state plane survey and NGVD was used by occupying a control network consisting of roughly 70 points established by a professional land surveyor.
Figure 4. Contour maps depicting streambed elevation before and after gravel placement at Site A, lower Mokelumne River California.

Figure 5. Contour maps depicting streambed elevation before and after gravel placement at Site B, lower Mokelumne River, California.
Point data was downloaded into an ASCII file and then translated to the grid-based graphics program Surfer® (Golden Software, Inc.) where they were used to construct grid files for each site. A blanking file was created using the perimeter of specific enhancement features (such as placed gravel piles and boulders) to ensure only elevational and associated volumetric changes were measured where gravel, woody debris and boulders were specifically placed within each site. The volume of gravel material placed at the site and net cut/fill of gravel after specific time periods and flow events was calculated using the Grid Volume Report within the Surfer program, which computes net, cut and fill volumes between two grid files (Golden Software Inc. 1999). Downstream tracking of exported sediment was not necessary for the sediment budget.
Whereas placed gravels create easily discernable, localized features, exported grains may be only 1-2 D_{90} thick and spread over a large area so that it is impractical to resolve using standard surveying.

To estimate potential error from bathymetry mapping and net cut and fill calculations, two areas (13.28 and 8.55 m²) were marked off along the stream bank and surveyed three times each, within a 15-minute time span (mean point density: 5.9 m⁻²). Point data from the surveys were run through the Grid Volume Report, mentioned above, to note discrepancies in bathymetry volume estimates. Mean error for DEM calculations were +/- 0.01955 m³ for each m² surveyed within the LMR channel. Due to proximity of these sites to Camanche Dam, regulated flows and stable banks, we assumed gravel recruitment to the sites via upstream sources was negligible during this study.

**Flow-based Scour Predictions**

The potential for flow-based scour was predicted using equations 1-4 for several site-specific and typical 1-phi grain sizes (Table 1). Given continuing debate over the appropriate value of τ* as either 0.03 or 0.045, and insufficient resources or opportunity to determine it locally for each site in this study, discharge entrainment threshold predictions were made using both values. Then the duration of flow above each threshold was calculated by comparing the threshold values to the actual flow record below Camanche Dam. The additional step of predicting bedload export rates using standard cross-section equations was not performed, because lateral variability in gravel placement design would yield large uncertainties in such cross-section predictions. Spatially explicit predictions of mobilization at the 0.1-2 m scale for the 1999 and 2001 sites pre- and post-project were previously published (Wheaton and Pasternack, 2002;
Pasternack et al., 2004). As an alternative to process-based predictions, flow-based scour was also evaluated by using statistical regressions between gravel volume changes and measures of flow magnitude and duration.

Surface mobilization of course bed material (16-90 mm diameter) as well as the verification of scour predictions was done with tracer rocks. Groups of 800 and 500 randomly selected rocks were collected from gravel enhancement material for Site A and B respectively (1300 total). These rocks were separated into groups of 100 each. Rocks were re-washed by hand and allowed to dry. The rocks were then painted with RUST-OLEUM gray primer (aerosol) and allowed to dry for another 12 hours. Distinct color

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

<table>
<thead>
<tr>
<th>Variable</th>
<th>Values for site-specific grain sizes</th>
<th>Values for 1 phi grain sizes</th>
<th>Values for site-specific grain sizes</th>
<th>Values for 1 phi grain sizes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D_{10}, D_{50}, D_{90}</td>
<td>8 mm 16 mm 32 mm 64 mm 128 mm</td>
<td>D_{10}, D_{50}, D_{90}</td>
<td>8 mm 16 mm 32 mm 64 mm 128 mm</td>
</tr>
<tr>
<td>Constants</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>\gamma_{sediment}</td>
<td>25945 25945 25945 25945 25945</td>
<td>N m(^{-3})</td>
<td>25945 25945 25945 25945 25945</td>
<td>N m(^{-3})</td>
</tr>
<tr>
<td>\gamma_{water}</td>
<td>9790 9790 9790 9790 9790</td>
<td>N m(^{-3})</td>
<td>9790 9790 9790 9790 9790</td>
<td>N m(^{-3})</td>
</tr>
<tr>
<td>f(Re)</td>
<td>0.045 0.045 0.045</td>
<td></td>
<td>0.03 0.03 0.03</td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>0.043 0.043 0.043</td>
<td></td>
<td>0.043 0.043 0.043</td>
<td></td>
</tr>
</tbody>
</table>

Site A (1999)

D_{10} 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

Site B (2000)

D_{10} 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

Site C (2001)

D_{10} 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

Surface mobilization of course bed material (16-90 mm diameter) as well as the verification of scour predictions was done with tracer rocks. Groups of 800 and 500 randomly selected rocks were collected from gravel enhancement material for Site A and B respectively (1300 total). These rocks were separated into groups of 100 each. Rocks were re-washed by hand and allowed to dry. The rocks were then painted with RUST-OLEUM gray primer (aerosol) and allowed to dry for another 12 hours. Distinct color
patterns were made using, Krylon Interior/Exterior 2015 Teal Green; OSH Appliance White 603-3145 Spray Enamel; and RUST-OLEUM Fluorescent Orange 1954 Multi-Purpose Paint for each group of 100 rocks. Paint was allowed to dry for 48 hours. Painted tracer rocks were clustered into pre-determined diameter groups by using a Plexiglas template (round holes) (22mm; 32 mm; 44 mm; 64 mm; 89 mm). Eight evenly placed transects were set up perpendicular to stream flow at Site A in September of 1999 and five were set up at Site B in September of 2000. Rebar (1.3 cm diameter; 90 cm long) was hammered into the bank on opposite ends of each transect. A 60 m measuring tape was stretched across the river at each transect and fastened to the adjoining rebar. A random number sheet was used to select one site on each transect. One group of 100, similarly painted and sized tracer rocks was carried by bucket to each site and dumped in a single pile at the selected location. The measuring tapes were removed but the rebar was left in place to facilitate site relocation. After 12 months, the transects were relocated and tapes stretched across the stream to locate the original placement sites. We used snorkels, masks and dry suits to swim and crawl slowly along the bottom of the stream, looking for painted rocks. When a rock was located, a 10 cm diameter, steel washer with approximately 60 cm of fluorescent flagging tape attached was placed at each location of an observed tracer rock along the river bottom. Approximately 2 hours was spent searching for tracer rocks from each transect. When no more tracers could be located, a measuring tape was used to measure the distance the tracer rock had moved downstream of the original release site. The diameter of the rock was then measured and the two measurements were recorded. Tracer rocks were then placed back where each washer was located. The washer marker was then removed. This was repeated again the
following 12 months and the data recorded. 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. We used the JMP linear regression model function, which performs an analysis of variance (ANOVA), to compare distances tracer rocks moved to stream velocity at initial placement (Sall et al. 2001).

*Gravel Slope Landsliding*

To test the hypothesis that bed slopes constructed at oversteepened (>23 degrees) angles could have a potentially large influence on local readjustment of enhancement site morphology, we conducted slope analyses of the DEMs. Slope analyses were performed within the terrain module of Land Desktop R3 by calculating the slope (in degrees) of each triangular plane on the TIN and adding its area to predefined bins of slope range. Although friction angles have been reported to vary from 10 to 110 degrees in gravel streambeds (Kirchner et al. 1990; Buffington et al. 1992), Barabási et al. (1999) suggest that critical slope for stability is in the area of 23 degrees for spherical particles and Handin (1966) suggest 25 – 40 degrees for filling angles of rock and sand. As such bin ranges of 0 to 10, 10 to 15, 15 to 17, 17 to 20, 20 to 23, 23 to 25 and upwards of 25 degrees were analyzed. So that consistent geometries were used for comparison and generally steep channel banks were not included in the analysis, the original gravel placement boundaries were used as slope analysis boundaries. A maximum hypothetical volume of scour attributed to over steep bedslopes was calculated by multiplying the area of bins over 23 degrees by the maximum observed scour depths. This yielded a conservative estimate of the maximum volume reasonably attributed to readjustment of these slopes.
Gravel Porosity and Potential Compaction Estimates

To assess the volumetric change possible from compaction, dry bulk density of the gravel used within the three spawning enhancement sites was measured prior to placement and empirically estimated after placement. To measure it in advance, we used a 0.020 m³ bucket to collect 6 gravel samples from the source quarry. Bulk density was calculated as kg/m³. To calculate porosity of placed gravels within each site, we used the Winterkorn (1970) formula:

\[
K = 0.385 - 0.08 \log_{10} \frac{d_{\text{max}}}{d_{\text{min}}}
\]  

(7)

where \(d_{\text{min}}\) and \(d_{\text{max}}\) represent the smallest and largest particle sizes present, respectively. We used the minimum and maximum porosity observed by Milhous (2001) in gravel and cobble rivers and calculated porosity for gravels from the three enhancement sites to estimate potential substrate deflation at various depths of placed gravels.

Scour At Boulders and LWD

To quantify placed boulder redistribution, we surveyed boulders topographically at each monitoring time step. Boulders diameters range between 60 and 120 cm, weigh between 250 and 500 kg, and occupy between 0.01 and 0.25 m³. Although we surveyed the same boulders repeatedly, the exact location and density of survey points on the boulders varied between 1 and 20 points. As such, points taken on top of individual boulders were pooled together and their average elevation calculated. We then compared the elevations across each appraisal period to assess change. These calculations were performed for 12 boulders over six time steps at Site A, seven boulders over three time steps at Site B and three boulders over one time step at Site C. We used the average elevational change of boulders between each survey period and divided the measurement
by the number of days between each survey to estimate average daily elevational change.
We used a one-tailed t-test (Zar 1996) to compare average elevations of boulders at initial
placement in the stream channel to elevations after selected time periods (e.g. every 12
months). We used a one-tailed t-test to compare depth change of the stream channel at
each site to depth change of boulders at each site after given time periods (typical time
between surveys was 3 –12 months). Elevation measurements were taken from Z
coordinates provided by channel bathymetry at corresponding XY coordinates.

During channel bathymetry surveys, at least 3 individual points were recorded on
each piece of woody debris to record location of each piece of material within each site to
monitor the fate of LWD within enhancement sites. After 12 months, points were
recorded again to compare location and numerical change for woody debris within each
site. High density point surveys (8-14.3 points m\(^{-2}\)) were recorded around 9 pieces of
LWD at Site A after initial construction (August 1999). These surveys were repeated in
August 2000 to estimate scour volume using the Grid Volume Report within the Surfer
program.

*Salmon Pedoturbation*

To assess the extent improved spawning attractiveness has on bed volume change,
we used bathymetry surveys to estimate change to channel morphology caused by seven
individual Chinook salmon redds. Average point density per redd was 89.79 m\(^{-2}\) (min:
36.16; max: 132.45; std: 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 female Chinook salmon. Average estimated volumes
were then multiplied by the number of redds observed each season to estimate annual total volume of bed material redistributed by spawning Chinook salmon at each enhancement site. Too few steelhead redds were observed during this study to provide an estimate.

RESULTS

The LMR flow was largely unchanged at 10 m³ sec⁻¹ for most of the relatively dry study period (Figures 3 and 7). During its first snowmelt season of 2000, the 1999 site was subjected to a 77-day flow release with a peak of 70 m³ sec⁻¹ lasting eight days. The peak flow corresponded to a 1.29- year event pre dam or a 2.5- year event post dam. Three years later all sites were subjected to a pre-designed 8-day release of 65 m³ sec⁻¹ in June 2003, this time specifically for environmental purposes.

Figure 7. Flow duration curves for the lower Mokelumne River, 1 January 1999 through 31 December 2003.
Gravel Storage Measurement

Analysis of gravel storage change was performed considering overall, annual, and event time scales. DEM differencing of the eleven surveys performed over four years showed an overall decrease in volume (Table 2). The total bed volume of 2948 m$^3$ created in the river among all sites was reduced by 28% by the end of the study. The average bed-elevation change in enhancement sites was 0.153 mm day$^{-1}$ (range of 0.022-0.323 mm day$^{-1}$). The 1999 site experienced a 50% reduction in volume over the initial 45 months between September 1999 and June 2003. The 2000 site experienced a 30% decrease over its initial 37 months while the 2001 site experienced a 20% decrease over its initial 20 months.

Among annual re-surveys, normalized volumetric decreases ranged from 0.07 – 0.73 m$^3$ day$^{-1}$ (26 – 266 m$^3$ year$^{-1}$) 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 the rate of change until period 4, when it showed an increase. Sites B and C showed strong drops in rate of change after the first year.

Sites A and C had significantly higher event-based normalized volumetric decreases than those observed on an annual basis. For sites A, the 266-day period prior to the designed release had a normalized volumetric change of 0.33 whereas during the release increased to 0.92. For site C, the same numbers were 0.07 and 0.72 respectively. These changes are 3-fold and 10-fold increases for sites A and C, respectively.

Flow-based Scour

Based on the predicted entrainment thresholds in Table 1, significant differences in flow-based scour were evident between sites and between periods (Table 2). Site B
has ~4.5-times higher slope than either sites A or C, thus yielding a much lower discharge required to move its sediment. Site B was predicted to have experienced the most flow-based scour overall. In terms of periods, Period 1 had the longest durations of high flows and thus yielded the greatest overall potential for scour, although that could only affect Site A, as sites B and C were not built yet.

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 D₉₀ particles, there were no days when flow was high enough to entrain them using t*₉₀ = 0.045 for any site (just 5 days at Site B for t*₉₀ = 0.03). For the median substrate size (D₅₀), sites A and C were not predicted to experience scour ever using t*₅₀ = 0.045, but for t*₅₀ = 0.03 they would have both scoured ~35% of the time during the first year post-placement, though not in any subsequent periods. The mediansized material at site B was predicted to be mobile for a significant portion of time. Finally, for the smaller bed particles (D₁₀), sites A and C were predicted to experience

Table 2. Time periods, river discharge rates and gravel volume calculations made at 3 spawning gravel enhancement sites on the lower Mokelumne River, California, 1 September 1999 through 23 September 2003. Flows are measured in m³ sec⁻¹ and gravel volumes in m⁶.

<table>
<thead>
<tr>
<th>Flow period</th>
<th>Time period</th>
<th>Number of days</th>
<th>Site</th>
<th>Total volume (m³ x 10⁶)</th>
<th>Ave daily volume (m³ x 10³)</th>
<th>Peak Flow</th>
<th>Number of Days &gt; Qcrit for</th>
<th>Number of Days - Qcrit for</th>
<th>Volume remaining (m³)</th>
<th>Ave daily volume lost (m³)</th>
<th>Total percent lost</th>
<th>Daily percent lost</th>
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<tbody>
<tr>
<td>1 Sept 1999 to 30 Aug 2000</td>
<td>364</td>
<td>1999(A)</td>
<td>432.3</td>
<td>22.8</td>
<td>56.7</td>
<td>1(5%)</td>
<td>0</td>
<td>0</td>
<td>8(42%)</td>
<td>0</td>
<td>663.1</td>
<td>17.44</td>
</tr>
<tr>
<td>1 Sept 1999 to 30 Aug 2000</td>
<td>364</td>
<td>1999(A)</td>
<td>2751.1</td>
<td>7.5</td>
<td>15.9</td>
<td>1(1%)</td>
<td>0</td>
<td>0</td>
<td>92(25%)</td>
<td>0</td>
<td>768.1</td>
<td>83.24</td>
</tr>
<tr>
<td>1 Sept 1999 to 30 Aug 2000</td>
<td>364</td>
<td>1999(A)</td>
<td>2990.3</td>
<td>8.1</td>
<td>13.4</td>
<td>6(2%)</td>
<td>0</td>
<td>0</td>
<td>134(4%)</td>
<td>0</td>
<td>851.4</td>
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</tr>
<tr>
<td>1 Sept 1999 to 30 Aug 2000</td>
<td>364</td>
<td>1999(A)</td>
<td>5630.9</td>
<td>16.0</td>
<td>70.0</td>
<td>50(13%)</td>
<td>0</td>
<td>0</td>
<td>139(38%)</td>
<td>126(35%)</td>
<td>0</td>
<td>1059.4</td>
</tr>
<tr>
<td>1 Sept 2000 to 30 Aug 2001</td>
<td>364</td>
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<td>2000(0)</td>
<td>4048.1</td>
<td>11.0</td>
<td>12.5</td>
<td>38(100%)</td>
<td>12(33%)</td>
<td>38(100%)</td>
<td>262(73%)</td>
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<tr>
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<td>364</td>
<td>2000(B)</td>
<td>2751.1</td>
<td>7.5</td>
<td>15.9</td>
<td>36(100%)</td>
<td>13(36%)</td>
<td>36(100%)</td>
<td>291(80%)</td>
<td>0</td>
<td>919.1</td>
<td>56.54</td>
</tr>
<tr>
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<td>364</td>
<td>2000(B)</td>
<td>2990.3</td>
<td>8.1</td>
<td>13.4</td>
<td>36(100%)</td>
<td>26(71%)</td>
<td>36(100%)</td>
<td>260(74%)</td>
<td>5(1%)</td>
<td>947.6</td>
<td>224.00</td>
</tr>
<tr>
<td>1 Sept 2001 to 30 Aug 2002</td>
<td>364</td>
<td>2001(C)</td>
<td>432.3</td>
<td>22.8</td>
<td>56.7</td>
<td>3(16%)</td>
<td>0</td>
<td>0</td>
<td>9(47%)</td>
<td>3(16%)</td>
<td>0</td>
<td>524.9</td>
</tr>
<tr>
<td>1 Sept 2001 to 30 Aug 2002</td>
<td>364</td>
<td>2001(C)</td>
<td>2751.1</td>
<td>7.5</td>
<td>15.9</td>
<td>36(100%)</td>
<td>13(36%)</td>
<td>36(100%)</td>
<td>291(80%)</td>
<td>0</td>
<td>919.1</td>
<td>56.54</td>
</tr>
<tr>
<td>1 Sept 2001 to 30 Aug 2002</td>
<td>364</td>
<td>2001(C)</td>
<td>2990.3</td>
<td>8.1</td>
<td>13.4</td>
<td>36(100%)</td>
<td>26(71%)</td>
<td>36(100%)</td>
<td>260(74%)</td>
<td>5(1%)</td>
<td>947.6</td>
<td>224.00</td>
</tr>
<tr>
<td>1 Sept 2002 to 30 Aug 2003</td>
<td>2002(C)</td>
<td>432.3</td>
<td>22.8</td>
<td>56.7</td>
<td>3(16%)</td>
<td>0</td>
<td>0</td>
<td>9(47%)</td>
<td>3(16%)</td>
<td>0</td>
<td>524.9</td>
<td>13.75</td>
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<tr>
<td>1 Sept 2002 to 30 Aug 2003</td>
<td>2002(C)</td>
<td>2751.1</td>
<td>7.5</td>
<td>15.9</td>
<td>36(100%)</td>
<td>13(36%)</td>
<td>36(100%)</td>
<td>291(80%)</td>
<td>0</td>
<td>919.1</td>
<td>56.54</td>
<td>0.15</td>
</tr>
<tr>
<td>1 Sept 2002 to 30 Aug 2003</td>
<td>2002(C)</td>
<td>2990.3</td>
<td>8.1</td>
<td>13.4</td>
<td>36(100%)</td>
<td>26(71%)</td>
<td>36(100%)</td>
<td>260(74%)</td>
<td>5(1%)</td>
<td>947.6</td>
<td>224.00</td>
<td>0.61</td>
</tr>
</tbody>
</table>
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 of daily bed sediment volume cut was significantly related to average daily (Figure 8A) and total volume of water released from Camanche Dam (Figure 8B). Enhancement sites lost 0.05% of remaining material daily (range of 0.01-0.14%). We measured 17.4 m$^3$ of cut occurred during the 19-day flood increase from Site A.

![Figure 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.](image)

**Tracer Rocks**

Of the 800 tracer rocks released in August 1999 at Site A, 245 were recovered in August of 2000 (31%). Eighty-six percent (211) of those recovered 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) (Figure 9). Of those recovered that moved, 4 (12%), moved out of the site. Piles 2, 6, 7 and 8 were completely scoured or buried by 10 June 2003 (Figure 10). No tracers were recovered from these sites. Twenty-two (22%) of tracer rocks at release location 1 were mobilized upstream. Similarly, of the 500 tracer rocks released in August 2000 at Site B, 124 (20%) were
recovered the following year. Three (2% of recovered, mobilized tracers) were recovered downstream of the site. Tracer rocks at Site B 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 (Figure 9), typically near the channel center (Figure 10). This was also observed for LWD (Figure 11). By June 2003, 4 of the original 8 tracer rock piles were completely scoured from the 1999 enhancement site. Maximum distance tracer rocks were recovered from original release locations was 121.9 m downstream in Site A, 4 years after original placement.

![Figure 9. Distance downstream tracer rocks were recorded after 12 months, compared to velocities recorded at initial release, Site A, lower Mokelumne River, California.](image)

![Figure 10. Location of tracer rock release sites on 8 September 1999 and recover location of tracer rocks on 10 June 2003. Numbers indicate tracer rock release pile designation.](image)
Gravel Slope Landsliding

Overall, the percentage of the “as-built” project areas with slopes over 23 percent was between 6 and 12 percent with the highest percentage at Site C (Figure 12). This equates to 1405, 1393 and 2057 m² of area susceptible to slope landsliding at sites A-C, respectively. Greatest reduction in overall site slope (increase in area of slope 0-10°) occurred after the first year at each site (Figure 12). Predicted areas of high failure potential corresponded well with tracer rock results (Figure 13).

Gravel Porosity and Potential Compaction

Estimated bulk density from our six enhancement gravel quarry samples was 1.644 g • cm⁻³ (std: 0.054). Mean porosity estimates for placed gravels at the three sites was 0.281 (Tables 3 and 4). Likely porosity change for Sites A-C are 0.059, 0.107 and 0.072 respectively, with maximum plausible porosity change 0.34 for all three sites.
Figure 12. Slope analysis distribution for Sites A - C. Flow Period duration and magnitude are provided in Figure 3 and Table 2.
Based on our porosity calculations, we estimate between 28 and 41% of observed gravel volume reduction can be explained by deflation alone (maximum: 130-190%) (Table 4).

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

<table>
<thead>
<tr>
<th>Site</th>
<th>DMin</th>
<th>Dmax</th>
<th>Estimated Porosity (K)</th>
<th>Estimated percent volume lost 1st year</th>
<th>Total time monitored</th>
<th>Overall percent volume lost</th>
<th>Estimated percent volume lost day⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999 (A)</td>
<td>16</td>
<td>178</td>
<td>0.301</td>
<td>25</td>
<td>1385</td>
<td>50</td>
<td>0.0360</td>
</tr>
<tr>
<td>2000 (B)</td>
<td>4</td>
<td>178</td>
<td>0.253</td>
<td>24</td>
<td>1104</td>
<td>25</td>
<td>0.0226</td>
</tr>
<tr>
<td>2001 (C)</td>
<td>8</td>
<td>127</td>
<td>0.289</td>
<td>17</td>
<td>651</td>
<td>18</td>
<td>0.0270</td>
</tr>
</tbody>
</table>

Figure 13. Tracer rock release and recovery locations in relation to estimated bed areas were slope meets or exceeds the angle of repose. Base map is of as-built contours of Site A, 30 August 1999.
Table 4. Estimated gravel deflation at 3 spawning enhancement sites due porosity.
Sites A-C, lower Mokelumne River, California.

<table>
<thead>
<tr>
<th>Site</th>
<th>Porosity:</th>
<th>Calculated Fill:</th>
<th>Plausible Deflation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.301</td>
<td>1323 m³</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Likely Deflation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Volume (m³)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Proportion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>264.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>207</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>83.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>87.58</td>
</tr>
<tr>
<td>Flood Flow</td>
<td></td>
<td>17.44</td>
<td>184.6</td>
</tr>
<tr>
<td></td>
<td>Total Lost:</td>
<td>660.16</td>
<td>184.6</td>
</tr>
<tr>
<td>B</td>
<td>0.253</td>
<td>1277 m³</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Likely Deflation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Volume (m³)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>224</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>56.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>48.9</td>
</tr>
<tr>
<td>Flood Flow</td>
<td></td>
<td>13.75</td>
<td>136.6</td>
</tr>
<tr>
<td></td>
<td>Total Lost:</td>
<td>329.44</td>
<td>136.6</td>
</tr>
<tr>
<td>C</td>
<td>0.288</td>
<td>707 m³</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Likely Deflation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Volume (m³)</td>
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<td>93.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>17.57</td>
</tr>
<tr>
<td>Flood Flow</td>
<td></td>
<td>13.75</td>
<td>50.9</td>
</tr>
<tr>
<td></td>
<td>Total Lost:</td>
<td>124.53</td>
<td>50.9</td>
</tr>
</tbody>
</table>

Comparison of likely and plausible volumetric fill distributions due to deflation
Fill distribution by area
Scour At Boulders and LWD

Site bed elevations lowered 0.022 to 0.323 mm day\(^{-1}\) (mean: 0.153). Mean elevation change for placed boulders was 0.588 mm day\(^{-1}\) (range of -0.053 to 2.054 mm day\(^{-1}\)). Average boulder elevational changes were significantly higher than average channel bed elevation between each monitoring period (\(t = -1.825; \text{df} = 16; p = 0.043\)) (Table 5).

Table 5. Mean elevations of channel bed and boulders, enumeration of large woody debris, and longitudinal distance tracer rocks moved at 4 spawning gravel enhancement sites within the lower Mokelumne River, California.

<table>
<thead>
<tr>
<th>Site</th>
<th>Construction</th>
<th>Sep-99</th>
<th>Sep-00</th>
<th>Sep-01</th>
<th>Sep-02</th>
<th>May-03</th>
<th>Jun-03</th>
<th>Sep-03</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Aug-99</td>
<td>27.60</td>
<td>27.57</td>
<td>27.55</td>
<td>27.43</td>
<td>27.42</td>
<td>27.42</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>Aug-00</td>
<td>-</td>
<td>27.43</td>
<td>27.38</td>
<td>27.28</td>
<td>-</td>
<td>-</td>
<td>27.15</td>
</tr>
<tr>
<td>C</td>
<td>Aug-01</td>
<td>-</td>
<td>-</td>
<td>27.44</td>
<td>27.39</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Site</th>
<th>Construction</th>
<th>Sep-99</th>
<th>Sep-00</th>
<th>Sep-01</th>
<th>Sep-02</th>
<th>May-03</th>
<th>Jun-03</th>
<th>Sep-03</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Aug-99</td>
<td>28.28</td>
<td>27.53</td>
<td>27.27</td>
<td>27.14</td>
<td>27.05</td>
<td>27.01</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>Aug-00</td>
<td>-</td>
<td>27.73</td>
<td>27.59</td>
<td>27.38</td>
<td>-</td>
<td>-</td>
<td>27.31</td>
</tr>
<tr>
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<td>Aug-01</td>
<td>-</td>
<td>-</td>
<td>27.75</td>
<td>27.77</td>
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<table>
<thead>
<tr>
<th>Site</th>
<th>Construction</th>
<th>Sep-99</th>
<th>Sep-00</th>
<th>Sep-01</th>
<th>Sep-02</th>
<th>May-03</th>
<th>Jun-03</th>
<th>Sep-03</th>
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<tbody>
<tr>
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<td>12</td>
<td>29</td>
<td>32</td>
<td>31</td>
<td>34</td>
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<td>-</td>
<td>16</td>
</tr>
<tr>
<td>C</td>
<td>Aug-01</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-</td>
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<table>
<thead>
<tr>
<th>Site</th>
<th>Construction</th>
<th>Sep-99</th>
<th>Sep-00</th>
<th>Sep-01</th>
<th>Sep-02</th>
<th>May-03</th>
<th>Jun-03</th>
<th>Sep-03</th>
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<tbody>
<tr>
<td>A</td>
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<td>-</td>
<td>416.56</td>
<td>716.28</td>
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<td>-</td>
<td>683.26</td>
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</tr>
<tr>
<td>B</td>
<td>Aug-00</td>
<td>-</td>
<td>437.9</td>
<td>509.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</table>

Enhancement sites contained from 0.5 to 6.0 pieces of LWD per 1000 m\(^2\) of channel bed. While LWD was not captured in Site C, we observed nearly a 300% increase in LWD at sites A and B over a 4-year period. Some LWD was mobilized
during the study, with individual pieces moving completely out of enhancement sites within a year of placement (Table 5). Distinct clumping and mobilization patterns were observed, during a short-duration flow increase (Figure 15). Seven of the 9 pieces of LWD used in the high-density surveys were still intact in August 2000. Average cut around LWD was 0.58 m$^3$ (std = 0.231).

Salmon Pedoturbation

Spawning use of the 3 enhancement sites by Chinook salmon was highly variable over several spawning seasons (Table 6; Figure 15). All three of the enhancement 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; stdev: 2.16). Estimated annual bed material mobilization within each of the enhancement sites by spawning Chinook salmon was 2.26-65.5 m$^3$ (mean: 19.13 m$^3$).

<table>
<thead>
<tr>
<th>Year</th>
<th>Number</th>
<th>Percent Total$^a$</th>
<th>Percent Volume (m$^3$)</th>
<th>Percent mobilized$^a$</th>
<th>Number</th>
<th>Percent Total</th>
<th>Percent Volume (m$^3$)</th>
<th>Percent mobilized$^a$</th>
<th>Number</th>
<th>Percent Total</th>
<th>Percent Volume (m$^3$)</th>
<th>Percent mobilized$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>1</td>
<td>0.2</td>
<td>2.3</td>
<td>0.2</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.2</td>
<td>3</td>
<td>0.5</td>
<td>6.8</td>
<td>0.2</td>
</tr>
<tr>
<td>2000</td>
<td>29</td>
<td>2.9</td>
<td>65.3</td>
<td>6.2</td>
<td>18</td>
<td>1.8</td>
<td>40.5</td>
<td>6.2</td>
<td>1</td>
<td>0.1</td>
<td>2.3</td>
<td>6.2</td>
</tr>
<tr>
<td>2001</td>
<td>5</td>
<td>0.6</td>
<td>11.3</td>
<td>1.1</td>
<td>11</td>
<td>1.3</td>
<td>24.8</td>
<td>1.1</td>
<td>7</td>
<td>0.8</td>
<td>15.8</td>
<td>1.1</td>
</tr>
<tr>
<td>2002</td>
<td>2</td>
<td>0.2</td>
<td>4.5</td>
<td>0.4</td>
<td>16</td>
<td>1.9</td>
<td>36.9</td>
<td>0.4</td>
<td>5</td>
<td>0.6</td>
<td>11.3</td>
<td>0.4</td>
</tr>
<tr>
<td>2003</td>
<td>8</td>
<td>1.1</td>
<td>18.0</td>
<td>1.7</td>
<td>17</td>
<td>2.1</td>
<td>38.3</td>
<td>1.7</td>
<td>4</td>
<td>0.5</td>
<td>9.0</td>
<td>1.7</td>
</tr>
</tbody>
</table>

$^a$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

DISCUSSION

Numerous methods have been used to estimate bed material transport and sediment entrainment rates for large rivers. McLean and Church (1999) presented a
sediment budget to estimate long-term transport rates along a 45 km section of the Fraser River, British Columbia based on repeated channel surveys. Wilcock et al. (1996) used local observations of depth-averaged velocity and tracer gravel installations on the Trinity River, California to relate flow and gravel entrainment on a large gravel-bed river. According to Fuller et al. (2003), when comparing digital elevation models (DEM) to channel planform and cross-section surveys in the River Coquet in Northumberland, northern England, cross-sections underestimate the magnitude of volumetric changes that occur when calculating reach-scale sediment transfers. In this study, we used channel bathymetry, complimented with estimates of gravel porosity and tracer rock, boulder and woody debris surveys, calculations of bed sediment mobilization due to salmonid spawning and estimation of gravel slope landsliding to assess short-term annual bed material volumetric change for Chinook salmon spawning habitat enhancement sites within the lower Mokelumne River California.

Our data show that LMR spawning gravel enhancement sites of 649 – 1323 m³ of gravel lost from 11-24% of remaining gravel volume annually during controlled flows of 8 – 70 m³ sec⁻¹ and 2.6% of placed material during short-duration (19 days) flow releases of 57 m³ sec⁻¹. Site A lost 50% of gravel volume in a four-year period. By using mean estimates of volume loss from the mechanisms quantified in this study, we can accounted for 86 to 113% of the volume reductions observed (Figure 16; Table 7). Overall, deflation appears to be the greatest influence on volumetric loss. This is not surprising due to the restricted flows in the system (Gilvear et al. 2002).
Figure 15. Contour maps depicting streambed elevation and annually constructed chinook salmon redds within Site A, lower Mokelumne River California (1999 – 2003). Rings indicate location of individual redds, October through December, annually.
We observed significant reductions of bed material volume (up to 20%) during the first year after gravel placement at all three sites. Bement and Selby (1997) showed that although it took many minutes to fully reduce the volume of a range of granular soils (uniform Leighton Buzzard sands to a sandy fine-to-medium gravel) 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. Due to the 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 propensity to settle. However, since in-situ bed porosity and/or bulk density were not measured.

<table>
<thead>
<tr>
<th>Site</th>
<th>Original Purchase Volume (m³)</th>
<th>Original DEM Error (m³)</th>
<th>Operational Volume (m³)</th>
<th>Operational DEM Error (m³)</th>
<th>Duration of Monitoring (Days)</th>
<th>Total Volume Loss (m³)</th>
<th>DEM Error (m³)</th>
<th>Mechanism</th>
<th>Portion of Total Volume Loss</th>
<th>Remaining Volume (m³)</th>
<th>DEM Error (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1659 +/−31.52</td>
<td>300 to 363</td>
<td>1323 +/−25.1</td>
<td>1380</td>
<td>659.9 +/−12.52</td>
<td>663.1 +/−12.6</td>
<td></td>
<td>Deflation</td>
<td>30 to 160%</td>
<td>51% 1.9%</td>
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</tr>
<tr>
<td></td>
<td>1.9%</td>
<td>18.1 - 21.9%</td>
<td>80% 1.9%</td>
<td>49% 2%</td>
<td></td>
<td></td>
<td></td>
<td>Faunal Pedoturbation</td>
<td>8 to 15%</td>
<td>76% 1.9%</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Surface scour</td>
<td>1.5 to 3.5%</td>
<td></td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>Local scour</td>
<td>3.1 to 9.8%</td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>Slope angle (slippage)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1200 +/−22.8</td>
<td>25 to 71</td>
<td>1147 +/−21.79</td>
<td>1118</td>
<td>247.8 +/−4.71</td>
<td>870.2 +/−16.5</td>
<td></td>
<td>Deflation</td>
<td>40 to 130%</td>
<td>76% 1.9%</td>
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</tr>
<tr>
<td></td>
<td>1.9%</td>
<td>2.1 - 5.9%</td>
<td>1.9%</td>
<td>25% 1.90%</td>
<td></td>
<td></td>
<td></td>
<td>Faunal Pedoturbation</td>
<td>4.5 to 27%</td>
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<td></td>
<td></td>
<td>Surface scour</td>
<td>0.8 to 2.0%</td>
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<td></td>
<td>Local scour</td>
<td>0.4 to 2.3%</td>
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<td>Slope angle (slippage)</td>
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<tr>
<td>C</td>
<td>794 +/−15.1</td>
<td>128 to 158</td>
<td>649 +/−12.33</td>
<td>650</td>
<td>125.1 +/−2.38</td>
<td>524.9 +/−9.9</td>
<td></td>
<td>Deflation</td>
<td>40 to 190%</td>
<td>81% 1.9%</td>
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<tr>
<td></td>
<td>1.9%</td>
<td>16.1 - 19.9%</td>
<td>1.9%</td>
<td>19% 1.90%</td>
<td></td>
<td></td>
<td></td>
<td>Faunal Pedoturbation</td>
<td>5.4 to 32.5%</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Surface scour</td>
<td>0.4 to 0.8%</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Local scour</td>
<td>0.9 to 2.9%</td>
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<td></td>
<td>Slope angle (slippage)</td>
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</tbody>
</table>

Table 7. Observations of volumetric changes to the channel bed at three spawning gravel enhancement sites in the lower Mokelumne River California.
through time, we cannot quantify what proportion of the volumetric change predicted by DEM differencing is due to settling. Measurement error must also be taken into consideration (Fuller et al. 2003).

While our predictions of entrainment and compaction indicate Site B should have the highest potential for volume loss, several site-specific aspects may explain why this did not occur. Due to a channel bend, Site B was the only study site that received flow somewhat diagonally across the placed gravel, from the southeast to northwest portion of the site. Flow actually cut into the north bank of the site. The slower flow on the south bank, further protected from a group of trees, actually had fines (<8 mm diameter) settle 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 enhancement sites, placement of shallow berms, LWD and boulders are used to attract spawning Chinook salmon to enhancement sites. Such features specifically alter uniform gravel beds, adding complexity. Our data suggest that these features increase gravel cut within enhancement sites and this has been supported in the literature (Rosenfeld and Huato 1993).

LWD can also have a significant effect on secondary morphological structures within a channel (Mutz 2000). We observed no net loss of LWD from the three sites over the monitoring period. 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 LWD from upstream. This suggests that adjacent riparian vegetation, is generating 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) found that such debris is important to spawning Chinook salmon in the Mokelumne River 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 United States (Martin and Benda 2001; Benda and Sias 2003). The importance of this debris has been associated with the maintenance of riverine gravel bars and structures (Everest and Meehan 1981; Sedell et al. 1982). To date, we know of no LWD budget estimated for California Central Valley streams. It is important to note that to further benefit these enhancement sites, a LWD
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. This is due, in part, because they are subject to the same laws of physics that affect any piece of matter. Among these is the second law of thermodynamics, which states that whenever energy is converted from one form to another, some of the input energy is lost in the process of conversion, resulting in less output energy. Furthermore, a stream channel will adjust to a new state of equilibrium if energy is added or removed. Therefore, complex sites with edges, high velocity chutes and obstructions such as LWD and boulders, will become less so (scour, sinking of boulders and even salmon erode and simplify a complexly constructed site) (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 of the appropriate size and frequency, is receiving increasing attention as a mechanism for maintaining diversity of habitat and biota in large, temperate streams (Huston 1996; Townsend et al. 1997; Sparks and Spink 1998). Our observations of tracer rock mobilization and 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 is added to the site to keep it organized and complex. 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 (Figure 15). The 2003 flood release removed a significant amount of rooted vegetation within the spawning gravel, which appeared to positively correlate with increased spawning use. Therefore, in regulated systems, such as the LMR, it seems that continued gravel augmentation, flow or mechanical adjustment must be added to the equation or sites may become simple, degraded and continuously less functional over time.

This then begs the question as to whether form or function is the ultimate goal of spawning habitat rehabilitation. Unfortunately, the 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 failure. 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) argue that attempts to build “stable” habitats may interrupt long-term processes that maintain a diversity of habitats. Our observations suggest that features that remain stable in such regulated streams as the LMR may actually become less attractive and functional to spawning salmonids over time.

Numerous authors discuss the importance of habitat heterogeneity to restoration (Jungwirth et al. 1995; Harper et al. 1999). 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 increases in species diversity of aquatic and riparian biota. Merz and Setka (2004) infer that the addition of complexity to restoration sites within a highly regulated stream attracted spawning salmon to those sites. Increased benthic macroinvertebrate production and increased survival of Chinook salmon and steelhead embryos have also been observed (Merz and Chan In Press; Merz et al. 2004). 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 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 structure, such as boulders, have been placed.

According to Hole (1961), animals perform 12 activities within soils. They are: mounding, mixing, forming and filling voids, forming and destroying peds, and regulating soil erosion, plant and animal litter, nutrient cycling and the movement of air and water in the soil. It is quite clear that these activities can be transferred to the aquatic environment. 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 (unpublished data). This suggests that while salmon may not necessarily mobilize material completely out of a site, they can have a significant impact on site morphology.

Considering the average volume of gravel placed at each site was 1217 m$^3$, an average female Chinook salmon could mobilize ~0.2% of a LMR enhancement project. Therefore, 538 spawning female Chinook salmon could potentially mobilize an entire
enhancement site. Average annual construction at these enhancement sites has been 11 redds suggesting fall-run Chinook salmon could potentially mobilize an entire enhancement site in 49 years. Changes to the number of salmonids naturally spawning in the LMR may significantly affect this time period. This implies that while over the short term, increased complexity attracts more spawning fish, shortened lifespan of the habitat 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 or low levels of spawning activity over a longer time period? This suggests that such a myopic management goal is inappropriate and site-specific enhancement programs must be incorporated into the larger watershed scale (Kondolf et al. 1996).

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 entrained in future spawning sites instead of large gravel pits downstream.

While our study provides a clear path to estimate a material budget for site-specific spawning enhancement projects within a spawning reach of the LMR, it is important to note that our present method does not take into account the sediment deficit due to historic mining and channel aggradation caused by flow regulation. Nor does it specifically take scale into account. According to Kondolf (1998), if changes in dammed rivers, due to altered flow and sediment transport are not recognized, restoration designs are likely to be ineffective or inappropriate. Therefore, this budget should be supplemented with an appropriate volume of material to restore an acceptable channel
geometry and to reduce the size and number of abandoned mining pits to satisfactory levels (Kondolf 1994). This amount of material may be constrained more by fiscal budgets and material available than geomorphic and hydrologic science. Once these two factors are addressed, calculation of the gravel budget must be re-evaluated. Although the expense of developing reservoir sediment flow-through technology may seem excessive, developing such methods is critical to the maintenance of regulated river systems, including both upstream reservoir capacity and downstream ecological processes.

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