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Evaluation of a Spawning Habitat Enhancement Site for Chinook Salmon in a Regulated California River

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Abstract.—An evaluation of the effectiveness of a project to enhance spawning habitat for Chinook salmon *Oncorhynchus tshawytscha* was conducted in the Mokelumne River, a regulated stream in California's Central Valley. Approximately 976 m^3 of clean river gravel (25–150 mm) was placed in berm and gravel bar configurations along the 45-m enhancement site. Physical measurements taken before and after gravel placement indicate that 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 during the three spawning seasons encompassed by the study. Bed material movement was documented by channel bathymetry surveys over two water years. Topographical channel surveys provide a useful tool for monitoring bed material transport and layering redd locations on contour maps. Although its usefulness in restoring salmon populations is poorly understood, gravel enhancement can be an effective means for improving salmon spawning habitat in rivers where upstream dams have effected low gravel recruitment.

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 effects on native salmonid populations (Yoshiyama et al. 1998; Levin and Tolimieri 2001). Riverine salmonids typically spawn in cool, clear, well-oxygenated streams with depth, water velocity, and gravel size suitable for the species (Bjornn and Reiser 1991). Dams and other fish migration barriers have made spawning reaches of many streams inaccessible and have degraded or depleted the remaining habitat. 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). Although 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-type 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 historical 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

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et al. 1996; Scruton et al. 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). Moreover, 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 attributes associated with survival of these early life stages. Our objective in this study was to test the hypothesis that gravel augmentation would improve physical habitat characteristics—specifically, depths, water velocities, and intergravel water quality—which would subsequently attract spawning Chinook salmon *Oncorhynchus tshawytscha*.

Study Area

The Mokelumne River is a modified system that drains approximately 1,700 km^2 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 nonpassable dam (to migratory fishes) on the river and was constructed for flood control and river regulation. The subsequent altered flow regime stabilized active sediment and enabled inchannel vegetation survival. According to Pasternack et al. (2004), the active channel is now half its former width, as documented from historical aerial photos, and overdeepend. Before Camanche Dam, annual peaks exceeded 200 m^3/s for 21 of 57 years. Since 1964, annual peaks have never exceeded 200 m^3/s. The predam mean monthly hydrograph shows the highest flow in May to June from snowmelt after the precipitation peak. The postdam hydrograph shows significant reduction in late spring snowmelt runoff below the dam. A flood frequency analysis using annual extreme predam and postdam data shows a dramatic reduction in flow for all recurrence intervals after the dam was built. Estimated Q2, Q5, Q10, and Q100 (the 2-, 5-, 10-, and 100-year peak discharge recurrence intervals) decreased by 67, 59, 73, and 75%, respectively. The statistical bankful discharge (Q1.5) before Camanche Dam was 120 m^3/s, which is now only released about every 5 years (Pasternack et al., in press). Flow out of Camanche Dam has a step hydrograph, and lows are near the minimum (4.25 m^3/s) prescribed in the Joint Settlement Agreement for relicensing (FERC 1993). The lower Mokelumne River is an approximately 54-km reach of regulated stream between Camanche Dam 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, is characterized by alternating bar complex and flatwater habitats with a gradient of 0.0017. The lower Mokelumne River 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 third of the lower Mokelumne River. Although 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 lower Mokelumne River floodplain is predominated by agriculture, including walnut and grape production, livestock grazing, and an increasing number of single-family dwellings. Riverbanks are characterized by 50–100-m sections of broken concrete and stone riprap with a thin ribbon of Fremont cottonwood *Populus fremonti*, valley oak *Quercus lobata*, willow *Salix* spp., and red alder *Alnus rubra*. Numerous nonnative 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 lower Mokelumne River 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; Figure 1). Abundant nonnative fish species include western mosquitofish *Gambusia affinis*, golden shiner *Notemigonus crysoleucas*, and spotted bass *Micropterus punctulatus*.

Historical records of 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 lower Mokelumne River fish life, including whole year-classes of salmon (CDFG 1959; Finlayson and Rectenwald 1978). From 1980 to 1988, over 90% of Mokelumne River Hatchery production originated from imported eggs and fry, all suggesting

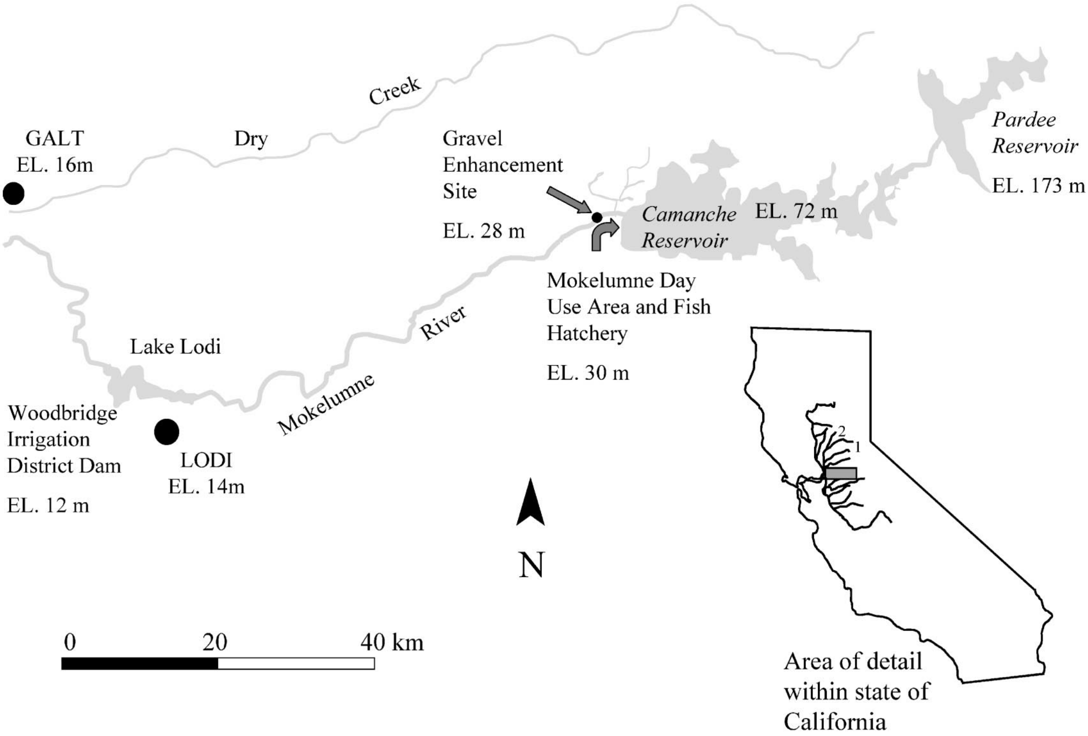

FIGURE 1.—Features of the Mokelumne River, California, including the gravel enhancement site to augment fall-run Chinook salmon spawning. Also depicted is the river's location in relation to the American River (1) and the Feather River (2).

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 2–4 years in the ocean before returning to their natal stream to spawn (Healey 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, and few fish spawned elsewhere. 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 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 at river kilometer (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 escapements in the Mokelumne River, based on counts at the Woodbridge Irrigation District Dam, have 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.

By ranking the factors limiting the production of Chinook salmon in the lower Mokelumne River, FERC (1993) determined that spawning habitat (quality and quantity) was second in importance. 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, the owner and operator of Camanche Dam, performed annual Chinook salmon spawning habitat enhancement projects in the lower Mokelumne River. 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 382–1,147 m^3 of washed river rock (diameter 25–150 mm) in berms and staggered bar configurations as a means to increase natural reproduction of these fish. Sites were typically 30–100 m long and spanned the river channel; average depth was 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 lower Mokelumne River for the 5 years before this study was 28.3 m^3/s, whereas maximum discharge over the 24-month study was 69.9 m^3/s. The maximum flood release rate, set by the Army Corp of Engineers, for Camanche Dam is 142 m^3/s (FERC 1993).

Methods

Site selection and gravel placement.—The study site is located in the Mokelumne River day-use area approximately 0.75 km 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 1933–1963 aerial photographs to select a site that had been shallow gravel before being 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 front-end loader (rubber tires) in berm and staggered toe-bar configurations perpendicular to stream flow along the 45-m enhancement site (Geist and Dauble 1998). 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 quasisystematic 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 1999). 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 were calculated using the Grid Volume Report within the Surfer program, which computes net, cut and fill volumes between two grid files (Golden Software 1999).

Pebble counts.—Pebble counts were conducted at four randomly selected transects (about 100 samples per transect) at each site before 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 0.3 m along the transect and used a 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. Measurements were repeated 12 months after gravel placement.

Hydrologic data.—Immediately before and after gravel placement we measured velocities and depths with a Marsh-McBirney Flo-Mate model 2000 flowmeter and a depth-setting wading rod at every 0.6 m along five evenly-spaced cross-sections over the site (Camanche release rate: 7.0 m^3/s). We measured intergravel water quality at three haphazardly chosen (presumably random) stations (3 replicates/sample) within the enhancement site and an adjacent reference site before, immediately following, and at 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 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 laboratory to measure turbidity (nephelometric turbidity units or NTU) and total sus-

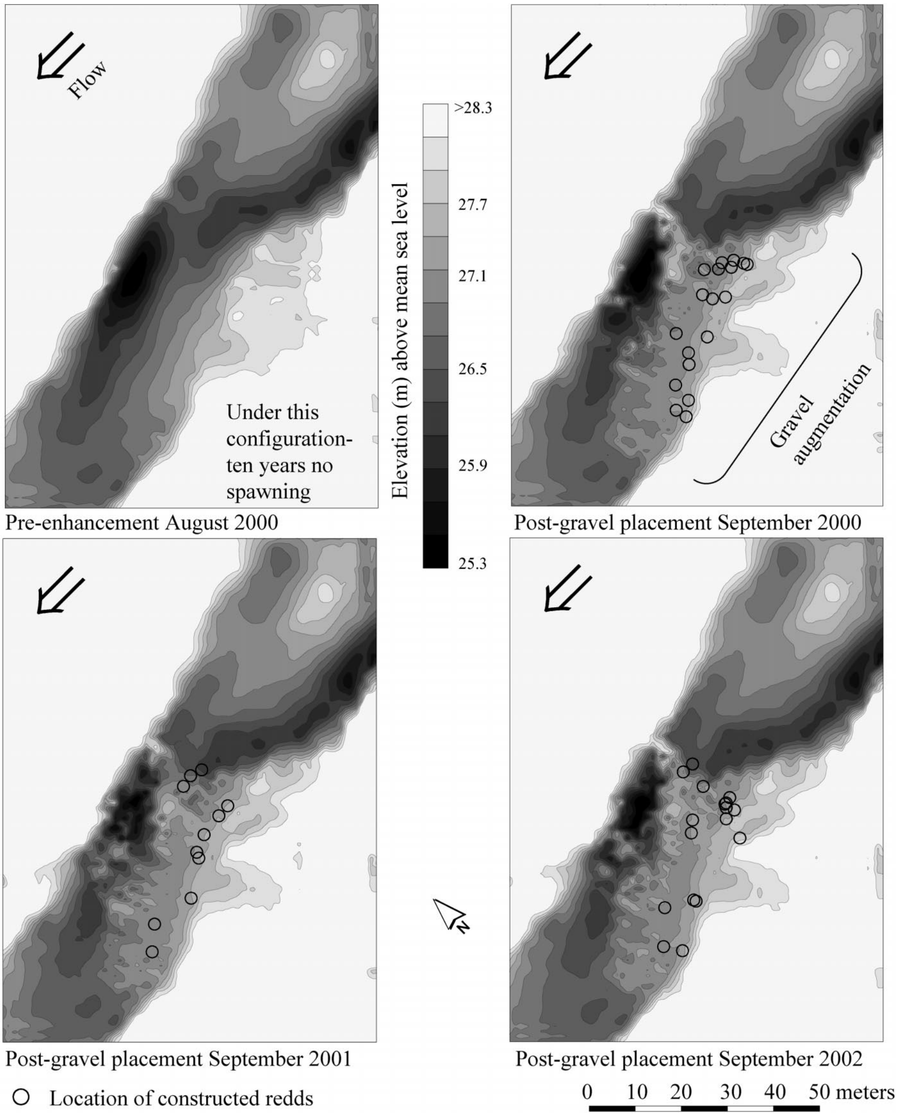

FIGURE 2.—Fall-run chinook salmon spawning gravel enhancement site at river kilometer 101.4 on the lower Mokelumne River, California. Note changes and stability through 3 years of study. Redds (indicated with circles) indicate use from October through December each year.

pended solids (TSS). Turbidity was measured with a Hach 2100P Turbidimeter. The TSS samples were filtered through a 50-μm sieve, then passed through a precombusted gas fiber filter, dried to 60°C, and weighed (APHA et al. 1995). Water temperature and DO were measured at 15 cm below the water surface and within the gravel with a YSI 55 dissolved oxygen meter.

Redd surveys.—From September to January each year, salmonid spawning surveys, conducted weekly, included all available spawning habitat along the 16-km reach 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 previously mentioned. 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 216 mm steel bolt with a 40 mm drywall toggle wing anchor. Tags enabled us to differentiate between old and new redds during subsequent surveys and to 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, using likelihood ratio chi-square, that the amount of bed material 8 mm or larger was not related to whether new gravel was placed at the site (Sall et al. 2001). In all statistical testing $\alpha = 0.05$.

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 ($t = 5.51$, 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 ($t = 14.22$; df = 203; $P < 0.001$). After 12 months, increased velocities created scour along the north bank (Figure 2).

Bed Material

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

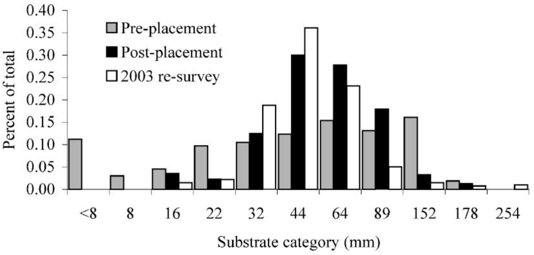

FIGURE 3.—Grain-size distribution for substrate-surface pebbles as measured and counted before, immediately after, and 12 months after gravel placement along the Chinook salmon spawning reach of the lower Mokelumne River, California.

Hyporheic Environment

Intergravel water temperature was significantly cooler in enhanced gravel ($t = -7.23$, df = 8, $P < 0.001$; Table 1) and DO was significantly higher in enhanced gravel ($t = 2.07$; df = 8; $P = 0.036$) immediately after placement. Turbidity and TSS within water samples collected immediately after gravel placement were significantly lower in enhanced gravels than in unenhanced gravels ($t = -3.03$; 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. Intergravel turbidity and TSS remained significantly lower in enhancement bed materials ($t = -3.63$, df = 8, $P = 0.003$; $t = -3.03$, df = 8, $P = 0.008$).

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 rescour were observed within the site and are captured in the topographic surveys. Total estimated deficits of 216 m^3 and 303 m^3 of placed gravel were 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 after gravel placement, 1.3% in the second, and 1.9% in the third (Figure 2); total number of Chinook salmon redds observed in the Mokelumne

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 (TSS). Mean measurements (SDs) are provided for each depth.

Characteristic at the stated depth below gravel surface	Aug 24, 2000 (Pre-placement)	Sep 6, 2000		Sep 10, 2001		Oct 1, 2002 (Enhanced)
		Enhanced	Unenhanced	Enhanced	Unenhanced	
Gravel permeability (mL/s)						
15 cm	23.5 (1.8)	26.8 (3.8)	13.8 (2.4)	27.5 (4.3)	22.3 (6.7)	29.0 (3.4)
30 cm	19.6 (9.4)	24.8 (3.3)	5.03 (2.4)	22.9 (3.0)	18.6 (11.4)	26.6 (4.9)
45 cm	11.7 (8.3)	26.4 (1.2)	3.48 (0.6)	26.3 (1.2)	6.2 (1.3)	23.8 (7.13)
Temperature (°C)						
Ambient	13.5	13.9	13.9	15.4	15.4	13.1
15 cm	14.6 (0.3)	14.6 (0.3)	15.9 (0.2)	15.5 (0.1)	16.1 (0.4)	13.1 (0.6)
30 cm	15.0 (1.1)	14.5 (0.3)	17.9 (0.7)	15.9 (0.3)	17.7 (1.4)	13.4 (0.4)
45 cm	15.9 (1.7)	14.5 (0.3)	18.0 (0.3)	15.9 (0.4)	17.4 (1.2)	13.4 (0.2)
Dissolved oxygen (mg/L)						
Ambient	8.5	8.6	8.6	8.2	8.2	7.8
15 cm	8.0 (0.1)	8.3 (0.3)	8.1 (0.1)	8.0 (0.2)	8.0 (0.1)	8.1 (0.2)
30 cm	7.6 (0.4)	8.1 (0.1)	8.1 (0.1)	7.8 (0.1)	7.6 (0.4)	7.5 (0.3)
45 cm	6.7 (1.4)	7.2 (1.2)	6.6 (0.7)	7.5 (0.3)	6.8 (0.1)	7.7 (0.3)
Turbidity[a]						
Ambient	4.6	3.5	3.5	5.1	5.1	6.0
15 cm	411.0 (357.7)	6.3 (2.3)	24.6 (33.3)	55.7 (72.2)	96.3 (54.5)	26.3 (7.6)
30 cm	534.7 (342.2)	36.0 (30.6)	288.3 (43.7)	132.8 (65.5)	389 (177.3)	153.7 (108.7)
45 cm	481.7 (226.4)	30.2 (18.5)	425.3 (39.5)	352.0 (87.5)	525 (129.3)	428.7 (77.0)
TSS (mg/L)						
Ambient		2.6	2.6	3.2	3.2	
15 cm		2.6 (0.5)	7.3 (7.1)	20.2 (19.0)	26.2 (6.5)	
30 cm		6.2 (3.9)	124.4 (146.3)	32.8 (13.4)	91.3 (44.5)	
45 cm		5.9 (3.0)	66 (16.4)	79.1 (13.7)	124.5 (44.3)	

[a] Nephelometric turbidity units.

River by season 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 0.1–2.1 m deep over large portions of the enhancement area. Features 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 attributes such as intergravel DO, temperature and permeability can have profound effects on developing eggs and embryos of salmonids (Coble 1961; Phillips and Campbell 1961; Beacham and Murray 1990; Heming 1982). Compared with other salmonid life stages, the fertilized egg–alevin stages is a very dynamic period that can be disproportionably influenced by environmental attributes. One reason is that alevins are limited in their ability to escape unfavorable conditions. Salmonid alevins 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 the early life stages 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 salmonid metabolic rates and somatic growth of early life stages. Time to emergence varies significantly with water temperatures, but for Chinook salmon it takes approximately 40–60 d for temperatures of 10°C and 14°C, respectively (Piper et al. 1982). 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 (Heming 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 (Bjornn 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. keta* and Chinook salmon. Chinook salmon were attracted to areas where there was downwelling and intergravel temperatures were equal to surrounding river temperatures, whereas chum salmon were attracted to areas of upwelling and intergravel temperatures warmer than surrounding river temperatures. Our results suggest that the enhancement improved interconnected pore spaces to allow downwelling and equalize temperatures between the hyporheic zone and the surrounding water, and that attracted spawning Chinook salmon.

Gravel permeability is directly related to fine sediments within the interstitial spaces of the gravel and, as such, is a proxy for hyporheic flow, which can influence redd temperature and DO and remove metabolic wastes. Depending on the particle size, fines can have deleterious effects on developing salmonid eggs (Reiser and White 1988; Sowden and Power 1985; Platts et al. 1989). It has been generally shown that fines less than 0.85 mm 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 4–12 mm 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 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 features 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. Although spawning bed enhancements can provide immediate physical improvements to specific sites, their longevity and effects 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 percentage of total loss is due to actual transport from the site versus 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 downstream (<5 m). However, Harvey and Lisle (1999) showed that redds of fall-spawning Chinook salmon 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 improve assessments of the degree of sediment travel and the potential for redd scour (Nawa and Frissell 1993).

Although spawning adult Chinook salmon used 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 effects on numerous other organisms, including other fish and benthic macroinvertebrates and this should be fully appraised.

Although 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 enhancement—increased salmon production. For example, since the inception of our enhancement monitoring program in 1999, major changes in sport harvest regulations have taken place. These include changes in take and size limits. Furthermore, annual variation in other effects on salmon yield, including precipitation and runoff, ocean conditions, water diversion rates, and predation rates can all greatly influence salmon numbers. Although 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 the true range of augmentation capabilities.

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