Studies of Spawning Habitat for Fall-Run Chinook Salmon in the Stanislaus River Between Goodwin Dam and Riverbank from 1994 to 1997

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Abstract

The spawning habitat of fall-run chinook salmon (*Oncorhynchus tshawytscha*) was studied in the Stanislaus River between Goodwin Dam and Riverbank between 1994 and 1997 to evaluate whether habitat quality was potentially limiting the population and whether two restoration projects improved spawning conditions. Redd surveys in 1994 and 1995 indicated that spawning was concentrated in the riffles located in the 12-mile reach between Goodwin Dam and Orange Blossom Bridge. Most of the spawning (73%) occurred upstream of the riffles' crests where the streambed gradient was positive (for example, the tail of a pool). Sample areas were divided into the upper, middle, and lower portions of riffles to determine why the salmon used the upper areas.

Substrate samples collected from the upper six inches of the streambed indicated that predicted survival probabilities for chinook salmon eggs using Tappel and Bjornn's (1983) laboratory study averaged 75.6% in the reach above the Orange Blossom Bridge, 58.6% in the lower spawning reach between the bridge and town of Riverbank, and 95.4% at two restoration sites near the U.S. Army Corps of Engineers' Horseshoe Road park where gravel was added in 1994. Predicted egg survival probabilities averaged 73.2% upstream of riffle crests and 62.1% downstream of riffle crests at four natural riffles with pronounced crests.

Intragravel dissolved oxygen (DO) concentrations were relatively constant at 32 piezometer sites in the 12 study riffles during five surveys conducted at 10-day intervals in November and December 1995. The DO levels declined markedly in early February 1996 at nine sites shortly after runoff from four major storms increased base flows from 300 cfs to as much as 800 cfs for several days after each storm. Prior to the storms in November and December, intragravel DO concentrations were less than 5 ppm at six piezometer sites (19%) and less than 8 ppm at eleven sites (34%). Immediately after the fifth major storm in early February, intragravel DO concentrations were less than 5 ppm

at 11 piezometer sites and less than 8 ppm at 16 sites (50%). Many of the sites where DO concentrations were low were associated with intragravel water temperatures that were between 1° and 6° F higher than surface temperatures. The elevated temperatures suggest the inflow of oxygen-poor groundwater. A high rate of groundwater inflow into the Stanislaus River's riffles would explain the unexpectedly positive vertical hydraulic gradients upstream of the riffle crests measured at most of the piezometer sites in fall 1996.

A regression model of the average intragravel DO concentrations in November and December 1995 had an adj-R^2 of 0.80 with significant ($P \leq 0.05$) variables that include an index of groundwater inflow, abundance of Asian clams (*Corbicula fluminea*), percent fines <2 mm, and mean column water velocity. A model for the February 1996 DO concentrations had an adj-R^2 of 0.68 with significant variables that include the groundwater index and the percent fines <2 mm. Although streambed gradient indexes were not selected for the regression models, DO concentrations that were greater than 80% saturation in February 1996 usually occurred where the gradient was positive 2% or higher.

Not all restoration sites in the Stanislaus River where clean gravel was added were used by spawning salmon. Two riffles constructed with imported gravel from the Merced River were used by very few fish for three years even though intragravel DO levels were near saturation and spawning occurred in the immediate vicinity. After high flows deposited a large berm of native rock at the crest of one of these riffles in spring 1997, a relatively high number of salmon began spawning in the new substrate in fall 1997. In Goodwin Canyon, where gravel was lacking, many salmon quickly spawned in newly added gravel from the Stanislaus' floodplain placed in late summer 1997.

Introduction

Two studies, one conducted in summer 1993 by the California Department of Water Resources (DWR 1994) and the other conducted in fall 1994 by Carl Mesick Consultants, Thomas R. Payne & Associates, and Aquatic Systems Research (CMC and others 1996), suggest that a majority of the spawning habitat in the Stanislaus River between Goodwin Dam and Riverbank is unsuitable for fall-run chinook salmon (*Oncorhynchus tshawytscha*). These studies reported that chinook salmon primarily spawn in the upper 30-ft sections of riffles where the streambed usually had an upward slope. The explanation for this pattern was not obvious as there were suitable water depths and velocities and an abundance of gravel in the unused, lower riffle areas.

The DWR (1994) study of 22 riffles between Goodwin Dam and Riverbank indicated that 45% of the substrate samples collected from the upper 30-ft section of the study riffles had high levels of fines (silt and sand). DWR did not sample the middle and lower sections of the riffles, but it is likely that the spawning activity concentrated in the upper sections would remove fines and make the upper sections relatively "clean" compared to the middle and lower riffle sections. If true, the percentage of riffle habitat with excessive amounts of fines would have exceeded 45%.

This report describes three years of spawning surveys from fall 1995 to fall 1997 that evaluated two questions:

1. Is habitat in the Stanislaus River's primary spawning reach unsuitable for spawning?
2. Did a riffle restoration project implemented in summer 1994 and a gravel augmentation project implemented in summer 1997 improve spawning conditions for salmon?

The first question was investigated by measuring the percentage of fines and monitoring intragravel dissolved oxygen (DO) concentrations and temperatures with piezometers buried in artificial and natural redds in the upper 30 feet, middle 30 feet, and lower portions of natural riffles between Goodwin Dam and Riverbank in fall 1995 and fall 1996. Measurements of vertical hydraulic gradient (an index of upwelling and downwelling of flow into the substrate), intragravel nitrate concentration, percentage of fines in the substrate, weight of Asian clams (*Corbicula fluminea*), streambed gradient, and the depth and velocity of the surface flow were also made to evaluate the cause of low intragravel DO concentrations.

Two restoration projects were also evaluated. The first involved two riffles that were reconstructed at the Horseshoe Recreation Area (river miles 50.4 and 50.9) by DWR in September 1994. At these sites, the streambed was excavated to a depth of 1.5 feet and then refilled with washed gravel from 0.5 to 4 inches in diameter to provide a uniform streambed (–0.2% to –0.5% gradient). The imported gravel was river-rock obtained from the Blasingame Quarry near the Merced River. Rock weirs were constructed at the upstream and downstream boundaries of each site to retain the imported gravel during high flows. The two riffles near the Horseshoe Recreation Area were surveyed for spawner use from 1994 through 1997 and intragravel conditions were monitored in fall 1995.

The second restoration project involved adding 2,000 tons of gravel to four locations in the Goodwin Canyon (near river mile 58) in summer 1997. There was almost no gravel in these areas before this project. The project was designed to create bars of introduced gravel that would be gradually transported to downstream spawning areas by high flows. At two locations, the gravel bars were placed in pools just upstream from the pool's tail at a depth of about ten feet. At the other two locations, the gravel bars were placed across the width of the river in shallow, moderately swift water. The imported gravel was river rock from 0.35 to 5 inches in diameter that was obtained from a quarry near the Stanislaus River. Shortly after the rock was placed, flows were increased to 1,200 cfs for ten days to help distribute the gravel and attract adult salmon to the river. Spawner use at these sites was surveyed in fall 1997.

This report presents a summary of the surveys conducted in the Stanislaus River from 1994 to 1997. The complete data sets and analyses for the fall 1994 and fall 1995 surveys are presented in CMC and others (1996) and for the fall 1996 survey in CMC (1997).

Methods

Surveys were conducted in the primary spawning reach of the Stanislaus River at approximately ten-day intervals in fall 1995 and 1996 to monitor spawner use and measure intragravel conditions at natural riffles and the restoration riffles at the Horseshoe Recreation Area. In 1995, six surveys were conducted between 2 November and 22 December while salmon were spawning and a seventh survey was conducted between 2 and 7 February 1996 after the fry had begun to emerge from the gravel. In 1996, three surveys were conducted between 31 October and 19 November. Flood control releases were begun on 21 November that made it impossible to continue the 1996 study. In 1997, spawner use was surveyed at the restoration sites and 12 natural riffles on 29 October and 3 December. Two of the riffles surveyed (R27 and R78) had a substantial amount of newly deposited gravel across the crest of the riffle as a result of the spring 1997 high flows (5,000 cfs with a maximum of 8,000 cfs compared to 300 to 400 cfs base flows).

Study Area

The spawning reach for fall-run chinook salmon in the Stanislaus River is about 25.5 miles long and extends from Goodwin Dam, which is impassible for salmon, downstream to the town of Riverbank (Figure 1). In a 4.2-mile, high-gradient canyon between Goodwin Dam and the Knights Ferry, U.S. Army Corps of Engineers (ACOE) Recreation Area, there are only four short natural riffles near the Two-Mile Bar Recreation Area at river mile 56.9 and several very small areas that have sufficient gravel for spawning. The largest natural riffle, which is identified as TM1, is the tail of a relatively wide pool that is just upstream of where the river divides into two channels. The double-channel riffle that begins at the pool's tail is high gradient, has no gravel, and was unused by salmon for spawning in 1994, 1995, and 1996. Two other riffles, which are identified as TM2 and TM3, are just downstream of TM1 and are relatively short, each about 30 feet long. The fourth natural riffle, which is about 150 yards upstream of TM1, was very armored and received few spawners.

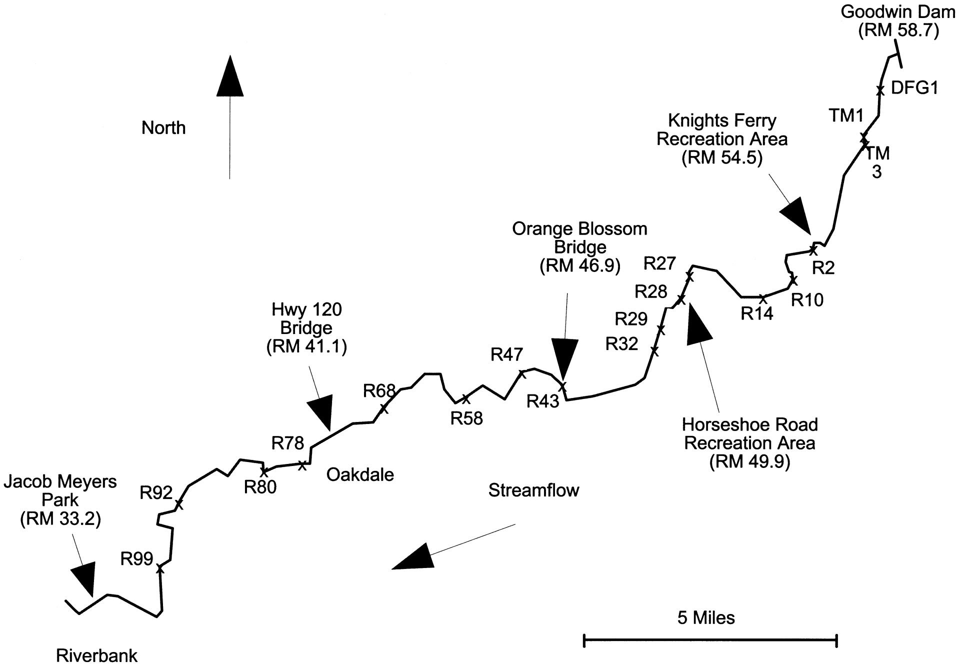

Figure 1 Location of riffles where spawning habitat for fall-run chinook salmon was studied in the Stanislaus River between Goodwin Dam and the town of Riverbank

During October 1995, 106 riffles between the ACOE Knights Ferry Recreation Area and Jacob Meyers Park in Riverbank were identified with a numbered 3-inch orange square that was nailed to either a tree or woody debris near the upstream boundary of each riffle. The riffle immediately upstream of the bridge at the ACOE Knights Ferry Recreation Area was identified as "R1." The other riffles were sequentially numbered in a downstream direction from there. During the fall 1995 surveys, salmon were observed at an additional 26 riffles and four small accumulations of gravel that were not numbered with orange squares. These areas were identified by adding a letter to the upstream riffle's number. For example, an unmarked spawning area downstream of Riffle R2 was called Riffle R2A.

Redd Distribution Within Riffles and the Spawning Reach, Fall 1995

Redds, “test-digs,” and the number of live and dead adult salmon were counted at each of the 135 riffles between Goodwin Dam and Riverbank during the 1995 November and December surveys. Redds were identified as a disturbance in the substrate, approximately four feet wide by eight feet long, with a shallow pit or depression near the middle of the disturbed area and a tail spill. Test-digs were assumed to be unfinished redds that lacked eggs, because they lacked a pit and tail spill. Redds and test-digs were most conspicuous when first constructed because (1) the depth of the pit and the height of the tail spill were gradually reduced by the “smoothing action” of streamflow and (2) redd construction temporarily reduced the amount of algae and silt on the substrate's surface. Since some, but not all, of the redds became indiscernible during the study, it was necessary to distinguish new redds from previous redds. New redds were identified by comparing their appearance to old redds in the same riffle, the location within the riffle, and whether adult salmon were observed near the new redds. The total number of redds at each riffle was estimated as the cumulative total of new redds observed during each survey.

Redd counts for each riffle were subdivided into a maximum of three sections with the two uppermost sections being about 30 feet long each. For example, a 30-ft riffle had only an upper section, whereas a 120-ft riffle was subdivided into an upper 30-ft section, a middle 30-ft section, and a lower 60-ft section. The boundaries between riffle subsections were not measured or marked but visually estimated for each survey.

Surveys were conducted on foot and by canoe. The Two Mile Bar Recreation Area was accessed by road and observations were first made from the streambank and then by walking through the riffles. The reach between the Knights Ferry Recreation Area and Jacob Meyers Park in Riverbank was surveyed with two canoes, one on each side of the river. Visibility in the water column was usually about eight feet and so most of the streambed and all redds were easily observed in riffles, which ranged in depth between one and 3 feet. Streamflows releases at Goodwin Dam were consistent at about 305 cubic feet per second (cfs) during the 1995 surveys and 400 cfs during the 1996 and 1997 surveys.

Intensively Studied Riffles

Spawning habitat and redd distribution was intensively studied at 12 riffles in fall 1995 and at seven riffles in fall 1996 (Figure 1). The fall 1995 study riffles (TM1, R2, R10, R27, R28, R32, R43, R47, R68, R80, R92, and R99), were selected at approximately two-mile intervals between Goodwin Dam and Jacob Meyers Park in Riverbank. They were selected because they were highly used for spawning during fall 1994, a condition that was necessary to evaluate the relationship between redd distribution and the quality of incubation habitat. Riffles TM3, R10, R14, R29, R43, R58, and R78 were selected for the fall 1996 study because each had an upper section with an upward slope or positive streambed gradient, a relatively flat middle section, and a bottom section with a negative streambed gradient. These selection criteria made it possible to evaluate the effect of streambed gradient on the downwelling of surface water and intragravel conditions. Riffle R10 was studied during both fall 1995 and fall 1996. Different sections of Riffle R43 were studied in 1995 and 1996; a small concrete weir separated the lower section which was studied in 1995 from the upper section studied in 1996.

Intragravel Water Quality

Intragravel water samples were collected from piezometers buried 12 inches deep in the substrate. Piezometers were installed between 2 and 4 November in 1995 and between 25 and 27 October in 1996. One piezometer was installed at each of the top, middle, and lower sections of each riffle, except at Riffle R10 where two were installed in each section in fall 1996.

Typical piezometers were 0.25-inch diameter copper tubes, each with eight 0.04-inch diameter holes at one end and a flexible tube at the other end that extended above the substrate surface (Figure 2). Redd construction was extensive at Riffle TM1 in October 1995, and so a different design, called a pipe-piezometer, was used which did not require streambed excavation. Pipe-piezometers consisted of 0.33-inch outside diameter hollow aluminum shafts that were driven straight down into the substrate so that eight 0.04-inch holes in the shafts were approximately 12 inches deep in the substrate and the top of the shaft extended about ten inches above the substrate. A 3-foot-long plastic tube was clamped to the upper end of the shaft for sample collection. Each pipe-piezometer was attached to a 4-foot-long, 0.5-inch diameter reinforcing bar with hose clamps to facilitate driving the shaft into the substrate. The pipe-piezometers at Riffle TM1 were left in place throughout the study, although they fell after the 20 December 1995 survey and had to be reinstalled on 3 February 1996. A pipe-piezometer was used at the top piezometer site in Riffle R2 because the buried piezometer was quickly vandalized. This pipe-piezometer was reinstalled during each survey.

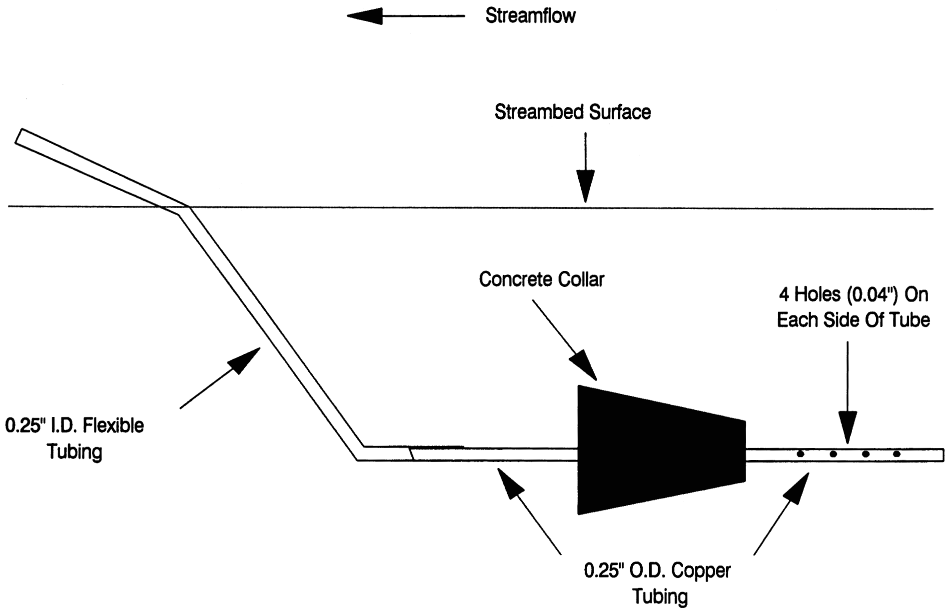

Figure 2 Typical piezometer used to collect intragravel water quality samples. The concrete collar was the shape and size of an eight-ounce Dixie cup. The copper tubing was about 11 inches long and the flexible tubing was about three feet long.

Piezometer sites were selected in areas where water depths ranged between 1.1 and 2.4 ft and mean column water velocities ranged between 1.6 and 4.2 ft/s, which were within the range used by spawning salmon. The typical piezometers (Figure 2) were installed to simulate sampling an egg pocket in a natural salmon redd. Pits were dug approximately 12 inches deep by 12 inches wide at the bottom with a hand-held hoe. The excavated substrate was piled downstream of the pit to simulate the tail spill formed in a natural redd. After the piezometer was placed in the pit, sediment was pulled into the pit in thin layers from the upstream areas using the hoe. The blade of the hoe was then fanned over each layer of gravel in the pit to flush most of the fines onto the tail spill. When completed, the piezometer was located at the upstream end of the tail spill which was raised several inches above the undisturbed streambed. An egg pocket would be expected to occur in this location in a natural redd. Immediately upstream of the tail spill, there was a two- to four-inch deep depression in the substrate that simulated the pit of a small, but natural-looking, redd. However, natural sediment transport filled the depression, and the tail spill was flushed away at most of the piezometer sites after approximately seven days. This smoothing of the streambed also occurred at natural redds.

Pipe-piezometers were also installed in the vicinity of the egg pockets of 21 completed salmon redds at study riffles R10, R14, and R43 on 11 and 12 November 1996. All of these redds had been observed on the previous survey when most had already been completed. These pipe-piezometers were driven approximately 12 inches into the upstream end of the tail spill of a completed redd. This was done by placing a 5/8-inch bolt into the upper end of the piezometer, inserting it into the bottom of a 4-foot-long, 0.5-inch ID steel pipe, placing a 3-foot-long, 0.25-inch diameter rod on top of the lag bolt, and then driving the pipe, rod, and piezometer into the redd. The pipe and rod were then removed and a plastic tube was fitted to the upper end of the piezometer, which extended about two inches above the substrate's surface to permit periodic collection of water samples. To avoid collecting surface water that may have been introduced into the redd during installation, the first measurements and samples were not collected until approximately five minutes after the pipe-piezometers had been installed. To minimize disturbance to the eggs, the pipe-piezometers were not removed between surveys.

Intragravel measurements of DO concentration, water temperature, and vertical hydraulic gradient were made at each piezometer in the artificial redds at approximately ten-day intervals. During the fall 1995 study, five measurements were made between 11 November and 22 December 1995 and a sixth measurement was made between 2 and 7 January 1996. During the fall 1996 study, three measurements were made between 31 October and 19 November 1996.

Two sets of measurements were taken from the redd-type piezometers between 11 and 19 November 1996. During 1997, measurements were made only at Riffles R27 and R78 on 3 December.

Intragravel water samples were collected to measure DO concentration and temperature using a 50-ml polypropylene, disposable syringe (Henke-Sass Wolf GmbH, Germany) fitted with a six-inch-long, 1/8-inch inside diameter polypropylene tube and a tapered connector that provided an airtight seal between the piezometer's tubing and the syringe's tubing. Samples were collected by first slowly withdrawing and discarding 50 ml of water, the approximate volume of water in the piezometer's tubing. Then a 70-ml sample was slowly withdrawn for a DO analysis using a LaMotte test kit, model EDO/AG-30. The LaMotte test kit uses the azide modification of the Winkler Method and a LaMotte Direct Reading Titrator for the final titration. The LaMotte Kit measures DO concentrations in 0.1 parts per million (ppm) increments. Kit reagents were replaced for each survey. During the fall 1995 and fall 1997 studies, samples were analyzed at the study riffles within five minutes of collection. During the fall 1996 study, the DO samples were fixed immediately after collection, placed in an ice chest, and analyzed at room temperature within ten hours.

After collecting the DO sample, a 100-ml sample was slowly collected and injected into a plastic sample bottle, which had been rinsed with surface water, for an immediate measurement of intragravel water temperature. Water temperature was measured with a Yellow Springs Instrument (YSI) model 55 meter in 1995 and with a mercury thermometer in both 1995 and 1996. A sample of surface water was also collected in the same 100-ml plastic bottle for a temperature measurement. The date and time that each water sample was collected were recorded for comparison with the thermograph recordings.

Nitrate concentration was determined for intragravel and surface water sampled during the 11–12 December 1995, 20–22 December 1995, and the 19 November 1996 surveys. During 1995, AquaCheck Nitrate/Nitrite test strips were used, which measure nitrate concentrations between zero and 50 mg/liter. The test strips were dipped into the samples collected for the LaMotte DO tests immediately prior to adding any of the LaMotte reagents. During 1996, one intragravel water sample was collected from one piezometer at each riffle for analysis of nitrate concentration. One surface sample was collected at Riffle R29 for nitrate analysis. These samples were immediately placed in an ice chest and analyzed by FGL Environmental in Stockton approximately 24 hours later.

The ratio of the differential head to the depth of the piezometer below the sediment-water interface (Lee and Cherry 1978; Dahm and Valett 1996) is known as the vertical hydraulic gradient (VHG). Negative VHG measurements indicate the downwelling of surface flow and positive values indicate the upwelling of intragravel flow. VHG was measured at each piezometer in fall 1996 and fall 1997. The differential head was measured with a manometer, which consisted of an 8-ft-long, 1/8-inch inside diameter, clear tube with one end attached to the piezometer's tubing and the other held near the substrate surface (Lee and Cherry 1978; Dahm and Valett 1996). A silicone pipet bulb with emptying and filling valves was attached to the middle of the tubing with a T-connector to facilitate filling the manometer with water. Measurements were made by partially filling the manometer's tubing with water and then holding the middle of the tube above the water's surface to form a loop with two vertical tubes and an air bubble, approximately 16 inches long at the top of the loop. After the water levels in both sides of the manometer's tubes stabilized, the differential head was read as the difference in height (centimeters) between the water levels in the two tubes. Negative measurements occurred when the water level in the side of the tube connected to the piezometer was lower than the level in the side of the tube submerged in surface water. VHG was computed as the differential head divided by 30 cm, the depth of the piezometers below the substrate's surface.

Streambed Elevation, Water Velocity, and Water Depth at Piezometers and Redds

Redds were identified by placing a numbered, three-ounce lead sinker with red flagging into the pit. The sinkers were replaced whenever redd construction buried or displaced the original sinker. The locations of redds and piezometers were mapped at each riffle using permanent headstakes (for example, 18-inch sections of reinforcing rods or nails partially driven into trees) on both sides of the river. The location of redds and water quality samples were determined by first running a tape measure from the redd or sample to the closest permanent transect at a perpendicular angle. The distance in feet from the right streambank along the permanent transect to the perpendicular line was recorded as the station. Then the distance in feet from the permanent transect to the redd or piezometer and the direction (upstream or downstream) from the permanent transect were recorded.

Water depth and mean column velocity were measured at the undisturbed substrate surface immediately adjacent to all piezometer sites, including those at redds, during 300-cfs releases in 1995 and 400-cfs releases in 1996. Mean column velocities were measured with a Marsh McBirney electronic flow meter and a top-set wading rod.

In fall 1995, a single longitudinal transect was used to measure the streambed elevation along the entire length of each study riffle. The transect was established by installing a three-foot piece of reinforcing bar about ten feet upstream of the riffle and then running a tape through the site to approximately ten feet downstream of the riffle. Relative streambed elevations were measured along the transect with an automatic level and a fiberglass stadia rod at five-foot intervals in steep gradient (>2%) sites or at ten-foot intervals in low gradient (<2%) sites. The absence of large structures in the study riffles produced a relatively uniform contour of the streambed across the river and it was assumed that the transect represented the entire width of the river.

In fall 1996, streambed elevations were measured at each piezometer site and at distances of 5 ft, 10 ft, and 20 ft immediately upstream of the piezometer to determine the streambed gradient.

Substrate Size Distribution, Crushed Rock, and Asian Clams

During 2–7 February 1996 substrate samples were collected at each of the piezometer sites after the water quality sample had been collected. Samples were taken with a six-inch diameter modified McNeil sampler. The sampler was placed over the approximate location of the piezometer and worked into the substrate to a depth of about six inches. If the sampler could not be inserted to a depth of six inches, the sampler was moved about one foot. The substrate inside the sampler was scooped into a plastic bag for transport to the laboratory for analysis. The water inside the sampler was not collected, because the sampler was too short to prevent a small amount of river water from entering at some sites, thereby resulting in the loss of some of the suspended sediments. Furthermore, it is likely that the total weight of the suspended sediments was small and would not have significantly affected the measured weight of fines <1 mm.

The samples were processed by first drying the samples, sorting the particles according to size, then determining the weight of each size class. The samples were dried by placing them in two-gallon metal buckets and occasionally stirring them as they were heated over a propane flame. After the sample had cooled, it was placed in the upper layer of a set of sieves of decreasing size. Sieve sizes used included 64 mm, 45 mm, 32 mm, 24 mm, 16 mm, 8 mm, 4 mm, 2 mm, 1 mm, 0.5 mm, and 0.25 mm. Sieves between 16 and 64 mm were shaken by hand for one minute, after which the size of the particles in each sieve was checked. Smaller sieves were shaken for about five minutes. After the sorting had been completed and before the sieve's contents were weighed, Asian clam (*Corbicula fluminea*) shells were weighed, counted, and removed from each sieve. Sieve contents were weighed on a triple-beam balance to the nearest 0.1 grams. The percentage of broken rock, 8-mm or larger particles with sharp edges, was determined for most of the samples, particularly those from Riffles R27 and R28, which are the 1994 restoration sites.

Percent fines were evaluated as two size classes, one as substrate particles less than 1 mm to correspond to the results of Young and others (1991) and the other as particles less than 2 mm, which corresponds to many other studies (Chapman 1988). Both of these size classes were evaluated as a percentage of the entire sample and as a percentage of the sample that excluded particles larger than 24 mm to minimize weight bias as recommended by Tappel and Bjornn (1983). To account for potential bias that would result if smaller sample volumes consisted of surface substrates that typically have lower percentages of fines, total sample weight was included in the statistical analyses of percent fines.

The predicted survival probability for chinook salmon eggs was estimated using the results of Tappel and Bjornn's (1983) laboratory study based on the percentages of substrate particles less than 0.85 mm and particles less than 9.5 mm in samples that exclude particles larger than 51 mm (largest size tested by Tappel and Bjornn). The percentages of particles less than 0.85 mm and 9.5 mm for Stanislaus River samples that excluded particles larger than 51 mm were estimated from a plot of the cumulative percentage of particles that passed through specific sieves versus the sieve apertures on a log scale. The following equation from Tappel and Bjornn (1983) was then used to compute predicted egg survival for chinook salmon:

$$\text{Percent Survival} = 93.4 - 0.171 S_{9.5} S_{0.85} + 3.87 S_{0.85}$$

Statistical Analyses

Multiple regression analyses were conducted to evaluate the environmental factors that appeared to influence DO concentrations during the November–December 1995 surveys and the February 1996 survey. The mean DO concentrations in percent saturation were used for the November–December surveys, since those concentrations were relatively stable and showed no increasing or decreasing trends during that period. DO concentrations measured during the February survey were substantially lower at some of the piezometer sites and so those data were evaluated separately.

The environmental factors evaluated for both analyses included six indices of percent fines, three indices of gradient, weight of clam shells, water depth, mean column velocity, two indices of nitrate concentration, a turbidity index, and the difference in temperature between the intragravel sample and the surface sample during the 20–22 December survey which served as an index of groundwater inflow (Tables 1 and 2). The variables for nitrate concentration, turbidity, and the temperature difference are described in further detail in the "Results and Discussion."

Transformations and tests were made on the assumptions of statistical analyses relating to normal distributions, linear relationships, and an absence of collinearity between independent variables (Sokal and Rohlf 1995). An arcsine transformation was made to variables consisting of percentages (which include DO concentrations, the absolute value of the gradient indexes, and substrate fines), to minimize bias resulting from the distribution of the variance being a function of the mean (Sokal and Rohlf 1995). "Wilk-Shapiro/rankit plots" were used to test the assumption of normality. Plots of standardized residuals versus fitted values of the independent variables were used to assess the assumptions of linearity and constant variances. A variance inflation factor was used to detect collinearity (Analytical Software 1994).

The regression analyses were affected by the absence of water depth and mean column velocity measurements at the piezometer sites at TM1 and the middle piezometer at Riffle R47. When the analyses included the depth and velocity variables, all variables from these sites were excluded from the analyses. To avoid this limitation, regression analyses were conducted with and without the depth and velocity variables.

Table 1 Habitat data from 32 piezometers at 12 riffles in the Stanislaus River, fall 1995

	Intragravel DO percent saturation [a]		*Groundwater Inflow Index (°C)* [b]		*Asian clam shells (g)* [c]	*Percent fines*					*Tappel and Bjornn Index* [d]		
						Entire sample		*Excludes >24 mm*			*Percent substrate*		
Site	*Nov-Dec*	*Feb*	*Dec*	*Feb*		*<1 mm*	*<2 mm*	*<1 mm*	*<2 mm*	*Sample Size (g)*	*<0.85 mm*	*<9.5 mm*	*Egg Survival*
TM1-TOP	94.3	100.0	0.1	1.1	0.0	2.3	5.9	3.7	9.3	7327.6	2.1	37.6	88.0
TM1-BOTR	95.1	100.0	0.05	1.3	0.0	2.6	7.1	4.6	12.5	9567.5	2.4	36.8	87.6
TM1-BOTL	99.6	100.0	0.05	1.3	0.0	1.5	3.2	5.2	11.5	8195.6	1.5	15.3	95.3
R2-TOP	96.8	100.0	0.3	1.4	0.0	5.3	7.3	22.9	31.7	4485.6	6.3	19.0	97.3
R2-BOT	88.8	54.8	0.3	1.2	7.0	3.0	8.8	7.7	22.5	7685.3	3.3	28.8	89.9
R10-TOP	94.4	84.3	0.2	1.0	0.0	3.7	7.6	7.8	15.8	9453.3	4.1	41.7	80.0
R10-MID	61.8	32.4	1.1	3.0	0.0	8.3	12.8	15.8	24.4	9597.4	7.7	40.4	70.0
R10-BOT	64.7	36.0	0.8	1.0	0.0	13.4	24.9	21.5	40.0	8147.5	11.7	50.7	37.2
R27-TOP	98.8	100.0	0.3	0.0	0.0	0.4	0.4	0.9	0.9	5376.4	0.4	3.6	94.7
R27-MID	97.4	100.0	0.3	0.5	0.0	0.5	0.5	1.8	1.8	5342.0	0.6	2.3	95.5
R27-BOT	97.8	100.0	0.4	0.5	0.2	0.1	0.1	0.2	0.3	4836.4	0.1	3.5	93.7
R28-TOP	99.4	98.6	0.5	1.0	28.7	9.2	9.9	27.3	29.4	7133.6	8.7	13.8	100.0
R28-MID	98.1	97.7	0.3	1.0	0.3	0.4	0.4	0.9	1.0	6113.1	0.4	3.4	94.7
R28-BOT	98.7	94.1	0.2	0.5	8.9	9.3	13.1	17.0	23.8	7057.1	7.6	22.4	93.7
R32-TOP	93.4	87.0	0.6	1.0	10.5	7.1	16.4	14.2	32.9	13483.0	7.8	48.5	58.9
R32-BOT	89.6	82.0	0.6	1.0	3.6	10.5	19.9	18.6	35.2	8263.9	10.9	48.9	44.4
R43-TOP	92.6	16.2	0.9	2.2	2.6	2.8	9.8	4.4	15.6	8383.0	2.7	47.3	82.0
R43-BOT	96.0	82.4	0.4	0.9	0.0	3.2	8.9	5.9	16.2	8887.1	3.0	35.4	86.8
R47-TOP	78.7	66.0	0.7	1.1	6.2	8.1	20.9	12.6	32.7	9240.6	6.8	47.1	64.9
R47-MID	42.3	41.2	0.8	0.7	95.1	12.1	19.7	19.7	32.0	10067.0	9.5	41.7	62.4
R47-BOT	44.1	34.1	1.1	1.1	79.5	21.0	28.9	26.8	37.0	9439.9	17.0	53.0	5.1
R68-TOP	39.0	40.1	1.1	1.1	57.9	12.0	23.1	14.3	27.5	8219.5	9.4	47.8	52.9
R68-MID	90.0	76.0	0.3	1.1	1.7	10.2	20.0	15.8	31.0	9459.6	9.0	45.9	57.6
R68-BOT	92.9	95.0	0.1	1.1	3.5	7.7	14.7	12.1	23.1	7423.4	6.3	41.4	73.2
R80-TOP	94.6	66.7	0.1	1.4	5.3	4.0	8.8	8.1	18.0	7651.1	3.4	24.4	92.4
R80-BOT	62.9	28.5	1.0	0.9	0.3	6.3	12.8	12.1	24.6	9396.5	5.5	31.9	84.7
R92-TOP	20.1	18.4	0.5	-0.2	147.0	20.8	33.4	27.4	43.9	7681.3	16.9	55.6	0.0
R92-MID	82.1	81.8	0.2	1.2	4.4	4.9	13.3	7.9	21.5	8620.7	4.0	39.2	82.1
R92-BOT	82.9	45.9	0.3	0.0	3.6	6.3	16.7	16.9	44.7	10394.0	9.2	52.2	46.9
R99-TOP	85.4	38.3	0.6	0.6	0.0	11.1	20.7	18.9	35.5	9551.9	10.9	45.4	51.0
R99-MID	94.5	86.2	0.4	0.3	1.8	4.0	8.8	8.7	19.3	9254.9	4.7	31.6	86.2
R99-BOT	53.1	27.7	0.8	0.1	2.8	8.0	18.2	11.9	26.9	8915.6	6.9	48.2	63.2

[a] Mean levels for five November and December 1995 surveys, including one measurement for February 1996.

[b] Computed as the difference in temperature between the intragravel sample and the surface sample during the 20–22 December 1995 survey.

[c] From February 1996 substrate samples.

[d] Source: Tappel and Bjornn 1983.

Table 2 Habitat data from 32 piezometer sites at 12 riffles in the Stanislaus River, fall 1995

	Streambed gradient upstream of samples [a]			*Mean column velocity (ft/s)* [b]	*Water depth (ft)* [b]	*Surface water turbidity (JTU)* [c]	*Intragravel nitrate concentration (ppm)* [d]		*Channel width (ft)*	*Distance downstream of Goodwin Dam (mi)*
Site	*5 ft*	*10 ft*	*20 ft*				*Sample*	*Diff*		
TM1-TOP	7.0%	3.6%	4.1%	-	-	3	1	0.5	99.0	1.5
TM1-BOTR	5.0%	7.6%	5.4%	-	-	3	0.5	0	99.0	1.5
TM1-BOTL	5.0%	7.6%	5.4%	-	-	3	0.5	0	99.0	1.5
R2-TOP	9.1%	8.7%	5.0%	3.1	1.8	3	0.5	0	92.0	3.9
R2-BOT	-5.8%	-5.2%	-2.7%	2.7	1.3	3	0.5	0.25	92.0	3.9
R10-TOP	4.8%	5.8%	2.7%	1.5	1.3	5	0.5	0	82.2	4.9
R10-MID	-1.2%	-0.8%	-0.0%	0.5	1.3	5	0.5	0	81.0	4.9
R10-BOT	-1.4%	-3.3%	-5.4%	1.3	1.1	5	0.5	0	80.0	4.9
R27-TOP	0.6%	5.5%	0.7%	2.1	1.5	10	0.5	0	91.0	7.4
R27-MID	9.8%	4.6%	1.6%	2.9	1.7	10	0.5	0	85.6	7.4
R27-BOT	-3.2%	-1.6%	-0.7%	1.4	1.6	10	0.5	0	75.0	7.4
R28-TOP	2.0%	2.1%	1.2%	3.0	1.3	10	0.5	0	84.0	7.9
R28-MID	-3.4%	-2.4%	-0.8%	3.2	1.3	10	0.5	0	86.0	7.9
R28-BOT	14.8%	8.3%	6.0%	2.4	1.0	10	0.5	0	88.0	7.9
R32-TOP	2.2%	4.1%	3.3%	3.4	1.7	7	0.25	0.25	63.4	8.9
R32-BOT	-4.2%	-2.2%	-2.3%	3.9	1.2	7	0.25	0.25	65.6	8.9
R43-TOP	0.6%	2.2%	6.8%	2.2	1.6	7	0.5	0	80.1	11.5
R43-BOT	1.0%	1.2%	1.0%	2.0	1.0	7	1.0	0	80.1	11.5
R47-TOP	0.8%	-1.3%	-1.6%	1.4	1.6	7	0.5	0	91.6	12.4
R47-MID	0.2%	0.2%	-1.0%	-	-	7	1.0	0.5	96.1	12.4
R47-BOT	0.3%	0.3%	0.2%	1.1	1.7	7	1.0	0	90.0	12.4
R68-TOP	0.8%	-0.2%	1.6%	1.6	1.2	5	5.0	2.8	143.0	16.3
R68-MID	-2.9%	-2.9%	-1.7%	1.8	1.2	5	1.5	0	70.7	16.3
R68-BOT	-0.6%	-0.6%	1.5%	1.7	1.9	5	0	0.3	62.5	16.3
R80-TOP	0.8%	1.3%	1.9%	2.5	1.4	10	2.0	0.5	64.0	19.1
R80-BOT	-3.6%	-1.5%	-0.4%	2.5	1.3	10	1.5	0	64.0	19.1
R92-TOP	-1.9%	-0.5%	0.4%	0.7	1.5	5	1.0	0	152.0	21.2
R92-MID	-1.2%	-1.2%	-0.5%	0.9	1.6	5	1.5	0.25	113.0	21.2
R92-BOT	3.4%	3.4%	1.5%	3.1	1.4	5	1.0	0	109.0	21.2
R99-TOP	0.6%	0.0%	0.1%	1.5	1.6	5	1.0	0	81.2	23.1
R99-MID	1.6%	1.6%	2.5%	2.5	1.5	5	1.0	0	86.5	23.1
R99-BOT	0.0%	0.0%	0.2%	1.3	1.5	5	2.0	0.8	82.2	23.1

[a] Measured 2–7 February 1996.

[b] Measured 2–4 November 1995.

[c] Measured 11 and 20 December 1995.

[d] Intragravel nitrate concentration and the difference between the intragravel sample and the surface sample. Collected 11–12 December 1995.

Habitat variables were selected for the final regression models by evaluating Pearson correlation coefficients (*r*), adjusted multiple coefficients of determination (adj-R^2) and Mallow's C_p statistic for all possible combinations of variables, and stepwise regression procedures using Statistix 4.1 software (Analytical Software 1994). The relative importance of the variables was evaluated with the *t*-statistic (Bring 1994).

Results and Discussion

The California Department of Fish and Game's preliminary estimate of chinook salmon escapement (grilse and adults) to the Stanislaus River was 1,079 for fall 1994, 611 for fall 1995, and 168 for fall 1996 (G. Neillands, personal communication, see "Notes"). Escapement during these studies was relatively low compared to an average of 4,800 salmon that occurred between 1967 and 1991.

Distribution of Redds in the Spawning Reach, Fall 1995

A total of 415 redds was observed during 1995, with the highest density (50) occurring at the uppermost Riffle TM1. In the downstream area between the Knights Ferry Recreational Area and the bridge at Orange Blossom Road, there was an average of five redds per riffle. Downstream of the Orange Blossom Bridge to Jacob Meyers Park in Riverbank, the average number of redds per riffle was less than two. No redds were observed in the lowermost three miles of this reach. During 1994, a total of 714 redds was observed between Two Mile Bar and Jacob Meyers Park that were distributed similarly to those in 1995.

As in 1994, most of the redds observed in 1995 were constructed near the head (upstream boundary) of the riffles, even though the entire riffle appeared to be suitable for spawning. Of the 337 redds that were observed at the 129 riffles between the Knights Ferry Recreation Area and Jacob Meyers Park, 72.6% (244 redds) occurred within the uppermost 30-ft section of the riffles, 13.4% (45 redds) occurred in the middle 30-ft section of the riffles, and 14.0% (47 redds) occurred in the lowermost section of the riffles, some of which were 200 ft long.

Redd Distribution at the Intensively Studied Riffles

The distribution and number of redds observed at most of the intensively studied riffles were similar from 1994 to 1997. The highest density typically occurred at Riffle TM1 (50 redds in 1995), moderate densities (6 to 18 per riffle) occurred at riffles R2, R10, R14, R32, R43, R47, R68, and R80 between Knights Ferry and Oakdale, while few or no redds were observed at riffles

R29, R58, and R78. Riffle TM3 had a moderate number of redds in 1995 (11) and 1997 (7), but only two redds had been completed by 19 November 1996. Riffles R92 and R99 each had nine redds in fall 1994, but none in fall 1995 when escapement was relatively low.

Of the 113 redds that were mapped with the longitudinal transects at the study riffles in fall 1995, 73 (64%) occurred where the streambed's gradient was increasing, 11 (10%) occurred where the streambed's gradient was decreasing, and 29 (26%) occurred where the streambed was relatively flat. Redd distribution and streambed configuration of Riffle R10 in fall 1995 were typical for the Stanislaus River (Figure 3).

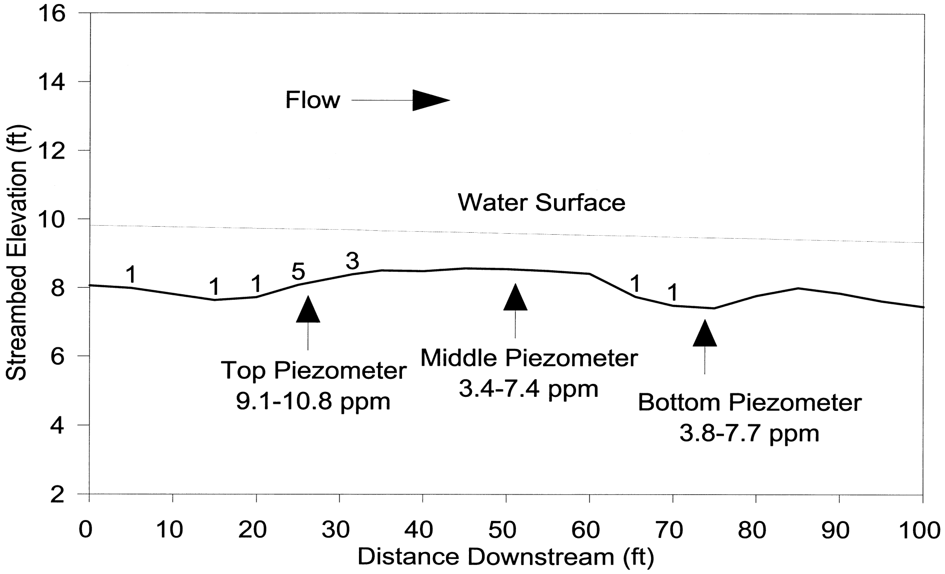

Figure 3 Map of Riffle R10 in the Stanislaus River showing the number of redds, locations of piezometers, range of DO concentrations observed between 11 November 1995 and 4 February 1996, and the water surface elevation relative to the streambed elevation recorded along a mid-channel longitudinal transect

1994 DWR Restoration Sites at the Horseshoe Recreation Area

At Riffles 27 and 28, few of the redds were constructed entirely in the added mitigation gravel obtained from the Merced River floodplain, whereas several redds were usually observed near the mitigation gravel in natural substrate. In fall 1994, all 11 redds observed at these riffles were constructed in the natural cobble substrate adjacent to the mitigation gravel. In fall 1995, only one redd at each riffle was constructed entirely in the mitigation gravel at R27 and R28. Two redds were observed immediately upstream of Riffle R27. Nine redds were constructed in cobble substrate upstream of the mitigation gravel, and two others were constructed in predominately cobble substrate where a fallen cottonwood tree had scoured away all of the mitigation gravel in the middle of Riffle R28 (Figure 4). No redds were observed in the large deposit of mitigation gravel approximately 20 ft downstream of Riffle R28 that had been moved by the high streamflows that occurred in spring 1995.

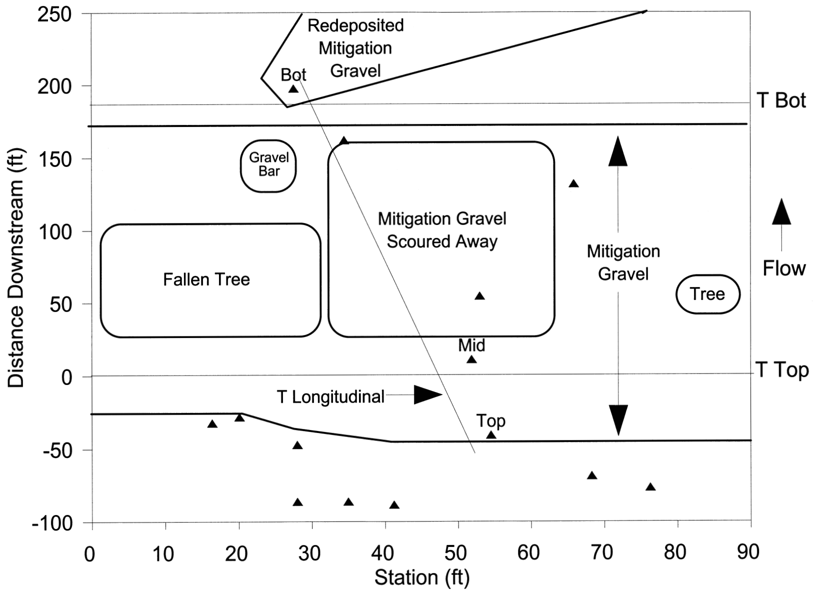

Figure 4 Map of Riffle R28, the lower mitigation site at the Horseshoe Road Recreation Area, in the Stanislaus River showing the locations of fall-run chinook salmon redds (black triangles), piezometers (black triangles identified as Top, Mid, and Bot sites), the permanent transects (T Top and T Bot) used to record the location of redds, the longitudinal transect (T Longitudinal) used to measure streambed elevations in fall 1995, and the location of mitigation gravel placed in summer 1994

By November 1996, all of the mitigation gravel from the lower one-third of Riffle R27 and from the entire riffle at R28 had been scoured away, presumably during high flows in spring 1996. The mitigation gravel that had been deposited immediately downstream of Riffle R28 in spring 1995 had been entirely scoured away in spring 1996. No redds or spawning fish were observed at Riffles R27 or R28 by 1 November 1996. Two redds were observed approximately 20 ft upstream of Riffle R28 on 1 November 1996.

In 1997, a 15-ft-long, 2-ft-high natural gravel berm had been deposited across the width of the river channel at the upstream boundary of Riffle R27, presumably as a result of the prolonged flows (5,000 to 8,000 cfs) in spring 1997. Nine redds and six pairs of spawning chinook salmon were observed in the newly deposited natural gravel on 29 October 1997; none were observed in the mitigation gravel that remained in the middle of the original riffle. On 3 December 1997, there were seven additional redds in the newly deposited natural gravel and one redd in the mitigation gravel. No redds were observed at

Riffle R28, although three adult salmon were observed near the top of the riffle on 29 October.

1997 DFG Restoration Sites in Goodwin Canyon

Chinook salmon spawned at all four locations where gravel from the Stanislaus floodplain had been added to the river in summer 1997. Most of the spawning occurred where gravel bars were placed across the width of the river in shallow, moderately swift water, but fish also spawned in the newly added gravel in pools where water velocities were quite low. On 29 October 1997, five redds were observed at both sites where gravel bars were placed across the width of the river in shallow (one to two feet deep), moderately swift water (about 2 ft/s). No redds were observed in gravel that had been mobilized and deposited in high gradient areas where the water was swift (>4 ft/s) or in the deep pools. On 3 December, there were three new redds at one shallow site, whereas the other shallow site appeared to be completely covered with redds (at least ten more redds). Two to three redds were also observed at each of the pool sites. However, no redds were observed where the new gravel had been redeposited in very swift water.

Evidence of Redd Superimposition

Seven piezometers had to be replaced in fall 1996, when salmon presumably constructed redds on top of them. The top piezometer at Riffle TM3 and the middle right piezometer at Riffle R10 and their thermographs had been excavated by adult salmon between the 31 October and the 11 November surveys. Pipe-piezometers were also lost from one redd (number 8) in Riffle R10, two redds (numbers 6 and 8) in Riffle R14, and from two redds (numbers 15 and 22) in Riffle R43 due to redd superimposition between the 11 November and 19 November surveys. In several cases, the pipe-piezometers were found several yards downstream of the original site indicating that the tail spills had been completely re-excavated. A superimposition rate of 24% (5 of 21 redds with pipe-piezometers) is surprisingly high, considering escapement was estimated to be only 168 fish. One possible explanation is that the substrate throughout the spawning reach in the Stanislaus River is cemented and the salmon construct redds in areas loosened by piezometer construction or redd building.

Intragravel Dissolved Oxygen

Fall 1995 Surveys

During the five surveys in November and December 1995, intragravel DO concentrations were relatively constant and suitable for egg incubation (>80% saturation) at most of the 32 piezometer sites (Table 1). The mean difference between the maximum and minimum levels of intragravel DO concentrations at the 32 piezometer sites during the five fall 1995 surveys was 1.3 ppm and none varied by more than a difference of 3.2 ppm. During the five surveys, intragravel DO concentrations were less than 5 ppm (about 50% saturation) at six sites (18.8%) and less than 8 ppm (about 80% saturation) at eleven sites (34.4%).

Mortality of chinook salmon eggs in Mill Creek, California, increased rapidly at oxygen concentrations below 13 ppm, averaging 3.9% at 13 ppm and 37.9% at less than 5 ppm (Gangmark and Bakkala 1960). Davis (1975), who reviewed the oxygen requirements of salmonids, reported a mean threshold of incipient oxygen response for hatching eggs and larval salmonids at 8.1 ppm, which was 76% of saturation. Silver and others (1963) reported that DO concentrations less than 11.7 ppm reduced the growth of chinook salmon embryos. A criterion of 8 ppm for intragravel oxygen concentration was adopted by the Environmental Protection Agency (EPA) and the U.S. Fish and Wildlife Service for the State Water Resources Control Board 1992 Water Rights Hearings for the Mokelumne River.

By the early February 1996 survey, intragravel DO concentrations had declined markedly at several piezometer sites (Table 1) after the runoff from four major storms in January 1996 increased base flows by a daily average of 200 to 500 cfs for several days after each storm. Intragravel DO concentrations at nine piezometer sites, declined to between 25% and 75% of the fall 1995 levels. During the February survey, intragravel DO concentrations were less than 5 ppm at 11 piezometer sites (34.4%) and less than 8 ppm at 16 sites (50%). The large declines were most frequently observed at the bottom piezometers, although the greatest decreases in DO concentration occurred at the top piezometers at Riffles 43 and 99. In addition, most of the piezometers where low DO concentrations occurred during the November and December surveys were located downstream of Riffle R32. However by February 1996, DO concentrations had substantially decreased at Riffles 2 and 10 and there were further declines at the downstream riffles. During the fall 1995 surveys, only one storm resulted in runoff (<80 cfs) between the fourth and fifth surveys and intragravel DO concentrations during the fifth survey were not low compared to the previous surveys at most of the piezometer sites. Gangmark and Bakkala (1960) demonstrated that flooding conditions in Mill Creek, California, were associated with low oxygen concentrations (<5 ppm) in spawning gravel and low intragravel flow rates.

DO concentrations remained high (>8 ppm) throughout all the 1995 surveys and February 1996 survey at all piezometer sites at Riffles TM1, R27, R28, and R32, which include both restoration sites at the Horseshoe Road Recreation Area. Other riffles where DO concentrations at individual piezometer sites remained above 8 ppm during all surveys include the top piezometers at riffles R2, R10, R80, and R99, and the middle or bottom piezometers at riffles R43, R68, R80, R99.

Fall 1996 Surveys

During the October and November 1996 surveys when no appreciable storm runoff occurred, a higher percentage of piezometer sites had intragravel DO concentrations below the EPA standard of at least 8 ppm compared to the percentages observed in November and December 1995. In 1996, eleven (46%) of the piezometer sites had DO concentrations less than 8 ppm, whereas three sites (13%) had concentrations below 5 ppm (Table 2). Low DO concentrations did not occur upstream of Riffle R14 and the lowest levels were usually observed at either the middle or bottom piezometers.

Intragravel DO concentrations at piezometers in the actual redds in riffles R10 and R14 were above 8 ppm during both November 1996 surveys (Table 2). However of the six redds sampled at Riffle R43, three had DO concentrations between 5.6 and 6.9 ppm and one had concentrations below 2 ppm during both surveys.

The distribution of salmon redds and intragravel DO concentrations at Riffles R10, R14, and R43 suggests while salmon typically spawned where intragravel DO concentrations were suitable for incubation (> 8 ppm), high densities of spawning salmon influenced the intragravel DO concentrations in nearby areas. Riffle R14 (Figure 5) provides an example where the fish appeared to avoid the area near the bottom piezometer where intragravel DO concentrations ranged between suboptimal and lethal. Almost all of the redds were constructed upstream of the riffle's crest where the piezometer in the artificial redd indicated that conditions were very suitable. DO concentrations were very similar between the two adjacent piezometers in the middle section of R14, one in an actual redd and the other in an artificial redd, which suggests the artificial redds provided a suitable surrogate for actual redds.

Riffle R10 provides an example where spawning activity slightly improved the intragravel conditions at some nearby piezometers (Figure 6). On 31 October 1996, the intragravel DO concentration at the bottom left piezometer in Riffle R10 was 8 ppm, whereas the concentrations at the other piezometers ranged between 9.5 and 12.1 ppm. By 11 November, after three new redds had been constructed within 80 feet upstream of the bottom left piezometer, intragravel DO concentrations increased to 10 ppm at the bottom left piezometer, whereas the concentrations at the other piezometers remained relatively constant or declined slightly. Intragravel DO concentrations remained high at the bottom left piezometer compared to the other piezometers during the 19 November survey (Table 2).

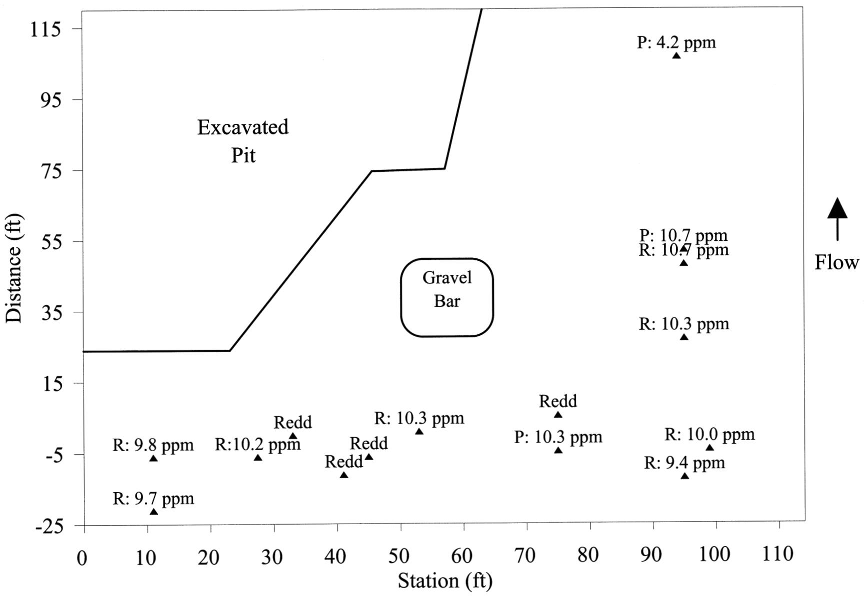

Figure 5 Map of Riffle R14 in the Stanislaus River showing redds (Redd) and the intragravel DO concentrations (ppm) at the piezometers in artificial redds (P) and fall-run chinook salmon redds (R) measured on 11 November 1996

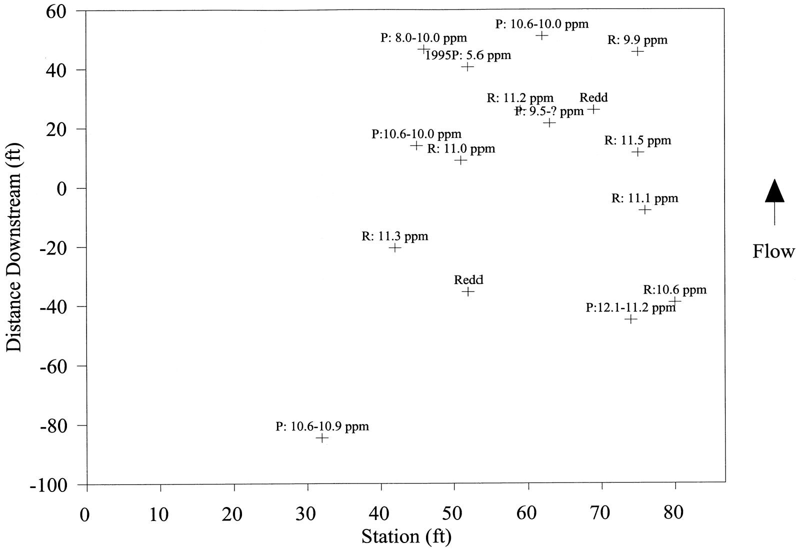

Figure 6 Map of Riffle R10 in the Stanislaus River showing the intragravel DO concentrations (ppm) at the piezometers in artificial redds (P) and fall-run chinook salmon redds (R) in fall 1996. The first DO concentration shown for the piezometers was measured during the 31 October survey and the second was measured during the 11 November survey. The DO concentrations for the redds were recorded during the 11 November survey. The DO concentration at the bottom piezometer installed in fall 1995 (1995P) was measured during the 19 November survey when atmospheric conditions reduced the concentrations by about 13% relative to the 11 November survey.

Riffle R43 provided an atypical example where redds were constructed in suitable areas that later became unsuitable (Figure 7). By 11 November 1996, intragravel DO concentrations below 8 ppm occurred at two salmon redds and one artificial redd located in the top and middle sections near the left streambank. By 19 November, another actual redd and artificial redd developed suboptimal intragravel DO concentrations. The area where the lowest intragravel DO concentrations occurred was adjacent to a grassy field with a large orchard about 100 feet from the water's edge. The left streambank of the bottom section was shielded from the orchard by a dense growth of willows. The ACOE recreation area was on the right bank of the riffle, which was vegetated with willows. The water depth gradually increased from about one foot along the left streambank to about four feet near the right streambank. These features suggest that willow growth may improve the quality or reduce the quantity of groundwater inflow from aquifers. The unusual pattern of intragravel DO concentrations in Riffle R43 also suggests that piezometers in artificial redds provide a suitable measure of conditions in actual redds.

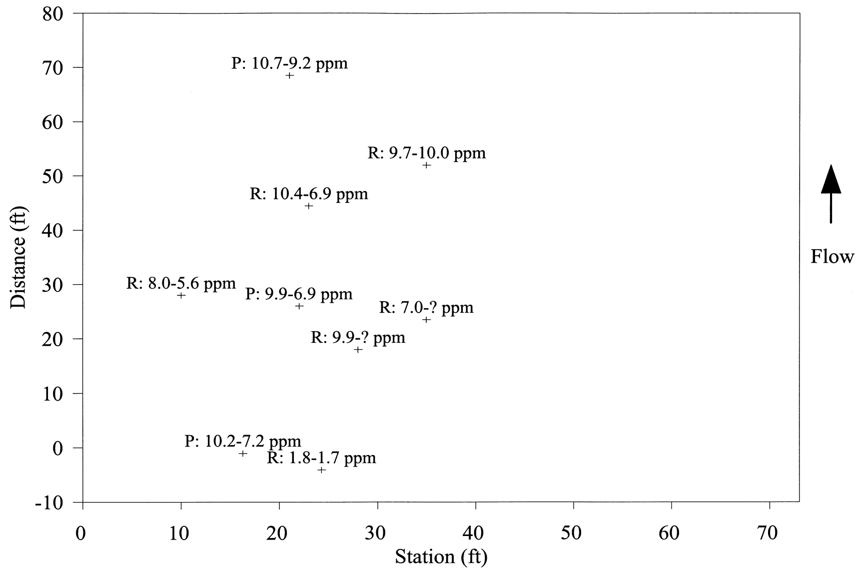

Figure 7 Map of Riffle R43 in the Stanislaus River showing the intragravel DO concentrations (ppm) at the piezometers in artificial redds (P) and fall-run chinook salmon redds (R) in fall 1996. The first DO concentration shown for the piezometers was measured during the 31 October survey and the second was measured during the 19 November survey. The first DO concentration shown for the redds was measured during the 11 November survey and the second was measured during the 19 November survey.

No redds were completed in riffles R29, R58, and R78, where intragravel DO concentrations at most piezometer sites gradually declined to minimally suitable levels (Table 2). One two-foot long salmon was observed constructing a redd in the vicinity of the top piezometer in Riffle R29 on 27 October 1996.

However, this redd and another were abandoned by 1 November when intragravel DO concentrations were measured at 90% and 92% at the top and middle piezometers respectively.

Fall 1997 Surveys

In fall 1997, intragravel DO concentrations and VHGs were measured at two pipe-piezometers installed in a newly deposited gravel berm at the head of Riffle R78. The gravel berm, deposited in a large horseshoe-shape during the spring 1997 flows, had an unexpectedly high proportion of fine substrates and no redds were observed there on 29 October or 3 December 1997. On 3 December, intragravel DO concentrations were 74.8% (8.9 ppm) and 79.8% (9.5 ppm) of saturation and the VHGs were +1.0 and +0.18 at the left and right piezometers, respectively. The high VHG at the left piezometer suggests that the low DO concentrations were caused by a very high rate of groundwater inflow. The presence of several large sewage treatment ponds adjacent to the right bank of this riffle probably contributed to this problem.

Additional evidence that intragravel DO concentrations were affected more by oxygen-poor groundwater from aquifers than by the intrusion of fine sediments was provided by samples collected in fall 1996 at two undisturbed piezometers originally installed in fall 1995. Since the substrate at these sites had been undisturbed since fall 1995, the accumulation of fine sediments and decomposing organic matter would be expected to have been greater in fall 1996 than in fall 1995. As expected, the intragravel DO concentrations at the bottom piezometers at riffles R2 and R10 in fall 1996 were 75.4% and 53.3% respectively, which is about 10% lower than the average concentrations observed in November and December 1995 (Table 2). Presumably this was due to the accumulation of fine sediments and decomposing organic matter. Conversely, the fall 1996 DO concentrations were about 20% higher than those observed in February 1996, when four major rainstorms presumably increased groundwater flow into the gravel (Table 2). Since the storm-influenced increase in groundwater flow would have been temporary, the increase in DO concentrations observed at both sites in November was probably in response to the reduction in groundwater inflow after the January storm effects subsided.

Intragravel Water Temperature

Fall 1995 Surveys

Temperature measurements made by withdrawing water samples from the piezometers with a 50-ml syringe, placing 100 ml of sample into a plastic bottle, and using a mercury thermometer, were inaccurate when compared to data recorded by thermographs. The inaccuracy was caused by the slow collection rate with a syringe and the plastic sample bottle, resulting in an overestimation of surface water temperatures by about 0.5 °F and an overestimation of intragravel water temperatures by about 1.0 to 2.5 °F as measured in fall 1996. Apparently the plastic sample bottle absorbed heat from the air, biologist's hands, thermometer, and the fanny pack used to hold the sample bottle. All readings from both thermographs and mercury thermometers used in the 1995 and 1996 studies were accurate as their measurements were within 0.2 °F when all were simultaneously placed in one gallon of water for ten minutes. The most highly suspect data were collected during 11–13 November 1995, when intragravel temperatures were measured to be 4 to 6 °F higher than surface water temperatures at all piezometer sites. The inaccuracy was probably worst during this survey because air temperatures were relatively high in early November compared to the other surveys and because more heat would have been transferred to the sample bottles by (1) using the large probe of the YSI meter to measure temperatures and (2) holding the plastic sample bottle by its neck. The variability in the overestimation observed in fall 1996 makes it impossible to determine whether intragravel water temperatures were actually elevated at any piezometer site in November 1995.

Temperature data collected during the 20–22 December 1995 survey may have been sufficiently accurate to show the effects of oxygen-poor groundwater inflow from warm aquifers. During this survey, heavy fog and low air temperatures may have reduced the temperature of the measuring equipment (and fingers) sufficiently to minimize heat absorption by the sample. Intragravel temperatures were less than 0.5 °F higher than the surface samples at many piezometer sites (Table 1), although intragravel temperatures were about 2 °F higher than surface temperatures a few of the piezometer sites. At most of the sites with elevated temperatures, intragravel DO levels were relatively low suggesting that relatively warm, oxygen-poor groundwater was influencing these sites.

The effect of groundwater inflow was apparent not only during the 20–22 December 1995 survey, when the first major rainstorm had just ended, but also during the 2–7 February 1996 survey, after five major storms had saturated the floodplain soils. The greatest difference in temperature occurred at Riffle R10 on 4 February about two hours after an intense rain storm had ended (Table 1). At Riffle R10, the intragravel temperature was 3.5 °F higher at the middle piezometer than at either the top or bottom piezometers at the same site. Two samples were taken at the middle site to confirm the difference in temperature on 4 February, whereas the temperature difference was only 0.5 to 1.0 °F higher at the middle site compared to the top and bottom sites at Riffle R10 during the previous surveys. Samples collected at the other riffles during the February survey occurred between one and two days after storm events and the observed temperature differences were lower than those observed at Riffle R10 (Table 1). This suggests substantial effects due to groundwater inflow may occur for only a few days after intense storm events. The differences in water temperature between the intragravel samples and the surface samples during the 20–22 December and 2–7 February surveys were both used as indices of groundwater inflow for the statistical analyses.

The effect of groundwater inflow on incubating salmonid eggs has been reported by other researchers. Curry and others (1994) reported that short-term declines in streamflow releases, which simulated a hydroelectric peaking regime, increased groundwater inflow into brook trout redds approximately 24 hours after the flow had declined. McNeil (1969) and Leitritz and Lewis (1980) reported that groundwater generally has a low DO concentration due to biochemical oxygen demand. This appeared to be true for the Stanislaus River as well, because the index of groundwater inflow based on water temperature differences was negatively correlated with intragravel oxygen concentration. Sowden and Power (1985) suggested the abnormally low egg survival (0.3% to 21.5%) observed for rainbow trout (*Oncorhynchus mykiss*) in a groundwater-fed streambed was partially caused by temporary declines in intragravel DO concentrations to lethal levels (minimums of 3.1 to 4.5 ppm). Unfortunately, they did not monitor groundwater-inflow throughout their study to determine whether pulses in groundwater inflow caused the temporary declines in DO concentration.

Vertical Hydraulic Gradient

The vertical hydraulic gradient (VHG) was atypical at most of the Stanislaus River piezometer sites. In typical rivers described by Lee and Cherry (1978), Creuze des Chatelliers and others (1994), and Dahm and Valett (1996), VHG is negative upstream of obstacles to surface flow, such as the crest of a riffle, and positive in areas downstream of flow obstacles, particularly at the tails of riffles. However, negative VHGs were observed only at the top piezometer of Riffle TM3 and the top right piezometer of Riffle R10 during the 31 October 1996 survey (Table 2); only one measurement was recorded at the top piezometer of Riffle TM3 because the device was displaced by spawning salmon. During the 11 November survey, VHGs were also positive at four new pipe-piezometers installed temporarily within 20 feet upstream of the riffle crest in riffles TM1 and TM3, where the streambed gradient was relatively steep (positive 7% to 9%). Unexpectedly, the middle left piezometer of Riffle R10 became negative on the last survey on 19 November. This site was on just upstream of the mildly upsloped riffle crest (positive 1.4% gradient), an unlikely area for downwelling. Based on these results, there appears to be relatively little downwelling of oxygenated surface water into the Stanislaus' riffles, but instead an upwelling of flow over a majority of the riffle's surface.

Changes in VHG at piezometer sites were unrelated to changes in intragravel DO concentrations, patterns in intragravel water temperatures, storm runoff, or precipitation (Table 2). Variability in VHGs has been known to result from changes in streambed permeability and morphology (Lee and Cherry 1978), streamflow (Lee and Cherry 1978), the depth of the water table (Price 1996), and atmospheric pressure in confined aquifers (Price 1996). Perhaps the effects of ongoing redd construction on streambed permeability and morphology that occurred throughout this study, and changes in groundwater flow from aquifers caused some of the variability in VHG measurements in the Stanislaus River.

Nitrate Concentration

Intragravel nitrate concentrations were usually higher than the surface water concentrations downstream of Orange Blossom Bridge (riffles R43 to R99) during both the 11–12 December and 20–22 December surveys 1995 (Table 2). The highest intragravel concentrations occurred at the top piezometers at Riffles R68 and R80 and the bottom piezometer at Riffle R99 during both of these surveys.

A few hours after an intensive rain storm had ceased, surface concentrations of nitrates were relatively high (1.0 ppm) at Riffle R68 and the downstream riffles on 11 December 1995 compared to Riffle R43 (the last site sampled on 11 December) and most of the riffles sampled on 12 December. The surface concentration was also high (1.0 ppm) at Riffle R47 compared to all the other riffles (0.25 ppm) during the 20–22 December survey. These results suggest nitrogenous compounds were entering the river primarily between the Orange Blossom Bridge and the town of Oakdale.

Two indices of nitrate concentration were used for the statistical analyses in fall 1995: the intragravel concentration and the difference in concentration between the intragravel sample and the surface sample during the 11-12 December 1995 survey (Table 2). The difference between the intragravel and surface concentrations was used to evaluate the relationship between groundwater and nitrate concentrations.

The high intragravel nitrate concentrations occurred further upstream in fall 1996 than during fall 1995. Intragravel nitrate concentrations in fall 1996 at riffles R29, R43, R58, and R78 were at least double (0.8 to 1.0 mg/L) the concentration of the surface water sample collected at Riffle R29 (0.4 mg/L) or the intragravel samples collected at the upstream riffle sites (0.5 to 0.6 mg/L).

Percent Fines, Crushed Rock, and Asian Clams in The Substrate in Fall 1995

The percent fines less than 2 mm in diameter for the entire substrate sample collected averaged 13% for the 32 piezometer sites and ranged between 0.13%

at the bottom piezometer site at Riffle R27 and 33.4% at the top piezometer site at Riffle R92 in fall 1995 (Table 1). The percent fines less than 1 mm for the entire substrate sample was strongly correlated (r = 0.95, P = 0.0000) with those less than 2 mm.

Predicted survival probabilities for chinook salmon eggs using Tappel and Bjornn's (1983) laboratory study averaged 76.5% in the reach above the Orange Blossom Bridge, 58.6% in the lower spawning reach between the bridge and Riverbank, and 95.4% at two restoration sites near the U.S. Army Corps of Engineers' Horseshoe Road park where gravel was added in 1994 (Table 1). Predicted egg survival probabilities averaged 72.3% upstream of riffle crests and 62.1% downstream of riffle crests at four natural riffles, Riffles R2, R10, R32, and R68, which had pronounced crests.

The total weight of substrate samples averaged 8,270 g and ranged between 4,486 g for the top piezometer at Riffle R2 and 13,483 g for the top piezometer at Riffle R32 (Table 1). There was a Pearson correlation coefficient (r) of 0.58 with a probability level of 0.0005 between sample weight and the percent fines less than 2 mm, which suggests that larger samples included deeper substrates, which contained a relatively high percentage of fines. However, including the sample weight in the multiple regression analysis had no significant effect on the final model.

The proportion of angular rock in the substrate samples was three to four times higher at the Horseshoe Road mitigation sites, Riffles R27 and R28, compared to the natural riffles. Approximately 60% of the rocks between 16 and 64 mm at Riffles R27 and R28 had sharp edges, indicating that they had been recently broken, whereas usually less than 20% of the rocks had sharp edges at the natural riffles. The amount of crushed rock at the Goodwin Canyon sites appeared to be similar to the substrate at the Horseshoe Road sites based on a casual comparison.

Some of the substrate samples at the piezometer sites at Riffles R47, R68, and R92 had high densities of Asian clams that ranged between 2 and 32 mm in diameter. At the top piezometer site at Riffle R92, there were 71 clams between 16 and 32 mm, 283 clams between 8 and 16 mm, and 15 clams between 4 and 8 mm per square-foot of streambed. Other sites, such at the top piezometer at Riffle R28 had high numbers of small clams: 306 between 2 and 4 mm and 868 between 4 and 8 mm per square-foot. Most of the clams in the samples had died prior to collection as evidenced by a strong putrid smell during sample collection. The clams, which normally live near the surface of the streambed, probably died as a result of becoming buried well below the surface during the installation of the piezometers. It is also likely that clams would be buried and die as a result of salmon building their redds. The total weight of the dried clam shells was used as an index of their biomass for statistical analyses.

Regression Analyses

Differences in DO concentration among the piezometer sites in fall 1995 were highly correlated with environmental factors. Based on the final multiple regression model, 80.4% (adj-R^2) of the variation in the mean DO concentrations during the November and December 1995 surveys was explained by groundwater effects, the weight of Asian clams, the percent fines less than 2 mm in diameter, and the mean column velocity at the piezometer site. The index for groundwater inflow, which was the difference in water temperature between the intragravel and surface samples during the 20–22 December survey, was the most important variable in the final model; it was negatively correlated with DO concentrations (*t*-statistic = –3.65, P = 0.001). Only slightly less important was the weight of Asian clam shells, which was also negatively correlated with DO concentrations (*t*-statistic = –3.41, P = 0.002). The percent fines less than 2 mm, as computed from the contents of the entire substrate sample recommended by Chapman (1988), was also negatively correlated with DO concentrations (*t*-statistic = -2.80, P = 0.010), although not as strongly as for groundwater inflow and clams. Although percent fines less than 2 mm based on the entire substrate sample was selected as the variable for the model, all four of the percent fines indexes were highly correlated (r) with DO concentrations (Table 3). Mean column water velocity was the least important variable in the final model and it was positively correlated with DO concentrations (*t*-statistic = 2.67, P = 0.014).

The final multiple regression model of DO concentrations during the February 1996 survey indicated that 68.3% (adj-R^2) of the variation was explained by groundwater effects and the percent fines less than 2 mm in diameter. Both of these variables were equally important to the model as they had similar *t*-statistics of about –4.1.

Although the gradient indexes were not selected for the regression models, low DO concentrations in February 1996 usually occurred where the streambed gradient immediately upstream of the piezometers ranged between –5% and 2% (Figure 8). This suggests that positive gradient, such as occurs at the tails of pools and at the heads of some riffles, minimized the occurrence of low DO concentrations to a greater degree than where streambed had the same gradient, but with a negative slope. This would explain why 77% of all redds observed throughout the spawning reach were located within the tails of pools and heads of riffles during both the 1994 and 1995 surveys. This skewed relationship also made it impossible to correctly evaluate the gradient indexes with linear regression analyses.

One exception occurred at the bottom piezometer at Riffle R92, where the gradient within 5 feet upstream of the piezometer was positive 3.4% and the DO concentration was low (4.5 ppm, 46% of saturation) during the February 1996 survey (Figure 8). This low DO concentration may be explained by an unusually high percentage of fines (<0.85 mm) and small gravel (<9.5 mm) which corresponds to a low gravel permeability and egg survival rate (Tappel and Bjornn 1983). High percentages of fines also occurred at the bottom piezometer of Riffle R10 and the top piezometer of Riffle R92, where DO concentrations were also low (<5 ppm) in February 1996.

Table 3 Dissolved oxygen concentrations (percent saturation), vertical hydraulic gradient, and stream gradient at 5-ft, 10-ft, and 20-ft distances upstream of piezometers at 29 piezometers in artificial redds (e.g., Top, Mid, Bot) and at 21 actual redds (e.g., Redd 20) at nine riffles in the Stanislaus River between 31 October and 19 November 1996

	D. O. concentration (percent saturation)			*Vertical hydraulic gradient*			*Streambed gradient*		
Piezometer Site	*10/31/96*	*11/11/96*	*11/19/96*	*10/31/96*	*11/11/96*	*11/19/96*	*5 ft*	*10 ft*	*20 ft*
TM1-BOTR	--	100.8	--	--	0.14	--	5.0	7.6	5.4
TM1-BOTL	--	99.2	--	--	0.14	--	5.0	7.6	5.4
TM3-TOP	95.0	95.0	97.2	-0.12	0.16	0.33	9.0	9.0	3.4
TM3-MID	96.7	96.7	92.6	0.33	0.20	0.13	5.0	10.0	0.0
TM3-BOT	93.3	92.5	92.6	0.40	0.41	0.32	2.8	0.1	-0.2
R2-TOP	--	100.0	--	--	0.27	--	9.1	8.7	5.0
R2-BOT	--	75.4	--	--	0.24	--	-5.8	-5.2	-2.7
R10-TOPR	97.6	93.3	90.5	-0.10	0.06	0.07	12.0	6.9	4.5
R10-TOPL	85.5	90.8	89.5	0.12	0.16	0.11	4.4	2.6	4.8
R10-MIDR	76.6	--	--	0.21	--	--	5.4	0.7	1.5
R10-MIDL	85.5	83.3	92.4	0.18	0.13	-0.17	-4.6	0.4	1.4
R10-BOTR	85.5	83.3	77.1	0.11	0.21	0.10	-1.8	-4.8	-2.5
R10-BOTL	64.5	83.3	88.6	0.13	0.11	0.16	-3.6	-2.8	-2.0
R10-BOT1995	--	--			53.3	0.05	-1.4	-3.3	-5.4
R10-REDD 20	--	88.3	85.7	--	0.05	0.04	12.6	6.8	7.2
R10-REDD 12	--	94.2	84.8	--	0.12	0.15	11.4	8.5	3.2
R10-REDD 14	--	82.5	85.7	--	0.27	0.23	12.0	9.6	2.5
R10-REDD 11	--	93.3	93.3	--	0.37	0.23	11.8	7.8	3.9
R10-REDD 10	--	95.8	85.7	--	0.25	0.13	1.2	1.1	0.3
R10-REDD 2	--	91.7	83.8	--	0.25	0.12	8.8	5.2	6.5

Table 3 Dissolved oxygen concentrations (percent saturation), vertical hydraulic gradient, and stream gradient at 5-ft, 10-ft, and 20-ft distances upstream of piezometers at 29 piezometers in artificial redds (e.g., Top, Mid, Bot) and at 21 actual redds (e.g., Redd 20) at nine riffles in the Stanislaus River between 31 October and 19 November 1996 (Continued)

	D. O. concentration (percent saturation)			*Vertical hydraulic gradient*			*Streambed gradient*		
Piezometer Site	*10/31/96*	*11/11/96*	*11/19/96*	*10/31/96*	*11/11/96*	*11/19/96*	*5 ft*	*10 ft*	*20 ft*
R10-REDD 9	--	92.5	--	--	0.26	—	9.6	6.5	3.3
R14-TOP	98.3	96.3	100.0	0.09	0.11	0.07	3.2	1.1	1.5
R14-MID	100.0	100.0	97.1	0.25	0.05	0.09	2.4	-0.8	-0.4
R14-BOT	69.5	39.3	37.9	0.07	0.09	0.04	-1.2	-1.0	-0.8
R14-REDD 12	--	90.7	90.3	--	0.08	0.08	5.8	5.5	7.2
R14-REDD 6	--	95.3	--	--	0.16	--	12.6	4.4	8.5
R14-REDD 1	--	96.3	99.0	--	0.11	0.05	10.8	6.7	4.4
R14-REDD 5	--	93.5	97.1	--	0.04	0.05	15.8	11.2	4.4
R14-REDD 10	--	91.6	91.3	--	0.19	0.23	6.2	3.6	4.6
R14-REDD 4	--	87.9	88.3	--	0.05	0.04	6.6	2.0	-0.4
R14-REDD 8	--	96.3	--	--	0.18	--	13.2	3.9	2.0
R14-REDD 17	--	100.0	97.1	--	0.23	0.10	0.0	-0.8	-0.4
R29-TOP	90.1	80.7	77.5	0.12	0.18	0.21	2.0	3.7	3.7
R29-MID	91.9	81.7	80.4	0.17	0.14	0.10	-1.8	-3.1	-0.7
R29-BOT	55.0	86.2	45.1	0.17	0.12	0.13	-2.0	-2.0	-1.1
R43-TOP	87.9	88.2	72.0	0.11	0.15	0.14	6.6	3.0	1.7
R43-MID	85.3	38.2	69.0	0.20	0.18	0.13	0.4	-1.1	0.1
R43-BOT	92.2	88.2	92.0	0.20	0.38	0.30	-4.2	-3.3	-5.8
R43-REDD 16	--	72.7	56.0	--	0.19	0.16	7.4	1.2	0.0
R43-REDD 22	--	63.6	102.0	--	0.14	0.22	17.4	7.9	5.0
R43-REDD 15	--	90.0	104.0	--	0.18	0.30	8.2	6.3	2.1
R43-REDD 18	--	94.5	69.0	--	0.29	0.33	9.0	7.6	2.7
R43-REDD 13	--	88.2	100.0	--	0.17	0.15	19.4	2.1	0.0
R43-REDD 30	--	16.4	17.0	--	0.13	0.11	5.4	2.8	2.1
R58-TOP	77.0	71.4	76.0	0.17	0.19	0.13	7.2	4.9	6.7
R58-MID	83.2	85.7	82.0	0.30	0.20	0.18	-1.8	-1.4	-0.6
R58-BOT	77.0	64.8	69.0	0.18	0.11	0.15	2.0	0.0	-0.8
R78-TOP	85.3	88.5	85.4	0.27	0.24	0.13	3.8	2.3	0.8
R78-MID	94.8	94.2	84.4	0.10	0.07	0.11	-4.0	-2.5	-1.5
R78-BOT	65.5	61.5	71.9	0.10	0.11	0.07	-1.6	-1.1	-0.8

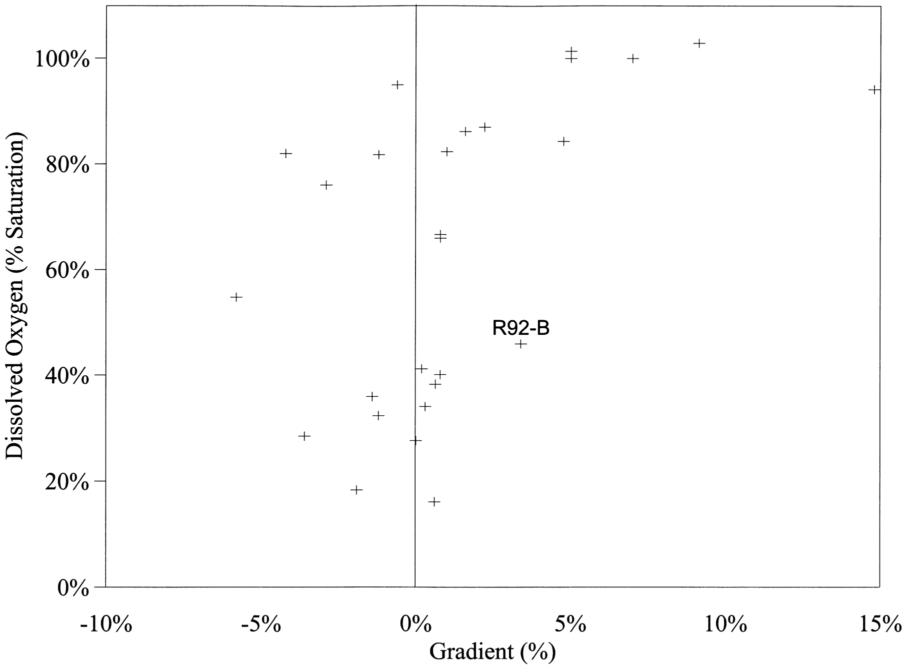

Figure 8 The relationship between intragravel DO concentrations measured at piezometer sites during the February 1996 survey and the gradient of the streambed within five feet upstream of the piezometer sites in the Stanislaus River study riffles TM1, R2, R10, R32, R43, R47, R68, R80, R92, and R99, and the bottom piezometer in Riffle R28

The most obvious explanation as to why high DO concentrations occur and salmon mostly spawn where streambed gradients are high and positive is that these areas are where downwelling of surface water typically occurs and downwelling would dilute the adverse effects of groundwater inflow and decaying clams. However, measurements of VHG upstream of riffle crests where the undisturbed streambed gradient at riffles TM1, TM3, R2, R14, R29, and R43 exceeded a positive 2% in fall 1996 indicated that upwelling occurred at these sites instead of downwelling (Table 2). Pipe-piezometers were also installed at two sites at Riffles R27 and R78 on 3 December 1997, and the VHG at these sites were also positive. Perhaps conditions, including the percentage of fines and groundwater inflow, are so extreme in the Stanislaus River that downwelling occurs at either a few, small locations or at a distance greater than 20 feet upstream from the riffle's crest.

Conclusions

Due to low intragravel DO concentrations and high concentrations of fine sediments, a majority of the riffle area in the Stanislaus River, particularly downstream of the Orange Blossom Bridge, was marginally suitable for spawning and incubation habitat for fall-run chinook salmon in 1995 and 1996. Survival of chinook salmon eggs would be expected to average 76.5% at the natural riffles at the Orange Blossom Bridge (Riffles TM1 to R43) and upstream, but only 58.6% at the riffles between the Orange Blossom Bridge and Riverbank (Riffles R47 to R99) based on a model from laboratory tests developed by Tappel and Bjornn (1983). These results are high in comparison to emergence trap studies on the Tuolumne River that indicate that egg-survival-to-emergence rates ranged between 0% and 68% (mean of 34%; EA Engineering, Science, and Technology 1992). Survival rates for Tappel and Bjornn's (1983) laboratory study may have been abnormally high for two reasons. First intragravel DO levels remained near saturation during all tests and so alevins would have been larger and stronger than those incubating in natural gravels where DO levels are lower. Second, embryos were incubated in a hatchery for 52 days before they were planted in test gravel mixtures to minimize handling mortality. Again this would have produced larger and stronger embryos compared to those incubated in natural gravels. Further research is recommended to accurately determine the relationship between gravel size and chinook salmon egg survival under natural conditions of intragravel flow and DO.

Intragravel DO concentrations were below EPA standards (80% of saturation) at 35% of piezometer sites in fall 1995 and at 42% of the sites in fall 1996. Intragravel DO concentrations declined to below EPA standards at 58% of the piezometer sites immediately following a February 1996 series of intense rain storms that made the river very turbid. Low intragravel DO levels were probably caused by the combined influence of groundwater inflow and fine sediment intrusion. If groundwater inflow increased as a result of the rain storms, the reduced intragravel DO levels associated with the February 1996 rain storms were probably temporary. On the other hand, it is also likely that the intrusion of fine sediments reduced gravel permeability, which reduced downwelling of surface flows. Regardless of the cause, intrusion of fine sediments and increased groundwater inflow did not reduce the DO levels at the 1994 restoration sites, which remained near saturation.

The predominance of nearly flat, silty riffles and fine sediment intrusion during rain storms when eggs are incubating may limit the production of chinook salmon in the Stanislaus River. A stock-recruitment analysis indicates that between 1945 and 1995, the number of spawners up to about 2,500 fish was directly correlated with the number of fish from their brood that returned to spawn in the Stanislaus River as adult fish (CMC 1996). However, once the number of spawners exceeded 2,500 fish, there was no corresponding increase in the number of returning fish. These results suggest that the Stanislaus River has enough suitable spawning habitat for only about 1,250 pairs of adult chinook salmon.

The restoration sites where gravel was added in 1994 and 1997 provided suitable incubation habitat, but only the 1997 sites were immediately used by spawners. It is possible that the source of the gravel used for restoration affected the salmon's use of spawning sites. Crushed gravel from the Merced River, 0.5 to 4 inches in diameter, that was placed at two sites in 1994 was not used by the spawners for three years until high flows washed natural Stanislaus River gravel into the site. In contrast, gravel obtained near the Stanislaus River (0.5 to 5 inches in diameter) and placed in Goodwin Canyon in 1997 was used immediately by many salmon. Although the source and type of rock used in the 1997 Goodwin Canyon project may have been more suitable for the spawners, the salmon may have used the sites because gravel is relatively scarce in Goodwin Canyon. Additional studies are needed to determine whether the salmon did not use the 1994 sites because the rock was imported from the Merced River, the rock was crushed, or if the gravel's size distribution was unnatural.

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Notes

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