..USIONS

The mid-channel bar at RM 16.5 has formed upstream of a sharp bend in the bedrock-..ised meandering channel, which under higher discharge conditions, causes backwater that ..ttens the energy gradient, and hence the ability of the flows to transport gravels and ..bbles that were entrained farther upstream in reaches that are unaffected by backwater. ..he behavior of the mid-channel bar is similar to that of a riffle in a pool-riffle sequence. ..uring high flows, velocity is greatest in the pools and lowest in the riffles which causes ..osion of previously stored sediments in the pool and deposition of sediment in the riffle. ..nder low flows, the velocity and sediment transport/storage patterns are reversed; the ..ols become depositional sites and the previously deposited sediments on the riffles are ..oded (Keller 1971). Dissection of the bar, during recessional flows, maintains the ..ntinuity of coarse sediment transport within the canyon reach. Coarse sediments (gravels ..nd cobbles) deposited on the mid-channel bar because of backwater conditions, during one ..igh discharge event, are entrained during both the falling limb of the same event and on ..e rising limb of the next event. Coarse sediment transport within the canyon reach is, ..erefore, an episodic phenomenon.

Although discharges greater than 10,000 cfs are responsible for the formation of the ..imary bar flushing of fines to prepare the clean cobble substrate required for spawning ..d egg adhesion is an erosional process that occurs during recessional flows. The flushing ..ows at RM 16.5 are in the range of 500 to 4,000 cfs depending on the location. As ..ischarge is reduced the tailwater downstream is lowered and the hydraulic slope increases. ..issection of the primary bar to form the secondary bar, and then dissection of the ..condary bar to form the riffles/tertiary bars in the branch channels results in a progressive ..moval of the fines.

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SEDIMENT FLUX, FINE SEDIMENT INTRUSION, AND GRAVEL PERMEABILITY IN A COASTAL STREAM, NORTHWESTERN CALIFORNIA

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ABSTRACT

Water and suspended sediment discharge (flux) and bed material properties were measured to document the downstream effects of fine sediment derived from highway construction on a the stream's physical character relative to reproductive success of anadromous salmonids. Results indicated that unit suspended sediment flux (tonnes/km²) was at least twice as high in stream reaches which received sediment from the highway than in an upstream control reach. Fine sediment (<4.7 mm) which intruded into artificial redds ranged from 2.1% in a control reach to 8.6% in the affected reach, but no difference in means of the two reaches was observed. Subsurface gravel permeability measurements gave mixed results, with no significant differences between the affected and the control reaches at the end of the study period. Regression analyses showed a dependence of fines intrusion on the amount of suspended sediment flux and geometric mean diameter of the coarse gravel framework. Longitudinal variability in fine sediment intrusion along the creek indicated a strong dependence of fines intrusion on proximity to upstream tributary inputs.

INTRODUCTION

The subsurface streambed environment provides important habitat for many species within the aquatic ecosystem (Milhous 1982). Many salmonid species deposit their eggs within nests, or "redds", dug within riffles. Survival of salmonids through the egg and fry life stages is dependent on a suitable hydraulic environment; one which provides an adequate flow of oxygenated water through the zones where eggs and fry are located and allows emergence of fry to the surface water column. Intrusion of fine sediment may cause mortality of eggs by reducing gravel permeability (and subsequently intragravel flow rate), and of fry when emergence upward into the surface water column is prevented by near-surface sealing of framework interstices (Alderdice and others 1958; Cederholm and others 1981; Coble 1961; Tappel and Bjornn 1983). Whether intruding fines penetrate deeply and cause direct damage to eggs or form a near surface seal depends on the size of fines relative to the size of the framework particles (Beschta and Jackson 1979; Diplas and Parker 1985; Lisle 1989).

Effects of fine sediment intrusion on reproductive success of salmonids has long been the subject of studies from both the biological and physical science perspectives (Chapman 1988; Young and

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others 1991). Numerous attempts to identify diagnostic criteria for assessing the impacts of elevated watershed erosion and sedimentation rates on a fishery resource have met with mixed success, probably owing to the large spatial and temporal variability in stream characteristics and species specific requirements for egg incubation. Despite these obstacles, this topic remains the subject of many studies because of dramatically declining populations of many wild stocks of salmonids and a continuing need for practical methods of assessing the health of aquatic ecosystems and their sensitivity to land use.

A large state highway construction project in the coastal mountains of northwestern California (Figure 1) contributed a relatively large pulse of fine sediment into the headwaters of Prairie Creek in October, 1989. This paper reports results of measurements in water year 1991 of physical stream processes related to the incident.

STUDY AREA

Prairie Creek, tributary to Redwood Creek, is located in the coastal mountains in the northwestern corner of California, USA (Figure 1). Most of the basin is underlain by the Gold Bluffs formation, which consists of weakly consolidated marine sediments and fluvial sediments from the ancient Klamath River. In the southern portions of the basin, slopes are underlain by highly sheared Franciscan sandstones and mudstones. The mediterranean-type climate causes most of the precipitation to fall as rain, and when snow falls, it exists for only short periods before melting. Average annual precipitation is 26 cm, most of which falls between October and April during intense rainstorms. Because of the temporal distribution of rainfall, streamflows are highly variable, ranging over five orders of magnitude in some years.

The Prairie Creek basin area is about 100 km^2, most of which consists of old-growth redwood forests within state and national parklands. Prairie Creek and its tributaries support both anadromous and resident salmonid populations, and the habitat the creek provides for these species is especially valued because it is relatively unaffected by land use. State Highway 101 has traversed the basin as a two lane highway for decades. This route is located in the broad terraces adjacent to the main stem of the creek, and has had little influence on the stream. In 1984, construction began on a freeway bypass around the highway section in the upper two-thirds of the basin (Figure 1). The bypass is 19 km long and traverses the headwaters of several tributary basins in Prairie Creek. Large sediment inputs occurred in the headwaters of several tributaries from Brown Creek downstream (Figure 1). Only minor sedimentation occurred above Brown Creek, consequently Prairie Creek above the confluence with Brown Creek was determined to be the best available control reach for the study. Although the study of the erosion event in Prairie Creek has been ongoing since 1989 and includes several other aspects, only results of physical monitoring from water year (WY) 1991 (October 1, 1990, through September 30, 1991) are presented here.

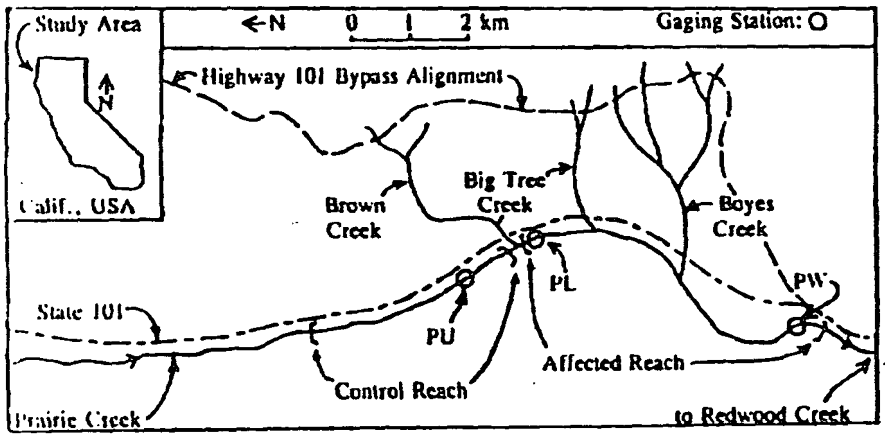

Figure 1. Location map of study area in Prairie Creek.

METHODS

Water and Suspended Sediment Transport

Three gaging stations on the main channel of Prairie Creek (Figure 1) record stream stage continuously throughout the rainy season. The lowest of these stations (PW, Figure 1), is at the same location used for a similar purpose by Lisle (1989). Discharge was recorded by programmable data recorders which also controlled automated water samplers (Eades and Thomas 1983) which obtain water samples when stormflows exceeded predetermined rates. Suspended sediment discharge, or flux (tonnes), was calculated by integration of flow rate and sediment concentration over the study period.

Bed Material Size and Fines Intrusion

To provide an index of what might be occurring in natural salmonid redds, 20 artificial redds were constructed to mimic the physical characteristics of a natural redd as closely as possible. Ten redds were constructed in both the control reach above Brown Creek and the affected reach below. The redds were distributed randomly along the two reaches, stratified into sub-reaches bounded on either end by tributary confluences. Pits about 1 m in diameter and 0.5 m deep were dug using shovels in likely spawning sites at riffle crests along the creek (Figure 2). Previous sampling in Prairie Creek indicated particles finer than about 4.7 mm in diameter were absent from newly constructed redds compared to adjacent samples outside of redds (data on file at Redwood National Park, Orick, California). Accordingly, particles finer than 4.7 mm were sieved out of the excavated material to mimic the cleaning action of spawning fish (Kondolf 1988). Prior to replacing the cleaned gravel back into the pit, a collapsed infiltration bag (Lisle and Eades 1991) was placed into the pit bottom. Backfilling the pit included an attempt to recreate an egg pocket near the base of the artificial redds, as Chapman (1988) noted the importance of this feature in studies using artificial redds. Finally, the surface of the artificial redds was shaped to mimic the pit and tailspill features found on a recently constructed natural redd (Chapman 1988).

The sampling period for the artificial redds spanned the incubation period for coho salmon (Onchorynchus tshawytsha), as indicated by a hatchbox operation on Prairie Creek. The redds were constructed when coho were spawning, and the infiltration bag samples were removed when eggs in the hatchboxes had hatched. This period was from January 11 through March 24, 1991. Because the study period only covered egg incubation, these samples did not address possible effects of fines intrusion on survival to emergence.

At the end of the sampling period, the infiltration bags were winched up out of the streambed. To avoid winnowing of fine sediment from the samples by the streamflow, the bags were winched up through a McNeil (McNeil and Ahnell 1960) sampler on the streambed. The material coarser than 8 mm in diameter was field sieved, and the finer material was wet sieved in the laboratory. Several gravel size indices were calculated from the sieve data. These were median diameter (D_{50}), percent finer (by weight) than 4.7 mm and 2 mm, and geometric mean diameter (D_g, after Lotspeich and Everest 1981). Following guidelines from Wentworth (1926), particle coarser than 128 mm in diameter were truncated prior to calculation of size indices.

To examine the dependence of fines intrusion on the variables measured, fines intrusion (percent by weight finer than both 2 mm and 4.7 mm) was regressed against unit suspended sediment flux (tonnes/km^2), D_{50}, and D_g individually and against combinations of unit flux with either size index. Regression analyses were performed on these data using linear regression procedures in the SPSS statistical software package. In these regressions, sites from the affected reach were lumped together with sites in the control reach.

Permeability

In addition to placing infiltration bags into the artificial redds, plastic standpipes were also placed in the redds above the center of the collapsed bag. Plastic standpipes 3.8 cm in diameter with 3.2 mm diameter perforations in the approximate zone of egg laying depth (30 to 40 cm below the surface). The pipes were modeled after those used by Gangmark and Bakkala (1958) for measuring dissolved oxygen and apparent velocity in artificial redds. The cleaned gravel was backfilled around the pipe, and an attempt was made to recreate an egg pocket composed of coarser gravel and cobble particles (Chapman 1988) around the perforated zone.

Permeability was measured using a modification of the technique developed by Terhune (1958), whereby the rate of intragravel water flowing into the pipe's perforations was measured upon development of a 2.54 cm (one inch) head using a vacuum pump. This yielded values of inflow rate (ml/sec). While Terhune, and others subsequently using his technique, reported actual values of permeability derived from a calibration curve relating permeability to inflow rate, the field values (inflow rate) are reported here because the pipes used in this study have not been calibrated to convert to values of permeability. In this sense, inflow rates are used as indices of permeability. Inflow rates were measured at both the beginning and end of the study period each year. Young and others (1989) found sampling error due to operator variability in permeability measurements taken using a hand pump. Use of an electric, battery powered vacuum pump in this study hopefully avoided the problem, although this has not yet been evaluated.

RESULTS

Water and Suspended Sediment Transport

The largest storms of the season occurred during the study period. As shown, the largest peak flow was less than one-third of the estimated 2-year recurrence interval (RI) peak discharge. Unit peaks (cms/km^2) at all gages were quite similar despite differences in drainage area. Although suspended sediment may be transported for many days following a high flow event, non-stormflow transport comprised only a small percentage of cumulative flux. No mobilization of the armored streambed occurred, except in the lowest part of the study area near PW, because of the lack of higher flows. Following several of the larger events, however, localized redistribution of coarse to fine sand was visually observed which indicated this material had moved as bedload.

Although unit peak flows (cms/km^2) were nearly identical at the three gaging stations, unit suspended sediment fluxes (tonnes/km^2) varied widely. At PL, which included sediment from Brown Creek, unit flux was nearly twice as high as the control. At PW, which includes sediment contributions from Brown Creek and several other affected tributaries, unit flux was more than four times greater than the control.

Table 1. Hydrologic and suspended sediment flux data from WY91, Prairie Creek.

Gage[a]	Drainage Area (km^2)	2-Year RI Peak Flow (cms)	Peak Flow of Study Period (cms)	Peak Flow of Study Period (cms/km^2)	Sediment Flux over Study Period (tonnes)	Sediment Flux over Study Period (tonnes/km^2)
PU	10.6	9.3	2.9	0.27	21.5	2.0
PL	16.6	14.5	4.8	0.29	64.9	3.9
PW	32.6	28.7	9.3	0.29	303.0	9.3

[a] designations refer to gaging stations shown in Figure 1.

Bed Material Size and Fines Intrusion

Table 2 summarizes streambed gravel framework size indices and fines intrusion for the artificial redds. Two of the twenty artificial redds (one each in both the control and affected reaches) were eliminated from analyses because of disturbance by spawning fish constructing natural redds. The measures of central tendency (D_{50} and D_g) were quite large compared to sizes reported in related literature. This reflects the nature of the parent material, which, as mentioned earlier, is composed of fluvial sediments of the ancient Klamath River which are now being reworked by the much smaller Prairie Creek. Additionally, these parameters are greatly affected by the diameter chosen for truncation (128 mm), which is fairly coarse. No significant differences were detected between means of any particle size indices from samples in the control and affected reaches using 2-tailed t-tests ($p > 0.10$).

Table 2. Particle size indices from artificial redds, Prairie Creek. Means of results from the two reaches are shown.

Reach	D_{50} (mm)	D_g (mm)	Percent Fines by Weight <2 mm	Percent Fines by Weight <4.7 mm
Control	49.3	43.0	2.9	3.5
Affected	53.6	48.1	3.3	4.4

To illustrate spatial trends in fines intrusion along Prairie Creek, fines intrusion rates were plotted versus stream longitudinal distance (Figure 2). Clear associations can be seen between amounts of fines intruded and locations of the mouths of three tributaries which were affected by erosion from highway construction activities. At sites immediately downstream of Brown, Big Tree, and Boyes Creeks, fines intrusion jumped relative to sites upstream. Downstream from each of these tributaries, fines intrusion tapered off to fairly low amounts until the confluence with the next downstream tributary was encountered.

From the regression analyses, the strongest relations were exhibited by regression of the two definitions of fines used (<2 mm and <4.7 mm) on both suspended sediment flux (tonnes) and D_{50}. These two variables explained 58% of the variability in the <2 mm fines, and 56% of the variability in the <4.7 mm fines which intruded into the artificial redds ($n = 18$) over the study period, with suspended sediment being the more important of the two predictors. Signs of the regression coefficients for sediment flux and D_g were positive and negative, respectively, indicating a direct relationship between suspended sediment flux and percent fines and an inverse relationship between D_{50} and percent fines.

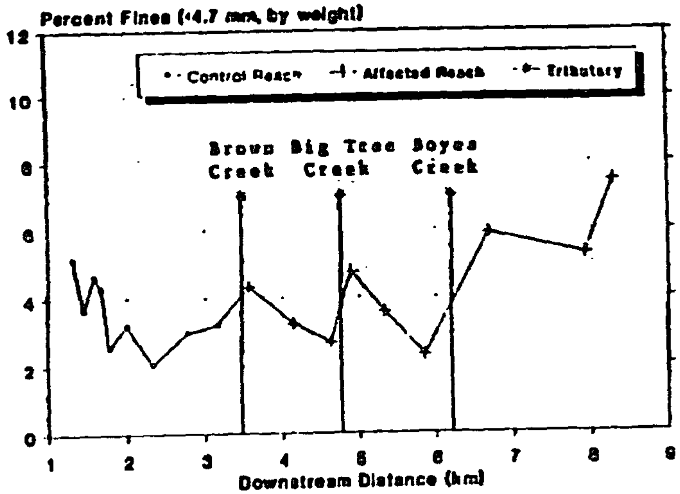

Figure 2. Longitudinal variability of fines intrusion (<4.7 mm) in Prairie Creek.

Permeability

Table 3 summarizes mean inflow rates from the beginning and end of the study period and mean percent change. Apparent changes in permeability, as indexed by inflow rate in standpipes, were difficult to interpret. Particularly, mean inflow rate of standpipes in the affected reach showed an increase at the end of the study period. Some sites exhibited apparent decreases in permeability, as would be expected following fines intrusion, while other sites showed increases. A possible explanation may be that the relative coarseness of the gravel framework in Prairie Creek caused turbulence in the surface water column to propagate downward through the streambed with relative ease. Rapid stage fluctuations of about 3 cm were occasionally observed in some standpipes during testing. This certainly may have introduced large errors in the results considering that testing procedures called for a continuous drawdown of 2.54 cm in the standpipe. Greater attenuation within the streambed of surface water turbulence would likely occur in a finer framework with greater amounts of matrix fines.

Table 3. Standpipe inflow rates at the beginning and end of the study period, and percent change over the study period, in Prairie Creek. Results are means for artificial redds in both the affected and control reaches.

Reach	Beginning Inflow Rate (ml/sec)	Ending Inflow Rate (ml/sec)	Percent Change
Control	102.5	81.8	+4.6
Affected	81.6	98.5	+2.4

DISCUSSION

Fines intrusion measured during the 1991 water year was low compared to what would probably occur during a year with more normal (2-year RI or greater) stream discharges. While sediment fluxes of over 20 to over 300 tonnes were measured at the three gaging stations, larger

magnitude stormflows would have mobilized even greater amounts of fine sediment, making more available for intrusion. Although no differences could be detected between fines intrusion in the control reach and the affected reach, large differences in suspended sediment flux were measured between the two reaches. For the type of water year experienced, suspended sediment flux appeared to be the best indicator of the degree of downstream effects from highway construction. Perhaps under the influence of higher magnitude stormflows, larger differences would be found between the two reaches. Much of the sediment remaining in Prairie Creek from the October, 1989, erosion event is stored subsurface in undisturbed areas of the streambed. Even the low flows which have prevailed since the event have resulted in removal of most of the surficial deposits of fine sediment. Only with flows of sufficient magnitude to mobilize the bed to some depth will this material be available for redistribution in the stream system and transport out of the system to the Pacific Ocean.

Clear relations between fines intrusion and proximity to an upstream tributary input were exhibited (Figure 2). The abrupt change in hydraulics as tributary flows of sediment laden water merged with those of the main channel caused immediate intrusion of fines into the bed of the main channel of Prairie Creek. This process was rapidly attenuated with distance downstream from tributary confluences as the "intrudable" portion of the sediment load (coarser element of the suspended load) dropped out of the surface water column once in the main channel. This phenomenon has obvious implications for experimental design in studies of this nature.

Regression analyses showed a significant, direct relation between fines intrusion and suspended sediment flux, and an inverse relation with framework particle size (D_{50}). While the regression equation itself is only applicable to the very low flows of the study period and is specific to Prairie Creek, the direct relation of suspended sediment flux with fines intrusion is consistent with the results of Slaney and others (1977). Suspended sediment flux may be considered a partial measure of the availability of fines for intrusion, although its relative predictive importance would probably diminish with the occurrence of streamflows sufficient to cause bedload transport.

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ON THE ARRESTED SALINE AND THERMAL WEDGES

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ABSTRACT

An integrated approach on the geometry of arrested saline and thermal wedges is presente[d] This approach is based on Schijf and Schoenfeld's one-dimensional model. The derive[d] mathematical models for the dimensionless length and shape of the saline wedge (in rivers, canal[s] and submarine conduits) and thermal wedge (in rivers and canals) are given as function of gros[s] flow and density parameters as well as function of the Darcy-Weisbach's interfacial and bed frictio[n] coefficients f_i and $f_{o/2}$, respectively. Therefore, saline wedge model needs calibration on field and/o[r] laboratory measurements of f_i and $f_{o/2}$, and thermal wedge model needs calibration only on f_i.

INTRODUCTION

Arrested or quasi-stationary saline or thermal wedges are formed in certain types of river[s] canals, and closed conduits, as a result of the hydrodynamic interaction of freshwater and saltwat[er] or warmwater. The freshwater layer is separated from the wedge by a relative thin zone of shar[p] density gradients. For modelling purposes this zone is normally simulated by a surface known a[s] interface, through which densities and sometimes velocities are assumed to vary discontinuousl[y]

The hydrodynamic behavior of arrested saline wedges in open channel flows has bee[n] theoretically and experimentally studied in the last fourty years. Schijf/Schoenfeld (1953) presente[d] the first one-dimensional theoretical analysis on a two-layered nonuniform stratified flow. Keulega[n] (1955) presented the first systematic theoretical and experimental research on saline wedges. Th[e] foundamental difference between the aforementioned two approaches lies on the bed she[ar] stresses. Dermissis (1984), and Dermissis/Partheniades (1985) presented a systematic theoretic[al] and experimental research on the dynamics of arrested saline wedges. Very interesting researche[s] on the saline wedges have been conducted by Arita/Jirka (1987) and Sargent/Jirka (1987[)] Davies/Charlton/Bethune (1988) presented a laboratory experimental study of saltwater intrusion i[n] circular pipe, associated with saline intrusion in tunnelled sea outfalls. A theoretical study of salin[e] wedge in closed conduits, associated with the problem of saltwater intrusion in karst aquifer through submarine karst conduits, has been presented by Dermissis (1992).

The first systematic experimental and analytical study on the arrested thermal wedge has bee[n] conducted by Bata (1957). His analytical model was based on the Schijf/Schoenfeld's (1953) one dimensional model. A theoretical analysis of the geometry of arrested thermal wedges has bee[n] presented by Dermissis (1989), and Dermissis/Dermissi (1991). In these studies approximated form[s] of the basic equations, and several graphs suitable for practical application are given.

In the present study an integrated one-dimensional approach of the geometry of arrested salin[e] and thermal wedges is presented. This approach includes the study of the: (a) saline wedge i[n] estuaries, rivers, canals, and submarine ducts and pipes, and (b) thermal wedge in rivers and canals

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