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Sediment Transport and Resulting Deposition in Spawning Gravels, North Coastal California

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Incubating salmonid eggs in streambeds are often threatened by deposition of fine sediment within the gravel. To relate sedimentation of spawning gravel beds to sediment transport, infiltration of fine sediment (<2 mm in diameter) into clean gravel beds, bed material size distributions, scour-fill depths, and sediment transport during 10 storm flow events were measured in three streams of north coastal California. Although suspended sediment comprised most (75-94%) of the clastic load during storm flows, bed load material (0.25-2 mm) accounted for most (70-78%) of the fine sediment accumulated in experimental gravel implanted in the streambeds. Sand trapped in the interstices of the top several centimeters formed a seal that impeded deeper deposition of very fine sand and finer material. The seal was responsible at least in part for a decrease in the rate of fine-sediment accumulation with increasing cumulative bed load transport. Areas of the streambeds commonly scoured or filled 0.1 m or more during storm flows, and thus scour and fill commonly created a sandy layer at least as thick as the seal formed by sediment infiltration. Scour could erode eggs laid in the bed and expose deeper levels of the bed to infiltration by fine sediment, but at the same time could allow fine sediment to be winnowed away. Great temporal and spatial variation in sedimentation in these streams suggests that individual storms of moderate size pose a threat to eggs in many but not all areas selected by fish for spawning.

INTRODUCTION

The interchange of fine sediment (sand and finer sizes) in transport with that stored in a natural gravel channel is an important link between the sediment transport regime and the suitability of benthic habitat for stream organisms. Although particle sizes of bed material and the sediment load are ultimately related, they are not always in phase. Logging and road construction, for example, can introduce sediment with abundant fine material to streams with relatively clean gravel beds [*Platts and Megahan,* 1975]. Even in channels without new sediment inputs, the size of sediment in transport can change with discharge because of size-dependent entrainment thresholds [*Jackson and Beschta,* 1982]. Changes in bed topography can alter transport vectors and local shear stress and thereby cause sediment that is coarser or finer than was present before in a local area to deposit. As a consequence, the spatial distribution of bed material size in natural gravel channels in undisturbed watersheds can vary considerably over time [*Adams and Beschta,* 1980; *Scrivener and Brownlee,* 1981].

Salmon and trout lay their eggs in a pit (redd) excavated most commonly just upstream of riffle crests and then bury them under 10-40 cm of bed material. The choice of location of redds and the initial winnowing of fine sediment by the female during redd construction enhances gravel permeability and intergravel flow to oxygenate the eggs and allow fry to emerge through the bed surface. Until the fry emerge (commonly 2-6 months), the redd is vulnerable to deposition of fine sediment within or over the bed, which reduces permeability, and to scour, which can remove the eggs. For many species and races, the incubation period coincides with seasons of high flow and sediment transport.

The depth to which fine sediment can infiltrate a stable gravel bed depends on the size of the fine sediment relative to the size of the bed material [*Einstein,* 1970; *Diplas and Parker,* 1985; *Carling,* 1984]. (Fine sediment infiltrating a streambed is the "matrix" material; bed material forming the pores through which fine sediment passes is the "framework" material.) Particles larger than gaps in the gravel framework are excluded from the bed unless they are incorporated in the surface material or deposited as the bed fills. Particles that are smaller than some interstices but larger than others or that are able to bridge gaps through interference with other ingressing particles become lodged in a layer just beneath the bed surface. Particles much smaller than interstices can readily pass into the bed and deposit deeply within. Ratios of framework particle diameter to matrix particle diameter that determine these three ranges of penetration of matrix particles depend on the sorting of matrix and framework material and the shape and packing of framework material.

Most commonly, sand is deposited near the surface of heterogeneous gravel beds and silt and clay pass through to deeper layers. Winnowing by turbulent bursts over the bed surface aids this segregation by removing suspendible fractions from the surface layer.

Laboratory experiments where fine sediment is fed into flow over a stable gravel bed have provided important insights into the infiltration of fine sediment into gravel beds [*Einstein,* 1968; *Beschta and Jackson,* 1979; *Carling and Reader,* 1982; *Diplas and Parker,* 1985], but they have been unable to simulate some important aspects of bed dynamics of natural channels. First, fine sediment fed into flumes has been smaller than the bed material, and in some cases, there has been little or no overlap in grain size distributions of material composing the bed and that fed into the channel. In natural channels, all sizes of transported sediment are already present in bed material. Thus grain size distributions of bed material and sediment in transport usually overlap to some degree during all transport stages. Second, natural gravel beds commonly scour and fill during high flows, altering the interface where fine sediment enters the bed.

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TABLE 1. Characteristics of Study Reaches

	Jacoby	Prairie	North Caspar
Drainage area, km^2	36.3	34.4	5.0
Gradient, m m^{-1}	0.0063	0.0032	0.0132
Bank-full			
discharge m^3 s^{-1}	19.6	~~9.9~~ 19.4	5.4
width, m	17.2	12.9	7.7
depth, m	1.0	0.77	0.55
Bed surface material			
D_{50}, mm	22.0	25.5	21.5
σ_g	5.0	3.1	6.1
Bed material*			
D_{50}, mm	8.0	9.0	8.8
σ_g	5.0	6.9	4.8
percent fines†	24.8	25.0	22.8
Bed load‡			
D_{50}, mm	2.6	3.3	3.5
σ_g	4.8	5.3	5.4
percent fines§	44.2	41.0	39.5

*$D<32$ mm.
†$D<2$ mm.
‡$0.25<D<32$ mm.
§$0.25<D<2$ mm.

Moreover, fine sediment in bed load can be deposited during the fill phase, a process quite distinct from infiltration.

The purpose of the study reported here was to relate infiltration of fine sediment and scour and fill to sediment transport in natural streambeds during individual hydrograph events. Experiments in three natural channels were designed to replicate what occurs in gravel streambeds after being cleaned by spawning fish and later subjected to storm flows.

STUDY SITES

Three gravel bed streams that drain 5-36 km^2 in the redwood forests of the Coast Range of northern California were studied: Jacoby, Prairie, and North Caspar Creeks (Table 1, Figure 1). Peak streamflow results primarily from moderately intense rain that falls mostly from late fall to early spring and averages 1000-2000 mm/annum. All three streams support runs of steelhead trout *(Salmo gairdnerii)* and coho salmon *(Onchorynchus kisutch);* Prairie Creek also contains chinook salmon *(Onchorynchus tshawytsha).* Jacoby Creek was described by *Lisle* [1986], Prairie Creek by *Briggs* [1953], and North Caspar Creek by *Rice et al.* [1979] and *Ziemer* [1981]. Variations in bed material size in North Caspar Creek were previously studied by *Burns* [1970].

The three streams provide contrasts in bed material and basin area, which may affect fine sediment deposition. Bed material of Prairie Creek, which lies mostly in Pliocene gravel and sands of the Gold Bluffs unit [*Moore and Silver,* 1968], is better sorted than that of Jacoby and North Caspar Creeks, which lie within interbedded sandstone and shale units of the Franciscan Assemblage [*Bailey et al.,* 1964]. Basin areas of Jacoby and Prairie Creeks are nearly equal, and each is approximately 7 times that of North Caspar Creek.

Study reaches (Figure 2) were 230-1600 m long and were selected to include at least four spawning areas upstream of a bridge to be used for measuring discharge and sediment transport. The channels appeared to be in equilibrium with their sediment loads and are formed predominantly in alluvium.

METHODS

Bed Material Size

Bed material was sampled at 1.3-m intervals across spawning areas using the frozen core technique [*Everest et al.,* 1980; *Walkotten*, 1976]. Three probes were driven 40 cm into the streambed and injected with liquid CO, which froze interstitial water around the probe. When the probes were withdrawn, a 20to 30-cm-thick frozen core was removed with them. The cores were vertically stratified by having them melt over a series of 4-cm-wide rectangular containers. Pounding the probes into the bed may have shaken fine material deeper into the bed, thus vertical distributions of fine material reported here should be regarded with caution. At a few sites, copper tubes ("freeze tubes") were inserted flush with the bed surface into 0.4-m deep volumes of streambed from which fine sediment (<2 mm) had been removed. After a storm, frozen cores around these tubes were taken to obtain an undisturbed stratigraphic record of fine sediment deposition.

All samples were dried, sieved into 2 phi intervals from 0.062 to 32 mm, and weighed. Sizes were truncated at 32 mm because of the smallness of core diameters and sample size (about 10 kg). On the basis of bed surface size distributions, I estimated that no more than about 20% of bed material at riffle crests was larger than 32 mm.

Pebble counts across the bed of each stream were taken at 10 locations selected by stratified random sampling [*Cochran*, 1963]. At least 100 particles were measured in each count. Channels were stratified longitudinally into reaches having three visually estimated grain size classes, and pebble count locations in each stratum were selected randomly in numbers proportional to the total channel length in that stratum. Stratified random sampling tends to reduce the standard error of the estimated mean, in this case, of the percent of bed material in each grain size class. Mean bed surface size distributions from pebble counts were computed by summing the weighted means of all strata.

Sediment Transport

Suspended and bed load transport rates were measured during six storms in Jacoby Creek, two in North Caspar Creek, and two in Prairie Creek and integrated over time to compute total transport for each storm. Gaging stations were installed at the downstream ends of the study reaches of each stream and operated continuously over the high runoff seasons from 1979 to 1986. North Fork Caspar Creek station has operated since 1962 [*Ziemer,* 1981].

Crews on rotating shifts measured suspended and bed load sediment transport rates throughout the storm flow periods, which ranged from 10 to 40 hours. Recurrence intervals of peak discharges (partial duration series) during measured storms was 0.6 years for Jacoby and Prairie Creeks and 2.2 years for North Caspar Creek. Suspended sediment was collected and analyzed using standard procedures [*Guy,* 1969; *Guy and Norman,* 1970].

Bed load was measured with a Helley-Smith sampler with a 3-inch-square orifice using the procedure of *Emmett* [1980]. Samples were taken at 7-16 points at constant intervals across the bed; each measurement included two transects. Individual sample time was 15-120 s. Because of the large spatial and temporal variations of bed load transport rates noted elsewhere [*Reid et al.,* 1985; *Campbell and Sidle,*

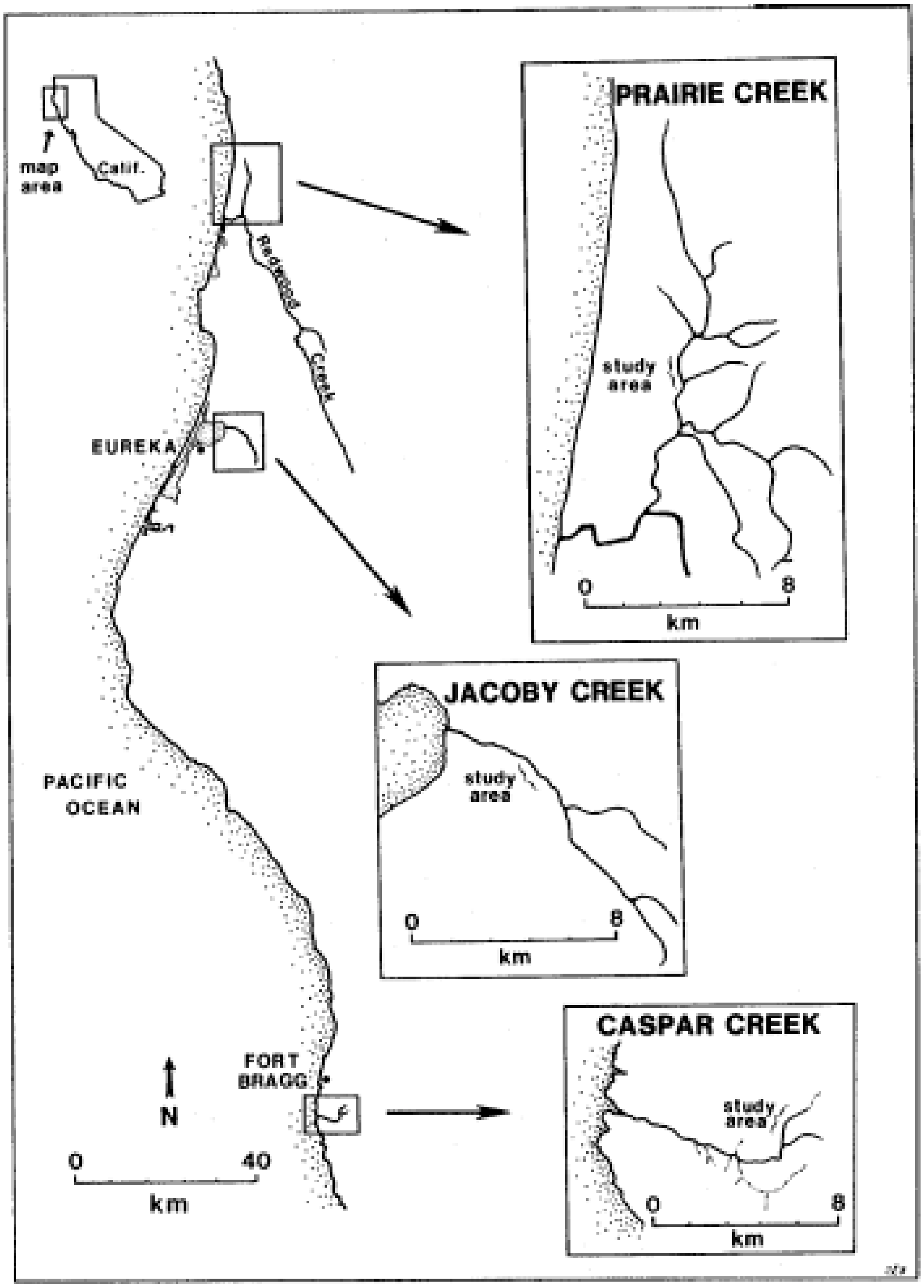

Fig. 1. Location of study reaches.

1985] and uncertainties in the efficiency of Helley-Smith samplers [*Hubbell,* 1987], transport rates reported here should be regarded as crude measurements with accuracy errors as large as 50-100%. We also measured bed load transport at a single point on the bed of Prairie Creek every 15 min for 36 hours to assess temporal variation. Bed load samples were processed in the same manner as bed material samples, but size-class intervals ranged between 0.25 and 32 mm.

Infiltration of Fine Sediment

Fine sediment infiltrating streambeds was collected in cans buried at 1.3-m intervals along transects across riffle crests in spawning areas (Figure 2). All spawning areas within the study reaches were instrumented. These areas were identified by signs of previous spawning activity or as likely spawning sites by a fishery biologist (William Brock, personal communication, 1978). Cans 17 cm in diameter by 22 cm deep were filled with well-sorted, subangular gravel $(D_{50} = 15.2$ mm; $\sigma_g = 1.8)$ and buried flush with the streambed during low flow. To install the cans, we first removed the armor layer, excavated a hole inside a metal cylinder, inserted the cans, and then replaced the armor layer over the cans. After a storm flow during which we measured sediment transport, we replaced the cans with ones filled with clean gravel. Thicknesses of strata inside the infiltrated cans were measured as they were emptied. The contents were dried, sieved into 2 phi size-class intervals between 0.062 and 8 mm, and weighed.

Solid-walled containers have been used in several exper-

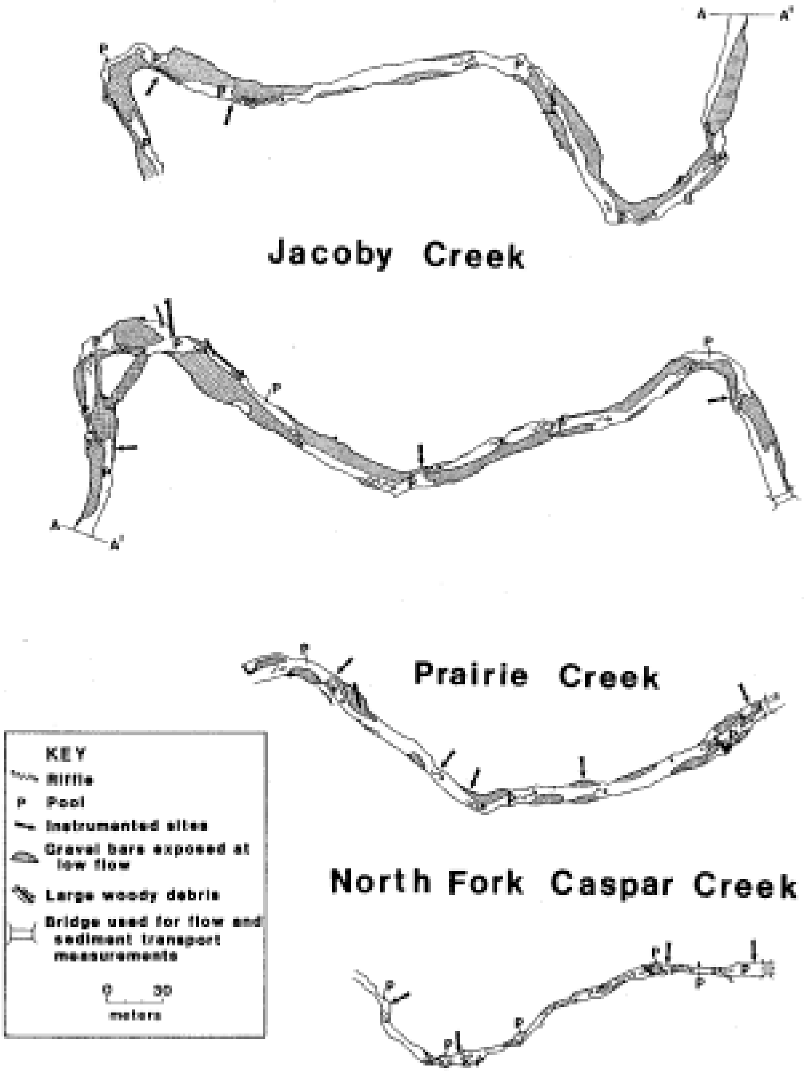

Fig. 2. Study reaches and instrumented spawning areas.

iments to measure sediment infiltration (*Slaney et al.* [1977], *Beschta and Jackson* [1979], *Carting* [1984], and *Frostick et al.* [1984] among others). Such containers collect only the sediment that enters a volume of bed material through the surface interstices and excludes sediment that is introduced laterally by intergravel flow, which can have high instantaneous accelerations due to turbulence near the bed. Gravity fall has been found to be the dominant mode of ingress of fine sediment into gravel beds [*Einstein*, 1968*; Slaney et al.*, 1977*; Beschta and Jackson*, 1979]. However, *Curling* [1984] found that impermeable container walls reduced trapping efficiency to 62% due to elimination of intergravel flow that could distribute sediment throughout a sample. Sand used in 22 of 25 runs of his experiment was apparently fine enough (smaller than 0.2 mm) to be significantly affected by the low instantaneous velocities of intergravel flow. The degree to which the walls of the cans used in my study affected trapping efficiency of fine sediment is not known. The finest sediment was probably affected most. In a single comparison of trapping rates of a can and an unbounded cylindrical section of experimental gravel in Prairie Creek, rates were found to be 3% greater in the can. Rates of sediment infiltration reported here should be regarded as minimum measures of true values.

The effect of the experimental gravel on infiltration of sediment as it would occur in natural streambed material cleaned by fish was tested in one section of Jacoby Creek. Accumulation in cans that were filled with experimental gravel was compared with that in cans filled with natural gravel ($4 < D < 45$ mm) from which fine and coarse fractions were eliminated. We placed three cans of each gravel mixture alternately in two lines running parallel to the channel centerline and separated by 1 m. We retrieved the cans after a storm and sieved their contents to measure the accumulation of material liner than 2 mm. Accumulation averaged 18.3 kg m^{-2} (SE = 1.0) in the cans with natural gravel and 18.8 kg m^{-2} (SE = 0.85*)* in cans with experimental gravel. Although the validity of standard error values is questionable because cans were not placed randomly, these results indicate no difference in accumulation rates between the two mixtures of gravel.

After storms, many cans were found to be either buried by several centimeters of fresh deposits or exposed by scour. However, analysis of covariance indicated that fine sediment accumulation rates in buried, unaffected, and exposed cans did not diner significantly (significance level = 5%). One fourth of the cans were lost altogether, most during the largest storms.

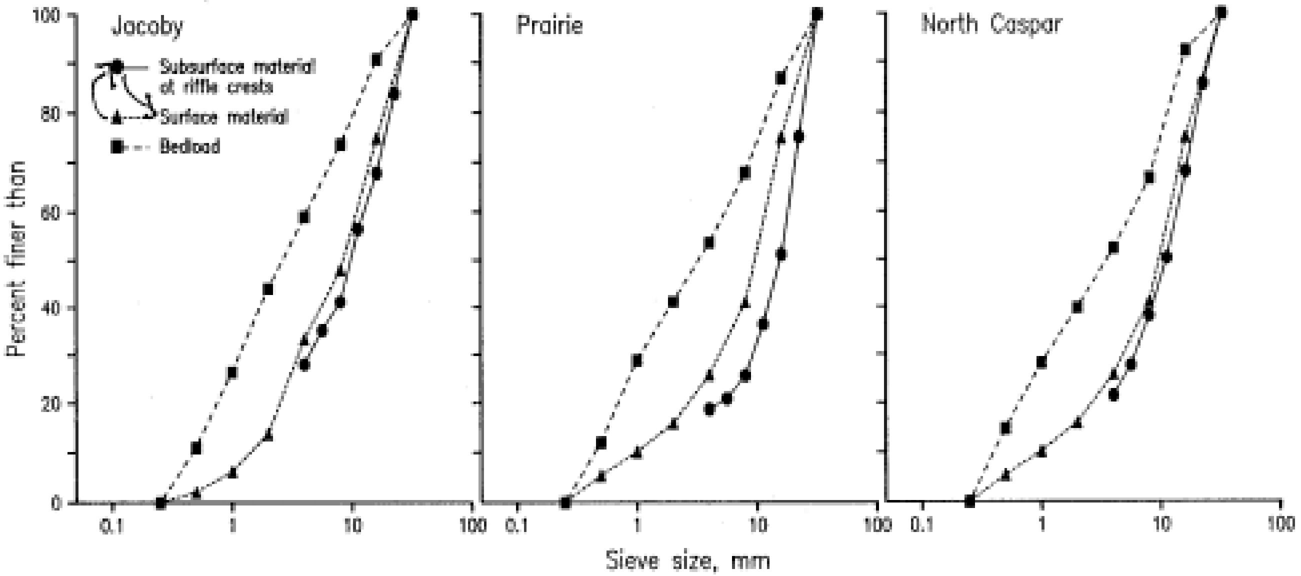

Fig. 3. Average size distributions of bed surface material in study reaches ($D < 32$ mm), bed load compounded over storm flows ($0.25 < D < 32$ mm), and subsurface material at instrumented sections ($0.25 < D < 32$ mm).

Scour and Fill

Cross sections were installed over each line of gravel cans in each stream and resurveyed after each storm for a 2- to 4-year period. Scour chains [*Leopold et al.*, 1964] were implanted during the fall before high runoff and excavated and resurveyed the following spring. Depths of scour or fill were measured by superimposing consecutive surveys of each cross section.

RESULTS

Bed Material

Surface material. Median particle sizes (D_{50},) in the surface of the three streambeds were similar (21.5-25.5 mm), but sorting of bed material in Prairie Creek was superior (Table 1). Considering the entire streambed, Prairie Creek offered more favorable spawning habitat than the other creeks because a greater majority of its surface material fell within the preferred range of sizes (80% between 10 and 100 mm). Prairie Creek's bed also felt the loosest underfoot. These differences in sorting may reflect the primary breakdown and sorting of Franciscan bedrock in Jacoby and North Caspar drainages and the secondary sorting of Tertiary gravels in Prairie Creek.

Subsurface material. Frozen core samples across riffle crests showed similar size distributions for all three streams (Table I). Within the size interval of <32 mm, D_{50} ranged from 8.0 (Jacoby) to 9.0 mm (Prairie); percent of bed material finer than 2 mm ranged from 22.8 (North Caspar) to 25.0% (Prairie). Grain size distributions were unimodal (Figure 3). Similarities in subsurface size distributions probably resulted in part from sampling in similar sedimentological environments and truncation of the upper end of the size distribution.

The proportion of material finer than 2 mm in streambeds showed little consistent variation with depth, although fines may have increased below the surface layer in Prairie Creek (Figure 4). This trend is questionable because of large standard errors for deep layers. Increases in fines with depth in Prairie Creek may have resulted from large pore spaces in its relatively well sorted bed surface, which would allow greater winnowing of fines from near-surface layers and deeper penetration of fines below surface layers than in the other streambeds. Fines could also have been displaced downward by insertion of the sampling probes. *Adams and Beschta* [1980] found no variation in concentration of fines with depth under the armor layer in coastal streams in Oregon, but *Scrivener and Brownlee* [1981] detected a small but significant increase in fines with depth in some sections of Carnation Creek, Vancouver Island, British Columbia.

Size compositions varied widely across the sampled riffle crests. The coefficient of variation in the percentage finer than 2 mm for sampled transects was 0.29 for Jacoby Creek and 0.20 for Prairie Creek. In riffles downstream of bends or large bedrock obstructions (Figure 5a), bed material commonly contained more fine material at greater distances from the outside bank (Figure 5b). Transverse components of

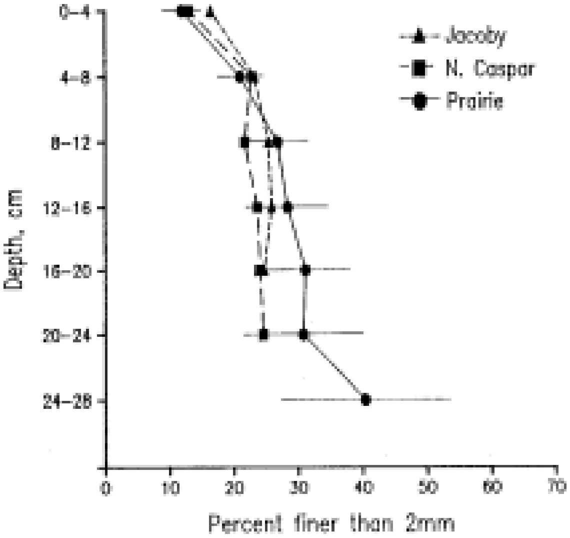

Fig. 4. Variation of fine sediment ($D < 2$ mm) with depth in bed material at instrumented sections in Jacoby, Prairie, and North Caspar Creeks.

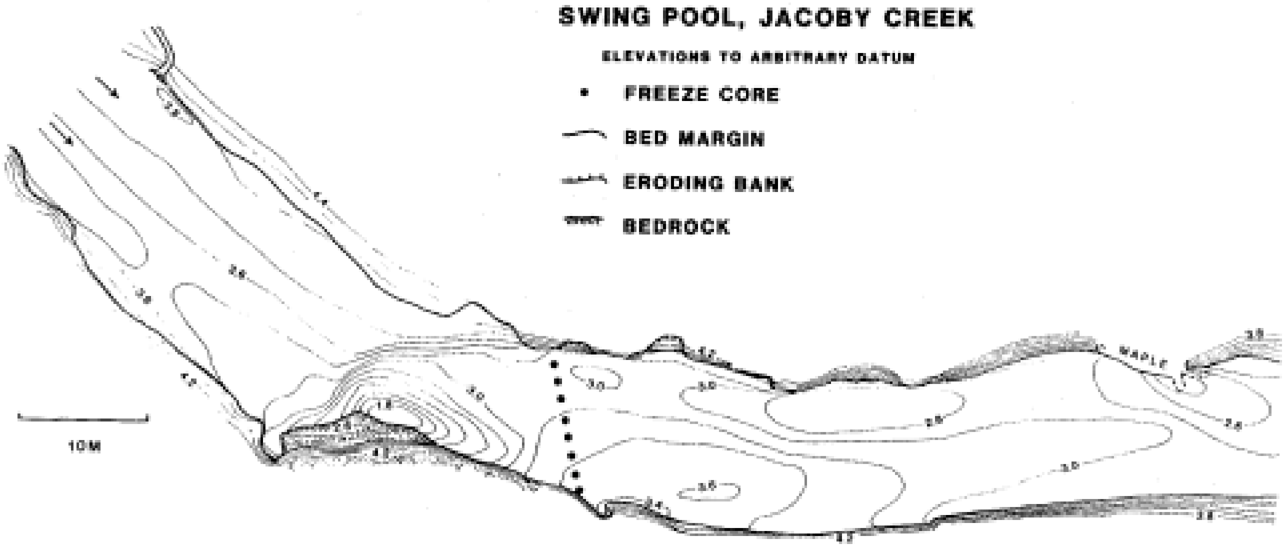

Fig. 5*a*. Frozen core locations downstream of a bend in Jacoby Creek.

near-bed velocities directed away from the outside bank may have swept fine sediment toward the inside bank [*Dietrich and Smith*, 1984].

Size distributions of bed load and bed material. Within the same size range ($0.25 < D < 32$ mm), bed material in transport was consistently finer than in the surface of the entire streambed and the subsurface material at riffle crests (Figure 3, Table 1). Bed load size compositions were averaged by integrating transport rates of each size fraction over all storms. Subsurface and surface grain size distributions do not have a lower bound, but can be compared with those of bed load because bed material finer than 0.25 mm comprised only a few percent.

Ratios of median sizes of surface material to bed load were 3.2 (North Caspar), 3.7 (Jacoby), and 4.7 (Prairie). These ratios are larger than 2.5, the ratio of D_{50} of surface to subsurface material for streams in Colorado [*Andrews,* 1983]. This difference could arise from greater armoring in the California streams, or possible reduced trapping efficiency of the bed load sampler for large particles.

Although size distributions of bed load and subsurface material can be expected to be equal [*Parker*, 1982; *Andrews,* 1983], bed load was substantially finer than subsurface material sampled at riffle crests. The proportion of sand in bed load, for example, was 2-3 times greater (Table 1). This is probably due in part to the relative coarseness of riffle crests, where subsurface material was sampled. Apparently, riffle crests already contain lower proportions of fines than other areas before spawning fish clean the bed during redd construction.

Sediment Transport

Suspended sediment. Suspended sediment concentrations in the three streams were moderate, ranging over one to two orders of magnitude, with the lowest concentrations in Prairie Creek. Suspended sediment concentrations were usually low *(*50-200 ppm) during initial and final stages of storm hydrographs and moderately high (500-2000 ppm) during peak stages. Suspended sediment constituted 75-94% of the total clastic load transported during sampled storm flows. The proportion of sand ($D > 0.062$ mm) in suspended sediment samples averaged 24-38% in each creek and ranged from a few percent at low discharges in Jacoby and Prairie Creeks to 55% at high discharges in all three creeks. Maximum particle size of sediment suspended during bank-full stages was 0.3 mm, as calculated from *Bagnold's* [1973] suspension criterion.

Suspended sediment transport relations (transport rate (kilograms per second per kilometer) versus runoff rate (cubic meters per second per square kilometer) (Figure 6) did not differ significantly for Jacoby and North Caspar Creeks, but Prairie Creek had a different relation from that for Jacoby Creek (Chow's test, significance level = 0.05). At low storm runoff rates, Jacoby and North Caspar Creeks carried higher concentrations of suspended sediment than Prairie Creek, but this difference disappeared at high runoff rates. Differences in suspended sediment curves may not be significant because of the nonrandomness of selecting times to sample sediment [*Thomas*, 1985] and the small sample size for Prairie Creek.

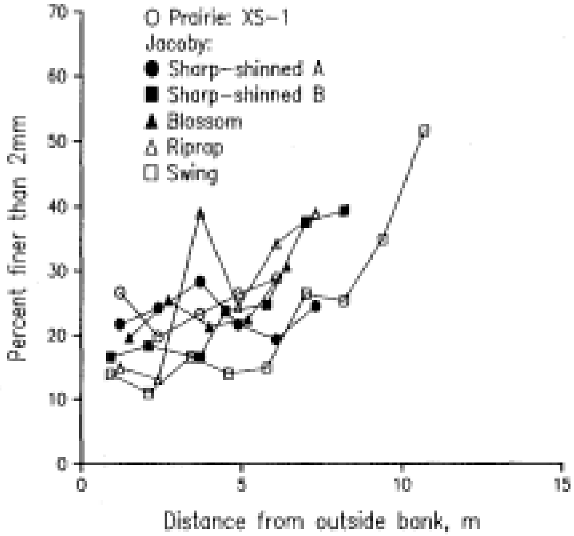

Fig. 5*b*. Variation of the proportion of fine sediment ($D < 2$ mm) in frozen cores with distance from the outside bank of bends in Jacoby and Prairie Creeks. Locations are shown in Figure 2.

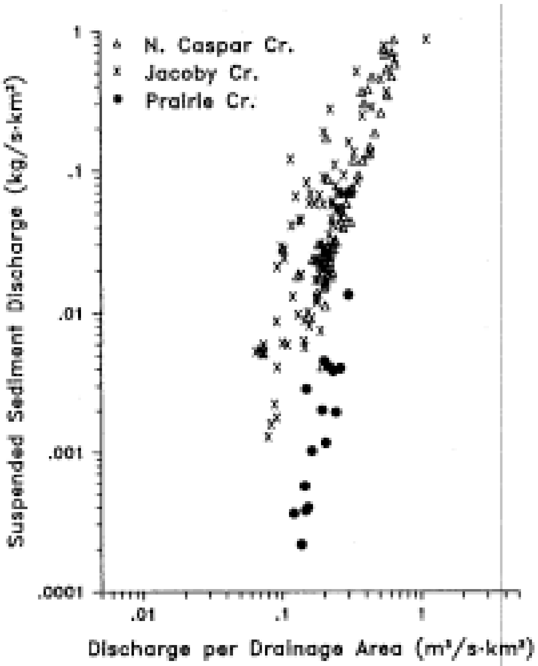

Fig. 6. Variation of suspended sediment discharge with runoff rate.

Bed load transport. Bed load transport rate increased rapidly with increasing shear stress in each creek and varied widely for a given shear stress (Figure 7). Such rapid increases are common for shear stresses less than twice the entrainment threshold [*Carson and Griffiths*, 1987) Mean bank-full shear stress, calculated from mean hydraulic radius and water surface slope, exceeded threshold shear stress, estimated from bed load transport data, by factors of 1.7 (Jacoby), 1.6 (Prairie), and 2.1 (North Caspar). These factors exceed a theoretical factor (1.2) for stable gravel channels [*Parker*, 1978]. Mean shear stress calculated in this manner, however, includes that exerted on banks, bars, beds, and large roughness elements such as woody debris and outcrops, and thus it is greater than that exerted solely on bed particles.

Prairie Creek showed significantly higher rates of bed load transport for a given shear stress than the other streams. This difference is associated with low hydraulic friction in Prairie Creek, which had a poorly developed pool-riffle sequence and low sinuosity. A common but inverse measure of friction is the ratio of mean velocity to shear velocity, which is proportional to the square root of shear stress. This value at bank-full stage was nearly twice as much in Prairie Creek (8.0) as in Jacoby (4.6) and North Caspar (4.8) Creeks.

Appreciable transport of sand over a stable gravel bed during moderately high discharges [*Jackson and Beschta*, 1982] did not occur in these streams. Sand would be selectively transported between a discharge (Q_0) corresponding to incipient bed load transport (defined as 0.0001 kg m^{-1} s^{-1}) and a discharge (Q_c) corresponding to entrainment of the median size of the bed surface (defined here as that below which the median size is not present in bed load simples). During discharges between Q_0 and Q_c, however, maximum size classes of bed load were most commonly coarser than sand (Figure 8). The median size of the armor layer (21-26 mm) was represented in bed load sampled at discharges as low as those approximately equal to Q_0 and wits represented in all samples at discharges greater than 1.6-3.0 times Q_0. Because of the smallness of bed load samples taken at low transport rates, gravel particles would be rarely captured even if they were entrained [*Wilcock*, 1988]. Thus true values of Q_c were probably closer to those of Q_0.

The most likely cause for the absence of selective transport of sand was a lack of supply of sand in these streambeds, manifested in part by the unimodality of size distributions of surface and subsurface material. In addition, deposits of unarmored sand in pools, for example, were small. In North Fork Caspar Creek, however, maximum bed load particle size was less (commonly finer than 2 mm) during rising stages than falling stages. This difference suggests that more sand was available for transport at rising stages or that gravel, once entrained during high stages, continued to be transported at low falling stages before finding a stable position on the streambed. This pattern was not evident in the other streams.

Bed load was entrained at rising stages, and transport rates remained high and fluctuated after peak discharge passed (Figures 9*a* and 9*b*). Bed load transport measured at a single point every 15 min for 36 hours in Prairie Creek (Figure 9*c*) showed that gravel continued to be transported at waning discharges which were lower than those for incipient gravel transport at rising stages, as *Reid et al.* [1985] observed. Transport of gravel ($2 < D < 32$ mm) varied more than that of sand ($0.25 < D < 2$ mm) and, as in Jacoby and North Caspar Creek, gravel transport rates at a given discharge covered a greater range than those for sand. Discontinuities in transport rates may have been caused by the passage of low bed forms or bed load sheets [*Whiting et al.*, 1988; *Kuhnle and Southard*, 1988]. Autocorrelation of bed load transport rates for the Prairie Creek point samples failed to show any significant periodicity, however, suggesting that pulses of bed load were irregular or had periods shorter than 15 min.

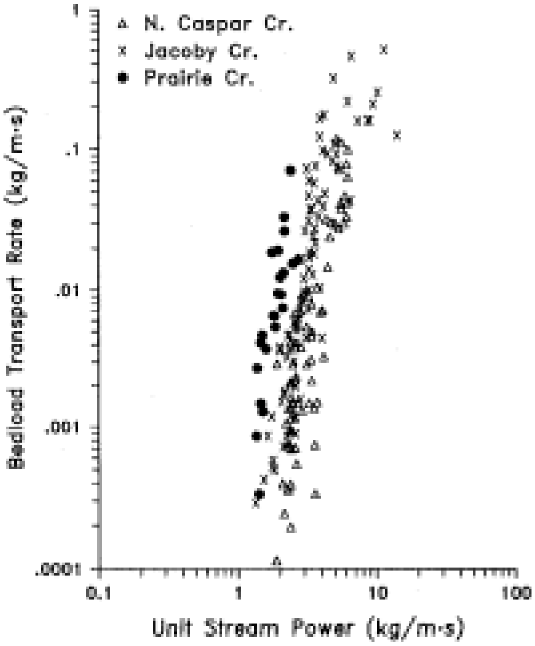

Fig. 7. Variation of unit bed load transport rate with mean shear stress.

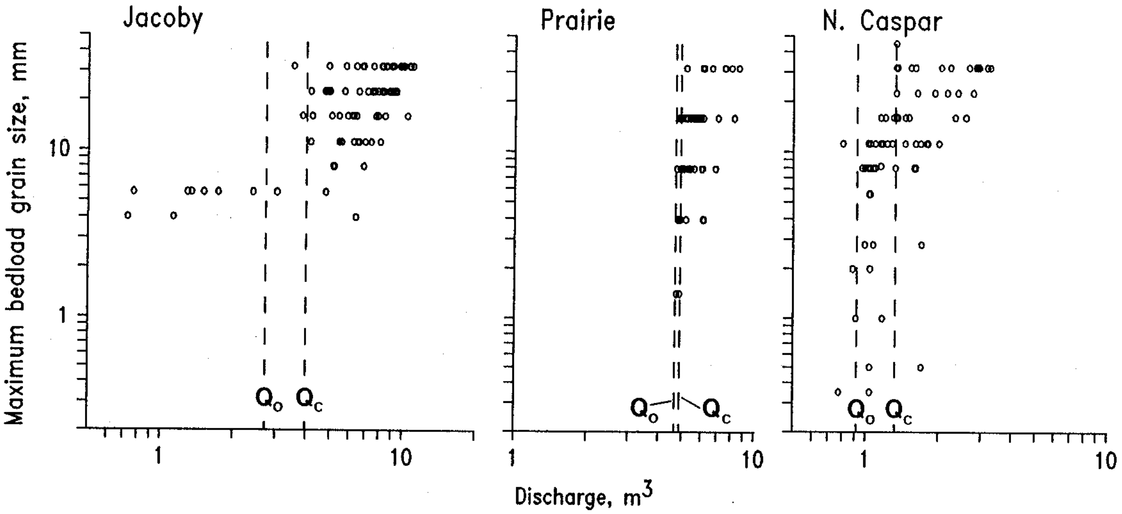

Fig. 8. Variation of maximum bed load particle size with discharge. Samples were truncated at 32 mm. Maximum bed load size is the sieve size larger than that retaining the coarsest fraction of a bed load sample.

Deposition of Fine Sediment in Gravel Beds

Gravel cans. Fine sediment that infiltrated into gravel cans was found predominately at the tops and bottoms of the cans (Figure l0). A similar pattern was observed in a core obtained from a freeze tube inserted into the bed of Prairie Creek and frozen after a storm (Figure 11). Sand and fine gravel completely filled interstices from the top layer of gravel as far down as several centimeters. The seal thus formed would seem to hinder deposition into underlying layers. Natural bed load particles as large or larger than the experimental gravel were sometimes found in these deposits, indicating that some of the experimental gravel had been scoured from the cans and replaced by gravel bed load. Fine sand, silt, and fine organic matter were deposited mostly on the bottoms of cans; small amounts were found also in the middle depths of the experimental gravel. Formation of a surface seal appeared most pronounced following stormflows which were large enough to entrain the armor layer. Deposition during smaller storms was concentrated at the bottoms of cans.

Accumulation in cans varied widely across the channel and from reach to reach. Rates of accumulation of sediment finer than 2 mm ranged mostly between 10 and 70 kg m^{-2}. The coefficient of variation (CV) across channel for all lines with three or more cans remaining after a storm averaged 0.30. (This is not a true measure of variation, however, since cans were located nonrandomly.) In Jacoby Creek, the variation across channel (CV = 0.23-0.47) approximately equalled the longitudinal variation of mean values of' each line (CV = 0.24-0.49) for five storms. The downstream-most line of cans consistently accumulated relatively small amounts of sediment, perhaps because this line was wider than the others and thus unit bed load transport rates were less. Similarly, the range in cross-channel variation for one storm in Prairie Creek (CV = 0.31-0.49) encompassed the longitudinal variation (CV = 0.38). Zones of high accumulation of fine sediment did not necessarily correspond to zones of high concentration of fines in natural bed material, perhaps because unit bed load transport in some of these areas was low.

Relation to sediment transport. Although suspended sediment comprised 75-94% of the elastic load during storm flows, sizes most likely carried in suspension (<0.25 mm) accounted for only 22-30% of the sediment accumulated in gravel cans (Table 2). The cans were a barrier to lateral intrusion of suspended sediment carried by intergravel flow, but low concentrations measured in the frozen cores (averaging 6-8%) indicated that rates of lateral intrusion would be low naturally. Relatively little suspended sediment was deposited in the streambeds because most was carried in the flow above the bed surface. Also, suspended sediment could most easily enter a clean gravel bed at low discharges before bed load particles could plug surface interstices, but suspended sediment concentrations at discharges less than Q_0 rarely exceeded a few hundred ppm.

The most abundant particle size fraction deposited in the gravel cans was medium sand ($0.25 < D < 0.5$ mm). In all three streams, sediment accumulation increased with grain size and peaked at the medium sand size range. Medium sand, which was the finest bed load fraction, was also the most abundant bed load fraction in North Fork Caspar and Prairie Creeks, but it was the least abundant in Jacoby Creek. Accumulation efficiency (the ratio between accumulation and total transport) was greatest for medium sand in Jacoby and North Caspar Creeks. Intermittent suspension and traction of very fine to medium sand would cause accumulation efficiency for finer-than-medium sand (here classified as part of the suspended load) to be calculated too low and that for medium sand (classified here as bed load) to be too high. Large amounts of medium sand were deposited, most likely, for these reasons: it was abundant in the sediment loads of the three streams and large enough to be in intermittent contact with the bed yet small enough to pass through small interstices.

Despite the large proportion of coarse sand ($1 < D < 2$ mm) in bed load in Jacoby Creek, relatively little was deposited in the cans because large interstices near the surface that would allow ingress of coarse sand would tend to quickly plug. Accumulation efficiency was greatest for coarse sand in Prairie Creek, however, perhaps because superior sorting and rounding of its armor layer created larger interstices than in the other two creeks.

Log-transformed values of accumulation of fine sediment ($0.25 < D < 2$ mm) averaged for all gravel can lines and

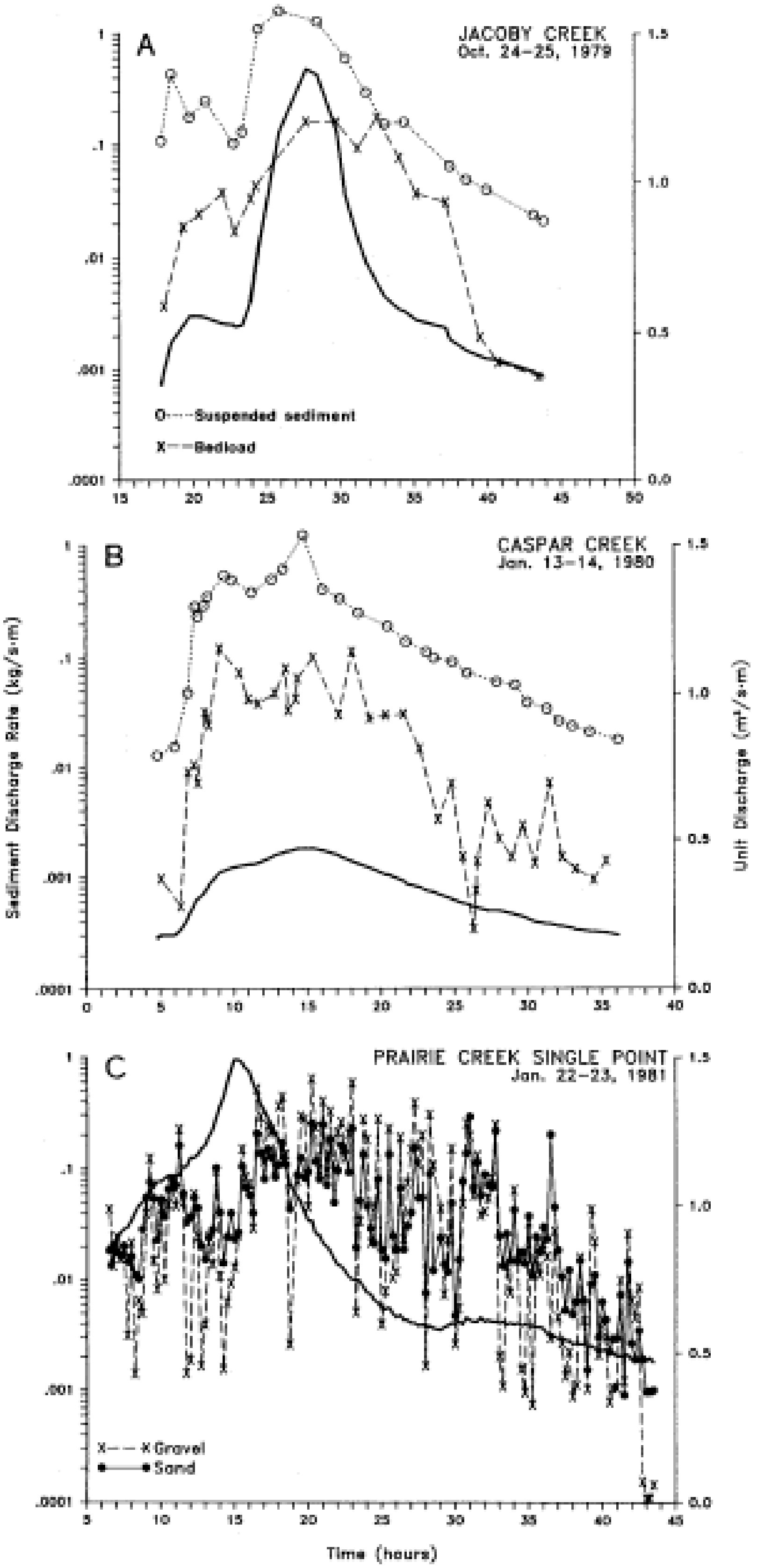

Fig. 9. Sample of storm flow hydrographs and bed load and suspended sediment discharge rates in (*a*) Jacoby and (*b*) North Caspar Creeks. (*c*) Storm hydrograph and sand and gravel transport rates taken at a single point in Prairie Creek.

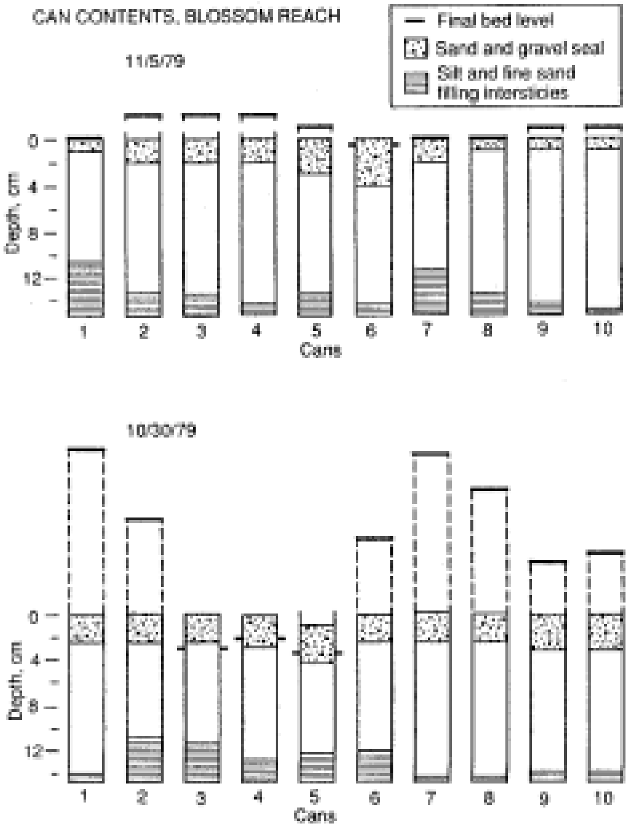

Fig. 10. Stratification of fine sediment infiltrated into experimental gravel in cans.

cumulative unit bed load transport during storms (same size range) correlated well ($r^2 = 0.93$) when data from all three creeks were combined (Figure 12):

$$A = 1.88(q_B)_T^{0.365}$$

where A is the accumulation of dry sediment per unit bed area (kilograms per square meter) and $(q_B)_T$ is the cumulative unit bed load transport (kilograms per meter). The line describing this relation passes through points selected from *Beschta and Jackson's* [1979] experiment to best represent conditions in the three stream channels (Froude number less than 1 and introduced sediment 0.5 mm in diameter).

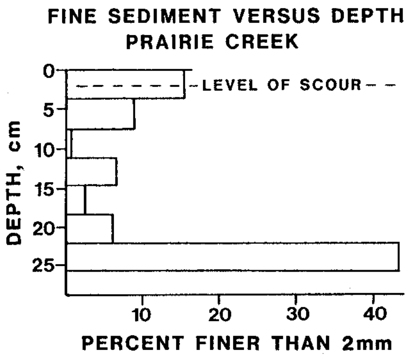

Fig. 11. Variation in fine sediment ($D < 2$ mm) with depth deposited around a freeze tube inserted into a clean gravel bed in Prairie Creek.

The percentage of fine sediment that accumulated in cans decreased as the cumulative volume of bed load passing over the bed increased. In fact, the data suggest that sediment accumulation reached a maximum of about 40 kg m^2 and remained constant after cumulative unit bed load transport surpassed about 3000 kg m^{-1} (Figure 12). This accumulation corresponds to a concentration of fines (<2 mm) of 20.5% in a 10-cm-deep bed or 11.4% in a 20-cm-deep bed, which roughly corresponds to the level that begins to seriously reduce the survival of incubating fish eggs [*Raiser and Bjornn*, 1979].

Slaney et al. [1977] report a similar relationship between accumulation of fines ($D < 1.19$ mm) and cumulative suspended sediment concentration (milligrams per liter per days) in Carnation Creek, British Columbia. A large y-intercept value (~10 kg m^2) for a linear relationship among three data pairs indicated that accumulation increased at lower rates as cumulative sediment transport increased. Maximum accumulation equalled 25 kg m^2.

Thickness of a seal formed by completely filling the voids

TABLE 2. Accumulation Efficiency by Grain Size of Sediment Collected in Gravel Cans

	Grain Size, mm				
	<0.062	0.062–0.25	0.25–0.5	0.5–1	1–2
		Jacoby			
Accumulation kg m^{-1}	145	568	658	632	446
Transport, kg	1.47×10^6	4.62×10^{6}*	31,500	47,800	64,600
Efficiency, m^{-1}	1.00×10^{-4}	4.18×10^{-4}	0.0209	0.0132	0.0069
		North Fork Caspar			
Accumulation, kg m^{-1}	12.6	66.0	72.1	59.4	54.4
Transport, kg	1.67×10^5	58,700	3100	2840	2460
Efficiency, m^{-1}	7.55×10^{-5}	0.00112	0.0232	0.209	0.0222
		Prairie			
Accumulation, kg m^{-1}	13.6	48.6	90.4	79.3	47.8
Transport, kg	1.16×10^5	72,400	3870	3380	1860
Efficiency, m^{-1}	1.18×10^{-4}	6.71×10^{-4}	0.0233	0.0235	0.0257

Accumulation efficiency is the ratio of accumulation (in kilograms per meter length of channel) to transport (in kilograms). Data is from all measured storms. Bed load sediment ranges from 0.25–2 mm in diameter; suspended sediment finer than sand is <0.062 mm, and suspended sand is assumed to range from 0.062 to 0.25 mm.

*Suspended sand sizes were not segregated between 0.062–0.12 and 0.12–0.25 mm.

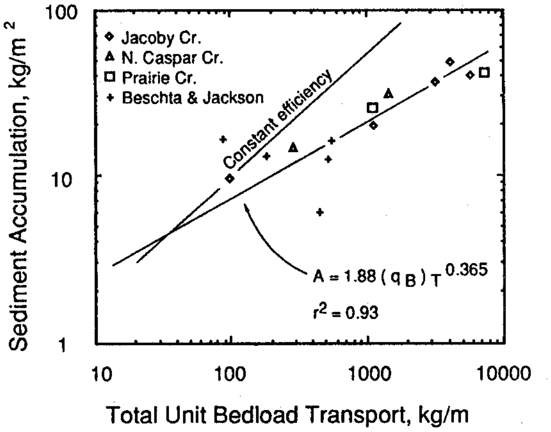

Fig. 12. Variation in accumulation of fine sediment in gravel cans with cumulated bed load transport for $0.25 < D <$ [illegible]2 mm. The line labeled "constant efficiency" shows constant values of the ratio of accumulation to transport.

of a layer of gravel can be estimated from values of sediment accumulation in mass per area by using the equation

$$T = 0.1A[\rho_s P_g(1 - P_s)]^{-1}$$

where T is seal thickness (in centimeters), ρ_s is density of sediment, P_g is porosity of gravel, and P_s is porosity of sand. Using average values for the three creeks ($\rho_s = 2.3$, $P_g = 0.42$, and $P_s = 0.35$), maximum seal thickness equals 6.4 cm. Relative seal thickness expressed as a ratio to the 90th percentile fraction of the framework material, T/D_{90}, equals 2.6 for natural bed material finer than 32 mm or 3.6 for the experimental gravel. These values agree well with those measured in experimental channels, 2.4-3.0 [*Diplas and Parker,* 1985] and 2.5-5.0 [*Beschta and Jackson,* 1979].

In the study period (1979-1986), storm flows that had magnitudes estimated to be capable of causing the maximum deposition of fine sediment cited above (40 kg m^2) were relatively frequent in Jacoby and Prairie Creeks, but relatively infrequent in North Caspar Creek. Such flows occurred 2.3 times/year, on average, in Jacoby and Prairie Creeks, and ranged in frequency between 0 and 5/year. The frequency for such flows in North Caspar Creek averaged 0.25/year and ranged from 0 to 2/year. Their recurrence intervals (partial duration series) were 0.5 years for Jacoby and Prairie Creeks and 2.25 years for North Caspar Creek. Thus sedimentation by fines clearly posed a threat to incubating ova, especially in Jacoby and Prairie Creeks.

Scour and Fill

Scour and fill of the streambeds was sufficiently deep and frequent to affect particle size composition of spawning gravels as much or more so than infiltration of fine sediment. Cross sections surveyed between storms showed that local bed elevations commonly changed several centimeters or more during storms (Figure 13), presumably as a result of imbalances between transport and deposition of bed load moving as individual particles or in bed forms a few grain diameters thick. Despite frequent scour and fill, cross sections maintained their same general shape, reflecting an overall channel stability borne out by inspecting the study reaches after storms with reference to detailed maps. Occasional movement of large woody debris caused the deepest scour or fill, as when a woody debris jam formed and collected as much as 0.3 m of new gravel and sand at a spawning section (6A) in North Caspar Creek (see also Figure 9 in the work by *Lisle* [1986]).

Depths of scour and fill varied widely both at individual cross sections and between sections. The mean elevations of cross sections remained roughly constant from storm to storm (Figure 14). However, segments of these sections commonly scoured or filled to depths of 0.1 m or more during

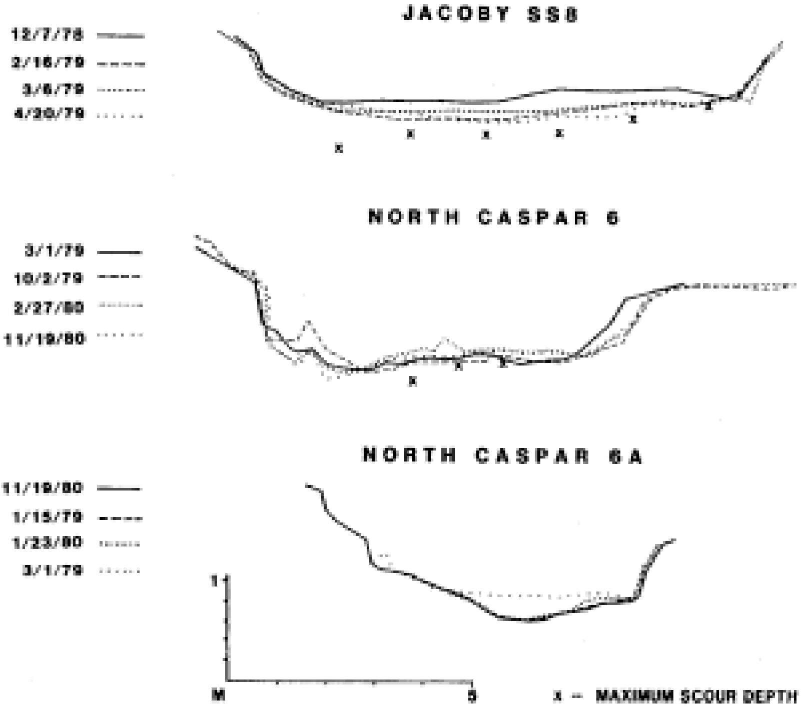

Fig. 13. Examples of scour and fill at cross sections surveyed between storm flow events. Jacoby cross section SS8 is in sharp-shinned B reach; North Caspar cross section 6A is 5 m upstream of cross section 6 (Figure 2).

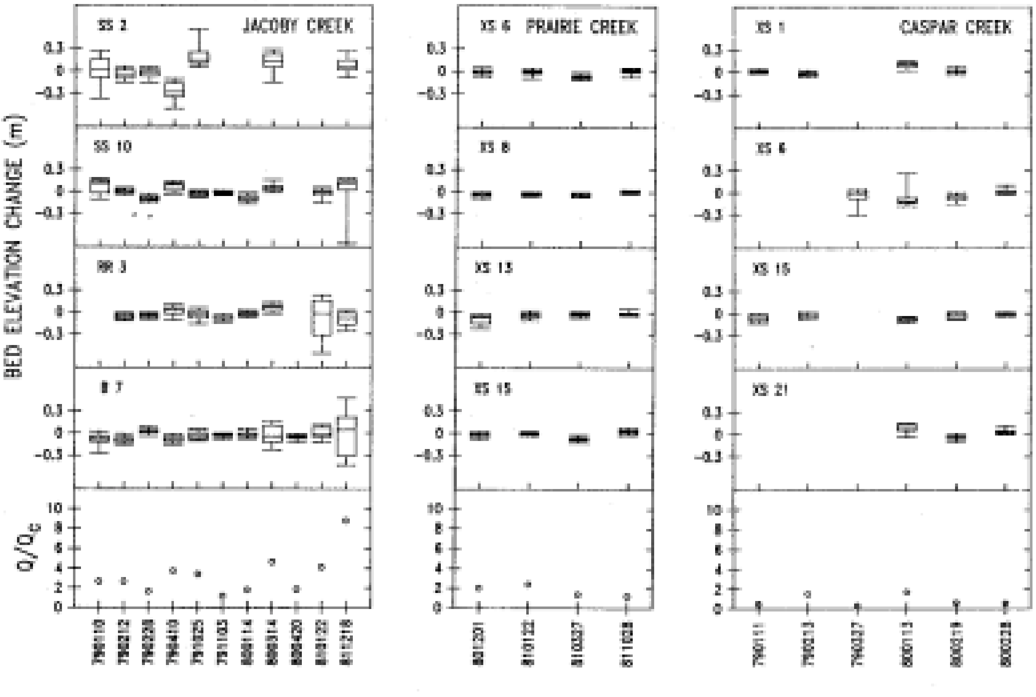

Fig. 14. Bed elevation changes resulting from storm flows and peak discharges expressed as ratios to discharge at the entrainment threshold of bed material at cross sections at spawning sites. Horizontal lines through boxes express median bed elevation change, upper and lower limits of boxes express 75th and 25th percentiles, and brackets express 95th and 5th percentiles. Positive values express fill; negative values express scour. Locations are shown in Figure 2. Jacoby cross section SS2 is in Sharp-shinned A Reach, SS10 in Sharp-shinned B, RR3 in Riprap, and B7 in Blossom.

individual storms. Jacoby Creek sections showed the greatest scour-fill range, but sampled storm size (measured as the ratio between peak storm discharge and threshold discharge for bed load transport) was also greatest in this stream. The range of mean scour-fill depths increased with storm size, but even the largest storms caused less than 0.1 m of net scour or fill at some sections.

During high flow periods, channel beds can scour below the level surveyed beforehand or afterwards. This "excess" scour accounted for more than one half of the active bed thickness in as many as 10 of 17 cross sections and showed the same magnitude of variation as scour-fill depths measured from between-storm surveys (Figure 13, Table 3). Active bed thickness, defined as the difference between the highest bed elevation surveyed between storms and the lowest level of scour measured by scour chains, was more than twice as great in Jacoby (mean value 0.32) and Prairie Creeks (0.39) than in North Caspar Creek (0.11 m). The maximum values of active bed thickness were approximately equal to one half of the mean depth of the highest flow recorded during the period when scour chains were in place. This maximum value equals those measured by *Palmquist* [1975].

DISCUSSION

Infiltration of Fine Sediment

The ratio of pore size to matrix material size determines whether a particle is excluded, becomes trapped near the surface, or passes through to the base of the bed. This ratio varies widely in natural streambeds because of the wide range of framework and matrix particle sizes, particle shape, and structure of the framework. Matrix particles too large to fit through some interstices become trapped near the surface of the bed and form successively smaller interstices that trap successively smaller matrix particles. As a result, the subsurface layer of the framework soon becomes plugged, preventing deeper penetration of matrix particles. On the other hand, matrix particles much finer than the framework particles pass through the framework interstices and settle at the base of the permeable gravel layer and on top of individual framework particles. If unhindered by a surface seal, these finer matrix particles can fill framework interstices from the base to the surface of the bed. Since deposition of coarser, seal-forming material (usually sand) can hinder deeper deposition of finer material, the mixture of matrix material sizes affects not only the level but also the total amount of deposition.

In the streams studied, most fine sediment entering the bed was deposited in a subsurface layer up to several centimeters thick. Size distributions of bed material were unimodal. Therefore distinctions between populations of matrix and framework particles were not clearcut. (The upper level of matrix particles was drawn arbitrarily in this study at 2 mm, the boundary between sand and gravel.) Even at low transport stages, enough coarse sand, granules, and small pebbles were entrained to plug the largest interstices near the bed surface. At the same time, few large interstices were available because of the heterogeneity of bed particles. As a result, infiltration of fines into the beds oh these streams was mostly restricted to the surface layers, although minor amounts of silt and clay were deposited at the base of experimental gravel beds and were concentrated in Prairie Creek beneath the level of scour and fill of the bed.

Because of the wide spread in particle sizes in most

TABLE 3. Scour-Fill Depths Measured With Scour Chains

Cross Section	Chains Lost/Implant	Excess Scour Depth* (m) and Mean (s.d.)	Active bed Thickness† (m) Mean (s.d.)	Bed Thickness/Mean Depth‡
Jacoby Creek				
Winter 1978–1979				
B6	1/7	0.055 (0.12)	0.27 (0.27)	0.35
B7	0/6	0.0027 (0.0065)	0.15 (0.053)	0.19
SS2	3/5	0.21 (0.20)	0.42 (0.23)	0.52
SS3	0/6	0.091 (0.047)	0.35 (0.11)	0.43
SS8	2/6	0.16 (0.14)	0.36 (0.13)	0.44
SS9	1/6	0.12 (0.074)	0.29 (0.12)	0.35
Winter 1979–1980				
B6	0/8	0.054 (0.044)	0.22 (0.43)	0.25
B7	0/7	0.011 (0.017)	0.19 (0.060)	0.21
SS2	2/5	0.19 (0.18)	0.28 (0.27)	0.32
SS3	1/6	0.11 (0.10)	0.19 (0.10)	0.22
SS8	5/6	0.33 (0.15)	0.45 (0.095)	0.48
RR2	7/7	0.30 (0.088)	0.48 (0.10)	0.55
RR3	7/7	0.37 (0.083)	0.50 (0.062)	0.57
North Fork Caspar Creek				
Winter 1979–1980				
1	0/3	0.006 (0.010)	0.14 (0.037)	0.37
6A	0/3	0.057 (0.069)	0.16 (0.058)	0.59§
15	0/2	0.076 (0.065)	0.15 (0.027)	0.28
21	0/3	0.0 (0.0)	0.15 (0.023)	0.43
January–November 1980				
6A	0/3	0.067 (0.043)	0.085 (0.061)	0.35
15	0/2	0.053 (0.033)	0.084 (0.011)	0.18
21	0/3	0.0 (0.0)	0.066 (0.0087)	0.19
Prairie Creek				
October 1980 to May 1983				
6	1/3	0.12 (0.060)	0.26	0.24
8	5/5	0.22 (0.10)	0.43 (0.07)	0.29
13	6/6	0.40 (0.03)	0.49 (0.08)	0.33

*Depth of maximum scour measured by scour chains below the lowest bed elevation surveyed between storms.

†Difference between the highest surveyed bed elevation and the level of maximum scour.

‡Mean depth over sections at peak flow during measurement period.

§Fill behind newly formed log jam.

natural gravel beds, the formation of a surface seal after a bed has been cleaned of fine sediment appears to be inevitable once bed load transport begins. Critical ratios governing the depth of ingress are most easily determined for uniform spheres [*Sakthivadivel and Einstein*, 1970]. In a tightly packed framework of equal-diameter spheres, the ratio of sphere diameter to pore diameter is 6.5. When the ratio of framework particle diameter to matrix particle diameter (D_f/D_m) is between 6.5 and 13, two matrix particles can bridge gaps in the framework, and thus matrix particles tend to lodge near the bed surface. For D_f/D_m greater than 14, matrix particles pass to the base of the bed or come to rest in dead zones.

Zones of deposition observed in experiments that have used natural framework gravels appear consistent with theory and experiments using uniform spheres. In the case of natural materials, the ratio of minimum framework particle diameter to maximum matrix particle diameter (min D_f/max D_m) is used to express the least potential for matrix particles to penetrate into the bed, and the ratio of mean diameters (D_f/D_m) is used to express the average potential (Table 4). In laboratory experiments, matrix material has been deposited predominantly in the uppermost layers of the framework when min D_f/max D_m is less than 17. For values of min D_f/max D_m small enough to suggest that the largest matrix material cannot enter the framework, values of D_f/D_m are much larger than the critical ratio for particle entry. Thus the range of particle ratios conducive to the deposition of matrix particles within surface layers of the framework are well represented. In such cases a layer of mostly sand has been deposited in framework interstices just below the surface of the bed. Moreover, a coarse surface layer enhances deposition of fines in surface layers [*Frostick et al.*, 1984], and yet an armor layer has been formed as a condition in only one of these experiments [*Diplas and Parker,* 1985].

The difference between framework and matrix grain sizes must be quite large ($D_F/D_M > 60$) to allow infiltration of fines below the surface layer of framework particles. This could be achieved in channels that have bimodal distributions of bed material, but the ratio of diameters of the modes would have to exceed 60, and there could be little overlap between the coarse tail of the distribution of the fine mode and the fine tail of the distribution of the coarse mode. Silt is perhaps fine enough to penetrate most interstices in many gravel streambeds, and silt and clay entering streams as pollutants have found their way into gravels [*Turnpenny and Williams*, 1980]. Suspended sediment (very fine sand, silt, and clay) accounted for 80-95% of the total load of 10 storms in the study streams. Silt and clay constituted only about 10% of the material deposited in gravel cans, however, and less than

TABLE 4. Ratio of Median Diameters of Framework and Matrix Material (D_M/D_F) and Depth of Penetration of Fines Into Bed

Source	Framework Material	D_f/D_m	min D_f/max D_m	Depth of Deposition
Einstein [1968]	poorly sorted gravel		85	base of bed
			21	base of bed
Sakthivadivel and Einstein [1970]	uniform spheres	<7		no entry
		7–14		surface layers
		>14		base of bed
Beschta and Jackson [1977]	well-sorted gravel	30	6.5	surface layers
		75	22	base of bed
Dhamotharan et al. [1980]	poorly sorted gravel	19	~1	surface layers
Carling [1984]	well-sorted gravel	104	28	base of bed
		82	17	base of bed
		11	2.5	surface layers
Diplas and Parker [1985]	poorly sorted gravel	30	3	surface layers
		22	1.8	surface layers

5% of bed material at riffle crests. Accumulation of silt in streambeds is also inhibited by winnowing from the surface layers of a stable gravel bed and infrequent contact with the bed during transport.

Winnowing of fines probably has limited effectiveness in removing fines from deep within a stable bed. Fines can be winnowed no deeper than a few median armor particle diameters [*Beschta and Jackson,* 1979; *Carling and Reader,* 1982; *Diplas and Parker,* 1985; *O'Brien,* 1987], and only suspendible fractions can be removed [*Caning,* 1984]. Differential levels of deposition and susceptibility to winnowing both tend to concentrate sand near the bed surface and silt, clay, and suspendible sand deeper within the bed.

Origin of bimodal bed material. Natural gravel streambeds commonly have a bimodal size distribution with a gravel framework and a sandy matrix [*Pettijohn,* 1975]. *Pettijohn* [1975] argued that framework and matrix material must be deposited as separate populations at different times and under different conditions in beds in which the framework gravels are in grain-to-grain contact; framework and matrix could be deposited contemporaneously in beds that have matrix-supported frameworks. However, a gravelly framework and a sandy matrix are close enough in size, in most cases, to cause entrapment of most matrix material in the surface layers of the framework. Deep infiltration of matrix material appears therefore to be an unlikely mechanism for introducing matrix material into a bed in which there is grain-to-grain contact of framework particles. More likely, matrix particles are deposited nearly contemporaneously with framework particles near the bed surface as the bed fills.

Filling of open frameworks by matrix material could result from the segregation of sand and gravel fractions into thin sheets during transport [*Iseya and Ikeda,* 1987]. Gravel at the front of a gravel sheet is in grain-to-grain contact and relatively free of sand. When the front advances, gravel left behind is infiltrated by the advancing sand sheet. Thicker lenses of gravel could remain relatively free of sand if a surface seal prevented deeper penetration by successive sheets of sand. As sand exceeds a certain proportion of bed material (50%, in *Iseya and Ikeda's* [1987] experiment), sand and gravel are no longer segregated during transport and thus are likely to be deposited together. Beds with matrix-supported frameworks commonly contain more than about 30% matrix material, while beds with framework-supported frameworks contain less [*Church et al.,* 1987]. The distinction in origins of matrix- and framework-supported beds in fluvial deposits therefore does not depend necessarily on a widely separated sequence of events but on the concentration of matrix material.

Scour and Fill

Scour and subsequent filling of streambeds can deposit fines abundantly in the bed depending on local concentrations of fines in bed load and near-bed velocities affecting winnowing of surface layers. Scour-fill depth from individual storms is frequently greater than the thickness of the seal formed by infiltrating fines trapped in the interstices of the bed surface. Scour exposes lower levels of the bed to infiltration by fines, and as the bed subsequently fills, succeedingly higher layers can be infiltrated. Scour and fill of a bed may reduce the concentration of suspendible fines in the bed, however, provided that the bed fills rapidly and winnowing of the surface removes fines faster than they infiltrate the bed. Scour and fill therefore appear to be critical to changes in the concentration of fine sediments in gravel beds.

Scour and fill of streambeds posed a serious threat to salmonid ova in all three study streams, depending on storm flow magnitude and frequency, and on shifts in channel structure. The pit and tailspill of redds were obliterated by the first high flow event to exceed the entrainment threshold of the armor layer, which usually occurred several times per year. In contrast, the topography of redds can be preserved over the incubation period in channels with less active armor layers and in those in which eggs incubate in seasons of low or moderate flow (William Platts, personal communication, 1986). Active bed thicknesses measured annually and Scour-fill depths measured between storms were frequently equal to the depth at which salmonids buried eggs (20-40 cm). Therefore eggs were in danger of being scoured from the bed or buried by thick layers of sandy gravel.

The potential survivability of ova appears to be greatest in North Caspar Creek, the smallest stream of the three. Scour-fill depths were least. Flows capable of transporting enough bedload to cause deleterious amounts of deposition of fines in cleaned gravel beds had a recurrence interval of over 2 years, compared with less than 1 year for the other two streams. Because geology, sedimentology, and suspended sediment transport curves were similar to those for Jacoby Creek, the more favorable spawning habitat in North Caspar Creek is most likely due to its being higher in a drainage. Thus there appears to be an advantage for fish to migrate as far upstream as possible before spawning.

Variation in Processes of Sedimentation

The preceding discussion has generalized some of the processes of fine sediment deposition in gravel beds. However, the distribution of bed material sizes, depths of scour and fill, and rates and grain sizes of sediment transported over a streambed are characterized better by their variability than by their average condition.

For example, fine sediment can infiltrate deeply into gravel streambeds if size distributions of transported sediment and framework particles do not overlap, at least temporarily in local areas of a stable bed. Fine sediment can become segregated from coarser bed load during waning transport stages and become concentrated in pools and other areas of low shear stress [*Lisle*, 1979; *Jackson and Beschta*, 1982]. At subsequent rising stages, fine material can be transported over the bed before the armor layer is entrained [*Jackson and Beschta*, 1982]. Spawning beds cleaned by fish in the tails of pools between the falling stage of one storm flow and the rising stage of another may thus be vulnerable to deep infiltration by fines before a seal is formed during entrainment of the armor layer. The potential for this problem could become serious during long intervals between high flows when fines tend to accumulate over streambeds [*Adams and Beschta*, 1980; *Scrivener and Brownlee*, 1982; *Frostick et al.*, 1984]. Significant volumes of sand transported before entrainment of the armor layer were not measured in the study streams because there was an insufficient supply of fines, and also, perhaps, because bed load was not measured immediately downstream of pools. During these same stages, suspended sediment concentrations did not exceed a few hundred ppm.

Bed material is sorted locally as a result of complexities in channel morphology, which cause differences in magnitude of shear stress and divergences in bottom velocity and local bed slope. Bed material commonly contains less fine material, for example, at the heads of bars where fish commonly spawn than at the tails. Strong secondary currents set up by large obstructions and bends can sweep finer material away from one side of the channel. Unstable obstructions such as large woody debris that maintain a clean area of bed may shift locations and allow fine sediment to infiltrate a matrix-free area of bed. These complexities incur both opportunities and hazards for spawning fish and incubating ova.

The great variability of scour-fill depths indicates that on one hand, even small storm flows can destroy salmonid ova and embryos, and on the outer, some arcas of the streambed remain stable during the highest flows of several years. Shifts in channel structure such as woody debris can cause deep Scour or fill during flows even less than the entrainment threshold of the bed. Because of this high degree of variability and the multiplicity of factors causing scour and fill (migrating bed forms, shifting structure, flow magnitude and duration, channel migration, anomalies in sediment routing) accurately predicting scour-fill depths without highly detailed measurements of flow and sediment transport does not appear feasible.

CONCLUSIONS

Fine sediment can enter a stable bed by infiltrating through the framework interstices, or by depositing along with bed load in an active armor layer as the bed scours and fills. The distinction between these two processes is important in determining the amount and vertical distribution of fine sediment that accumulates in streambeds and the channel conditions under which fine sediment is a problem for salmonid egg survival.

Gravels cleaned by spawning fish in the three California streams appeared to change during the first storm flow according to the following sequence of processes, which should apply elsewhere to similar channels with mobile beds of unimodal material.

1. Fish excavate a pit, deposit eggs, and cover them with a mound of bed material that has reduced amounts of fine sediment.
2. During rising stages of a subsequent storm flow, increasing amounts of suspended sediment and fine bed load are transported over the bed. Some enters the bed, and because of its small size, deposits at all depths down to the level that eggs were laid.
3. As the entrainment threshold of the bed surface is exceeded, the topography of the redd is obliterated, and a surface seal of sand forms. The seal inhibits further infiltration of fine sediment, despite the increase of suspended sediment concentration in the surface flow.
4. As bed load transport fluctuates during peak flow, the bed scours, eroding and forming seals at successively lower levels. Scour may be deep enough to excavate and wash away the eggs.
5. Alternatively, bed load is deposited over the bed and forms a thick seal in combination with ingressing sand deposited below the original bed surface. Bed load deposited at riffle crests may be coarser than that in transport because of local sorting. Other scenarios are possible with different sequences of scour and fill.
6. Little change in bed material occurs after scour and fill cease during waning stages of the hydrograph.

In these channels with unimodal bed material of sand and gravel, bed load coarse enough to become entrapped in surface framework interstices was transported at all transport stages. The main component of sediment infiltrating the bed was fine bed load, not suspended sediment, because of its frequent contact with the bed and ability to fit into framework interstices. Deposition was necessarily most concentrated near the bed surface and sealed off underlying depths to more infiltrating sediment. The seal decreased the rate of infiltration as bed load transport progressed, but not before enough fine sediment was deposited to endanger egg survival.

Scour and subsequent fill deposited as much or more fine sediment in cleaned gravel matrices as infiltration. In some instances, scour extended below common depths of egg burial and thus posed a direct threat to egg survival.

Scour and fill depths and rates of fine sediment infiltration were best characterized by their variability in time and space. This variability poses the greatest challenge to predictions of spawning success as a function of flow and sediment transport. Small streams, however, apparently offer the least risk to spawning because of low rates of unit bed load transport. Given an adequate number of spawning fish, it appears that during any year some eggs will survive the effects of sediment transport and ultimately contribute to sustaining the presence of fish in the stream.

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