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Bed Load Transport Regime of a Small Forest Stream

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Bed load transport in a small gravel-bedded stream on Chichagof Island, Alaska, was measured for 33 autumn storm flows during 1980 through 1985 to determine temporal and spatial trends within a riffle-pool-riffle sequence. The transport of fine sediment was more frequent than coarse sediment. Scouring of coarse material in the reach appeared to be triggered only by high flows with $T_r \geq 5$ years. Within a given storm season, both antecedent storm history and cumulative flow (above the threshold for bed load transport, 0.25 m^3 s^{-1}) influenced bed load transport; however, the effects of these seasonal factors changed from year to year, presumably in response to storage and release of sediment around large organic debris upstream. Hysteresis loops existed in bed load transport versus flow plots for many storms. Fine bed load material was more subject to such differential transport over the storm hydrograph than was coarse material. During the 6-year period, both riffles scoured along most of the channel width while the middle portion of the pool filled.

Introduction

The dynamic nature of bed load transport in relation to stream channel morphology is of great importance to the habitat of anadromous and resident fish. The occurrence of pool-riffle sequences is an intrinsic characteristic of gravel-bedded streams that is maintained by stream hydraulics and that provides important fish habitat niches [*Keller*, 1971; *Meehan*, 1974; *Lisle*, 1982]. During smaller storm flows, transport competence at the riffle is greater than in the pool and largely sand-sized particles are transported [*Lisle*, 1979; *Jackson and Beschta* 1982]. As storm flows increase, the hydraulic gradient of the pool-riffle sequence tends to even out and coarse particles become entrained and are subsequently deposited on downstream riffles [*Keller*, 1971]. Riffles are typically sites for spawning (redd construction), and pools offer more protected habitat for juvenile fish. Transport of sediment along the streambed is vital to maintain the dynamic equilibrium of a stream system [*Schumm*, 1960].

Surface armoring of the streambed with coarse gravel tends to limit the availability of an otherwise abundant supply of finer bed materials [*Parker et al.*, 1982; *Parker and Klingeman*, 1982]. Fine sands often accumulate in deep pools during low flow periods and are available for transport during small storm flows [*Jackson and Beschta*, 1982; *Milne*, 1982]. Hence riffles normally have coarser bed material than pools [*Milne*, 1982].

Andrews [1983] found that the shear stress required to entrain a given size particle was affected by the size distribution of the gravel bed. Because particles between 0.3 and 4.2 times the mean subsurface diameter were entrained at nearly the same discharge, *Andrews* [1983] concluded that differential entrainment of bed sediment is not an important process in gravel bed streams. *Lisle* [1979] also found that grain size distribution of bed load in East Fork River, Wyoming, changed little with flow; however, the upper size limit of bed load was 4–8 mm. Coarser riffle gravel was believed to be protected by armoring and imbrication, with entrainment of coarse gravel occurring only at very high flows. Lisle assumed that the gravel matrix of the bed was nearly static because no large amounts of coarse gravel came from external sources. *Campbell and Sidle* [1985] measured a net import of coarse (>8 mm) sediment into pools during moderate storm flows and net export of sediment from pools at bank full or greater stages. *Jackson and Beschta* [1982] noted that bed load transport does not always involve the full range of available particle sizes. They proposed a two-phase model for bed load transport: during phase 1, movement of sand occurs over relatively stable gravel-surfaced riffles and flows are not sufficient to entrain much of the gravel found in the riffles; during phase 2, bottom velocities in pools approach or exceed those in riffles, and riffle armor is transported downstream from riffle to riffle.

Periodic changes in channel form related to bed load movement can affect fish habitat. After a major storm in northern California, streams underwent drastic channel changes that deteriorated fish habitat [*Kelsey*, 1980; *Lisle*, 1982]. Pools tended to fill with sediment and become more closely spaced, while channels widened [*Kelsey*, 1980; *Lisle*, 1981]. During less drastic storm flows, shifting gravels may displace or physically damage fish eggs during a scouring sequence or cause excessive deposition over eggs, hindering fry escapement [*Cordone and Kelley*, 1961; *Meehan*, 1974].

Although seasonal influences and patterns of storms are believed to influence bed load transport [*Milhous*, 1973; *Parker et al.*, 1982], very little work has been done to quantify these effects. *Lisle* [1979] measured the percentage of the pool bed covered with sand during three consecutive snowmelt runoff events and concluded that initial scour began at about bank full stage during the first event and then began at progressively lower flows during subsequent peak flows. *Milhous* [1973] postulates that organic detritus accumulated in forest streams can increase bed load transport during the first autumn storm flow event. *Estep and Beschta* [1985] noted consistent differences in bed load transport at two consecutive riffles during smaller storm flows (T_r < 1 year); however, during higher flows (T_r = 2–5 years) these spatial differences in bed load transport were reversed. *Campbell and Sidle* [1985] suggested that a seasonal sorting in fine bed load sediment may occur as a result of a progressive flushing of fines from stream gravels throughout the storm season. My study addresses the need to under-

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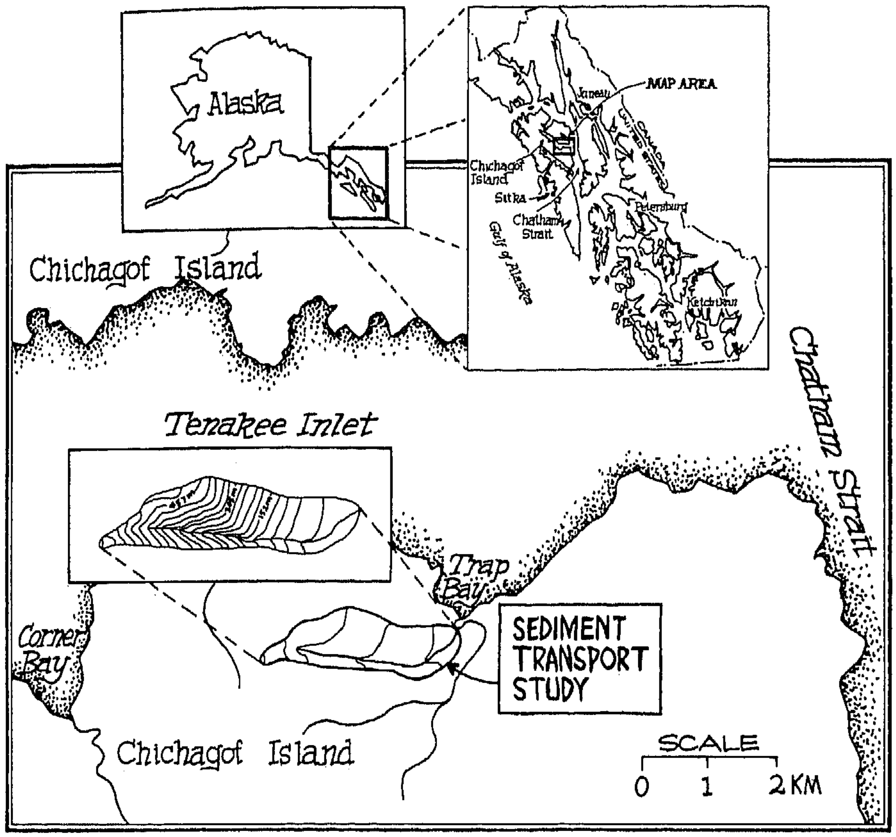

Fig. 1. Map of coastal Alaska showing Bambi Creek drainage at Trap Bay, Chichagof Island.

stand the temporal variation and trends of bed load movement and channel morphology, particularly in small forest streams. Specific objectives include evaluation of (1) multiyear trends in bed load movement through a riffle-pool-riffle reach; (2) seasonal changes in bed load transport; (3) within-storm patterns of bed load movement; and (4) changes in channel morphology related to bed load entrainment.

STUDY AREA

Research on sediment transport has been conducted since 1980 at Bambi Creek, a second-order forest stream within the Trap Bay watershed on northeast Chichagof Island, Alaska (Figure 1). The Bambi Creek drainage above the sediment sampling site has an area of 154 ha; elevation ranges from 8 to 614 m. Overall channel gradient at the bed load sampling site is 0.0082; gradients within the riffle-pool-riffle reach that was sampled are 0.0212 in the upper riffle, 0.0047 in the lower riffle, and 0.0029 in the intervening pool. Channel gradient increases to > 10% in the headwater reaches of Bambi Creek. Average channel width is about 3.6 m; average bank full depth is about 0.45 m. Bank full discharge is 1.7–1.8 $m^3 s^{-1}$. The study site is about 500 m upstream from the confluence of Bambi Creek and Trap Creek.

The mountains surrounding the Trap Bay basin were carved during retreat of Pleistocene ice. At lower elvations, surficial bedrock is composed of Silurian graywacke and argillite and Devonian limestone [*Lanphere et al.*, 1965]. Soils are largely spodosols with organic horizons up to 20 cm deep. Numerous bogs (muskegs) interspersed at lower elevations in the drainage may moderate peak runoff during major storms.

Steep headwater channels merge into a series of riffle-pool sequences in the lower gradient reaches of Bambi Creek. Large organic debris occurs throughout the stream system; however, the largest debris jams are located in a reach just upstream of the bed load sampling site. Organic debris forms a series of log steps and plunge pools in the stream and provides sites for the deposition of large quantities of sediment. Some of this sediment is stored upstream of large logs and is difficult to transport even during high flows. Other sediment, deposited in slackwater areas influenced by woody debris, may be readily transported at higher flows. Major sources of sediment in the lower reaches of Bambi Creek are bank sloughing, transport of sediment from upstream, and fluvial erosion within the stream channel. Median particle diameter (d_{50}) of the streambed pavement was 28 mm, and d_{50} of the subpavement was 9 mm. The particle size distribution of the streambed is given by *Campbell and Sidle* [1985].

Climate is typical of coastal Alaska: cool summers, high rainfall during fall and early winter, intermittent snow pack at low elevations during winter and spring, and moderate rainfall with occasional snow in the spring. Major peak flows generally occur during autumn and are characterized by moderate intensity rainfall of long duration associated with low pressure fronts moving in from the Pacific Ocean. Total precipitation during autumn averages 680 mm, based on data from a sea level station at nearby Tenakee Springs; mean annual precipitation is 1670 mm. Higher precipitation would

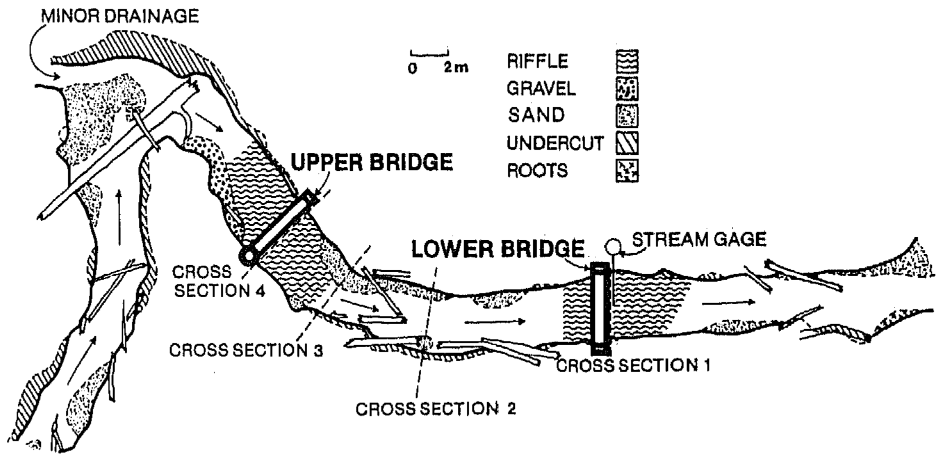

Fig. 2. Bed load sampling reach of Bambi Creek.

be expected in the Trap Bay watershed because of orographic influences.

METHODS

Bed load transport during the autumn storm season was measured at a riffle-pool-riffle sequence in Bambi Creek from 1980 to 1985 with a hand-held, Helley-Smith, pressur-differential bed load sampler [*Helley and Smith*, 1971]. To prevent clogging the sampler with fines or organics, a 6000-cm^2 collection bag (mesh size 0.2 mm) was substituted for the standard 2190-cm^2 bag [*Johnson et al.*, 1977; *Beschta*, 1981]. Bridges were built across Bambi Creek to facilitate sampling without disturbing the bed: the upstream bridge is near the middle of the upper riffle, and the downstream bridge is at the head of the next riffle downstream (Figure 2). Each composite bed load sample was collected during one pass containing either four or eight equally spaced points across each of the two bridges. Total sampling time at each point ranged from 15 to 60 s, depending on storm discharge. Bed load samples were collected on both rising and falling limbs of storm hydrographs when possible. Samples were taken as close together as practical at the upper and lower sites (generally within 3–5 min) so that accurate estimates could be made of net bed load storage within the reach. The frequency of paired samples (upper and lower bridges) depended partly on changes in discharge. If net bed load storage is examined, inferences can be made about long- and short-term bed load transport processes in the stream and storage or scouring patterns within the reach.

Bed load samples were returned to the laboratory where they were dried, sieved, and weighed. Organic matter was either physically removed or destroyed by ashing [*Campbell and Sidle*, 1985]. The mineral size fraction < 0.25 mm was discarded because it probably represented suspended sediment attached to organic debris. Thus fine bed load sediment, generally noted as < 1 mm, actually refers to the 0.25- to 1.0-mm size fraction. The largest size fraction analyzed was > 32 mm, although in this paper > 8 mm material is referred to as coarse material.

Stream stage was measured at the lower bridge when bed load was sampled. A stage-discharge relationship was developed for a cross section near the lower bridge. In 1982, a stage recorder was installed. The "threshold flow" for bed load movement was estimated at 0.25 $m^3\ s^{-1}$; corresponding critical shear stress was 11.3 N m^{-2} based on estimates of average depth of flow and water surface slope. During storms when actual bed load sampling began (on the rising limb) or ceased (on the falling limb) above this threshold, flow was extrapolated linearly to 0.25 $m^3\ s^{-1}$; bed load transport during this interval was estimated based on the first or last bed load sample collected. From 1983 to 1985, stream stage was measured concurrently at both bridges for each bed load sample. Water surface slope was calculated from these data.

Determination of seasonal trends in bed load transport involved multiple regression analysis. Total, fine (< 1 mm), and coarse (> 8 mm) mineral bed load transport were each evaluated in terms of three functional independent variables: (1) stream energy (unit stream power, average velocity, or discharge); (2) antecedent storm history (instantaneous discharge of the previous flood peak, volume of flow in the previous storm, or number of days between current storm and previous storm); and (3) seasonal influences (cumulative seasonal flow above the transport threshold weighted by instantaneous flow). The best independent variable for each of the three functional groups was determined using an R^2 criterion together with residual analysis and was included as a candidate in a forward, stepwise regression model (selection criteria $P \leq 0.05$).

A two-step procedure was followed to determine whether significant differences existed for the relation of bed load transport to stream flow between rising and falling limbs of storm hydrographs. First, an F test was used to test the equality of variances between rising and falling limb data for each storm [*Snedecor and Cochran*, 1967]. If the equality of variance assumption was met ($P \leq 0.01$), the difference between regression lines describing the rising and falling limbs for a given storm was then tested [*Neter and Wasserman*, 1974]. For regression lines to be considered different ($P \leq 0.05$), they must differ with respect to either the intercept, the slope, or to both. To be considered the same, the two lines must have equal intercept and slope coefficients ($P \leq 0.05$). Fundamental to these comparisons is that the random error terms in the regression models are uncorrelated random variables during a given storm. Storms with less than four bed load samples collected during either the rising or falling limb of the hydrograph were disregarded. Major multiple peaks within a storm sequence were analyzed separately if enough samples were collected.

Cross sections in the riffles and pool were surveyed throughout the study. Surveys were conducted after each bed load storm if possible and periodically throughout the rest of the year.

RESULTS AND DISCUSSION

Empirical Relations

During the period from September 1980 to December 1985, 33 storm flows capable of transporting bed load sediment were sampled. Maximum instantaneous bed load transport during the six annual flood peaks ranged from 2,340 to 8,270 kg h^{-1} at the upper bridge and 1,540 to 16,270 kg h^{-1} at the lower bridge. Peak discharges for these six events ranged from 1.50 to 2.30 m^3 s^{-1}; corresponding dimensionless discharge [*Griffiths*, 1980] ranged from 2840 to 4360. Total transport during each of the three largest storm flows was >9000 kg (Table 1), with the greatest total transport occurring at the upper riffle during the October 3, 1985, event (21,957 kg).

Rating curves based on 1112 individual bed load samples collected during the 6-year period were fitted to the power function

$$B = aQ^b \tag{1}$$

where B is the bed load discharge of any designated size fraction (kg h^{-1}); Q is streamflow (m^3 s^{-1}); and a and b are regression coefficients. Initially, the model was transformed by logarithms and then fitted by linear regression. Rating curves were developed for three size fractions of mineral bed load: total (B_{tot}), fines (B_{fin}) less than 1 mm, and coarse (B_c) greater than 8 mm. Empirical relationships developed with all of the bed load data explained 58, 59, and 52% of the variability in total, fine, and coarse material transport, respectively (Table 2). For each of these three size fractions, separate rating curves were developed for upper and lower bridge sampling sites and for rising and falling limbs of storm hydrographs (Table 2). Bed load transport for all size fractions was significantly greater and less variable at the upper sampling site than at the lower site. This difference can partially be attributed to the release of sediment stored behind large organic debris upstream of the sampling reach and the deposition of this sediment in the intervening pool (see section on channel morphology, Figure 13). Bed load transport during the rising limb of storm hydrographs was significantly greater and less variable than transport during the falling limb. The relation of these spatial and temporal variabilities to fluvial transport processes will be examined in this paper.

Multiyear Trends

During the 6-year period, a net increase of almost 19,000 kg of mineral bed load material stored in the study reach was calculated based on transport measurements taken during sampled storms. An interesting temporal trend in net storage was observed during larger storms (i.e., those with peak flows > 0.9 m^3 s^{-1}). Starting with the largest storm on October 1, 1980 ($T_r \sim 5$ years), a net export of mineral material was noted up through almost the end of the 1981 storm season. During the 1982 storm season, small accumulations of mineral bed load material occurred during all storms. Accumulation rates increased dramatically in the period from 1983 to 1985, with one major exception: the October 18, 1983, storm. The total measured aggradation during the 33 bed load storms represented an average filling of 13 cm within the reach, about twice the level of filling suggested by analyzing cross section changes during the 6-year period. Although some displacement of mineral sediment occurs during the winter, spring, and summer that is not accounted for in the net transport budget, an overlying periodicity may be associated with bed load transport and, in Bambi Creek, a peak flow of about a 5-year recurrence interval or greater may be necessary to initiate another scouring cycle.

A different frequency is associated with scouring and filling of fine sediment (<1 mm) compared to coarse material (> 8 mm). Net transport of fines within the reach was highly variable (Figure 3). Within each storm season were distinct scouring and filling events for fine material. Three of the annual peak flows generated accumulations of fines within the reach, and the other three annual floods scoured fines from the reach. The transport of fines into and out of the reach appeared to be related to changing hydraulic conditions within the reach and a variable supply of sediment from the streambed and from upstream storage areas.

During the entire 6-year period, only three of the sampled stormflows scoured significant quantities of coarse bed load material from the reach (Figure 3). These three storms included the largest event of the period (October 1, 1980) and the first two storms of 1981. The proximity of these scouring events to the largest storm of record suggests that scouring cycles for coarse material are triggered by flood events with return intervals ≥ 5 years. Any additions or movement of large organic debris upstream of the study reach could drastically affect the timing of scour and fill cycles for coarse material.

Net changes in storage of fine and coarse bed load material were quite different during several storms. In particular, the major events of October 17, 1981, October 11, 1982, October 18, 1983, and October 6, 1984, all transported significant quantities of coarse sediment into the reach (195–1622 kg) and scoured fine sediment (276–1380 kg) from the reach (Figure 3). Bed load mobility is indeed different for different grain sizes during some events. The role of large organic debris in storing, sorting, and ultimately releasing different sizes of sediment would influence this differential mobility.

Seasonal Trends

Bed load transport was quantitatively evaluated by regression analysis using three functional variables: stream energy, antecedent storm history, and seasonal influences. Based on previous analyses [*Sidle*, 1986a], some indicator of stream energy was assumed to be the most important predictor of bed load transport; thus these regression analyses were performed to examine the additional influences of storm history and seasonal effects.

Three variables were tested as indicators of stream energy: discharge, average velocity, and unit stream power. Because accurate water surface slope was available only after 1982, the three candidate predictor variables of bed load transport were only compared for 1983 and later years. Both discharge and average velocity were clearly superior predictors of bed load transport compared to unit stream

TABLE 1. Bed Load Transport During 33 Autumn Storms From 1980 Through 1985, Bambi Creek, Chichagof Island, Alaska

		Upper Bridge			Lower Bridge			
Storm Date	Q_p, $m^3 s^{-1}$	Total Mineral, kg	Fine (<1 mm), kg	Coarse (<8 mm), kg	Total Mineral, kg	Fine (<1 mm), kg	Coarse (>8 mm), kg	Net Mineral Transport, kg
Sept. 30, 1980	0.50	124	27	49	61	11	39	63
Oct. 1, 1980	2.30	9,476	2,119	4,046	12,793	3,389	4,275	−3,318
Oct. 2, 1980	0.63	472	121	67	194	71	10	278
Oct. 8, 1980	0.68	545	142	194	527	157	89	19
Oct. 16, 1980	0.90	676	213	148	324	165	81	352
Sept. 6, 1981	0.94	2,118	642	543	5,816	2,042	1,090	−3,698
Sept. 7, 1981	1.09	817	345	187	1,518	233	293	−701
Sept. 10, 1981	0.82	964	336	247	1,001	357	153	−37
Sept. 14, 1981	0.53	332	158	47	169	89	18	163
Oct. 17, 1981	1.78	9,822	2,096	3,220	10,724	3,476	1,598	−902
Nov. 4, 1981	1.36	7,830	2,442	1,124	8,486	1,805	846	−656
Nov. 9, 1981	0.79	591	274	57	140	74	16	451
Sept. 30, 1982	0.79	886	299	259	443	177	95	443
Oct. 5, 1982	0.97	1,362	446	239	1,139	395	192	223
Oct. 6, 1982	0.66	502	125	62	137	67	18	365
Oct. 11, 1982	1.50	3,735	1,158	1,042	3,547	1,434	730	188
Oct. 12, 1982	1.33	1,146	259	489	653	168	93	493
Oct. 25, 1982	0.55	149	63	47	37	29	0	112
Oct. 30, 1982	1.09	1,739	572	392	1,210	475	200	529
Nov. 2, 1982	0.73	1,022	334	297	644	276	76	378
Nov. 3, 1982	0.51	149	56	12	133	60	25	16
Nov. 9, 1982	1.49	3,900	121	1,474	3,188	1,110	682	712
Oct. 18, 1983	1.06	3,199	856	836	4,013	1,357	641	−814
Oct. 24, 1983	1.83	9,390	2,323	2,943	6,942	1,801	2,183	2,448
Oct. 27, 1983	1.56	14,999	4,246	3,153	6,881	2,200	1,230	8,118
Oct. 6, 1984	1.39	12,635	3,462	3,600	10,984	3,984	2,499	1,651
Oct. 10, 1984	0.53	372	104	143	195	85	33	177
Oct. 24, 1984	1.18	5,955	1,737	1,177	4,202	1,421	775	1,753
Nov. 16, 1984	0.97	4,492	1,373	993	3,118	1,007	428	1,374
Nov. 21, 1984	1.56	7,779	2,434	2,189	5,727	2,077	1,541	2,052
Nov. 22, 1984	0.74	1,236	459	301	1,514	556	226	−278
Oct. 3, 1985	1.95	21,957	6,530	5,580	14,900	3,657	5,107	7,056
Nov. 13, 1985	0.47	128	58	18	390	128	22	−262

Q_p, peak storm flow.

power. They explained 58–72% of the variability in total bed load transport during individual years at the upstream sampling site. Because bottom velocities were not measured, the logarithm of stream discharge was chosen as the best indicator of stream energy in the empirical relationship. Change in storm flow with respect to time (dQ/dt) was not significantly related to bed load transport.

Three variables were tested as indicators of antecedent storm history: instantaneous discharge of the previous flood peak (Q_{prev}), volume of flow in the previous storm (ΣQ_{prev}), and number of days between the current storm and the previous storm. Logarithm of Q_{prev} was more highly correlated with various size fractions of bed load transport than the other two variables. This appears justifiable because peak flow of the previous storm would relate best to the proportion of the channel or floodplain inundated by the preceding event. Thus availability of sediment stored in these upper channel or floodplain reaches should be influenced by Q_{prev}.

Seasonal influences were evaluated for storms sampled during the period from September to early December. Cumulative flow (ΣQ) for all discharges exceeding the "critical threshold" for bed load entrainment (about 0.25 $m^3 s^{-1}$ for Bambi Creek) was assumed to be a good indicator of seasonal trends in bed load transport. Because the influence of ΣQ on the relation of bed load transport to discharge was of more interest than simply the influence of ΣQ on bed load transport, the cumulative flow variable selected for the regression model was weighted by instantaneous discharge: log ($\Sigma Q \cdot Q$).

The following model was used to evaluate the importance of storm history and seasonal influences on bed load transport:

$$B = aQ^b Q^c_{prev} (\Sigma Q \cdot Q)^d \qquad (2)$$

where

TABLE 2. Empirical Bed Load Relations for Bambi Creek, Chichagof Island, Alaska, Based on the Model $B = aQ^b$

Portion of 1980–1986 Bed Load Data	Bed Load Size Fraction		
	Total	Fine (<1 mm)	Coarse (>8 mm)
All data	$B_{tot} = 396\ Q^{2.11}$ ($r^2 = 0.58$)	$B_{fin} = 125\ Q^{2.79}$ ($r^2 = 0.59$)	$B_c = 79\ Q^{2.79}$ ($r^2 = 0.52$)
Upper bridge	$B_{tot} = 470\ Q^{2.54}$ ($r^2 = 0.69$)	$B_{fin} = 139\ Q^{2.26}$ ($r^2 = 0.67$)	$B_c = 100\ Q^{2.95}$ ($r^2 = 0.60$)
Lower bridge	$B_{tot} = 334\ Q^{2.20}$ ($r^2 = 0.50$)	$B_{fin} = 112\ Q^{1.96}$ ($r^2 = 0.51$)	$B_c = 61\ Q^{2.46}$ ($r^2 = 0.46$)
Rising limb	$B_{tot} = 388\ Q^{2.81}$ ($r^2 = 0.73$)	$B_{fin} = 126\ Q^{2.39}$ ($r^2 = 0.70$)	$B_c = 76\ Q^{3.45}$ ($r^2 = 0.63$)
Falling limb	$B_{tot} = 381\ Q^{1.98}$ ($r^2 = 0.44$)	$B_{fin} = 118\ Q^{1.85}$ ($r^2 = 0.47$)	$B_c = 74\ Q^{2.23}$ ($r^2 = 0.40$)

Coefficient of determination given in parentheses.

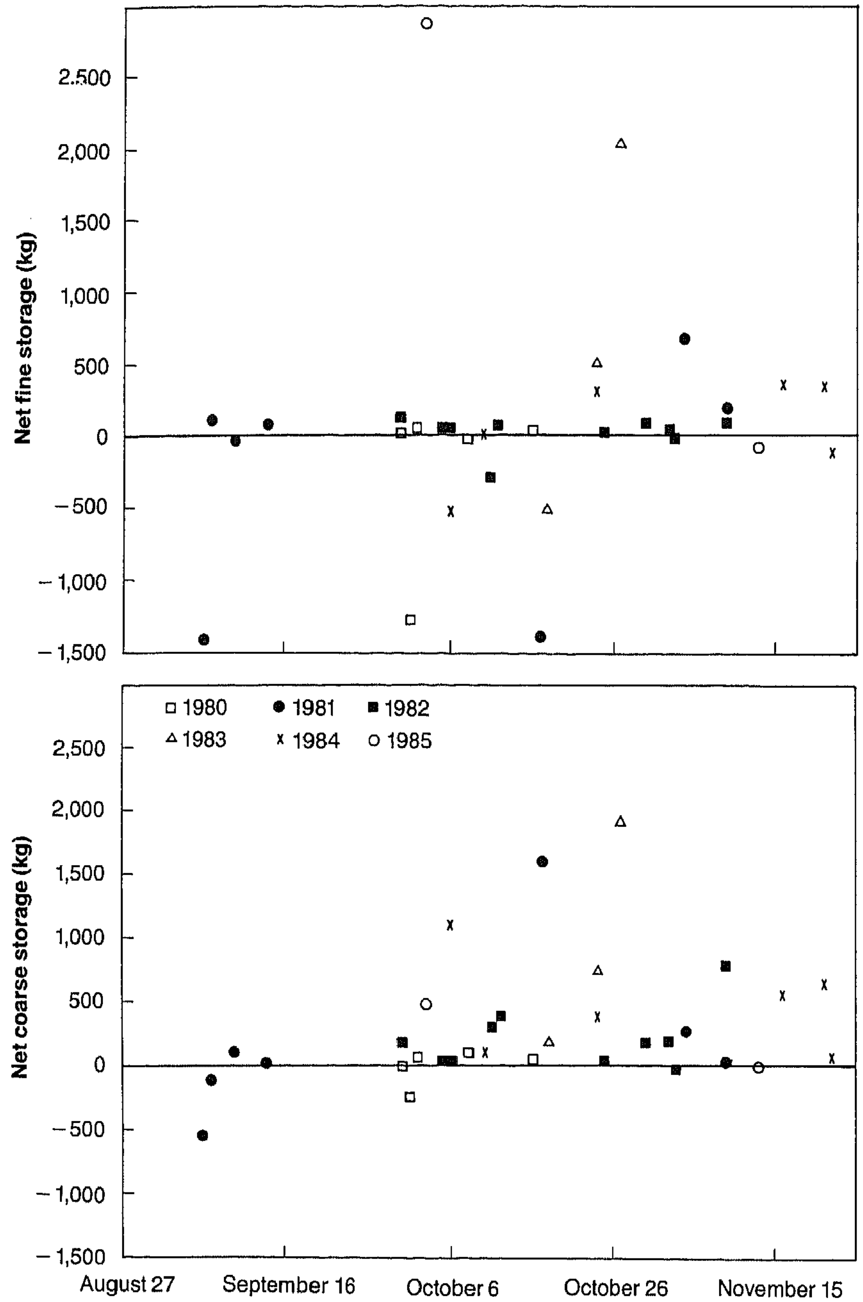

Fig. 3. Net transport of fine (< 1 mm) and coarse (> 8 mm) bed load sediment within the sampling reach from 1980 to 1985.

B bed load transport rate for any designated size fraction (kg h^{-1});
Q discharge (m^3 s^{-1});
Q_{prev} peak discharge of previous storm (m^3 s^{-1});
ΣQ cumulative flow above the threshold for bed load transport, 0.25 m^3 s^{-1} (m^3);
a,b,c,d coefficients based on regression analyses.

Table 3 summarizes regression coefficients for the three independent variables in the model; years were analyzed separately and collectively for both bridges. Coefficients for independent variables are included only if variables were significant at the $P \leq 0.05$ level. In all cases, discharge and the intercept term (coefficients a and b) were highly significant. Discharge was the only independent variable considered in the analysis of 1980 bed load transport because several storms were not sampled during that season.

Although seasonal trends in bed load transport are difficult to quantify for the 1980 storm season because of incomplete data, the influence of the October 1 storm (the largest of the 6-year period) is apparent. Even with a net export of more than 3,300 kg of bed load sediment from the reach during the October 1 event, the pool underwent extensive scouring during later fall storms (Figure 4). Much of this exported material was presumed to be fine sediment made available during the October 1 event either through extensive breakup of the armor layer of the streambed or through release of sediment stored behind large organic debris. For all storms sampled in the 1980 season (a total of 82 bed load samples), discharge alone explained a higher proportion of the variability in all size fractions of bed load transport (74–88%) than for any of the other years (Table 3). Discharge at adjacent Trap Bay Creek (a third-order drainage) explained 69% of the variability in total bed load transport during 1980 [*Estep and Beschta*, 1985].

During 1981, a seasonal decrease occurred in all sizes of bed load sediment at the lower bridge as evidenced by the significant negative coefficients (d) of the log ($\Sigma Q \cdot Q$) terms in the regression models (Table 3). Slopes of cumulative bed load transport versus cumulative flow were steepest during the first storm of the season (peak flow = 0.94 m^3 s^{-1}), indicating that sediment deposited in the pool over the preceding winter through summer became available for transport during this early storm (Figure 5). Before this first autumn storm flow (September 6), cross sections 2 and 3 in the pool had filled extensively, with most of the deposition occurring during the winter and spring (Figure 6). Because of the timing of the second and slightly larger storm (September 7), the cross sections were not remeasured between storms; however, net storage of all size fractions within the reach was negative during the September 6 event, which indicates an export of material that had accumulated in the reach during winter and spring. Neither seasonal trends nor antecedent storms significantly affected bed load transport at the upper riffle.

Transport of total and fine bed load sediment at the upper riffle during the 1982 storm season was significantly related to storm history (Table 3). During the fourth and largest storm of the 1982 season (peak flow = 1.5 m^3 s^{-1}), $dB_{tot}/d\Sigma Q$, and $dB_{fin}/d\Sigma Q$ were the highest. Double mass plots of cumulative total mineral transport versus ΣQ and cumulative fines versus ΣQ exhibited a decrease in slope after the large October 11 storm ($\Sigma Q \sim 52{,}000$ m^3) (Figure 7). In addition to the influence of antecedent storms on total bed load transport at the upper riffle, a seasonal effect was significant. Less total sediment was transported late in the 1982 season than earlier in the season at similar flows. The influences of antecedent storms and seasonal effects implies that some of the readily available sediment stored behind large organic debris upstream of the reach had been depleted during the storm season. A net increase occurred in storage of bed load material in the reach for all bed load storms (Table 1), which suggests that sediment stored behind large woody debris upstream of the upper bridge was released throughout the 1982 season.

Bed load transport at the upper bridge, especially the fine fraction, was highly influenced by the annual peak flow (1.83 m^3 s^{-1}) on October 24, 1983. Before the peak of the October 24 storm, bed load transport rates at the upper and lower bridges were similar; however, after the peak and throughout the final storm of the season, bed load transport at the upper bridge was more than twice that at the lower riffle (Table 1). One may speculate that this surge in fine sediment transport was caused by movement of woody debris upstream of the site during the annual peak flow. The double mass plot of cumulative fines versus ΣQ at the upper bridge indicates increased fine sediment from upstream sources near the timing of peak discharge for the October 27 storm (Figure 8). Because only three bed load storms occurred during 1983, distinguishing between the effects of antecedent storms and seasonal influences is difficult. A signifiant negative coefficient (d) was observed for the seasonal sorting term (log [$\Sigma Q \cdot Q$]) in the regression models for both total and coarse bed load transport at the lower bridge (Table 3), which is reflected in the gradual decrease in transport of these size fractions over the season (Figure 9). Fine bed load transport at the lower bridge was significantly influenced by log Q_{prev} (Table 3); however, the influence was mainly due to the first storm, and the overall seasonal pattern of fine material transport was similar to the coarser bed load fractions (Figure 9). The high levels of unexplained variability in the 1983 bed load equations developed for the lower bridge (i.e., R^2 ranged from 0.28 to 0.34), implied a supply-limited situation in this lower reach. This situation was corrected during the next season when fine sediment, transported past the upper bridge in late 1983, moved downstream.

TABLE 3. Regression Coefficients for the Bed Load Transport Model $B = aQ^bQ^c{}_{prev}(\Sigma Q - Q)^d$

Year	Bridge	Coefficients				
		a	b	c	d	r^2
		Total Mineral Transport				
1980	upper	282	2.418			0.88
1980	lower	177	3.106			0.88
1981	upper	354	3.026			0.70
1981	lower	51,300	3.670		−0.436	0.77
1982	upper	650	2.770	−0.255	−0.083	0.83
1982	lower	191	2.716			0.71
1983	upper	484	2.267			0.69
1983	lower	13,240	1.703		−0.358	0.28
1984	upper	798	2.461	0.356		0.65
1984	lower	566	2.255	0.370		0.52
1985	upper	8,147	1.506	−0.911	−0.281	0.83
1985	lower	891	1.421			0.38
All years	upper	469	2.562			0.69
All years	lower	292	2.222	−0.332		0.52
		Fine (<1 mm) Transport				
1980	upper	70	2.195			0.86
1980	lower	61	2.896			0.90
1981	upper	109	2.246			0.65
1981	lower	15,240	3.119		−0.431	0.66
1982	upper	78	2.262	−0.433		0.82
1982	lower	73	2.311			0.64
1983	upper	138	1.760	0.248		0.69
1983	lower	97	1.411	−0.495		0.34
1984	upper	239	2.292	0.401		0.67
1984	lower	196	2.110	0.433		0.59
1985	upper	220	1.513	−0.616		0.87
1985	lower	282	1.295			0.55
All years	upper	139	2.279			0.67
All years	lower	98	1.987	−0.333		0.54
		Coarse (>8 mm) Transport				
1980	upper	67	3.075			0.74
1980	lower	43	3.295			0.79
1981	upper	62	3.803			0.58
1981	lower	2,667	3.565		−0.349	0.59
1982	upper	61	3.365			0.63
1982	lower	29	3.452			0.57
1983	upper	113	2.671			0.68
1983	lower	2,649	2.293		−0.363	0.32
1984	upper	172	2.645	0.303		0.50
1984	lower	87	2.645			0.39
1985	upper	17,458	1.523	−1.314	−0.566	0.63
1985	lower	185	2.165			0.41
All years	upper	94	2.980	−0.146		0.60
All years	lower	51	2.693	−0.433		0.48

Only coefficients significant at the $P < 0.05$ level are given.

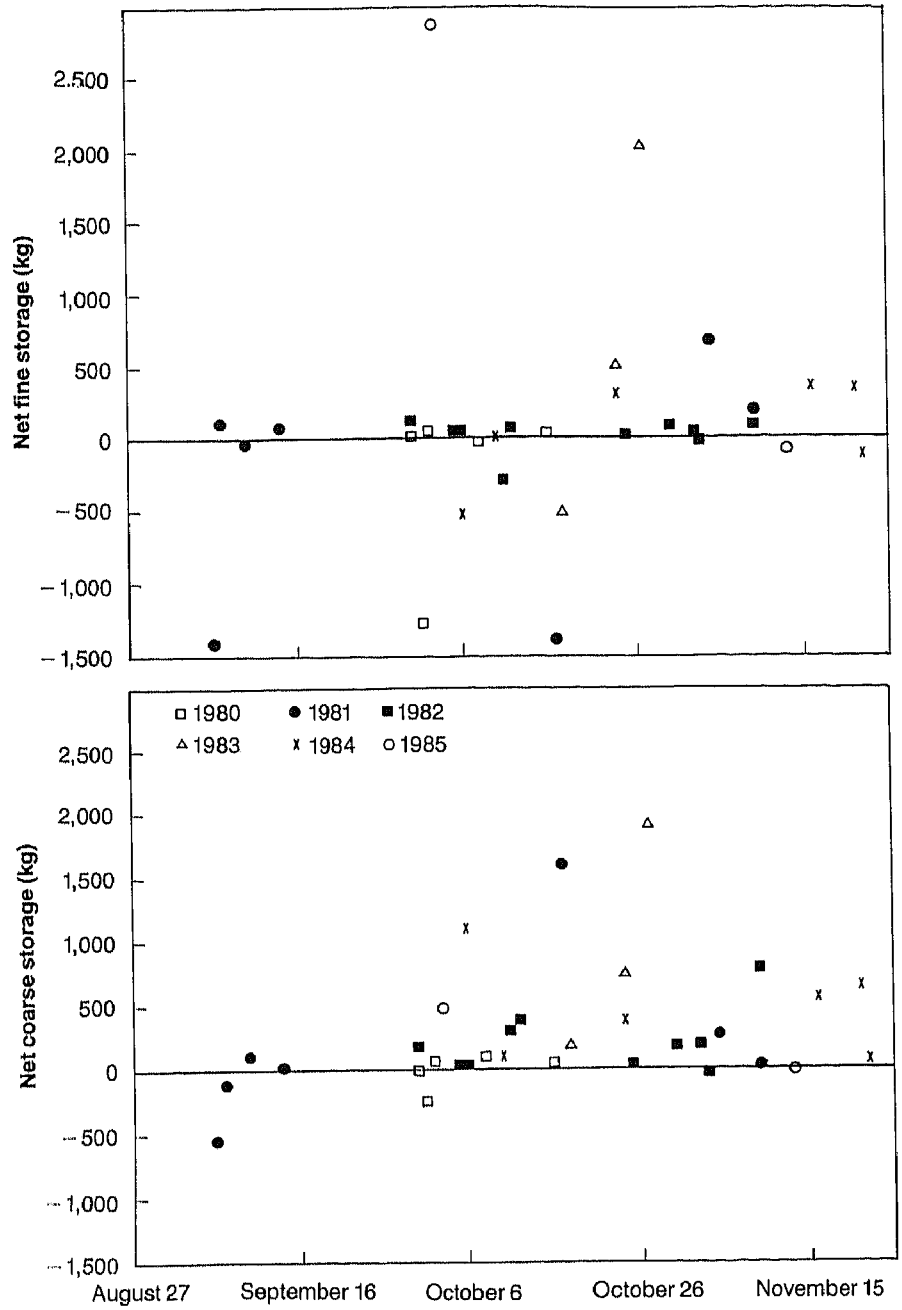

Fig. 3. Net transport of fine (< 1 mm) and coarse (> 8 mm) bed load sediment within the sampling reach from 1980 to 1985.

B bed load transport rate for any designated size fraction (kg h^{-1});
Q discharge (m^3 s^{-1});
Q_{prev} peak discharge of previous storm (m^3 s^{-1});
ΣQ cumulative flow above the threshold for bed load transport, 0.25 m^3 s^{-1} (m^3);
a,b,c,d coefficients based on regression analyses.

Table 3 summarizes regression coefficients for the three independent variables in the model; years were analyzed separately and collectively for both bridges. Coefficients for independent variables are included only if variables were significant at the $P \leq 0.05$ level. In all cases, discharge and the intercept term (coefficients a and b) were highly significant. Discharge was the only independent variable considered in the analysis of 1980 bed load transport because several storms were not sampled during that season.

Although seasonal trends in bed load transport are difficult to quantify for the 1980 storm season because of incomplete data, the influence of the October 1 storm (the largest of the 6-year period) is apparent. Even with a net export of more than 3,300 kg of bed load sediment from the reach during the October 1 event, the pool underwent extensive scouring during later fall storms (Figure 4). Much of this exported material was presumed to be fine sediment made available during the October 1 event either through extensive breakup of the armor layer of the streambed or through release of sediment stored behind large organic debris. For all storms

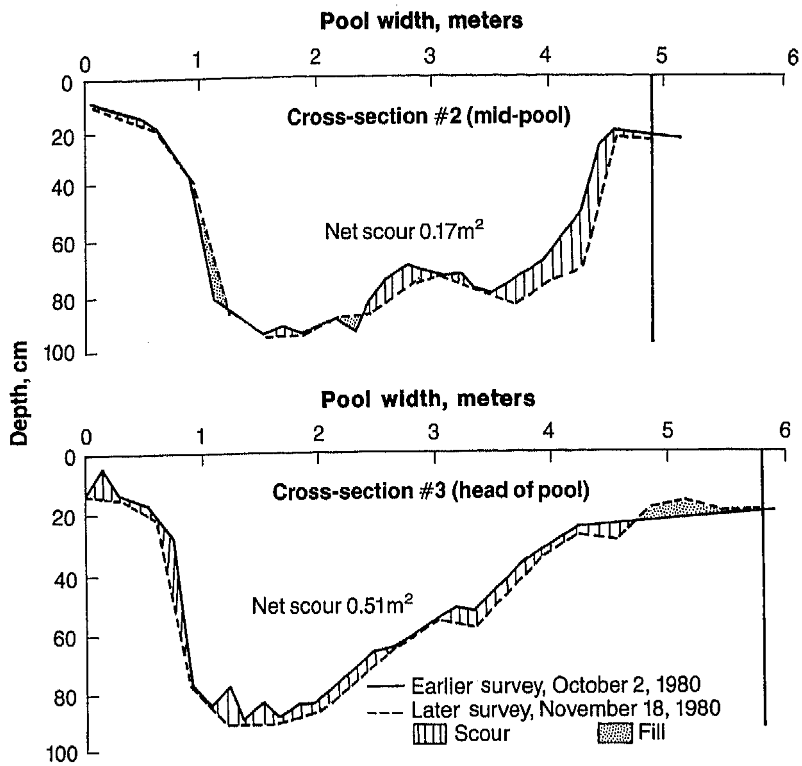

Fig. 4. Scouring of the pool (cross sections 2 and 3) after the large October 1, 1980, storm flow ($T_r \sim 5$ year).

During the 1984 storm season, all size fractions of bed load passing over the upper sampling site were significantly affected by antecedent storm magnitude (Table 3). Larger antecedent storms tended to generate greater bed load transport, probably related to the extent of disruption of the streambed. Movement of both total and fine bed load sediment at the lower riffle was similarly influenced by antecedent storms; movement of coarse bed load was not affected (Table 3). Interestingly, coarse and fine material moved over the upstream riffle at similar rates throughout the 1984 season; however, about 24% of the coarse material was deposited within the reach (Figure 10). The effects of antecedent storms overshadowed any influences of seasonal trends in bed load transport at either sampling site during 1984.

Because only two bed load transporting storms occurred in 1985 (only one of which was a major event), sorting out any differences between seasonal influences and the effect of antecedent storms is difficult. Both of these effects were significant for most size fractions of bed load at the upper riffle (Table 3). At this upper site, bed load transport declined during similar flows over the coarse of the two storms. This decline indicates a supply-limited situation upstream of the reach. At the lower bridge, neither of the variables sensitive

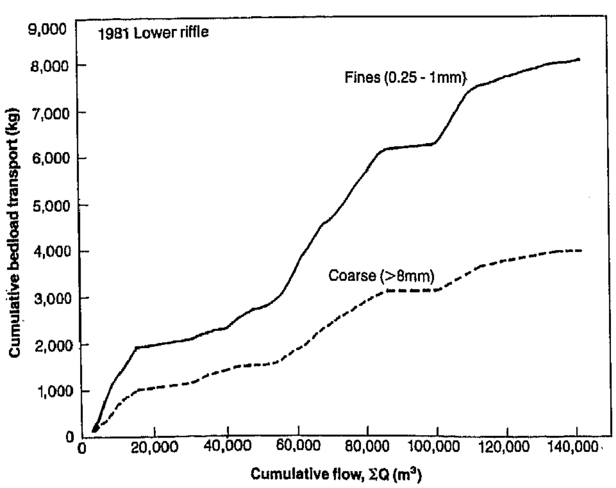

Fig. 5. Double mass plot of cumulative fine (< 1 mm) and coarse (> 8 mm) bed load transport at the lower riffle versus cumulative flow (ΣQ) during the 1981 storm season.

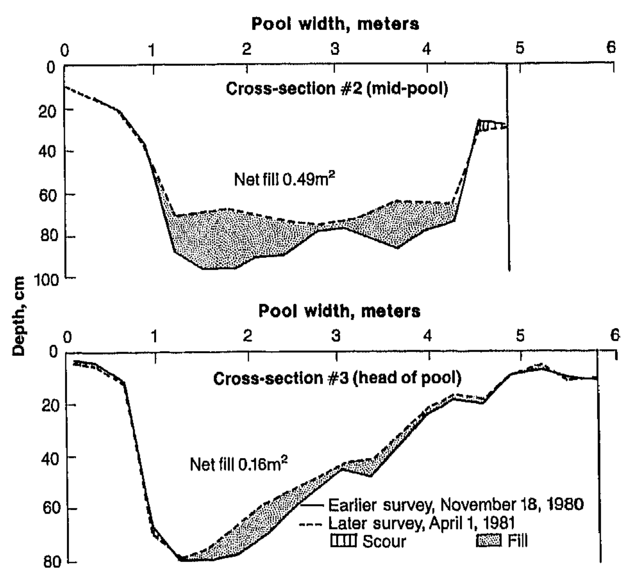

Fig. 6. Deposition in the pool (cross sections 2 and 3) during winter and spring of 1980 and 1981.

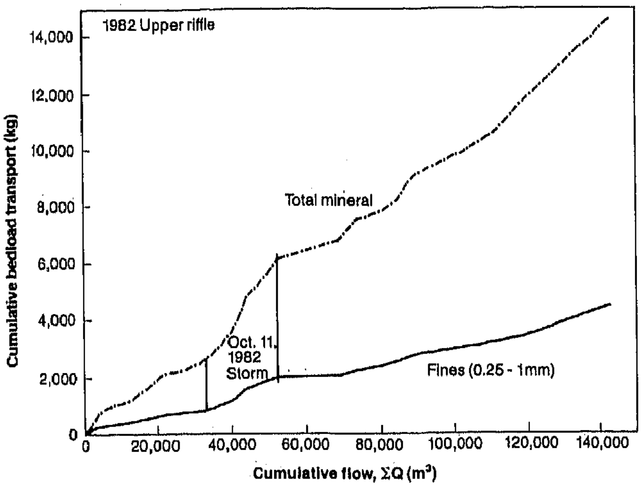

Fig. 7. Double mass plot of cumulative fine (< 1 mm) and total bed load transport at the upper riffle versus cumulative flow (ΣQ) during the 1982 storm season.

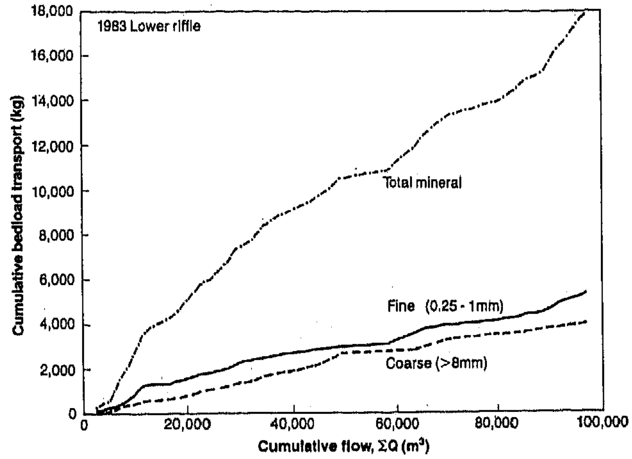

Fig. 9. Double mass plot of cumulative fine (< 1 mm), coarse (> 8 mm), and total bed load transport at the lower riffle versus cumulative flow (ΣQ) during the 1983 storm season.

to temporal trends were significant. During the two previous years, with slightly smaller peak events, larger antecedent flows tended to increase fine sediment transport over the upper riffle. During 1985, the reverse occurred. This reversal in trends could be related to a gradual depletion of fines stored behind large organic debris upstream of the reach. Inputs of woody debris just upstream of the sampling sites during a late November 1984 windstorm provided additional sediment storage sites and thus could have influenced this decline in bed load transport during the 1985 season.

Within-Storm Trends

Within-storm variability in bed load transport, independent of discharge, can be caused by the timing of extensive armor breakup, by sudden release of sediment stored behind large organic debris, by increased storage because of shifting or inputs of organic debris, and by depletion of available sediment (especially fines) from the channel and the upper portion of the floodplain. *Sidle and Campbell* [1985] note significantly higher concentrations of suspended sediment during rising limbs of storm hydrographs than for similar flows on falling limbs, which accounted for hysteresis loops in plots of total suspended solids versus stream flow in Bambi Creek. These within-storm patterns of sediment movement were not as common or pronounced for bed load movement as compared to suspended sediment, largely because of the more complex nature of bed load release and transport.

Comparisons of bed load transport rates between rising and falling limbs of 21 storm hydrographs were made for fine (< 1 mm), coarse (> 8 mm), and total mineral fractions. Statistical comparisons were made by testing for differences in slope or intercept of plots of log B versus log Q for rising and falling limbs of each storm flow. Storms with less than four bed load samples collected on either the rising or falling limbs of the hydrograph were not analyzed. Major multiple peaks within a storm sequence were analyzed separately if enough samples were collected.

Significant differences between rising and falling limb plots of log B versus log Q were found for at least one of the size fractions at one or both sampling sites during more than half of the storms. Although most of these within-storm differences showed higher levels of bed load transport on the rising limb of the storm hydrograph (Figure 11), several storms had greater bed load transport on the falling limb. Fine bed load material was more subject to differential transport over the storm hydrograph than was coarse material. Significant differences between rising and falling limb relationships for fines were noted for 7 and 10 out of the 21 storms at the upper and lower bridges, respectively. Significant differences in coarse bedload transport occurred in only two storms at the upper bridge and four storms at the lower bridge during the 6-year period. For two storms in a similar stream in coastal Oregon, *Milhous* [1973] found that the transport of fine sands (<1 mm) and particles >50 mm was higher on the rising limb than on the falling limb; the reverse was true for gravel (2–38 mm).

The most distinct hysteresis loops for coarse bed load transport occurred at the lower riffle during major peak flows (i.e., peak flows ≥ 1.4 $m^3\ s^{-1}$). Maximum coarse bed load transport occurred at discharges between 1.4 and 1.8 $m^3\ s^{-1}$ (just below bank full) during the three largest of these events, probably corresponding to the breakup of portions of streambed armor in the upstream riffle and intervening pool before the hydrograph peaks. In all four storms where

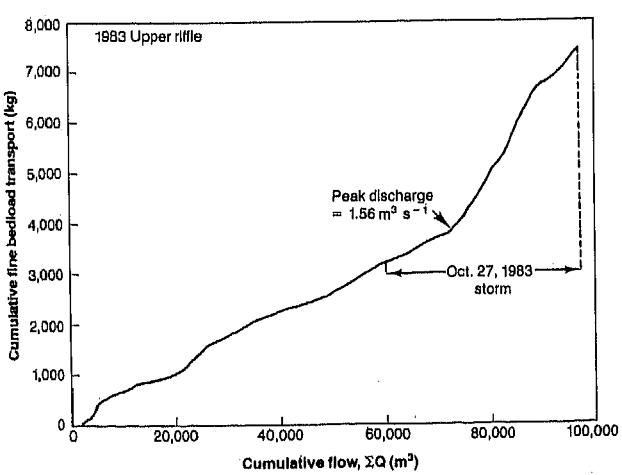

Fig. 8. Double mass plot of cumulative fine (< 1 mm) bed load transport at the upper riffle versus cumulative flow (ΣQ) during the 1983 storm season.

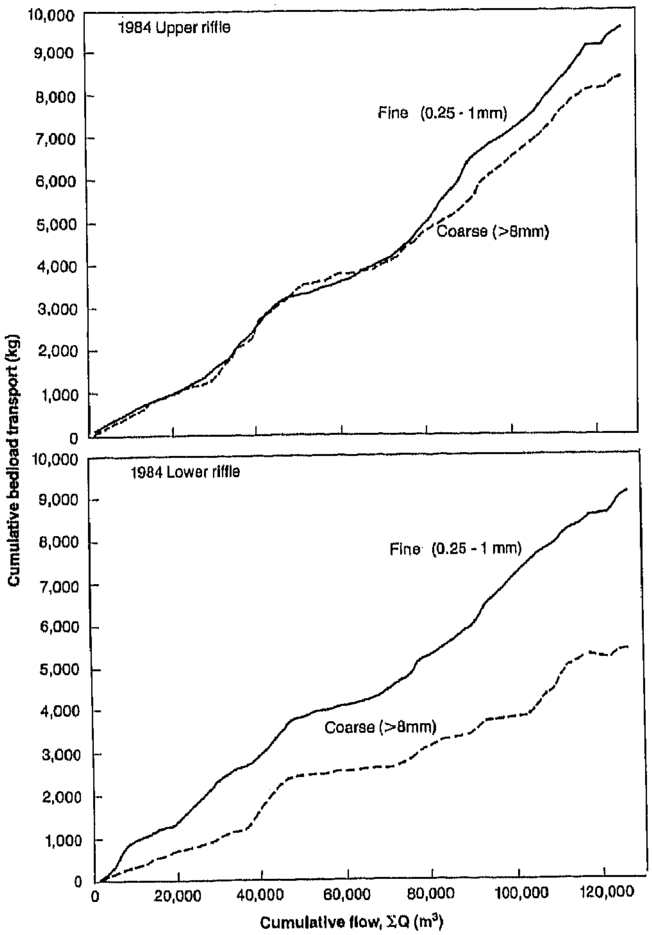

Fig. 10. Double mass plots of cumulative fine (< 1 mm) and coarse (> 8 mm) bed load transport at both riffles versus cumulative flow (ΣQ) during the 1984 storm season.

hysteresis effects were found for coarse bed load, a net accumulation of coarse material occurred in the reach, which indicates that streambed armor reformed during the recession limb of these storms.

The nonsteady nature of bedload transport was particularly noticeable during the last two storms of 1983 and the first storm of 1984. During the October 27, 1983, storm, less total and fine bed load was transported into the reach on the rising limb of the hydrograph than on the falling limb. Total and fine bed load transport out of the reach followed the opposite pattern: greater on the rising limb than on the falling limb. Similar temporal patterns of bed load transport within the other two storms as well as the large October 1, 1980, storm were noted, especially for fines. Sometimes the sequence of loading and unloading was reversed. Because of this nonsteady bed load transport, segregating rising and falling limbs of storm hydrographs in empirical bed load models is questionable, regardless of the size fraction.

Channel Morphology

Channel changes at cross section 2 in the middle of the pool were somewhat predictable in relation to peak flows during the years that were monitored. The greatest pool scour (up to 2,100 cm^2 in a given event) occurred during the largest storms; however, if two major storm flows (i.e., peak flows > 1.3 m^3 s^{-1}) occurred within a few days without the opportunity for some fine sediment deposition between storms, the second event typically scoured the pool only minimally and sometimes actually filled the pool. For example, the major storm of October 24, 1983, scoured the left side of cross section 2 as deep as 15 cm. Another major storm 3 days later slightly filled the entire width of the same cross section; however, a portion of the left bank was eroded (Figure 12). From 1980 to 1986, the midpool cross section aggraded as much as 20 cm (Figure 13). The left bank at cross section 2 eroded while sediment accumulated along the right bank during this 6-year period. Patterns of scour and fill near the head of the pool (cross section 3) were not as consistent. After the last autumn storm, cross section 3 underwent filling during winter and spring of most years; average depth of deposition during the winter of 1980–1981 was 5.4 cm. From 1980 to 1986, cross section 3 scoured on either side and filled in the middle.

Although scouring predominated at riffle cross sections during storm flows, temporal patterns of scour and fill were inconsistent. Cross sections at both riffles tended to scour during the winter and spring and then fill to some extent during summer. During the entire 6-year period, both the upper and, to a lesser extent, the lower riffle cross sections scoured along most of the channel width (Figure 13). The right stream bank at cross section 4 (upper riffle) also eroded.

SUMMARY

Bed load transport is an important component of the overall sediment budget for Bambi Creek. Based on estimates [*Sidle and Campbell*, 1985] of specific suspended sediment yield (20 tonnes km^{-2} yr^{-1}), average annual bed load transport represents 44% of the total sediment budget. More than 1100 bed load samples collected during 33 storms in a 6-year period were analyzed to determine both long- and short-term trends in bed load movement as well as spatial patterns of bed load movement within a riffle-pool-riffle sequence.

The transport of fine sediment is more frequent in Bambi Creek as compared to coarse sediment. Although research on larger or more uniform channels [*Andrews*, 1983; *Parker et al.*, 1982] has suggested that nearly all grain sizes are transported at about the same discharge, the results of this study indicate that scouring of coarse material is triggered

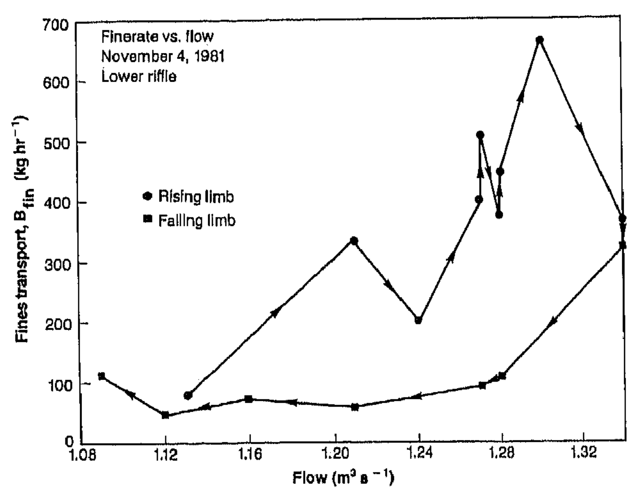

Fig. 11. Hysteresis loop in plot of fine (< 1 mm) bed load transport versus flow for November 4, 1981, storm, lower riffle, Bambi Creek.

only by very high storm flows ($T_r \geq 5$ yr). Results from *Andrews*' [1983] study are not directly comparable because he assumed the lower size limit of particles entrained at similar discharges to be 0.3 times the d_{50} of the subpavement, somewhat higher than the ratio for fines in Bambi Creek (0.11). In contrast to coarse material, fine bed load sediment in Bambi Creek often goes through several scour and fill sequences within a given storm season.

Both antecedent storm history and cumulative flow (above the threshold for bed load transport) are important factors influencing seasonal patterns of bed load transport. Often the effect of large antecedent storms dominates other measurable factors. The effect of antecedent storm history and cumulative flow on bed load transport can also change from year to year depending on sediment storage patterns upstream. These storage patterns are mainly influenced by large organic debris. Breakup of portions of debris jams can release large quantities of sediment, while additions of debris to the channel provide storage sites. The woody debris jams upstream of the bed load sampling site at Bambi Creek undoubtedly play an important role in the long-term dynamics of bed movement through the study reach. Wind throw that occurred in the riparian zone in late November 1984 appears to have influenced bed load transport in 1985. Another factor influencing seasonal trends in bed load movement may be inputs or accumulations of organic detritus which would increase the drag applied to the streambed [*Milhous*, 1973]. While *Milhous* [1973] noted increased bed load transport during the first major autumn storm flow in a coastal Oregon stream (attributed to earlier detrital inputs), storm flows in coastal Alaska generally occur at similar times as peak detrital inputs [*Sidle*, 1986b], thus the temporal influence of detritus in Alaskan streams would be less predictable.

Patterns of bed load movement within storms were inconsistent. Although in many storms higher levels of bed load (especially fines) were transported on the rising limb of the hydrograph than on the falling limb, the opposite pattern also

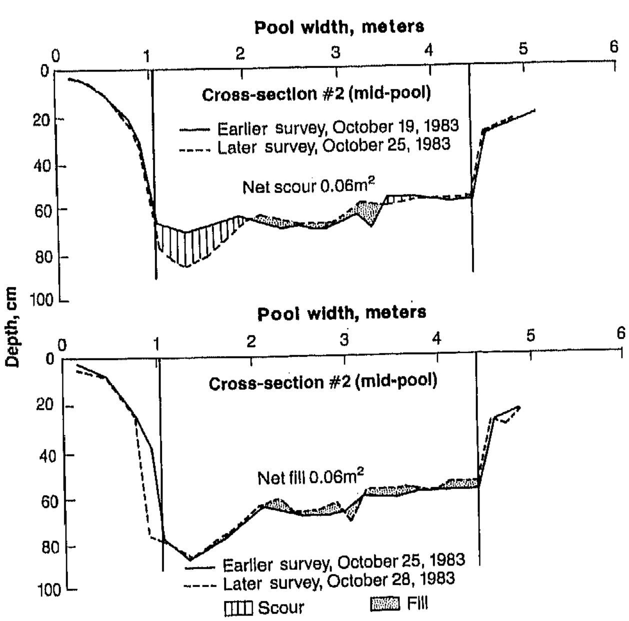

Fig. 12. Influence of two large storm flows within a few days on pool morphology. Cross section 2 scoured during the October 24, 1983, event and filled during the October 27, 1983, event.

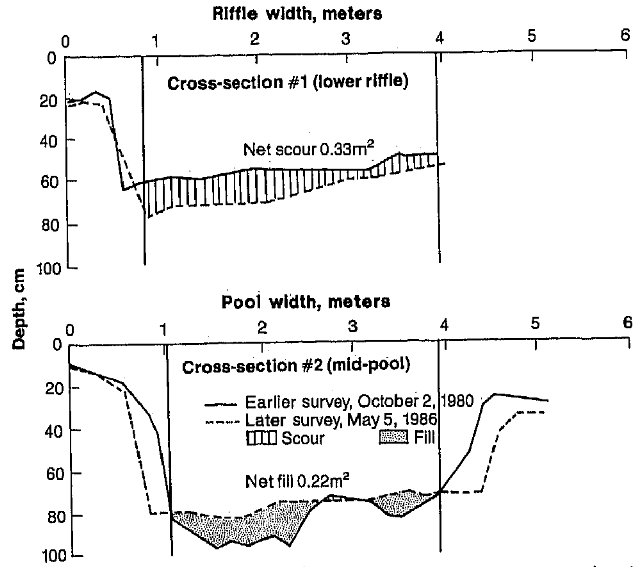

Fig. 13. Channel changes in the downstream riffle (cross section 1) and pool (cross section 2) during the study period (1980–1986).

occurred. These inconsistencies are attributed to the nonsteady storage and release of sediment during sporadic armor formation and breakup and to the additional complications associated with the storage and release of sediment around large organic debris upstream. Because of the unpredictable nature of within-storm and seasonal transport rates and the longer term trends associated with various grain sizes, improving simple bed load rating equations (i.e., equation (1)) which are based solely on stream flow for forest streams would be difficult. These rating equations explained about 58% of the variability in bed load transport at Bambi Creek over the 6-year period.

With specific regard to fish habitat, results from this study suggest that large storms are important in flushing fine sediment from streambed gravels. During some of these storm flows, however, scour may occur in portions of the channel to depths that would remove fish eggs. Alternatively, excessive deposition experienced during certain storm sequences may prevent successful emergence of fry from streambed gravels.

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