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Sediment Budgets and Routing in Forested Drainage Basins

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Sediment Transport and Channel Changes in an Aggrading Stream in the Puget Lowland, Washington

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ABSTRACT

Recent land-use changes increased sediment yield in a fourth-order stream in western Washington from 22 t/km² per year to 185 t/km² per year. In response, channel width increased and depth decreased, but channel gradient and mean flow velocity remained about constant. As a result of channel changes, sediment transport rates increased from 500 t/year to 4200 t/year. Active sediment constitutes 5 percent of stored sediment, and much sediment will be flushed from the system in about 20 to 40 years.

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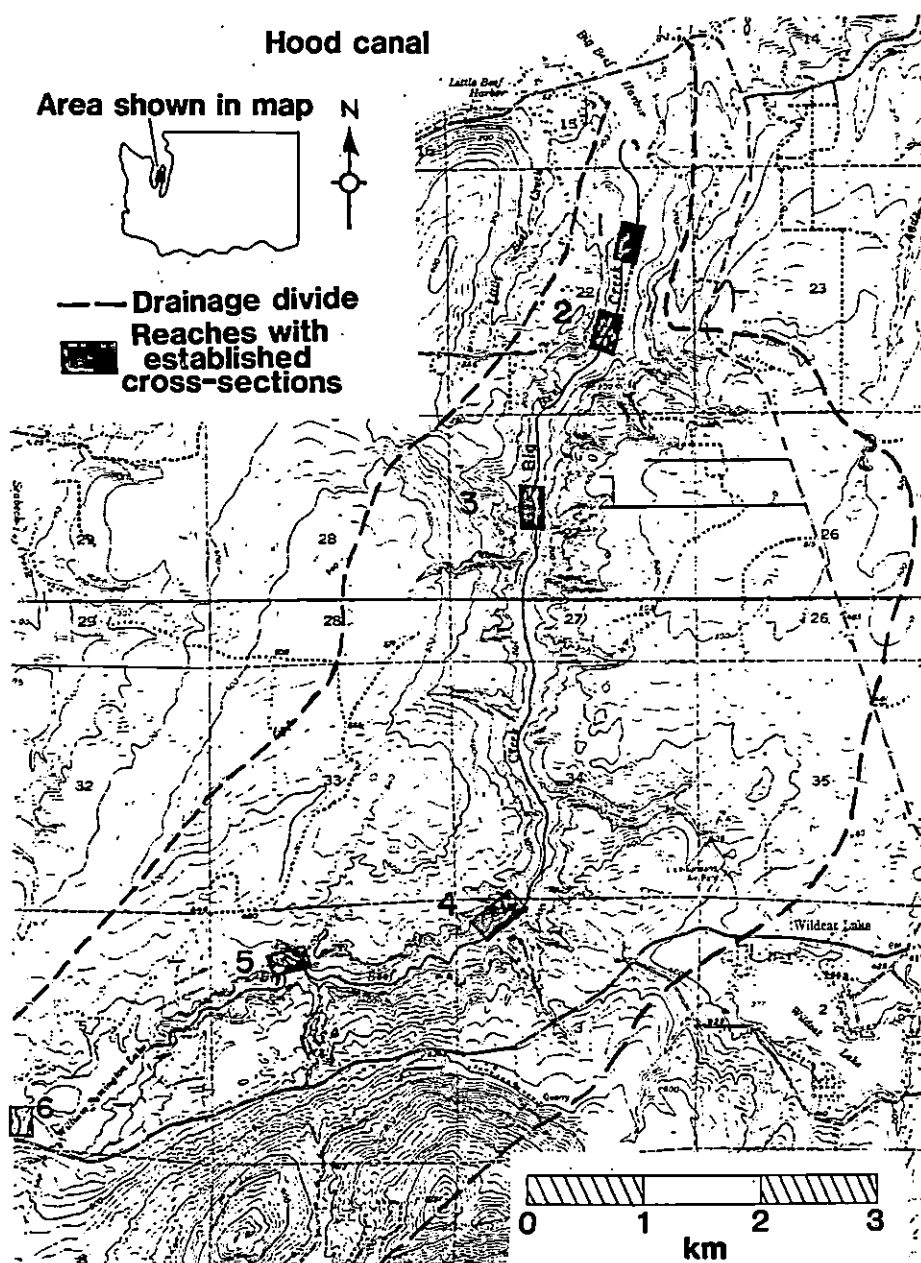


Figure 1.--Map of lower Big Beef Creek drainage basin showing reaches with established cross sections.

INTRODUCTION

The sediment load of a stream is determined by such characteristics of a drainage basin as lithology, vegetation, precipitation, and land use, and it enters the stream system by a variety of erosional processes. If stability is to be maintained, an equilibrium must exist between sediment entering the stream and sediment transported through the channel. Changes in sediment load can upset this balance and result in physical and biological changes in the stream system.

The purpose of this study is to determine the source and volume of sediment introduced into a stream, and its subsequent distribution, rate of movement, and influence on channel geometry. Three approaches were used. First, a sediment budget quantifies the amount of sediment

introduced into the stream channel. Second, sediment-transport equations predict how much sediment moves under conditions of various channel morphologies. Third, survey measurements indicate the volume and distribution of the deposited sediment.

FIELD AREA

Big Beef Creek, a gravel-bedded stream, was selected for study because high rates of sedimentation and channel instability during the last 10 years were evident and baseline data were available from records kept at the University of Washington Fisheries Research Station at the mouth of the creek. This fourth-order stream drains an area of 38 km² on the Kitsap Peninsula in Puget Sound, western Washington (fig. 1). More than 85 percent of the drainage basin is forested with

second-growth western red cedar (*Thuja plicata* Donn ex D. Don), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and associated species. The climate is characterized by cool, dry summers and mild, wet winters. Annual precipitation (predominantly rain) ranges from 1300 to 1700 mm, and most major storms occur between December and March.

The dominant surficial geologic unit in the drainage basin dates from the Vashon (late Wisconsin) glaciation. A mantle of compact till, composed of a bluish-gray mixture of cobbles, pebbles, and silt and clay, covers much of the area. In addition, poorly sorted recessional outwash sands and gravels form many of the surface deposits in the Big Beef Creek drainage basin.

The upper 15 km² of the Big Beef Creek basin has a low channel gradient (0.2 percent), an average hillslope gradient of 5 percent, and drains into an artificial lake. Because the lake acts as a sediment trap for suspended and bedload particles from the upper basin and most runoff and sediment discharge are generated below the lake, this study only considers a sediment budget for the lower drainage basin, where average channel gradient is 1 percent and hillslope gradients range from 10 to 70 percent. Drainage density below the lake is 2.5 km/km², as measured on 1:12,000 aerial photographs.

In 1969, the U.S. Geological Survey established a gaging station 1.6 km above the mouth of Big Beef Creek. The frequency of annual peak discharges was compiled from daily discharge records. The 10- and 50-year floods are about 30 and 56 m³/second, respectively. No flood has exceeded 30 m³/second in the past 10 years, and regional records indicate that no 50-year floods have occurred in the last 25 years. Thus recent changes in the Big Beef Creek basin occurred under fairly normal climatic patterns.

The principal activities in the drainage basin since the 1850's have been logging and some cattle grazing. Most virgin timber was logged by 1930 and a resurgence of logging activity occurred in the mid-1950's, when harvest of second-growth timber was initiated. Urban development is becoming widespread and this decreases the amount of forested land as well. In 1942, 3 percent of the land was deforested, by 1965 the figure was 12 percent, and today it is almost 20 percent. Likewise, road density tripled, from 1.2 km/km² in 1942 to 3.5 km/km² at present.

Personnel at the University of Washington Fishery Research Station noted heavy sediment deposition at the mouth of Big Beef Creek during the winters of 1966-67 and 1967-68; in the summer of 1969, the lower 500 m of the creek were channelized artificially. In 1970, a weir 2 m high was built across the mouth of the stream, which has acted as a small dam and has caused deposition of bed material for several hundred meters upstream of the weir.

METHODS

Cross-Section Surveys

Fifty-five cross sections along the main channel of Big Beef Creek were surveyed periodically from 1969-78 by Cederholm (1972) and me (fig. 1). Gradients of channel thalweg and water surface also were determined in several locations.

Detailed records of channel changes at one cross section were obtained from U.S. Geological Survey gaging station records for 1969-79. These records (Forms 9-207 and 9-275) consist of bimonthly measurements of width, cross-sectional area, mean velocity, discharge, and stage relative to gage datum.

Regional Channel Geometry Survey

Because the channel geometry of Big Beef Creek was not determined until after the drainage basin had been disturbed by road construction and timber harvest, predisturbance geometry was predicted from a regional channel-geometry relation developed from relatively undisturbed drainage basins in similar geologic and geographic settings. Estimates of regional channel geometry were obtained by measuring bankfull width and depth, channel gradient, and sediment-size distribution and correlating them with drainage area at 20 sites on nearby streams (Madej 1978). Comparison of dimensions of the present Big Beef Creek channel with those from undisturbed channels draining the same area indicates the extent of changes in Big Beef Creek.

Sediment Studies

Size distribution of sediment in the main channel and tributaries was characterized with the pebble-count method described by Wolman (1954). Samples of channel gravel, and hillslope and bank material were also collected, sieved, and weighed.

Sediment distribution within the main valley of the drainage basin was determined by mapping the location and volume of gravel bars, overbank sand deposits, terraces, tributary deltas, and debris fans. Aerial photographs at a 1:12,000 scale from seven flights between 1942 and 1976 allowed me to compare the locations and sizes of large gravel bars, log jams, and braided reaches through time. Area and location of mass movements were also mapped from photographs. Field checking provided more accurate estimates of volumes of material, as well as ages of mass-movement features dated by vegetation.

The size of the largest particle of bed material moved from a site by high flows during 1977 was obtained by observing marked rocks. Over 2,000 painted rocks were scattered on the upstream end of six gravel bars in the main channel and tributaries. The painted rocks ranged from 16 to 180 mm (D₅₀ = 64 mm). After high flows, the size of each rock found and the distance it had moved were recorded.

Bedload-transport rates were estimated by the methods proposed by Einstein (1950), Meyer-Peter and Müller (1948), and Emmett (1976). Dr. H. W. Shen of Colorado State University supplied a computer program of the Einstein Bed Load Function. This program was used to compute bed-material load under various conditions representative of the changing channel geometry from 1969 to 1978.

RESULTS

Measurements

Table 1 lists the results of cross-sectional surveys of six reaches during three periods. Generally, aggradation occurred in lower reaches, degradation in middle reaches, and little change occurred in upper reaches, as illustrated in selected cross sections (fig. 2).

Net aggradation occurred in Reach 1 above the weir. Between 1969 and 1976, the bed aggraded 0.5-1 m in the lower 300 m. Overbank flow deposited material over an area 70 m wide and built small levees to form new banks about 0.5 m above old banks. Alders rapidly revegetated overbank deposits and helped stabilize new banks. Overbank deposition is active, as indicated by several centimeters of sand burying young alders.

Net aggradation occurred in Reach 2 (fig. 2). The channel responded by assuming a more braided pattern in this reach and forming midchannel gravel bars. Bankfull width increased about 25 percent from 1973 to 1978, and bankfull depth decreased by a similar amount. Bankfull velocity (from U.S. Geological Survey records) remained about constant throughout this period.

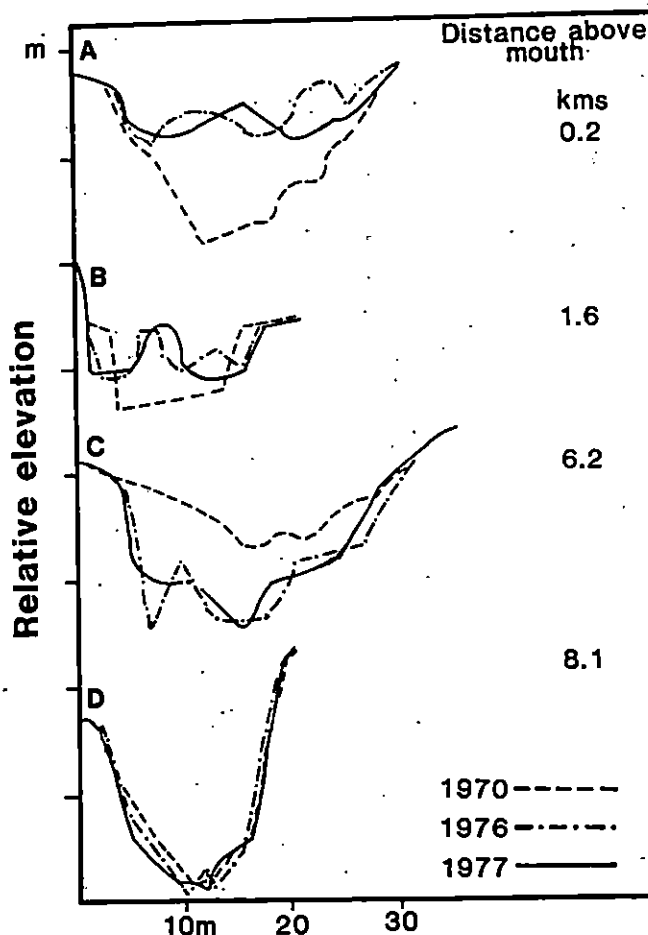


Figure 2.--Selected vertically exaggerated cross-sectional surveys in the main channel of Big Beef Creek.

Table 1--Results of channel cross-sectional surveys, Big Beef Creek, 1969-77

Reach	Approximate distance above mouth	Change ^{1/} in volume of sediment per unit length of channel		
		(m ³ /m of main channel per year)		
		1969-71 ^{2/}	1971-76	1976-77
<u>Kilometers</u>				
1	0-0.8	+5.05	+0.88	+1.26
2	1.1-1.6	+1.05	+0.34	-0.86
		<u>1969-76</u>		
3	2.9-3.2	-0.91		-0.05
4	6.2-6.6	-1.33		+0.86
5	7.7-8.0	-0.17		-0.01
6	9.6	-0.16		+0.50

^{1/}Net deposition is indicated by a plus, net erosion by a minus.

^{2/}Surveys conducted by Cederholm (1972).

Bank erosion and scour took place at several locations in Reaches 3 and 4, which may be a response to previous aggradation. Where roads are still contributing large volumes of sediment, aggradation and growth of gravel bars is apparent. In contrast, the channel just below the lake (Reach 5), which is located in a relatively undisturbed area, showed little change.

Longitudinal surveys indicate that, in the lower 2 km, channel gradient decreased from 0.090 to 0.085 between 1970 and 1977. Total channel length increased from 9785 to 10 010 m. Sinuosity increased from 1.30 to 1.32, and overall channel gradient decreased slightly.

Patterns of channel length changes correlate approximately with trends of cross-sectional changes. Where little cross-sectional change occurred, channel length remained constant. In degrading reaches, channel length increased; in the aggrading lower reaches of Big Beef Creek, channel length decreased.

The predicted and actual values of width for lower Big Beef Creek differ considerably (fig. 3), although the difference is negligible for the upper stream below the lake. Values for bankfull depth, channel gradient, and mean particle size are within limits of scatter in the regional pattern.

After one winter, 53 percent of the painted rocks were found. Large particles (>128 mm) did not move as far as intermediate sizes (45-90 mm). Surprisingly, small particles (<45 mm) did not move as far as those in the intermediate size class. Many of these small particles were found lodged behind large ones and were protected from further movement. Mean distance moved by intermediate-sized particles (45-90 mm) was 80 m.

Distribution of sediment stored in the channel is listed in table 2. In side channels, the volume of sediment above bedrock was measured. In the main channel, sediment was only measured to the depth of scour which was taken to be 0.4 m, the maximum depth of degradation in cross-sectional surveys.

Log jams are temporary sediment traps for bed material moving downstream. Logging activity may increase the number and magnitude of log jams in a stream channel, which in turn may increase the deposition of gravel and sand. In a relatively undisturbed reach, four log jams were noted, or 2.5 jams/km of channel. In reaches with recent logging, the concentration was 12 jams/km and these jams were larger than those in undisturbed reaches. Log jams are associated locally with braided channels as the stream bends around the jams.

Suspended sediment was sampled periodically at 0, 0.8, and 1.5 km above the mouth. Using U.S. Geological Survey daily discharge data, I constructed three suspended-sediment rating curves (Madej 1978). Average suspended-sediment load near the mouth of Big Beef Creek is 2325 t/year (110 t/km^2 per year), assuming the basin above the lake does not contribute any suspended sediment to downstream reaches.

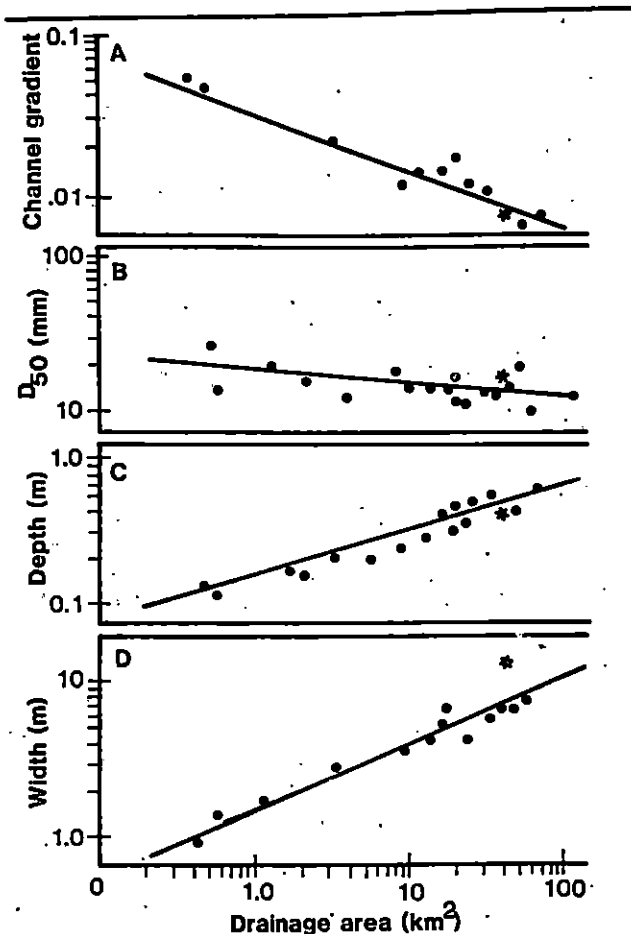


Figure 3.--Results of regional channel-geometry survey for Puget Lowland Streams (present dimensions for Big Beef Creek at 1.5 km are indicated by an asterisk).

Table 2--Distribution of alluvium in Big Beef Creek Basin (lower 23 km²)

Site of storage	Length of channels	Volume of sediment
	Kilometers	Cubic meters
3d-order tributaries	23	2.2×10^4
4th-order channel (to depth of scour)	8	4.5×10^4
(Active sediment in main channel ^{1/})	--	(2.3×10^4)
Floodplain (to depth of scour)	--	4.5×10^5
Total		5.2×10^5

^{1/}Material that has been transported recently and is temporarily stored in unvegetated gravel bars and behind log jams.

CALCULATIONS

Sediment Budget

The amount of sediment entering Big Beef Creek can be quantified by examining the contribution of processes supplying hillslope material to channels. Sediment input in an undisturbed area was considered to enter channels by soil creep and hillslope failures. Rate of soil creep under edaphic and climatic conditions in the Big Beef Creek drainage basin was estimated from published creep rates for other areas (table 3). Three studies have been conducted in temperate areas receiving about the same annual precipitation as Big Beef Creek (1300-1500 mm), and the coarse soil textures in these study areas are similar to the Big Beef Creek basin. Average rate of creep for the top 15-25 cm of soil for all the studies lies within a narrow range, and a value of 1.5 mm/year was chosen as a reasonable estimate of creep rate in the Big Beef Creek drainage. In addition, tree throw (Dietrich et al., this volume) contributes the creep equivalent of 1.5 mm/year on steeper, wetter hillslopes. The extent of tree throw in the Big Beef Creek basin is not as great, and I estimate 1.0 mm/year of soil movement by tree throw, or a total rate of 2.5 mm/year.

Table 3--Rates of soil creep in temperate, humid climates

Investigator	Precipitation	Gradient	Average soil creep (upper 15-25 cm)	
			Millimeters/year	Percent
Everett (1963)	990	25-65	0-2.2	
Young (1960)	1400	35-55	1-2	
Kirkby (1967)	1710	15-35	1-3	

The most active layer of soil in terms of creep is the upper zone, which is influenced by such processes as root growth and decay, tree fall, and burrowing of animals. In the Big Beef Creek basin, the observed thickness of this active layer is about 0.5 m on hillslopes of 25-45 percent, and it has a density of about 1.7 t/m³.

Total length of first- to fourth-order channels in the lower drainage basin is about 57 500 m. Because soil transported downhill by creep enters channels through shallow bank failures on both sides of a channel, the total amount of material introduced by creep is: $5.75 \times 10^4 \text{ m} \times 2 \times 0.5 \text{ m} \times 0.0025 \text{ m/year} \times 1.7 \text{ t/m}^3 = 245 \text{ t/year} = 10.6 \text{ t/km}^2 \text{ year}$. This is a minimum estimate, assuming soil deeper than 0.5 m contributes little material in comparison to the more active surface layer.

Material discharged through soil creep is transported either as bedload or suspended load, depending on the size of material. Suspended-sediment samples collected in Big Beef Creek have a maximum particle size of 1 mm. Textural

analyses of soil in the Big Beef drainage basin indicate that 40 percent of the active layer is greater than 1 mm. Thus, 147 t of material discharged into the channel through soil creep becomes suspended load, and 98 t is transported as bedload.

Some bedload may break down into particles small enough to be carried as suspended load. Tumbling experiments with rocks of similar lithology and size as material in Big Beef Creek (Kuenen 1956) show that 10 km of transport is insufficient to break down much material. Average rate of attrition is 0.1 percent/km of transport.

Large discrete hillslope failures are the second major contributor to a stream's sediment load. Field measurements of depth of slides averaged 0.6 m. During the last 10 years, 880 m² of land was affected by landslides that were not associated with roads, logging, or residential lots. So, the rate of mass wasting for undisturbed parts of the basin is: $880 \text{ m}^2 \times 0.6 \text{ m} \times 1.7 \text{ t/m}^3$: 10 years = 90 t/year. These slides, which occurred on slopes >15 percent or at the headcuts of first-order channels, were representative of an area of 6 km² in the lower drainage basin, so the rate can be expressed as (90 t/year)/(6 km²) or 15 t/km² per year. This rate is lower than estimates from other drainage basins in wetter, steeper environments (Swanston 1969, Dietrich 1975, Pierson 1977).

Because human activity significantly affected the remainder of the lower drainage basin, the rate of naturally occurring slides for the entire lower basin must be extrapolated from the rate of landsliding in the undisturbed sections. An area of 6 km² has hillslopes <15 percent, and probably does not contribute sediment through landsliding. The remaining 17 km² contributes 15 t/km² per year, or 255 t of sediment per year. This sediment is characterized by the size distribution of the average soil column. Thus, 153 t/year is suspended load, and the remainder becomes bedload.

Consequently, in an undisturbed state, sediment input into Big Beef Creek was:

Soil creep - 245 t/year	147 t/year of suspended load 98 t/year of bedload
Mass movements - 255 t/year	153 t/year of suspended load 102 t/year of bedload
Total load - 500 t/year (22 t/km ² per year)	300 t/year of suspended load 200 t/year of bedload

This value for total sediment yield lies at the lower end of the range of sediment yields reported from drainages wetter, steeper, or both--such as 28 t/km² per year in western Oregon (U.S. Environmental Protection Agency 1971), 73 t/km² per year in southwest Alberta (Hollingshead 1971), and 105 t/km² per year in British Columbia (Slaymaker and McPherson 1977).

The Big Beef Creek drainage basin is no longer an undisturbed system because of changes in land use. In areas undergoing logging and road construction, rates of occurrence of mass movement may increase (Anderson 1954, Fredriksen 1970). In addition, processes such as sheetwash and rainsplash erosion—normally insignificant in humid, well-vegetated areas—may transport material from roads to channels.

Annual sediment contribution by disturbance-related landslides was quantified by mapping volumes of slides originating on roads and cut areas, and dividing volumes by the age of slides. These slides were smaller but more numerous than naturally occurring slides on valley sides. Between 1968 and 1977, an average of 845 t/year entered the stream channel through debris slides induced by land-use changes.

Roads are an additional source of sediment. Sheetwash on roadbanks and roadbeds, erosion of roadside ditches and sidecast material, roadbank gully, and dry ravel from roadbanks are all active on roads in the Big Beef Creek basin. The volume of material eroded from roadside ditches was estimated in the field. Alluvial fans are not found at outlets of culverts draining ditches, and the largest painted rock moved in roadside ditches had a diameter of 64 mm. Thus, most eroded material probably reaches the stream channel. Roadside ditches contribute 440 t/year to the stream system.

Sheetwash carries sediment from roadbanks and roadbeds to stream channels. Few studies have directly measured amounts of sediment originating from roads, but these studies indicate the order of magnitude of sediment eroded from unpaved roads: Hornbeck and Reinhart (1964) — 9900 t/km² per year for fresh roads and 125 t/km² for abandoned roads; Diseker and Richardson (1961) — 20 000 to 60 000 t/km² per year; and Wolman and Schick (1967) — 20 000 to 50 000 t/km² per year. L. Reid and T. Dunne (University of Washington) are currently studying erosion on logging roads, and their results for moderately used and abandoned roads are of the same magnitude as those of Hornbeck and Reinhart. Of these estimates, the 9900 t/km² of Hornbeck and Reinhart seems the most reasonable to apply to the Big Beef Creek drainage basin, because these authors studied tractor-yarding skid roads under slope and precipitation conditions similar to those in the Big Beef drainage basin.

Although soil loss in the above studies was measured under a variety of conditions, sediment yields obtained were always far above the sediment yield in undisturbed areas. To apply these values directly to the Big Beef Creek drainage basin is risky because of variation in local conditions. Nevertheless, these values are useful estimates of soil loss from roads in the Big Beef Creek drainage.

Road prisms in the Big Beef Creek basin average 8 m in width. In 1977, 30 of the 65 km of unpaved roads were actively used. Using Hornbeck and Reinhart's values of sediment yield, I computed

soil loss on roads to be: .008 km [(30 km x 9900 t/km² per year) + (35 km x 125 t/km² per year)] or 2410 t/km² per year. By examining the size distribution of lag deposits of the road surface, I estimated that 80 percent of the eroded material (1930 t) was transported as suspended sediment. Scour of roadside ditches contributes an additional 440 t/year. Thus a total of 2850 t/year is eroded from roads, of which 685 t is bedload.

The total sediment load of the stream is the sum of the contributions of natural hillslope processes and erosion processes from disturbed areas (table 4). Although these estimates in the sediment budget are approximate, their concordance with other measurements indicates they are of the correct magnitude. The estimate of 3000 t of suspended sediment/year compares favorably with the 2325 t/year obtained from suspended sediment rating curves. Estimated bedload input is 1200 t/year; the volume of sediment deposited in the lowest kilometer of Big Beef Creek between 1970 and 1977 was 4700 m³, or 9000 t, an average load of 1400 t/year. Some of the 1400 t/year may represent sediment moving out of storage from upstream reaches, rather than bedload input from hillslope processes.

Table 4—Annual sediment input to Big Beef Creek

	Suspended load	Bedload
	Metric tons/year	
Soil creep	147	98
Naturally occurring landslides	153	102
Disturbance-related landslides	507	338
Sheetwash on road surfaces	1928	482
Scour of inboard ditches	264	176
Total	3000	1200

The computed sediment budgets suggest that total load of the stream increased from 500 t/year under undisturbed conditions to over 4200 t/year at present. Even if absolute values of sediment input are contested, the apparent contrast of sediment loads under undisturbed and disturbed conditions are large and significant.

Sediment Transport

Once sediment enters a channel, it is transported downstream during high flows. Bedload transport represents work done by a stream and is a function of the boundary shear stress generated at any given moment and place. Boundary shear stress, τ_b , produced by a fluid is calculated as:

$$\tau_b = u_* \rho \quad (1)$$

where u_* is related to velocity u at distance z from the channel boundary by

$$u = (u_*/0.4) (\ln z/z_0) \quad (2)$$

where ρ = density of the fluid, u_* = shear velocity, and 0.4 = von Karman's constant. The

depth at which velocity apparently goes to zero as the channel bed is approached is the roughness length of the boundary, z_0 , and is dependent upon particle size. It can be estimated by $D_{65}/30$, where D_{65} is the grain diameter that is greater than 65 percent of the bed material (Graf 1971).

Bedload transport rates for the gaging site at Big Beef Creek (fig. 1) before and after disturbance were calculated from Einstein (1950), Meyer-Peter and Müller (1948), and Emmett (1976) (table 5). I have discussed their equations and the applicability to Big Beef Creek (Madej 1978). Dimensions of the undisturbed channel were estimated from regional channel-geometry results; those of the disturbed channel were obtained from survey measurements. Measured frequencies of discharge for each year were used. The three equations predict that an average of between 600 and 1400 t of bedload/year would be transported past the gaging site.

INTERPRETATION

Present channel morphology allows greater bedload transport than the undisturbed channel (table 5). Analysis of boundary shear stress in the channel leads to the same conclusion. An increase in stream-channel capacity must be caused by an increase in τ_b . Using U.S. Geological Survey velocity and discharge measurements, I compared magnitude and distribution of shear stresses at four sites near the gaging station at equivalent discharges over a 4-year period (Madej 1978). Figure 4 shows the results of this analysis at one site, where erosion occurred at the right bank and the channel was 2 m wider in 1975 than in 1971.

Several common characteristics were found in the four analyses. The channel became wider and shallower through time (also shown by periodic cross-sectional surveys). Large gravel bars have low shear stresses above them and high shear stresses around them, perhaps caused by flow accelerating around the barrier. Most important, high shear stresses are found in areas of bank erosion, and the high stresses can be maintained over a shallower cross section. Thus, the ability of the channel to transport sediment is increased under the new channel configuration.

Channel Changes: Possible Modifications

The geometry of alluvial rivers can adjust to changing conditions imposed upon them (Mackin 1948, Leopold and Maddock 1953). In Big Beef Creek, an increase in sediment load was accommodated by changes in several interrelated hydraulic variables. Grain size and lithology of sediment supplied to a stream are variables independent of the stream system, as is discharge entering a stream. Other factors are semidependent and can undergo some modification by a stream in response to changes, i.e., flow resistance, mode of sediment transport, sediment-particle size, and channel pattern. Some parameters are almost totally functions of processes of the stream itself and can be considered to be dependent: velocity, width, depth, and channel gradient.

Table 5--Prediction of annual bedload transport in metric tons/year

	Investigator		
	Einstein (1950)	Meyer-Peter and Müller (1948)	Emmett (1976)
Undisturbed channel	645	580	340
1971	1510	1430	1030
1972	660	1270	630
1973	500	1350	470
1974	1940	3255	995
1975	70	55	30
1976	715	1090	395
Mean annual transport after disturbance	900	1410	590

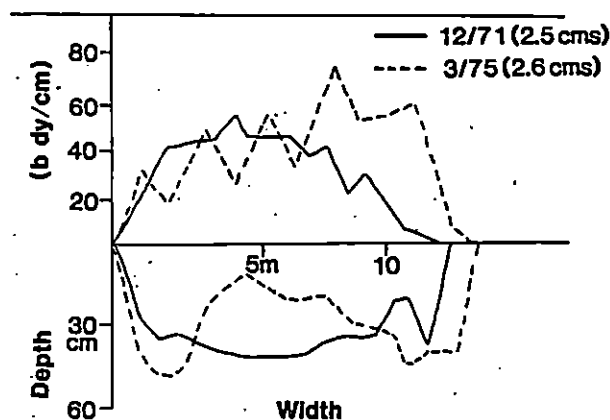


Figure 4.--Distribution of boundary shear stress in main channel, 1.6 km above the mouth of Big Beef Creek.

In response to an increase in sediment load, the more dynamic factors in a stream change to accommodate the increase. Adjustments are limited by certain physical relationships, however. The first of these is the continuity equation:

$$Q = w \bar{d} \bar{u} \quad (3)$$

where Q = discharge, w = width, $\bar{d}$ = mean depth, and $\bar{u}$ = mean velocity.

The Manning equation (4) defines the relationship between $\bar{u}$ and $\bar{d}$:

$$\bar{u} = \frac{\bar{d}^{2/3} s^{1/2}}{n} \quad (4)$$

where s = slope of the stream-energy line and n = turbulent-friction coefficient (roughness). In addition, sediment transport, Q_s , is here assumed to be dependent upon stream power:

$$Q_s \propto w \bar{d} \bar{u} s \quad (5)$$

The manner in which the Big Beef Creek channel changed is summarized in a previous section. Theoretically, however, these changes do not represent the only possible changes, and it is important to explain why the channel has been modified in this manner. Because transport of sediment represents work accomplished, the amount of sediment transport was used as the criterion for capacity for work among various channel configurations. The Einstein method was used to compare the transport capability of several channel configurations.

Several combinations of width, depth, and velocity (restricted by continuity and roughness relationships) were tested with the Einstein computer program (fig. 5). An increase in width/depth ratio indicates increased bedload sediment transport (Schumm 1968, Pickup 1976). This holds true if velocity is held constant (line A in fig. 5); implying a decreasing roughness coefficient.

In a second set of calculations, velocity changed. If slope and roughness are considered to be a constant, k , the value of velocity from the Manning equation is $kd^{2/3}$, and discharge is defined as: $Q = kw d^{5/3}$. In this case (line B in fig. 5), rates of sediment transport decrease with increasing width/depth ratio. Therefore a change in the roughness 'n' apparently is needed to increase transport rates.

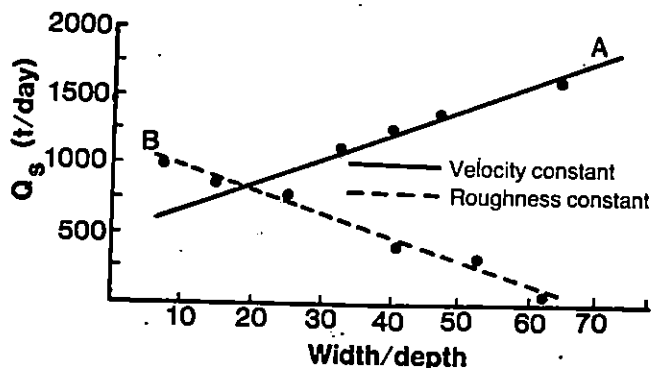


Figure 5.—Rates of sediment transport at various width-to-depth ratios.

Discharge measurements indicate that bankfull velocity remained about constant over the last 8 years, although the width-to-depth ratio, w/d , increased from 19 to 27. Line A in figure 5 suggests that w/d can increase indefinitely to transport increasingly larger sediment loads; however, in reality, stream width does not increase indefinitely. To understand what mechanism limits the increase and where these limits may be expected to occur, the effect of bed-particle roughness on flow must be considered.

Coarse surficial particles on a river-channel bed cause turbulence and energy loss in water flowing over them. The effect of these particles is most pronounced at low flows. Leopold et al. (1964, p. 160) described this phenomenon in gravel-bedded streams using a ratio of depth of water (d) to

particle size (D_{84}) of the armor layer. The relationship is described as:

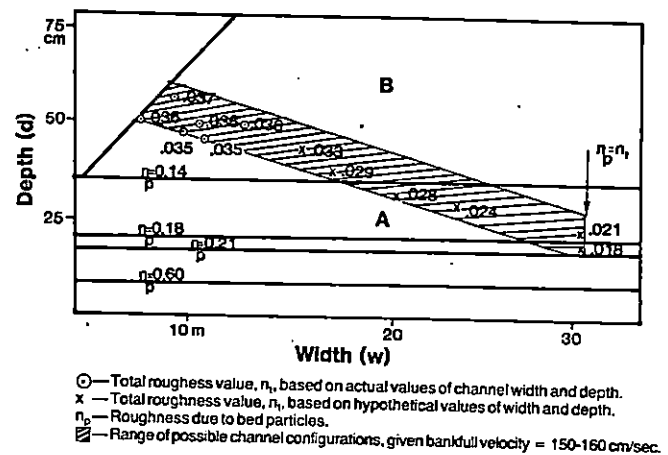
$$n_p = d^{1/6} [8g (2 \log d/D_{84} + 1.0)^2]^{-1/2} \quad (6)$$

where n_p is roughness from bed particles and g is the acceleration from gravity, 980 cm/second^2 .

Hence roughness from bed particles is dependent only on depth of water and not on width or velocity. Values of n predicted by this method are minimum values, because other forms of roughness such as gravel bars, log jams, bank roughness, and meanders increase n . But water cannot flow over a rough bed with values of n below that predicted by the d/D_{84} relationship (equation 6).

At any given discharge, if width and depth are defined, velocity is known through the continuity equation. If velocity and slope remain constant as depth changes, roughness as defined by the Manning equation must change. Figure 6 shows the relationships of width, depth, velocity, and roughness at bankfull discharge ($10 \text{ m}^3/\text{second}$) in Big Beef Creek. Because no streams in the regional survey show a w/d less than 18, only those greater than 18 are considered. Actual ratios are below 27, but hypothetical cases with higher ratios are considered as well. Because survey measurements show little change in channel gradient, gradient is assumed constant in this analysis. Manning's definition represents total roughness, n_t , contributed by several factors; the value of n_t decreases with increasing width and is given for each location considered.

With decreasing depth, roughness from bed particles, n_p , increases (from equation 6), and horizontal contours of figure 6 indicate the value of n_p at different depths of flow.



Records from the U.S. Geological Survey gaging station show that mean velocity at bankfull stage remained between 150 and 160 cm/second over an 8-year period. Only a small portion of the diagram represents channel configurations where bankfull discharge is accommodated within this velocity range (the stippled area of fig. 6). Because velocity remained constant despite changes in channel form, I assumed velocity would remain constant if the width/depth ratio increased, and so the stippled area also includes hypothetical configurations.

As long as discharge can flow with a roughness term greater than that predicted by the d/D_{84} relationship, the channel configuration is possible. Conversely, once bed-particle roughness is greater than the roughness needed to keep velocity constant, satisfying conditions of continuity, $Q = wdu$, becomes impossible. Thus, a hydraulic constraint prevents unlimited increases in channel width.

This relationship implies that the amount of sediment that can be transported as bedload is limited. Sediment transport can increase with width-to-depth ratio only as long as roughness-velocity constraints are met. If all sediment supplied to the channel cannot be transported at the maximum possible width/depth configuration, aggradation occurs.

Configurations that are not within the constant velocity envelope probably do not exist, because the amount of work necessary to create those situations is large. For example, point A in figure 4 is associated with a velocity of 213 cm/second, and $n_t = 0.0195$. Such a low value for total channel roughness is rarely, if ever, found in gravel-bedded streams (Barnes 1967). Alternately, point B in figure 4 represents a situation where velocity is 76 cm/second and $n_t = 0.087$. Because n_p is only 0.008 at this depth, the n_t value of 0.087 would be difficult to reach even with the contribution of other causes of roughness, and this configuration is improbable.

Big Beef Creek does not display the maximum theoretical width of 30 m. Several reasons may account for this. A stable channel must have boundaries that can withstand shear stresses imposed by the flow. Using Graf's method (1971), critical shear stress on channel walls in Big Beef Creek is between 55 and 150 dy/cm², above which erosion occurs. These stresses are approached and probably exceeded at high flows (fig. 4); however, the resistance of banks caused by vegetation must be considered. A cover of Bermuda grass can resist stresses up to 480 dy/cm² (Leopold et al. 1964). The thick mat of tree and grass roots on the banks of Big Beef Creek probably inhibits bank erosion.

Undercutting of banks below the root zone does occur, but not rapidly. The channel at the U.S. Geological Survey gaging station underwent the largest changes in 1973-74, when discharges were in excess of 20 m³/second. Maximum discharge since that time has been 13 m³ second. More widening may occur when another high

discharge is reached, but it seems unlikely under present vegetation and discharge conditions that the channel will erode 15 m to reach 30 m.

The valley widens near the mouth of Big Beef Creek, and channel width does reach 30 m, but this partly reflects weir and tidal action effects on channel geometry.

Storage of Sediment in the Channel

In several surveyed as well as unsurveyed reaches, much sediment eroded from roads and recently harvested hillslopes is obviously stored in the channel in the form of gravel bars. Field mapping indicates that the total volume of stored channel material is about 520 000 m³ (1 092 000 t), of which 23 400 m³ (49 200 t) is active material (i.e., in unvegetated bars down to a scour depth of 0.4 m) (table 2). Most active material lies in the lower 6.5 km, where channel braiding and log jams are prevalent.

An estimate of potential residence time for active material under present conditions is obtained by dividing the amount by the bedload-transport rate after disturbance, 1000 t/year, or 50 years. An average rate of movement can be estimated by dividing channel length, 10.3 km, by 50 years, or 206 m/year. Milhous (1975) obtained a particle-transport rate of 234 m/year through bedload measurements in an undisturbed, steeper channel with coarser gravel.

Relation of Channel Changes to Land Use

Changes in the Big Beef Creek channel can be related to land use in the drainage basin. Intense logging in the mid-1950's 2000 m above the mouth dramatically increased sediment load in that reach, and aggradation occurred. Assuming bed material moves 200 m/year, effects of excess sediment would be felt near the mouth in (2000 m)/(200 m per year), or 10 years, about 1965. In fact, local residents noted excessive sedimentation in the winters of 1966-68.

Present cross-sectional surveys show degradation in the logged reach and aggradation near the mouth, suggesting the slug of sediment is being transported downstream. A high bedload rate in this reach is also indicated by field observations. Channel length decreased, and the number and size of midchannel bars increased.

A similar trend is seen 6.2 km upstream (fig. 2C). Road construction and logging in the late 1960's caused aggradation of the adjacent stream channel. Presently, net degradation is occurring there, and channel widening and braiding occur downstream for 0.8 km. This accumulation constitutes a second distinct wave of sediment in Big Beef Creek, and it will affect the stream for several years to come.

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