WATER RESOURCES BULLETIN
VOL. 23, NO. 1 AMERICAN WATER RESOURCES ASSOCIATION FEBRUARY 1987

TRANSPORT OF ROAD-SURFACE SEDIMENT THROUGH EPHEMERAL STREAM CHANNELS[1]

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ABSTRACT: Since the majority of road drainage points in western Washington and Oregon enter small, often ephemeral streams rather than large, fish-bearing waters, impact of road-surface sediment on biota in permanent streams depends, to a large extent, on transport through these small watercourses. A series of experimental additions of road-surface sediment was made to two ephemeral streams to examine the downstream transport of this material as a function of discharge and channel characteristics. These small streams were found to store large amounts of sediment washed from road surface. In no instance did either stream transport more than 45 percent of the added material to their mouths, distances of 95 and 125 m. Larger-sized sediment particles were delivered at a lower rate than finer material. Added sediment <0.063mm in size was transported efficiently through the systems at all but the lowest flows tested. Material between 0.5 and 0.063 mm and from 2.0 to 0.5 mm in size were retained at progressively higher rates, with sediment in the coarser size category never exceeding a delivery of 10 percent of the added material. There were significant differences in the transport of sediment in the two larger size categories between the two streams. These differences were due to a much greater amount of Woody debris in the stream with the lower delivery rates, which acted to trap and hold sediment. as well as a slightly longer and less steep channel.

(KEY TERMS: sediment particle sizes; sediment retention; woody debris: logging effects on streams.)

INTRODUCTION

The construction: use, and maintenance of forest roads has often been implicated as a major cause of increased sediment yields seen during and after logging operations in a watershed (Packer, 1967: Fredrickson, 1970; Swanston, 1971; Megahan and Kidd, 1979; Reid, 1984). Increased amounts of sediment in streams may influence salmonid fish populations by clogging gravel used for spawning (Hausle and Cobble, 1976; Cederholm and Salo, 1979), reducing pool volumes or affecting food supplies by reducing aquatic invertebrate production (Bjornn, *et al.*, 1977). Excessive amounts of sediment in streams may also impair water quality in those systems utilized as domestic water supplies. There are two processes by which roads increase sediment loads in streams: (1) by increasing the incidence of mass failures; and (2) by erosion of the road surface, backslopes, and ditches and transport of this material to the stream. In areas of unstable soils and steep slopes landslides are responsible for the majority of road derived sediment delivered to streams (Megahan and Kidd, 1972) but material eroded from road surfaces and ditches can predominate in more stable watersheds. This study is concerned only with the latter material.

While sediment from road surfaces may enter directly into permanently flowing waters, more often ditches empty into ephemeral first- or second-order streams (Strahler, 1957). Irvin and Sullivan (unpublished report) found that 20 percent of the road runoff points discharged onto the forest floor while 80 percent emptied directly into the drainage system in three large watersheds in western Washington and Oregon. Of the stream entry drainage points, 88 percent entered first- or second-order channels while only 13 percent emptied directly into permanent water. Road sediment entering smaller water courses must be transported into larger streams before it influences water supplies or fish populations. In order to appreciate the magnitude of impact road sediment entering ephemeral channels will have on water quality and biota in downstream systems, it is necessary to understand the factors influencing the transport of fine sediment through these small streams. This study was designed to examine some effects of streamflow and channel characteristics on the transport of sediment generated on road surfaces from a road crossing downstream to a larger stream. Due to the importance of grain size in determining whether sediment is deposited or transported, the differential delivery of material in various size classes was carefully monitored.

SITE DESCRIPTION

This study was conducted on Mack Creek, a fourth-order tributary of the Chehalis River in the Willapa Hills of

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[1] Paper No. 85040 of the *Water Resources Bulletin*. Discussions are open until October 1, 1987.

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southwest Washington (Long. 123° 16'W, Lat. 46° 28'N). The Mack Creek watershed is 2.8 km² and has a relief of 420 m. Approximately 98 percent of the basin has been logged within the past 10 years and contains 9.8 km of gravel surfaced logging roads and 10.8 km of stream channel. The mainstem of Mack Creek contains populations of coho salmon (*Oncorhynchus kisutch*), cut throat trout (*Salmo clarki*), and torrent sculpin (*Cuttus rhotheus*).

Two second-order tributaries to Mack Creek were chosen to examine the movement of sediment from the road crossings of these streams to the mainstem of Mack Creek. A comparison of the physical characteristics of the study sections on these two streams may be found in Table 1. These two tributaries, which we have labeled A and K, are steep and contain large amounts of woody debris, brush and herbaceous vegetation. The streams are ephemeral, drying during the summer months. During periods of dry weather in winter, sections of these streams are dry as flow infiltrates through the bed. Tributary A, which has a somewhat larger watershed area than tributary K, enters Mack Creek about 1 km upstream from its mouth. Tributary K enters Mack Creek about 4 km above A.

METHODS

Transport of sediment downstream from the road crossing in our two study streams was examined by experimentally introducing a measured amount of sediment with known particle size distribution into the stream. Output of sediment at the mouth of the tributaries was monitored, enabling calculation of the delivery rate of each sediment size class.

Flow in each of the tributaries was monitored by installing pre-rated, metal H flumes at the road culvert outlet. A continuous recording stream gaging station was also, installed on Mack Creek. By correlating flow in the tributaries at any given time with simultaneous flow at the instrumented Mack Creek station, an approximate, continuous record of discharge for the two tributaries was produced. These data were ultimately used to construct flow duration curves for the two streams and sediment transport at each sampled discharge was interpreted in light of the expected frequency of occurrence of that flow during the year of the study.

Sediment introduced into the streams during this study consisted of road surface sediment excavated from a roadside settling pond. A subsample of the material added to the streams during each trial was drawn for determination of dry weight and particle size distribution. Approximately 6.5 kg of sediment was added to the study streams during each experiment. Three sediment size classes were used in this study, 2 mm to 0.5 mm, 0.5 mm to 0.063 mm, and <0.063 mm. These three size classes represented coarse sand, medium and fine sand, and silt and clay (Guy, 1969). The average size distribution by weight of the introduced sediment ± one standard deviation was 30.3 percent +/- 5.5 from 2.0 mm to 0.5 mm, 61.4 percent +/-6.2 from 0.5 mm to 0.063 mm, and 8.3 percent +/- 2.7 finer than 0.063 mm.

Introductions of sediment into the study streams were conducted during periods of receding flow. Sampling under these circumstances greatly reduced the problems which would have been associated with the rapidly changing discharge seen during periods of rising flow as well as avoiding the high background sediment levels which commonly occur due to road runoff during periods of precipitation. The background level of sediment carried at the stream mouths prior to the experiments was used to calculate the proportion of the sediment load attributable to pretreatment levels. Sediment levels prior to the experiments ranged from 1.0 to 15.2 mg/l on stream A and 2.2 to 20.3 mg/l on stream K. This background material was subtracted from the total load delivered at the downstream station in calculating delivery of the added sediment.

Prior to introducing sediment to the streams on each sample date, minimum downstream travel time of the material from the road crossing to the mouth was estimated by measuring the length of time it took dye to cover this distance. A bucket of the collected road sediment was then diluted in a plastic garbage can and released into the H flume over a short period of time (1-3 minutes). The sediment was added to the stream as rapidly as possible but the length of time of release was adjusted to minimize the impact of the addition on the flow level in the stream. Crab samples were drawn from the stream near the mouth, the first sample being taken before sediment addition to determine background conditions and the timing of the next sample being dictated by the travel time of the dye. Sequential samples were then drawn until the turbidity level in the stream returned to the pretest condition. This point had to be determined visually in the field. The length of each experiment varied inversely with discharge, ranging from 11 to 100

TABLE 1. Channel Characteristics of Study Reaches.

	Drainage Area (Ha)	Average Slope (percent)	Study Reach Length (m)	Average Channel Width (m)	Channel Area (m²)	In-Channel Wood and Vegetation Area (m²)	In-Channel Wood and Vegetation Area (percent)	Elevation Change Accounted for by Waterfalls (percent)
Tributary A	29.56	31	95.6	1.9	180.6	52.0	29	68
Tributary K	22.27	22	124.3	3.0	373.6	270.9	72	56

minutes on stream A and 19 to 90 minutes on stream K. On only 9 of 22 occasions was the sediment concentration of the final sample drawn more than 1.0 mg/l higher than the pre-experiment background level and in only 3 cases was the difference more than 4.0 mg/l. The largest discrepancy noted was 5.8 mg/l. The maximum sediment concentrations measured at the mouth of the study streams during each trial varied inversely with discharge and ranged from 10.8 to 408.5 mg/l on stream A and from 24.0 to 212.5 mg/l on stream K. In those instances when sampling ended before sediment concentration dropped to the pre-experiment level, the amount of material leaving the stream after the last sample was taken was estimated from a plot of sediment concentration over time during the trial. Adjustment of the sediment delivered at the stream mouth by this method increased the total amount of material only slightly, with values generally rising less than 1 percent as a result and never exceeding 6.4 percent of the total measured load.

Length of time between samples depended upon stream flow and was as short as 30 seconds during periods of high discharge when downstream travel of the sediment was rapid, and as long as 5 minutes during the lowest flows sampled. Samples were taken from the thalweg of riffles in each stream to help ensure that the sediment was mixed evenly in the water column, thereby giving an adequate representation of the entire stream volume. Since water depth at the sample sites did not exceed the width of the mouth of our sample bottles, depth integration was not necessary. Sampling in this manner may have produced some underestimation of the delivery of the coarsest size fraction (0.5-2.0 mm). Despite the turbulence at the saniple locations, a high proportion of this relatively heavy material may have been moving downstream near or on the streambed. Even though the bottle mouth was in contact with the bed at the time of sampling, the round-mouthed bottle necessarily undersampled material moving along the bottom. However, in view of the extremely small percentages of added sediment in this size category transported to the stream mouths during our experiments, the rate of delivery could have been increased appreciably without invalidating the conclusions reached during this study. Also, since the sampling method was consistent between the two streams, comparison of delivery of sediment by these systems should not be impaired. Twelve sediment introductions at six different flow levels were performed on tributary A and 10 introductions at six flow levels of tributary K.

The total amount of sediment contained in each sample was determined gravimetrically and particle size analyses were done using a modification of the native water-pipette method (Guy, 1969). This modification eliminated the addition of chemical reagents used for separating sediment aggregates into their constituent parts. We considered this method preferable for our purposes since it left intact naturally-occurring sediment aggregates. These aggregates behave like single Particles in terms of settling in the stream; thus, chemical separation would tend to overweight particle size distributions towards the finer size categories.

Channel characteristics of the two tributary streams between the sediment introduction point and the mouth were inventoried. Slope, channel width and length. and height of waterfalls were measured using a survey rod, hand level and measuring tape. Area of the stream channel covered by woody debris or vegetation was also measured. Influence of these channel parameters on sediment movement was examined by comparing efficiency of transport downslope at similar flows in the two streams.

RESULTS AND DISCUSSION

The flows at which trials were run in the two tributaries during this study represent a fairly good cross section of the discharges occurring in these systems from October 1982 to April 1983. Flow duration curves for the two streams over the study period are shown in Figure 1. It is evident from the plots that stream A carries substantially more water than stream K. The flows at which sediment additions were made are marked on the two curves. In order to put the sampled flows into perspective, bankfull discharge for each stream, as calculated using the formula from Dunne and Leopold (1978), is also shown. The average recurrence interval for a bankfull flow is approximately 1.5 years (Dunne and Leopold, 1978).

As would be expected, in both tributary A and K the proportion of the introduced material which was delivered at the stream mouth increased as streamflow increased (Figure 2). However, both streams proved to be very effective at retaining sediment. Stream K delivered 30 percent of the added sediment during the highest flow sampled but moved very little of the material through the study stretch during low flow periods. Stream A behaved similarly to K but transported a significantly higher percentage (ANOVA $P<0.05$) of the sediment at any given flow. Stream A exported 45 percent of the introduced sediment during the highest discharge we sampled but, like stream K, very little material moved during low flow.

Delivery rate of each of the three particle-size fractions of the added sediment revealed markedly different behavior. In both tributaries, the finer the material the higher the proportion exported from the system. In stream A, delivery exceeding 10 percent of the added material in the 2.0 mm to 0.5 mm size class occurred only three times and only at flows greater than 41 l/s (Figure 3). A higher percentage of the 0.5 mm to 0.063 mm material was moved downstream at any given flow; however, material of this size also tended to remain in tributary A with a 50 percent delivery rate being achieved only once, at the highest flow measured. While sediment finer than 0.063 mm comprised the smallest percentage of total sediment added, of the three size classes it predominated in terms of material recovered at the tributary mouth. In stream A, this fine material was exported at a rate over 50 percent at all except the lowest flow measured. On three occasions more material in the less than 0.063 mm size class was delivered at the tributary mouth than was added

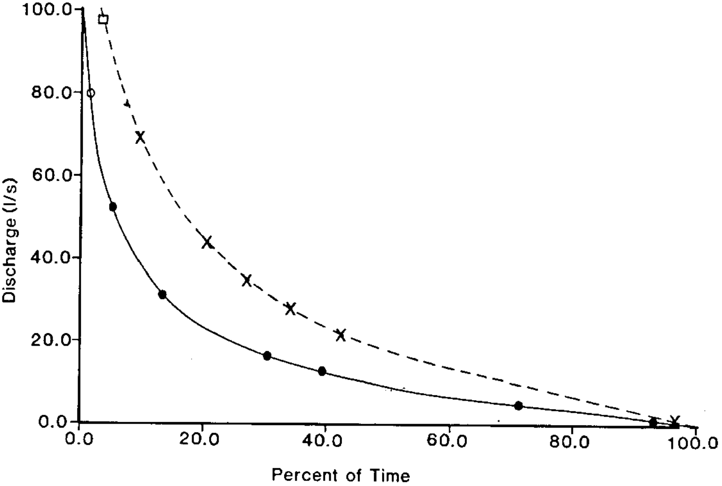

Figure 1. Flow Duration Curves for Stream A (– – – –) and Stream K (————) from October Through April 1982-83. Flows at which experiments were conducted are marked on each curve. Two experiments were run at each indicated discharge, except for the lowest sampled flow on stream K. Estimated bankfull flow is also indicated (□ – K, ○ – A).

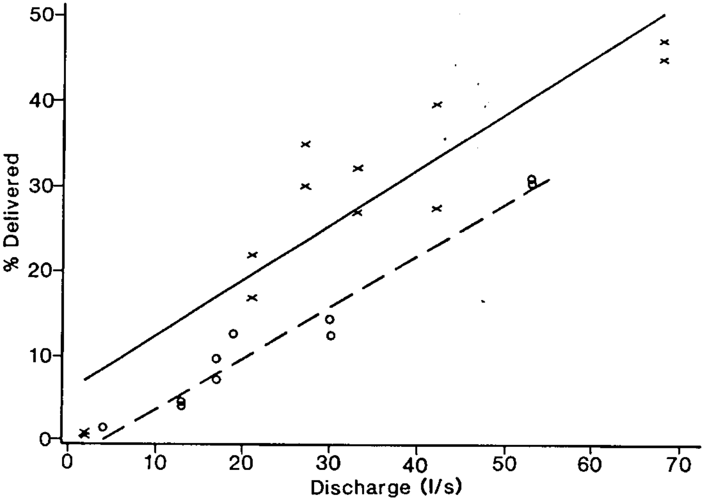

Figure 2. Proportion of the Total Added Sediment Recovered at the Stream Mouth as a Function of Flow in Stream A (X) and K (O). Regression equation for Stream A is $Y = 0.65\ x + 5.78$, $r^2 = 0.84$ and for stream K, $Y = 0.61\ x - 2.34$, $r^2 = 0.96$.

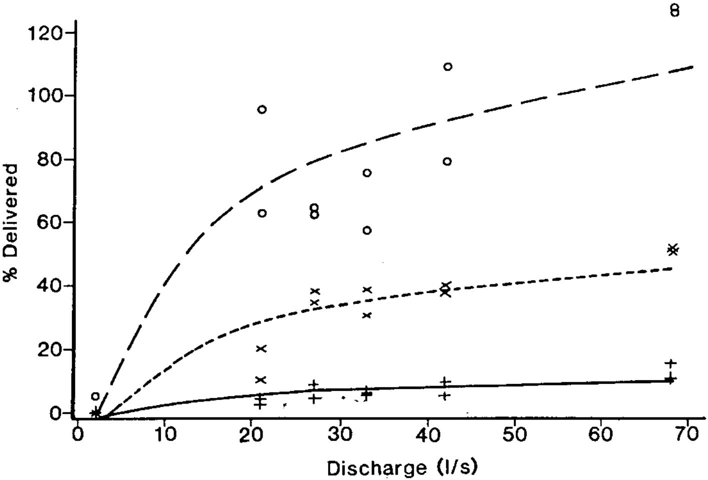

Figure 3. Proportion of Added Sediment Recovered at the Stream Mouth in Each of the Three Size Classes as a Function of Flow in Stream A (2.0 to 0.5 mm +, $Y = 7.70 \log x - 3.60$, $r^2 = 0.94$, 0.5 to 0.063 mm –×–, $Y = 32.28 \log x - 13.24$, $r^2 = 0.94$, < 0.063 mm –○–, $Y = 71.80 \log x - 23.53$, $r^2 = 0.93$).

to the stream at the road crossing, indicating resuspension of fine sediment previously deposited on the streambed.

Tributary K showed basically the same pattern of export as tributary A except that delivery of the two larger size classes of introduced sediment was lower (Figure 4). Material from 2.0 mm to 0.5 mm was retained at a high rate by stream K, a 5 percent delivery rate being exceeded only twice at the highest flows measured. Sediment in the 0.5 mm to 0.063 mm size class also was retained at a high rate by the stream. The finest size class was moved downstream efficiently, exhibiting a delivery rate in excess of 100 percent on one occasion.

A significant difference in delivery rate between the two streams is seen in the 2.0 mm to 0.5 mm and the 0.5 mm to 0.063 mm size classes (ANOVA $P<0.025$). In both cases, stream A moves a higher proportion of the introduced sediment out of the system than stream K at a given discharge. For example, export in excess of 5 percent of the added sediment in the 2.0 mm to 0.5 mm size class and over 30 percent in the 0.5 mm to 0.063 mm size class occurred at a flow of 27 l/s on stream A but required a flow of 53 l/s on stream K.

The difference in delivery rates is most likely a product of the channel characteristics of the two streams (Table 1). Stream K has less slope than stream A and sediment traveled approximately 125 m to reach Mack Creek as opposed to 95 m on stream A. The stream K channel is also wider than stream A, thus bed surface area is greater and the locations favorable for sediment deposition are potentially more numerous. Stream K also has much more in-channel woody debris and vegetation. This woody debris is generally coinposed of limbs, tops and other logging slash varying in diameter from 5 cm to l m. This material has been shown to be extremely effective at retaining sediment in small stream systems both slowing water velocity upstream from the debris. thereby causing sediment in transport to settle. and forming waterfalls which cause a loss in the potential energy of the stream's water with no consequent sediment movement (Heede, 1972; Bilby, 1981). Sediment accumulations behind pieces of debris and among herbaceous plants growing in the channel were much more common on stream K than A. The existence of these accumulations, in part, caused the greater channel width of stream K than A even though watershed area is smaller. Vertical drop of water in the two streams was not very different, however, accounting for 68 percent of the change in elevation over the study reach on stream A and 56 percent on stream K. Woody debris was the predominant factor in waterfall formation on both streams. causing 79 percent of the measured vertical free-fall on stream A and 93 percent on stream K.

These channel characteristics, however, apparently have little direct influence on the transport of material finer than

0.063 mm. In both streams A and K. this fine material was retained at a high rate only during the lowest flows and even modest increases in discharge substantially elevated the delivery rate. Visual inspection of the streams during those trials when the less than 0.063 mm size class was being held in the channel revealed areas where all streamflow infiltrated into the bed. It is likely that this action filtered most of the sediment from the water. The rapid increase in delivery rate seen with rise in flow may indicate a threshold level where discharge exceeds infiltration rate into the channel in these periodically dry areas. However, it is interesting to note that even this very fine sediment was prevented from reaching fish-bearing waters until some minimum flow was achieved. This level of discharge was between 2 l/s and 21 l/s on tributary A and between 4 l/s and 17 l/s on tributary K (Figures 3 and 4). Discharges of this magnitude were equaled or exceeded at least 50 percent of the time on stream A and 25 percent of the time on stream K during the winter (Figure 1).

These experiments demonstrate the effectiveness of small headwater streams at retaining, at least temporarily, the coarser-size sediments (>0.063 mm) washed from roads. By acting as storage areas, small tributary streams reduce the immediate input of sediment of this size to larger streams during storms of moderate intensity. While much of this sediment must ultimately be moved out of the headwater streams, the flow required to do this would be substantial, in view of the fact that only about 10 percent of the material in the 2.0 mm to 0.5 mm size class was moved through stream A and 5 percent through stream K at the highest flows measured (Figures 3 and 4). These discharges represented 69 percent and 66 percent, respectively, of the calculated bankfull flow (Figure 1). Therefore, the tributaries provide a site of temporary storage for the coarser road sediments. During flows of the magnitude necessary to flush stored sediment from ephemeral tributaries, discharge in downstream channels would also be high, As a result, deposition of the sediment released from the tributaries may be substantially less than would be expected if the road sediment had been entering fish-bearing streams directly during each precipitation event. In this fashion, the sediment storage capability of ephemeral tributaries may be contributing to the maintenance of water quality and productive fish habitat.

A comparison of sediment delivery rates between stream A and K displays the importance of physical characteristics of the channel in sediment retention. While both slope and reach length of the two study stream sections were somewhat different, the greatest divergence was seen in the amount of woody debris and herbaceous vegetation in the channels. Inspection of both channels revealed that the largest sediment accumulations invariably occurred behind debris. Debris was also seen to be the predominant waterfall-forming structure on both streams, which further reduces sediment transport. Sediment deposits behind debris were

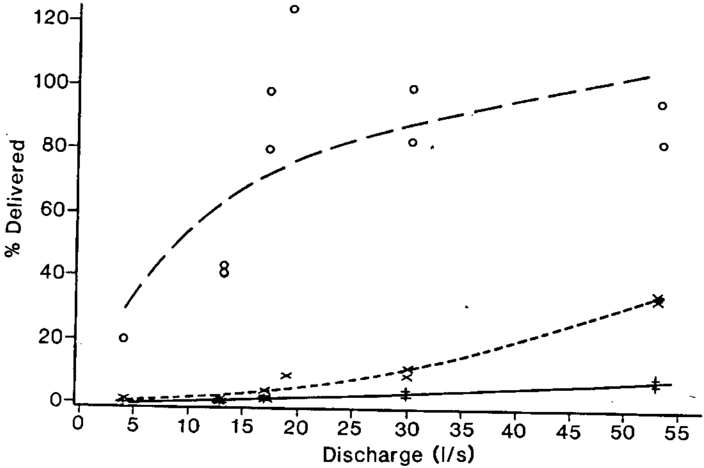

Figure 4. Proportion of Added Sediment Recovered at the Stream Mouth in Each of the Three Size Classes as a Function of Flow in Stream K (2.0 to 0.5 mm +, $Y = 0.027\ x^{1.41}$, $r^2 = 0.99$, 0.5 to 0.063 mm –x–, $Y = 0.012\ x^{2.02}$, $r^2 = 0.99$, <0.063 mm –○–, $Y = 66.63 \log x - 10.77$, $r^2 = 0.97$).