SEDIMENT AND ORGANIC MATTER TRANSPORT IN OREGON COAST RANGE STREAMS

by

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ABSTRACT

Bedload transport, particulate organic matter transport, total suspended solids concentration, and turbidity were monitored during storm runoff at Flynn Creek and Oak Creek in central Oregon's Coast Range. Flynn Creek drains a 2.2 km^2 watershed and Oak Creek drains a 7.5 km^2 watershed; the dominant vegetative cover on both watersheds is Douglas-fir.

Winter precipitation amounts were relatively low during the 1976-1980 water years investigated during this study. Frequency analyses indicated that peak flows had recurrence intervals of less than two years. Rating curves were developed between particulate transport (Y) and streamflow (Q) using using the equation form:

$$Y = a\ Q^b$$

Exponential increases of 3.4 to 4.5 in bedload transport rates with increasing flows were measured using both vortex tube and Helley-Smith bedload samplers. The median particle diameter (d_{50}) of bedload sediments averaged less than 0.5 mm and less than 2 mm for Flynn Creek and Oak Creek, respectively. Coarse particulate organic matter (> 0.2 mm) represented an important but variable component of the total material in transport along the streambed. Channel cross-section measurements indicated localized scour and fill was common during periods of storm-generated runoff.

Rating curves of total suspended solids with streamflow were highly variable but exponential increases in total suspended solids concentrations with increasing flow were generally 1.1 to 1.6 when a wide range of flows were sampled. Total suspended solids concentrations were influenced by (1) streamflow, (2) hydrograph characteristics, and (3) the sequence of storm events. Total suspended solids averaged approximately 60% inorganic sediments and 40% organics. Total suspended solids concentration was found to be highly correlated with turbidity. Turbidities (and total suspended solids concentrations) returned to relatively low levels within 24 hours after peak flows had occurred.

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INTRODUCTION

In the past decade, extensive progress has been made toward the control of point sources of water pollution. Federal and state water quality goals have been established in an attempt to reduce the magnitude of cultural impacts upon aquatic ecosystems. However, achievement of these goals may be overshadowed by the effects of non-point sources (Cannon, 1976; Government Accounting Office, 1978). The major non-point pollution problem resulting from man's land use activities is accelerated sedimentation (Guy and Ferguson, 1970; Livesey, 1970; Froehlich, 1976).

Theory indicates that a certain fluvial sediment load is necessary to maintain the physical integrity of a stream system (Committee on Erosion and Sedimentation, 1977). A dynamic equilibrium is established between channel form and the natural sediment regime that provides for both stability and resiliency (Heede, 1975; Park, 1976). However, increases in sediment load can initiate channel adjustments that alter the physical and biological processes maintaining stream stability. Repeated episodes of sediment loading may throw the system into disequilibrium (Rosgen, 1978).

Material transfer from undisturbed forested watersheds in the Pacific Northwest is controlled by channel processes that ultimately break down and transport dissolved and particulate substances derived primarily from the hillslopes (Swanson *et al.*, in press). The ability of a stream to transport available solids is dependent on local hydraulic and streambed conditions, and on the size and density of the material. Solution transport is the only persistent process. Dissolved solids may be viewed as the dominant export mode, representing a large fraction of the total load in wet climates (Leopold *et al.*, 1964). In contrast, particulate transport may range from frequent, low-magnitude suspended transfer to infrequent, but high magnitude debris torrent activity in mountain watersheds (Swanson *et al.*, in press). The inchannel substrates that support biotic processes consist of both inorganic and organic matter. These materials determine the quality of habitat available to the predominantly heterotrophic communities present in headwater streams. Thus, particulate matter transport, primarily of bed material, is an important parameter in studies of both stream channels and the associated biotic community.

A stream bed represents a unique liquid-solid interface that is subject to periodic deformation (Graf, 1971). Bed material transport is of primary concern since its movement reflects channel stability and determines gravel bed composition (Johnson, 1970; Milhous and Klingeman, 1973; Beschta and Jackson, 1979). Sediment motion results from the action of hydrodynamic and gravitational forces on particles within a turbulent medium. This interaction results in a biphase flow, which varies continuously in time and space. Particles may either move on or near the bottom as bedload or be transported in suspension. Momentary hydraulic conditions determine the extent of active interchange between the static components of the bed, the bedload, and the suspended load (Graf, 1971).

Thus, distinctions between the two modes of transport near the stream bed are arbitrary.

Present knowledge of the mechanisms of sediment tranport is at a qualitative level (Committee on Erosion and Sedimentation, 1977). Adequate characterization of the sediment regime in natural streams requires simultaneous study of both the suspended and bedload components of bed material load. Suspended sediment measurement techniques are well documented (Vanoni, 1975). Although bedload may comprise a relatively small portion of the total sediment load, its movement has the dominant influence on channel characteristics. Direct measurement of bedload is difficult due to the highly stochastic nature of this transport mode (Graf, 1971; Griffiths, 1980). Sampling requires an intensive field effort during high flow events initiated by storm or snowmelt runoff. In addition, field studies of bedload movement have been limited by a lack of reliable sampling methods. Variations in research techniques have compounded the problems of data analysis and comparison.

As a consequence, various bedload transport equations have been developed to estimate this total load fraction (Graf, 1971; Vanoni, 1975). The formulas predict the maximum transport capacity of a stream in equilibrium at given hydraulic conditions and sediment characteristics (Graf, 1971). The applicability of these steady-state models to bedload movement in small mountain streams has been studied by a number of investigators (Klingeman, 1971; Nanson, 1972; Haddock, 1978). The models appear inapplicable to high energy, headwater streams in which sediment supply limitations exist as a result of flushing, deposition, and armoring (Milhous and Klingeman, 1973; Haddock, 1978).

Relationships between particulate transfer processes in a mountain stream are not well understood. The supply of transportable bed materials may be strongly dependent on the condition of the bed armor layer and the magnitude of transient flow events (Klingeman, 1971). The natural flushing regime in a mountain stream may be hindered by input of additional fines which, while being transported, could utilize stream energy otherwise available to disturb the stream bed (Beschta and Jackson, 1979). The retention-transport mechanisms and possible interactions of coarse particulate organic debris in the fluvial transfer system are not well known.

The transport of sediment and organic matter in mountain streams is the result of numerous interacting processes. Before comprehensive models of particulate (organic and inorganic) transport in streams can be developed, these processes must be more thoroughly described through field research. A unified concept of material transport would enhance our ability to: 1) estimate sediment yields, 2) assess the physical and biological consequences of sediment movement, and 3) prescribe land use quidelines for the mitigation of potential instream damage (Cannon, 1976).

Although a substantial number of watershed studies have been conducted in forested regions and have measured sediment yields from both undisturbed and managed watersheds (e.g., Fredriksen, 1970; Megahan,

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1975; Beschta, 1978, Rice *et al*., 1979), few of these have attempted to evaluate sediment transport rates during storm periods. In contrast, this study utilized time-intensive sampling to evaluate transport processes during periods of high flow when hydraulic conditions within the channel were rapidly changing.

OBJECTIVES

The overall objective of this study was to provide an improved understanding of sediment and organic matter movement in mountain streams. Specific objectives included the following:

(1) Determine rates of suspended sediment, bedload sediment and particulate organic matter transport during periods of storm runoff.

(2) Evaluate the effect of flow conditions upon the variability in suspended sediment concentrations and resultant sediment rating curves.

(3) Identify relationships between turbidity and suspended sediment concentrations.

(4) Develop an improved understanding of the interactions between suspended sediment, bedload sediment, and particulate organic matter transport.

(5) Develop correlations between bedload transport rates and streamflow for identifying conditions necessary for incipient bedload movement and the frequency of occurrence of bedload transport.

This report summarizes streamflow and sediment transport data for water years (WYs) 1977-1980 and WYs 1976-1980 at Flynn Creek and Oak Creek, respectively. At Flynn Creek, data collected during the first two years of the study, WYs 1977 and 1978, formed the basis of a Masters of Science thesis by O'Leary (1980). WY 1979 results at Flynn Creek have been reported in another Masters of Science thesis by Edwards (1980). Previously unreported data for WY 1976 at Oak Creek and for WY 1980 at both Flynn Creek and Oak Creek are included in this report.

Suspended sediment and turbidity comparisons for both watersheds have been reported by Paustian (1978), Paustian and Beschta (1979), and Beschta (1980c). Additional bedload transport and channel morphology data were collected at Flynn Creek during WY 1979 (but not included in this report) as part of another study and forms the basis for a conceptual model of bed material routing in mountain streams (Jackson, 1980). It should also be noted that Flynn Creek was used as the undisturbed "control" watershed in the Alsea Watershed Study during WYs 1959-73. Summaries of that study can be found in Brown (1972), Harris (1973, 1977), Moring (1975 a, b), Moring and Lantz (1975), and Beschta (1978). Previous studies of bedload transport at Oak Creek include those by Milhous and Klingeman (1973) and Heineke (1976).

STUDY AREAS

The two streams monitored in this study drain watersheds located in the central Oregon Coast Range (Fig. 1). The Flynn Creek Watershed is located about 20 km southeast of Newport and is a designated "Research Natural Area" administered by the Siuslaw National Forest. The Oak Creek Watershed, located 11 km northwest of Corvallis, is managed by the School of Forestry at Oregon State University. This watershed is used as a teaching and research facility in addition to commercial forest management activities (road construction, yarding timber, regeneration operations, etc.).

The Flynn Creek Watershed is 2.2 km^2 in size and ranges in elevation from 180 to 400 m. The Oak Creek Watershed is approximately 7.5 km^2 in size and ranges in elevation from 150 to 660 m. More detailed descriptive information for Flynn Creek is reported by Paustian (1978), O'Leary (1980), and Edwards (1980). Paustian (1978) also presents detailed information of Oak Creek. Additional streamflow data for Flynn Creek, collected prior to this study (i.e., WYs 1959-73), have been summarized by Harris (1977).

Climate

The climate at both watersheds is largely influenced by marine air masses which move inland from the Pacific Ocean. Characteristically, summers are warm and dry, and winters are wet and cool. Almost 90% of the annual precipitation occurs between October and April. Most of this winter precipitation results from long duration, low intensity frontal storms. However, periods of relatively high precipitation intensities may occur within any given storm and result in freshets or periods of storm flow from the watersheds. Annual precipitation averages 230 cm at Flynn Creek but only 150 cm at Oak Creek. Snowfall amounts are typically small and any accumulations of snow on the ground may last for only a few days. Because of orographic effects and variations in characteristics of frontal storms, precipitation amounts and intensities for any given storm can vary appreciably between the two watersheds.

Vegetation

Both basins are densely forested with predominately 100- to 200-year-old stands of Douglas-fir (Pseudotsuga menziesii) on the hillslopes and red alder (Alnus rubra) throughout the riparian zones. Western redcedar (Thuja plicata) is found on the uplands of both watersheds. At Oak Creek, Oregon, white oak (Quercus garryana) and bigleaf maple (Acer

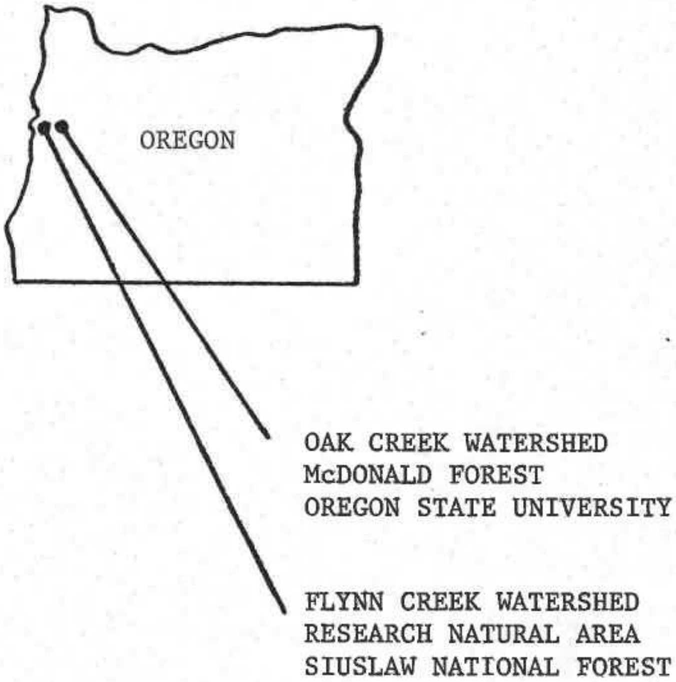

FIGURE 1. Location of Flynn Creek and Oak Creek Watersheds in the Oregon Coast Range.

macrophyllum) are also common. Understory vegetation is normally dense and provides protection from surface erosion processes. Large organic debris (root wads, boles, or large branches) has a major influence on channel morphology for both watersheds; debris dams and log steps are a major factor influencing pool-riffle sequences within the channel system.

Soils, Geology and Topography

The geological characteristics of the two watersheds are considerably different. The Flynn Creek Watershed is underlain by the Flornoy Formation (formerly designated as Tyee sandstone), a rhythmically bedded sandstone and siltstone which is subject to rapid attrition. Soils in the drainage are thus derived from sandstone parent material, with 60% of the watershed covered by soils in the Slickrock Series. Soils on the remainder of the watershed are mostly in the Bohannon Series (USDA, 1973). Both soil series have moderate to high erosion potential. Bed material in the channel is also sandstone which often rapidly weathers or mechanically abraids to sand-sized particles. Except for bedrock sections of the channel, cobbles 1-10 cm in diameter typically overlay sandy bed material. Additional hillslope and channel characteristics for Flynn Creek and Oak Creek are summarized in Table 1. Morphometric analysis indicates the Flynn Creek Watershed has 9.0 km, 2.9 km, and 1.1 km of 1st-, 2nd-, and 3rd-order channels (Marston, 1978).

The Oak Creek Watershed is located within the Marys Peak Instrusion Formation. Bedrock consists of basalts which weather into clay-loam soils. Dixonville and Price-Ritner Soil Series comprise most the watershed. Streambed sediments along the main channel are heterogenous mixtures of gravel, sand, and silt overlain by a distinct armor layer with particles averaging 5-10 cm. The upper reaches of Oak Creek are deeply incised and portions appear similar to a gully system.

Mass soil movements (debris avalances, slumps, and creep) with associated streambank undercutting at high flows are thought to be the major sediment contributing processes at both watersheds.

TABLE 1. Selected hillslope and channel characteristics of Flynn Creek and Oak Creek Watersheds.

Characteristics	Flynn Creek	Oak Creek
Average Hillslope	34%[a]	--
Channel Length	1433 m[b]	2900 m[d]
Channel Gradient	0.025 m/m[c]	0.04 - 0.24 m/m[d]
Mean Summer Width	1.74 m[b]	4 m[d]
Mean Summer Depth	0.13 m[b]	10 cm riffles[d] 1 m pools

[a] Williams, 1964

[b] Chapman, 1961

[c] Moring and Lantz, 1975

[d] Paustian, 1978

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METHODS

Precipitation and Streamflow

A weighing precipitation gage was installed at each watershed during the winter months (October through March) to provide supplemental information on rainfall intensity, duration and amount during storm runoff periods.

Water level records at Flynn Creek were obtained at a broad-crested v-notch weir approximately 300 m upstream from the mouth of the watershed. Periodic stream gaging was used to establish and check rating curves. At Oak Creek, a rectangular section of concrete channel (i.e., flume) was used as a control section for stream gaging and water level records. A rating curve developed by Heineke (1976) was used throughout this study for estimating flows at Oak Creek.

Bedload and Particulate Organic Matter Transport

Vortex Tube Sampler

At the mouth of the 2.2-km^2 Flynn Creek Watershed, a concrete fishtrap was constructed in 1960 as part of a previous fisheries study. The fishtrap provided a uniform rectangular control section (2.54-m wide, 1.37-m deep, and 5.38-m long) which was easily modified for installing a vortex bedload sampler in the summer of 1976. The vortex sampler at Flynn Creek (Figure 2) is similar in principle to those used by Hayward and Sutherland (1974) and Klingeman and Milhous (1970).

The vortex sampler at Flynn Creek consisted of a 30.5-cm diameter tube, with a 20.3-cm opening along the top, which was placed into the bed of the fish trap (control section). The tube was placed at an angle of 65° to the direction of flow and had a total length of 2.8 m. Five-centimeter wide wooden strips of cedar were mounted at each edge of the tube to provide a tight contact with the concrete bed of the fishtrap (Figure 3). Experience at Oak Creek had shown that without the wood, concrete near the edge of the tube would chip and crack after several years and perhaps alter hydraulic conditions at the edges of the vortex tube. Four years of use at Flynn Creek have shown that these wood strips appear to have overcome this problem.

As a mixture of water-sediment enters the tube, a circular or vortex flow pattern is established. With one end of the tube open, this mixture is discharged into a sampling area adjacent to the channel where flows can be either bypassed back into the stream between sampling periods or

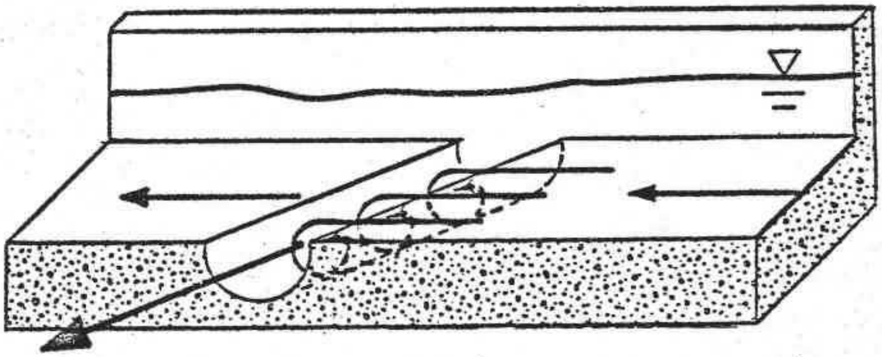

FIGURE 2. Schematic of vortex tube bedload sampler at Flynn Creek (After Hayward and Sutherland, 1974, p. 42).

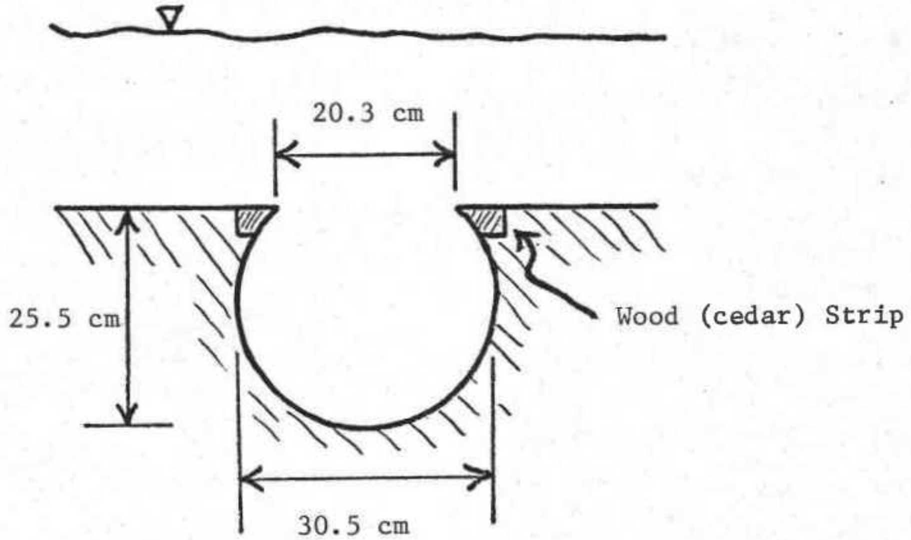

FIGURE 3. Cross-section of vortex tube bedload sampler at Flynn Creek.

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into a 0.3-m^3 sampling box. Bedload paticles are deposited in the sampling box and the overflow water returned to the stream. A sample volume of about 6 ℓ or less of material was considered desirable for ease of handling. Thus, sampling periods varied from 3 minutes to 1 hour in length, depending upon flow and sediment transport conditions, to accumulate a sample of approximately this size.

The vortex sampler at Flynn Creek was operational for the WYs 1977-1980, although it was only used extensively only in WYs 1978 and 1979. Vortex samples were dried at 105°C for 24 hours after which any visible organic matter was removed by hand. The samples were then sieved and weighed to obtain total weights and particle size distributions. Because the vortex sample box had a variable trapping efficiency for sediments from 0.15 to 10 mm in diameter, an adjustment procedure was used for these particle sizes to obtain more accurate estimates of that bedload transport and median particle sizes (O'Leary, 1980).

Helley-Smith Sampler

A Helley-Smith pressure-differential bedload sampler (Helley and Smith, 1971) with a bag surface area and mesh size of 1950 cm^2 and 0.2 mm, respectively, was used to provide supplemental transport information in the 1978 WY. This hand-held version was subsequently modified by increasing the bag size to 6000 cm^2 (Johnson, et al., 1977; Beschta 1980a) and was used as the primary sampling method during the 1979 and 1980 WYs at Flynn Creek. At Oak Creek, this sampler was employed only during the 1980 WY.

At Flynn Creek, the Helley-Smith bedload sampler was used near the upstream end of the fishtrap where an excellent contact between the concrete bed and the sampler was assured. Equally-timed subsamples were obtained at seven equally spaced locations across the channel and combined to produce a single composite sample. In WY 1978, subsamples were taken for 15 s at each of the first three locations across the channel. The sample bag was then emptied and sampling continued at the remaining four locations. Upon changing bag size (WYs 1979 and 1980), clogging of the mesh was not as significant a problem and all seven subsamples (sampling time = 30 s at each location) were obtained before the sampler was emptied. However, during periods of high flow and high transport rates, total sample times were reduced below 210 s to minimize clogging of the sample bag. Although subsample times were always equal, total sample time for a composite sample was varied from 35 to 210 s depending upon the amount of sediment in transport. After allowing the bedload sediments and organics from each sample to settle for several minutes in a collection pan, water was decanted from the sample and the sample was stored in a plastic bag for later analysis.

In the laboratory, Helley-Smith bedload samples were dried at 105°C for 24 hours, weighed and then ashed at 320°C to remove organic materials. After reweighing the samples, both inorganic (bedload sediment) and organic (particulate organic matter) transport rates were calculated.

Samples were also sieved to determine particle size distributions of the inorganic component.

Channel Measurements

During the summer of 1976, 12 cross-sections were located at Flynn Creek between the fishtrap and the weir. These cross-sections were spaced at approximately 30-m intervals. Profile measurements were taken during succeeding years to index net scour and/or deposition. In addition, glass marbles of varying sizes (9.5, 14, and 22 mm) were placed within 5 cm of the bed surface at each cross-section. The marbles at each cross-section were used to estimate relative distances of travel for particles in 9.5- to 20-mm diameter range.

Total Suspended Solids and Turbidity

Automatic pumping samplers (Instrument Specialties Company, Model 1392) were used to collect samples for subsequent laboratory analysis of suspended solids and tubidity. At Flynn Creek, the sampler intake was located in the plunge pool directly downstream of the weir so that a well-mixed sample could be obtained. At Oak Creek, after trying a variety of methods, the intake was supported in midstream on the end of a metal rod attached to a small bridge (Beschta, 1980b).

The automatic pumping samplers were connected to a "stage-activated" system whereby the sampler would begin sampling when the stage (water level) of the stream reached a preset level (Beschta, 1980b). Once activated, the pumping sampler would continue to sample until the 28-bottle capacity was exhausted. Subsamples were obtained every 0.5 hours with two subsamples per bottle. Thus, each bottle contained a sample from which the average hourly suspended solids concentration could be determined.

Standard filtration and gravimetric techniques were utlized for the laboratory analysis of total suspended solids (American Public Health Association, 1976). Selected samples from the 1980 WY were ashed at 500°C to obtain an estimate of the organic component of the total suspended material. Methods outlined by the American Public Health Association (1976) were similarly utilized for determining turbidity using a model 2100A laboratory turbidimeter (Hach Chemical Company).

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RESULTS AND DISCUSSION

Precipitation and Streamflow

Precipitation amounts during the study period were below normal. As a result, streamflow volumes were similarly low. During the November through March periods in WYs 1977-1980, approximately 65% of the winter precipitation was measured as streamflow at the mouth of these watersheds.

The 1977 WY had particularly low amounts with November through March precipitation totals for both Flynn Creek and Oak Creek (Table 2 and Table 3) less than one-half of average. The November-March water yield of WY 1977 at Flynn Creek was the lowest measured during 19-years of record. This period of extremely low precipitation was not a local phenomenon but prevailed throughout most of the western states that year.

Hydrographs of daily streamflow at Flynn Creek (Figure 4) further reflect the relatively low flows during the study. Although seasonal streamflow volumes are not necessarily good predictors of peak flows, the effects of the relatively low runoff volumes was also apparent in the peak flows experienced over the four years. Frequency analysis of instantaneous peak discharges at Flynn Creek, based on 20 years of record (WYs 1959-72 and 1976-80), indicates the instantaneous peak flows for WY 1977 and WY 1980 were the lowest of record (annual series, Figure 5). In addition, WY 1978 and WY 1979 had recurrence intervals of less than two years.

Utilizing the largest 20 flow events of record (partial series) shifts the expected recurrence intervals for the WY 1978 and WY 1979 peaks to 1.30 and 1.24 years, respectively (Figure 5). Frequency analysis for daily flows at Flynn Creek (Figure 6) show similar patterns. Long-term flow records were not available for Oak Creek and thus flow frequency analyses were not undertaken. Hydrographs of daily streamflows at Oak Creek are shown in Figure 7. In any event, precipitation and flow data confirm that both watersheds experienced relatively low instantaneous, daily, monthly, and seasonal flows during the study.

Sampling Efficiency of Bedload Samplers

Vortex Tube Sampler

One of the initial concerns of this study was the sampling efficiency of the vortex sampler. Thus, several types of measurements were undertaken to quantify the relative efficiency of this bedload sampler.

TABLE 2. Monthly precipitation and streamflow at Flynn Creek.

	Months					
Water year	Nov.	Dec.	Jan.	Feb.	Mar.	Total
	Precipitation, cm					
1977	9.1	9.6	7.4	25.6	34.5	86.2
1978	46.7	53.1	32.8	--	8.4	--
1979	24.6	20.8	14.0	50.3	14.0	123.7
1980	21.6	41.6	39.6	24.9	20.8	148.5
	Streamflow, cm					
1959-72[a]	20.9	35.3	44.7	31.4	27.8	160.1
1977	2.8	3.4	5.4	9.5	33.5	54.6
1978	33.7	59.4	32.6	17.4	9.3	152.4
1979	4.3	15.9	9.4	39.8	18.4	87.8
1980	10.4	25.9	31.1	12.6	15.4	95.4

[a] From published U.S. Geological Survey streamflow records.

TABLE 3. Monthly precipitation and streamflow at Oak Creek.

	Months					
Water year	Nov.	Dec.	Jan.	Feb.	Mar.	Total
	Precipitation, cm					
1977	3.8	5.6	3.6	12.7	17.8	43.5
1978	21.8	27.9	17.3	11.4	4.1	82.5
1979	--	6.3	6.6	24.9	--	--
1980	13.0	15.8	13.0	11.7	11.6	65.1
	Streamflow, cm					
1977	--	3.1	2.4	2.3	7.1	--
1978	6.3	20.3	12.9	7.8	1.8	49.1
1979	0.7	2.4	1.8	15.0	7.2	27.1
1980	5.2	8.0	16.1	5.0	10.7	45.0

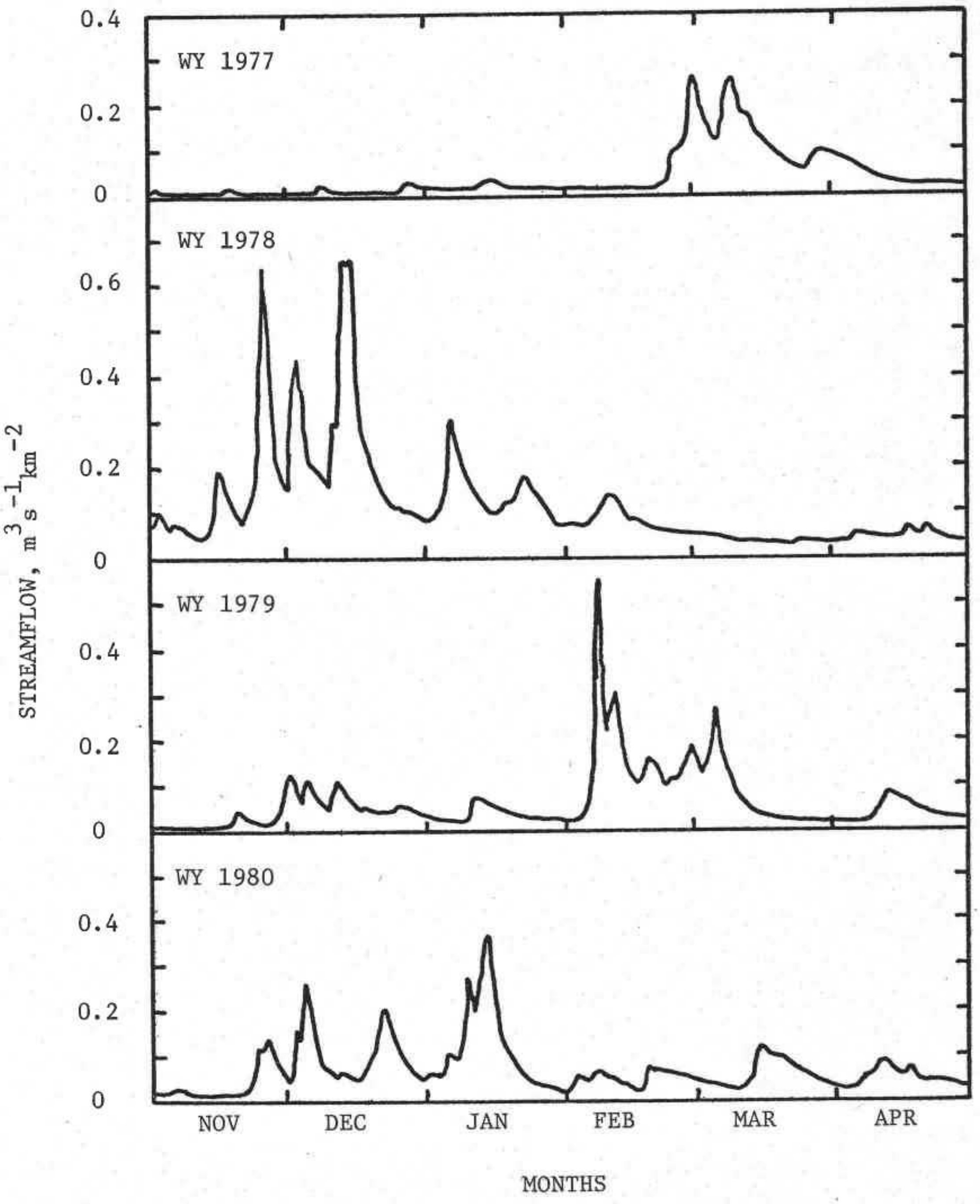

FIGURE 4. Daily streamflow for November through April at Flynn Creek, WYs 1977-1980.

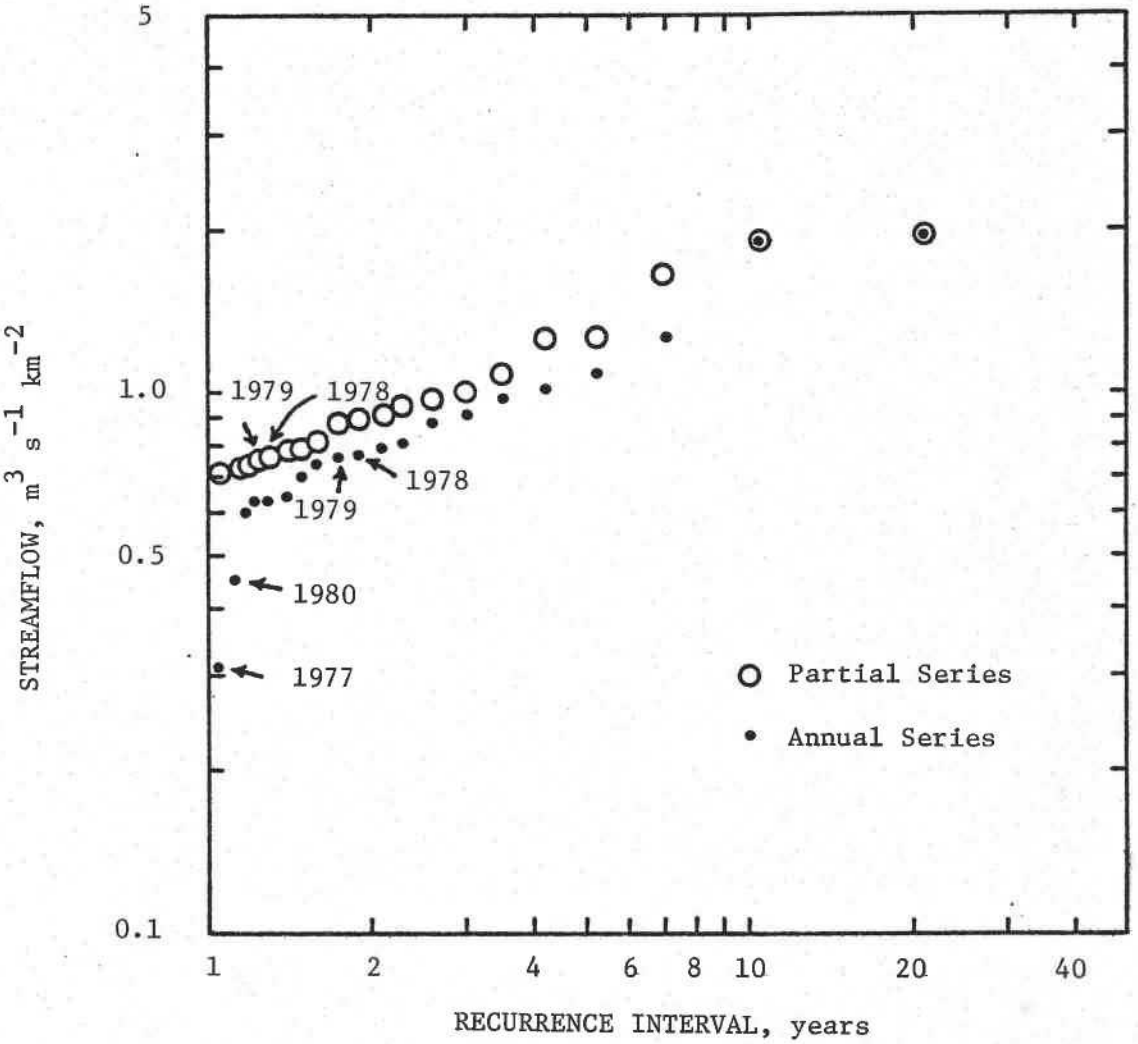

FIGURE 5. Frequency of instantaneous peak flows at Flynn Creek (20 years of record).

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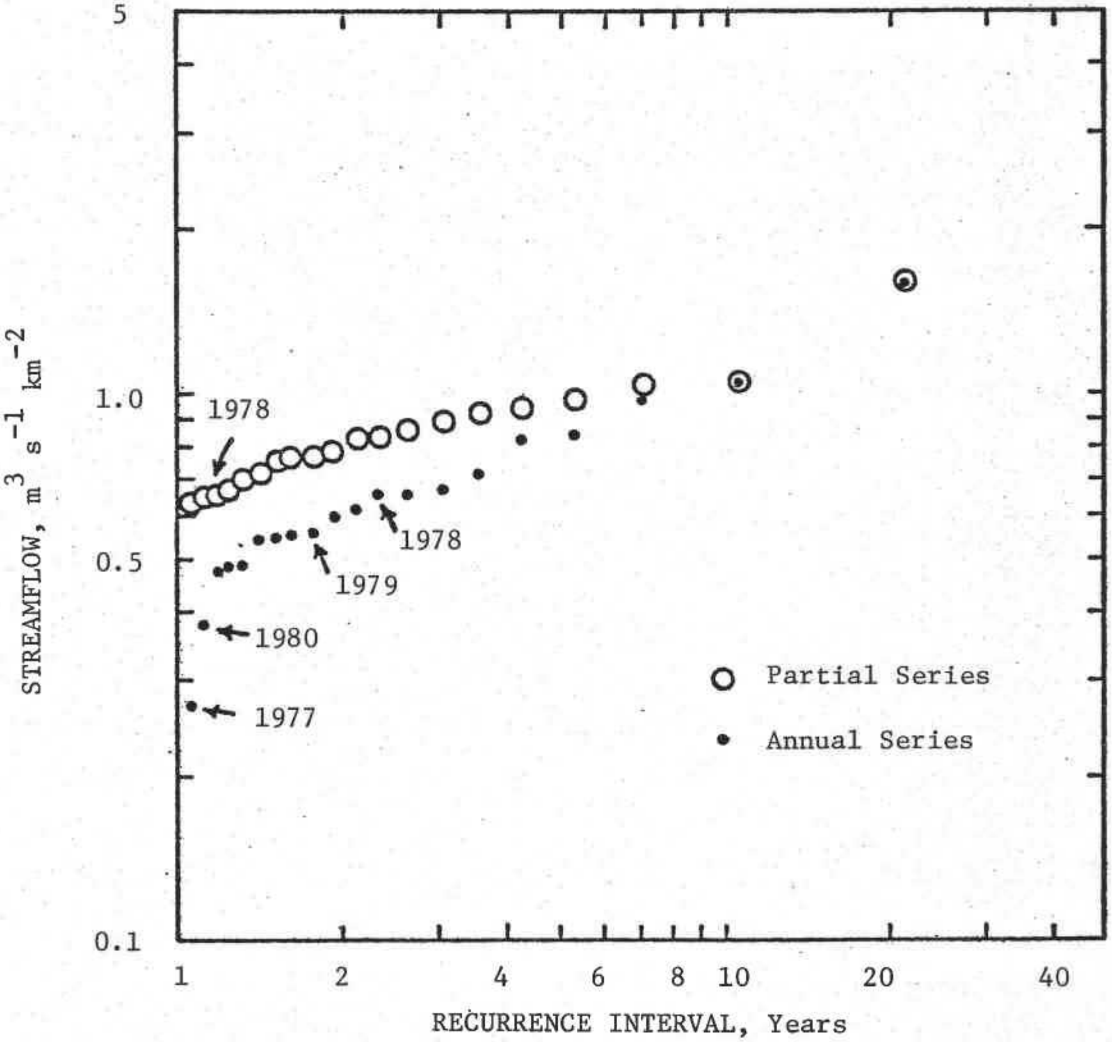

FIGURE 6. Frequency of peak daily flows at Flynn Creek (20 years of record).

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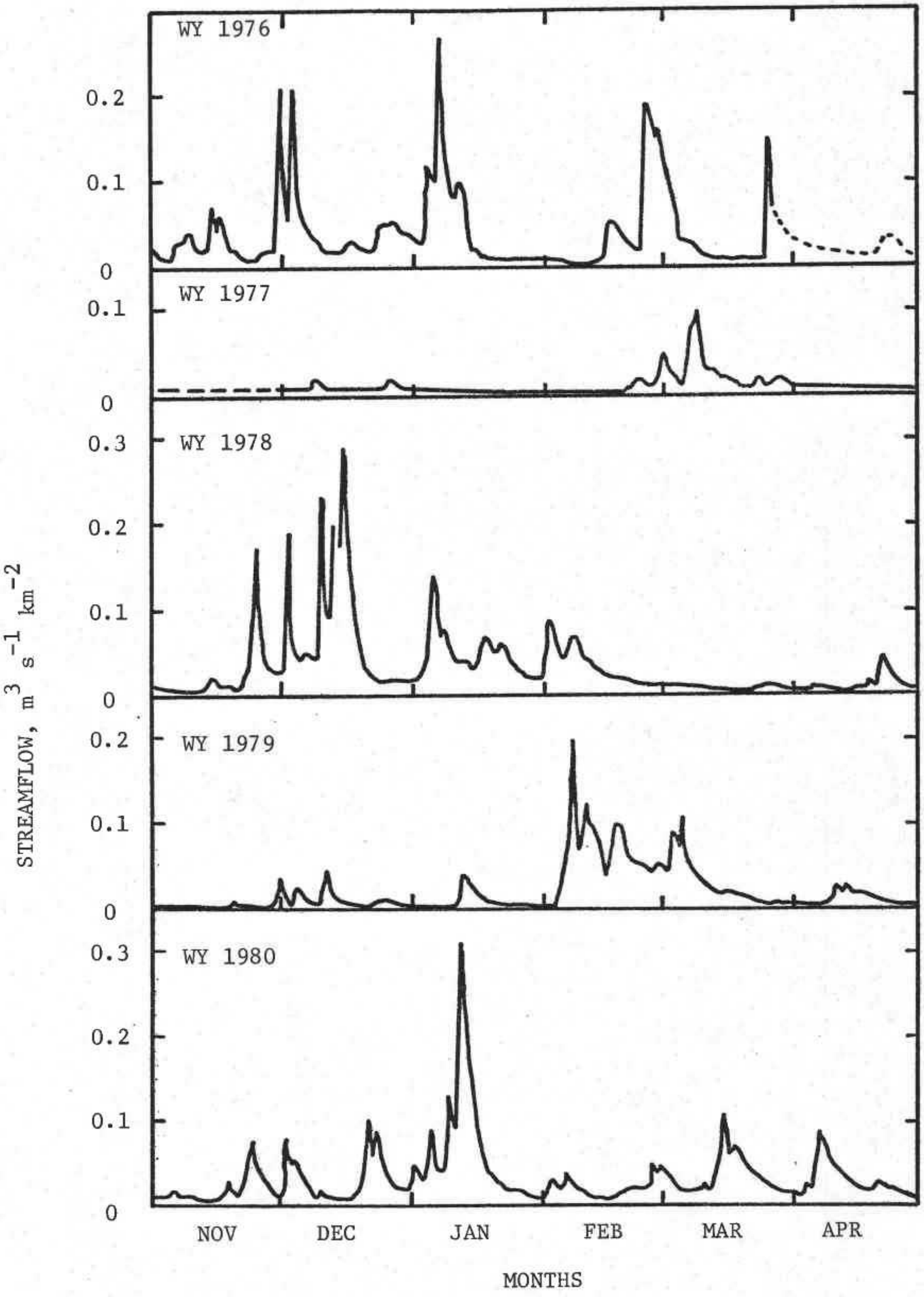

FIGURE 7. Daily streamflow for November through April at Oak Creek, WYs 1976-1980.

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It was originally assumed the sampler would be inefficient with clay and silt-sized particles, a variable efficiency through the sand sizes and nearly 100% efficient in the gravel sizes. The sampler was also expected to be ineffective at trapping organic matter. However, one of the major advantages of the vortex device is that it samples the entire channel width and thus sampling errors due to variations in transport rates across the channel should be minimal.

Bed material samples collected immediately upstream from the Flynn Creek fishtrap showed that the median particle size (d_{50}) ranged from 1 to 11 mm and averaged 5 mm. Unfortunately, based on measurements of sampling efficiency, this particle-size range represents a size that the Flynn Creek vortex tube was not 100% efficient at trapping. This was the primary reason for not utilizing the vortex sampler extensively after the 1979 WY. A sampling efficiency of less than 100% was the result of two characteristics of the sampler. One involved the sampling efficiency of the vortex tube in the stream and the second was due to the sample box.

During periods of storm runoff, the amount of organic matter (leaves, needles, cones, pieces of wood and small branches) is relatively high in Flynn Creek and at times may represent 50% of the total particulate load in transport. This is particularly the situation with the first major fall storms. While operating the vortex sampler during these storms, we observed that leaves, twigs, and branches would accumulate on the downstream edge of the vortex tube. Periodically, these organics had to be manually removed. Whether this buildup substantially affected the trapping efficiency of the vortex tube is not known. Although the sampling efficiency (based on a comparison with Helley-Smith samples) appeared to be lower during periods of high organic matter transport, variability in the data precluded any definitive conclusions.

The hand-held Helley-Smith bedload sampler (0.2-mm mesh size; 1950-cm^2 bag surface area) was used during WY 1978 to measure transport rates immediately upstream and downstream from the vortex tube. Regression analysis indicated that approximately 63% of the material in transport upstream from the vortex was being measured by the downstream sampler (Figure 8). Thus, only 37% of the material ($\geq$ 0.2 mm) in transport within the lower 7.6 cm of the stream was being sampled by the vortex tube.

Because the vortex sampler would most likely be effective at trapping the larger particles in transport, the d_{90} of upstream and downstream samples were also compared. Any change in d_{90} between upstream and downstream samples would thus index the relative efficiency of the vortex tube over a range of particle sizes. Regression analysis resulted in the following:

$$Y = 0.74\ X^{0.54} \qquad r^2 = 0.53$$

where Y = d_{90} of downstream Helley-Smith samples, mm
X = d_{90} of upstream Helley-Smith samples, mm

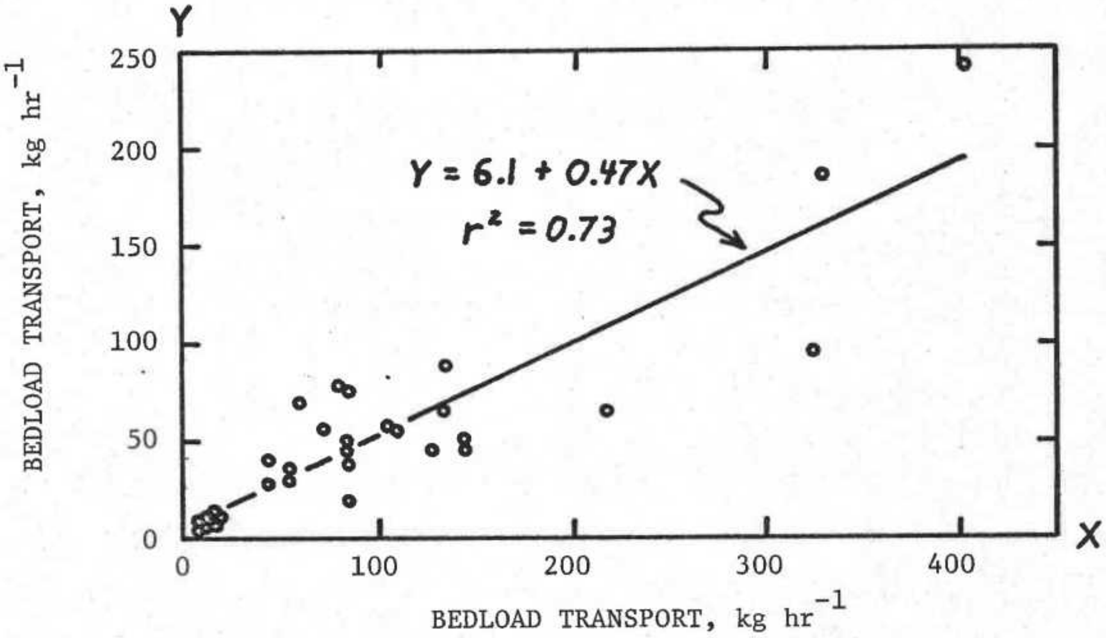

FIGURE 8. Comparison of bedload transport rates measured with the Helley-Smith sampler immediately upstream (X) and downstream (Y) of the vortex tube.

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The range of d_{90}'s over which the above equation was developed was from 0.5 to 5.2 mm for upstream samples. This relationship indicates that as particle size increases, an increasing proportion of the particles will be trapped by the vortex tube. For example, at a d_{90} upstream of 1.0 mm, the d_{90} downstream would be 0.74 mm. This relatively small change indicates the vortex tube at Flynn Creek is inefficient at trapping sand-sized particles. However, for an upstream d_{90} of 5 mm, the downstream d_{90} would be 1.76 mm, indicating the vortex tube is increasing efficient with larger particle sizes. Sampling efficiencies of the vortex tube at Flynn Creek are probably close to 100% for gravel particles > 10 mm in diameter and cobble particles (64-256 mm).

Once water and sediment enter the vortex tube, they then flow to the sample box where the sediments settle out and the overflow water returns to the stream. Tests conducted during the summer of 1976 indicated that the trapping efficiency of the sample box varied with particle size but that it was also nearly independent of the amount of water diverted by the vortex tube. The amount of water diverted through the tube during these tests ranged from 0.10 to 0.16 $m^3\ s^{-1}$. Additional confirmed tests conducted in the summer of 1977 (at a vortex flow of 0.16 $m^3\ s^{-1}$) confirmed a rapid drop in sample box efficiency with a decrease in particle size (Figure 9). For particles > 10 mm in diameter, the sample box was nearly 100% efficient, whereas for particles < 0.2 mm trapping efficiencies are essentially zero. Thus, even if the vortex tube was 100% efficient for particles 0.2 to 10 mm in diameter (which it was not) the variable efficiency of the sample box over this particle-size range created additional problems. A comparison of bedload transport rates based upon the amount of material caught by the sample box and the upstream Helley-Smith indicated the vortex system (including inefficiencies due to both the tube and sample box) was trapping only 15% of the total bedload in transport (Figure 10). Because the d_{50} of bedload in transport at Flynn Creek is typically < 1 mm, the vortex sampler may not accurately measure actual transport rates. After the 1979 WY vortex measurements at Flynn Creek were deemphasized and more intensive sampling with the Helley-Smith sampler (0.2-mm mesh size; 6000-cm^2 bag size) was employed.

During the runoff events of WY 1978, nearly 200 bedload samples were obtained with the vortex sampler. These samples were individually sieved to obtain particle-size distributions. The relationship shown in Figure 9 was then used to adjust transport rates based on the measured inefficiencies of the sample box. No attempt was made to further adjust sample weights to compensate for the effects of the vortex tube. Thus, the transport rates based on the vortex sampler and presented in this report represent conservative estimates of actual transport rates in Flynn Creek. Although absolute transport rates averaged only 40% to 50% of those measured by the Helley-Smith sampler (Figure 10), the bedload transport rates measured with the vortex sampler are assumed to index relative transport rates over time and with changing flows. These data thus provide important insights and evidence regarding the dynamics of bedload transport in Coast Range streams.

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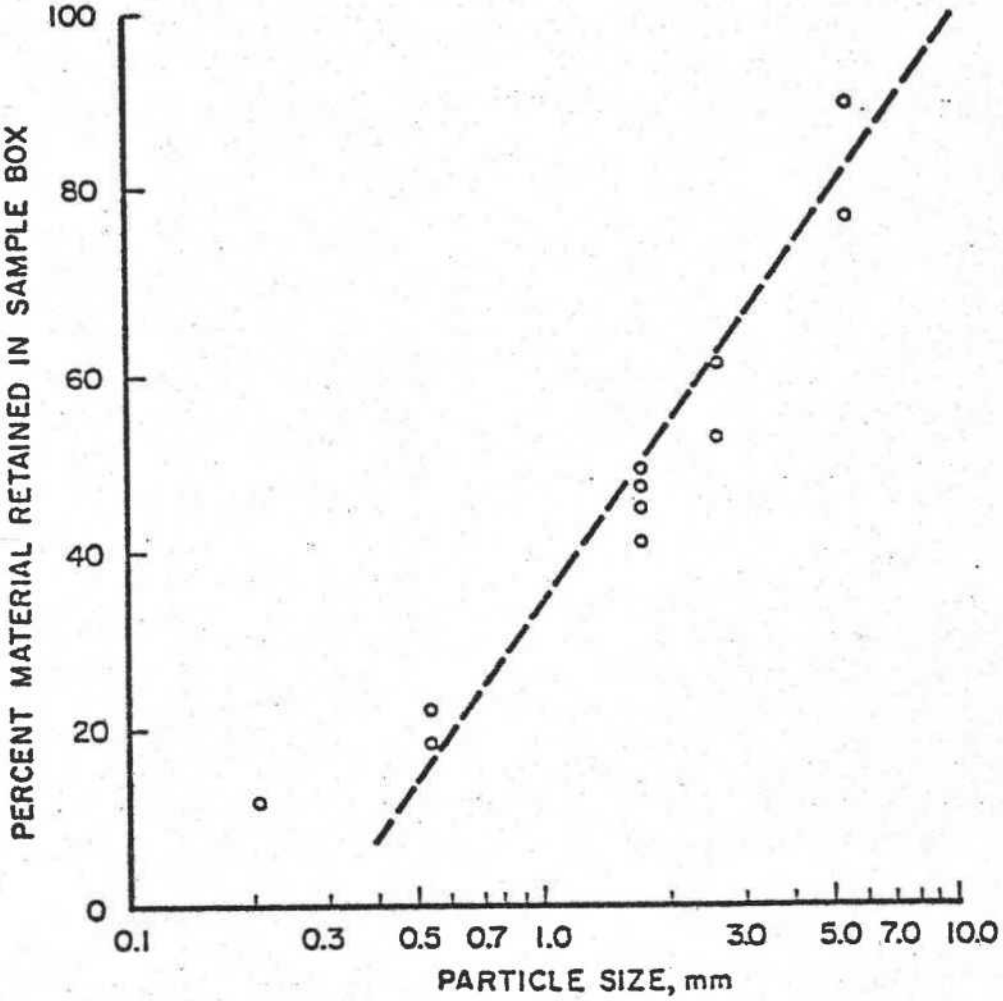

FIGURE 9. Trapping efficiency of the vortex sampling box in relation to sediment particle size at a constant water flow of 0.16 m^3 s^{-1} through the vortex tube.

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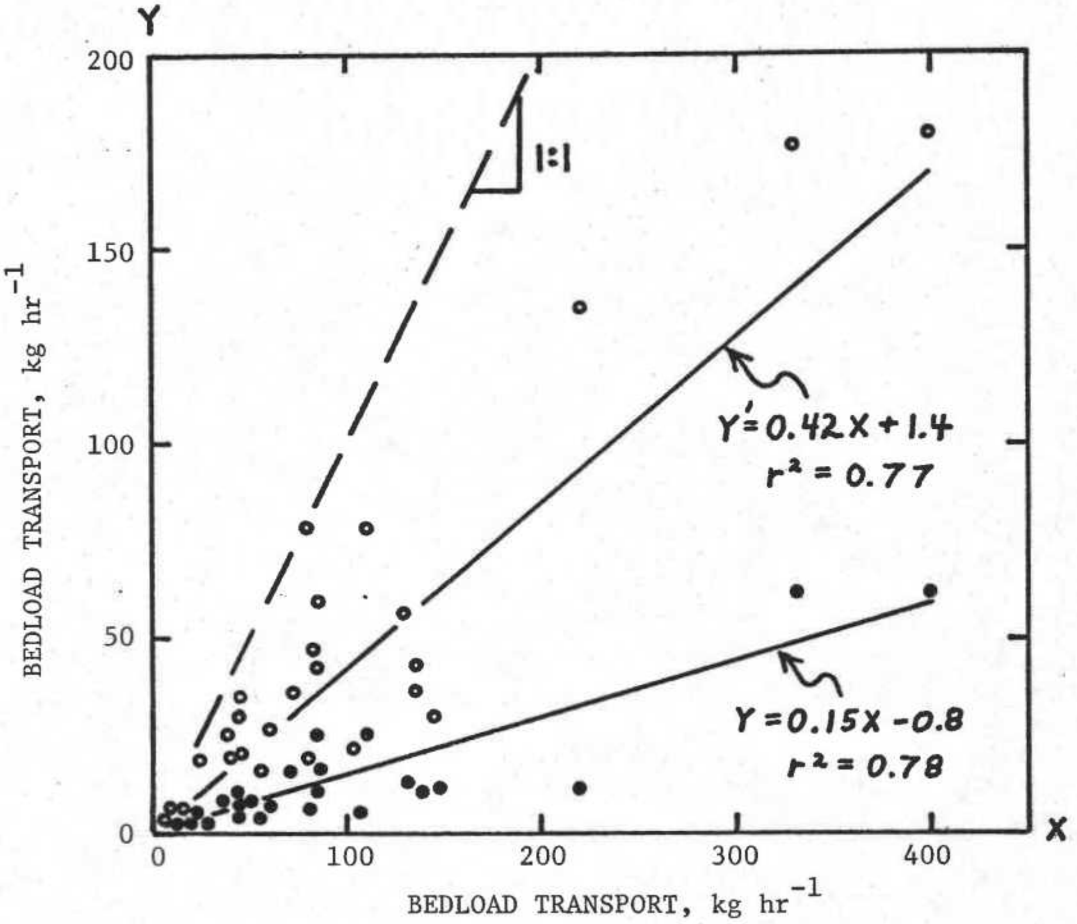

FIGURE 10. Comparison of bedload transport rates measured concurrently with the vortex tube sampler (Y) and the Helley-Smith sampler (X). Values of Y are unadjusted rates whereas values of Y' have been adjusted to correct for inefficiencies of the vortex sample box.

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In summary, the vortex sampler provides a unique method of obtaining bedload transport measurements in small streams. Criteria specified by Robinson (1962) and Klingeman and Milhous (1970) were utilized in the design of the vortex sampler at Flynn Creek. Advantages of this sampler include: (1) an integrated sample across the channel is obtained and (2) the length of time over which sampling occurs can be easily varied depending upon flow conditions and transport rates. Disadvantages of the vortex sampler at Flynn Creek include: (1) substantial modification of a natural channel is necessary to install the device, (2) the sampler is inefficient for trapping small gravels (i.e., < 10 mm), sand-sized particles and particulate organic matter, and (3) organic matter in transport accumulates on the downstream edge of the vortex tube and causes an unknown effect (if any) on the sampling efficiency of the tube.

Helley-Smith Sampler

Because the Helley-Smith sampler was not designed for streams with high amounts of organic matter and sand-sized sediments, a number of instream and flume measurements were made to evaluate sampling efficiency (Beschta, 1980a). In summary, these tests showed that the Helley-Smith sampler with a standard collection bag (0.2-mm mesh size; 1950-cm^2 bag surface area) quickly clogged during periods of bedload transport. In an attempt to reduce the effects of the bag clogging (and an associated reduction in samping efficiency) sampling times were kept short (one minute or less). As indicated previously, the Helley-Smith sampler with a standard collection bag was used during both WYs 1977 and 1978.

As a result of measurements by Johnson et al. (1977) and Beschta (1980a), a larger bag (0.2-mm mesh size; 6000-cm^2 bag surface area) was initially used during the 1979 WY. The threefold increase in bag surface area appeared to greatly reduce the problem of clogging (Beschta, 1980a). Because the Helley-Smith sampler (with the larger bag) appeared to perform adequately over a range of sediment transport and flow conditions, this device was used as the principal sampling method in WYs 1979 and 1980 and only infrequently were vortex samples obtained. However, due to the change in sampler characteristics, the Helley-Smith data for WYs 1979 and 1980 are not directly comparable with those of previous years.

Advantages of the Helley-Smith sampler include: (1) a capability to measure transport rates of both sand-sized sediments and particulate organic matter, (2) flexibility in sampling at selected points across the channel to evaluate spatial variability in transport, and (3) the sampler is inexpensive and easy to use. Disadvantages include: (1) the necessity to composite subsamples for estimating average transport rates and (2) an unpredictable reduction in sampling efficiency when the bag begins to clog. If the sampler is used in an undisturbed stream channel, one must also be careful to prevent "scooping" of bed materials during placement or removal of the sampler at the stream bed. This was not a concern at the Flynn Creek fish trap or at Oak Creek. In both instances, the sampler rested on a flat, concrete portion of the channel during sampling.

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Bedload and Particulate Organic Matter Transport

Flynn Creek: Vortex Tube Sampler

Although the vortex tube had been installed in the late summer of 1976, the record low flows of WY 1977 (Figure 4) resulted in essentially no bedload transport at Flynn Creek. Thus the storms for WY 1978 represent the first period of measurements with the vortex sampler. Streamflow and bedload transport data for several storms are illustrated in Figure 11. Although all three storms in WY 1978 peaked within a range of 0.66 to 0.79 $m^3s^{-1}km^{-2}$, a pronounced trend towards increasing bedload transport during the latter storms is apparent. Why this progressive increase in transport rate occurred from storm to storm is not known but may be the result of channel adjustments upstream from the vortex due to raising the streambed slightly during installation of the vortex tube. During the 1977-78 winter approximately 7.0 cm of deposition had occurred immediately upstream from the fishtrap. Thus, if bedload sediments were accumulating in the upstream channel during the first several storms, this could account for the relatively low transport rates. The higher rates measured during the December 13-15 storm may indicate upstream storage had largely been satisfied and bedload transport was returning towards equilibrium rates.

Bedload rating curves from WY 1978 to WY 1979 (Figure 12) show additional evidence of a progressive increase in transport rates in relation to stream discharge. The regression equations for each rating curve are included in Table 4. However, this shift in the rating curve may also have been caused by changing the hydraulic conditions of flow over the vortex tube. During the high flows of the 1978 WY, supercritical flow was observed over the vortex tube. Flows entering the hydraulically "smooth" fishtrap accelerated, became supercritical over the vortex tube and returned to subcritical flow at a standing wave less than 1 m downstream from the sampler. To eliminate this condition, a control board (the top of which was at the same elevation as the top of the vortex tube) at the downstream end of the fishtrap (approximately 2 m downstream from the vortex tube) was raised 9 cm in elevation during the summer of 1979. This increased elevation of the control board decreased the velocity of flow over the sampling tube and storm flows remained subcritical during the 1979 and 1980 WYs. For example, during the WY 1979 peak flow of 0.75 $m^3\ s^{-1}\ km^{-2}$ at Flynn Creek, the Froude number $(\overline{V}\ \sqrt{g\overline{y}}\ )$ was only 0.52 over the vortex tube. However, the increase in height of the control board could also have caused additional deposition upstream from the fishtrap. Indeed, over the 1979-80 winter, several centimeters of additional deposition occurred in a 40-m reach immediately upstream from the fishtrap. However, if material was being deposited, this would tend to keep transport rates at a given discharge relatively low and does not explain the increases demonstrated in WY 1979. Although it was unfortunate that such a change in the characteristics of the fishtrap occurred mid-way through the study, the effects of raising the

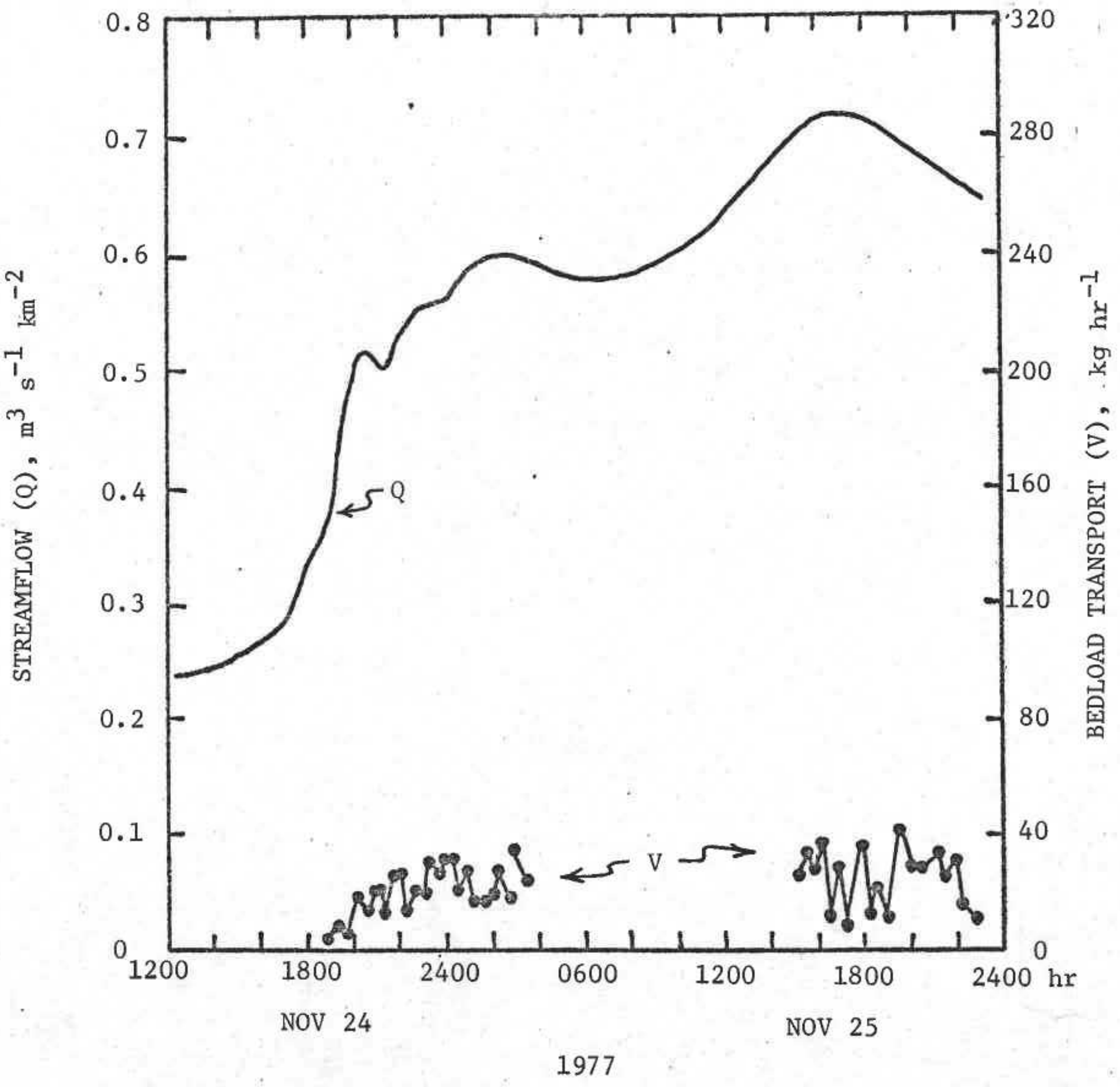

FIGURE 11. Time-series of streamflow (Q) and bedload transport (V) measured with the vortex tube sampler for several storms at Flynn Creek.

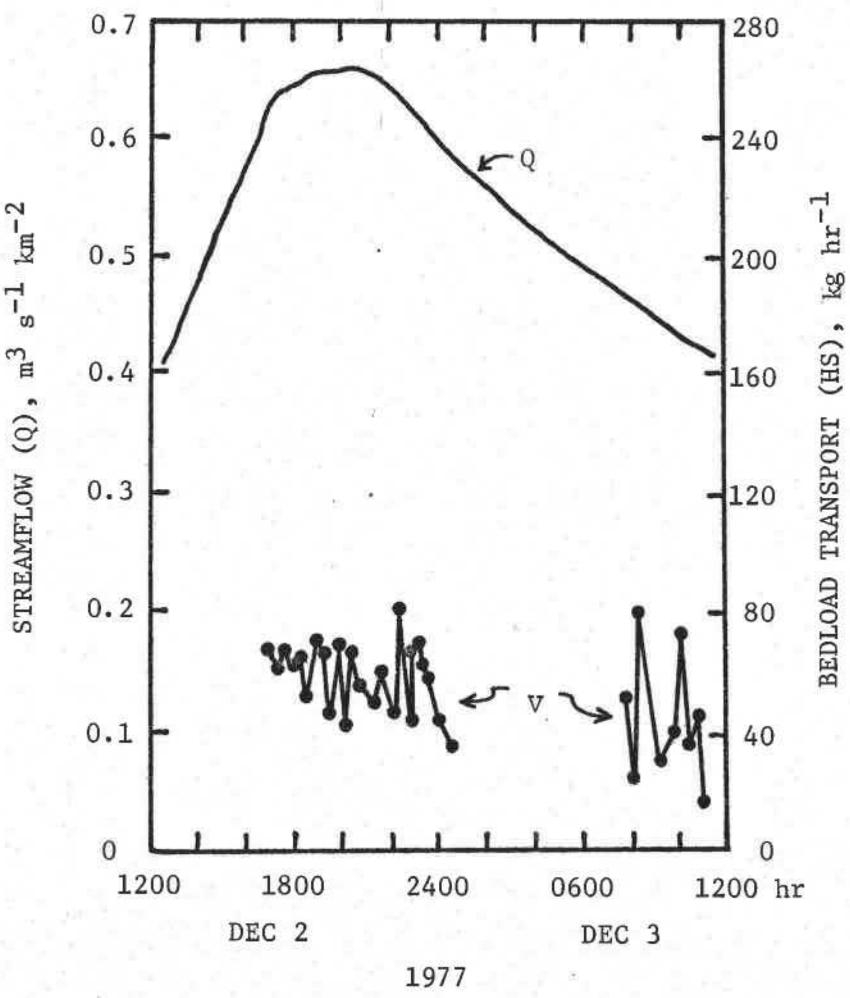

FIGURE 11. (Continued)

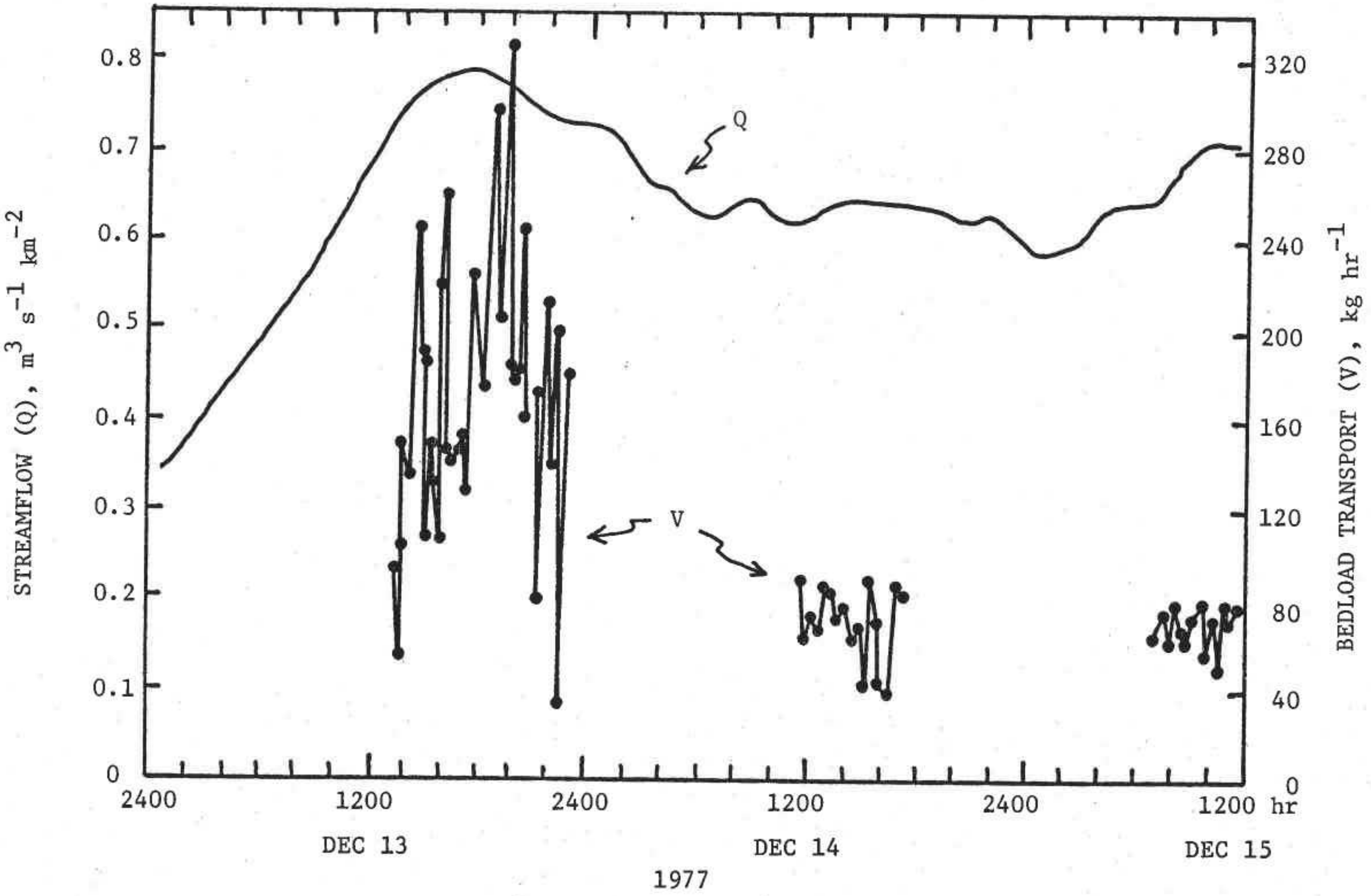

FIGURE 11. (Continued)

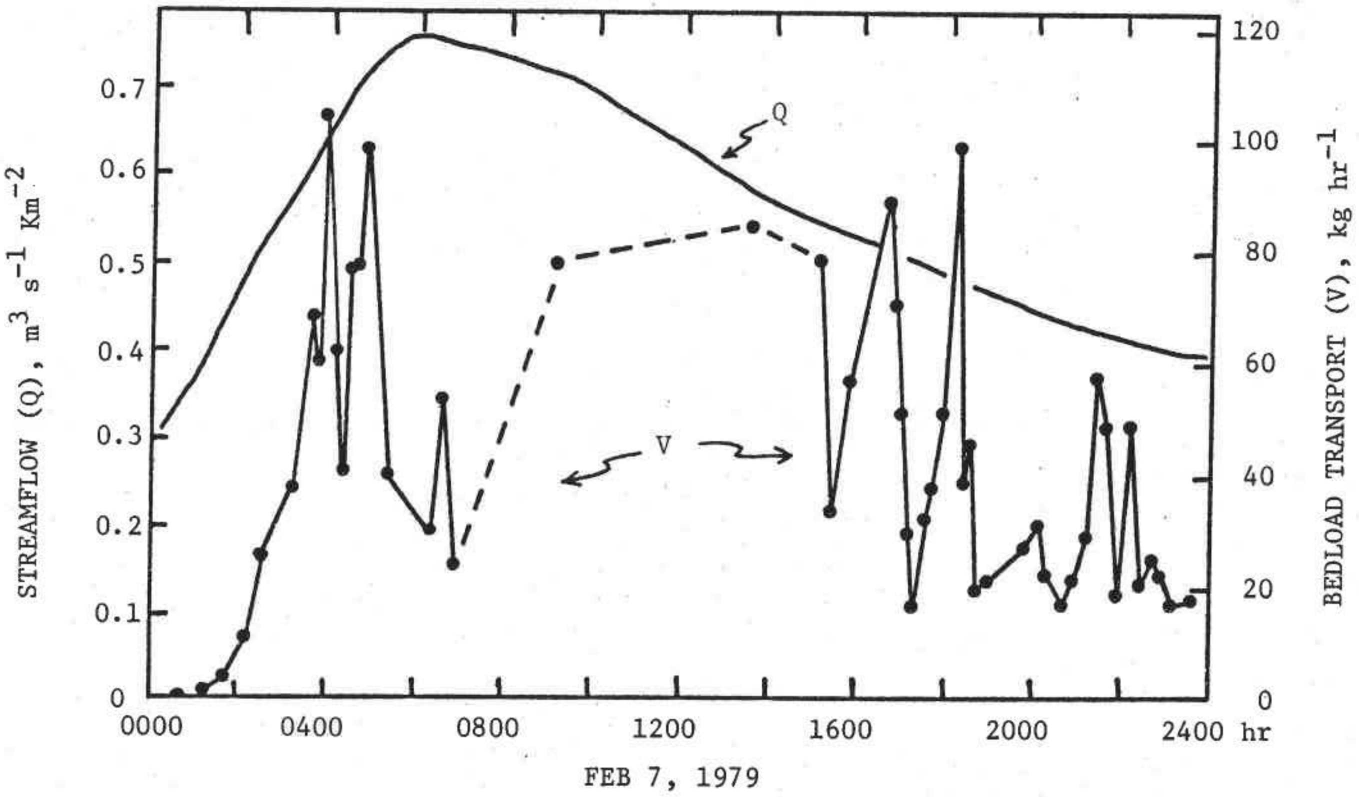

FIGURE 11. (Continued)

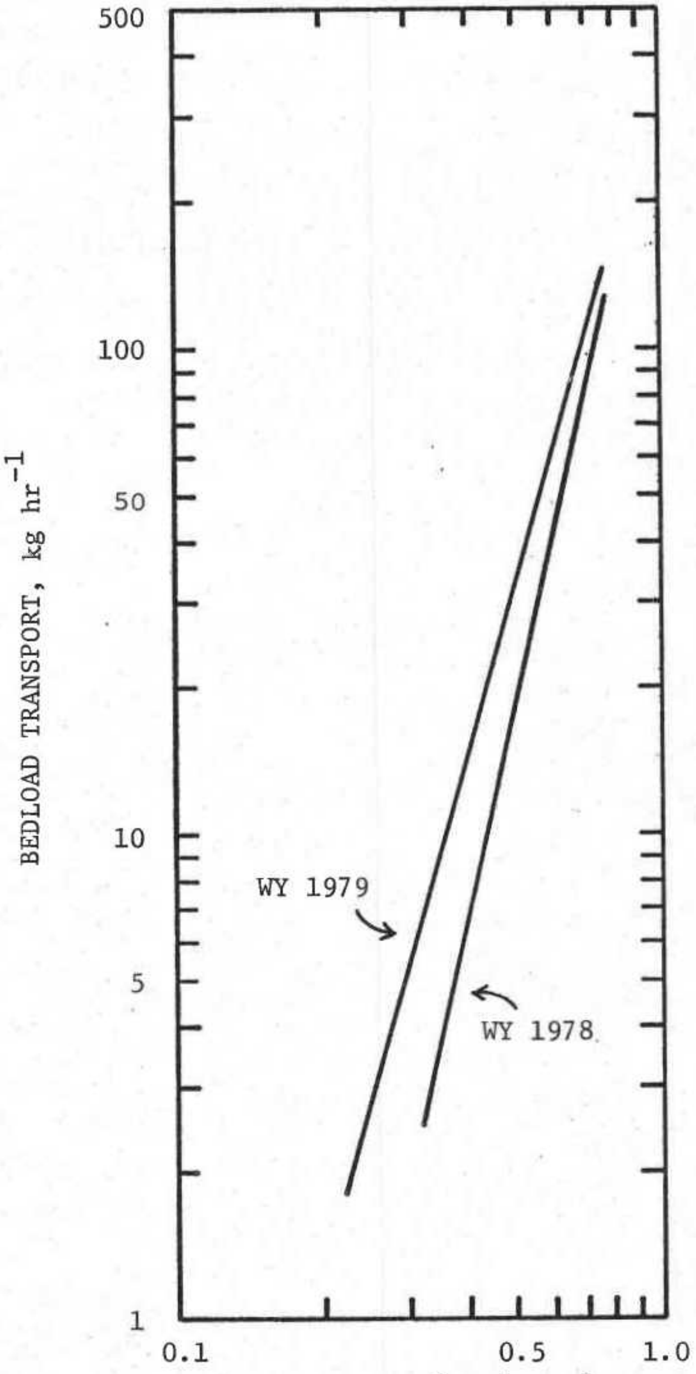

FIGURE 12. Bedload rating curves for WYs 1978 and 1979 based on vortex tube samples at Flynn Creek.

TABLE 4. Summary of regression equations relating to streamflow to bedload transport and to total suspended solids concentration.

Water Year	Regression Equations[a]	n	r^2
Flynn Creek: Bedload			
1978	$V = 422\ Q^{4.51}$	187	0.58
1978	$HS = 446\ Q^{3.87}$	24	0.36
1979	$V = 376\ Q^{3.41}$	86	0.72
1979	$HS = 9.6\ Q^{3.41}$	157	0.92
1980	$HS = 11.4\ Q^{-1.22}$	114	0.62
Oak Creek: Bedload			
1980	$HS = 21{,}650\ Q^{3.44}$	183	0.86
Flynn Creek: Total suspended Solids			
1978	$TSS = 188\ Q^{1.33}$	82	0.16
1979	$TSS = 424\ Q^{1.56}$	118	0.65
1980	$TSS = 28\ Q^{-0.11}$	145	0.01
Oak Creek: Total Suspended Solids			
1976	$TSS = 579\ Q^{1.26}$	194	0.47
1977	$TSS = 238\ Q^{0.57}$	12	0.14
1978	$TSS = 525\ Q^{1.12}$	80	0.35
1979	$TSS = 61\ Q^{0.25}$	293	0.03
1980	$TSS = 1{,}225\ Q^{1.44}$	212	0.49

[a] Q = streamflow, $m^3\ S^{-1}\ km^{-2}$.
V = bedload transport based on vortex tube samples, kg hr^{-1}.
HS_1 = Bedload transport based on Helley-Smith samples using a bag with 0.2 mm mesh size and 1950 cm^2 of surface area, kg hr^{-1}.
HS_2 = Bedload transport based on Helley-Smith samples using a bag with 0.2 mm mesh size and 6,000 cm^2 of surface area, kg hr^{-1}.
TSS = Total suspended solids from pumped samples, mg ℓ^{-1}.

control board may not be unlike those caused when large woody debris naturally enters the channel, a common situation in Oregon Coast Range streams. In any event, a shift in the rating curve between WYs 1978 and 1979 is evident. Whether this shift is due to sampling error, changes in sampling efficiency of the vortex, channel adjustments upstream, or natural variation in transport versus streamflow is not known.

The median particle diameter (d_{50}) of material in transport ranged from 0.2 to 1.8 mm in WY 1978 and 0.2 to 0.8 mm in WY 1979. The average d_{50} for each year was 0.5 mm indicating that most bedload transport in Flynn Creek involves sand-sized particles.

Flynn Creek: Helley-Smith Sampler

As was found with the vortex sampler, bedload rates measured with the Helley-Smith sampler showed pronounced fluctuations over time (Figure 13). Although the apparent "cyclic" variations in transport rates are not systematic, the fluctuations appear to last anywhere from one to three hours. In addition, maximum bedload transport typically occurred after peak streamflow in any given storm. Thus, sediment rating curves developed from individual storms would demonstrate a hysteresis between streamflow and bedload transport (i.e., transport rates being relatively low during rising flow conditions and relatively high during flow recession).

Sediment rating curves of bedload transport versus stream discharge for WYs 1978, 1979, and 1980 at Flynn Creek are illustrated in Figure 14 and summarized in Table 4. Only a few samples were obtained during the relatively low flows of WY 1977 and are not included in Figure 14. Similar to the results of the vortex sampler, a shift in the rating curves between WY 1978 and WY 1979 is evident. The installation of a higher control board (for improved sampling efficiency of the vortex sampler) should not be a factor in causing the rating curve shift shown here. However, after WY 1978, the sampling bag of the Helley-Smith sampler had been increased in size (from 1950 cm^2 to 6000 cm^2 of bag surface area) to overcome clogging problems. Thus, whether the upward shift in the curve is a result of increased sampling efficiency or higher transport rates (following upstream channel adjustments), or both, is not known.

The rating curve for WY 1980 (based on 114 samples) represents an interesting paradox whereby bedload transport rates are actually shown to be relatively high at lower discharges. Theoretical considerations of stream power, tractive forces, etc., would all indicate a direct relationship between stream discharge and bedload transport as is shown for WYs 1978 and 1979. Initially then, the results for WY 1980 do not seem plausable. Data for the 1980 WY were collected during four storms (December 4 and 12, 1979, and January 9 and 14, 1980). Although these were the largest flow events of that winter, the sampled flows ranged from only 0.22 to 0.44 $m^3\ s^{-1}\ km^{-2}$. Many of these samples were collected during the falling limb of a storm hydrograph when often the highest bedload transport rates are observed in Flynn Creek. As a result of the

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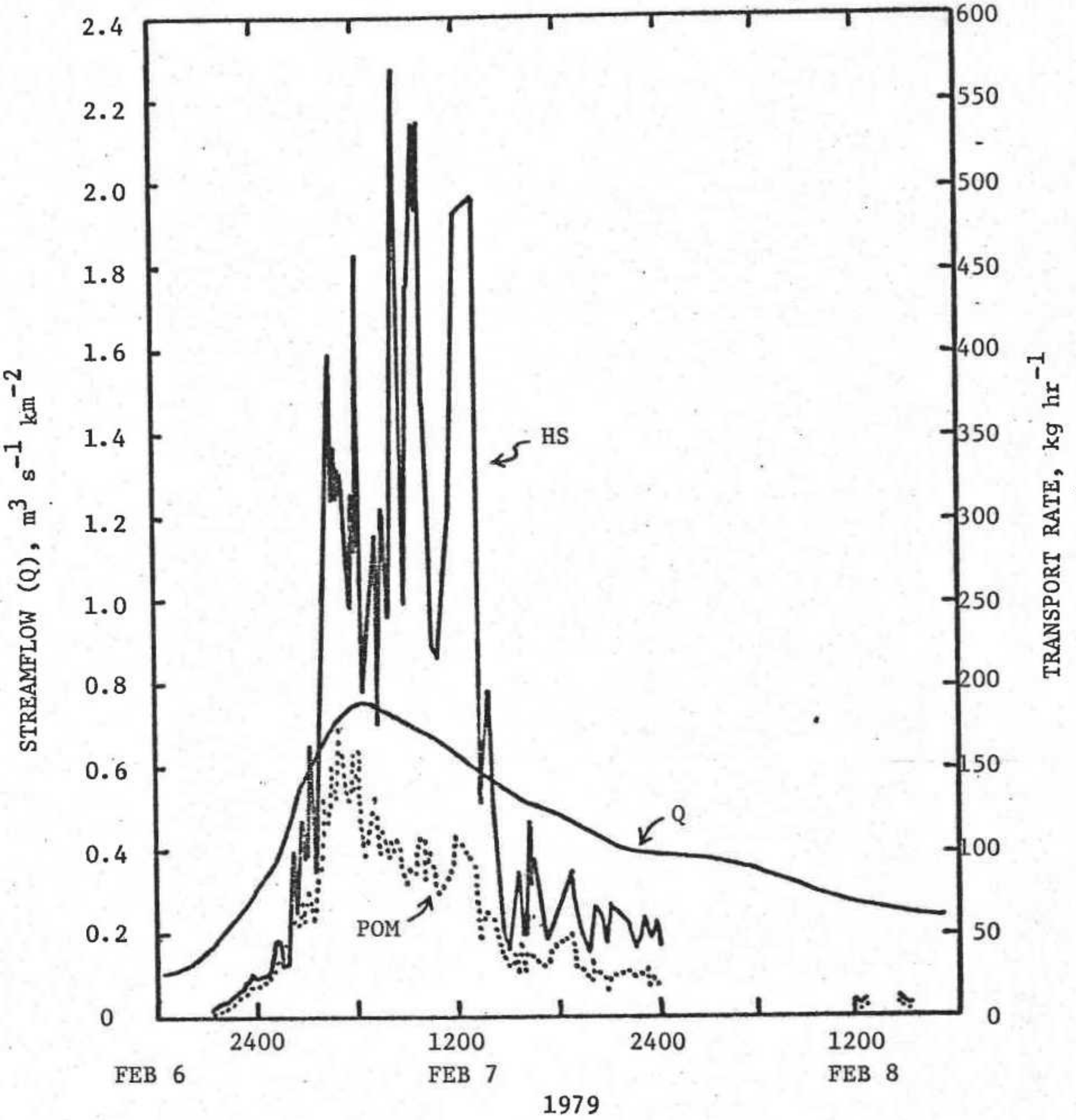

FIGURE 13. Time series of streamflow (Q), bedload transport (HS) and particular organic matter transport (POM) for a storm at Flynn Creek. Both bedload and particulate organic matter transport were measured with the Helley-Smith bedload sampler.

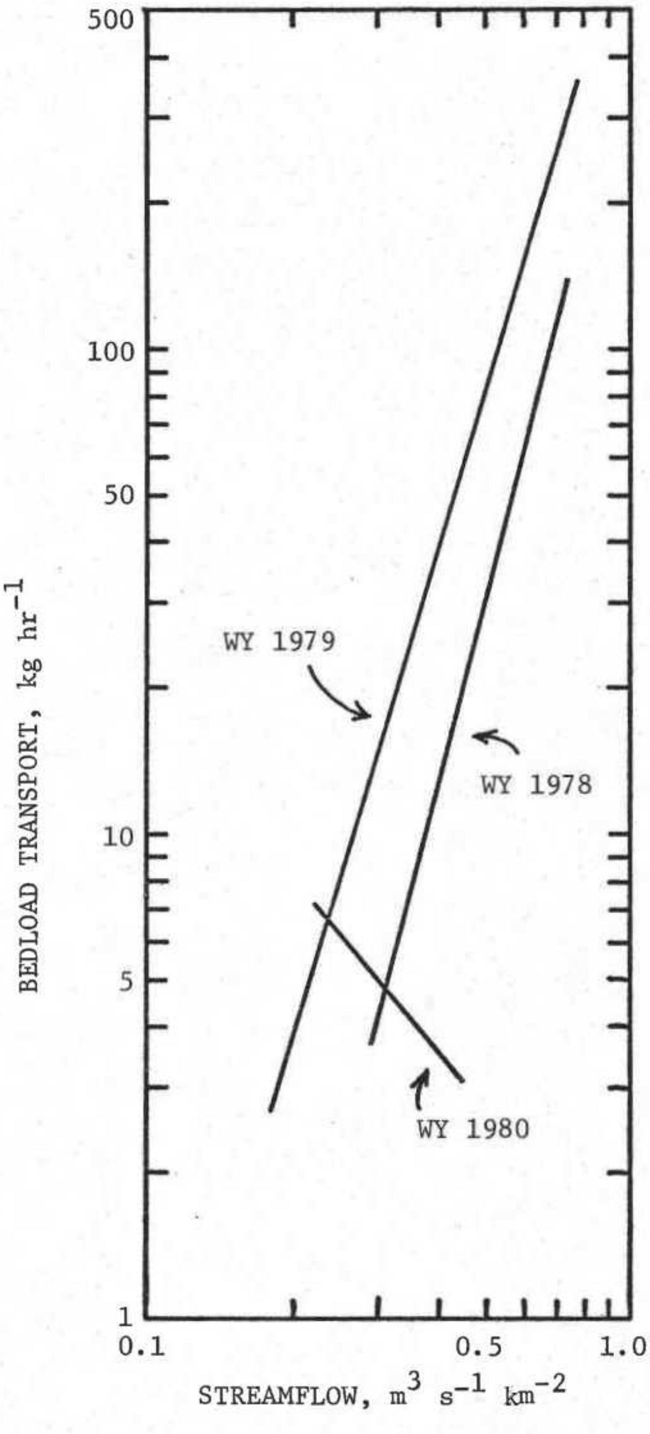

FIGURE 14. Bedload rating curves for WYs 1978, 1979 and 1980 based on Helley-Smith samples at Flynn Creek.

timing of sample collection in relation to the hydrograph peak, the hysteresis in bedload transport versus flow, and the relatively small range in flows over which samples were collected, a rating curve with a negative slope resulted (it should be noted that the slopes of rating curves for individual storms in WY 1980 were all positive). Such results indicate that a wide range of flows must be sampled in order to obtain a direct relationship between bedload transport and streamflow.

With the exception of WY 1980, the exponential slopes of the rating curves derived from both the vortex and Helley-Smith samplers range from 3.41 to 4.51 for an average of 3.8. Thus, a doubling of streamflow results in approximately a 14-fold increase in bedload transport which in turn implies that the larger and relatively infrequent flow events on the Oregon Coast Range are responsible for moving the majority of bedload sediments. Nearly all bedload transport at Flynn Creek occurs at discharge of greater than about 0.2 $m^3\ s^{-1}\ km^{-2}$, a flow that occurs less than 6% of the time.

As indicated previously, there is a tendency for maximum transport rates of bedload to occur after the peak of the hydrograph. In addition, because streamflow recession at Flynn Creek occurs much slower than the rise in flow during a storm, the volume of bedload sediments moved during receeding flows is much greater than during the rising flows. For a given storm, data collected at Flynn Creek indicate 75% or more of the total bedload transport occurs during conditions of receeding streamflow. Furthermore, the amount of suspended solids (inorganic sediments and organic matter) and particulate organic matter are also relatively low following the peak in stream discharge. Thus, if riffle scour and deposition processes are active after peak discharge, this situation may provide a mechanism for the flushing of fine sediments and organic matter from gravels. Movement of the streambed gravels is necessary before flushing of fines can occur (Beschta and Jackson, 1979; Adams and Beschta, 1980).

The d_{50} for samples collected with the Helley-Smith bedload sampler averaged 0.5 mm, a result identical with that of the vortex sampler. Also, the d_{50} appeared to be relatively insensitive to changing flow conditions.

In contrast to the variability in bedload transport, the transport rates of particulate organic matter (POM) seemed relatively "well behaved" and in-phase with the storm hydrograph (Figure 13). POM rates increased during the rising limb of the storm hydrograph, peaked slightly before the hydrograph peak, and then followed a fairly uniform decay with time as flows receeded. This pattern of response is similar to that of the suspended solids (discussed later). During the early and late portions of the storm hydrograph, POM transport was of nearly the same magnitude as the bedload component.

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Oak Creek: Helley-Smith Sampler

Bedload and particulate organic matter measurements with the Helley-Smith bedload sampler (0.2-mm mesh bag, surface area of 6000 cm^2) were obtained only in WY 1980. Although four storms were sampled (December 23, 1979, January 9 and 14, 1980, and March 14, 1980) only data from the largest storm (peak flow = 0.36 $m^3\ s^{-1}\ km^{-2}$) are illustrated in Figure 15. In contrast to Flynn Creek, storm hydrographs at Oak Creek typically have steeper rising and falling limbs and hence a "flashier" stream response to rainfall even though Oak Creek is a larger drainage. During the rapid rise in flow for the storm of January 14, 1980, bedload transport rates increased rapidly and peaked prior to the peak of the storm hydrograph. However, similar to Flynn Creek, substantial fluctuations in transport rates occurred throughout the period of stormflow.

Bedload rating curves for individual storms at Oak Creek along with a composite rating curve based on all data are shown in Figure 16. For the individual storms, exponential increases in bedload transport with increasing discharge vary from 1.72 to 4.50 indicating individual storm relationships are not useful for extrapolation purposes. The exponential increase in bedload transport of 3.44 as a function of discharge for the composite rating curve (Table 4) is similar to that found for Flynn Creek, although the intercept is approximately 3.5 times higher. Thus, for a given stream discharge per unit area of watershed ($m^3\ s^{-1}\ km^{-2}$) the bedload transport rate at Oak Creek is higher than that at Flynn Creek. This higher transport rate appears to be nearly proportional to the ratio of drainage areas (e.g., 7.5 km^2/2.2 km^2 = 3.4) of the two watersheds. This is an interesting result in view of the differing geology, soils, topography, channel morphology, percipitation amounts, etc., characterizing the two watersheds.

Median particle diameters for Helley-Smith samples at Oak Creek, although larger than those at Flynn Creek, averaged less than 2 mm. The d_{95} for all samples was less than 15 mm.

Particulate organic matter (POM) comprises a relatively small component of the total transport measured with the Helley-Smith sampler at Oak Creek (Figure 15). As at Flynn Creek, POM transport rates tend to increase or decrease in direct response to changes in flow rates. This inphase relationship of POM with the storm hydrograph is in contrast to the hysteresis effects often seen with the suspended solids and bedload components.

Channel Measurements

At channel cross-sections above the Flynn Creek fishtrap, measurements indicated localized scour and fill of the channel was a common occurrence. Even during the relatively low flows of WY 1977, a net degradation of 5 cm was measured at the 12 cross-sections in the 300-m

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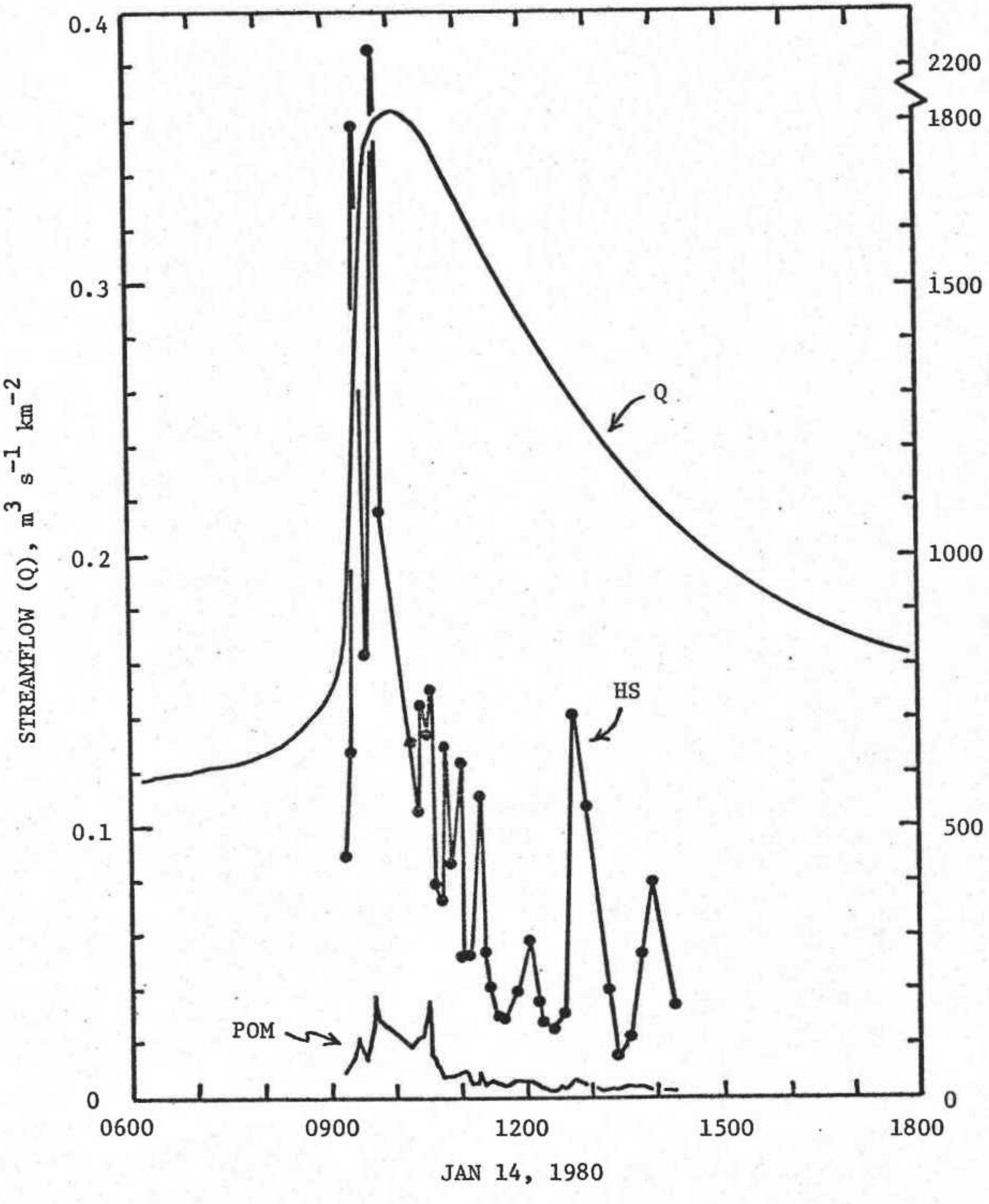

FIGURE 15. Time series of streamflow (Q), bedload transport (HS) and particulate organic matter transport (POM) for a storm at Oak Creek. Both bedload and particulate organic matter transport were measured with the Helley-Smith bedload sampler.

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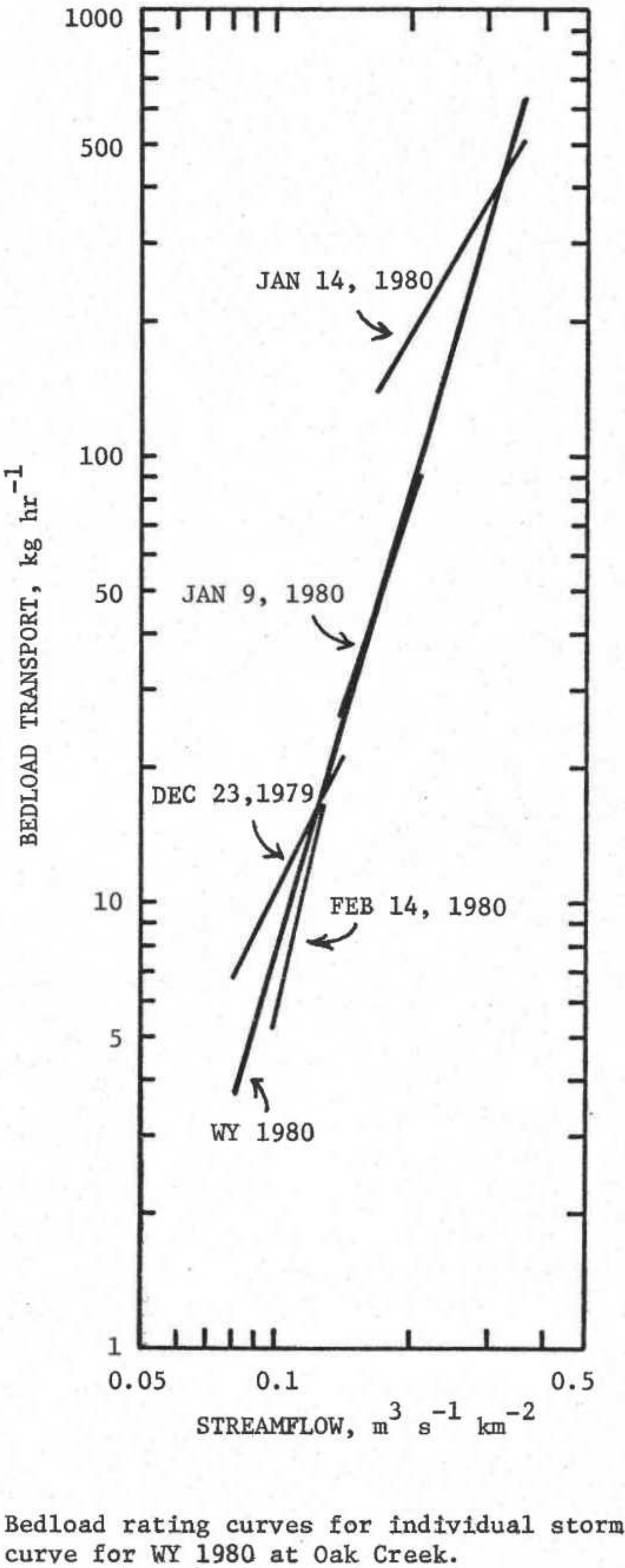

FIGURE 16. Bedload rating curves for individual storms and a composite curve for WY 1980 at Oak Creek.

reach upstream of the fishtrap. Because essentially no bedload transport was measured at the fishtrap in WY 1977, these data indicate local adjustments within the reach. No significant aggradation or degradation of the reach occurred in WYs 1978 and 1979 even through individual cross-sections showed net scour and/or fill and bedload transport had definitely occurred. The cross-sections were not remeasured after the winter flows of 1979-80.

The use of 12 cross-sections, spread over a 300-m reach of channel, may not be adequate for accurately defining changes in the channel morphology resulting from small to moderate runoff events at Flynn Creek. The highly variable occurrence of pools and riffles makes interpretation of the above data difficult. For example, the 5-cm changes which occurred in the WY 1977 indicate general changes occurred and we can only hypothesize that this material was moved into pools. However, because none of the cross-sections were established at pool locations, definitive evidence to support this hypothesis is not available. The dynamics of riffles, pools, and intermediate locations in the channel regarding bedload routing (storage and transport) represents a major void in our knowledge of sedimentation processes in mountain streams. Unfortunately, the measurement of state variables (channel depth, width, etc.) between seasons or between storms provide limited insights as to how the various portions of the channel respond to and interact with bedload transport at high flows. Concurrent measurements of channel geometry with those of bedload transport during storms are needed to overcome this situation.

Results of the marble studies were also inconclusive due to the problems in recovering them after movement had occurred. The following tabulation summarizes average transport distances for all recovered marbles:

Marble diameter	1976-77 winter	1977-78 winter
22 mm	1.3 m	2.3 m
14 mm	0.7 m	7.5 m
9.6 mm	---	23.8 m

It was orginally hoped that the marbles would be trapped by the vortex sampler during stormflow periods and could be used to index transport distances. And because marbles at each cross-section were a distinct color, they would also indicate whether certain sections of the channel were scouring while other sections remained stable. Unfortunately, no marbles were ever found in any of the vortex samples and no conclusions can be drawn regarding the above hypothesis.

Total Suspended Solids

Because of the substantial amounts of particulate organic matter in transport along the bottom of the stream (as indexed by Helley-Smith samples), we attempted to evaluate the composition of suspended solids in transport. Essentially, the question was--what percent of the total suspended solids was sediment (inorganics) and what percent was organic matter? The transport of particulate organics, particularly close to the bed where larger sediment particles (sands and gravels) were moving, could result in rapid abrasion and shredding of this organic matter into smaller particles. Thus, during WY 1980, suspended solids samples (54 samples from Flynn Creek and 123 samples from Oak Creek) were ashed at 500°C to remove the organic component. Samples that originally had total suspended solids concentrations of ≤ 15 mg ℓ^{-1} had been excluded from analysis because the relative errors involved in weighing small samples could have large effects on the calculated percentages. As a result of the ashing procedure, we found that the organic matter content averaged 39 and 38 percent for samples at Flynn Creek and Oak Creek, respectively. There also appeared to be an inverse relationship between stream discharge and percentage organic matter. For example, at the highest total suspended solids concentrations measured in WY 1980, the relative amount of organic matter had dropped to approximately 30 to 35 percent at Flynn Creek and 20 to 25 percent at Oak Creek. Such data indicate that the use of terminology such as "suspended sediment" when describing the total suspended solids concentrations and yields from forested watersheds in western Oregon may be misleading and inappropriate. Previously published "suspended sediment" data for Flynn Creek and Oak Creek (Brown, 1972; Harris, 1977; Beschta, 1978; Paustian and Beschta, 1979; and Beschta, 1980c) undoubtedly reflect a relatively large but unknown proportion of organic matter.

This relatively large organic component may further affect the conclusions drawn from previously published results for the Alsea Watershed Study (Brown 1972; Harris 1977; and Beschta 1980), of which Flynn Creek served as the untreated control watershed. During that study, two watersheds adjacent to Flynn Creek were logged (with associated road construction, yarding and slash disposal operations). If the increases in "suspended sediment" concentrations and yields that were measured after logging were almost entirely inorganic in composition (as a result of accelerated erosion by mass soil movements) the relative increases in sediment production would be considerably greater than previously reported. This conclusion assumes that the organic component of the total suspended solids yielded from the treated watersheds was not markedly increased from that measured during pretreatment periods. Unfortunately, the above arguments are only speculative but should be considered in any future watershed studies attempting to evaluate the effects of land use activities on the export of "suspended sediment."

Flynn Creek

No samples of total suspended solids were collected at Flynn Creek in WY 1977 because of the low streamflow. However, total suspended solids rating curves in relation to stream discharge for individual storms during WYs 1978, 1979, and 1980 are shown in Figure 17. Although regression analysis was used to define each relation (based on the equation form $Y = aX^b$, Table 4), the significance level of each regression equation is not included in this report. The concentration of total suspended solids in a sample collected at time t is not independent of t-1, t-2, etc. (where units are in hours). Thus the linear regression assumption of independent X and Y data pairs is not met and the power of any subsequent statistical test cannot be defined. Because of the dependency characteristics associated with time series data collected over relatively short time intervals, tests of significance regarding any regression equations, such as illustrated in Figure 17, have limited utility. Identifying the memory characteristics and structure of this dependency component in time series data of suspended solids represents one of the important tasks facing research hydrologists and statisticians.

In spite of the above problems and the inherent variability of relationships shown in Figure 17, several general comments about the rating curves can be made. For example, within a storm, the concentration of total suspended solids at any given discharge may vary by nearly an order of magnitude (i.e., 10-fold). There is also a tendency for concentrations to be higher on the rising limb of a storm hydrograph than they are at the same flow on the falling limb. This situation can result in a pronounced hysteresis loop (which is opposite to that for bedload transport and streamflow) when individual data points for a particular storm are connected in chronological order (see storm C, WY 1979, Figure 17). Such hysteresis effects do not always occur but are often prominent in the larger runoff events that do not have complex hydrographs. The exact cause of this hysteresis effect undoubtedly involves the availability of suspendable sediment and organic matter in and along the immediate channel. Sediments picked up for transport during conditions of rising flow are no longer available during the recession limb of the storm hydrograph. Further evidence supporting the sediment availability concept occurs during storms with the same peak discharge, but which have either relatively fast or relatively slow rising limbs of the storm hydro-graph. Invariably, the storm with the relatively fast rise in flow will have the higher suspended solids concentrations yet the total suspended solids yielded during the rising limb of both storms may be essentially the same. The concentrations are higher on the storm with the steep rising limb because suspended solids are being made available (as the wetted perimeter of the channel increases and the stream network expands headward in the drainage) at a faster rate. The interaction of these two factors, (1) rising vs. recession flow conditions and (2) relative rate of increased flow (i.e., steepness of the rising limb of the storm hydrograph), are thus important factors affecting the variability in total suspended solids concentrations found for successive storms. Because overland flow is a relatively unimportant process for undisturbed forested watersheds such as Flynn Creek, most suspended sediments and organics must originate within or close to the channel network.

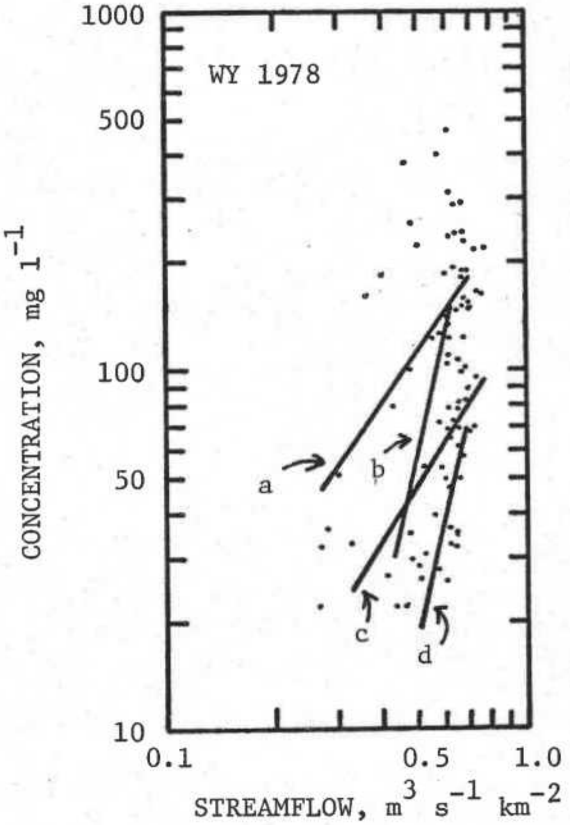

FIGURE 17. Total suspended solids rating curves for individual storms at Flynn Creek, WY's 1978-1980. Letters indicate chronological sequence of storms (i.e., a = 1st storm, b = 2nd storm, etc.).

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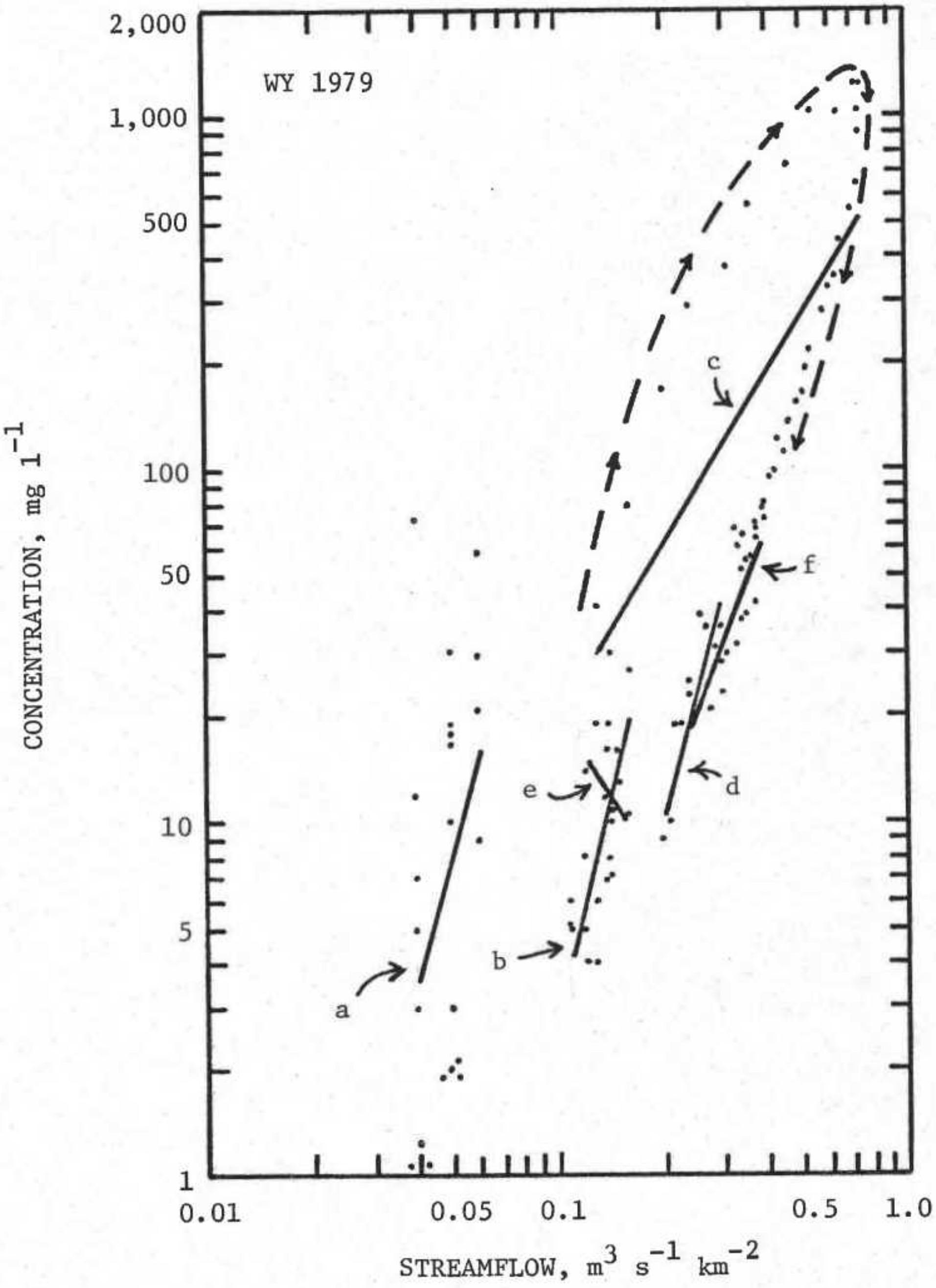

FIGURE 17. (Continued).

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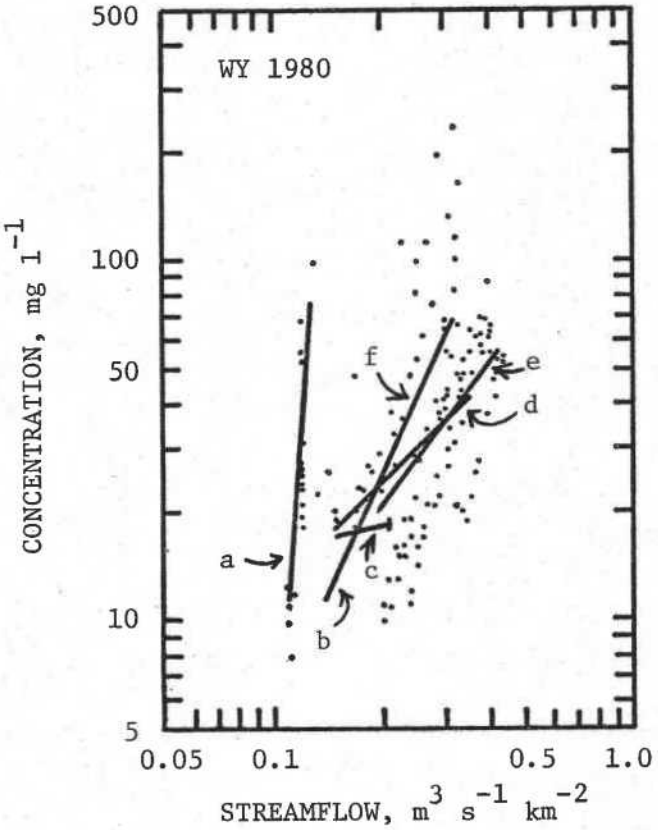

FIGURE 17. (Continued)

In addition to the above factors affecting total suspended solids concentrations, another watershed reponse can be identified in Figure 17. Generally, there tends to be a pattern of reduced concentrations, at a given flow, as the winter runoff season progresses. This situation confirms that the early fall storms tend to have higher concentrations and that a flushing of suspendable solids occurs during the winter storm season. Thus, storms in late winter or spring, after the occurrence of previous storm peaks, tend to have greatly reduced suspended solids concentrations and lend additional variability to the graphed data (and resultant rating curves).

An upward shift of the total suspended solids rating curves from WY 1979 to WY 1980 (Figure 18), similar to the shift found for the bedload rating curves, also occurred at Flynn Creek. The reason for this shift in the relationships is not known. However, those factors that were identified as possibly causing the shift in the bedload curves should not be a factor here because the suspended solids samples were collected at the stream gaging station, approximately 300-m upstream from the fishtrap. Furthermore, the total suspended solids rating curve for WY 1980 has a negative slope (similar to the 1980 WY bedload rating curve). The relatively small runoff events that occurred in WY 1980 and the limited range of flows (0.11 to 0.32 $m^3 s^{-1} km^{-2}$) in conjunction with the timing of sample collection apparently resulted in this inverse relationship. Although the WY 1980 curve lies within the general relationships shown for WYs 1978 and 1979, the potential errors from extrapolating this relationship for predicting concentrations at higher or lower flows are obvious.

Rating curves developed from years when flows exceeded 0.3 $m^3 s^{-1} km^{-2}$ (i.e, WYs 1978, 1979) have slopes ranging from 1.32 to 1.56 (Table 4) and average 1.44. This indicates that at the higher flows, a doubling of flow would result in approximately a 2.7-times increase in suspended solids concentration.

Oak Creek

As at Flynn Creek, the total suspended solids rating curves for individual storms at Oak Creek (Figure 19) show pronounced variability. WY 1976 data (although not collected as part of this study) are included in Figure 19. The hysteresis effect also occurs at Oak Creek, but it is usually not nearly as pronounced as at Flynn Creek due to the rapidity at which flows change during storms. However, there is a similar general downward shift in the positioning of each curve with successive storms.

By combining data from individual storms, annual rating curves of total suspended solids and discharge were developed (Figure 20). Even though each curve is based on a relatively large number of samples (Table 4), considerable variability in the resultant rating curves is evident. It is readily apparent that total suspended solids at Oak Creek cannot be simply characterized by a single rating curve. In addition, the collection of numerous samples does not reduce the inherent variability between

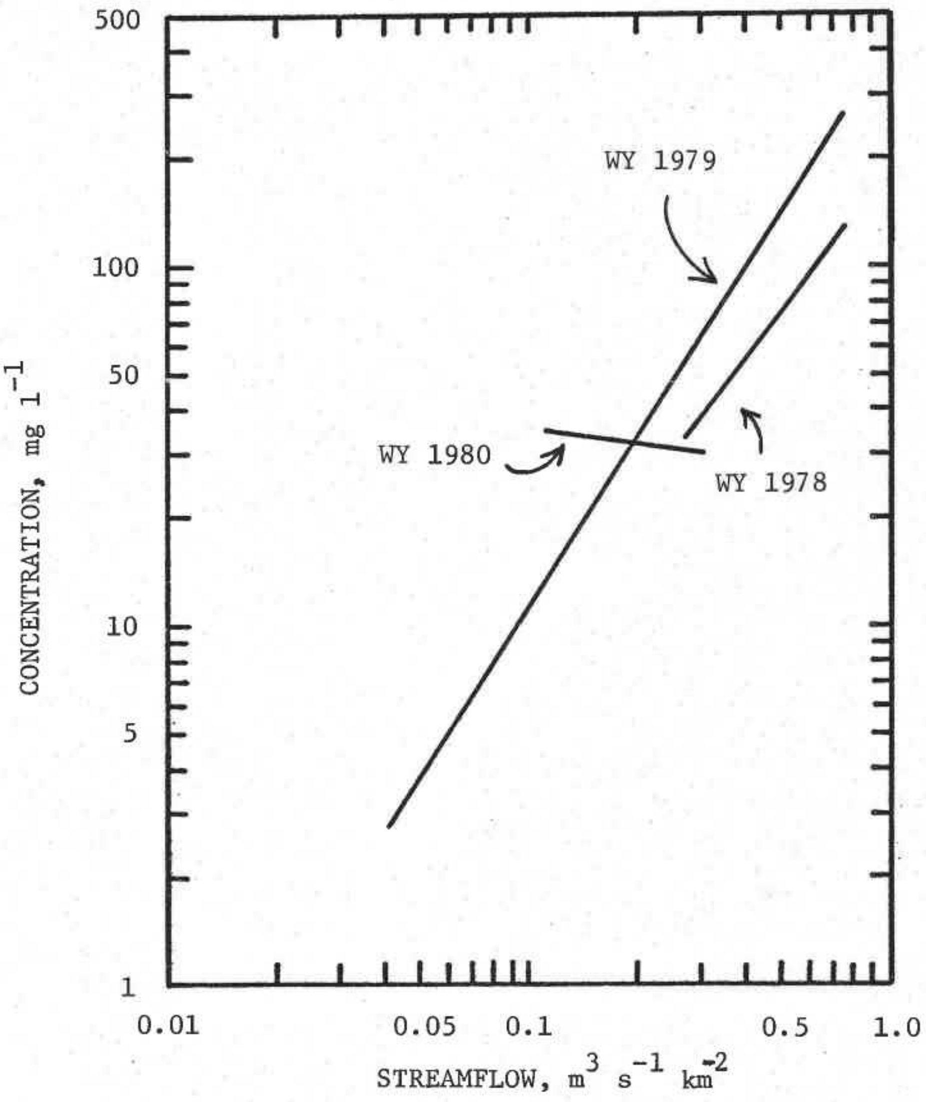

FIGURE 18. Total suspended solids rating curves for WY's 1978, 1979 and 1980 at Flynn Creek.

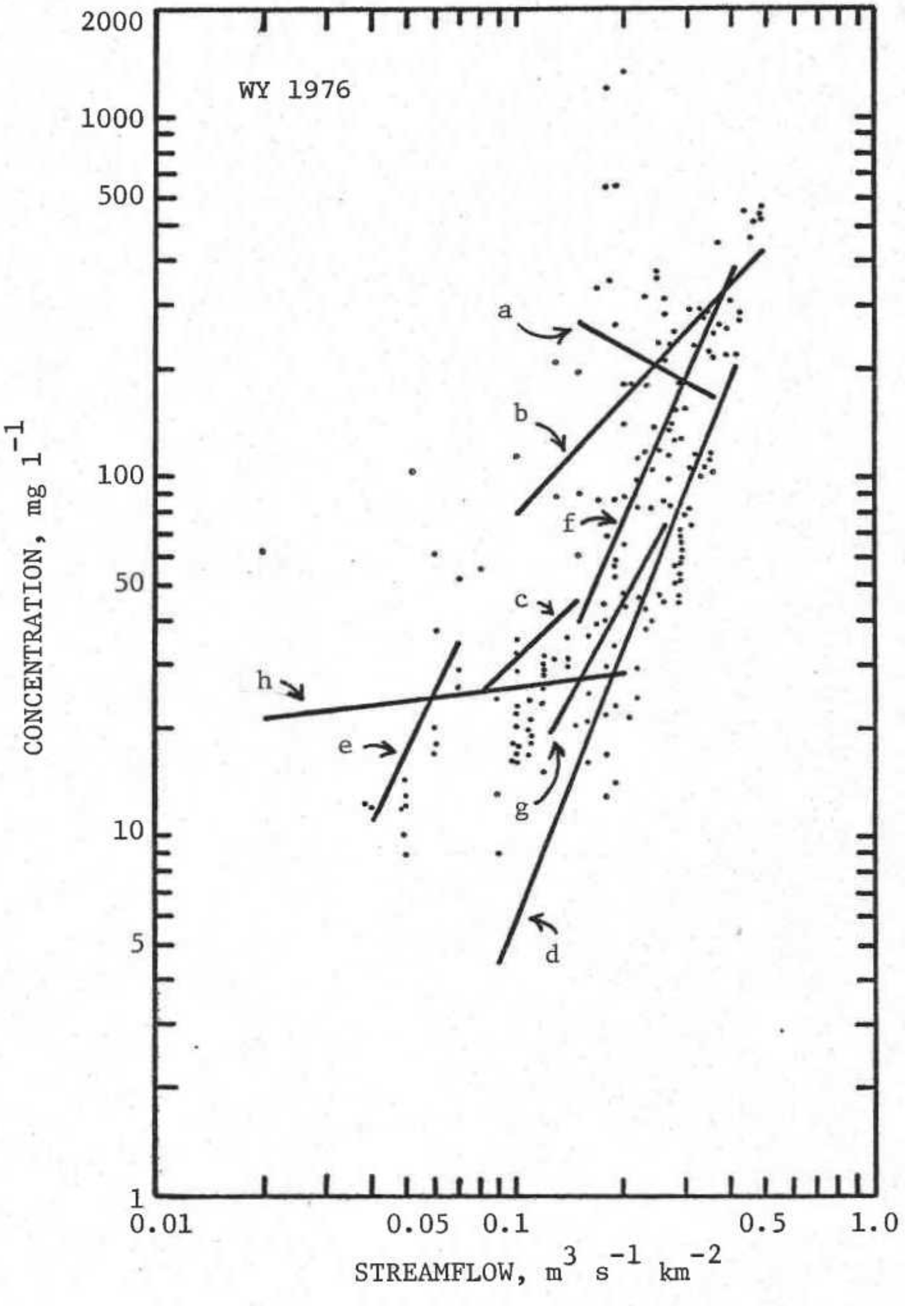

FIGURE 19. Total suspended solids rating curves for individual storms at Oak Creek, WY's 1976-1980. Letters indicate chronological sequence of storms (i.e., a = 1st storm, b = 2nd storm, etc.).

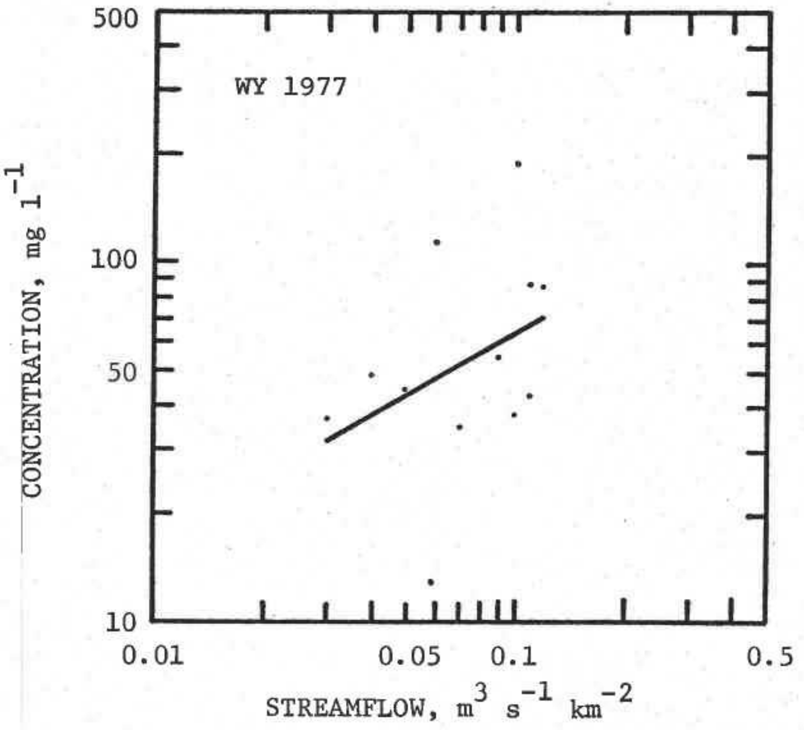

FIGURE 19. (Continued)

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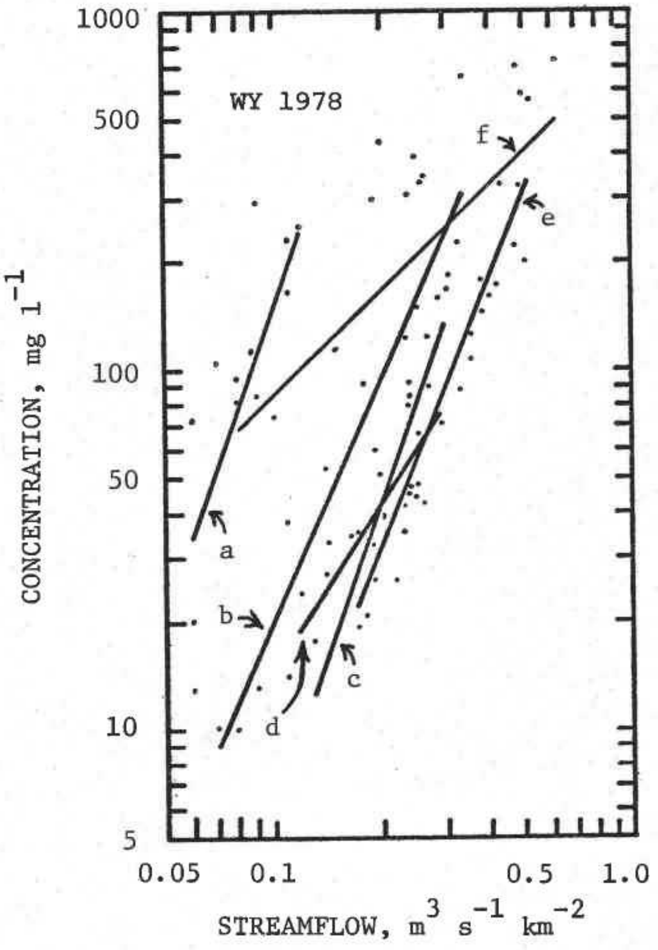

FIGURE 19. (Continued)

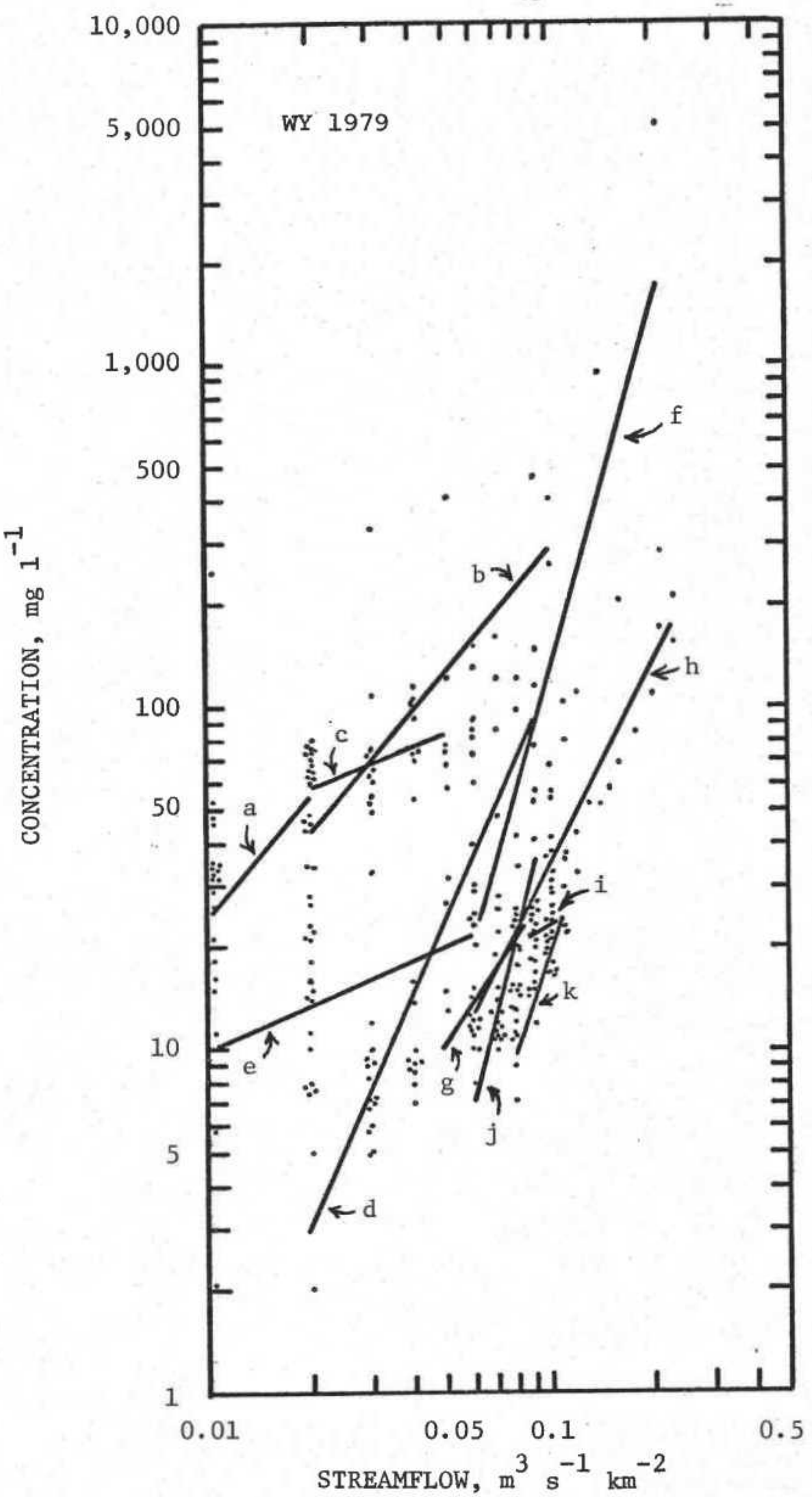

FIGURE 19. (Continued)

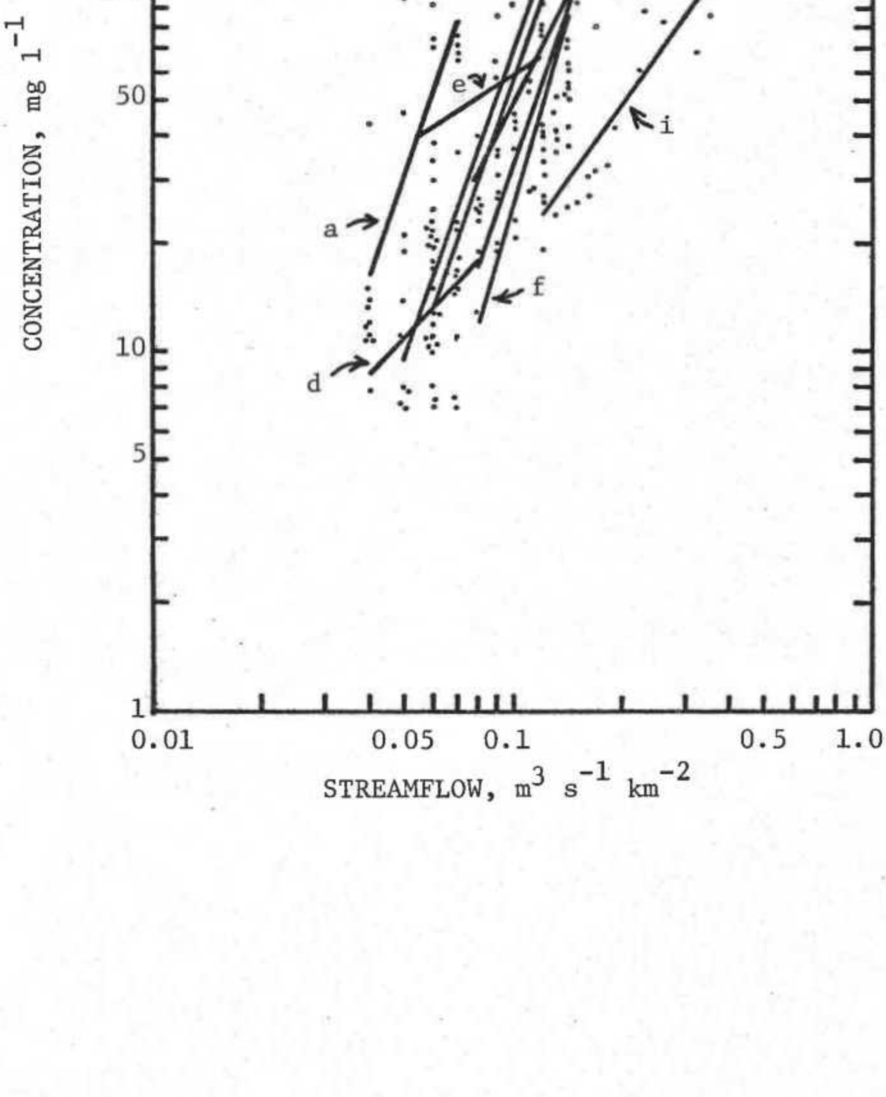

FIGURE 19. (Continued)

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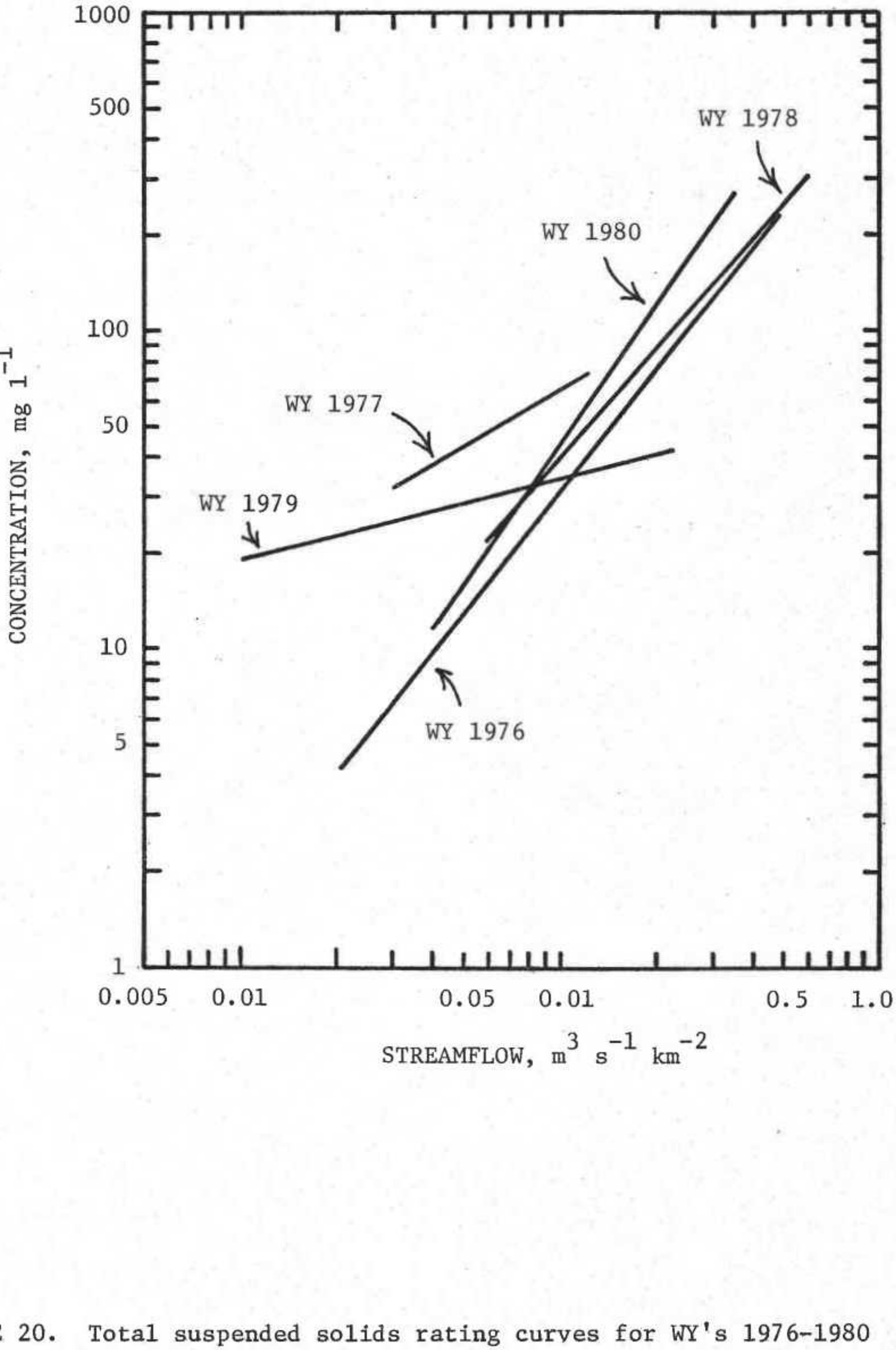

FIGURE 20. Total suspended solids rating curves for WY's 1976-1980 at Oak Creek.

total suspended solids and streamflow. Rating curves developed during years when flows exceeded 0.3 $m^3\ s^{-1}\ km^{-2}$ have slopes ranging from 1.12 to 1.44 and average 1.27. This indicates that at the higher flows, a doubling of flow would result in approximately a 2.4 times increase in total suspended solids concentration.

Total Suspended Solids and Turbidity

In the Pacific Northwest, state regulatory agencies (Department of Environmental Quality, 1974) often use turbidity to define acceptable and unacceptable changes in total suspended solids concentrations (or suspended sediment concentrations) of streams and rivers. Detailed comparisons of suspended solids concentrations and turbidity for Flynn Creek and Oak Creek have been previously reported by Beschta (1980c). Those results confirmed that total suspended solids was the most important factor affecting turbidity of Oregon's Coast Range streams. However, the relationships between these two parameters varied between storms and between drainages illustrating that predictive relationships must be developed on a watershed-by-watershed basis. The results also demonstrated that turbidities (and hence total suspended solids concentrations) quickly return to less than 30 ntu (nephlometric turbidity units) following runoff peak. For example, an analysis of ten storm hydrographs at Flynn Creek with peak discharges ranging from 0.28 to 1.26 $m^3\ s^{-1}\ km^{-2}$ showed that turbidities dropped below 30 ntu within 14 hours after the peak--eight storms were actually less than 30 ntu within 6 hours after the discharge peak. At Oak Creek, an analysis of 24 storms with peak discharges ranging from 0.10 to 0.62 $m^3\ s^{-1}\ km^{-2}$ showed that within 12 hours, 71 percent of the storms had turbidities less than 30 ntu. Within 24 hours of the peak, 96 percent of the storms had turbidities which had returned to levels of less than 30 ntu. Thus, even though total suspended solids concentrations and rating curves of either suspended solids or turbidity with stream dischange are highly variable, these results indicate Coast Range streams return to relatively low levels of turbidity (i.e., < 30 ntu) within 24 hours of a storm peak.

SUMMARY AND CONCLUSIONS

Intensive sampling, over time, during periods of storm runoff were utilized to gain insights regarding the effect of streamflow upon bedload transport, particulate organic matter transport, total suspended solids concentration and turbidity. Additional precipitation and channel morphology information were also collected.

Precipitation and Streamflow

Approximately 65% of the winter precipitation (November through March) was measured as streamflow at the mouth of these two watersheds. However, during the study period, both seasonal precipitation amounts and flows remained relatively low in comparison to other years. Based on a frequency analysis of 20 years of record at Flynn Creek, the instantaneous peak flows measured at Flynn Creek in WY's 1977 and 1980 were the lowest on record. Even the instantaneous peaks for WY's 1978 and 1979 had recurrence intervals of less than 2 years. Thus, the results presented within this report must be viewed within the context that they are the result of relatively frequent but small to moderate runoff events.

Bedload Samplers

Two methods of sampling bedload transport were employed at Flynn Creek: (1) the vortex tube bedload sampler and (2) the Helley-Smith bedload sampler. Only the Helley-Smith bedload sampler was used at Flynn Creek although previous studies by Milhous and Klingeman (1973) and Heineke (1976) utilized a vortex tube sampler. Although the vortex sampler provided a sample taken from across the entire width of the channel, the device proved to be relatively inefficient at trapping bedload particles less than 10 mm in diameter. This situation resulted from the combined effects of trapping inefficiencies (1) at the entrance of the vortex tube where water and sediment were removed from the flow and (2) at the sample box where bedload particles were to settle out from the water overflowing the top of the box. The sampler was entirely ineffective at trapping particulate organic matter.

In contrast to the vortex sampler, use of the Helley-Smith bedload device required that several subsamples be taken across the channel and then combined to determine an overall transport rate. A threefold increase in bag surface area, from 1,950 cm^2 to 6,000 cm^2, reduced clogging at the 0.2-mm mesh bag. Subsamples were collected over short time intervals (30 seconds or less) to further minimize the effect of bag

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clogging and a resultant rapid decreases in sampler efficiency. The Helley-Smith sampler was used for quantifying both bedload (inorganic sediments) and particulate organic matter transport.

Bedload and Particulate Organic Matter Transport

Results of bedload measurements at both Flynn and Oak Creek illustrate the highly stochastic nature of the transport process. Although transport rates do not occur in a strict "cyclic" pattern over time, there are alternating periods of relatively high and relatively low transport rates. It is suspected that periods of high transport indicate active scour (localized degradation) of the streambed somewhere upstream. Conversely, relatively low transport would indicate that the deposition process is active upstream. Because various sections of the upstream channel may be undergoing scour and fill at different times, their additive effect upon the transport of bedload sediments (measured at a downstream location) would cause unpredictable and apparently random fluctuations in transport rates. The longitudinal channel distance between any reach of active scour and deposition and the point of bedload measurements would also influence measured transport rates. As a result, it is highly probable that transport rates measured at a given location in the channel may be considerably different from those measured several tens of meters either upstream or downstream from that location. This would be particularly true for the small to moderate sized storms measured during this study. During larger runoff events, where storms have recurrence intervals of greater than approximately five to ten years, transport rates may become more uniform along the longitudinal dimension of a channel. However, such speculation requires additional verification with field measurements of bedload transport during large runoff events.

At any given location along the streambed, the bed sediments will remain in place (stable) until the bed shear stress or tractive force exceeds a critical value, after which active transport of bedload sediments may begin. However, because of variability in hydraulic characteristics of the flow during storm runoff, variability in particle sizes comprising the bed, and variability in channel geometry, a particular flow cannot be identified at which "incipient motion" of the bed occurs. Instead the transport of sediments occurs as a continuous power function of streamflow and thus any designation of incipient motion for the bed of a channel is arbitrary and perhaps a result of sampling techniques.

Results of this study confirm that bedload transport, with its associated scour and fill, is an extremely important process shaping the character of natural streams and the quality of stream habitats. Yet bedload transport occurs during relatively limited periods of time as is indicated by the following tabulation for Flynn Creek:

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Bedload transport rate (kg hr^{-1})	1	10	100
Streamflow (m^3 s^{-1} km^{-2})	0.15 - 0.2	0.25 - 0.35	0.5 - 0.7
Percent of time that indicated flow is exceeded	6	4	1

In other words, based on 15 years of continuous flow data and the bedload rating curves established in this study, transport rates > 100 kg hr^{-1} occur only one percent of the time or approximately 3.5 days each year. This information indicates that the transporting capability of bedload sediment is relatively limited during a "typical" runoff year and that the accelerated entry of bedload sediments due to management activities may quickly alter the dynamic equilibirum characteristics of a channel system. In addition, these data further illustrate that the relatively infrequent but relatively large runoff events are the major transport periods for bedload sediments in mountain streams. The slope of the bedload rating curves indicate that doubling flows causes a 10 to 20 times increase in bedload transport rates.

Because of the vertical and horizontal velocity profiles found at any given cross section in the channel, the transport rates of bedload sediments do not occur uniformily across the channel. Field measurements and observations indicate that the material is moving downstream in "ribbons" (longitudinal zones of relatively high particle concentrations) that may continually shift back and forth near the center of the channel. This behavior poses serious sampling problems when attempting to measure transport rates with portable samplers (such as the Helley-Smith bedload sampler used in this study). This lateral migration back and forth may also cause apparent "pulses" of bedload transport measurements. However, the fact that similar pulses in transport rates were also measured with the vortex sampler (which samples across the entire channel) indicates the large variation in transport rates over time is not an artifact of the sampling methods employed in this study. Hayward and Sutherland (1974) similarly found bedload transport to be highly unsteady even during conditions of relatively constant flow in a New Zealand stream.

The movement of bedload particles in mountain streams is the result of numerous interacting processes. Historically, flume studies have been used in an attempt to characterize transport rates and mechanisms utilizing conditions of uniform flow and uniform channel geometry. Unfortuantely, none of these criteria adequately describe Flynn Creek or Oak Creek. Due to the complex channel geometry (pools, riffles, meanders, etc.) and large roughness elements (logs, root wads, boulders, etc.) found in these streams, flows are seldom uniform through any given reach. As a result, flows are accelerating or decelerating along various sections of the channel and velocity profiles are highly variable. In addition, the transient nature of storm hydrographs indicates that flow rates are continually changing with time. The problem of nonuniform particle size is also a major confounding feature (unlike in flume studies where particle sizes in transport are often rigidly controlled) that creates problems in the interpretation of field data. Within any given reach of a stream, median particle diameters may range over an order of magnitude in size. In addition, the occurrence of armoring at the streambed-water interface is undoubtedly an important factor limiting the transport of the underlying (and smaller) bed sediments. The periodic disruption of this armor layer may be the major mechanism by which "pulses" of bedload sediment are released for transport downstream.

Median particle diameters (d_{50}) of bedload samples collected with the vortex sampler at Flynn Creek (after adjusting for the inefficiencies of the sample box) were generally within the range of 0.2 to 0.8 mm and averaged 0.5 mm. Although this result was somewhat surprising due to the low trapping efficiency of the sampler for these particle sizes, it nevertheless indicates that the vast majority of bedload sediments in transport at Flynn Creek are of sand size. Similarly, all Helley-Smith samples had a d_{50} of less than 0.5 mm. Larger bedload particles were typically carried by Oak Creek where the d_{50} and d_{95} averaged less than 2 mm and 15 mm, respectively.

The transport rates of particulate organic matter indicated in the results section represent conservative estimates of actual rates. This is because these data are based on measurements obtained with the Helley-Smith bedload sampler which only samples the lower 7.6 cm of the water column. Although the amount of particulate organic matter in transport measured near the surface of the water was often only one-tenth that measured at the bed, a relatively large but unknown amount of organics were carried over the top of the sampler.

Channel Morphology

Cross-section profiles at 12 locations at Flynn Creek indicated a net degradation of 5 cm in WY 1977 and no change in WY 1978. However, localized scour and fill at individual cross sections was common even when no net change occurred over the entire reach.

Total Suspended Solids

Almost 40 percent of the total suspended solids concentration at both Flynn Creek and Oak Creek were found to consist of organic matter, based on samples analyzed for the 1980 WY. The percentage organic matter appeared to decrease with an increase in flow.

Total suspended solids concentration was regressed against streamflow for individual storms and water years at each watershed. Coefficients of determination (r^2) for water year relationships ranged from 0.01 to 0.65. However, those years that experienced a relatively wide range in flows showed exponential increases in total suspended solids concentrations from 1.12 to 1.56 indicating a doubling of flow would result in approximately a 2.5 times increase in total suspended solids concentration and a 5 times increase in total suspended solids discharge. This rate of increase in total suspended solids discharge is much lower than that for bedload and indicates that material transport in Coast Range streams shifts towards the bedload component at high flows. The bedload component of the total material discharge also becomes more important during the recession limb of a storm hydrograph because of the opposing hysteresis relationships of bedload and suspended solids with streamflow.

Several storm characterisitics were also found to be important in influencing total suspended solids concentrations. These factors include (1) streamflow, (2) hydrograph slope, and (3) sequence of storm events. In general, increases in total suspended solids were positively correlated with increases in streamflow. Thus, as expected, the higher flows usually have higher concentrations and discharges (concentration x streamflow) of total suspended solids. However, the effect of factors (2) and (3) is to create additional variability in any computed rating curves. The role of hydrograph slope can be further subdivided into several factors. First, pronounced differences in total suspended solids concentrations occur between periods of flow increases (positive slope) and periods of flow decreases (negative slope). Almost always, concentrations are higher on the rising limb of a storm hydrograph at any specified streamflow than on the falling limb, at that same flow. However, this situation may not be apparent when a complex hydrograph (i.e., a storm with several streamflow peaks) occurs. Second, the rate of flow increase with time (dQ/dt) also affects resultant concentrations. Relatively fast increases in streamflow tend to have higher concentrations than when streamflow increases are slower. However, the total amount of material discharged from the watershed during two storms that have the same peak flow may be essentially the same even though the storm which causes the most rapid rise in flow will also have higher concentrations.

The third factor, the sequencing of storm events each winter, further confuses attempts to obtain useful correlations between concentration and flow. A general shift in the rating curves of individual storms each winter indicates that runoff events which occur later tend to have lower concentrations for a given flow. This seasonal "flushing" thus adds additional variability to the composite rating curves for each year and may cause the negative exponent illustrated in the relationship for the 1980 WY at Flynn Creek (Table 3). The factors identified above do not operate independently of each other.

The interaction of factors (1), (2), and (3) makes the use of regression analysis of limited value in attempting to develop accurate predictive relationships between concentration and flow. This is particularly evident by inspecting the individual storm rating curves. Thus, curves developed for a given storm cannot be used to predict concentrations for other runoff events even though the hydrographs may be identical. Similarly, individual storm relationships cannot be extrapolated to predict the total suspended solids concentrations for flows larger or smaller than those sampled. A wide range of flows (at least an order of magnitude) and a variety of runoff events should be sampled in Oregon's Coast Range watersheds to establish a total suspended solids rating curve that is "representative" of a particular drainage. A large number of samples over a limited flow range will not be adequate. The data presented here also indicate that year-to-year shifts in rating curves may occur and represent another problem when attempting to utilize a rating curve approach for assessing the effects of land management activities upon stream sediment loads.

Total Suspended Solids and Turbidity

Results indicated that total suspended solids concentrations are highly correlated with turbidity. However, the relationships between these two variables are highly varied necessitating that predictive equations must be developed on a watershed-by-watershed basis. Both Flynn Creek and Oak Creek generally have turbidities less than 30 ntu within 24 hours after a hydrograph peak. Because turbidity is a relatively sensitive indicator of changing erosive conditions on a watershed, coupled with its ease of measurement, this variable may well serve as a useful variable for indexing changes in water quality brought about by land use activities.

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