

BEDLOAD TRANSPORT IN AN OREGON COAST RANGE STREAM¹Susan J. O'Leary and Robert L. Beschta²

ABSTRACT: Bedload transport was measured with two sampler types (vortex tube and Helley-Smith pressure differential) for three major storms at Flynn Creek, which drains a 2.2-km² forested watershed in the Oregon Coast Range. The largest flow during two winters of monitoring had a peak discharge of 0.79 m³ s⁻¹ km⁻², with an associated recurrence interval of ~1.3 yr. The median particle diameter of sediment in transport was generally <1 mm. The vortex tube and its associated sample box were relatively inefficient at trapping particles <10 mm in diameter; however, even after transport rates were adjusted to account for sampling deficiencies of the sample box, they still averaged 42-47 percent of those obtained with the Helley-Smith sampler. Organic matter and sand sized sediments in transport also were observed to partially plug the 0.2-mm-mesh bag of the Helley-Smith sampler. Large temporal variability in bedload transport rates was measured during periods of high flow.

(KEY TERMS: bedload; sediment transport; Oregon.)

INTRODUCTION

Fluvial sediment studies have largely emphasized measuring and analyzing suspended sediment — possibly because the suspended sediment load of mountain streams can be greatly increased by land-use activities, visibly affecting water quality. Samplers that collect suspended sediment have been relatively easy to design and use in the field; in addition, pumping samplers have allowed automatic sample collection. In contrast, research on bedload transport has largely been confined to laboratory flume studies due to design problems with early samplers, which were often difficult to use in the field and highly inefficient in sampling bedload particles.

Over the past several decades, particularly since the late 1960's, various attempts have been made to measure bedload transport in streams draining mountainous terrain. Samplers used were box or basket, pan or tray, pit, pressure differential, or vortex types. Of these five categories, the vortex and pressure differential [specifically, the Helley-Smith (1971) sampler] probably come closest to approximating the requirements of the U.S. Federal Interagency River Basin Commission (1940), which specified that an ideal instrument for measuring bedload must sample a definite portion of the moving stream of water and solids, collect all the solids from the

sampled portion, and securely contact the bed when in operation without influencing flow upstream or obstructing particle entrance. Our study used both these samplers.

Vortex samplers were originally developed to remove unwanted sediment from irrigation canals in India, but modification by Parshall (1933) and Rohwer (1935) led to their use in the United States. Advantages of the vortex sampler include a spatially integrated sample across the channel, a relatively high sampling efficiency for particles >10 mm, and variability in the length of time over which sampling occurs, depending upon flow conditions and transport rates. On the basis of Robinson's (1962) criteria for field engineers, Klingeman (1971) designed and installed a vortex sampler to remove bedload sediment from Oak Creek, which drains a 7.3-km² watershed in the Oregon Coast Range. The smallest bedload material trapped in the vortex during winter runoff was fine (~0.15 mm) sand. The critical discharge for initiating bedload transport was 0.17 m³ s⁻¹ km⁻². Median bedload particle size (d₅₀) increased with transport rate up to a maximum of 14 mm.

Hayward and Sutherland (1974) used a vortex sampler on a 3.9-km² catchment in the Torlesse Range of New Zealand. Incipient motion began at flows of 0.05-0.07 m³ s⁻¹ km⁻², considerably lower than those observed by Klingeman (1971). Bedload appeared to travel as "bursts" that were not related to water discharge: at a constant discharge of 0.096 m³ s⁻¹ km⁻², bedload transport ranged from 3-76 kg min⁻¹. Hayward and Sutherland concluded that bedload transport must largely depend upon factors other than stream flow, such as bank failure, breakdown of part or all of an armor layer of the streambed, or movement of large boulders. Additional results were later summarized by Hayward (1979, 1980).

The Helley-Smith bedload sampler (Helley and Smith, 1971) is probably the most widely used pressure differential sampler today. Molnau, *et al.* (1975), used it in central Idaho in several mountain streams whose bed material consists of sand and fine gravel. Results indicated highly variable bedload transport rates during both rising and falling limbs of the snowmelt hydrograph.

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Emmett (1975) obtained Helley-Smith bedload samples from three streams in the upper Salmon River area of central Idaho. Although bedload transport generally increased with increasing stream flow, up to a 10-fold variation in transport rate at a given flow rate was noted. A break in the relationship between bedload transport and stream power occurred at intermediate values of stream power, thought by Emmett to result from the bimodal size distribution (gravels of intermediate size missing) of the bed material. On the basis of Helley-Smith samples obtained in the Snake and Clearwater Rivers of Idaho and Bagnold's (1966, 1973) definition of stream power, Emmett (1976) proposed two separate relationships between bedload transport rate and stream power: one that applies to low values of stream power (when coarse particles are stationary and fines limited), and another that applies to higher values of stream power (when nearly all bed material sizes are moving). Similarly, Jackson (1981) has identified a two-phase system of bedload transport in small mountain streams, which showed that relatively high and low bedload transport rates were associated with periods of localized scour and deposition, respectively, of the stream bed.

Knowledge of rates and yields of bedload sediments for mountain streams draining both undisturbed and managed watersheds is pivotal for understanding the interrelationships between land management activities and accelerated sedimentation and their impacts on stream environment. Because of the importance of bed material in affecting channel characteristics and the paucity of field measurements, we undertook this two-year study at Flynn Creek in the central Oregon Coast Range to improve our understanding of bedload transport mechanisms in small mountain streams.

STUDY AREA

Flynn Creek is located in the Siuslaw National Forest approximately 80 km west of Corvallis, Oregon (Figure 1). The stream drains a 2.2-km² undisturbed watershed that ranges in elevation from 183-457 m. Douglasfir (*Pseudotsuga menziesii*) forests dominate most slopes and ridges, and red alder (*Alnus rubra*) prevail along the stream channel. Hillslopes are moderately steep (25-37 percent). Soils have derived from the underlying Tyee formation, which consists of horizontally bedded sandstone-siltstone layers. Those soils associated with the steeper slopes are generally shallow, well drained, and medium textured; those associated with gentle, uneven hillslopes are deep, moderately drained, and moderately fine textured. Mass soil movements (both soil-mantle creep and debris avalanches) are the primary mechanisms by which sediments enter the channel.

The streambed consists primarily of a mixture of sand to coarse gravel, with 22 percent, by weight, of the bed material < 1 mm in diameter. Most streambed sections are armored with fine to coarse gravel. At the mouth of the watershed, the channel is 2-4 m wide and has an average gradient of < 1 percent. Large organic debris (stems, root wads, branches) deflect flows and vary channel morphology. At low flows, water

depths average 0.1 m, with pools up to 1 m in depth approximately 10-15 m along the channel.

In-stream sediment transport occurs during winter freshets when moist air masses move inland from the Pacific Ocean. These winter frontal storms, accentuated by orographic effects of the Coast Range, account for over 80 percent of the 230 cm of average annual precipitation. Stream flow responses to storms are rapid. Although the mean daily discharge for Flynn Creek is 0.0024 m³ s⁻¹ km⁻², the instantaneous peak discharge for a two-year recurrence interval flow is approximately 0.90 m³ s⁻¹ km⁻².

METHODS

A vortex sampler was our primary monitoring device for determining bedload transport. Additional measurements were taken with a Helley-Smith sampler to provide a comparison with vortex sampler data.

A concrete "fishtrap" had been constructed in 1960 at the mouth of the Flynn Creek watershed as part of the Alsea Watershed Study (Moring and Lantz, 1975). During late summer 1976, a vortex sampler was installed in the 2.57-m-wide main channel of the fishtrap (Figure 2). This sampler, a steel tube 30.5 cm in diameter and 2.8 m long, was placed into the bed of the fishtrap (control section) at an angle 65° to the direction of flow. A 20.3-cm opening was cut along the entire length of this tube to allow entry of water and bedload sediments. At high flows, water and sediments moving along the stream bottom entered the tube, where a circular or vortex flow pattern was established. The water sediment mixture was discharged through the (open) downstream end of the tube into an adjacent sampling area where it was diverted into a 0.3-m³ sampling box; bedload particles were deposited in the box, and the overflow water was returned to the stream. Between sampling periods, the water sediment mixture was diverted past the sample box and returned to the stream at the downstream end of the fishtrap. To determine whether flow rates entering the sample box influenced trapping and retention of particles, during periods of no bedload transport we diverted flows of 0.09-0.16 m³ s⁻¹ into the vortex tube and added known quantities of sediments.

The length of time during which a sample was collected varied depending upon stream flow and bedload transport conditions, but generally was restricted to that necessary to collect approximately 0.006 m³ of sediment in the sampling box. This volume was selected to facilitate handling and analysis. These relatively short sampling intervals were also useful for quantifying temporal variability in bedload transport.

We also held a Helley-Smith sampler (7.62 x 7.62-cm orifice; 0.2-mm-mesh bag with 1,950-cm² surface area) on the bottom of the fishtrap for 15 s at each of seven sampling points (Figure 2); the subsamples collected were then combined to form a single, composite sample. The concrete channel bottom provided an excellent contact surface for the Helley-Smith and eliminated potential sampling errors due to scooping of bed materials during sampler placement or removal.

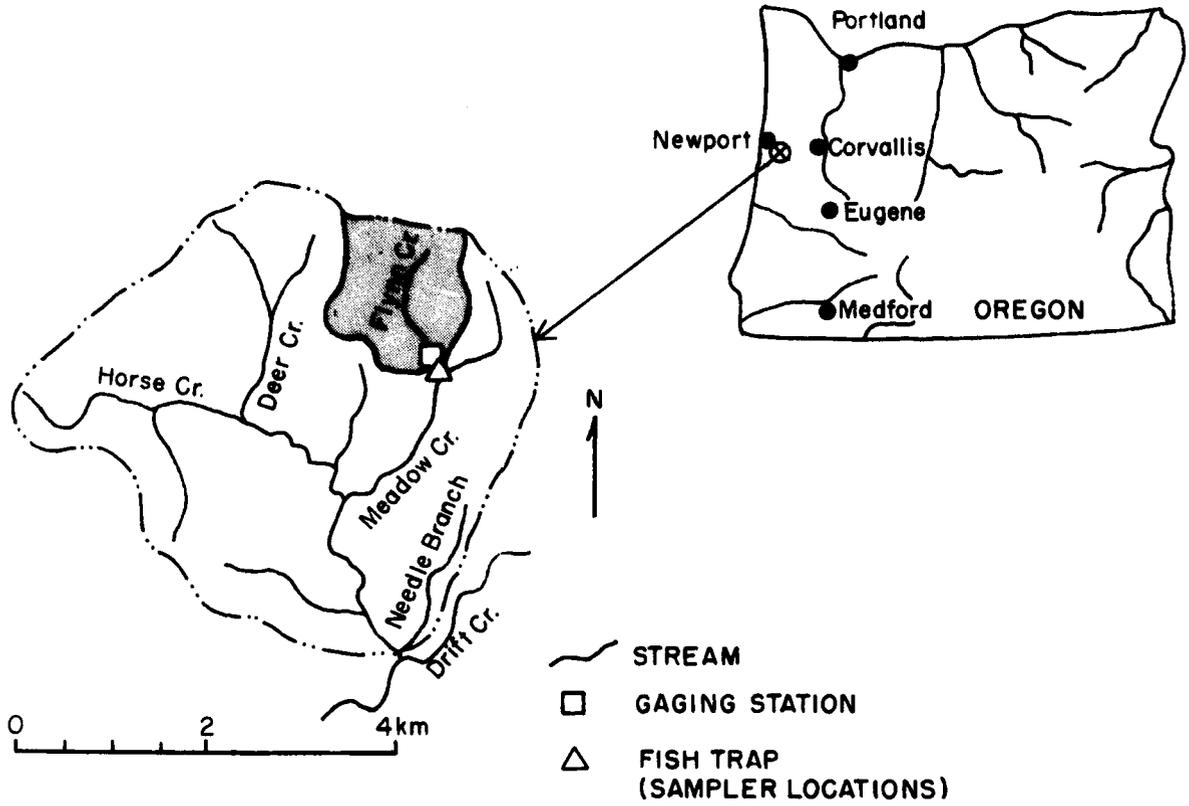


Figure 1. Location Map of the Flynn Creek Watershed (after Williams, 1964).

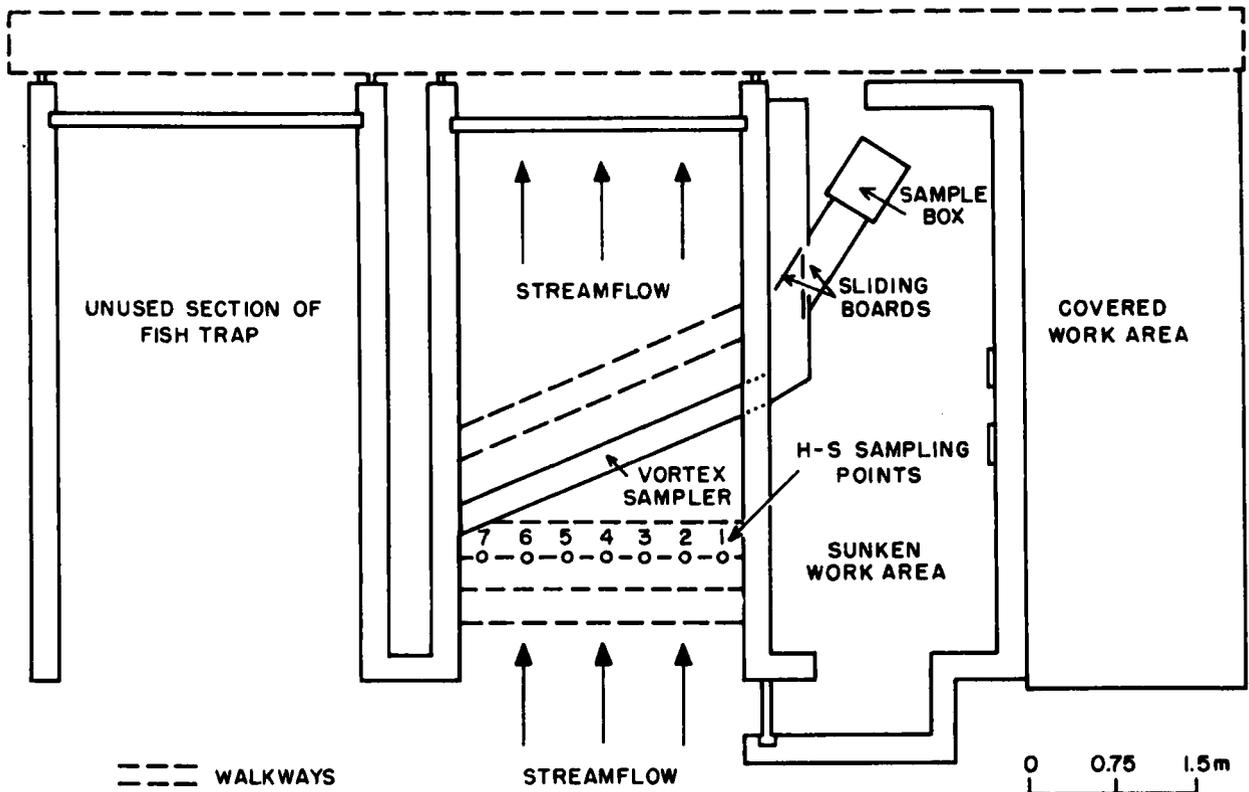


Figure 2. Plan View of Vortex Tube Bedload Sampler and Sampling Points for the Helley-Smith Bedload Sampler at the Flynn Creek Fishtrap.

In the laboratory, vortex samples were dried at 105°C for 24 hours, after which any visible organic material was removed by hand. The samples were then sieved and weighed to determine particle size distributions and total weights. We used an adjustment procedure to correct for the variable trapping efficiency of the sample box for sediments ranging from 0.15-10 mm in diameter. Helley-Smith samples also were dried at 105°C for 24 hours, weighed, placed in a muffle furnace at 550°C for 24 hours to burn off organic matter, sieved, and weighed again to determine particle size distributions and total weights.

RESULTS AND DISCUSSION

Vortex Tube and Sample Box Efficiencies

The trapping efficiency of the sample box was independent of flow rate through the vortex tube. Results indicated a relatively narrow grouping for each particle diameter tested (Figure 3); at a given diameter, differences between the maximum and minimum amounts of sediment retained were usually less than 20 percentage units. No consistent pattern between flow rate and trapping efficiency of the sample box emerged. However, these tests confirmed the strong dependence of particle size upon sample box efficiency. If the curve in Figure 3 were extrapolated to particle diameters of ~10 mm, the sample box would appear to be 100 percent efficient. Because trapping efficiency is a direct function of diameter for particles ≥ 0.2 but ≤ 10 mm, the relationship in Figure 3 was combined with analysis data for bedload particle sizes to adjust sample weights for sample box inefficiencies. Measurements conducted after this study was completed (Edwards, 1980; Beschta, *et al.*, 1981) further confirmed that this efficiency problem existed.

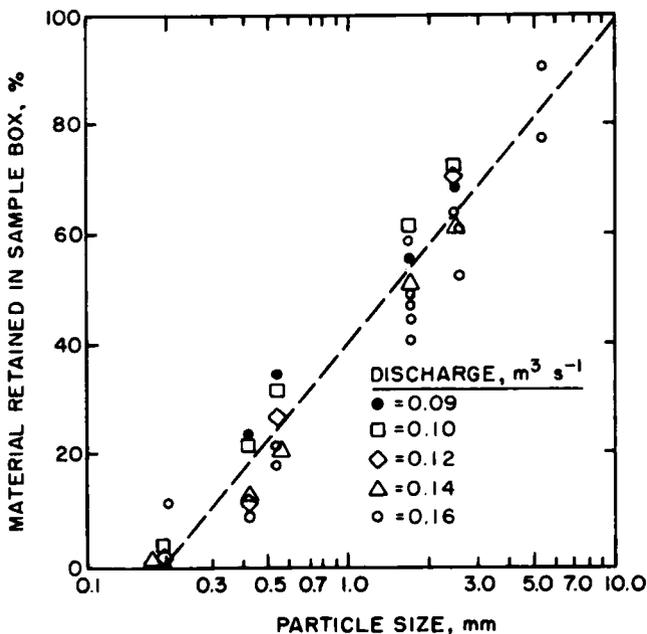


Figure 3. Trapping Efficiency of the Sample Box for Various Particle Sizes and Water Discharges Through the Vortex Tube.

Helley-Smith bedload samples were not obtained frequently enough during high flows for us to be able to evaluate temporal variations in transport; however, they provided a valuable comparison between the two distinctly different sampler types. Results (Figure 4) indicated that an average of only 15 percent of the bedload measured with the Helley-Smith sampler was measured in the vortex sample box. After adjusting for the trapping inefficiencies of the sample box, we found that the vortex sampler accounted for 42 percent of the sediment measured with the Helley-Smith sampler. Helley-Smith bedload samples collected immediately upstream and downstream of the vortex tube indicated that an average of 47 percent of inorganic sediments (> 0.2 mm) in transport within 7.6 cm of the bed were being removed by the tube. Clearly, the vortex system undermeasured the amount of bedload sediment in transport along the bottom of Flynn Creek. These upstream-downstream samples further indicated that the tube is probably almost 100 percent efficient at trapping particles > 10 mm. Because most bedload sediment in transport at Flynn Creek is considerably smaller than 10 mm – in the sand size range – much of this material apparently bypasses the vortex tube at high flows. As a result, the data reported here are conservative estimates of actual bedload transport rates at this site. Although the absolute accuracy of the presented data is unknown, we nevertheless consider the relative changes in transport rates measured with the vortex sampler to accurately depict temporal variability during storm runoff in Flynn Creek.

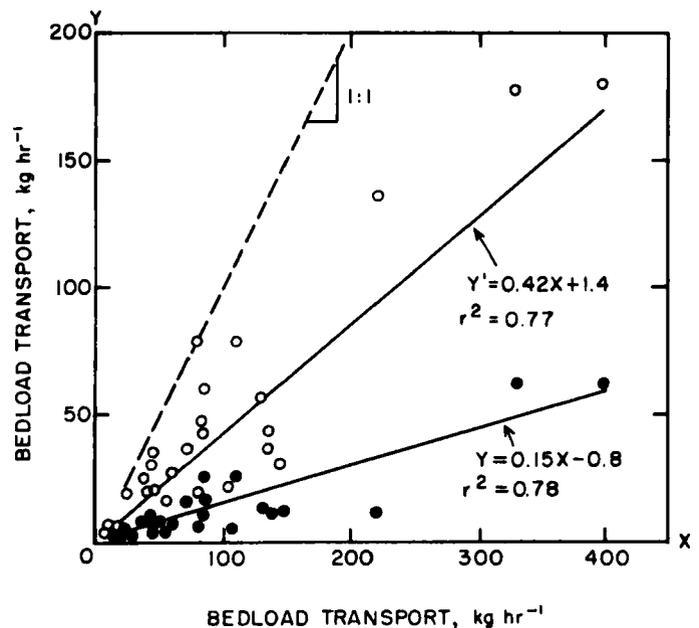


Figure 4. Comparison of Bedload Transport Rates Measured Concurrently With the Helley-Smith (X axis) and Vortex Tube (Y axis) Samplers. Values of Y are unadjusted transport rates, whereas values of Y' have been adjusted to correct for trapping inefficiencies of the vortex sample box.

Helley-Smith Efficiency

Although we originally assumed that the Helley-Smith sampler would have greater sampling efficiency than the vortex system, we observed that the 0.2-mm-mesh bag was often partly plugged by organic matter (leaves, needles, cones, twigs) or fine sands in transport along the streambed. Plugging of the bag would substantially decrease sampling efficiency, and much of the material that would normally enter the orifice and be filtered from the flow by the bag would bypass the sampler. If the observed plugging was affecting sampling efficiency, calculated transport rates would be expected to decrease as sampling time increased.

To evaluate this problem, Helley-Smith samples were obtained from the center of the stream at 15, 30, and 60-s intervals. Several samples were collected for each interval and combined to form a composite sample; this procedure was repeated over a variety of flows ($0.50\text{-}0.67\text{ m}^3\text{ s}^{-1}\text{ km}^{-2}$). In general, results confirmed that bedload transport rates calculated from Helley-Smith samples decreased as the sampling interval (length of time that the sampler remained on the channel bed) increased (Figure 5). Several of the samples do not show a consistent decrease with increased sample time, probable because of differences in the amounts of organic matter in transport at the time of sampling; samples that contained relatively high amounts of organic matter usually had relatively low calculated transport rates. In summary, large amounts of organic matter or fine sands or relatively long sampling times reduced the efficiency of the Helley-Smith sampler at Flynn Creek. Although a three-fold increase in bag size (to approximately $6,000\text{ cm}^2$) helps minimize the plugging problem (Beschta, 1981), relatively short sampling times ($< 15\text{ s}$) are recommended when the Helley-Smith is used in streams with high rates of sand or organic matter transport.

Bedload Transport During Storms

During winter 1976-1977, precipitation was less than 1/2 the long term normal: only 862 mm of precipitation was measured at Flynn Creek for November through March. Not just a local phenomenon, this period of extremely low precipitation prevailed throughout most of the western United States that year. These unusual precipitation patterns were reflected in the relatively low runoff volumes for Flynn Creek (Figure 6). Water yield for November through March was 546 mm, only 37 percent of average. Similarly, the instantaneous peak discharge of $0.32\text{ m}^3\text{ s}^{-1}\text{ km}^{-2}$ was the lowest annual peak measured over 20 years of flow record. As a result, essentially no measurable bedload transport occurred during that winter.

Water yield for November through March for winter 1977-78 at Flynn Creek was 1,524 mm, or 4 percent above average (Figure 6). Three major storms occurred during this period, with instantaneous peak flows of 0.72, 0.66, and $0.79\text{ m}^3\text{ s}^{-1}\text{ km}^{-2}$ on November 25, December 2, and December 13, respectively (Figure 7). The December 13 storm produced a complex hydrograph and secondary discharge peak of $0.71\text{ m}^3\text{ s}^{-1}\text{ km}^{-2}$ on December 15. On the basis of a partial series frequency analysis (for 20 years of flow record), the

instantaneous peak discharge of $0.79\text{ m}^3\text{ s}^{-1}\text{ km}^{-2}$ has a recurrence interval of ~ 1.3 year.

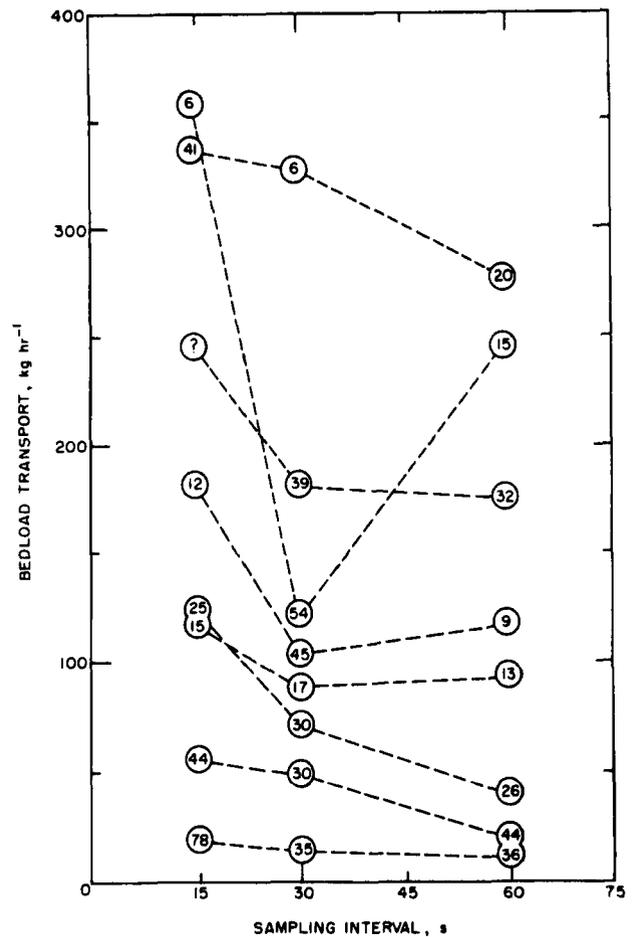


Figure 5. Relation of Bedload Transport to Duration of Sampling Period for the Helley-Smith Bedload Sampler in Flynn Creek. The number at each point is the percentage of organic matter within a sample (Beschta, 1981).

We measured bedload transport with the vortex sampler during portions of the three major storms that occurred during winter 1977-78. Results for the first storm, that of November 24-25 (Figure 8a), indicated that bedload transport generally increased in response to increased stream flow. Small fluctuations in transport rate can be noted over the first 10 hours of sampling, during which a peak transport of 34 kg hr^{-1} was measured. Bedload measurements for an 8-hour interval on November 25 indicated a maximum transport rate of 42 kg hr^{-1} and increased temporal variability. Median particle sizes for bedload samples fluctuated from 0.2-1.8 mm throughout the sampling periods but generally were higher after the hydrograph peak.

For the December 2-3 storm (Figure 8b), bedload transport generally declined with time, although fluctuations in bedload transport concurrently increased. The trend of bedload transport decreasing on the falling limb of the hydrograph was

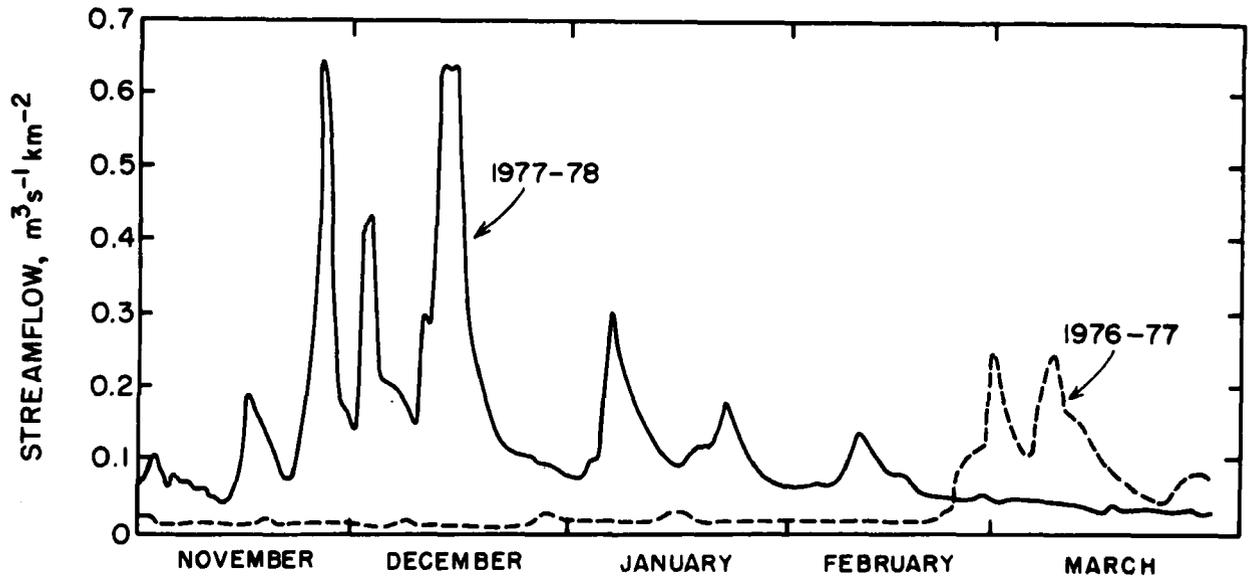


Figure 6. Daily Stream Flow for Two November-March Periods at Flynn Creek.

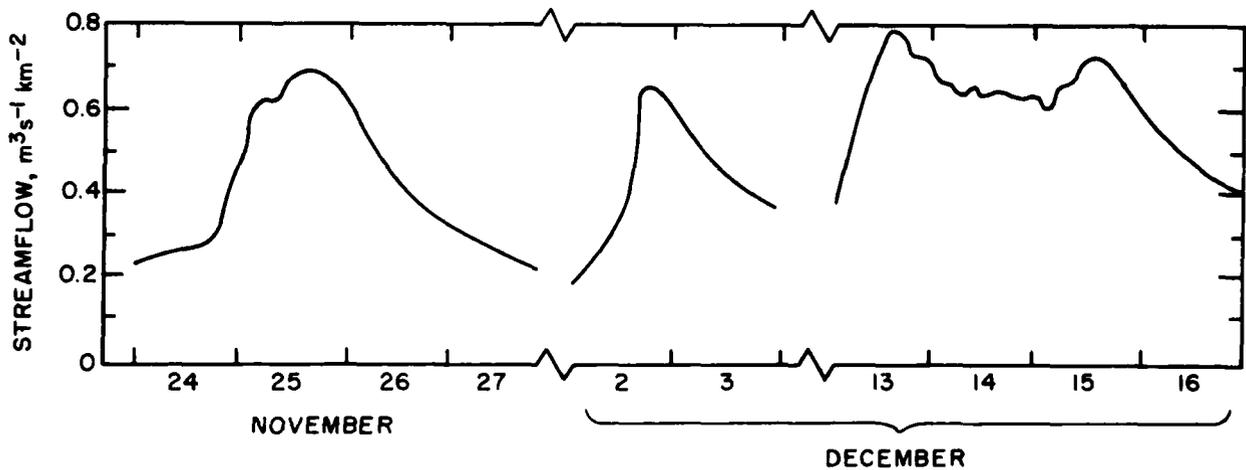


Figure 7. Stream Flow for the Major Storms of November and December 1977 at Flynn Creek.

similar to that for the November 24-25 storm; however, the average transport rate for the December 2-3 storm was approximately 2.5 times larger than that for the November 24-25 storm, even though flows for the December 2-3 storm were lower. Median particle sizes for the vortex samples remained approximately 0.4 mm throughout this storm.

The December 13-15 storm (Figure 8c) and its associated, relatively complex hydrograph produced the largest runoff during the 2-year study period. Although the peak flow was only $0.07 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ greater than that of the November 24-25 storm, bedload transport rates were often an order of magnitude greater. Large fluctuations in transport rates were evident, particularly for samples collected on December 13. Transport rates continued to increase until after the hydrograph peak on December 13 but then rapidly declined. On

December 14 and 15, rates of bedload transport ranged from $36\text{-}90 \text{ kg hr}^{-1}$, well below the 324 kg hr^{-1} measured on December 13. Median particle sizes generally increased from $0.3\text{-}1.0 \text{ mm}$ on December 13 but remained close to 0.5 mm on December 14 and 15. By 1800 hour on December 16, the bedload transport rate had dropped to 20 kg hr^{-1} , which is similar to that observed for the November 24-25 storm. Median particle size also decreased to 0.35 mm . Stream flow during sampling on December 16 averaged $0.39 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$.

The relatively large fluctuations in bedload transport rates over time intervals during which stream flow did not appreciably change seems an important characteristic of bedload movement in mountain streams. Our data further indicate that these temporal fluctuations occur rapidly — within minutes. Such results tend to confirm that the high variability

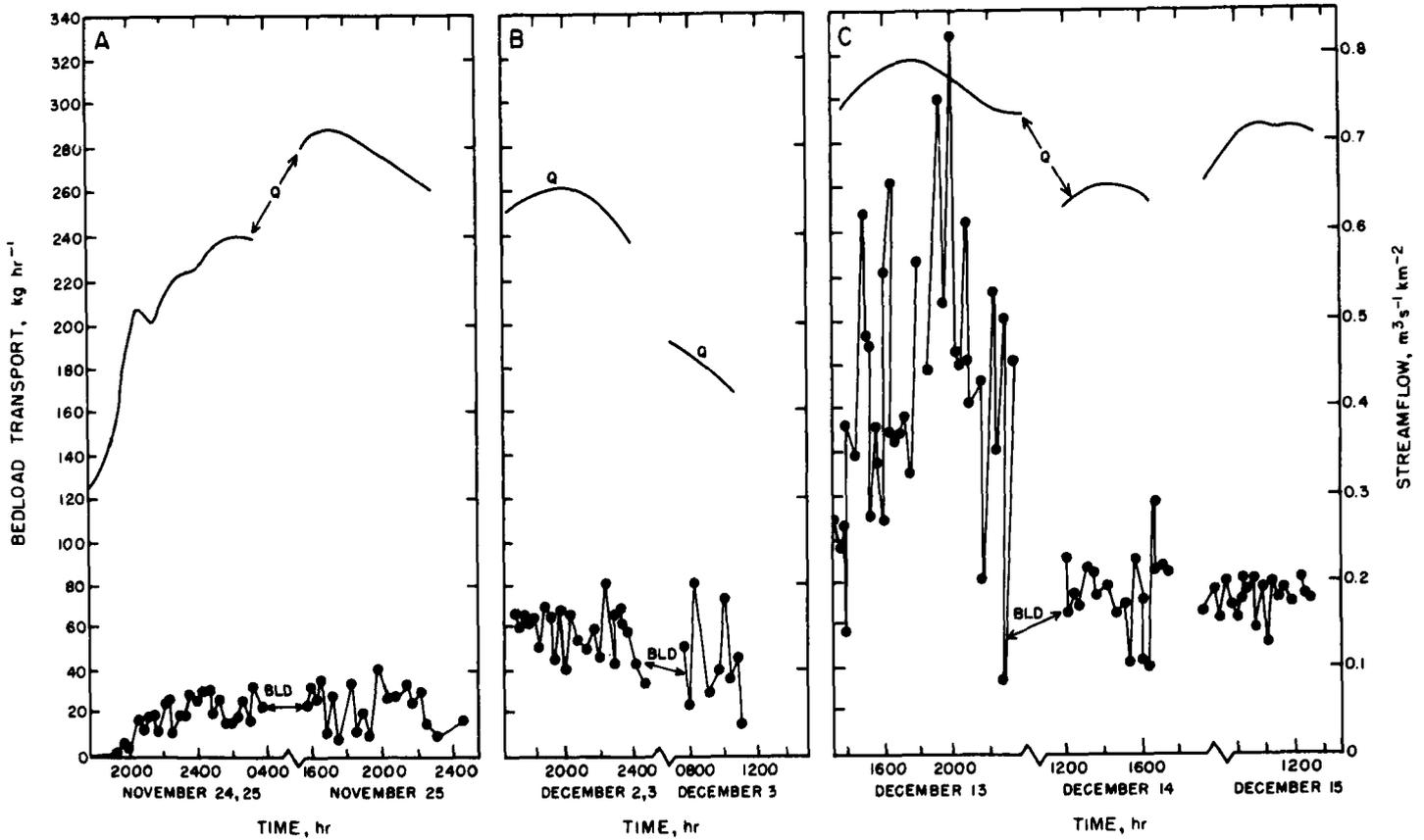


Figure 8. Stream Flow (Q), Bedload Transport (BLD), and Median Particle Diameter (d_{50}) of Vortex Tube Samples for (a) November 24-25, (b) December 2-3, and (c) December 13-15.

noted by Hayward and Sutherland (1974) and Hayward (1980) in a mountain grassland catchment of New Zealand also occurs in the forested mountain watersheds of the Pacific Northwest. Although part of this variability may be explained by sampling error, we feel that most of the measured variability is indeed real and not an artifact of the vortex sampler. If the variability is real, what is its cause?

The proposed answer is not a simple one. It requires that we characterize the type of channel system and hydrology responsible for bedload transport. Several characteristics are exceedingly important:

1. **Nonuniform Channel Geometry.** Flynn Creek, like most mountain streams, has a pool-riffle channel configuration. Water moving downstream is continually accelerating and decelerating as it follows the tortuous channel configuration of alternating pools and riffles. As a result, flows are not spatially uniform. At Flynn Creek, pools are invariably found in conjunction with large trees or organic debris. These vegetative materials deflect flows laterally and vertically, causing relatively deep sections in the channel to be formed from the alluvial sediments composing the bed and banks.

2. **Nonuniform Particle Size.** Particle sizes differing over several orders of magnitude are found in Flynn Creek and most mountain streams. In addition, armoring of bed material further influences the availability of these sediments.

3. **Transient Flows.** Over several minutes, the flows of Flynn Creek generally remain relatively unchanged. Yet over several hours or days, flows rise or fall rapidly in response to precipitation.

Thus, sediment transport over short time intervals is governed by factors affecting sediment availability. Localized disruptions in the armor layer could cause the rapid release of bedload sediments in a "burst" or "pulse" downstream, as previously suggested by Klingeman and Milhous (1970), Hayward and Sutherland (1974), and Molnau, *et al.* (1975). Recent measurements of bedload and channel morphology (Jackson, 1981) further confirm that relatively high and low transport rates are closely tied to scour and deposition, respectively, of the streambed. As a result, bed material sediments periodically become available to the flow and are transported downstream. The variability in transport rates measured in this study is thought to reflect the alternating scour and fill processes at various locations in the upstream channel. Unfortunately, the characteristics identified above prevent the rigorous application of bedload equations (typically developed for uniform flows, uniform particle sizes, and steady state conditions) for predicting bedload transport in most mountain streams. However, where hydraulic conditions and sediment characteristics are similar to those from which bedload equations have been developed, relatively good agreement between

measured and predicted transport rates may result (Andrews, 1981).

Although all three storm hydrographs peaked within a range of 0.66-0.79 m³ s⁻¹ km⁻², a pronounced trend towards increasing bedload transport during the latter storms was apparent (Figure 9). Why this progressive increase in transport occurred from storm to storm is not known but may be the result of channel adjustments upstream from the fishtrap due to our raising the streambed slightly when the vortex tube was installed in late summer 1976. Because the record low flows of winter 1976-77 resulted in essentially no bedload transport at Flynn Creek, the storms of winter 1977-78 represented the first opportunity for channel adjustments as a result of the vortex tube installation. Indeed, deposition of bed material 7.0 cm deep occurred immediately upstream of the fishtrap. Accumulation of bedload sediments in the upstream channel during the first several storms could have accounted for the relatively low initial transport rates. The higher rates measured during the December 13-15 storm would indicate that upstream storage had largely been satisfied and that bedload transport was returning towards equilibrium rates.

The regression equations (bedload rating curves) shown for the three major storms of winter 1977-78 (Figure 9) were not only statistically significant ($\alpha = 0.01$) but were also significantly different ($\alpha = 0.01$) from each other. The pattern of significant differences between rating curves, by storm, for bedload is similar to that found for suspended sediment (Beschta, *et al.*, 1981) and for relationships between suspended sediment and turbidity (Beschta, 1980). Apparently, bedload rating curves developed for a given storm do not accurately predict bedload transport for other storms or flow conditions. Again, factors other than stream flow seem to greatly affect measured rates of bedload transport.

Combining the data from all three storms produced the relationship:

$$\begin{aligned} \text{BLD} &= 422 Q^{4.51} \\ r^2 &= 0.58 \\ n &= 187 \end{aligned}$$

where:

$$\begin{aligned} \text{BLD} &= \text{bedload transport from vortex tube samples, kg} \\ &\text{hr}^{-1} \text{ and} \\ Q &= \text{stream flow, m}^3 \text{ s}^{-1} \text{ km}^{-2}, \end{aligned}$$

which does indeed indicate that flow has an important effect on overall transport rates. For example, a 10 percent increase in flow would be associated with a 54 percent increase in transport rate. The relatively large exponent of 4.51 may be a result of changing characteristics in the upstream channel during winter 1977-78. Measurements for the following winter resulted in a similar relationship, although the exponent had decreased (Beschta, *et al.*, 1981):

$$\begin{aligned} \text{BLD} &= 376 Q^{3.41} \\ r^2 &= 0.72 \\ n &= 86 \end{aligned}$$

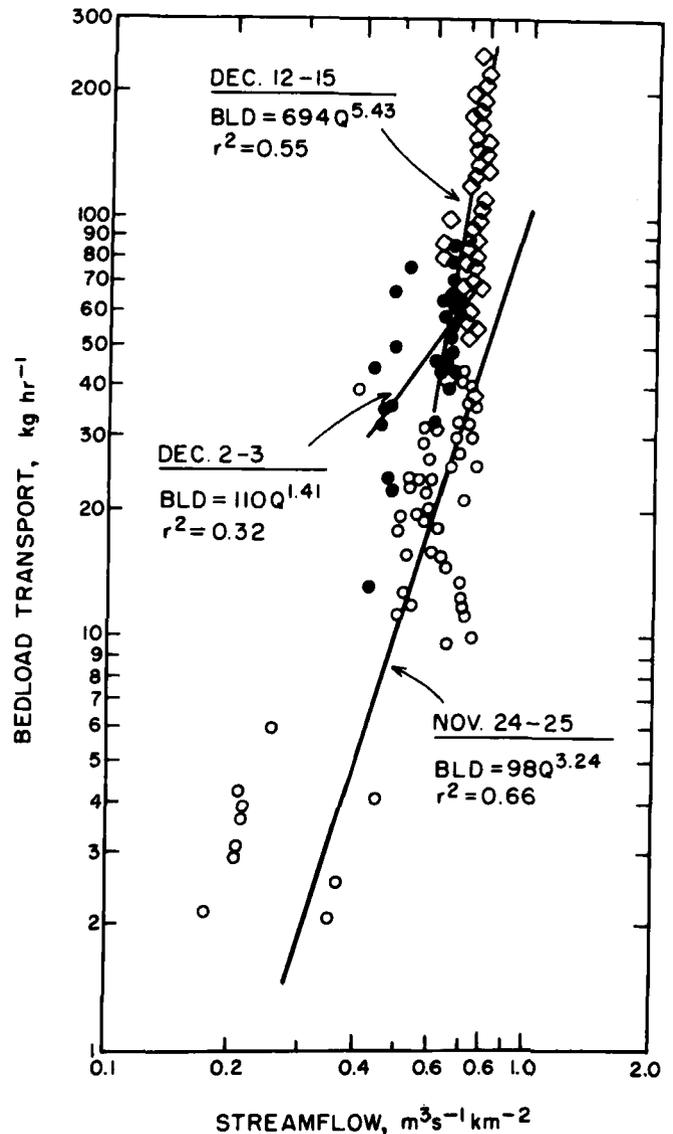


Figure 9. Relation of Bedload Transport (BLD) to Stream Flow (Q) for Three Storms During Winter 1977-78.

Even though bedload transport is an extremely important process shaping the channel characteristics of mountain streams, actual movement of the bed occurs only during relatively large storms and over limited periods of time. On the basis of the bedload rating curve developed from the data for winter 1977-78 and a daily flow duration curve (based on 15 years of record), the percentage of time that selected rates of bedload transport occur can be identified:

Bedload Transport Rate, kg hr ⁻¹	Stream Flow, m ³ s ⁻¹ km ⁻²	Time That Indicated Rate and Flow Are Exceeded, Percent
1	0.26	3
10	0.44	1
100	0.73	<0.5

Intensive sampling during high flows has provided an important perspective from which to view bedload transport (and associated scour and fill of bed material) in mountain streams. Our results indicate that large fluctuations in transport can occur rapidly – which, in turn, makes measurement and prediction of bedload transport difficult. Before the interrelationships between land use activities and accelerated sedimentation and their impacts to stream environment can be distinguished and understood, we feel that many fundamental sampling and measurement problems are yet to be overcome. In addition, a much broader data base of transport measurements for other undisturbed stream systems is needed. Without this perspective, our ability to evaluate in-channel impacts from sedimentation will remain severely limited.

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