Sediment transport measurements on Flynn Creek, a headwater stream in the Oregon Coast Range, have illustrated the magnitude of fluvial transfer processes, primarily of the bedload component, during a moderate storm runoff season (1979 water year). The total dissolved solids concentration of storm runoff averaged 40 mg/L, and was independent of water discharge. Most particulate export from the 202 ha forested watershed occurred during the annual peak flow of 0.75 m³/sec-km² (2-year return interval). Suspended load was the most important transport mode, with a total yield of $5.7 \times 10^4$ kg during the 24 h peak flow period. The export of coarse particulate organic matter during the same period was $1.5 \times 10^3$ kg.

Bedload discharge, as measured with vortex tube and Helley-Smith samplers, occurred in pulses of short duration that did not necessarily coincide with peak streamflow. For the same 24 h storm runoff period, the total bedload yield at the mouth of the watershed was only $2.6 \times 10^3$ kg (particles > 0.25 mm), and consisted primarily of sand-size material. Bedload discharge at an upstream site (1.3 x
10^-1 kg) was dominated by gravel-size particles. Channel morphology and in-stream obstructions (organic debris, fish trap) appear to cause significant spatial and temporal variations in sediment transport and streambed composition.

Although streamflow was the principal variable controlling sediment transport, results suggest that supply limitations exist. The supply of transportable materials is dependent on the retention characteristics of the stream channel and on local hydraulic conditions. The discharge of both suspended solids and coarse particulate organic matter peaked early in the storm; however, pulses of the latter component on the recession limb appeared to be related to streambed disturbances. Bedload movement is an important process regulating both bed composition and particulate yields in this Coast Range stream.

The Helley-Smith sampler was the preferable method for use in streams having a large fraction of bedload in the sand-size range. The vortex tube trapped from 60-70% of the bedload sediment measured by an upstream Helley-Smith sampler, with trapping efficiency of the former increasing as transport increased. The variability in bedload movement suggests that monitoring designs must address: (1) rapid temporal fluctuations in bedload discharge, (2) variations in bedload transport along a stream, (3) lateral variations in bedload discharge at a cross section, and (4) the type of sampler used.

Keywords: bedload transport, vortex tube sampler, Helley-Smith sampler, suspended load, bed material load, coarse particulate organic matter, mountain streams, channel morphology, sedimentation.
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Date thesis is presented: November 6, 1979

Typed by Donna Lee Norvell for Richard Earl Edwards
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Special thanks is extended to my loving wife, Wendy, who provided aid throughout the study, and was willing to remain patiently at home while we waited for the big storm.

Mother Nature deserves a word of thanks for being merciful to a storm-less graduate student.
"Much water [and sediment] goeth by the mill
That the miller knoweth not of."

- Epigrams and proverbs of John Heywood, first printed 1546
  (from Liddell, 1927)
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SEDIMENT TRANSPORT AND CHANNEL MORPHOLOGY
IN A SMALL MOUNTAIN STREAM
IN WESTERN OREGON

I. INTRODUCTION

Extensive progress has been made in the past decade toward the control of point sources of water pollution. Federal and state water quality goals have been established that forecast a reduction in the magnitude of cultural impact upon aquatic ecosystems. However, achievement of these goals may be overshadowed by the effects of uncontrolled non-point agents (Cannon, 1976; GAO Report, 1978). The major non-point pollution problem resulting from man's current 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 stability 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). 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). The capability of a stream to route these sediment inputs is primarily a function of its transport capacity.
Fluvial Transport Processes

Material transfer from an undisturbed forested watershed 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 transport 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 (Swanson et al., in press). The transient substrate that supports fluvial processes consists 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 bi-phase 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 transport 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). 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; Hanson, 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 consume stream energy otherwise available to disturb the stream bed (Beschta and Jackson, 1979). The retention-transport mechanisms and possible interactions of organic debris in the fluvial transfer system are not well known.

The mechanisms governing particulate transport in mountain streams must be more thoroughly described through field research before more comprehensive models can be developed. A unified concept of material transport will serve to improve the ability to: (1) estimate sediment yields, (2) assess the physical and biological consequences of sediment movement, and (3) prescribe land use guidelines for the mitigation of potential in-stream damage (Cannon, 1976).

Objectives of Research

This study involved measurement of particulate transport rates
and associated channel morphology changes in Flynn Creek, a small mountain stream in the Oregon Coast Range. Objectives of the research were:

1. Quantify particulate transport rates, especially of the bedload component, to determine the magnitude and conditions of material transfer in a mountain stream.

2. Measure related hydrologic parameters to define the mechanisms and consequences of sediment movement.

3. Identify possible interactions between the fluvial transport processes in a mountain stream.

4. Evaluate and compare the efficiency of the Helley-Smith and vortex bedload samplers in a small mountain stream.

These objectives are integral parts of a continuing research program addressing transport processes in mountain streams being conducted by the Department of Forest Engineering, Oregon State University. This project represents a basic study involving time-intensive sediment sampling during peak flow events in an undisturbed watershed. A vortex tube (Milhous and Klingeman, 1971) and Helley-Smith pressure differential (Helley and Smith, 1971) sediment samplers were used to measure bedload transport. The results reported here represent data collected during the 1979 water year (WY).
II. STUDY AREA

Watershed Description

The study was conducted on an instrumented reach of Flynn Creek (Lincoln County, Oregon), a small second order stream in the Alsea River Basin (Figure 1). This undisturbed, forested watershed served as the control during the Alsea Watershed Study (Moring and Lantz, 1975). Scientific installations along the stream consist of a fish trap structure, a United States Geological Survey (USGS) gaging station, and monumented stream cross sections. The sediment sampling facilities used in this study were installed in 1976 (O'Leary, 1980).

Thorough discussions of the climate, soils, vegetation, and stream characteristics of the watershed have been published (Williams, 1964; Hall and Lantz, 1969; Moring and Lantz, 1975; O'Leary, 1980). Pertinent morphometric and hydrologic data for the basin are summarized in Table 1. The Pacific maritime climate of Oregon's Coast Range is characterized by cool wet winters. Ninety percent of the annual precipitation occurs between November and May in the form of long duration frontal storms. Soils on the moderate to steep sideslopes are derived from sandstone bedrock and are relatively deep. Douglas-fir (Pseudotsuga menziesii) and red alder (Alnus rubra) dominate the overstory. The dense understory vegetation provides significant erosion protection for the fine-textured surface soils.
FIGURE 1. Location and details of the study area in the Flynn Creek watershed, Lincoln County, Oregon (after Williams, 1964 and Marston, 1978).
### TABLE 1. Selected morphometric and hydrologic characteristics for the Flynn Creek Watershed, Lincoln County, Oregon

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Watershed Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Above Bedrock Chute</td>
<td>151 ha</td>
<td>Harris, 1977</td>
</tr>
<tr>
<td>- Above USGS Gage</td>
<td>202 ha</td>
<td>O'Leary, 1980</td>
</tr>
<tr>
<td>- Above Fish Trap</td>
<td>218 ha</td>
<td>Adams, 1990</td>
</tr>
<tr>
<td>Elevation Range</td>
<td>183-457 m</td>
<td>Williams, 1964</td>
</tr>
<tr>
<td>Watershed Length</td>
<td>2,060 m</td>
<td>Hall &amp; Krygier, 1967</td>
</tr>
<tr>
<td>Watershed Relief Ratio</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>Mean Basin Slope Range</td>
<td>34%</td>
<td></td>
</tr>
<tr>
<td>Mainstem Length</td>
<td>1,433 m</td>
<td>Chapman, 1961</td>
</tr>
<tr>
<td>Mean Mainstem Gradient</td>
<td>0.025</td>
<td>Moring &amp; Lantz, 1975</td>
</tr>
<tr>
<td>Mean Summer Width</td>
<td>1.74 m</td>
<td>Chapman, 1961</td>
</tr>
<tr>
<td>Mean Summer Depth</td>
<td>0.13 m</td>
<td></td>
</tr>
<tr>
<td>Mean Annual Precipitation</td>
<td>244 cm</td>
<td>Hall &amp; Lantz, 1969</td>
</tr>
<tr>
<td>Mean Annual Air Temperature</td>
<td>-7° to 32° C</td>
<td>Williams, 1964</td>
</tr>
<tr>
<td>Mean Annual Runoff a</td>
<td>196 cm</td>
<td>Moring &amp; Lantz, 1975</td>
</tr>
<tr>
<td>Mean Minimum Daily Discharge a,b</td>
<td>0.0051 m³/s</td>
<td>Harris, 1977</td>
</tr>
<tr>
<td>Maximum Recorded Discharge a,c</td>
<td>3.94 m³/s</td>
<td>Harris, 1977</td>
</tr>
<tr>
<td>Mean Annual Water Temperature a</td>
<td>9.7° C</td>
<td>Moring &amp; Lantz, 1975</td>
</tr>
<tr>
<td>- Range</td>
<td>2.2° to 16.6° C</td>
<td></td>
</tr>
</tbody>
</table>

* Low flow attained during August and September.
* Water Years 1959 - 1965.
Stream Characteristics

Flynn Creek is considered typical of perennial headwater streams in the V-shaped valleys of the Oregon Coast Range (Moring and Lantz, 1975). Storm runoff events occur in response to increased interflow as the soil moisture deficit is satisfied with the onset of winter rains. Summer low flow is usually attained in August-September as soil moisture levels decline (Harris, 1977). Sediment yield from the watershed is highly variable, with most sediment discharge occurring during limited periods of freshets (Beschta, 1978a).

Channel form in the study reach is mediated by the dense streamside vegetation and in-stream debris. Large organic debris is a dominant influence producing log steps that serve as settling basins and tend to obscure any systematic pool and riffle sequence. When suspended above the stream bed, such debris may create local scour pockets when reached at high flows.

Streambanks are moderately stable, varying with the degree of vegetative cover and relation to the thalweg and debris. The stream bed consists primarily of a mixture of sand to coarse gravel, with sand increasing in importance downstream. The friable sandstone parent material is susceptible to rapid attrition (Klingeman, 1971). Most sections of the stream bed are armored with fine to coarse gravel. Sediment sources within these reaches are predominantly lateral terrace cutting and soil creep, with occasional streamside slumping.

The longitudinal profile of the stream is interrupted by a steep canyon approximately 305 m upstream of the USGS weir (Figure 1). This narrow, 250 m long reach is characterized by boulders, large
organic debris, and sections of exposed bedrock. Channel form is strictly bedrock controlled. Soil creep from the steep banks in this canyon is a primary sediment source.

**Bedload Sampling Sites**

Bedload samples were obtained at three cross-sections within the study reach (Figure 1). Table 2 summarizes local site conditions and methods employed at these sites. The vortex tube bedload sampler (vortex sampler) is located at the fish trap structure, the primary sampling site. The stream bed immediately upstream is predominantly sand with fine to medium gravel. This relatively straight reach lies between alluvial terrace deposits.

A second sampling station (riffle site) was located approximately 200 m upstream of the fish trap at the downstream end of a gravel bar (Figure 1). The stream bed consisted primarily of sand with medium to coarse gravel. Immediately downstream from this site, the stream is eroding colluvial deposits at the toe of the sideslope. No in-stream modifications were made in this reach.

A third bedload sampling site (bedrock chute) was established approximately 325 m upstream of the USGS weir (Figure 1). The sampling cross section was located on a bedrock surface confined by sandstone banks. The channel upstream of the site was littered with boulders and large organic debris.
TABLE 2. Characteristics of Flynn Creek bedload sampling sites, 1979 water year

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SAMPLING SITE</th>
<th>FISH TRAP</th>
<th>RIFFLE SITE</th>
<th>BEDROCK CHUTE</th>
</tr>
</thead>
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<tr>
<td>Sampler Used</td>
<td></td>
<td>Vortex Tube; Helley-Smith</td>
<td>Helley-Smith</td>
<td>Helley-Smith</td>
</tr>
<tr>
<td>Bed Type</td>
<td></td>
<td>concrete</td>
<td>gravel</td>
<td>bedrock</td>
</tr>
<tr>
<td>Channel Width $^b$ (m)</td>
<td></td>
<td>7.9</td>
<td>4.3</td>
<td>3 - 4</td>
</tr>
<tr>
<td>Maximum Bankfull Depth (m) $^b$</td>
<td></td>
<td>0.9</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Channel Gradient $^b$ (%)</td>
<td></td>
<td>&lt;1</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Sinuosity Ratio $^b,c$</td>
<td></td>
<td>1.9</td>
<td>1.5</td>
<td>1.2</td>
</tr>
</tbody>
</table>

$^a$ See Figure 1 for channel location.

$^b$ Data from Adams (1980).

$^c$ Stream distance/straight line distance.
III. METHODS

Methods established during the first two years of the Flynn Creek study (O'Leary, 1980) were generally followed and exceptions are indicated below.

**Precipitation and Streamflow**

A weighing precipitation gage (Fischer-Porter Series 1559) was used to obtain rainfall measurements at 15-minute intervals (Figure 1). In addition, a non-recording gage at the fish trap was monitored during storm events. This limited gaging network was used to relate rainfall intensities to storm runoff, and does not indicate the mean areal precipitation over the entire watershed.

A continuous record of stage (Leopold & Stevens Model A35 water level recorder) was obtained at the USGS gaging station (Figure 1). A broad-crested, V-notch weir serves as the channel control at this gaging site. Discharge measurements were also made at the fish trap with a Price Type AA current meter using the technique described by Buchanan and Somers (1969). A water level recorder (Leopold & Stevens Model F) was installed at the fish trap to provide immediate information on hydrograph development during sampling periods. Streamflow records are considered accurate to ± 5%.

A Log-Pearson Type III distribution was fit to the available annual peak flow data for Flynn Creek. This annual series frequency distribution was used to characterize the relative magnitude of events.
samples during the study. The 19-year record included WY’s 1959-1973 (Harris, 1977) and WY’s 1976-1979.

Seven metal staff gages were located throughout the study reach (O'Leary, 1980) between the fish trap and the USGS gage (Figure 2). These gages were read periodically during high and intermediate flows. The readings are assumed to represent instantaneous water surface profiles since little time elapsed between consecutive readings.

Channel Morphology

Results of a theodolite survey were used to produce a planimetric map of the study reach showing the locations of all in-stream structures, staff gages, and monumented channel cross sections (Figure 2). Streambanks were subsequently measured at each cross section and a low water (4 August 1979) channel boundary was sketched. Large organic debris was also mapped. Streambed gradients and the vertical relationships between successive staff gages were determined. The cumulative error of the survey is estimated to be ±15 cm in the vertical and ±30 cm in the horizontal.

Twelve channel cross sections about 30 m apart were located between the fish trap and the USGS gage in order to quantify net changes in bed and a horizontal tape at 30 cm intervals. Measurements were made at the beginning and end of the storm season and following each major stormflow period. Accuracy of the profiles is estimated to be ±2 cm.
FIGURE 2. Planimetric map of the study reach along Flynn Creek, Lincoln County, Oregon (surveyed March, 1979).
Total Suspended Solids and Specific Conductivity

Application of the term "suspended sediments" to the suspended matter transported in this mountain stream is considered to be misleading. A large fraction of the suspended component may consist of very fine (VPOM: 0.45-0.53 μm) to fine (FPOM: 0.53 μm - 1.0 mm) particulate organic matter. Hence, the term "total suspended solids" (TSS) has been adopted to denote both the inorganic and organic material collected in the suspended transport mode.

TSS samples were obtained with an automatic pumping sampler (Instrument Specialties Company Model 1392). This stage-activated device obtained a composite sample each hour (two 30-minute subsamples) during peak discharge events. The sampler intake was located below the weir at the USGS gage (Figure 2). Sample aliquots were filtered through 0.45 μm glass fiber filters and analyzed gravimetrically. TSS samples were not analyzed for particle size.

Specific conductivity (μmhos/cm) was determined for selected TSS samples using a portable conductivity meter (Hach Model 16300) referenced at 25°C.

Bedload Transport Measurements

Bedload samples were collected with a vortex sampler and a Helley-Smith pressure differential sampler. Although the vortex sampler theoretically samples the total bedload discharge, its efficiency is less than 100% for sand and fine gravel (O'Leary, 1980). In comparison, the Helley-Smith sampler has a higher efficiency for particles...
in the medium sand range and larger (Emmett, 1979).

Vortex Sampler

The vortex sampler (O'Leary, 1980) consists of a 2.8 m long, circular steel tube (30.5 cm in diameter) with a top opening 20.3 cm wide (Figure 3). The tube is oriented at a 66° angle to the flow, with both edges at the same elevation. Sediment-laden flow in the vortex is routed to an off-channel pit where it is either returned to the channel downstream or diverted into a 0.3 m$^3$ sampling box in which bedload particles settle out.

During 1978 storm runoff events, super-critical flow occurred across the vortex tube (O'Leary, 1980). To eliminate this condition, the control board at the downstream end of the fish trap was raised from 29 cm to 38 cm prior to the 1979 sampling season. A reduction in the Froude number at the vortex cross section was expected to improve the trapping efficiency of the sampler. The control board was necessary to provide sufficient water depth upstream for the passage of anadromous fish.

Vortex sampling procedure remained essentially unchanged from the previous years (O'Leary, 1980). The tube was flushed out prior to sampling, and the first sample was discarded. Samples of approximately 0.006 m$^3$ of bedload material were typically obtained. This was accomplished by varying the length of the sampling interval according to the ambient transport rate. Sample lengths varied from one hour to as little as three minutes, depending on bedload discharge. Consecutive vortex samples were obtained during peak transport periods,
FIGURE 3. Schematic views of the vortex tube bedload sampler at Flynn Creek, Lincoln County, Oregon (side view after Hayward and Sutherland, 1974).
whereas sampling was intermittent during periods of low bedload discharge. Approximately 3 - 5 minutes elapsed between consecutive vortex samples.

Helley-Smith Sampler

A hand-held Helley-Smith sampler was used to obtain bedload material at all three sampling sites (Table 2). The device had a standard 7.6 cm square aperture. Ideal contact between the sampler and the stream bed was assured at the fish trap and bedrock chute locations. At the riffle site, care was taken to reduce scooping of bed materials by the sampler. During WY's 1977-78 the Helley-Smith sampler was fitted with a standard collection bag (surface area 1,950 cm²; mesh size 0.2 mm). During the 1979 WY, a larger bag was used (surface area 6,000 cm²; mesh size 0.2 mm). Larger bags have been shown to improve sampler efficiency by reducing mesh clogging (Johnson et al., 1977; Beschta, 1978b). Thus, Helley-Smith data for the 1979 WY are not comparable with that of previous years.

The spatial variability in bedload movement necessitates use of sampling methods that account for lateral variations in transport rates (Emmett, 1979). Accordingly, each Helley-Smith sample consisted of a composite of subsamples taken along the cross-section. At the fish trap, the sampler was held at seven equally spaced positions across the channel. Composite samples were also obtained below the vortex tube in order to evaluate the amount and particle size of material bypassing the vortex. Sample times at each position in the cross section varied from 5 - 30 seconds, depending on the ambient
bedload discharge. A Helley-Smith sample was obtained every 3 - 7 minutes during peak transport periods at the fish trap. Groups of from two to four samples were taken hourly during periods of lower bedload discharge. Sampling frequencies were lower at the riffle and bedrock chute sites. Samples were taken at two to five positions across the channel at the riffle. Five to seven positions were used at the bedrock chute.

**Bedload Sample Analysis**

**Laboratory Methods**

A flow chart illustrating the details of the bedload sample analysis is shown in Figure 4. Sample weights were obtained either on a Mettler P1210 top pan balance (to ± 0.01 gm; 1,200 gm capacity) or on a heavy-duty Ohaus solution balance (to ± 1.0 gm; 20 kg capacity). Helley-Smith samples were ashed at 320°C to eliminate organic matter. Since the trapping efficiency of the vortex sampler for low-density materials is minimal, organic debris present in vortex samples was either discarded or ashed, and was not considered in any further analysis. All vortex samples and those Helley-Smith samples larger than 70 gm were sieved individually. The remaining Helley-Smith samples were composited over periods of equal discharge prior to sieve analysis. The 0.075 mm sieve used previously by O'Leary (1980) was considered unnecessary due to the low trapping efficiencies of the samplers for smaller particles.
Weigh ASH 320 °C 24 hrs

PARTICLE SIZE ANALYSIS

Bedload Sample Analysis

FIGURE 4. Flow chart illustrating details of the bedload sample analysis procedure.
Discharge Calculations and Presentation Format

Weight data for vortex samples obtained from sieves between 0.15 mm and 1.0 mm were corrected for the catch efficiency of the sampling box (O'Leary, 1980). Particle size distributions were then determined for each sample or sample composite, and distribution data were obtained by interpolation. The median particle size (D<sub>50</sub>) is considered the simplest choice to represent the effective grain size of heterogeneous beds (Bagnold, 1977). The D<sub>95</sub> is assumed to be representative of the largest particles in a sediment sample (Klingeman, 1971). The USDA soil texture classification was used throughout this paper (Hillel, 1964).

As a result of the variability in bed composition, hydraulic conditions, and sampler efficiencies, the particle size range of interest for bedload movement is highly dependent upon the method of measurement. In this study, all inorganic material larger than 0.25 mm in diameter (medium to coarse sand and gravel) was considered in the calculation of total bedload discharge (D<sub>BLD</sub> > 0.25 mm). The mesh size of the Helley-Smith sampler (Emmett, 1979) and the trapping efficiency of the vortex sampling box (O'Leary, 1980) predetermined this convention.

Some suspended solids are probably included in this calculation. Bedload transport rates were also expressed in terms of larger particle sizes that may be free of suspended load interference (e.g., D<sub>BLD</sub> > 2.0 mm; gravel). These conventions were adopted somewhat arbitrarily since no particle size data on suspended material were available. The transport of medium to coarse sand could be conveniently distinguished as the difference between D<sub>BLD</sub> > 0.25 mm and D<sub>BLD</sub> > 2.0 mm. Although
all vortex data were corrected for the efficiency of the sampling box, no attempt was made to adjust for the in-stream efficiency of the vortex tube. The Helley-Smith sampler was assumed to be 100% efficient for particles > 0.25 mm. Subsequent calibration studies of these devices may require further refinement of the data.

Sediment discharge graphs and discharge rating curves for the various transport components were derived. Each vortex sample was assumed to adequately represent the bedload discharge during the sampling interval. The Helley-Smith data are the averages of nearly consecutive samples taken in groups (two to six samples per group). These averages represent periods ranging from 4 - 60 minutes depending on the sampling frequency. The average of systematic Helley-Smith traverses across a channel may be a more reliable indicator of bedload transport rates than individual measurements (Bagnold, 1977). Bedload transport data points were connected by lines on the discharge graphs for illustrative purposes, even though actual rates were probably more variable. The rating curves show transport relationships for both the pre- and post-peak streamflow periods. The resulting power equations were tested for significance using an F-test (p = 0.10). However, the temporal dependency of the data precludes the general use of these relationships for predictive purposes.

Organic Matter Determination

The Helley-Smith sampler serves the same function as a drift net commonly used in the collection of macroinvertebrates and coarse particulate organic matter (CPOM: > 1.0 mm). Weight loss after ashing
the Helley-Smith samples was assumed to represent the organic matter content. However, since the device only traps material travelling near the bed, the data represent a fraction of the total CPOM discharge. In addition, the mesh size of the Helley-Smith collection bag (0.2 mm) results in a sample of particles in the upper end of the FPOM range, as well as of CPOM. Since no particle size analysis of the organic fraction was performed, the Helley-Smith catch will be considered CPOM in this discussion.

The large Helley-Smith sample volumes obtained precluded the use of a standard gravimetric furnace for the elimination of organic matter at the accepted ashing temperature of 550° C (American Public Health Association, 1976). In addition, Adams (1980) notes that the ignition of sediment samples at such high temperatures may not be recommended due to the loss of bound water from inorganic matter, particularly clays. Even at 320° C, some of the observed weight change may be due to the loss of bound water. Adams considered the use of the lower ignition temperature adequate to index organic matter content, and showed that an additional but constant weight loss of from 2.2 - 2.5% was obtained in samples ignited stepwise at 310° C and 550° C. Thus, the data presented here may represent relative amounts of CPOM in transport, but are not accurate absolute estimates. Even with the above limitations, the Helley-Smith CPOM data provide insight into the minimum discharge levels of particulate organicances during transient flows.
Precipitation and Streamflow

Precipitation between November 1978 and April 1979 totalled 146 cm, or only 66% of the expected average for the period. The limited rainfall during October 1978 and after April 1979 produced little measurable streamflow response. During most of the storm season, normal weather patterns were disrupted by the unusual persistence of coastal high pressure that deflected cyclonic systems to the south. Those storm systems that did pass through in November-January (Figure 5) were short-lived, producing only slight streamflow response since the soil moisture deficit was still being satisfied. A series of frontal systems in February and March generated the only significant freshet period of the year. Seasonal precipitation trends in the Pacific Northwest fluctuate tremendously, and the unusually low precipitation during the 1979 WY can be considered a part of the normal pattern of climatic variability.

Mean daily discharge at Flynn Creek reflects the delay in streamflow response in relation to antecedent rainfall (Figure 5). Since average daily discharge values are poor measures of maximum instantaneous peakflows on small basins (Klingeman, 1971), discharges for each storm event are also illustrated in Figure 5. The 1979 WY can be characterized as one of moderate to low storm runoff. Bedload sampling was limited during the five minor peakflows in December, January, and April. The period between 5 February and 10 March was marked by several high flow events. Sediment sampling
FIGURE 5. Daily/monthly precipitation, average daily discharge, and instantaneous peak flow discharge for Flynn Creek, 1979 water year.
was concentrated during 6 - 8 February, when the maximum annual peak flow of 0.76 m³/s-km² was measured (Figure 6). Bedload samples were also obtained between 9 February and 5 March during storm runoff periods. Instantaneous discharge hydrographs for the smaller, partially sampled events are not included.

The Log-Pearson Type III flow frequency distribution for Flynn Creek annual peak flows (Figure 7) may be useful for identifying major discharge events. Based on this analysis, the 1979 peak flow has a return period of about two years or nearly that of a mean annual flood. The stream peaked at or slightly above bankfull stage during this event.

The 1979 WY rating curves for gaging sites within the study reach were as follows:

1) Weir rating curve: \( Q_w = 0.178 \cdot S^{0.54} \) \((R^2 = 0.99)\)
For \(0.89 \text{ m} < S < 1.24 \text{ m}\)

2) Fish trap rating curve: \( Q_w = 3.46 \cdot S^{2.47} \) \((R^2 = 0.98)\)
For \(0.22 \text{ m} < S < 0.53 \text{ m} \) (vortex open),

where \( Q_w \) = water discharge (m³/s-km²) and \( S \) = stage (m). The fish trap rating is valid for a control board height of 38 cm. The new rating curve for the USGS gage was established after it was discovered that the stage-discharge relationship at the weir had shifted since the previous year.

**Longitudinal Profile**

O'Leary (1980) identified three distinct channel segments along Flynn Creek. A steep bedrock canyon separates two lower gradient
reaches that extend upstream to the upper watershed slopes and downstream to the fish trap, respectively (Figure 1). These low gradient reaches have beds composed primarily of sand and gravel with armor layer particles of up to 10 cm in diameter and exhibit similar channel characteristics.

The longitudinal profile of the stream bed through the study area illustrates the decrease in gradient characteristic of the lower reach (Figure 8). The mean channel gradient between the weir and the fish trap is 0.008, whereas the average mainstem gradient is approximately 0.025 (Table 1). The detailed profile exhibits considerable variation due to the presence of riffles and pools and to the arbitrary selection of survey points along the channel centerline. Appreciable scour has occurred below the USGS weir, probably as a result of the tendency of this structure to disrupt bed material transport during moderate to low discharges. Throughout the study reach, it is common for sediment to accumulate behind small debris dams or obstructions. As the stream approaches the fish trap, the profile flattens, and depositional areas are evident above and within the reach bounded by the meander cutoff (Figure 2). A gradual decrease in gradient, from 0.011 to about 0.008, occurs between the weir and the fish trap. Both the weir and fish trap structures have influenced channel development since their construction in 1959. However, this effect could not be documented using hydraulic geometry analyses developed by Park (1976) to identify man-induced channel changes. A developing meander cutoff 50 m upstream of the fish trap (Figure 2) may be affecting the downstream transport of sediment. This side channel is shallow and appears to have developed in response to large organic debris just downstream.
FIGURE 8. Longitudinal streambed profile through the study reach along Flynn Creek (surveyed March, 1979).
from the inlet which deflects water out of the mainstem at high stages. The geometry of the confluence of the mainstem and cutoff channels prohibits coarse streambed sediment from entering the cutoff. Thus, sediment-laden flow continues along the mainstem where it may tend to deposit part of its load due to the cutoff-induced decrease in discharge. An accumulation of sediment along the affected meander reach is suggested in the longitudinal profile.

**Bed Composition**

Bed material in Flynn Creek is derived from the weakly cemented sandstone bedrock. This rock is easily broken down into a wide range of particle sizes, the larger of which are sub-rounded. These non-cohesive bed sediments are underlain by either bedrock or older alluvium. Clayey aggregates of floodplain soil are sometimes present in the bed material.

Bed composition data were obtained from Adams (1980). A nitrogen freeze core technique (Skaugset, 1980) was used to obtain bed samples (25 cm deep; 20 cm diameter) at five locations within the study reach (#1-5, Figure 2) and at two sites (#6 and #7) just upstream of the USGS weir. Surface samples were obtained at these sites by hand-picking bed material present within a randomly placed sampling ring. Core samples were analyzed in a manner similar to that used for bedload samples. These data are influenced significantly by the placement of the core sampler, since marked longitudinal and transverse variation in bed composition occurs even within a small section of stream bed (Adams, 1980). Core samples were taken at the mid-point in the
channel at each site. It is assumed that the sampled materials are representative of those available for fluvial transport.

Particle size data for the bed samples vary widely (Figure 9, Table 3). The broad gradation of particle size at a given site suggests that bed stabilization might occur due to the presence of fines in the intragravel spaces (Graf, 1971). However, colloidal size material required for particle adhesion and cohesion are not present in appreciable amounts in upper bed layers. The range of particles available for transport is dominated by medium to coarse sand and fine gravel (0.25-8.0 mm). Thus, the bed consists primarily of particles for which the vortex sampler has a sampling efficiency of less than 100% (particles <10.0 mm); whereas, the dominant bed particle size range lies at the lower end of the range in which the Helley-Smith sampler appears to be 100% efficient (Emmett, 1979). Particles on the streambed surface are appreciably coarser than the sub-surface materials, illustrating the presence of a protective armor layer.

Both the particle size distributions and mean armor sizes reflect a coarsening trend in bed composition upstream of the fish trap structure (Figure 9). In the 25 m section directly above the trap, the bed surface consists primarily of sand mixed with fine gravel. Further upstream, fine gravel grades into medium to coarse gravel (8-32 mm) as the predominant surface particle size. The stream bed appears to have high proportions of fines (<1.0 mm) throughout the reach affected by the trap. Coarse sand (0.5-2.0 mm) becomes more dominant in the intragravel spaces as distance above the fish trap increases. The decrease in channel gradient near the fish trap and backwater from the vortex control section are responsible for local
FIGURE 9. Mean armor particle sizes and particle size distributions for 0-25 cm deep bed material samples from Flynn Creek (data from Adams, 1980).
TABLE 3. Particle size indices for 0-25 cm deep bed material samples from Flynn Creek \(^a\)

<table>
<thead>
<tr>
<th>PARTICLE SIZE INDEX</th>
<th>SAMPLING SITES (^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>$D_{50}$ (mm)</td>
<td>0.49</td>
</tr>
<tr>
<td>$D_{50}$ (mm)</td>
<td>0.88</td>
</tr>
<tr>
<td>$D_{95}$ (mm)</td>
<td>0.5</td>
</tr>
</tbody>
</table>

\(^a\) Data from Adams (1980).

\(^b\) See Figure 2 for location of samples 1-5. Samples 6 and 7 obtained 50 m upstream of weir.
deposition of sediment upstream during moderate to low discharge. The sorting of bed material may be viewed as a result of the localized decrease in energy gradient.

The effect of this gradient change is also apparent in the vertical composition of the stream bed. Liquid CO₂ cores taken upstream from the fish trap on 2 October 1979 showed vertical layering of coarse and fine sediment. Several fine to medium gravel lenses were sandwiched between thicker strata composed primarily of sand and fine gravel. A medium to coarse gravel matrix was evident at the base of these cores. This stratification indicates that the channel may have undergone phases of net aggradation since reconstruction of the fish trap (1967) and installation of the vortex sampler (1976). The presence of gravel-bearing strata buried within the bed suggests that coarse pavements established during high flow events may be subsequently covered by finer material transported at lower discharge. A sand to fine gravel lens was present on the bed surface above the fish trap both before and after the 1979 storm season. A CO₂ core taken about 40 m above the structure showed no indication of particle size stratification in the gravel bed, and may mark the upstream limit of the layering effect.

The longitudinal variation in bed composition throughout the entire study reach seems to support the concept that particle size decreases in the downstream direction (Klingeman, 1971). This trend is apparent in a comparison of the bed materials found above and below the USGS weir (Figure 9). The samples above the weir have higher D₀₅'s than those downstream. The bed material gradation can be attributed primarily to the selective deposition of sediments as a function
of hydraulic gradient. The influence of the weir in mediating the
downstream passage of coarse material may be significant.

The within-stream variability in bed composition observed by
Adams (1980) is shown in the particle size distributions for core samp-
les #4 and #5 (Figure 9). Although a general trend of coarsening is
apparent, each stream segment is subject to a specific depositional
regime which gives rise to extreme local variability in bed material.
The transverse distribution of shear forces produces distinct lateral
variations in the composition of the bed, even at a single cross
section (Dietrich et al., 1979; Adams, 1980). Variation in armor par-
ticle size and channel geometry throughout the study reach suggests
that considerable variability in bedload transport thresholds could
be exhibited in the longitudinal direction.

Net Channel Changes

The extent of scour-fill and the approximate low flow channel for
each monumented cross section (Figure 2) are illustrated in Figure 10.
Such profiles depict the sequential net changes in channel configura-
tion, and do not necessarily reflect the degree of actual bed dis-
turbance during particular storm events (Klingeman, 1971).

Cross sections A, B, and C, located in the reach directly above
the fish trap, were influenced by the backwater effect of the trap
structure. The construction of the vortex sampler and subsequent
raising of the control board (June, 1978) have compounded the back-
water effect, as illustrated by the bed composition data. The change
in hydraulic gradient appears to influence streambed composition for
FIGURE 10. Net channel changes at Flynn Creek cross sections, 1979 water year (after Kingman, 1971).
FIGURE 10 (Continued)
FIGURE 10 (Continued)
FIGURE 10 (Continued)
FIGURE 10 (Continued)
approximately 40 m upstream. As a result, net deposition occurred at all three cross sections during period I (22 September-22 December). Storm runoff during this time was relatively low (Figure 5), and characterized by low rates of bed material transport. Period II (22 December-17 February) included the annual peak flow event during which sediment transport was significant. Cross section A showed additional aggradation, primarily next to the right bank (looking upstream) where an eddy is present. The moderate to low flows experienced during period III (17 February-23 June) produced slight scour at section A. The scour-fill pattern at sections B and C appeared to be controlled by acceleration of the flow along the left bank as it exited the bend just upstream. No bank cutting was evident at any of these sites.

The net changes at cross sections D and E were in marked contrast to those downstream. The cross-channel deposition at site D, located downstream from the meander cutoff, occurred at the outside of a bend where scour would be expected. This channel adjustment may be attributable to deposition resulting from the reduction in streamflow downstream from the meander cutoff (Figure 2). Backwater from the fish trap may also promote the deposition of coarse materials at this site during high flows. Cross section E, just upstream of the meander cutoff inlet, was subject to mid-channel deposition which may have been initiated by backwater effects from the debris deflecting flow into the cutoff.

The remaining cross-section profiles illustrate the variability in both the magnitude and extent of channel changes during a season. The stability of the root-strengthened, cohesive banks throughout the
study reach is apparent at station F. No bank cutting occurred at this site even though flow was directed toward the left side of the channel. Channel form at sections G and H is probably controlled by the accumulations of large organic debris within this reach (Figure 2). Many large boles are present along the channel, either totally or partially submerged or suspended above the surface at low stages. During period II, a mid-stream gravel bar was eroded at section H and another such bar was formed downstream at section G. It is not known whether these changes are related, however. The side-channel scour at station H may have resulted from overbank flow and the interaction of the flow with debris upstream. The channel changes at cross-section I were moderated by a sediment-filled debris dam just upstream which controlled sediment transport through the reach. Cross sections J-L exhibited little net change through the season, except for the erosion of a gravel bar at station K.

These channel changes illustrate the dynamic behavior of stream beds and indicate that variation in sediment transport rates may occur along a channel. Scour-fill is controlled by hydraulic conditions and the nature of the bed materials, and moderated by streambank stability, vegetation, and local relief. The dominant roles of streamside vegetation and bank composition in the development of mountain stream channels is well recognized (Klingeman, 1971; Froehlich, 1973; Swanson et al., 1976; Swanson and Lienkaemper, 1978).

Specific Conductivity and Total Dissolved Solids

Specific conductivity measured throughout the storm season varied
from 55 to 75 \textmu mhos/cm (mean = 60 \textmu mhos/cm). A decrease in conductivity, from 65 to 75 \textmu mhos/cm prior to 5 December to 55 to 65 \textmu mhos/cm after 5 December, was observed, although such a minor trend might be due solely to measurement error. Conductivity can be used to estimate the concentration of total dissolved solids (TDS) present in natural waters (Lind, 1979). The mean TDS concentration of the Flynn Creek runoff was estimated to be 40 mg/L, using the empirical factor (0.65) suggested by Rainwater and Thatcher (1960). Unpublished data from the 1958-72 Alsea Watershed study also indicate an average TDS concentration of 40 mg/L (195 samples; standard error ± 16 mg/L).

Bormann and Likens (1970) have shown that the export of dissolved substances from undisturbed forested watersheds may be minimal and typically independent of streamflow. The relatively low ionic content of Flynn Creek runoff and the lack of a significant TDS response to increased interflow suggests that this ecosystem exerts a strong control over its limited nutrient capital. Solute concentrations in this mountain stream are extremely stable, even over a wide range of streamflow. The slightly higher concentrations observed earlier in the storm season may reflect: (1) the initial flush of subsurface water that has had a long residence time in the soil profile, (2) higher nutrient content of throughfall early in the season, and (3) increased levels of leachate from fresh inputs of particulate organic matter. The relative importance of dissolved organic matter (DOM) is unknown, although this fraction is a dominant form of organic export in other mountain streams (Bilby and Likens, 1979).
Total Suspended Solids

Suspended solids may not represent an important weight fraction of the bed, but they play a significant role in influencing water quality by occupying intragavel pore spaces (Klingemen, 1971). TSS concentrations measured in Flynn Creek during the 1979 storm season were relatively low (<75 mg/L), except during the February peak flow. During this event, TSS reached a maximum concentration of 1,250 mg/L just prior to the peak streamflow (Figure 11). In general, suspended load increases more rapidly than streamflow at a site (Graf, 1971). The high proportion of sand-size material in the bed suggests that the suspended component in Flynn Creek exhibits a highly exponential concentration profile. The well-mixed conditions at the TSS sampling site served to reduce sampling error due to variation in the suspended load profile.

No data were obtained on the organic matter content of TSS samples, although it is believed to comprise a significant fraction. Sedell et al. (1978) showed that VPOM may represent more than 70% of the total weight of organic particulates exported by streams. Particle organic matter larger than 106 μm represented less than 10-20% of the total organic export. The predominantly deciduous riparian vegetation and favorable conditions for rapid degradation of organic detritus in and along Flynn Creek suggest that VPOM and FPOM transport from the watershed is high.

An advanced TSS peak is typical for Flynn Creek, and gives rise to a hysteresis effect that indicates a post-peak decline in the supply of suspended materials. The smooth TSS response during the
FIGURE 11. Total suspended solids (TSS) concentration and streamflow ($Q_w$) in Flynn Creek, 6-8 February 1979.
1979 peak flow produced a distinct hysteresis curve (Figure 12). Nan-
son (1972) observed a seasonal decline in the suspended sediment load
of a high mountain stream in Alberta. He attributed this phenomenon
to a decrease in the activity of geomorphic supply processes through
the summer. In a study of another Oregon Coast Range stream, Milhous
and Klingeman (1971) showed that the flushing of suspended material is
a function of both the timing and magnitude of storm events. The
within-storm variability observed in suspended load was significantly
affected by the behavior and conditions of the stream bed. Beschta
(1976a) has identified a pattern of seasonal flushing of suspended
matter in the Alsea Watersheds (Moring and Lantz, 1975). Recently,
Bilby and Likens (1979) have documented the rapid flushing of FPOM
from a mountain watershed prior to the peak streamflow. Adams (1980)
has shown that the level of fine sediments (<1.0 mm) in gravel beds
of Coast Range streams may be reduced after high flow events. Thus,
a flushing of suspended material both during a storm and within a
given storm season is characteristic of these mountain streams. Early
flushing precludes attainment of maximum transport rates later in the
season during similar flows (Graf, 1971). This general trend can be
disrupted by subsequently higher flows that may accelerate bank ero-
sion, scour new source areas, or initiate the release of fines stored
within previously stable sections of stream bed. Hillslope mass
movement processes also represent potential sediment sources. Leo-
pold et al. (1964) identified differences in suspended sediment con-
centration at a given discharge which were related to variations in
streamflow sources. Temperature induced changes in fluid viscosity
may be important in increasing the transport of fines less than
FIGURE 12. Total suspended solids (TSS) and streamflow \( Q_m \) hysteresis curve for 6-8 February 1979 at Flynn Creek.
0.5 mm, although this effect is small for shallow channels with narrow temperature regimes (Graf, 1971). All of these phenomena increase the variability in suspended matter rating curves. Much of this variation depends on the capacity and condition of the fines reservoir in the stream bed (Milhous and Klingeman, 1973).

**Bedload Discharge**

**Vortex Sampler**

Total bedload discharge \((Q_{BLD} > 0.25 \text{ mm})\), as measured with the vortex sampler, was low \(< 5.0 \text{ kg/hr}\) during most of the 1979 storm season. During the storm runoff periods of 7 February \((Q_{\text{max}} = 0.75 \text{ m}^3/\text{s-km}^2)\) and 11 February \((Q_{\text{max}} = 0.37 \text{ m}^3/\text{s-km}^2)\), maximum bedload discharges of 105 kg/hr and 15 kg/hr were measured, respectively. In contrast, the 1978 WY was marked by three major flow events during which maximum total discharge rates were 36 kg/hr \((Q_{\text{max}} = 0.69 \text{ m}^3/\text{s-km}^2)\), 61 kg/hr \((Q_{\text{max}} = 0.62 \text{ m}^3/\text{s-km}^2)\), and 290 kg/hr \((Q_{\text{max}} = 0.76 \text{ m}^3/\text{s-km}^2)\). The data reflect the paucity of bedload movement during the 1979 storm season. The role of the more frequent but lower storm-flows in transporting fines becomes prominent during such a low storm runoff year. During periods of low bedload discharge, practically all the material collected was finer than 2.0 mm.

The bedload discharge curve for vortex samples taken during the 1979 peak flow event illustrates transport rates for material greater than 0.25 mm and 2.0 mm (Figure 13). Transport of particles larger than 10.0 mm was infrequent and never exceeded 2.0 kg/hr. During the
FIGURE 13. Streamflow ($Q_w$) and bedload discharge ($Q_{BLD}$) measured with the vortex sampler at Flynn Creek, 7 February 1979.
period from 0700 to 1500 h (2/7/79), consecutive vortex sampling was not possible due to a lack of personnel. The vortex curve shows a smooth response to the initial rise in flow to the maximum observed bedload discharge of 105 kg/hr at 0400 h. Thereafter, considerable pulsation in bedload transport was measured, irrespective of streamflow. Peak transport rates on the rising and falling limbs were similar, although the recession peaks were associated with lower streamflows. The two samples obtained between 0700 and 1500 h fell within the range of variation observed at other stages. The plot of $Q_{\text{BLD}} > 2.0 \text{ mm}$ mirrors the response of the total discharge at much reduced magnitudes. Most of the bed material transported through this reach consisted of sand-size particles.

The smooth initial response in bedload transport is reminiscent of that typically observed for TSS and probably reflects the gradually increasing transport of fines from the bed above the fish trap. The material would initially be transported along or near the bottom. Even during maximum streamflows, sand-size material in transit would be concentrated near the stream bed (Vanoni, 1975; Beschta and Jackson, 1979), defying any attempt to classify it as either bedload or suspended load.

The bedload discharge peaks on the rising limb were characterized by higher gravel transport than during similar periods on the recession. These pulses may be attributable to several factors. An increasing tractive force may have caused scour of the sand lens upstream sufficient to expose a previously buried layer of coarser material. Stream power may have reached a threshold level which initiated disturbance of the fine gravel beds above the sand dominated
reach. In addition, material was probably being released from the more heavily armored beds upstream.

It is unfortunate that vortex sampling was discontinued during much of the falling limb, since it appears that this was the period of highest bedload transport based on Helley-Smith results. Those vortex samples taken on the falling limb show an irregular decline in transport marked by large pulses of sand discharge. Sampling after 2400 h (2/7/79) was discontinued until 1200 h (2/8/79) when rates of less than 2.5 kg/hr were measured. The predominance of sand in transit during the falling limb presumably reflects the passage of pulses of finer material released from gravel beds upstream.

The changes in D50 and D95 of vortex samples during the 1979 peak-flow are illustrated in Figure 14. A slight increase in D50 was observed during the initial rise in bedload transport, but, in general, this parameter proved to be a relatively insensitive indicator (mean = 0.46 mm; range = 0.23-0.78 mm) of the change in competence. The constancy of the D50 emphasizes the predominance of medium to coarse sand in vortex samples. On the other hand, the D95 increased steadily during the initial rise in bedload discharge and generally mirrored subsequent rising limb peaks. The direct relationship between stream competence and particle size in transit is predicted by tractive force equations (Graf, 1971). The D95 variation of falling limb samples showed less correspondence to bedload peaks, but continued to decline steadily with transport. In a gravel-bottomed stream, Milhous and Klingeman (1971) showed that the D50 in transport increased directly with streamflow, but that the sample D95 showed little variation. This difference in the behavior of the size parameters is attributable
FIGURE 14. Bedload discharge (Q_{BLD}) and particle diameters (D_{50}, D_{95}) measured with the vortex sampler at Flynn Creek, 7 February 1979.
to the coarser bed composition of the latter stream. Both the D50 and D95 of vortex samples from Flynn Creek were appreciably smaller than those observed for bed samples throughout the study reach. The D95 never exceeded 7.2 mm, much smaller than the 10.0 mm particle size that the vortex sampling box is 100% efficient in retaining.

Bedload rating curves for total and gravel discharge illustrate the change in transport with streamflow (Figures 15 and 16). Both pre- and post-peak relationships for each transport class were statistically significant (p = 0.10), and explain at least 86% of the variation in bedload discharge. The relationship between streamflow and bedload transport is predicted in theory and has been documented in field studies (Graf, 1971; Vanoni, 1975). An attempt to estimate stream power for use as an independent variable was abandoned because the staff gages placed throughout the study reach were too far apart to calculate a reliable value for the hydraulic gradient.

For \( D_{BLD} > 0.25 \) mm (Figure 15), transport on the rising limb remained less than 1 kg/hr until a flow of about 0.4 m³/s-km² (0.87 m³/s) was reached. Bedload discharge then rapidly increased two orders of magnitude. The shift in the falling limb relationship produced a higher transport rate for a given streamflow, indicating an increase in supply and/or transport capacity. As flow continued to recede, bedload discharge dropped sharply. This decline was probably initiated by stabilization of the bed upstream and a loss of transport capability. In addition, a coarser pavement may have been established in the reach upstream of the fish trap which could have restricted particle movement. This armor layer would be concealed during intermediate flows by the infilling of intragravel spaces.
VORTEX BEDLOAD RATING CURVES

$Q_{BLD} > 0.25 \text{ mm}$

Rising Limb
$Q_{BLD} = 140 Q_{w}^{0.33}$
$R^2 = 0.86$

Falling Limb
$Q_{BLD} = 1021 Q_{w}^{0.9}$
$R^2 = 0.90$

Composite
$Q_{BLD} = 338 Q_{w}^{0.68}$
$R^2 = 0.84$

FIGURE 15. Vortex bedload ($Q_{BLD}$) rating curves for material > 0.25 mm at Flynn Creek, 7 February 1979.
FIGURE 16. Vortex bedload ($Q_{BLD}$) rating curves for material $> 2.0$ mm at Flynn Creek, 7 February 1979.
and eventual burial by fines.

The rating curve for gravel-sized particles (Figure 16) also shows a shift in the bedload discharge on the falling limb. The rate of change for the pre- and post-peak relationships was essentially equal, however. Gravel transport responded rapidly to changes in flow as indicated by the slope of the regression lines.

Although the rating curves appear to account for a large fraction of the variability in bedload transport, an order of magnitude span of $Q_{BLD}$ observed at any given streamflow indicates that other factors are important. Milhous and Klingeman (1971) determined that much of the variability observed in bedload transport could be supply-related. In their study utilizing a vortex sampler in another Oregon Coast Range stream, they identified the possible importance of the armor layer in controlling bed material discharge. A critical flow could be achieved at and above which armor particles were dislodged, releasing the finer bed material beneath. In addition, variations in the size of exposed armor particles could cause variations in threshold flow values, and observed transport rates. Thus, the armor layer appeared to be the single most important factor limiting the availability of bed sediment for transport. In other geomorphic regions, supply has also been identified as an important factor controlling bedload discharge (Manson, 1972; Hayward and Sutherland, 1974).

Vortex Efficiency

Plots showing the variation in depth, mean velocity, and Froude
number \((\sqrt{\frac{V}{g D}})\) with streamflow at the fish trap site are provided (Figure 17). During the 1979 peak flow event, a mean velocity of 1.2 m/s was attained in a 0.59 m depth. The maximum Froude number attained across the vortex tube was 0.52. The additional height of the control board had eliminated the development of critical flow conditions at moderate streamflows, as indexed by the calculated Froude number.

The vortex sampler used in this study is subject to sample loss in several ways: (1) some bedload material may pass over the tube during high flows, (2) some material caught in the vortex may be thrown back out into the flow, and (3) some material may be blown out of the sampling box by the turbulent inflow during sampling. The principal concern with the system involves the in-channel efficiency of the vortex tube. The catch efficiency of the tube is a function of the particle sizes in transport, the sediment concentration, the hydraulic characteristics of the flow, and the amount of flow diverted by the tube (O'Leary, 1980). Robinson (1962) conducted extensive tests (granitic sand; \(D_{50} = 0.53 \text{ mm}\) on the vortex device to determine design specifications for use by engineers in sediment removal applications. He found that the velocity and depth across the vortex should produce a Froude number of about 0.8 (range = 0.7-0.9) for maximum efficiency. Following Robinson's design criteria, the vortex tube could remove 80% of the material greater than 0.5 mm, with trapping efficiency rapidly decreasing with particle size. All material larger than 0.83 mm was effectively trapped and removed. Edling et al. (1977) claim that the in-stream efficiency of the vortex sediment trap is dependent on the flow pattern and transverse velocities in
FIGURE 17. Depth, mean velocity, and Froude number for Flynn Creek at the fish trap cross section, 1979 water year.
They state that the upward velocities must be small enough to prevent expulsion of sediment, and develop a method to estimate the velocity profile in a vortex that could be used in future analyses.

The laboratory calibration of a vortex tube bedload sampler would be difficult and costly, since the performance of a particular design varies as a function of sediment size and momentary hydraulic conditions, thus requiring a range of variables to be considered. As Robinson (1962) points out, under variable discharge regimes, a design flow must be selected for which optimum trap conditions prevailed. At flows above and below this optimum design, trapping efficiencies would decline at variable rates. For sediment research applications, the selection of a design flow might lead to the over-design of the facility for efficient operation during smaller but more frequent stormflows.

In subsequent applications of the vortex tube to sediment transport research (Klingeman and Milhous, 1970; Hayward and Sutherland, 1974; O'Leary, 1980), only Hayward and Sutherland (1974) performed actual laboratory studies to quantify tube catch efficiencies under a variety of conditions. The performance of both semi-circular and square tubes was examined with a variety of sediment sizes (up to 38 mm) over a wide range of flow conditions (Froude range = 0.67 - 0.92). Unfortunately, the complete results of these tests have not been reported, and no attempt to correct preliminary transport data was documented.

The difficulty in obtaining and applying flume study results to natural streams has prompted researchers to evaluate the in situ
efficiency of operational vortex samplers. The first vortex device used for in-stream sediment research bore only slight resemblance to Robinson's (1961) optimum specifications, since appropriate design data for the study reach were lacking (Klingeman and Milhous, 1970). The resulting facility included a vortex tube and a static back-up trough installed in a rectangular control section at a 60° angle to the flow. The design proved satisfactory in operation, and the following observations were made after two years (WY's 1970-71) of experience with the system: (1) the sampler was 100% efficient for particles larger than 4.75 mm, (2) trap efficiency for finer particles was inversely related to discharge, and (3) the low efficiency for material smaller than 4.75 mm was attributed to turbulence in the vortex tube and collection box which resulted in the expulsion of finer particles. A shift in the channel configuration upstream of their study section during a 1970 storm event reduced the Froude number for a given discharge across the vortex, and seemed to improve the efficiency of the device for medium to coarse sand (Klingeman and Milhous, 1970). The lack of coarse material trapped in the back-up trough indicated that the vortex tube was efficient in removing gravel-size particles.

The field installation of Hayward and Sutherland (1974) followed the design criteria obtained from Robinson (1962) and from their own laboratory testing. The resulting facility resembled that of Klingeman and Milhous (1970) with the exceptions that the main tube (45° orientation) was semi-circular in cross-section, and that the back-up tube had an outlet to the side-channel work pit. The main vortex tube proved efficient in trapping bedload sediments, although the
The smallest particles collected were coarse sand (0.5-2.0 mm). Since the collection basket was capable of retaining material down to fine sand (0.125-0.25 mm), turbulence in the vortex tube and collection basket eliminated finer particles from the samples.

The in-stream efficiency of the Flynn Creek vortex sampler has been indexed by a series of Helley-Smith samples taken above and below the tube. In the hydraulic regime of the 1978 storm season, the vortex removed approximately 50% of the bedload measured by a Helley-Smith sampler upstream (O'Leary, 1980). During the 1979 flow conditions, the efficiency relation (Figure 18) showed that the tube trapped from 60-75% of the sediment measured by the upstream Helley-Smith. Thus, the reduction in Froude number during the 1979 WY seems to have improved the trapping efficiency of the vortex tube.

The slope of the vortex efficiency relationship (Figure 18) suggests that the tube becomes more efficient as bedload discharge increases. This can be attributed to the increase in gravel transport with an increase in total bedload discharge. The vortex sampler has a high probability of trapping most of the larger particles passing through the cross-section. At the highest transport rate shown in Figure 18, the transport of gravel-size particles below the vortex was only 6% of that measured above the tube. At lower discharge rates, no gravel was collected below the vortex tube. For the same Helley-Smith above-below series, the D95 of downstream samples (range: 0.41-1.35 mm) was always smaller than those for matching upstream samples (range: 0.56-4.74 mm), reflecting the selectivity of the tube for larger particles.

The catch efficiency of the vortex sample collection box at
FIGURE 18. Vortex tube trapping efficiency as indexed by the Helley-Smith bedload discharge above \( Q_A \) and below \( Q_B \) the tube at Flynn Creek, 1979 water year.
Flynn Creek was determined by O'Leary (1980). Turbulence within the box tended to expel finer particles, so that catch efficiencies were zero for material smaller than 0.20 mm. The box appeared to be 100% efficient for particles larger than 10.0 mm.

In addition to the hydraulic and sediment characteristics mentioned above, the trapping efficiency of the vortex may also be influenced by the presence of CPOM (primarily leaves and twigs) which often accumulates on the downstream edge of the tube. During the 1979 peak flow, CPOM discharge usually exceeded 30% of the total particulate load, as indexed by the Helley-Smith sampler. The influence of this component on the catch efficiency of the tube is unknown.

Experience with the Flynn Creek vortex sampler has emphasized the following major problems with the device for quantitative sediment research: (1) The two-stage efficiency problem (tube and sampling box) precludes an accurate determination of the net efficiency of the device. (2) The sampler may have limited applications in streams characterized by high transport rates of sand-size materials. (3) In the inevitable selection of a design flow, the tube may need to be installed in a contracted channel or in a section with an elevated floor in order to achieve the optimum Froude number across the tube (Robinson, 1962). Both of these installations would lead to some aggradation upstream (Vanoni, 1975). Such a channel disturbance adds uncertainty to the resulting interpretations. The first two problems are typical of those associated with other bedload measuring devices. The latter difficulty may arise in any situation where major in-stream modification of the study site is required, as in the construction of a control section or a concrete sill to improve the bed
contact with point samplers.

Helley-Smith Sampler at the Fish Trap Site

Total bedload discharge ($Q_{BLD} > 0.25 \text{ mm}$), as measured with the Helley-Smith sampler, was also less than 5 kg/hr during most 1979 storm events. During the peak flow periods of 7 February and 11 February (Figure 5), maximum bedload discharges of 409 kg/hr and 29 kg/hr were measured, respectively. During periods of low bedload discharge, nearly all of the material collected was finer than 2.0 mm.

The bedload discharge curve for Helley-Smith samples taken during the 1979 peak flow event (Figure 19) illustrates discharge rates for particles larger than 0.25 and 2.0 mm. The transport of material larger than 10.0 mm was only measured near the streamflow peak, and never exceeded 3 kg/hr. The graph shows pulses of bedload transport occurring irrespective of streamflow. Total transport increased irregularly to post-peak maxima of 380 kg/hr and 409 kg/hr. Bedload discharge then fell sharply to an average of 35 kg/hr. This rate continued to decline with streamflow to less than 5 kg/hr by 1200 h on 8 February. The plot of $Q_{BLD} > 2.0 \text{ mm}$ corresponds to that of the total discharge at greatly reduced magnitudes. The discharge curve clearly demonstrates the abundance of medium to coarse sand moving on or near the bed at this site. Sand transport becomes especially dominant at streamflows above 0.6 m$^3$/s-km$^2$. These size fractions lie at the lower limits of the particle size range suggested for use with the Helley-Smith sampler (Emmett, 1979). The low transport rates for gravel-size particles is indicative of their small fraction in the
FIGURE 19. Streamflow ($Q_w$) and Helley-Smith bedload discharge ($Q_{BLD}$) at the fish trap site along Flynn Creek, 7 February 1979.
bedload at this site, and of the lower likelihood of capturing larger particles with a point sampler (Emmett, 1979). Hydraulic conditions, since the first major storm event following the installation of the vortex (11/77), appear to have reduced the discharge of coarse bed materials through the fish trap reach.

The smooth initial response in bedload discharge that characterized the vortex discharge curve is not apparent in the Helley-Smith data due to the more discrete nature of the latter sampling technique. Pre-peak total transport rates for the two samplers are of similar magnitude, although the timing of peaks shows little correspondence. The Helley-Smith peak of 192 kg/hr at 0500 h was nearly coincident with the vortex discharge of 99 kg/hr at 0450 h. Helley-Smith samples taken during the hours when vortex sampling was limited (0700-1500 h) show this to be the peak bedload transport period. The two vortex samples taken during this time (Figure 13) did not reflect the fourfold increase in bedload discharge that occurred.

The delayed peak in bedload discharge at the fish trap suggests that this component might exhibit a hysteresis effect. A plot of Helley-Smith \( n_{BLD} > 0.25 \text{ mm} \) (not shown) reveals a hysteresis trend the reverse of that observed for TSS, indicating a post-peak increase in transport. This trend was also apparent in a similar plot for gravel-size materials. Possible reasons for the post-peak timing of transport maxima at this site are discussed in a later section.

The rapid decline in the Helley-Smith \( n_{BLD} > 0.25 \text{ mm} \) after the peak discharge suggests that sediment supply might have become limited by the re-stabilization of gravel beds upstream (Milhous and Klingeman, 1971). The decline in bedload discharge after 1500 h may repre-
sent: (1) the gradual flushing of available bed fines and (2) the eventual re-entrainment of fines into the gravel matrix. The winnowing of fines from beside and below larger armor-size particles may tend to partially bury the latter particles in the bed (Milhous and Klingeman, 1973). This process may be responsible for the entrainment and concentration of gravel-size particles into distinct strata in the bed above the fish trap. This mechanism could be followed by the deposition of fines on the surface of the bed, leading to the formation of a sand to fine gravel lens.

$D_{50}$ and $D_{95}$ plots for Helley-Smith samples taken at the fish trap during the 1979 peak flow (Figure 20) are similar to those for vortex samples. The $D_{50}$ trend is relatively insensitive to changes in competence, reflecting the dominance of sand in transit. The $D_{95}$ showed appreciable irregularity, but did reflect the coarsening of samples as bedload discharge increased. The $D_{50}$ and $D_{95}$ of Helley-Smith samples were appreciably lower than those observed for the bed material samples.

Bedload rating curves for the Helley-Smith at the fish trap (Figures 21 and 22) show considerable scatter, although the significant ($p = 0.10$) power curve relations explain nearly 93% of the variation in $Q_{BLD}$. Again, the falling-limb bedload discharge was higher for a given streamflow. The shift in the rating relationships is more apparent in the curves for gravel-size particles. The change in the relations suggests an increase in the availability of transportable materials, and/or a variation in transport conditions.
FIGURE 20. Bedload discharge ($Q_{BLD}$) and particle diameters ($D_{80}$, $D_{95}$) measured with the Helley-Smith sampler at the fish trap site on Flynn Creek, 7 February 1979.
FIGURE 2.1. Helley-Smith bedload \( Q_{BLD} \) rating curves for material > 0.25 mm at the fish trap site on Flynn Creek, 7 February 1979.
FIGURE 22. Helley-Smith bedload \( Q_{BLD} \) rating curves for material \( > 2.0 \) mm at the fish trap site on Flynn Creek, 7 February 1979.
Bedload sampling at the riffle site occurred primarily during the 7 February peak flow event. The Helley-Smith data in this section were provided by William Jackson (Graduate Research Assistant, School of Forestry, Oregon State University, Corvallis, Oregon), and are presented here as a contrast with the bedload transport observed at the fish trap site.

The bedload discharge curve for the riffle site (Figure 23) illustrates a markedly different pattern and magnitude of transport compared to the fish trap data. Bedload transport may be initiated by streamflow, but is also dependent on other factors. The peak bedload discharge period coincided with the peak streamflow, reaching a maximum rate of $2.2 \times 10^3$ kg/hr. The transport of gravel-size materials was correspondingly large, with a maximum discharge of $1.5 \times 10^3$ kg/hr. The transport of particles larger than 10 mm peaked at $6.2 \times 10^2$ kg/hr. A hysteresis plot (not shown) revealed only a slight increase in bedload transport on the recession limb. Medium to coarse sand still comprised a large fraction of most samples (mean = 46%; range = 21-70%) except during the peak transport periods (range = 21-36%).

Plots of $D_{50}$ and $D_{95}$ for Helley-Smith samples taken at the riffle site reflect the local bed composition (Figure 24). Bedload samples obtained between 0500 and 1300 h had $D_{50}$'s and $D_{95}$'s equal to or exceeding those measured in the stream bed. A large fraction of the material transported during this period consisted of surface layer particles. The riffle site was well armored with medium to coarse
FIGURE 23. Streamflow ($Q_n$) and Helley-Smith bedload discharge ($Q_{BLD}$) at the riffle site on Flynn Creek, 7 February 1979 (unpublished data, William Jackson, Graduate Research Assistant, School of Forestry, Oregon State University, Corvallis, Oregon).
FIGURE 24. Bedload discharge ($Q_{BLD}$) and particle diameters ($D_{50}$, $D_{95}$) measured with the Helley-Smith sampler at the riffle site on Flynn Creek, 7 February 1979 (unpublished data, William Jackson, Graduate Research Assistant, School of Forestry, Oregon State University, Corvallis, Oregon).
gravel sizes. Both the D_{50} and D_{95} plots show an increase in particle size during peak bedload transport periods, although some irregularity was apparent. The variations shown in these parameters differ by an order of magnitude over the same values at the fish trap site.

Helley-Smith rating curves for material > 0.25 mm are statistically significant (p = 0.10), and indicate a decrease in bedload discharge at a given flow on the falling limb (Figure 25). This condition is opposite that found at the fish trap, and may reflect the difference in bed composition between the two sites. The rising-falling limb rating curves for material > 2.0 mm at the riffle were the only such relations that proved to be not significantly different (Figure 26). The scatter shown in the data for gravel-size material suggests that streamflow is an increasingly poorer predictive variable for Q_{BLD} as particle size in transit increases.

**Helley-Smith Sampler at the Bedrock Chute**

The limited accessibility of the bedrock chute precluded extensive sampling at this site. During each visit, six to seven channel traverses were made with the Helley-Smith and the samples were composited for analysis. The streamflow data presented for this site are estimates made from visual observations.

The resulting bedload rating curve (Figure 27) was derived from six data points representing samples taken throughout the storm season. The power curve is significant (p = 0.10), and explains 90% of the variation in bedload transport. Bedload discharge increases rapidly as the square of streamflow. The plot of D_{95} versus streamflow
FIGURE 25. Helley-Smith bedload ($Q_{BLD}$) rating curves for material > 0.25 mm at the riffle site on Flynn Creek, 7 February 1979 (unpublished data, William Jackson, Graduate Research Assistant, School of Forestry, Oregon State University, Corvallis, Oregon).
FIGURE 25. Helley-Smith bedload \( Q_{\text{BLD}} \) rating curves for material > 2.0 mm at the riffle site on Flynn Creek, 7 February 1979 (unpublished data, William Jackson, Graduate Research Assistant, School of Forestry, Oregon State University, Corvallis, Oregon).
FIGURE 27. Helley-Smith bedload discharge ($Q_{\text{BLD}}$) and $D_{95}$ at the bedrock chute site on Flynn Creek, 1979 water year.
(Figure 27) shows a gradual increase in particle size with transport. The bedrock chute data do not lend themselves to a comparison with those obtained downstream.

Bedload transport through the bedrock chute may be influenced by organic and inorganic debris along the channel. Large boulders and tree trunks both obstruct and divert the flow of water. During moderate to low streamflows (<0.6 m³/s-km²), transport through the reach is dominated by medium to coarse sand and fine gravel. Sample D₅₀'s ranged from 0.31-0.9 mm. The transport of gravel-size material never exceeded 6.0 kg/hr. At flows greater than 0.6 m³/s-km², larger particles were more readily transported down the channel. For point A, 50% of the sample was larger than 2.0 mm (188 kg/hr) and 10% was larger than 10.0 mm (63 kg/hr). The increased gravel transport may be associated with flows capable of dislodging or bypassing channel debris. Transport would gradually decline with streamflow as material became trapped behind obstructions.

**Helley-Smith Efficiency**

The primary design criterion used in the development of the Helley-Smith sampler was to document sediment transport within 7.6 cm of the bed to complement suspended sediment sampling with a DH-48 (Helley and Smith, 1971; Vanoni, 1975). The device was designed for use in sampling coarse bedload (2.0-10.0 mm) in transit at streamflow velocities less than 3.0 m/s. Initial tests of the sampler showed that it may over-register (150%) for sand-size material and that it could dig into a loose bed and produce local scour. In a subsequent
laboratory study, Drufel et al. (1976) determined that the hydraulic efficiency of the standard Helley-Smith sampler averaged 1.54, suggesting that the flow net into the device included a larger area than that delineated by the orifice. This condition would account for the over-registration of sand-size materials.

The sampling efficiency of the Helley-Smith has recently been investigated in a field calibration by Emmett (1979). He suggests that the device be considered 100% efficient for particles between 0.5 and 16.0 mm, with no change in efficiency as transport rates vary. This application range fits the bed composition of Flynn Creek. At the upper end (>16.0 mm) of the particle size range suggested by Emmett (1979), the Helley-Smith may tend to underestimate fractional discharges since larger particles may be encountered too infrequently by this point sampler. In addition, the device should not be used to collect material that may be transported in suspension, and in no case for material finer than 0.25 mm. In a comparison of the Helley-Smith transport rates for medium sand (0.25-0.50 mm) with those of the East Fork River bedload trap, Emmett concludes that the former exhibited an efficiency of 175% relative to the latter. He discouraged the use of the Helley-Smith sampler for collecting medium sand, especially considering that the limiting particle size for suspended materials in the East Fork River appeared to be around 0.50 mm. The observed over-registration of the Helley-Smith in the medium sand range was presumably based upon an assumed 100% efficiency for the bedload trap, since no calibration data for the trap were presented.

The exclusion of particle size fractions at the lower limit of
Emmett's (1979) calibration is a function of the size of particles in suspension and the objectives of sampling. The exclusion of materials transported in suspension is a logical but difficult rule to apply. The exponential concentration profiles typical of sand-size particles complicates the distinction between suspended load and bedload near the stream bed. Changing hydraulic conditions would require constant variation in a limiting particle size for bedload transport. The bedload discharge calculation format used in this paper has proven satisfactory for the present objectives. However, such a scheme might result in an overestimate of bedload sediment yields by including some suspended materials.

Another important problem with the field use of the standard Hefley-Smith sampler is that of bag clogging. Johnson et al. (1977) and Beschta (1978b) observed the tendency for fine sands and particulate organic matter to reduce the effective flow-through area of the sampler bag. Clogging of the mesh produces a back pressure at the orifice and reduces sampler efficiency. Johnson et al. (1977) recommended the use of larger collection bags or standard size bags with a larger mesh (1.0 mm). Beschta (1978b) showed that the trapping efficiency of a standard bag became a function of the length of the sampling period when the device was exposed to a 0.50 mm (D50) sand mixture transported in a flume. He found that a larger bag (6,000 cm² surface area; 0.20 mm mesh) reduced the effect of mesh clogging by fine sands, so that trapping efficiency remained constant over sampling periods less than eight minutes. Longer sampling intervals and the presence of CPDM in transit would tend to reduce bedload discharge estimates. Based on field observations, the large bags used
in this study appeared to eliminate the clogging problem. The bag remained flexible when immersed and captured material was flushed to the rear of the bag by the action of the flow.

In streams draining forested watersheds, CPOM (primarily leaves and twigs) may collect on the aperture effectively reducing the size of the Helley-Smith sampler. A leaf pack was observed to form over the entire orifice of the sampler during an early storm event (1 December 1978) when CPOM transport was high. However, such a condition was a relatively rare occurrence. Any debris accumulation across the orifice would drastically reduce the trapping efficiency of the device.

An additional concern with the Helley-Smith sampler is its contact with the stream bed. Helley and Smith (1971) point out that the device may cause local scour at the point of placement. In addition, contact between the sampler and an irregular gravel bed may prevent the collection of fines moving between armor particles. The former problem would lead to an overestimate, and the latter an underestimate of actual transport rates. Johnson et al. (1977) installed concrete sills at sampling sites to insure good bed contact and reduce scour caused by machine operated Helley-Smith samplers.

In this study, conditions at the fish trap and bedrock chute sites assured good contact with the bottom. At the riffle site, some local bed disturbance probably occurred despite careful sampling technique. On the other hand, riffle site data could possibly underestimate the discharge of fine bed materials which were moving among armor layer particles beneath the sampler lip.
Vortex - Helley-Smith Comparison

The comparison of vortex and Helley-Smith bedload discharge curves at the fish trap (Figures 13 and 19) has illustrated the difficulties inherent in comparing these two sampling methods. It must be recognized that the two devices sample somewhat different "populations" of sediment in transit. The Helley-Smith device removes a distinct fraction of the material in transport within 7.6 cm of the stream bed, whereas the vertical range sampled by the vortex tube must vary with hydraulic conditions, and is presently unknown. In addition, the Helley-Smith data are more variable due to the temporal discontinuity of the sampling procedure.

Comparative plots of vortex and Helley-Smith results, representing approximately the same time periods, for \( D_{50}^{BLD} > 0.25 \) mm (Figure 26) and \( D_{50}^{BLD} > 2.0 \) mm (Figure 29) illustrate a relatively large degree of scatter. However, Helley-Smith total bedload discharge was usually larger due to the greater efficiency of this device for sand. On the other hand, Figure 29 shows the higher efficiency of the vortex sampler for gravel-size particles. The apparently large errors inherent in pairing transport data for the two methods makes it difficult to identify a systematic trend.

The particle size selectivity of the two sampling methods is readily seen in a comparative plot of sample \( D_{50} \)'s, which were all larger for vortex samples (Figure 30). The vortex sampler is more selective for larger particles characteristically classified as bedload. Applications of the device in coarse-bedded streams have shown it to be an effective method of collecting bedload samples.
FIGURE 28: Comparison between Helley-Smith and vortex bedload discharge ($Q_{BLD}$) for material $> 0.25$ mm at the fish trap site on Flynn Creek, 6-8 February 1979.
FIGURE 29. Comparison between Helley-Smith and vortex bedload discharges \( Q_{\text{BLD}} \) for material > 2.0 mm at the fish trap site on Flynn Creek, 6-8 February 1979.
FIGURE 30. Comparison between Helley-Smith and vortex sample $D_{90}$'s at the fish trap site on Flynn Creek, 6-8 February 1979.
(Milhous and Klingeman, 1973; Hayward and Sutherland, 1974). However, the limited efficiency of the vortex sampler for finer materials renders it relatively ineffective when used in streams characterized by high sand transport. As a result, the Helley-Smith sampler appears to have definite advantages over the vortex sampler for more accurately measuring bedload movement in Flynn Creek.

Coarse Particulate Organic Matter

CPOM discharge ($Q_{CPOM}$) at the fish trap during the 6-8 February, 1979 peakflow period exhibits the same pre-peak response observed for TSS (Figure 31). CPOM discharge increased rapidly to a maximum rate of 140 kg/hr at 0500 h (2/7/79). CPOM transport then began a decline characterized by pulses that tended to precede increases in Helley-Smith bedload discharge. A similar pattern was observed in CPOM data obtained at the riffle site.

Pre- and post-peak rating curves at each site (Figures 32 and 33) are significantly different, and exhibit a decline in CPOM discharge on the recession limb. The magnitude and variability in CPOM transport at the fish trap and riffle site were remarkably similar. The reduction in CPOM discharge for a given flow on the falling limb is readily illustrated in a hysteresis plot of the data from the fish trap site (Figure 34). The hysteresis trend is interrupted by pulses in CPOM discharge that may correspond to bed and band disturbance upstream. CPOM appears to be flushed from the watershed in a manner similar to that shown for fine particulate suspended matter. However, export of the CPOM fraction is also moderated by bed roughness and in-channel retention structures. Stream systems may be effective in
FIGURE 31. Coarse particulate organic matter (CPOM) transport and total suspended solids (TSS) concentration in Flynn Creek, 6-8 February 1979.
FIGURE 32. Coarse particulate organic matter (CPOM) rating curves for the fish trap site on Flynn Creek, 5-8 February 1979.
FIGURE 33. Coarse particulate organic matter (CPOM) rating curves for the riffle site on Flynn Creek, 6-9 February 1979 (unpublished data, William Jackson, Graduate Research Assistant, School of Forestry, Oregon State University, Corvallis, Oregon).
FIGURE 34. Coarse particulate organic matter (CPOM) and streamflow ($Q_w$) hysteresis curve for 6-8 February 1979 at Flynn Creek.
retaining large amounts of CPOM and processing it into finer fractions through biological and mechanical break down (Bilby and Likens, 1978; Sedell et al., 1978). Export of organic matter from these mountain watersheds occurs primarily in the fine particulate and dissolved states (Sedell et al., 1978).

CPOM recovered in Helley-Smith samples consisted of leaves, needles, twigs, and cones, in various stages of decomposition, and in varying proportions. Visual inspection of samples revealed that the CPOM fraction would, at times, be dominated by a particular type of material. Periods were observed during which conifer debris predominated over deciduous matter. This interesting phenomenon may reflect the expansion of the stormflow source area into upslope sites dominated by conifer species. The initial channel expansion during the rising limb would tend to flush CPOM deposited in and along the mainstem where the riparian zone is characterized by deciduous trees and shrubs. The change in composition of CPOM samples may also reflect local flushing of depositional areas as flow velocities increased.

Another qualitative observation concerning the CPOM samples was the presence of large amounts of particulate charcoal. Historically, the Flynn Creek watershed was subjected to a major fire nearly 150 years ago, after which the present forest stand developed. Charred material must have reached the stream channel for a number of years after the burn, where it was either transported and/or stored in the stream bed and banks. Charcoal must also have been buried in floodplain deposits that were subsequently exposed in stream bank cuts.
In addition, the anoxic decomposition of coarse, woody debris buried deep in bed and bank deposits may also account for some of this charcoal material. An anoxic environment is readily developed in bed strata sealed by fines. Whatever the origin, the presence of charcoal in nearly every Helley-Smith sample is indicative of bed and bank disturbance during the high flow event.

A nutrient analysis was performed on three CPOM samples obtained throughout the February peak flow period (Table 4). No discernible difference in the nutrient content of these samples was noted.

Channel Transfer Relationships

Material transport measurements on Flynn Creek have documented several transfer processes during a bankfull flow event. Comparative plots of streamflow ($Q_s$), total suspended solids ($N_{TSS}$), coarse particulate organic matter ($Q_{CPOM}$) and bedload ($Q_{BLD}$) discharges at the fish trap and riffle sites during the 7 February 1979 peak flow (Figures 35-37) illustrate the relationships between these components. Export data derived from these plots for the storm period between 0000 and 2400 h on 7 February are shown in Table 5.

Particulate Yields

The overwhelming dominance of suspended transport during this bankfull event is evident in the yield figures. Freeze core data indicate that Flynn Creek has a high level of bed fines (< 1.0 mm) compared to other disturbed and undisturbed Coast Range streams (Adams,
TABLE 4. Results of nutrient analysis of coarse particulate organic matter retained in Helley-Smith samples

<table>
<thead>
<tr>
<th>NUTRIENT</th>
<th>MEAN CONCENTRATION</th>
<th>RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium</td>
<td>0.86 %</td>
<td>0.78 - 0.83 %</td>
</tr>
<tr>
<td>Magnesium</td>
<td>0.16 %</td>
<td>0.12 - 0.20 %</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.70 %</td>
<td>0.56 - 0.80 %</td>
</tr>
<tr>
<td>Phosphorous</td>
<td>0.06 %</td>
<td>0.03 - 0.08 %</td>
</tr>
<tr>
<td>Potassium</td>
<td>0.04 %</td>
<td>0.01 - 0.06 %</td>
</tr>
<tr>
<td>Aluminum</td>
<td>583 ppm</td>
<td>164 - 978 ppm</td>
</tr>
<tr>
<td>Boron</td>
<td>8 ppm</td>
<td>5 - 10 ppm</td>
</tr>
<tr>
<td>Copper</td>
<td>10 ppm</td>
<td>9 - 12 ppm</td>
</tr>
<tr>
<td>Iron</td>
<td>827 ppm</td>
<td>125 - 1,607 ppm</td>
</tr>
<tr>
<td>Manganese</td>
<td>718 ppm</td>
<td>570 - 880 ppm</td>
</tr>
<tr>
<td>Zinc</td>
<td>40 ppm</td>
<td>27 - 62 ppm</td>
</tr>
</tbody>
</table>

\(a\) Average of three samples.


\(c\) Calcium-potassium expressed in % of total dry weight of sample. Aluminum-zinc expressed in ppm of total dry weight of sample.

\(d\) All or a portion of initial data obtained by extrapolation beyond range of method calibration.
FIGURE 35. Relationships between streamflow ($Q_{w}$), total suspended solids (TSS), coarse particulate organic matter (CPOM), and vortex bedload ($Q_{BLD}$) discharges at the fish trap site on Flynn Creek, 7 February 1979.
FIGURE 36. Relationships between streamflow ($Q_w$), total suspended solids (TSS), coarse particulate organic matter (CPOM), and Helley-Smith bedload ($Q_{BLD}$) discharges at the fish trap site on Flynn Creek, 7 February 1979.
FIGURE 37. Relationships between streamflow ($Q_s$), total suspended solids (TSS), coarse particulate organic matter (CPOM), and Helley-Smith bedload ($Q_{BLD}$) discharges at the riffle site on Flynn Creek, 6-8 February 1979 (unpublished data, William Jackson, Graduate Research Assistant, School of Forestry, Oregon State University, Corvallis, Oregon).
<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>YIELD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Streamflow</td>
<td>$1.0 \times 10^5 \text{m}^3$</td>
</tr>
<tr>
<td></td>
<td>$(4.8 \text{ area-cm})$</td>
</tr>
<tr>
<td>Total Dissolved Solids</td>
<td>$4.2 \times 10^3 \text{ kg}$</td>
</tr>
<tr>
<td>Total Suspended Solids</td>
<td>$5.7 \times 10^4 \text{ kg}$</td>
</tr>
<tr>
<td>Bedload Sediments</td>
<td></td>
</tr>
<tr>
<td>- Vortex</td>
<td>$&gt; 0.25 \text{ mm}$</td>
</tr>
<tr>
<td></td>
<td>$1.0 \times 10^3 \text{ kg}$</td>
</tr>
<tr>
<td></td>
<td>$&gt; 2.0 \text{ mm}$</td>
</tr>
<tr>
<td></td>
<td>$2.7 \times 10^2 \text{ kg}$</td>
</tr>
<tr>
<td></td>
<td>$&gt; 10.0 \text{ mm}$</td>
</tr>
<tr>
<td>- Helley-Smith</td>
<td></td>
</tr>
<tr>
<td>- At Fish Trap</td>
<td>$&gt; 0.25 \text{ mm}$</td>
</tr>
<tr>
<td></td>
<td>$2.6 \times 10^3 \text{ kg}$</td>
</tr>
<tr>
<td>- At Riffle Site</td>
<td>$&gt; 2.0 \text{ mm}$</td>
</tr>
<tr>
<td></td>
<td>$3.1 \times 10^2 \text{ kg}$</td>
</tr>
<tr>
<td></td>
<td>$&gt; 10.0 \text{ mm}$</td>
</tr>
<tr>
<td></td>
<td>$1.3 \times 10^4 \text{ kg}$</td>
</tr>
<tr>
<td></td>
<td>$&gt; 2.0 \text{ mm}$</td>
</tr>
<tr>
<td></td>
<td>$7.8 \times 10^3 \text{ kg}$</td>
</tr>
<tr>
<td></td>
<td>$&gt; 10.0 \text{ mm}$</td>
</tr>
<tr>
<td></td>
<td>$3.1 \times 10^3 \text{ kg}$</td>
</tr>
<tr>
<td>Coarse Particulate Organic Matter</td>
<td></td>
</tr>
<tr>
<td>- At Fish Trap</td>
<td>$1.5 \times 10^3 \text{ kg}$</td>
</tr>
<tr>
<td>- At Riffle Site</td>
<td>$1.7 \times 10^3 \text{ kg}$</td>
</tr>
</tbody>
</table>

\(^a\) Period from 0000-2400 on 7 February 1979.

\(^b\) Assuming mean TDS concentration of 40 mg/L.

\(^c\) Insignificant yield.
The Hjulstrom curve (mean velocity versus particle diameter) predicts that loose fine sand is the easiest to erode and to maintain in transit (Graf, 1971). Suspendable materials are accessible to the flow from: (1) surficial deposits of fines in low gradient and backwater areas, (2) streambank deposits, and (3) subsurface deposits once the critical flow for the displacement of the armor layer has been attained (Milhous and Klingeman, 1973). The sequence of storms within a season has been shown to be an important factor in determining the variability of suspended material loads (Beschta, 1978a). The 7 February peak flow was the first major event of the year, and had access to a large amount of transportable materials. TSS export during the 24-hour storm period was 14 times greater than that estimated for TDS. Suspended transport exceeded the total bedload discharge (Helley-Smith data) at the fish trap and riffle sites by 22 and four times, respectively.

The comparison of material yields at the fish trap and riffle sites illustrates the variation in export that may be observed in the longitudinal direction. Bedload data show an order of magnitude difference in export between the two locations. Especially significant is the dominance of gravel transport at the riffle site, as opposed to the predominantly sand discharge at the fish trap. CPOM transport through the two reaches was not appreciably different. The neutral or slightly negatively buoyant organic particulates are apparently transportable under a wide range of hydraulic conditions. Transport hydraulics of loose silt and detritus are not the same as those governing bed scour (Graf, 1971).
Milhous and Klingeman (1973) developed a sediment transport model that emphasized the role of the armor layer in regulating particulate transport in a gravel-bedded stream. The gravel matrix acts as a storage site for finer materials that become entrained in the bed at moderate to low flows. When the protective armor layer is disturbed at higher flows, finer sub-surface materials may be flushed from the bed. On the falling limb of the storm hydrograph, released bed fines remain in motion until trapped by a stable gravel bed at some distance downstream. Thus, the supply limitation exerted by the armor layer may effect suspended load as well as bedload transport. The condition and capacity of the bed "fines reservoir" determine its ability to contribute suspendable material to the flow when the armor is disturbed. During stable periods, the continual intrusion of fine sediments may result in the sealing of gravel pores and eventual blanket-ing of the bed (Beschta and Jackson, 1979). The flushing of fines from the gravel matrix at high flows (Adams, 1980) represents the principal mechanism responsible for maintaining biologically acceptable conditions in the intragravel environment.

Observations from Flynn Creek suggest that the armor layer and bed roughness play significant roles in controlling the transport of both inorganic and organic particulates. The relationship between suspended load and bedload can be illustrated by a unitless plot of the ratio of the discharges of the two components at a given time during a storm (Klingeman, 1971). Klingeman (1971) observed that the ratio increased with streamflow toward a limiting value, and that
bedload discharge rarely exceeded that for suspended load (mean ratio = 0.25). Such a plot involving Helley-Smith data at the fish trap (Figure 35) shows the combined effect of suspended load and bedload hysteresis. At the fish trap, bedload discharge was much less than that of TSS, with the maximum calculated ratio being 0.24. Indeed, recognizing that some of the material included in the total bedload calculation (BLD > 0.25 mm) was probably suspended, these ratios might be considered overestimates. At the riffle site, the BLD/TSS plot (not shown) was extremely varied, with a maximum calculated ratio of 0.38 during the peak bedload transport period. These results reflect the dominance of suspended load transport during this bankfull event. Research in a variety of fluvial systems has shown that bedload discharge rarely exceeds 25% of the suspended load (O'Leary, 1980). The bedload may comprise a significant fraction of the total load in mountain streams, depending on the limiting particle size in the bed. It can be speculated that the flushing of fines from the bed would cause the BLD/TSS ratio to continue to increase as the storm season progressed. In this sand-gravel stream, the theoretical curve used to describe the relationship between suspended load and bedload in coarse-bedded streams (Klingeman, 1971) may not be applicable.

The relationships between TSS, CPOM, and bedload discharge maxima were markedly different at the two sampling sites. At the riffle, the peak particulate discharges are essentially coincident with that of streamflow (Figure 37). The lag in the maximum bedload discharge at the fish trap site (Figure 36) may be attributable to several factors: (1) The delayed peaks may represent increased scour of sand-size materials from above the fish trap. The transport of material
FIGURE 38. Variation in the bedload (BLD)/suspended load (TSS) ratio at the fish trap site on Flynn Creek during 7 February 1979.
stored above the trap is obviously occurring, but scour-fill cycles are not known since profile measurements were not obtained during the storm. (2) The delay may represent the lag time required for the passage of fines released from gravel beds upstream. (3) The phenomenon may also be due to an energy limitation at the site. Channel gradient above the fish trap is much less than that at the riffle site. The more sluggish fish trap reach would possess less stream power for a given flow. The suspended materials (TSS and CPOM) transported through the reach early during the storm may have represented sufficient solid load to dampen turbulence at the bed and postpone peak bedload transport until the discharge of the former materials had subsided. Vanoni and Nomicos (1960) have indicated that the higher mean velocity of sediment-laden flow may not give rise to an increase in sediment concentration, since bed shear may be diminished. Thus, suspended materials might suppress turbulence and lower bedload transport rates. On the other hand, observations of bed material transport in sand-laden flow in an experimental flume have shown that bed movement may be enhanced (William Jackson, Graduate Research Assistant, School of Forestry, Oregon State University, Corvallis, Oregon). No data are available on the additional effects of CPOM in transit. A range of flow and bed conditions must be observed in order to delineate such interference mechanisms, if they exist.
V. CONCLUSIONS

This study has attempted to identify some of the mechanisms governing fluvial transport, primarily of the bedload component, in a sand-gravel bedded mountain stream. The limited data collected during the 1979 WY represent only a fraction of that necessary to adequately document the conditions of and interactions between various channel transfer processes.

Streamflow has been identified as the driving variable for sediment transport, but transport rates are moderated by supply limitations. The constancy of the TDS concentration of runoff from Flynn Creek suggests that the watershed exerts a strong control on the displacement of its nutrient capital. The export of particulate material occurred primarily during storm runoff periods. Suspended load was the dominant transport mode during the bankfull flow event that represented the annual peak flow for the 1979 WY. TSS underwent flushing during the early development of the storm hydrograph. The relative contribution of organic matter to the TSS discharge is unknown, although it is considered to be significant in this densely vegetated watershed.

Bedload movement is the principal process influencing streambed composition and morphology. Bedload transport in Flynn Creek is a highly unsteady process, that occurs in discrete pulses. Maximum bedload discharge periods were of relatively short duration, and were not necessarily coincident with peak streamflows. Bed composition data illustrate the longitudinal variation in armor layer size which
suggests that incipient motion thresholds along the channel are highly variable. Cross-sectional profiles through the study reach show the degrees of net channel change that may occur during a moderate storm-flow year. These morphology changes have resulted from bed material transfer moderated by channel geometry, bed composition, local hydraulics conditions, and in-channel obstructions (e.g., organic debris and man-made structures).

Adams (1980) observed changes in the composition of stream beds (percent fines < 1.0 mm) following freshet periods. He found that most Oregon Coast Range streams had sufficient fines to fill intragravel spaces, and that the material flushed out during high flows was often replaced during the summer. The high fines content of the bed in Flynn Creek suggests that bedload movement is extremely important in controlling the release of bed material and, ultimately, flushing material from upper bed layers. Indeed, the presence of an armor layer may not prevent the movement of fines through reaches in which the intragravel spaces are filled.

The CPOM yield from this watershed reflects the density of the riparian zone vegetation contributing material to the channel area. CPOM underwent the same flushing process characteristic of the TSS component; however, observed pulses in CPOM discharge were independent of water discharge. The pulses appeared to result from streambed disturbances which could have released organic accumulations at or near the bed surface. CPOM transport appears to be moderated by the retention capacity of the bed and in-stream debris. In addition, the hydrodynamics governing the transport of this low-density material is markedly different from that for inorganics.
In streams having high proportions of sand-size material, the delineation of bedload sediment is extremely difficult since the lower limit of suspended transport is poorly defined. Ultimately, the demarcation becomes dependent on the method of measurement. The comparison of data from the vortex and Helley-Smith samplers at the fish trap has illustrated some of the difficulties inherent in the direct measurement of bedload transport rates. Variability in local site and transport conditions complicates the selection of both the measuring technique and sampling location. The Helley-Smith sampler is the method of preference for use on Flynn Creek due to its greater overall efficiency and its compatibility with standard suspended sediment techniques. The device can be modified to account for local sampling conditions, such as the use of larger collection bags to reduce the potential for mesh clogging. In contrast, the vortex sampler has applications in permanent monitoring or research facilities on coarse-bedded streams.

The spatial and temporal variability of bedload movement indicates that monitoring schemes involving limited sampling at a single site may not adequately index the transport of this component. The three sampling sites on Flynn Creek were each characterized by different sediment transport rates. Data suggest that the fish trap reach is subject to a depositional regime resulting from the combined effects of backwater from the trap structure and the interruption of coarse particulate transport due to a meander cutoff. Transport at the riffle site was dominated by gravel-size materials and appeared to be dependent on the scour-fill cycles of the local bedforms (William Jackson, personal communication, Graduate Research Assistant,
School of Forestry, Oregon State University, Corvallis). The bedrock chute represented a high energy reach in which material transfer was moderated by in-channel debris. Thus, the selection of an ideal cross section for the collection of bedload samples is not straightforward. Even at a single site, changes in the surface layer composition during a storm may cause variations in the response of the bed at a given flow.

The variables governing fluvial transport are not well understood, and man-induced changes in the natural sediment regime will produce channel changes of unknown consequences. Alterations in the natural regime will result from increases in stream competence and/or sediment supply. Klingeman (1971) has suggested that storm runoff increase could produce corresponding temporary increases in bedload transport which could initiate long-term channel changes. The spring and fall peak flow increases observed after clearcutting (Harr, 1975) may represent important channel-shaping flows. Fines introduced into a stream as a result of land use activities may interfere with the natural flushing action of the channel.

The complexity of the possible interactions between fluvial transport processes requires much further work for the clarification of cause-effect mechanisms. Since small headwater streams depend on allochthonous CPOM as a primary source of metabolic energy (Bilby and Likens, 1978), determination of the retention-transport mechanisms of this component is an important topic for future research. Additional baseline data from streams like Flynn Creek will be needed to characterize material transport processes under undisturbed conditions. Land use studies should begin to address the possible changes
in factors controlling particulate transfer. Furthermore, techniques must be developed to predict changes in channel morphology and sediment discharge resulting from land use activities. The application of prudent management techniques is necessary until the impacts of accelerated sedimentation have been more thoroughly investigated.
VI. LITERATURE CITED


