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Title: VARIATIONS IN GRAVEL BED COMPOSITION OF SMALL STREAMS IN THE OREGON COAST RANGE

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A study of the temporal and spatial variability of stream gravel bed composition and the factors affecting the amount of fine sediment within the bed was conducted in the streams of the Oregon Coast Range. Streambed samples were obtained by frozen core techniques and the amount of sediment smaller than 1.0 mm in diameter was expressed as a percentage by weight of the total sample.

The amount of fine sediment in stream gravel beds was found to be highly variable in time and space. Temporal variability in percent fines was caused by flushing of fines from the gravel beds during high streamflow events. This flushing of fine sediment seemed to occur randomly during winter freshets. Seven of 13 total streambed sample locations on five small streams showed trends of decreasing amounts of fine sediment during the winter high streamflow season.

The percent fines within the stream bed was also found to display large variation (a) between streams, (b) between locations in the same stream, and (c) between locations in the same riffle. Bed samples were collected on 21 watersheds in the Coast Range during the summer of 1978. The amount of fine sediment averaged 19.4% and ranged from

10.6% to 29.4%. Comparisons between locations on the same stream showed bed composition to be highly variable. Approximately 75% of the bed composition comparisons were significantly different at the 95% confidence level. One gravel bed was sampled on a 1.2 by 1.2 m grid design and significant (95% confidence level) changes in percent fines were found to exist both perpendicular and parallel to the streamflow in this small area of the stream.

Regression analysis on the samples collected on the 21 streams indicated that the amount of fine sediment in the bed is influenced by the slope, area, relief, and land use characteristics of the watershed. Within a single stream, however, regression analysis indicated that gravel bed composition was dependent on sinuosity and bankfull stage. These two variables suggest that the intrusion of fines into the stream bed is influenced locally by hydraulic conditions within the channel.

Regression analysis and field observations suggest that the amount of fine sediment in stream gravel beds might be increased by road construction and logging operations. However, increases in levels of bed fines after disturbance should be temporary due to the flushing of fines with high flows.

Key Words: Bed sediments, forest harvesting, Oregon Coast Range, sedimentation, stream channels, water quality.

Variations in Gravel Bed Composition of Small Streams in the Oregon Coast Range

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I. INTRODUCTION

Problem

Fine sediment trapped within the interstices of gravel beds is an important characteristic of Pacific Northwest streams. The relative amounts of fine and large sediments exhibit large temporal and spatial variability. Understanding the processes and factors that influence this variation would provide additional insights into the ecology of small streams and assist in evaluating impacts from land use activities.

In Oregon Coast Range streams, the amount of fine sediment within the gravel bed is an important factor affecting anadromous fish. Both natural and man-caused erosion introduce sediment into mountain streams. However, accelerated erosion caused by man may have severe environmental impacts. Excessive fine sediment in stream beds reduces invertebrate diversity and populations by reducing available living space and reducing their early survival. The invertebrate population in a stream provides one of the most important food bases for anadromous fish in their early stages of life. Fine sediments also reduce these food resources for fish by filling gravel interstices and promoting unstable substrates for aquatic invertebrates and periphyton communities (Gibbons and Salo, 1973). The commercial and recreational benefits derived from anadromous fish populations make any factor affecting their survival extremely important.

Fine sediments can also affect the survival-to-emergence ratios of anadromous fish populations. Fine sediments fill the gravel interstices, reducing intergravel water flow and the availability of dissolved oxygen to incubating salmon ova. Toxic metabolites produced by the ova may not be carried away by reduced intergravel flows. Fine sediment may damage the eggs by adhering to or abrading the chorion and also act as a physical barrier to the emergence of alevins (Phillips, 1971). The success of anadromous fish reproduction is so critically dependent on the quality of the spawning bed environment that the U. S. Forest Service has attempted to develop a machine capable of maneuvering in natural streams and cleaning fine sediment from the gravel beds (Mih, 1976).

The Search for a Stream Quality Criterion

There is currently considerable interest by regulatory agencies in the use of in-channel criteria to judge the reproductive capacity of a stream for fish and to monitor the effects of land use activities on the stream environment. Iwamoto et. al. (1976) suggested that streambed composition might be a useful criterion. The authors specified that the percentage by weight of particles less than 0.84 mm in diameter should be monitored and that 20% fines in a gravel bed be set as the maximum allowable level of sedimentation. The authors noted that the effects of fines on the spawning success of salmonids have been well documented. In an Idaho study, Bjornn et. al. (1977) advocated using the percentage of fine sediments in selected riffle areas as an index for monitoring the deposition of sediment in streams and for determining when too much deposition has occurred. If percent fines is to be used as a stream quality criterion, a general understanding needs to be gained about the inherent variability of the amount of fine sediment within gravel beds of small streams.

Variability in Percent Fines

Within a given stream, the percentage of fine sediment in the gravel tends to show large spatial and temporal variability (Smedley et. al., 1970). Furthermore, the bed compositions of streams draining adjacent undisturbed watersheds are often quite different. Therefore it is necessary to understand the magnitude of natural variations in streambed composition so that these will not be confused with possible changes in composition due to land use activities (Sheridan et. al., 1965). A land manager who is knowledgeable of the factors that influence sediment movement and deposition will hopefully be able to manage mountain watersheds without drastically altering the streambed composition.

Objective

The objective of this study is to determine and evaluate the factors and processes that influence the composition of gravel bed sediments in Oregon Coast Range streams. Specifically, this study will address the following questions:

(1) What are the representative levels of fines within a stream bed? How does percent fines vary with location in a stream?

(2) Does the composition of the bed change with time? Is there a period of a flushing action when the fines are washed out of the gravel? Is the temporal variability of the percentage of fine sediments controlled primarily by high flows?

(3) What physical variables account for the composition of bed sediments? These variables might include channel geometry, watershed characteristics, flow conditions, and other parameters.

(4) Does land management affect the percentage of fine sediments in a stream bed? Is the percentage of fine sediments in gravel beds a sensitive measure of the land use in a watershed?

II. LITERATURE REVIEW

Natural Levels of Sediment

Hillslope Processes

Soil erosion in undisturbed watersheds is controlled by several environmental factors. These factors include the form, amount, and intensity of rainfall; the orientation, degree, and length of slopes; and the condition and drainage density of the channel (Guy, 1964). Natural geologic erosion, as contrasted with accelerated erosion caused by man, has always been an important process in the mountainous terrain of western Oregon. The erosion process consists of the detachment, transport, and deposition of soil or rock material by some moving force (Linsley et. al., 1975). In the Oregon Coast Range, the components of this moving force consist primarily of water and gravity.

In mountainous terrain, three major erosional processes deliver sediment to the channel; these are surface erosion, mass soil movements, and stream bank erosion (Anderson, 1971). These processes vary from one watershed to another in their relative contributions of sediment to the channel. For the Coast Range, Anderson estimated that surface, streambank, and mass erosion accounted for 20%, 25%, and 55%, respectively, of the sediment delivered to the stream channel.

Landslides serve to deliver large amounts of soil and rock material to the stream (Swanson and Swanston, 1977). Mass soil movements are a natural, if infrequent, occurrence in the geologically young mountainous terrain of the western United States. These inputs of sediment into the channel may have an important effect on the gravel composition of the stream bed.

Since sediment is transported in a downstream direction, there must be a means by which sediment is continually supplied to the stream channel. Overland flow and its associated surface erosion are rare in forested areas in humid climates, so this process may be ruled out as a major sediment input to the channel for undisturbed watersheds (Hewlett and Nutter, 1969). Infrequent soil mass movements supply large pulses of sediment to the channel which may be stored in banks, behind debris jams, or in alluvial fans (Ketcheson and Froehlich, 1977). This sediment may become available for transport during high flows. Another process which may account for continual inputs of sediment into the channel is soil creep. Creep is the slow continuous downslope movement of mantle material due to gravitational stresses and is an important erosional process on the steep slopes of the Coast Range (Swanston, 1971). If a stream is draining a steeply incised valley, which is common in Coast Range watersheds, soil creep may represent a direct input on sediment into the channel. Swanson and Swanston (1977) estimated that soil creep may represent an annual input of 64 t of material per km of stream length in the Cascade Range of Oregon.

Channel Processes

Once sediment is in a stream, several processes serve to transport, rework, and redeposit it. Sediment transport in streams may occur as either suspended load or bedload. Suspended load consists of the particles small enough to be entrained within the flow by its turbulent action. The suspended load tends to be uniformly distributed with depth in the flow. In contrast, the bedload component consists of particles too large to be continually suspended in the flow and are moved on or near the bed by sliding, rolling, or saltating along the bottom of the stream (Iwamoto et. al., 1976). In the small streams of the Oregon Coast Range, bedload movement is an important process only during high flows.

Sediment supplied to the channel by hillslope processes may be stored in the channel bed and banks or behind debris barriers. However, this sediment is often available for transport during high flows. In western Oregon, the primary rain events typically occur from November through February and produce periods of high flow. In the Oregon Cascades, Rothacher et. al. (1967) noted that the sediment concentration in samples taken at similar streamflows was greater in the early fall than during mid-winter storms. This phenomenon is probably due to a flushing of the sediment during the first few storms of the rainy season.

The stream bed and banks are the primary sources of sediment transported during high flows (Brown, 1976). Brown noted that many random events occur in a stream during high discharges to supply sediment to the flow. These events include trees tipping into the stream and diverting the flow into banks, bank caving due to undercutting, and the breaking up of armor layers on the stream bed with the exposure of the fine sediments beneath. In small turbulent streams, sediment supply and transport processes may be very complex.

The Alsea Watershed Study was a comprehensive investigation of the effects of logging on the aquatic resources of three small streams in the Oregon Coast Range (Moring, 1975a). Before two of the experimental watersheds were treated, a seven year calibration period was used to characterize the natural rates of sediment yield for undisturbed watersheds. The suspended sediment concentration was highly dependent on flow and 98% of the annual sediment load was discharged during the winter months of November through March (Harris and Williams, 1971). The average annual pre-treatment sediment yields for Needle, Deer, and Flynn creeks were 53, 97, and 102 t km^{-2} y^{-1}, respectively (Beschta, 1978a). Thus, erosion and sedimentation represent important natural processes in undisturbed watersheds of the Oregon Coast Range.

Natural Levels of Intergravel Fines

Compared with other locations in the Pacific Northwest, the streams of the Coast Range tend to have unusually large amounts of fines in their beds. Fine sediments are generally considered to be less than about one or two mm in diameter. Moring and Lantz (1974) attributed these high levels of fines to the underlying geology of the area. The Coast Range is largely composed of the Tyee formation, which consists of rythmically bedded layers of sandstone grading towards siltstone at the top of the layer (Baldwin, 1964). This rock is relatively noncohesive and weathers rapidly to sand and silt sized particles. Bedload transport and weathering of these sandstone rocks are sufficient to break them down into the smaller fractions over a relatively short period of time.

Major topographic peaks in the Coast Range consist of intrusions of basaltic sills and dikes (Baldwin, 1964). This basaltic material weathers much more slowly than the sandstone and can have a large effect on the composition of stream beds. Therefore, it is not uncommon to find entirely different bed compositions in streams draining the higher peaks than those draining the other areas of the Coast Range. The portion of the Coast Range affected by the basaltic intrusions is relatively small, however, so most streams tend to have large amounts of fines in the gravel.

Beschta and Jackson (1978) indicated that climate, soils, parent materials, watershed characteristics, and land use activities can influence the particle size distribution of the bed materials in a stream. Furthermore, conditions within the channel can also affect the composition of gravel beds. These factors might include the bed composition during formation, the intrusion of fines into the bed once it's stable, and the net flushing of fine material during subsequent bed disturbances.

The composition of stream gravel beds displays large amounts of variability. For example, Tagart (1976) reported that the composition of spawning gravels was heterogenous in space but stable with time in the Olympic Peninsula of Washington. Wendling (1978) reported that natural variations in percent fines in the gravel might have been large enough to mask measurable changed in bed composition of streams influenced by the construction of the trans-Alaska pipeline. This natural variation is an important consideration in any study designed to monitor the composition of the gravel bed.

Renard (1974) found large variations in gravel bed composition between locations within a channel. He also noted that there was appreciable variation across individual cross sections in the same stream. Spatial variations in bed composition within a stream are largely due to local changes in water flow and sediment transport conditions. The intrusion of fines into a gravel substrate is controlled to a large degree by the flow conditions over the gravel bed (Beschta and Jackson, 1977). It is logical to assume then, that the amount of fines and the composition of the gravel bed will vary as the flow conditions vary along the length and width of the stream. Flow conditions will also influence the deposition and particle size distribution of the gravel substrate, even before fine sediments fill the interstices.

Gravel bed composition is variable with time (Smedley, et. al., 1970). These variations are largely due to the intensity, duration, and frequency of occurrence of storms (Shirazi, 1970). Storm generated runoff affects the scour and fill of gravel and the intrusion and flushing of fine sediments from the gravel substrate (Beschta and Jackson, 1978).

The gravel beds in Coast Range streams make productive spawning sites for anadromous fish despite naturally high levels of fine sediments. When spawning, the female salmon or trout digs a hole (redd) and cleans the gravel of fine sediments and organic matter before depositing the eggs (Sheridan and McNeil, 1968). After the eggs are deposited, the female covers them with gravel. This redd digging activity and the removal of fine sediments significantly improves the intergravel environment for the incubating eggs (Ringler and Hall, 1975). Greater permeabilities and the altered surface of the gravel bed provides improved conditions for intergravel water flow.

Once the eggs have been buried, however, the spawners have no control over the subsequent sedimentation of the redd and fine sediments deposited in the redd after this point in time may adversely affect the survival of the eggs and alevins. Ringler (1970) collected numerous bed samples from redds in Deer Creek and Needle Branch, two of the streams studied in the Alsea Watershed Study. He sampled redds dug the current year and the year before, designating them as current and former redds, respectively. He found that the former redds contained an average of 29.6% more fine sediment than the current redds. This increased amount of sediment was attributed to the extra year of sedimentation that the former redds had been subjected to. Since this type of sedimentation can occur, the suspended sediment concentration of the water flowing over spawning redds may be an important factor affecting egg survival (Cordone and Kelley, 1961).

Effects of Land Use Activities on Sediment Production

In mountainous regions, forest harvesting activities (road construction, timber felling, yarding, and slash burning) can have a major impact on site erosion and accelerated delivery of sediment to the stream channel (Swanston, 1976). Logging roads are usually the greatest source of man caused sediments (Gibbons and Salo, 1973). However, since road construction is an integral part of forest harvesting activities, separating it from logging as a separate cause of sediment production seems pointless, except for the fact that improved road design, construction, and maintenance techniques offer us our best hopes for reducing erosion and sedimentation related to this management activity. Studies assessing the impacts of forest harvesting activities on erosion and sedimentation will be reviewed in the following paragraphs.

Forest Harvesting

Logging and its associated ground disturbance may increase surface erosion of soils. Bethlahmy (1967) investigated the effect of logging on runoff and erosion in Utah. Using simulated rainfall, he found that logging was related to increased erosion only on southwest facing slopes. The different responses of the different aspects to logging was attributed to the different moisture and plant relationships on these slopes.

In western Oregon, felling and cable yarding of trees alone rarely causes increases in erosion and sedimentation. Soil disturbance and compaction are usually slight if care is taken to suspend the front end of the log during high lead yarding (Brown, 1972). In the Oregon Cascades, Fredriksen (1970) noted that logging alone had little affect on erosion and sedimentation. Slash burning, however, increased sediment yields 67 and 28 times above normal levels for the first and second years after burning, respectively. This increase was attributed to the destruction of soil stabilizing plant and root systems and the formation of impermeable layers within the soil. Nonwetable soil conditions may result from extremely hot burns.

The Alsea Watershed Study represents one of the most comprehensive efforts ever undertaken to document the effects of logging on erosion and sedimentation. Three small headwater drainages in the Alsea river basin were chosen for study, and streamflow and sediment transport were monitored for several years prior to treatment (Harris, 1973). Needle Branch was almost entirely clearcut, Deer Creek was 25% clearcut in patches, and Flynn Creek was left as an undisturbed control. Deer Creek and Needle Branch both had increased sediment loads following road construction, clearcutting, and slash burning. Sediment production was drastically altered in the clearcut watershed. Sediment production was doubled after road construction and tripled after clearcutting and burning (Brown and Krygier, 1971). Most of the increased sediment production was blamed on the high intensity slash fire following harvesting (Brown, 1971). The fire exposed mineral soil and may have promoted nonwetable soil conditions.

Timber harvesting activity may also increase erosion by landslides. Bishop and Stevens (1964) estimated that logging on steep glacial till soils in Alaska increased erosion by landslides by 4.5 times or greater. The increase in landslide activity was attributed to deterioration of soil stabilizing root systems and increased pore water pressures in the soil due to decreased evapotranspiration.

Ketcheson and Froehlich (1977) conducted a field inventory of non-road related mass movements on clearcut and undisturbed areas in the Oregon Coast Range. They found that on the average, mass failures were 3.2 times larger and traveled 1.7 times farther in clearcuts than in undisturbed areas. There was a general increase in landslide erosion rates with logging of 3.5 times normal for six years after cutting. Channel impacts and damages to aquatic ecosystems were also considered in this study. The average travel distance of debris torrents was 1.8 times farther in clearcuts than in undisturbed watersheds. These channel scour events have a drastic effect on the channel when the stream is scoured to bedrock. Sediment and debris is stored in debris jams or alluvial fans and may be further reworked during subsequent high flows.

Swanston and Swanson (1976) estimated that clearcutting accelerated debris avalanche erosion by a factor of two to four times in the humid regions of the Pacific Northwest. These numbers agree fairly closely with other estimates of the effects of logging on landslide erosion.

Forest Roads

The construction of forest roads has the most drastic impact of any forest harvesting activity on a watershed in mountainous terrain. Roads are a permanent slope modification and they affect erosion and sedimentation on a watershed through their initial construction and the occurrence of mass wasting events distributed over at least a few decades (Froehlich, 1976). Road construction undercuts the toes of slumps and earthflows, deposits unstable fill material on steep slopes, and modifies the drainage system, concentrating water and adding it to unstable areas.

The relative contributions of roading and logging activities to increased erosion and sedimentation are often difficult to separate. Anderson (1971) estimated that of the total increase in suspended sediment in streams draining logged watersheds, 80% of the increase was associated with logging. He attributed increases in sedimentation to poor logging techniques and low standard roads.

In the Oregon Cascades, drastic changes in suspended sediment concentrations following road construction were documented by Fredriksen (1965). During the first storms after road construction, the stream draining a roaded watershed carried 250 times the sediment concentration of that of an adjacent undisturbed watershed. This increased sedimentation was attributed to the considerable areas of raw soil that were exposed during road construction. Within two years sediment levels had returned to normal on the roaded watershed. In a later paper, Fredriksen (1970) reported that landslides adjacent to roads accounted for 93% of the volume of soil moved by landslides in the patch cut watershed. These landslides created three new types of sediment sources; they exposed soil on landslide scars, regraded stream channels, and exposed soil along the stream bank.

Swanson and Dyrness (1975) estimated that eight percent of a watershed in roads and 92% of the area in clearcut contributed about equally to the total impact of management activity on erosion by landslides. Clearly, improved road standards and maintenance techniques offer one of the best alternatives for reducing impacts of land use on erosion and sedimentation. The interactions and relative contributions of roads and logging on sedimentation are important factors affecting the composition of stream beds.

During the Alsea Watershed Study, Lantz (1971) reported that road construction was the major cause of increased stream sediment levels following logging. These increases were attributed to headwall failures, landslides from sidecast materials, and increased erosion along road beds due to the interception and disturbance of natural drainage patterns.

In the Idaho Batholith, Megahan and Kidd (1972) reported that a dense network of roads associated with jammer logging increased the rate of erosion to 750 times that of the undisturbed rate, whereas logging caused only a 0.6 times increase. Jammer skidding on steep slopes requires a very dense road network, which may disturb up to 30% of the area. Road construction in the jammer unit produced significant sheet and gully erosion and landslide activity during large storms. Megahan and Kidd (1972) further indicate that most of the road failures resulted from improper location or construction practices such as lack of fill compaction. They concluded that some type of skyline logging system would be preferable to jammer logging because of its reduced road density requirements.

Swanston (1971) ranked road building well above fire and logging in relation to their influence on mass movement processes. He noted that sidecast material overloads the surface below the road and creates saturated conditions above fills. Road back slope cuts remove support for the slopes above the road. These conditions tend to decrease shear strength and increase shear stress in the soil, increasing the chances for failure.

Although forest removal reduces rooting strength and alters the hydrologic regime of the soil, road construction has a much greater influence on mass movements because of several factors that tend to disrupt the balance between the downward stress of gravity and the resistance of the soil to failure. Roads disturb marginally stable slopes and alter subsurface and surface water movement. Common problems include construction on marginally stable slopes, poor construction and placement of fills on steep slopes, and improper drainage design. Swanston and Swanson (1976) reported that roads accelerated debris avalanche erosion 25 to 30 times above background levels and further noted that road location (midslope or ridge top) made a difference in the magnitude of this increase. They found that roads on the H. J. Andrews Experimental Forest continued to be active sites for debris avalanche erosion 16 years after construction or at least twice the duration of the impact of clearcutting.

Swanston and Swanson (1976, p. 212) stated "When roads and clearcutting impacts are weighted by the area influenced by each activity, the two types of forest engineering activities contribute about equally to the total level of accelerated debris avalanche erosion." Clearly there is need to reduce surface and mass erosion from roads. Principal erosion control methods include identification and characterization of unstable ground, avoidance of disturbances damaging to slope stability, and the reduction of landslide incidence after disturbance (Swanston, 1974). Methods for controlling erosion from logging alone include the careful selection of a silvicultural system, logging method, and proper level of management (Swanston, 1976).

Research studies have generally shown that the initially high sediment levels caused by road construction and logging eventually recover to pre-treatment levels. In a study on road fill erosion in Idaho, Megahan (1974) reported that rates of erosion increased rapidly just after the disturbance and then decreased over time. He attributed this decrease in erosion rates to the formation of an erosion pavement of larger particles after the smaller ones had been eroded away and to the recovery of vegetation.

Brown (1971) and Beschta (1978a) reported that increased sediment yields in the Alsea watersheds approached pre-treatment levels six to eight years after cutting and burning. The recovery of vegetation on a watershed, and the fact that most road related failures tend to occur during the first few big storms, should allow sediment levels on most disturbed watersheds to return to normal levels before ten years pass.

Bed Processes

Intrusion of Fine Sediment

If water flowing over or through a clean gravel bed carries suspended or bedload sediments, these particles will tend to fill the interstices between the gravels. Water velocities need not be low for intrusion to occur.

Cooper (1965) noted that a sediment particle smaller than that having a sufficient settling velocity to deposit out of a turbulent flow may still be deposited in the gravel if it enters the laminar sublayer of the stream bed. In this section of the flow, its settling velocity will be sufficient for it to be deposited within the bed. Intergravel flows of water usually have very slow velocities which will allow almost any sediment particle time to settle out of the flow. Cooper noted that gravel beds with high permeabilities are especially susceptible to fines being deposited because they allow large volumes of sediment laden water to flow through them. The author stressed the importance of maintaining very low suspended sediment concentrations in water flowing over gravel beds in order to minimize the sedimentation of the bed.

The suspended sediment load and the smaller particles transported as bedload are the sources of fine sediments deposited in the gravel. Iwamoto et. al. (1976) reported that the intergravel flow of water is slow enough to allow for deposition of silt within the gravel although rates of flow at the surface exceed those allowing for deposition. Thus, the intrusion process may occur at almost any stream discharge as long as there is a stable gravel bed and a supply of fine sediment in the flow.

Miner (1968) conducted a study of suspended sediment concentrations in a stream with a point source of sediment input from a road construction operation. The study was carried out on a stream draining the Bull Run experimental watershed in the Oregon Cascades. He noted that there was a ten-fold reduction in total suspended solids within a 320 meter long section of stream. He attributed this reduction in sediment to dilution by streamflow and a settling of the larger particles into the stable stream bed.

Several studies have been carried out that attempted to quantify the intrusion of fine sediment into gravel beds and describe the processes involved. One of the first such studies was carried out by H. A. Einstein (1968). The author used an artificial gravel bed in an experimental flume to quantify the intrusion process. He noted that the coarser sediment particles settled out first, filling the gravel from the bottom up. The bed surface always remained clean. Although water flow velocity was insignificant in predicting the deposition of fines in the gravel, the depth of water and the settling velocity of the grains were very important factors. The rate at which each particle size settled out was proportional to the local sediment concentration. In summary, Einstein found that the intrusion of fine sediments was controlled by the particle size of the sediment, its concentration, and the depth of water. In another series of flume studies, Cooper (1965) found that the factors that controlled the deposition of suspended sediment within gravel beds were the intergravel flow rates, the amount of fines in transport, the characteristics of the gravel, and the surface configuration of the stream bed.

Garvin (1974) conducted a study on the intrusion of organic sediments into an artificial gravel bed in a flume fed by a diverted stream. Organic debris was placed in the upper reaches of the flume and the intrusion of organic material was measured in the lower reaches of the flume after a given period of flow. The variables which influenced the intrusion of organic sediment were the horizontal and vertical position within the gravel bed, the size of the organic debris, the time allowed for intrusion to occur, the pore volume within the gravel bed, and the flow characteristics.

Beschta and Jackson (1977) conducted a flume study on the intrusion of fine sediment into a gravel bedded channel. The initial deposition of fines was found to be a function of the settling velocity of the sediment and hydraulic conditions of streamflow. The continued intrusion of sediment was a function of the filtering effectiveness of the gravels, streambed composition, and the size and gradation of the transported sediments. The authors reported that sedimentation was affected by the Froude number of the flow and increased with the rate of sediment input. Particle size and gradation of the sediment significantly affected the intrusion process. Finer sands led to significantly higher intrusion rates. Larger sands tended to seal the surface pores and prohibit the further intrusion of sediment as long as the surface of the bed was stable. The smaller sands tended to fill the pores from the bottom up and needed only to be transported by the flow to intrude into the bed. Beschta and Jackson (1978) also reported that the particle size and the rate of sediment transport were the most important factors affecting intrusion, and that due to the processes involved, intrusion may be selective towards the smaller sediment particles.

Flushing of Fine Sediment

During large runoff events, the stream energy is sufficient to disturb the armor layer and set bed material in motion. The armor layer is the layer of rocks or gravels on the very surface of the stream bed. Klingeman (1971) suggested that the breakup of the streambed armor layer and the subsequent movement of the bed underneath is the dominant process supplying fine sediments to the flow during high discharges. Milhous (1973) reported that the armor layer may be the single most important factor controlling the availability of streambed sediment to the flow. Apparently, the armor layer controls the availability of sediment by preventing fine material from the bed from being entrained in the flow unless the armor particles are first moved.

Following a storm hydrograph peak, the bed reforms and, depending on the amount of intrusion of fines on the falling limb, may be relatively clean of fine sediment. With the exception of the redd digging activities of spawning anadromous fish, this flushing effect of high flows is the only way a gravel bed can be naturally cleaned of fine sediment. Since intergravel flow velocities are too low to allow fines to be entrained in the flow, the stream bed must be set in motion before this flushing can occur (Beschta and Jackson, 1978).

Although several studies have noted this flushing affect of high flows, few have documented the processes involved. For example, McNeil and Ahnell (1964) reported that high streamflows during flooding periods removed large amounts of silt from salmon spawning beds in Alaska. Gravel bed sample plots used as controls in an Alaskan study were reported to have decreased in fine sediment content as a result of a small freshet (Shapley and Bishop, 1965). Saunders and Smith (1965) reported drastic increases in streambed siltation due to erosion from road construction and cultivated areas on Prince Edward Island, Alaska. However,heavy freshets during the winter of 1959-60 were reported to have cleaned away most of the silt. Similarly, Sheridan and McNeil (1968) reported that increased levels of streambed fine sediment attributable to road construction and landslides were temporary since they tended to be flushed from the system by spawning salmon and the first few floods.

In another Alaskan study, an artificial stream channel was constructed next to a natural stream channel. The artificial channel was filled with gravel and a portion of the natural streamflow was diverted through it for a long period of time. The artificial channel was not subject to the storm flows that the natural channel experienced. The gravel in the artificial channel accumulated ten times more fine sediment than the gravel in the adjacent natural stream channel. This phenomenon was thought to be due to the fact that the high flow events and gravel flushing did not occur in the artificial channel (Meehan and Swanston, 1977).

If high inputs of fine sediment into a stream are reduced, the natural flushing of fines by high flows should be sufficient to flush most of the excess fines from the stream system. Platts and Megahan (1975) reported that the relative amount of fine sediment in the South Fork Salmon River in Idaho decreased over a number of years after a moratorium on logging and road construction was declared on the watershed. They stressed the fact that effective flushing of sediments can only occur when sediment inputs into the channel are not greater than that which the stream can handle. If inputs are greater than this amount, sediment will accumulate in the channel.

Apparently, bed particle movement is initiated by bursts of turbulent flow that penetrate the boundary layer at the bottom of the stream (Sutherland, 1967). The magnitude of these bursts may be dampened by high levels of suspended sediments. Yalin and Finlayson (1972) reported that increased levels of suspended sediments reduced the amplitude of turbulent fluctuations in the flow. If increased levels of sediment dampen the turbulent fluctuations in a flow, they reduce the chances for the initiation of bed movement and subsequent flushing of fines. Stated in another manner, if stream sediment levels are increased, more energy is used in transporting them, and less is available to move the bed and flush the fines (Beschta and Jackson, 1978). So, increased levels of suspended sediments within a stream have two deleterious effects on the composition of the gravel bed. They increase the deposition of fines in the bed and reduce the chances for flushing of fines from the gravel.

Progression of Events During a Freshet

Beschta and Jackson (1978) outlined the entire process of scour and fill of gravel beds as it might progress through a normal high flow event. During low discharges, fines in transport will intrude into any available pore space in the gravel bed. As the discharge increases and reaches a critical value for the breakup of the armor layer and initiation of bedload movement, the gravel beds are scoured and the intergravel fines are entrained in the flow. After the hydrograph peaks, the armor layer reforms and the bed becomes relatively stable. For the remainder of the falling limb, the intrusion of fine sediment into the gravel interstices will be the primary process affecting the composition of the bed. This account of sediment transport and storage processes is consistent with observations of trends in suspended sediment concentrations during storm events. Walling (1977) noted that suspended sediment concentrations are usually much higher at identical discharges during the rising limb than on the falling limb of the hydrograph. Presumably, this response pattern is partially due to the release of fines with bed movement and the filtering of fines back into the gravel bed after it reforms.

Influence of Land Use on Gravel Composition

Forest Harvesting and Road Construction

Numerous studies have shown that logging and road construction in mountainous terrain generally increase the availability of sediment to a stream (Fredriksen, 1965; 1970; Anderson, 1971; Brown, 1971; 1972; 1976; Brown and Krygier, 1971; Moring and Lantz, 1974; Moring, 1975a). It would then seem logical to assume that logging and road construction would generally increase the amount of fine sediment within the stream bed. Several studies have been conducted to test this hypothesis, with variable results.

In a spawning bed sedimentation study in California, Burns (1970) reported that the composition of the spawning bed changed roughly in proportion to the amount of direct stream bank disturbance. Several streams were located on drainages scheduled for logging. Bed sediment samples were taken during the low streamflow period the year before, during, and after road construction and logging.

Logging alone had little affect on the bed composition. Road construction and bulldozer operations in or near the stream, however, caused significant increases in fine sediment in the bed. Logging and road construction increased the percentage (by weight) of sediments less than 0.84 mm from 10.2% to 13.2% on Bummer Lake Creek, from 20.0% to 33.3% on Little Fork Noyo River, from 16.4% to 22.1% on Yager Creek, and from 20.6% to 34.2% on the south fork of Casper Creek (Burns, 1972). Flushing of fines by high flows returned fine sediment contents of the beds to pre-treatment levels within two years after disturbance. The author noted that prolonged disturbances tended to prolong sedimentation.

Moring and Lantz (1974) conducted a study of changes in gravel bed composition associated with the logging of several streams in the Oregon Coast Range. They reported that fine sediment less than 3.33 mm in diameter increased following logging without buffer strips on three of four clearcut watersheds. Only one of four streams with buffer strips exhibited an increase in fines. The authors concluded that buffer strips probably played an important role in preventing streambed and bank erosion.

Platts and Megahan (1975) reported that intensive management on the South Fork Salmon River in Idaho drastically altered the size composition of the gravel bed. By 1965, 15% of the 3300 km^2 watershed had been logged and 0.30 km/km^2 of road had been constructed.

Severe storms during the winters of 1962 through 1965 increased erosion and suspended sediment loads to levels 350% greater than in 1950 before road construction and logging had gotten underway. There was excessive sedimentation and spawning redds were buried under thick blankets of sand. In 1965 the Forest Service declared a moratorium on roading and logging and started a watershed rehabilitation program. Continued sediment inputs into the river were checked. After flushing by high flows, the relative amount of fine sediment in the stream bed decreased and the percentages of gravel and rubble increased.

In the Alsea Watershed Study, there was an increase in the fine sediment content of redds in Needle Branch and Deer Creek after logging (Ringler, 1970). Sedimentation of the gravel beds in Needle Branch severely reduced the porosity of the bed and the exchange between surface and intergravel water (Brown, 1972). The percentage of fine sediment (by volume) less than 3.33 mm in diameter increased from 40.5% to 44.8% on Needle Branch and from 32.7% to 40.4% on Deer Creek. Percent fines less than 0.84 mm increased from 26.5% to 32.2% on Needle Branch and from 23.3% to 29.1% on Deer Creek. However, due to a scarcity of pre-treatment samples, only one of the increases was statistically significant. The increase in percent fines less than 3.33 mm in Deer Creek was significant at the 95% confidence level (Moring, 1975a).

Influence of Mass Soil Movements

Mass soil movements that reach the stream channel can influence the composition of the bed material. Landslides and creep are a major process by which the gravel substrate is naturally supplied to the stream. However, most mass soil movements influenced by logging and road construction tend to be shallow slides consisting of mostly soil material (Swanston, 1971). These slides may adversely affect the amount of fine sediment in stream gravel beds.

In a study of landslide siltation of salmon and trout spawning grounds in the Olympic Peninsula of Washington, Cederholm and Lestelle (1974) reported that spawning areas affected by landslides had significantly (95% confidence level) higher levels of fine sediment than unaffected areas. Intergravel sediment monitors were placed in the gravel beds above and below the influence of the slides. Monitors downstream from the slides accumulated an average of 248 g of fine sediment whereas the upstream monitors accumulated an average of only 90 g. Obviously, landslides which introduce predominately fine material to the stream channel can temporarily degrade the quality of the bed.

Effects of Gravel Composition on Aquatic Resources

Gravel bed composition is a very important factor affecting anadromous fish populations. The composition of the spawning bed influences spawning activities, survival and emergence of alevins, habitat, and the benthic populations upon which fish feed. In all of these affects, increases in fine sediment appear to have deleterious effects on fish populations. Even moderate amounts of deposition may be detrimental (Cordone and Kelley, 1961). Extensive literature reviews on the subject of the effects of sediment on fish are available (Gibbons and Salo, 1973; Iwamoto et. al., 1978).

Fish Reproduction

The fisheries of the Pacific Northwest support eight species of anadromous fish, all of which are important from both a commercial and recreational standpoint. These include five species of salmon, two species of trout, and one species of char. The bulk of the natural reproduction of these species occurs in the headwater and small tributary streams of coastal rivers (Koski, 1972). After journeying from the ocean to upstream spawning areas, adult salmon deposit fertilized eggs in the streambed gravel. These fish generally spawn during the months of November through January and the eggs incubate in the gravel for approximately two months. After hatching, the alevins spend about two more months in the intergravel environment before emerging as fry in March through May. With the exception of resident cutthroat trout, the juvenile fish spend up to two years in the freshwater stream before migrating to the Ocean (Anon., 1978). The resident cutthroat make the stream their permanent home.

It is during the intergravel stages of life that the fish may be most susceptible to damages from high levels of fine sediments. The embryos and alevins require clean gravel 1.0 to 10.0 cm in diameter with high permeabilities to allow for good flow of intergravel water and freedom of movement (Koski, 1972).

Gravel beds are often harsh environments for alevins and incubating salmon ova. High levels of fine sediments may damage the ova by adhering to or abrading the chorion of the incubating salmon eggs (Gibbons and Salo, 1973). Natural mortality of eggs deposited in gravel beds sometimes exceeds 75% (McNeil, 1966). Since the intergravel stages of life of these fish represent a critical phase of their life cycle, special efforts may be necessary to avoid degradation of the quality of the bed.

Alevins and incubating salmon ova require certain levels of dissolved oxygen in the intergravel water for adequate survival and growth. Estimates of the minimum level of dissolved oxygen necessary for normal survival and growth range from 6 to 11 mg/l (Phillips and Campbell, 1961; Ringler, 1970; Phillips, 1971). There are interactions between dissolved oxygen and other environmental factors, so minimum requirements will vary between different redds. However, it has been noted that eggs and alevins incubated at lower dissolved oxygen levels generally have lower survival, emerge later, and are generally smaller and less able to compete with other fish than those raised at higher levels of dissolved oxygen (Phillips, 1965). Intergravel flows must be sufficient to remove the toxic metabolites produced by the eggs (Iwamoto et. al., 1976). Since high intergravel flow velocities are required for adequate survival to emergence, the processes controlling intergravel flow are important in egg and alevin survival.

Sheridan (1962) reported that the primary source of intergravel dissolved oxygen was the surface water of the stream. He noted that there was interchange of flowing stream water with the water in the gravel of the stream bed. He demonstrated dynamic interchange of water both ways by tracing water movement with dyes. Gravel beds influenced by ground water were apparently harmful to incubating salmon eggs due to extremely low dissolved oxygen content of ground waters. The author indicated that siltation of the stream bed might lower gravel permeability and interfere with the exchange process.

Vaux (1962) reported that the factors controlling interchange of stream and intergravel water were the stream gradient, stream surface profile, bed permeability, bed dimensions, and the irregularity of the stream bed surface. He further illustrated that a convex water surface profile lead to a downdraft of water into the stream bed, and a concave surface profile caused an upwelling of intergravel water. The extent of interchange was governed by variations in gravel permeability resulting from siltation, gravel compaction, organic matter content, and gravel bed shift. The direction of interchange was found to be dependent on the stream surface profile and the bed surface configuration.

During the Alsea Watershed Study, Lantz (1971) detected a long term decrease in intergravel dissolved oxygen levels after the logging of Needle Branch. He attributed this reduction to several factors. Increased water temperatures, due to the removal of streamside vegetation, lowered the saturation levels of dissolved oxygen in the stream. Large amounts of organic debris were introduced to the stream during logging. The additional organics in the surface waters and those deposited in the gravel bed had large biochemical oxygen demands and greatly reduced the oxygen content of the water. Even after surface waters recovered in dissolved oxygen content, the increased sedimentation of the gravel bed reduced permeabilities and restricted exchange of water between the stream and the bed and was a major factor contributing to the long term depression of intergravel dissolved oxygen levels (Hall and Lantz, 1969; Brown, 1972). Intergravel dissolved oxygen levels remained depressed for six years after logging (Moring, 1975a).

In a study conducted on Needle Branch, Coble (1961) found a positive correlation between the embryonic survival of steelhead trout and the velocity of the intergravel water. He attributed this relationship to the fact that higher intergravel flows were more efficient in supplying dissolved oxygen and removing toxic metabolites.

The survival of the eggs was also directly related to the dissolved oxygen content of the intergravel water. The author considered the dissolved oxygen content of the water flowing through the redd to be the most important factor affecting survival.

Cooper (1965) reported that the apparent velocity of intergravel flow was drastically reduced by the deposition of sediment in a stream bed. In a series of flume studies, he noted that gravel permeability decreased in proportion to the rate of silt deposition and that finer sediments were more effective than coarser sediments in reducing flow through gravel. He also noted that gravel beds with high permeabilities were especially susceptible to the deposition of fine sediment.

In southeast Alaska, McNeil and Ahnell (1964) reported that the potential of a gravel bed to produce fry was directly related to its permeability. Permeability was found to be inversely related to the amount of fine sediment in the gravel. Permeability of streambed samples was measured with a constant head permeameter and a strong inverse relationship was found between the coefficient of permeability and the percentage (by volume) of sediments passing the 0.84 mm sieve. They noted that, in general, the most productive spawning streams had lower levels of fine sediments. The size composition of bottom materials influenced water quality in the bed by affecting rates of flow within the gravel and the exchange between intergravel and stream water.

Another detrimental effect of fine sediments is that they restrict movement of alevins and may even effectively entomb them in the gravel (Iwamoto et. al., 1976). The interactions between this entrapping phenomenon and the reductions in intergravel dissolved oxygen have serious implications concerning the survival and emergence of alevins.

Phillips (1965) found statistically significant (95% confidence level) interaction between the effects of dissolved oxygen and gravel size on the survival of alevins. In experiments at the Alsea study site he found that the combined affects of these two factors caused weaker fry that had difficulty in emerging from the bed. Fewer fish were able to emerge from the smaller gravel than from the larger gravel.

Koski (1966) conducted a comprehensive field study on the factors affecting the emergent survival of alevins in the three Alsea Watershed Study streams. He was able to estimate the percent survival of the eggs deposited in the redd by trapping and tagging females moving upstream, observing where they spawned, and then trapping the emergent fry. The number of eggs laid by the female was estimated from a regression equation that predicted the fecundity as a function of the length and weight of the fish. Several environmental factors were measured at each spawning site and then correlated with the percent survival in the redd. The percentage of fine sediment was the only variable to be significantly correlated with survival. As percent fines (by volume) less than 3.33 mm increased, the survival decreased. His values for survival ranged from 0% to 80% over a range of fines from 26% to 52%. The regression equation had an r^2 value of 0.48. Larger amounts of fines also tended to delay emergence as compared to redds with smaller amounts of fines. Many dead alevin were observed in excavated redds which contained relatively large amounts of fine sediment. Failure to emerge may have been caused more by blockage of movement by fines rather than poor survival of the embryos (Koski, 1966).

In a similar study at Big Beef Creek, Washington, Koski (1975) estimated that the survival to emergence ratio for chum salmon decreased about 1.26% for each one percent increase in fines in the redd. A decrease in fry numbers and fitness was directly related to low dissolved oxygen levels and high percentages of sand in the spawning gravel. Koski noted that reductions in fry fitness might have pronounced effects on survival following emergence and suggested that redds with high percentages of fines might exert a selective mortality against larger fry.

In an aquarium study of preemergent coho alevin, Dill and Northcote (1970) reported that the fish did move both laterally and vertically prior to emergence. The authors compared the effects of large (3.2 to 6.3 cm) gravel and small (1.4 to 3.2 cm) gravel on the movement and emergence of the alevins. They reported that alevins moved significantly farther in large gravel than in small gravel and that the area occupied by each alevin was significantly greater in the larger gravel. Emergence was not significantly affected by gravel size, egg burial depth, or egg density. However, the period of emergence was significantly longer in the small than the larger gravel.

Phillips et. al. (1975) reported that there was an inverse relationship between the emergent survival of coho fry and the quantity of fines in the gravel. The experiment was carried out in a series of experimental troughs with amounts of fine sediment between 1.0 and 3.3 mm in diameter ranging from 0% to 70% by volume. The experiment was designed only to test the effect of fines on the emergence of fry, not their survival during their early stages of life. For this reason, fine materials less than 1.0 mm were excluded to allow for adequate percolation of water and supply of dissolved oxygen. The authors found an inverse relationship between the amount of sand and the days to mean emergence for coho alevins. High concentrations of sand caused the fry to emerge early. The authors attributed this early emergence to stress from the entrapment effect. The early emergents weighed less and retained more of their yolk than the later emergents. For these reasons, the early emergents were less vigorous and their chances of survival were reduced.

Taggart (1976) trapped emergent fry from 19 redds on eight tributaries of the Clearwater River, Washington. He characterized the intergravel incubation environment by measuring the gravel composition, the bed permeability, and the dissolved oxygen content of the intergravel water. He defined good gravel as being between 3.35 and 26.9 mm in diameter, and poor gravel less than 0.84 mm in diameter. Survival was inversely correlated with the percent poor gravel and positively correlated with the percent good gravel and bed permeability. Fry size was positively correlated with dissolved oxygen and negatively correlated with poor gravel.

In summary, excessive fine sediments may have many detrimental effects on anadromous fish reproduction. They damage the eggs by adhering to or abrading the chorion, blocking the exchange of intergravel and oxygen rich surface waters, and slowing intergravel water flows which deliver dissolved oxygen and remove toxic metabolites from the eggs. Finally, fines also restrict intergravel movement and emergence of alevins.

Fish Habitat

Relatively few studies have been conducted on the effects of fine sediment on fish habitat. Those that have been done, however, stress the point that excessive fine sediment is generally damaging to anadromous fish in this respect also.

Saunders and Smith (1965) conducted a study on the changes in a stream population of trout associated with drastic siltation of the bed.

The study was carried out in Ellerslie Creek on Prince Edward Island, Alaska. Cultivation and road construction introduced unusually large amounts of sediment to the stream. Drastic reductions in trout populations accompanied this sedimentation. Population reductions ranging from 20% to 25% occurred in different reaches in the stream. The authors attributed these population reductions to the destruction of habitat and hiding places. They noted that they remaining trout searched out the few areas of clean gravel for feeding purposes.

Phillips (1971) noted that fine sediment might be an important factor affecting the early survival of emergent salmon fry. The fry often feed in the gravel bed and escape from predators in the interstices. Increased amounts of fines would reduce the cover for escape and reduce early survival. Similarly, Gibbons and Salo (1973) reported that excessive fines tended to smother the gravel bed and reduce the numbers of smaller fish by reducing the available living space and escape cover.

A comprehensive study on the effects of sand on fish habitat was carried out in both natural and artificial stream channels in Idaho (Bjornn et. al., 1977). The authors reported that fewer fish remained in the artificial channels where sediment was added to the pools. The reduction in fish numbers was attributed to a loss of cover in the interstices between large rocks. When sediment was introduced into natural channels, a loss in pool volume reduced fish numbers proportionally. No change in fish numbers was observed due to riffle sedimentation. The authors reported that excessive fine sediments could reduce the summer rearing capacity of streams when deposited in the pools, and reduce the winter fish capacity when deposited in the larger intersticial spaces of the stream substrate since fish often enter the gravel bed when the water temperature drops.

Benthos

The benthic community is the major food source for anadromous fish in freshwater streams. Excessive fine sediment tends to reduce these food resources by filling gravel interstices and promoting unstable substrates for aquatic invertebrates and periphyton communities. Fine sediments reduce invertebrate diversity and populations by reducing the available living space and reducing their early survival (Gibbons and Salo, 1973).

Cordone and Kelley (1961) reported that an increasing amount of fine material in the stream bottom eventually results in a declining bottom fauna. The authors noted that algae is the very basis of the food chain in streams. They attributed fine sediment with the destruction of algae through abrading or covering the bottom with a layer of silt, effectively shutting off the light necessary for photosynthesis.

Nuttal (1972) evaluated the effects of increased sedimentation on macroinvertebrate fauna of the river Camel in England. Increased erosion deposited approximately 10,000 m^3 of sand in the main river within a two year period. A decreased incidence of plants and macroinvertebrates was associated with the unstable shifting nature of the sand deposits. The deposition of sand resulted in a low diversity and elimination of species. There was a drastic decrease in species diversity at the point of sediment input, with a gradual recovery downstream. Rubble tended to support more insects than sand due to the greater living space and the better chances for organic matter food sources to become lodged among the stones.

In studying the effects of landslide activity on the siltation of the Clearwater River in Washington, Cederholm and Lestelle (1974) found a strong inverse relationship between the total number of benthic organisms within gravel beds and percent fines less than 0.84 mm in diameter.

Bjornn et. al. (1977) reported that benthic insect density in the artificial channel study in a fully sedimented riffle was half that of an unsedimented riffle. In the natural stream, they found that benthic insects were 1.5 times more abundant in a plot cleaned of fine sediment than the other sections of the stream. At this plot, mayflies and stoneflies were four times and eight times more abundant, respectively.

In summary, high levels of fine sediment in stream beds tend to reduce the food resources for fish by reducing the numbers and diversity of the benthic community.

III. PROCEDURES

Study Areas

Five streams were intensively sampled during the course of this study; these were Needle Branch, Deer Creek, Flynn Crrek, Meadow Creek, and Green Creek. The first four streams are located approximately 16 km south of Toledo, Oregon, and are tributaries to Drift Creek, which eventually flows into Alsea Bay approximately 6.4 km east of Waldport. The majority of the sampling conducted during this study was on the undisturbed Flynn Creek watershed (Figure 1). Needle Branch, Deer Creek, and Flynn Creek were intensively studied during the Alsea Watershed Study.

The undisturbed Flynn Creek watershed encloses about 225 ha. Sample collection was concentrated in this watershed to gain insight on the processes that affect the composition of bed sediments in an undisturbed stream. The adjacent Meadow Creek watershed, 138 ha in size, contains approximately 1.2 km of forest road and a 51 ha clearcut which was harvested in 1963. Both watersheds are administered by the U. S. Forest Service. The principal tree species on the Flynn Creek and Meadow Creek watersheds are Douglas-fir (Pseudotsuga menziesii) and red alder (Alnus rubra). Douglas-fir are present in 30 to 50 and 70 to 110 year old stands. Alder stands are about 30 to 70 years old and are concentrated near the stream. Understory vegetation consists of salal (Gaultheria shallon), sword fern (Polystichum

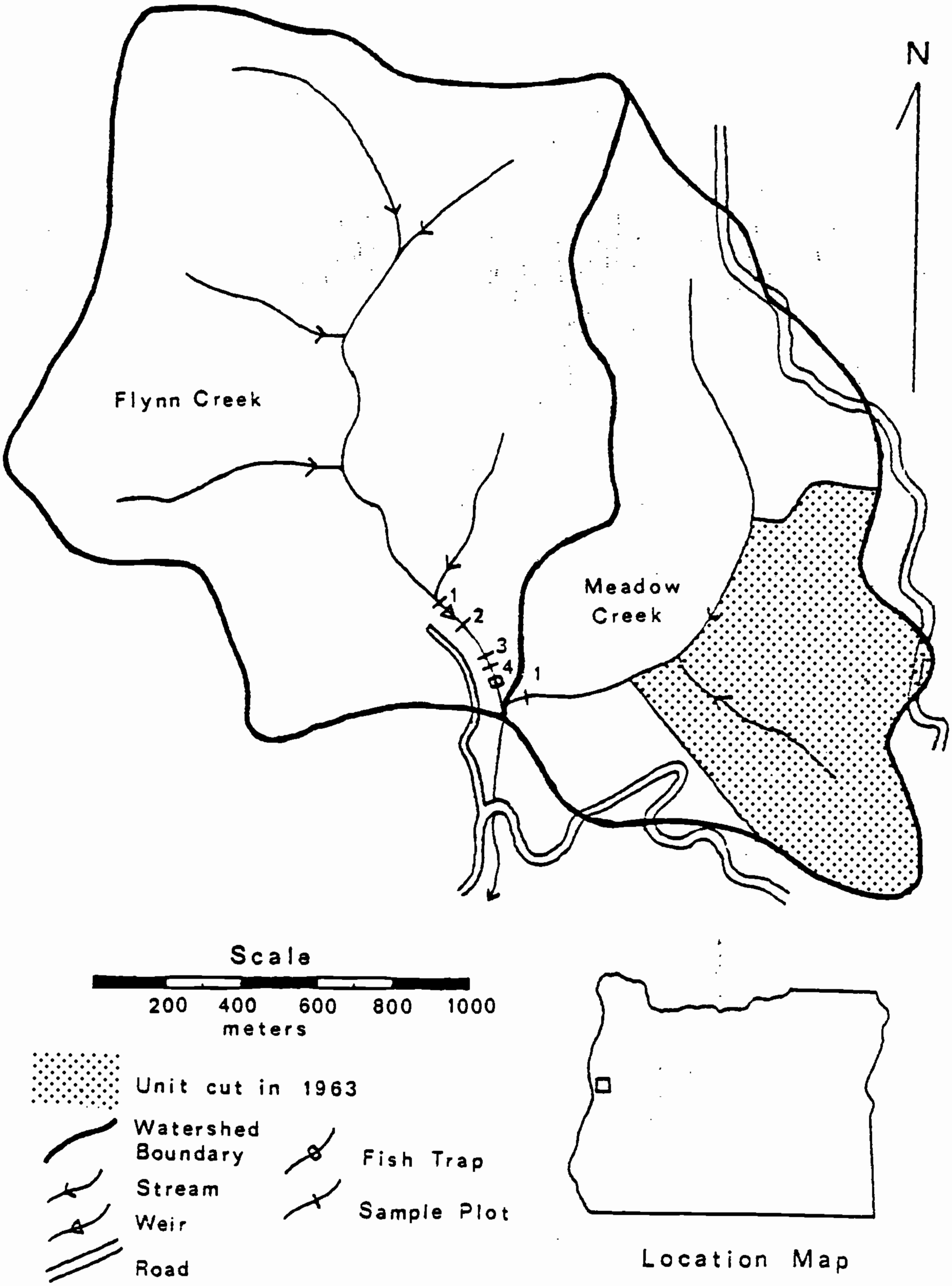

Figure 1. Map of Flynn Creek and Meadow Creek Watersheds.

mumitum), vine maple (Acer circinatum), salmonberry (Rubus spectabilis), and isolated groups of bracken fern (Pteridium aquilinum) (Moring and Lantz, 1975).

A stream gaging station is maintained and operated by the Oregon State Department of Forest Engineering on Flynn Creek. Stream discharge records from this station were used to index flow patterns (size and sequence of storm events) on the other study streams.

The Deer Creek watershed is the largest of all five study streams, covering approximately 304 ha. Most of the watershed is administered by the U. S. Forest Service, with a small section at the base owned by Georgia Pacific Corporation. Three clearcuts totaling about 82 ha were harvested in 1966. One of these units is near the mouth of the watershed and the other two are in the headwall areas. Another unit about 30 ha in size in the upper reaches of the watershed was harvested during the fall of 1977. Two of the four units have buffer strips near the stream. The Deer Creek watershed contains about 6 km of forest road, most of which was constructed near the ridges. The remaining vegetation on the watershed consists of mostly 50 to 110 year old Douglas-fir stands. Alder stands, 40 to 60 years old, are concentrated near the stream. The understory vegetation consists of salmonberry, vine maple, sword fern, and isolated patches of salal and bracken fern (Moring and Lantz, 1975).

The Needle Branch watershed covers 75 ha and was 82% clearcut in 1966. No buffer strip was left and little effort was made to protect the stream. Large organic debris was eventually removed from the channel (Moring and Lantz, 1975). The watershed contains about 2.4 km of road concentrated near the ridges. Dense growth of red alder now cover the area near the stream and planted Douglas-fir are revegetating the slopes of the watershed. The drainage is almost entirely owned by the Georgia Pacific Corporation. There is a small block of privately owned land near the mouth of the watershed.

The other stream sampled intensively during this study was a small unnamed creek approximately 16 km southwest of Alsea, Oregon. It will be called Green Creek for the purposes of this study (Figure 2). The watershed has its mouth located near U. S. Forest Service road number 15003 in the N. W. 1/4 of section 27, T. 15 S, R. 9 W, Willamette P. M. Green Creek is a headwater tributary to Five Rivers, a stream which eventually flows into the Alsea River approximately 18 km east of Waldport. The Green Creek watershed encloses 56 ha and has approximately 1.1 km of road within its boundary. Approximately 15 ha were harvested in 1955 within the watershed. Unit three of the Ryan Green '76 timber sale encloses 16 ha within the watershed and is scheduled to be harvested before December of 1979. The entire watershed is owned by the Forest Service. The principal tree species is Douglas-fir. Scattered western hemlocks (*Tsuga heterophylla*) and red alders are also present on the area. The understory vegetation consists of salal, sword fern, vine maple, and salmonberry.

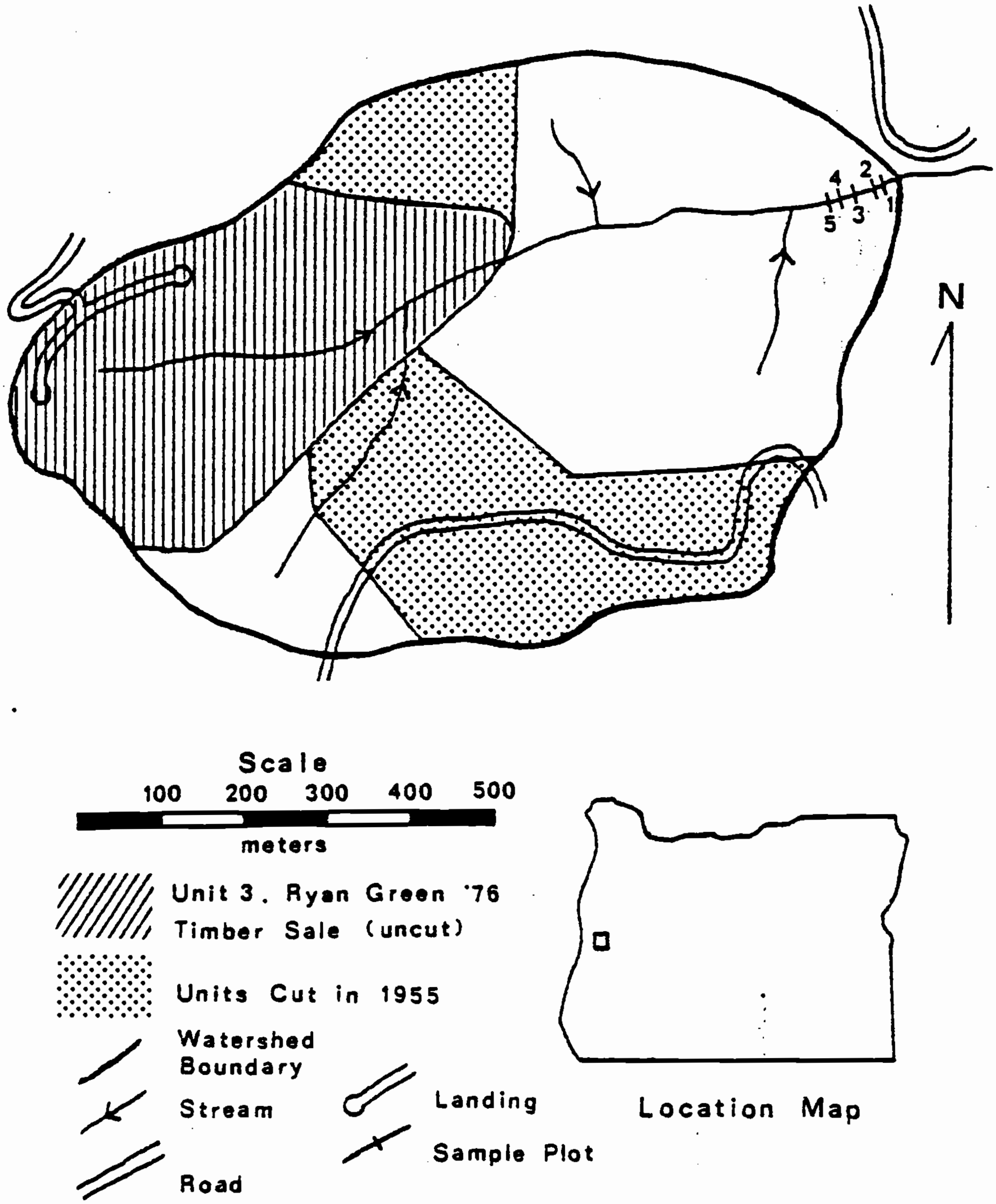

Figure 2. Map of Green Creek Watershed.

Sample Collection

Streambed samples were collected by two methods in this study. Both involved the removal of a frozen core of the bed sediments. However, the two methods for freezing the core differed. One method used liquid carbon dioxide and the other used liquid nitrogen. The carbon dioxide technique was used for all the samples in the study with the exception of the ones taken from the 21 streams sampled during the summer months. Liquid nitrogen cores were collected on those streams.

Carbon Dioxide Method

The carbon dioxide frozen core sampling technique was first described and then modified by Walkotten (1973; 1976). The design of the sampling apparatus used in this study is identical to his (Figure 3). Several pointed probes were constructed from one meter lengths of 1.9 cm diameter hard drawn copper pipes. The probe tips are fashioned from machined brass. A four-way-cross pipe is fastened to the top of the length of pipe and short sections of pipe are attached for handles. A smaller diameter pipe was constructed so that it could be inserted into the full length of the outer probe. Liquid carbon dioxide is supplied to the bottom of the probe by the smaller section of

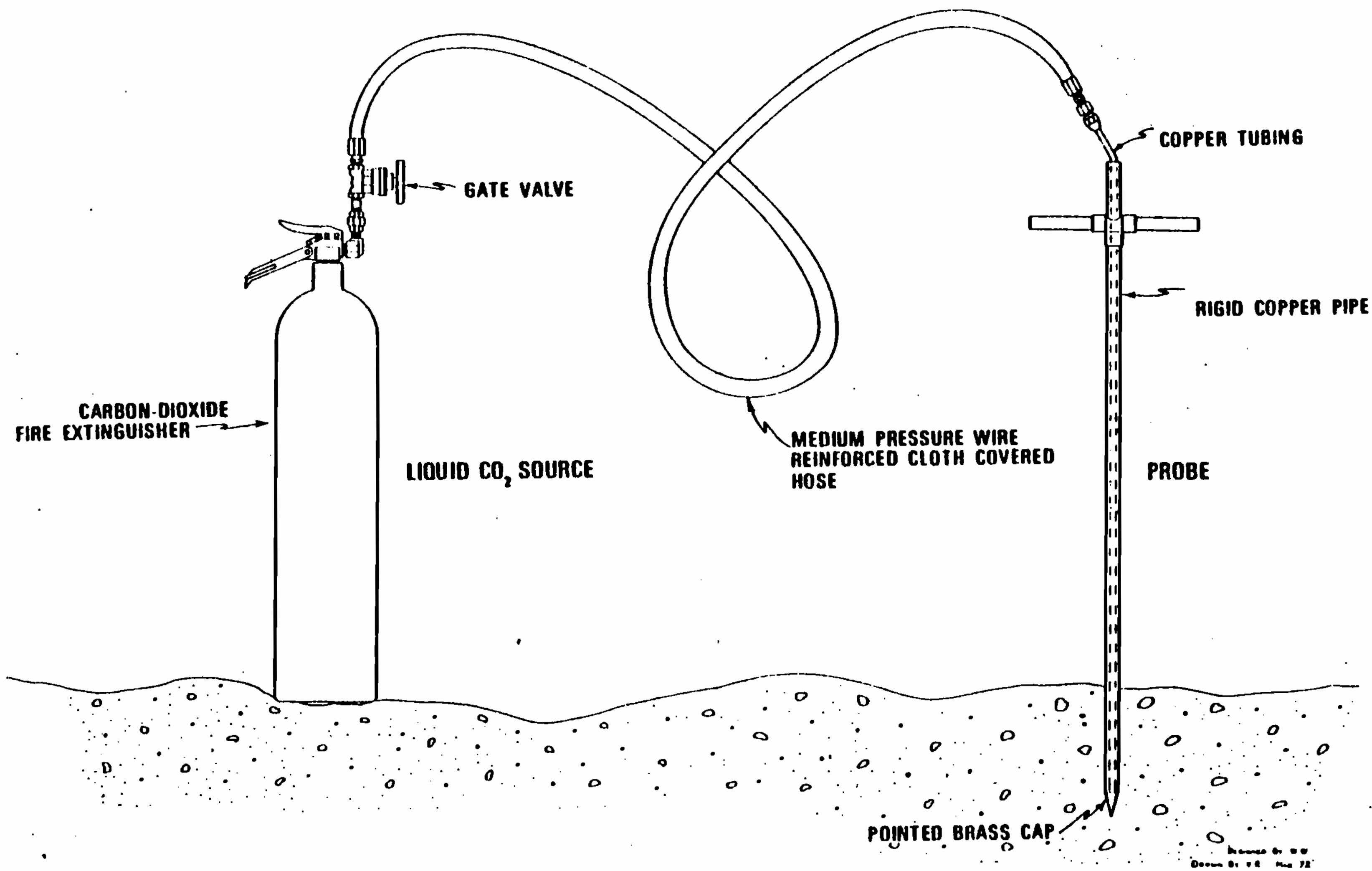

Figure 3. Carbon dioxide frozen core sampling aparatus (from Walkotten, 1973).

pipe. This inner probe is connected to a fire extinguisher supply bottle by a length of wire-reinforced delivery hose. A 9.1 kg (20 lb.) capacity tank was used for the carbon dioxide supply. This size allowed for field portability and an adequate supply of gas. Four nozzles are spaced five cm apart and staggered around the base of the inner probe to deliver the liquid carbon dioxide to the base of the outer probe. The nozzles have 0.15 mm diameter orifices that allow pressurized liquid carbon dioxide to bleed off slowly after filling the inner probe and supply hose. These orifices are easily plugged by impurities in the carbon dioxide or the supply line, so a ten micron filter was installed at the top of the inner probe to prevent this type of material from reaching the base of the probe.

Liquid carbon dioxide has a heat of vaporization of 42.9 cal/g at 15°C (Chemical Rubber Company, 1966). As liquid carbon dioxide is supplied to the interior of the base of the outer probe, it vaporizes at atmospheric pressure and cools the base of the probe to about -80°C. The probe absorbs heat from the stream bed and freezes the sediment, organic matter, and intergravel water. The frozen core can then be pulled out of the stream bed with the probe. The core can then be removed from the probe by pouring hot water down the length of the pipe. The water heats the probe and the interior of the core so that it may be slid off the probe and stored in a plastic bag.

Liquid carbon dioxide was supplied at a rate such that a moderate amount of dry ice snow was blown out of the top of the probe. This rate represents a flow of about 0.45 kg (one lb.) of gas per minute. This rate of gas delivery, when supplied for three minutes, would freeze a core between five to ten cm in diameter. Six samples could be taken with each tank. All samples were taken to a depth of about 25 cm.

Liquid Nitrogen Method

Streambed samples were collected on the 21 streams sampled during the summer months by a liquid nitrogen forzen core technique. In this method, a 3.8 cm diameter iron pipe with a pointed steel cap was driven into the stream bed to a depth of about 40 to 50 cm. The pipe was then filled to about the level of the streambed surface with liquid nitrogen.

Liquid nitrogen has a heat of vaporization of 475 cal/g at the boiling point (Sargent-Welch Scientific Company, 1968). This substance boils at a temperature of -195.8°C (Chemical Rubber Company, 1966). The liquid nitrogen is rapidly volatilized and produces extremely cold temperatures within the pipe (Hess, 1977). Liquid nitrogen was poured into the pipe from a Dewer flask at about the same rate as it boiled away. Ten liters of nitrogen were used for each sample. This amount would freeze a core about 20 cm in diameter in approximately 15 minutes. With some effort, the core could be removed from the stream bed and stored for later analysis.

Possible Sample Bias

Frozen core samples may have a bias towards the larger particle sizes in streambed sediments since only a small portion of a large particle needs to be frozen for it to be withdrawn from the bed with the probe (Hess, 1977; Sharma, 1978; Walkotten, 1973). It might be expected that this bias towards the larger particles would be less in the nitrogen samples than for the carbon dioxide samples due to the reduced surface area per unit volume of the nitrogen cores.

In order to test for significant differences in the results obtained with the two sampling techniques, ten paired samples were collected on Needle Branch and Flynn Creek in June of 1978. The nitrogen core pipe was driven into the stream bed. Before the nitrogen core was taken, two carbon dioxide cores were taken about 15 cm on either side of the pipe on a line perpendicular to the streamflow. The carbon dioxide cores were composited before analysis. The percent fines and percent organic matter were determined for both samples to an equivalent depth and the difference in the means was evaluated with a paired t-test. Throughout this study all statistical tests were conducted at the 95% level of confidence (95% CL).

Sample Analysis

All frozen core samples were oven dried at 105°C for 24 hours. The samples were then removed from the oven and allowed to cool to room temperature. Total weights were recorded for all the samples before particle size analysis was performed.

Particle Size Analysis

Particle size analysis on all samples was carried out by dry sieving the samples through a set of eleven nested sieves. The sieve openings (in mm) used in the analysis were 50.8, 38.1, 25.4, 19.0, 16.0, 9.5, 6.3, 4.0, 2.0, 1.0, 0.42, and the pan. In other studies, particle size analysis has been performed by both the gravimetric and volumetric methods. However, Moring (1975a) reported that the two different analysis techniques yield essentially the same results. Gravimetric analysis of the samples was used in this study.

Particle size distribution curves were plotted for each sample and the amount of fine sediment was expressed as a percentage of the total sample weight. For the time series data and most other data in the study, percent fines were taken to be less than 1.0 mm in diameter with material greater than 50.8 mm excluded from the total sample weight. For the data on the 21 streams, percent fines were expressed in several ways. The upper limit of fine sediment was taken at 2.0, 1.0, and 0.84 mm and the material larger than 50.8 mm was both excluded and included for the calculation of percent fines at the 2.0 and 1.0 mm breaks. The percent fines less than 0.84 mm was interpolated directly from the particle size distribution curve.

Rocks larger than 50.8 mm were excluded from the sample weights to attempt to avoid the overpowering effect they would have on the measure of the relative amounts of fine and coarse sediment in the sample. This is essentially a sampling problem. One large stone will have a large effect on the percent fines within a sample even though it might have little influence on the variable we actually wish to measure - the composition of the bed as it relates to the reproductive success of anadromous fish. For the carbon dioxide cores, rocks larger than 50.8 mm would usually have most of their bulk outside of the frozen front of the core. This was also true to a lesser extent with the nitrogen cores. In these cases, although the rocks were physically attached to the core, they did not belong in the cylindrical sample of the stream bed defined by the frozen front. It was hypothesized that excluding the larger material from the sample would give a more representative measure of the composition of the stream bed and reduce the variance in percent fines for a given sampling location. An experiment was conducted to test this hypothesis.

During October of 1978, a gravel bed with unusually large amounts of relatively large stones was located on Flynn Creek and sampled. Twelve random samples were taken by the carbon dioxide technique. Seven of the twelve samples contained stones larger than 50.8 mm. The samples were sieved and the percentage by weight of fines less than 1.0 mm was calculated including and excluding the rocks larger than 50.8 mm. The variance in the twelve samples was calculated for both measures of fine sediment and an F-test for the differences in the two variances was conducted. The same test was conducted for the organic matter content of the samples.

Several other researchers working with streambed composition also excluded large rocks from the particle size distribution analysis in order to avoid their large spurious effects on the measure of fine sediment. McNeil and Ahnell (1964) excluded all material greater than a minimum diameter of 100 mm before sample analysis. Wendling (1978) excluded all material greater than 25 mm from his samples.

Organic Matter Analysis

The organic matter content of all samples was determined by weight loss on ignition. Samples were placed in aluminum pans, weighed, and then placed in a muffle furnace set at 310°C for 48 hours. After the samples were removed from the oven, they were allowed to cool for six to eight hours before reweighing. Organic matter contents were expressed as a percent of the total sample weight. Again, material larger than 50.8 mm in diameter was excluded from the sample weight.

The temperature of 310°C was used for organic matter analysis because this was the highest temperature that the muffle furnace chosen for use in this study could attain. This was the only available oven which had a large enough capacity to handle the number of samples that were collected.

Since most analyses for organic matter are carried out by burning at 550°C, it was of interest to know if there was a relationship between the estimates of organic matter content obtained at the two temperatures. For this reason, twenty samples were taken after they had been ashed at 310°C and were ashed again at 550°C and the additional weight loss was determined for each.

The burning of sediment samples at high temperatures for organic matter analysis is not recommended due to the fact that some of the weight loss upon ignition may be due to the loss of bound water from the sediment particles. The weight loss may represent more than just the organic material. These considerations were further justification for burning the samples at the lower temperature. However, one still cannot be sure that the weight loss at 310°C is representative of only the organics. Some bound water may be driven off at this temperature also. This method should be thought of as an index of organic matter content within the samples, not an absolute measure. The temperature of 310°C did allow for complete ignition of the organics in all the samples.

Study Design

Temporal Variability

The percentage of fine sediments in individual gravel beds of the five study streams was monitored to document any changes in the composition of the bed material with time. Sample collection plots were located immediately downstream from pools in gravel bars that would be suitable as spawning areas for anadromous fish. No randomized sample plot location was attempted because it was desireable to locate the sample plots in areas where fish might spawn. Spawning fish are not random in redd site selection. They search out areas in the stream with the proper bed configuration and streamflow conditions. If a study is designed to measure bed composition as it affects the reproductive success of anadromous fish, sampling sites should be located by criteria similar to those used by the fish to select redd sites (Cederholm and Lestelle, 1974). For these reasons, sample plots were located in riffle areas immediately downstream from a pool.

Four sample plots were established on Flynn Creek, the undisturbed stream, and one was established on Meadow Creek. Sample plots 1 and 2 on Flynn Creek are located approximately 20 m upstream and downstream from the stream gage, respectively. Plot 3 is about 30 m upstream from the fish trap. Plot 4 is located only 8 m upstream from the fish trap and is under the ponding influence exerted by the structure. Plot 1 on Meadow Creek is located approximately 15 m upstream from the confluence with Flynn Creek.

Only one plot was installed on Needle Branch, about 15 m upstream from the stream gage. It was moved another 5 m upstream in July of 1978 because the pool immediately upstream filled in with bedload sediment near the end of the first storm season and the plot no longer had the pool and riffle configuration that was desireable for sampling points.

Two sample plots were located on Deer Creek. Plot 1 was located just below a debris accumulation about 20 m upstream from the stream gage. Plot 2 was located about 10 m upstream from Plot 1.

Five sample plots were installed on Green Creek, all within 50 m of the mouth of the watershed. A crest gage was also installed along a relatively stable straight reach of the channel. Since Green Creek is approximately 27 km south of the other four watersheds, the extrapolation of the Flynn Creek discharge records to Green Creek needed verification. The gage was installed for this purpose.

The crest gage consisted of a 1.3 cm diameter clear acrylic pipe and a styrofoam float inside a larger 2.5 cm diameter PVC pipe perforated with holes along its length. The outer pipe was bolted to a stake set deep in the stream bed in concrete. The gage was located next to a cut bank about 10 m downstream from plot 5. As the stream rose, the float would rise up on the inside of the acrylic pipe and stick at the highest point the water reached. The stream crest was measured each time Green Creek was sampled and the peaks were assumed to have occurred the same day as the ones on Flynn Creek. The stream bed was profiled at the crest gage and cross-sectional areas of flow were computed for each peak stage. Velocity measurements were made once during a relatively high stream discharge and this velocity was assumed to apply to all discharges. With this assumed velocity and the known cross-sectional areas of flow, the peak discharges were estimated and compared to those measured at the Flynn Creek stream gage.

All sample plots were set up as a stream cross section or line defined by two stakes, one on either side of the stream. The two cross-section endpoints were set at the stream bankfull stage and were used to define a level reference line across the stream channel. Stretching a tape tight between these two endpoints allowed for the making of measurements of the vertical distance to the stream bed at intervals along the tape. Cross-section measurements were made before sampling each plot in order to determine the net amount of scour or deposition of bed material at that plot since the last sample.

Bed sediment samples were taken on a monthly basis and as soon as possible after major storm events. Samples were collected by removing a frozen core of the sediment with the carbon dioxide probe. The samples were taken to a depth of about 25 cm. Each month, two samples were collected at each plot and were composited for analysis. Samples were limited to the area within the stream 1 m on either side of the cross-section line. The exact location of each sample was recorded in terms of its coordinates in relation to the cross-section endpoints. This procedure allowed for the collection of undisturbed samples by avoiding a spot previously sampled. After large storm events that caused major gravel bed movement, the entire plot was considered to be open for sampling and the record keeping was begun again.

It was of particular interest to know if the removal of one core from a given spot within a stream bed would require that one go to another spot for the next core in order to obtain an undisturbed sample.

One hypothesis was that a second core out of the same hole would have drastically different amounts of fine sediment than the first and would not represent an undisturbed sample. To test this hypothesis a series of 12 paired samples was taken on Flynn Creek during the fall of 1978 and the difference in the sample means was tested with a paired t-test.

Sampling began on the three Alsea watersheds in October 1977. Cross-section measurements began in February of 1978. Although the first storm season was about over before intensive cross-section measurements were begun, there were other bed profile measurements made in close proximity to some of the plots in conjunction with another study (Sue O'Leary, 1979. Georgia Pacific Corporation, Ft. Bragg, California, Personal communication). These data were used to index the occurrence of bed movement near some of the sample plots during the first storm season. Plot 2 on Deer Creek was sampled beginning in August of 1978. Sampling and cross-section measurements began on Green Creek in February of 1978. All data collection was terminated in April of 1979.

The time trends in the percentage of fine sediment and organic matter within each sample will be presented in graphical form in conjunction with the streamflow hydrographs. For all time series samples, 1.0 mm was used as the upper limit of fine sediment and all material greater than 50.8 mm was excluded in the sample analysis. Confidence limits were calculated for the percentage of fine sediment in each plot during the summer low flow season.

Spatial Variability

One of the problems in using the percentage of fine sediment in gravel beds as a stream quality criterion is the large amount of spatial variability in this parameter. In the Coast Range, percent fines varies between streams, between locations in a given stream, and even between different locations in a particular gravel bed.

In order to document the variability between the percentage of fine sediments in the gravel within a given stream, comparisons were made between sample plots on the same stream. Averages were calculated for each plot over all the months data was collected and again only for the low flow periods. During the low flow periods, the amount of fine sediment in the gravel should remain relatively constant since it is not affected by the scour and fill of gravel associated with high flows. Statistical comparisons were made between the plot averages and any differences noted.

The variability of percent fines within the gravel bed of a given riffle area is of particular interest in sample design. One experiment was carried out to attempt to document the variability within a single gravel bed. In September of 1978 a gravel bed with a relatively uniform surface appearance was located on Flynn Creek and 16 samples were taken on a 1.2 by 1.2 m grid superimposed on the bed. The samples were analyzed for fine sediment and organic matter content and the changes in these values parallel and perpendicular to the direction of flow was tested by a two way analysis of variance (Ott, 1977).

Variables Affecting Streambed Composition

Twenty-one watersheds ranging from 23 to 537 ha in size were sampled in the Coast Range during the months of June, July, and August of 1978. Samples were collected on watersheds over a wide range of disturbance classes. Five uncut, ten partially cut, and six totally cut watersheds were sampled. Road densities ranged from no roads to 4.35 km of road per km^2 of watershed area. Samples were collected during the summer low flow months in order to avoid variations in bed composition associated with winter high flows. The organic matter in these samples is being analyzed in another study and will not be presented in this paper[1].

Three bed sediment samples were taken at least 10 m apart on each stream. Samples were collected by the liquid nitrogen technique. Since Flynn Creek was an easily accessible and undisturbed stream, four extra samples were collected on it. All cores were stratified by depth into three sections: 0 to 10 cm, 10 to 25 cm, and 25 to 40 cm. The difference in the mean percent fines in the three layers for the samples was tested with an F-test to check for any general trends in the stratification of fine sediment with depth in the gravel bed.

The percentage of fine sediment by weight was the dependent variable of interest in this study. Independent variables comprised three categories: channel, watershed, and land use characteristics.

[1]Fine Organic Debris and Dissolved Oxygen in Streambed Gravels in the Oregon Coast Range. Proposed thesis title, Arne Skaugset, Dept. of Forest Engineering, Oregon State University.

Channel characteristics often have a large influence on the bed composition at a particular point in the stream. For example, Osterkamp (1978) reported that samples of bed and bank material taken at points in the stream provided strong indications that sediment characteristics of the channel were related to channel geometry. Zimmer and Bachman (1978) noted that there were definite interrelationships between channel characteristics and bed form and composition. They reported significant positive correlations between channel sinousity and the variability of water depth and current velocity. They noted that these factors might influence the composition of the bed. They also found that bed particle size was directly related to channel gradient. Beschta (1978b) noted that the characteristics of the stream bed and banks were important factors affecting stream morphology and sediment transport. He reported that there was an increasing need for quantitative information on the stream and channel system and outlined several techniques for inventorying streams.

Watershed characteristics may also affect the composition of stream beds. Beschta and Jackson (1978) reported that the particle size distribution of the bed materials might be affected by parent materials, soils, and other watershed characteristics. In a study in Alaska, the productivity of pink and chum salmon streams was adequately predicted by a model containing eight quantitative geomorphic variables measured from aerial photographs and maps (Swanston et. al., 1977). These variables included the basin area, percent of slopes greater than 34^{o}, avalanche index, bifurcation ratio, stream length, basin relief, basin length ratio, and the basin orientation. Salmon productivity in these streams is largely controlled by gravel bed composition, so these variables might be controlling productivity indirectly through their influence on the gravel bed.

Several land use variables were also measured on the watersheds to index the degree of disturbance on the basins. If road building and forest harvesting greatly accelerate the rates of erosion and sediment delivery to the stream, then increased sediment loads might lead to greater rates of sediment deposition within the gravel beds.

The variables measured at each sample plot and watershed are listed in Table 1. The first five variables represent different ways of expressing the percentage of fine sediments within a sample.

The stream order for each segment of stream sampled was determined by the methods proposed by Strahler (1957). For consistency, all stream orders were taken from the same 1:31,680 scale quadrangle map.

Bankfull stage is the vertical distance from the stream bottom to the bank capacity level and was measured at the deepest point along the sample plot cross section. The cross-sectional area of flow was calculated from bed profile measurements at each plot. The width-depth ratio is the width of the stream channel divided by the bankfull stage.

Table 1. Listing of dependent (1-5) and independent (6-26) variables for Coast Range watersheds.

Variable	Units[a]
1. Fines (1.0 mm exc. rocks larger than 50.8 mm)[b]	%
2. Fines (1.0 mm inc. rocks larger than 50.8 mm)	%
3. Fines (2.0 mm exc. rocks larger than 50.8 mm)	%
4. Fines (2.0 mm inc. rocks larger than 50.8 mm)	%
5. Fines (0.84 mm exc. rocks larger than 50.8 mm)	%
6. Stream order	-
7. Watershed area	ha
8. Bankfull stage	m
9. Stream cross-sectional area at bankfull stage	m^2
10. Width-depth ratio	-
11. Stream gradient	%
12. Stream sinuosity	-
13. Watershed relief ratio	-
14. Average watershed slope	%
15. Watershed sediment yield ranking	-
16. Road density	km/km^2
17. Amount of watershed harvested	%
18. Percent area time factor	%
19. Amount of direct stream disturbance	%
20. Armor layer average diameter	cm
21. Average log transformed armor layer diameter	cm
22. Channel stability rating	-
23. Basalt present in stream (yes=1, no=0)	-
24. Large scale mass movements (yes=1, no=0)	-
25. Private timber holdings (yes=1, no=0)	-
26. Index of uniformity	-

[a]A dash indicates that the variable is dimensionless.

[b]Percent fines by weight.

Stream gradient was measured at each plot with a clinometer and recorded to the nearest one percent.

Sinuosity is the ratio of the stream distance between two points to the straight line distance between the same two points in the channel. At each plot, a straight line distance of at least 15 m to another point upstream was measured and then the distance along the stream was measured.

The relief ratio for the watershed was calculated by dividing the difference in elevation between the highest point and the mouth by the straight line horizontal distance between the two points. This measure is an index of the overall steepness of the watershed.

The average slope was also calculated to index the steepness of the drainage. Grids were randomly placed over a topographic map of the watershed and percent slopes perpendicular to the contours were calculated at each point on the grid. At least ten points were sampled within each drainage.

The sediment yield ranking is a property of the soils mapped on the watershed. The ranking is intended to index the potential for stream sedimentation from silt and clay particles eroded from the soil and carried in suspension (Badura, 1974). The rankings are expressed as being low, moderate, or high with gradations between the three groups. For this study, the rankings were assigned numbers from one to five, with "low" being one and "high" having a value of five. The soil types mapped on each watershed were assigned their respective sediment yield rankings and the numbers were weighted by the area of the watershed having that ranking.

The total length of all roads within the watersheds was determined and expressed on a per unit area basis in km of road length per km^2 of watershed area.

Clearcut units harvested up to 20 years ago were sketched on base maps using information gathered from fireman's maps, aerial photographs, and field surveys. The ages of the cut units were determined from dendrochronological measurements or Forest Service records. The percentage of the area in clearcuts was determined and recorded for each watershed. Partial cuttings or thinnings were not considered to be cut units in this study. No partial cuts were observed on any of the watersheds and only one light thinning was encountered.

The Percent Area Time Factor is a land use index designed to take into account stream sediment inputs from roads and clearcut units. The index is designed to account for the gradual return of increased sediment inputs from cut units to pre-treatment levels over a period of time.

The first step in developing the factor was decided on an equivalent clearcut area that would represent about the same sediment production as a given area of a watershed in roads. What percentage of an otherwise undisturbed watershed's area in roads is equivalent to clearcutting the entire watershed without roads? In all cases, the road widths were assumed to be 15 m. This width was sufficient to include the driving surface, ditches, and cut and fill slopes, all of which are sources of erosion and sediment problems. This clearcut equivalent for the roads was estimated from information gathered from several sources.

Several researchers have estimated the relative contributions of roads and clearcuts in relation to increased sediment delivery to the stream (Anderson, 1971; Swanson and Dyrness, 1975; Swanston and Swanson, 1976). These estimates indicate about six to eight percent of a watershed in roads may be equivalent to clearcutting the watershed.

Several watershed studies had periods of time between the road construction and timber harvest or gave other separate estimates of the increased sediment yield due to roads and clearcuts (Fredriksen, 1970; Megahan and Kidd, 1972; Moring, 1975a). These results show that from 0.01% to 1.5% of an area in roads may produce an equivalent amount of sediment as a clearcut.

Based on these estimates, four percent of a watershed's area in roads was assumed to be equivalent to clearcutting and cable yarding the entire watershed in terms of sediment delivery to the stream.

The area of each watershed in roads was calculated by multiplying the length of roads times the 15 m assumed road width and then it was expressed as a percentage of the entire drainage area. The clearcut equivalent area was calculated from the following formula:

$$C = \frac{(100)\ R}{4}$$

Where C = Clearcut equivalent (percent)

R = Watershed area in roads (percent)

The Percent Area Time Factor was designed to take into account the return of erosion and sedimentation rates on clearcut units to pretreatment levels over a period of time. This reduction in erosion rates over time has been well documented (Brown, 1971; Megahan, 1974). A period of ten years was assumed for the return to natural levels of sedimentation following clearcutting. This estimation of reduction in sediment yields was not applied to the roaded area since roads were considered to be continuous sources of sediment. The Percent Area Time Factor was calculated for each watershed by the equation below.

$$F = \frac{H\ (10 - T)}{10} + C$$

Where F = Percent Area Time Factor (percent)

H = Area of the watershed harvested (percent)

C = Clearcut equivalent area for roads (percent)

T = Time since harvest (years)

$$\text{for } T > 10 \text{ years}, \frac{H\,(10 - T)}{10} = 0$$

If watersheds contained several units harvested at different times, each was considered separately. Time reduction factors were calculated for each one, and these values were summed before being added to the clearcut equivalent for the roads.

With this system, it was possible to have a Percent Area Time Factor of well over 100%. Watersheds with recent cut units and high road densities tended to have factors of 100% or greater. In contrast, watersheds entirely harvested more than six or seven years ago with low road densities tended to have much lower factors.

The amount of direct stream disturbance from forest harvesting activities was quantified on all the watersheds sampled. When the cut units on the watersheds were field inventoried, the presence or absence of a commercial or hardwood stream buffer was noted. When neither type of buffer strip was present, that length of stream was considered to be directly disturbed by logging activities. The amount of direct stream disturbance was expressed as a percent of the total stream length.

The streambed armor layer was sampled at each plot. Transects were made perpendicular to the flow at each cross section and a metal ring 9.2 cm in diameter was placed on the stream bed at regular intervals across the transect. All particles of the armor layer within or extending into the area of the ring were collected as long as they could be lifted off the top layer of the stream bed. Collection of rocks within the ring was stopped as soon as the only ones remaining were embedded and had to be dug out to be removed. The width of the sample intervals along the transect varied with the width of the channel to ensure that at least four ring samples were taken at each plot. The diameter of each rock was measured along the second longest axis. This axis was used for the measurement since it is usually the axis which prohibits a rock from passing a sieve in a particle size analysis.

The armor layer data was represented in two ways. The mean was calculated for all the diameters at each plot. Since some skewness of the data was indicated, a natural log transformation of the diameters was performed and another mean was calculated.

The channel stability rating was used to attempt to quantify the stability of the streambed and bank materials through a systematic inspection of the channel (Pfankuch, 1975). This rating was carried out on the segment of the stream enclosing all three sample plots and the reach of stream about 50 m beyond the plot furthest upstream.

Variables 23, 24, and 25, in Table 1 are all "dummy" variables that were included because field observations indicated that they might have an effect on the amount of fine sediment in the stream bed.

Basaltic rocks tend to weather much more slowly and form stream beds with high proportions of large stones. Streams having basalt present in the bed generally tended to have less fine sediment than those streams with beds composed entirely of sandstone rocks. This variable was assigned a value of one if basalt was present in the channel, and a value of zero if no basalt was present.

Deep seated large scale mass movements such as large scale slumps or earthflows seemed to be introducing bedrock material to the stream channel faster than the stream could break the material down and transport it. Streams cutting down through the toe of large slumps tended to have high proportions of large stones which tended to affect the particle size distribution of the bed material. If large mass movements were noted on a watershed, a value of one was assigned to this variable. If no indications of mass movements were observed, a value of zero was assigned.

All the private land holdings on the 21 watersheds that were sampled had been harvested. Compared to operations on Forest Service lands, road construction and timber harvest activities on private lands appeared to be carried out with much less attention given to environmental concerns. Thus, ownership of the watershed might affect the rates of erosion and sedimentation. This third dummy variable was assigned a value of one if over half of the watershed was held in private ownership by timber corporations. If the majority of the watershed was in Forest Service ownership, the variable was assigned a value of zero.

The index of uniformity is a measure of the uniformity of the particle size distribution of each sample. It is the ratio of D_{60} to D_{10} where these are the particle diameters having 60% and 10% by weight of the sample finer than the indicated size, respectively (Klingeman, 1971).

The fine sediment data for the 21 sample watersheds was analyzed in several ways. First, it was desireable to have only one dependent variable for use in the multiple linear regression analysis. The percentage of fine sediment less than 1.0 mm in diameter excluding the sample material greater than 50.8 mm was selected as the dependent variable. This criterion was selected for consistency with the time series data and all the other data that was collected during the study. For comparison, this measure of fine sediment was regressed against the four other measures of fines for all 67 samples.

The percent fines variable was also regressed against the two mean armor layer measurements and the index of uniformity. These independent variables represent different measures of bed composition. In addition, the mean value of percent fines for the three samples on each stream was calculated and used to quantify the variability in this parameter between streams in the Coast Range.

Multiple linear regressions of the percentage of fine sediments in the stream bed against the independent variables in Table 1 were carried out on three data sets: all 67 samples, the average values for the 21 watersheds, and the seven samples on Flynn Creek. Since the two armor layer measurements and the index of uniformity are also measures of bed composition, they were not included in this analysis. The regression analysis was performed in the REGRESS subsystem of the SIPS (Statistical Interactive Programming System) program. This program is bound to the CYBER 70/30 computer and the NOS control system at Oregon State University (Rowe et. al., 1976).

A backwards stepwise method of model selection was used in the analysis. This method of model selection was chosen over the forward stepwise method because it is better adapted to account for any interaction between any of the independent variables (Neter and Wasserman, 1974).

The models were not developed for predictive purposes. They were developed to quantitatively describe a set of data. It should be noted that the models are only appropriate for the frozen core sampling technique and are reliable only within the ranges that the independent variables took on during the sample collection.

Effects of Forest Harvesting on Streambed Composition

The study design for the sample collection on Green Creek was originally intended to be used for the evaluation of the impacts of forest harvesting activity on the composition of the stream bed. Unit number three of the Ryan Green '76 timber sale was scheduled to be cut in June of 1978. However, market conditions led to a delay in the harvest of this unit. The unit remained uncut throughout the duration of the study. However, the timber sale contract expires in December of 1979, so the unit will probably be harvested before then.

It should be noted that the Green Creek watershed is not an undisturbed drainage. Approximately 15 ha within the basin were harvested in 1955 before the land was acquired by the Forest Service. However, 24 years should be sufficient time for any increased erosion and sedimentation to return to background levels.

IV. RESULTS AND DISCUSSION

Evaluation of Field and Lab Techniques

Frozen Core Sampling Technique

Frozen core sampling of streambed materials offers several advantages over other methods. The frozen core represents an undisturbed section of the stream bed with the exception of a slight disturbance when the pipe is inserted into the gravel. Frozen core samples have been found to give more accurate measures of fine sediment content in gravel beds of known composition than other sampling techniques (Walkotten, 1976). The only other technique used extensively for sampling streambed composition involves inserting a metal cylinder into the bed and hand cleaning its contents. Fines remaining in suspension in the cylinder are siphoned off or removed with a plunger (McNeil and Ahnell, 1960). This method has been found to overestimate the amount of fine sediment in the bed (Jeff Cederholm, 1979. University of Washington, Personal communication).

The carbon dioxide technique for obtaining frozen cores has several advantages over the liquid nitrogen method. The CO_2 bottle may be mounted on a back pack for field portability. Six samples can be taken from a single bottle; one every five minutes if two probes are used. The frozen cores are relatively small, so there is little disturbance to the stream bed when the sample is taken. Carbon dioxide is relatively inexpensive (approximately $1.50 per sample) and easy to obtain.

There are several disadvantages to the carbon dioxide technique. A large amount of field equipment is required. Supply lines and nozzles plug occasionally and require constant maintenance. The frozen cores have a relatively high surface area per unit volume and might be more biased towards large particles than the nitrogen cores.

The liquid nitrogen cores are larger and would tend to be less susceptible to the spurious effects caused by larger particles. They represent a larger sample of the stream bed and would be desirable from a statistical standpoint if only one sample can be obtained in a gravel bed. The method is fairly simple and the equipment requires little maintenance.

The liquid nitrogen method has several disadvantages. The larger cores require heavy duty pipes and other equipment. This equipment and the ten liters of liquid nitrogen required for each core are bulky and less field portable than the carbon dioxide apparatus. Liquid nitrogen may be hard to obtain and is relatively expensive (approximately $8.00 to $10.00 per core).

Both methods require that safety precautions be taken by the field personnel. Liquid carbon dioxide is under extreme pressure and should be handled accordingly. Liquid nitrogen is extremely cold and can cause severe burns if it contacts the skin in large quantities.

Ten paired samples were taken on Needle Branch and Flynn Creek with the nitrogen and carbon dioxide methods and the means of the fine sediment and organic matter content for each method were compared (Table 2). There was no statistically significant difference (95% CL) in fine sediment or organic matter content in the paired samples taken at Needle Branch and Flynn Creek. If there was a significant bias towards the larger particles in the carbon dioxide cores compared to the liquid nitrogen cores, it would have probably shown up as significantly lower levels of fine sediment in the carbon dioxide samples.

Repeated Samples at the Same Spot

Twelve paired samples were obtained at Flynn Creek. After the first core was removed from the bed the probe was inserted into the original location and a second sample was then obtained (Table 3). There was no statistically significant difference (95% CL) in percent fines or percent organic matter between the first and second samples. The results of this experiment were rather surprising because it was hypothesized that after the first sample was extracted from the bed, the hole would fill in with fine sediment and the next sample would have higher levels of fines. All these samples were collected in Flynn Creek, which is characterized by a loose unconsolidated stream bed. Rather than filling only with fine sediment after the first sample was removed, the holes seemed to cave in on themselves and were filled with material representative of the surrounding bed. This fact would explain the absence of a change in fine sediment or organic

Table 2. Percent fine sediment and percent organic matter, by weight, for paired frozen core samples obtained with carbon dioxide and liquid nitrogen.

Sample Number	Percent Fines[a]		Percent Organics[b]	
	CO_2	N_2	CO_2	N_2
1	13.4	18.0	c	c
2	12.0	19.0	4.6	5.1
3	18.5	17.2	5.3	4.5
4	50.1	52.4	5.5	6.0
5	28.0	30.5	4.5	5.0
6	27.3	28.4	c	c
7	41.5	46.2	5.1	5.8
8	17.9	24.5	c	c
9	25.5	17.3	c	c
10	28.2	30.6	5.8	4.5
Mean	26.2	28.4	5.1	5.2

[a] Percent fines less than 1.0 mm, rocks larger than 50.8 mm excluded from the sample.

[b] Samples ashed at 550°C.

[c] Samples not analyzed for organic matter content.

Table 3. Percent fine sediment and percent organic matter, by weight, for paired samples from the same spot.

Sample Number	Percent Fines[a] first sample	Percent Fines[a] second sample	Percent Organics[b] first sample	Percent Organics[b] second sample
1	26.7	23.1	3.9	3.5
2	21.7	24.1	3.6	3.4
3	16.7	19.3	3.1	3.1
4	15.5	15.9	3.2	3.0
5	27.4	26.6	3.4	3.5
6	20.4	18.1	3.2	3.7
7	18.8	17.1	3.2	3.2
8	16.0	14.2	3.5	3.3
9	24.1	22.4	3.2	3.1
10	20.7	16.7	3.0	3.0
11	20.8	32.7	3.4	3.2
12	21.9	17.0	3.2	3.3
Mean	20.9	20.6	3.3	3.3

[a] Percent fines less than 1.0 mm, rocks larger than 50.8 mm excluded from the sample.

[b] Samples ashed at 310°C.

matter content in the second sample as compared with the first. Thus, a single stream riffle can apparently be sampled repeatedly with the carbon dioxide probe without significantly changing the composition of the bed. However, since this test was only conducted for two samples from the same spot, care was still taken during the time series data collection not to sample the same spot twice between period of gravel bed movement.

Percent Fine Sediment Criteria

The percentage (by weight) of fine sediment less than 1.0 mm in diameter excluding material greater than 50.8 mm from the sample was compared to other ways of measuring percent fines. The 67 liquid nitrogen frozen core samples were used for this comparison (Appendix A). The coded variables are shown in Table 4. The comparison with the other two variables that also excluded material greater than 50.8 mm from the sample resulted in the following regressions:

$$\text{F1EXC} = 1.07\,(\text{F8EXC}) + 0.44 \qquad r^2 = 0.98$$

$$\text{F1EXC} = 0.78\,(\text{F2EXC}) - 0.04 \qquad r^2 = 0.97$$

These regression equations are strongly linear as indexed by the high r^2 values. Apparently, within the range of 0.84 to 2.0 mm, any convenient sieve size chosen as the upper limit of fine sediment will give comparable results with any other size. The choice of 1.0 mm as the limit of fine sediment seems a logical one for this study because it has been used in other research studies and is a convenient sieve size.

Table 4. Codes for percent fines (by weight) variables.

Code	Description
F1EXC	Percent fines less than 1.0 mm, excluding rocks larger than 50.8 mm
F8EXC	Percent fines less than 0.84 mm, excluding rocks larger than 50.8 mm
F2EXC	Percent fines less than 2.0 mm, excluding rocks larger than 50.8 mm
F1INC	Percent fines less than 1.0 mm, including rocks larger than 50.8 mm
F2INC	Percent fines less than 2.0 mm, including rocks larger than 50.8 mm

F1EXC was also compared with the percent fines variables that included all rocks in the sample weight, regardless of their size:

$$F1EXC = 0.90\ (F1INC) + 3.71 \qquad r^2 = 0.95$$

$$F1EXC = 0.70\ (F2INC) + 3.79 \qquad r^2 = 0.93$$

The relationships are still strongly linear, although the r^2 values are slightly lower than those attained for the other two measures of fine sediment. All four of the regressions are statistically significant (95% CL). Over the large number of samples collected for this study, it seems to make little difference whether one includes or excludes large rocks when calculating percent fines. The vast majority of the samples had no rocks larger than 50.8 mm and there was no difference in the two criteria.

The difference between the value of percent fines variables including and excluding the 50.8 mm material, however, may be large for any given sample. The most extreme case in this study was sample 17, Appendix A, which had a F1INC of 7.1% and a F1EXC of 21.6%. The benefits gained in excluding large rocks from the particle size analysis will be discussed later. Unless specified otherwise herein, percent fines will be defined as the percentage by weight of sediment less than 1.0 mm in diameter in each sample after rocks larger than 50.8 mm in diameter have been excluded.

There appeared to be little correlation between F1EXC and the average armor layer diameter or the average log transformed armor layer diameter for each sample. The linear relationships had r^2 values of 0.20 and 0.19, respectively. However, the best r^2 was obtained for F1EXC versus the log transformed average armor layer diameter:

$$\text{F1EXC} = -8.73 \ln(\text{Armor layer average diameter}) + 27.88$$

$$r^2 = 0.32$$

This regression is statistically significant (95% CL) and may suggest that there is a relationship between the percentage of fine sediment in the bed and the mean armor layer diameter. However, there is too much scatter about the regression line to use measurements of the armor layer mean diameter to predict the percent fines in the bed.

The index of uniformity was not significantly associated with the percentage of fine sediments in the bed.

Exclusion of Sediment Greater than 50.8 mm in Diameter

An F-test was conducted to see if excluding the material greater than 50.8 mm in diameter from the samples would significantly reduce the variance in the measure of percent fines in the bed within a particular riffle area (Table 5). After a logarithmic transformation of the data, the variance was significantly (95% CL) reduced by excluding the larger material from the sample. The variance for the untransformed data was reduced from 12.95 to 7.46.

However, a complication arose in that excluding the larger material increased the variance in percent organic matter content from

Table 5. Percent fine sediment and percent organic matter, by weight, used to test the reduction in variance following exclusion of sediments larger than 50.8 mm.

Sample Number	Percent Fines[a,c] Including rocks > 50.8mm	Percent Fines[a,c] Excluding rocks > 50.8mm	Percent Organics[b,c] Including rocks > 50.8 mm	Percent Organics[b,c] Excluding rocks > 50.8mm
1	4.1	9.2	4.8	10.9
2	6.1	8.1	3.9	5.3
3	7.7	15.2	3.3	6.4
4	7.8	9.1	3.7	4.3
5	12.8	12.8	3.2	3.2
6	9.2	9.2	3.1	3.1
7	5.1	9.5	3.9	7.3
8	8.3	14.6	3.3	5.8
9	16.3	16.3	3.3	3.3
10	11.7	11.7	3.4	3.4
11	8.7	11.7	4.2	5.7
12	13.1	13.1	3.4	3.4
Mean	9.2	11.7	3.6	5.2
Variance	12.95	7.46	0.25	5.30
Standard Deviation	3.60	2.73	0.50	2.30

[a] Percent fines less than 1.0 mm.

[b] Samples ashed at 310°C.

[c] Data were normalized (log transform) before testing for the differences in variances.

0.25 to 5.30 for the 12 samples. This increase was statistically significant (95% CL). Since the primary objective of this study was to study fine sediments, it was decided to exclude particles larger than 50.8 mm from the sample for calculating percent fines and percent organic matter. It should be recognized that this procedure might reduce the accuracy of the estimated organic matter content in the samples.

Temperature for Organic Matter Analysis

Organic matter content was determined at 310°C and 550°C for 20 samples (Appendix D). The percent weight loss at 310°C in comparison to the cumulative percent weight loss at 550°C is illustrated by the following equation:

$$\text{Percent weight loss at } 310^{\circ}\text{C} = 1.01 \text{ (Percent weight loss at } 550^{\circ}\text{C)} + 2.34$$

$$r^2 = 0.92$$

The relationship is statistically significant (95% CL), strongly linear, and has a slope of one, which suggests that the two methods of organic matter determination differ by a constant amount, the value of the Y intercept. The mean difference between the organic matter content measured at the two temperatures is 2.36% $\pm$ 0.17% (95% CL). Therefore, we may conclude that burning the samples at 550°C rather than at 310°C adds another 2.2% to 2.5% (by weight) to the estimated organic matter content.

Percent Fine Sediment with Depth

The fine sediment content for the three depth strata of 0 to 10, 10 to 25, and 25 to 40 cm for the 59 liquid nitrogen samples is presented in Appendix E. Only 59 of the total 67 samples were used for this analysis. Some of the samples could not be used because they either did not freeze the surface of the stream bed sufficiently or they were sectioned at depths different than those listed above. The mean percent fines for the 59 samples for the 0 to 10, 10 to 25, and 25 to 40 cm strata were 17.5%, 22.3%, and 22.2%, respectively. An analysis of variance indicated a significant difference (95% CL) in at least one of the mean values of percent fines for the three depths. The mean value of 17.5% fines for the top strata is obviously much lower than the means for the other two layers. This difference in percent fines with depth was also observed in the field. Intergravel pore spaces show up as clean frozen water in the core just after it is removed from the stream bed. Large pores of frozen intergravel water were rarely observed in the lower sections of samples. The majority of clean pore space was usually in the top section of the cores.

These results are in direct contrast to conclusions drawn by other authors. Ringler (1970) reported that stratification of fine sediment with depth was observed in individual frozen cores, but that no overall trend was present. However, Garvin (1974) found that the vertical position in the bed was a significant factor affecting the amount of fine organic material intruded into that level within the stream bed. Presumably, fine sediment would behave similarly. Beschta and Jackson (1978) found that sand sized particles tended to accumulate near the surface of the gravel bed, rather than deeper in the bed.

The smaller amounts of fines in the surface of the bed documented in this study may be explained in several ways. If the fine sediments are evenly distributed throughout the gravel bed, the nitrogen core may be inefficient in sampling the bed surface. When the forzen core method was first used, it would sometimes fail to freeze the surface of the bed because intergravel water flow velocities near the surface were fast enough to continually warm the bed and prevent it from freezing to the pipe. However, early in the summer we found that an open ended cylinder, or "baffle can," pressed into the gravel surrounding the pipe would restrict the flow of water over and in the gravel bed and allow the surface of the bed to be frozen as effectively as the rest of the core. This technique was used on all the remaining samples and complete cores were attained in most cases. Since only complete cores were used in the analysis of the depth strata, any failure of the core to adequately sample the top of the bed can be ruled out as the cause of the lower amount of fine sediment near the surface of the bed.

The driving of the pipe into the stream bed may have caused some settling of the fines farther down in the bed. This disturbance of the bed and movement of fines accompanying the insertion of the probe has been noted by several authors (Beschta and Jackson, 1978; Wendling, 1978). Although fines were never observed to wash away from the bed or filter down into lower interstices when the pipe was driven into the bed, these processes might still have influenced the fine sediment content of the upper layer. In addition, it has been shown that the surface material in the gravel bed becomes progressively coarser as the bed forms on the falling limb of the hydrograph (Garde et. al., 1977). This coarse layer of material at the surface of the bed is the armor layer and is common to most gravel bedded streams (Milhous and Klingeman, 1971; Milhous, 1973). The relatively coarse armor layer particles would typically result in lower levels of fines near the surface of the bed.

Any of the above factors, singly or in combination, may have caused the stratification of fine sediment with depth as observed in this study.

Temporal Variability in Percent Fine Sediment

Alsea Watersheds

The occurrence of gravel bed movement on the eight sample plots located on the four Alsea watersheds is indexed by the channel cross-section measurements (Table 6). These measurements illustrate net changes in the bed form between points in time. It should be noted that the bed may have undergone repeated cycles of scour and fill between cross-section measurements.

Table 6. Incidence of gravel bed movement and net scour and fill as indexed by cross-section measurements on Needle, Deer, Flynn, and Meadow Creeks.[a]

	Storm Dates[b]			
Plot	11/19/78 12/ 1/78	12/ 5/78 12/11/78 12/25/78	1/11/79 2/ 7/79 2/10/79	2/18/79 2/28/79 3/ 5/79
Needle 1	o	o	+ -	+ -
Deer 1	+	o	+ -	+ -
Deer 2	-	-	+ -	o
Flynn 1	o	-	+ -	o
Flynn 2	o	o	+ -	o
Flynn 3	o	-	+ -	+ -
Flynn 4	o	o	+	o
Meadow 1	o	+ -	+ -	o

[a]A (+) indicates net fill, a (-) indicates net scour, a (+ -) indicates that the sample plot was scoured in places and filled in places, and a (o) indicates no measurable change.

[b]Storms are grouped as they occurred between sampling intervals.

Percent fines and percent organic matter in the bed for each sample plot (Appendix F) are plotted over time in conjunction with the Flynn Creek hydrograph record (Figures 4 through 11). The average percent fines in the bed for the seven low flow months of May through November of 1978 is plotted as solid line terminating in tic marks. Ninety-five percent confidence limits for these seven samples are plotted as dashed lines extending the length of the time axis in the graphs. Any deviation of points far outside these confidence limits is considered to be significant temporal variation in percent fines induced by high flow events.

Plot 1 on Needle Branch (figure 4) displays no deviation of the sample points outside the 95% confidence limits for the seven low flow samples before or after the plot was moved, even though bed movement was documented during the storms in February and March of 1979. The first location had much larger variations in the monthly samples of bed fines than the second, even though the two locations were separated by a distance of only 5 m.

Plot 1 on Deer Creek (Figure 5) shows definite seasonal variation in bed content and a flushing of fines by high flows. This plot was sampled under unusual circumstances that require explanation. Plot 1 was located about 3 m below a large log lying across the channel at about bankfull height. Storms in December 1977 and January 1978 piled a large amount of organic debris behind this log and created a debris jam. Bed sediments accumulated behind the jam and

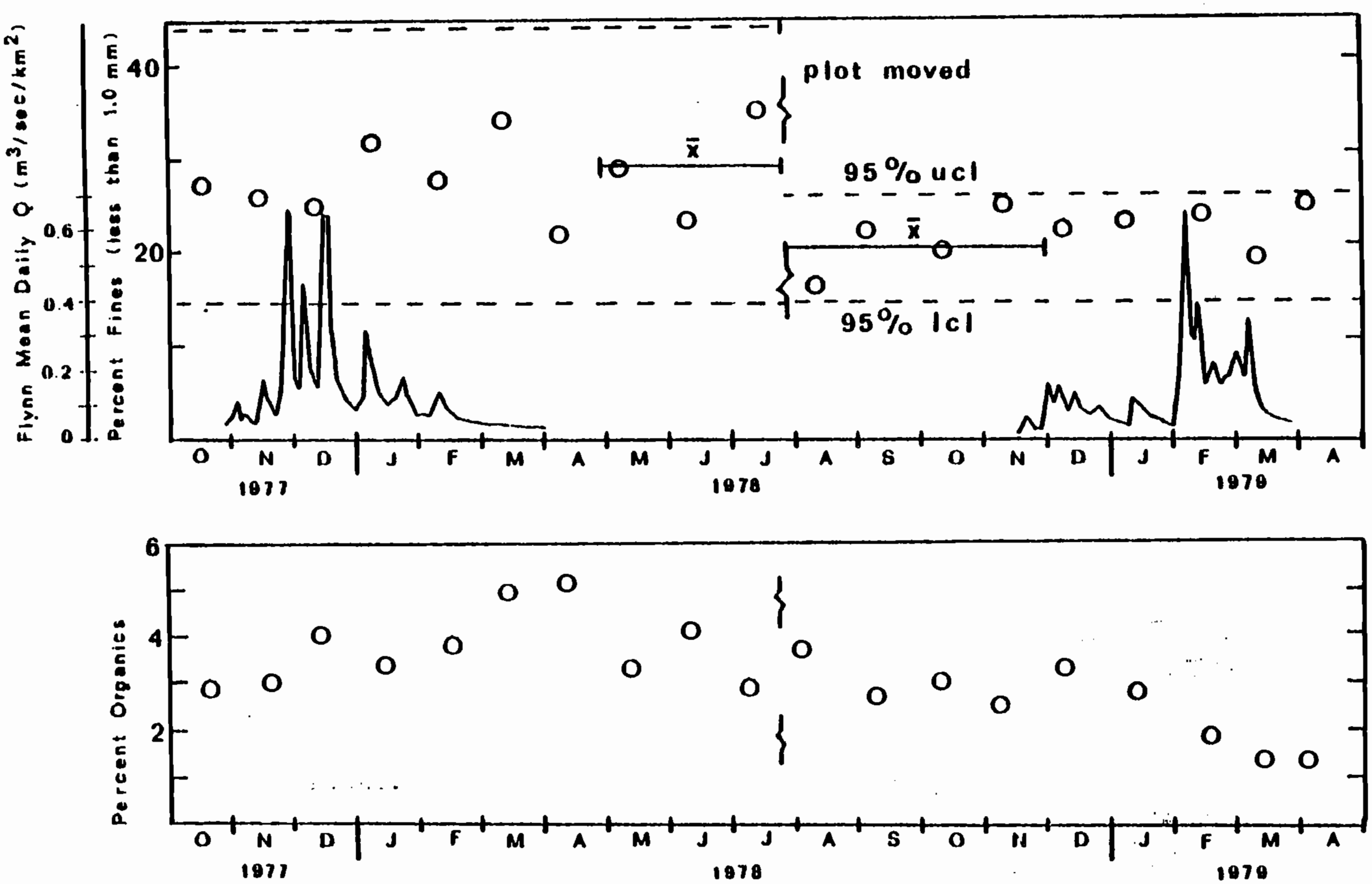

Figure 4. Time trends in percent fine sediment and percent organic matter, by weight, for Needle Branch Plot 1.

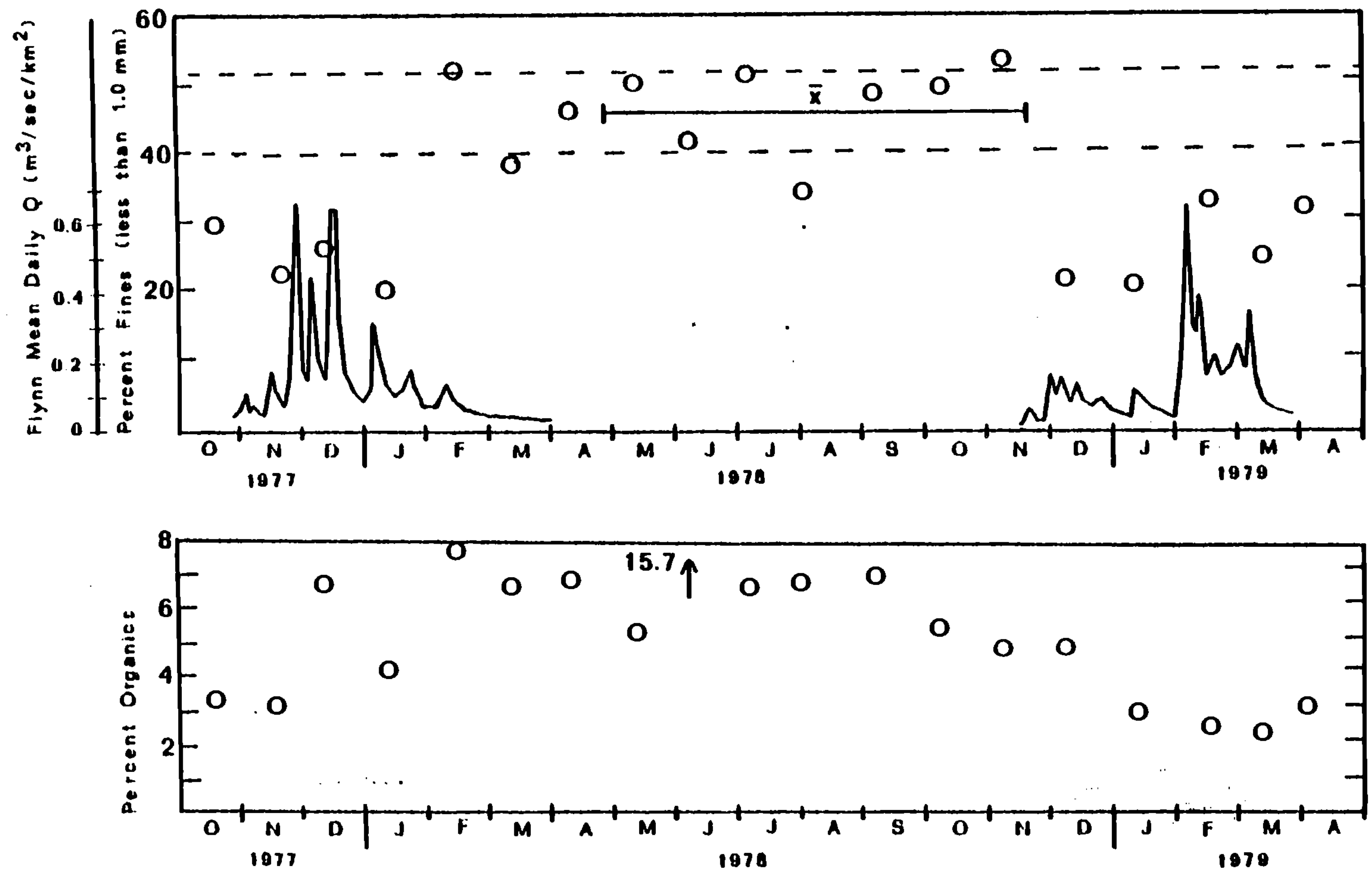

Figure 5. Time trends in percent fine sediment and percent organic matter, by weight, for Deer Creek Plot 1.

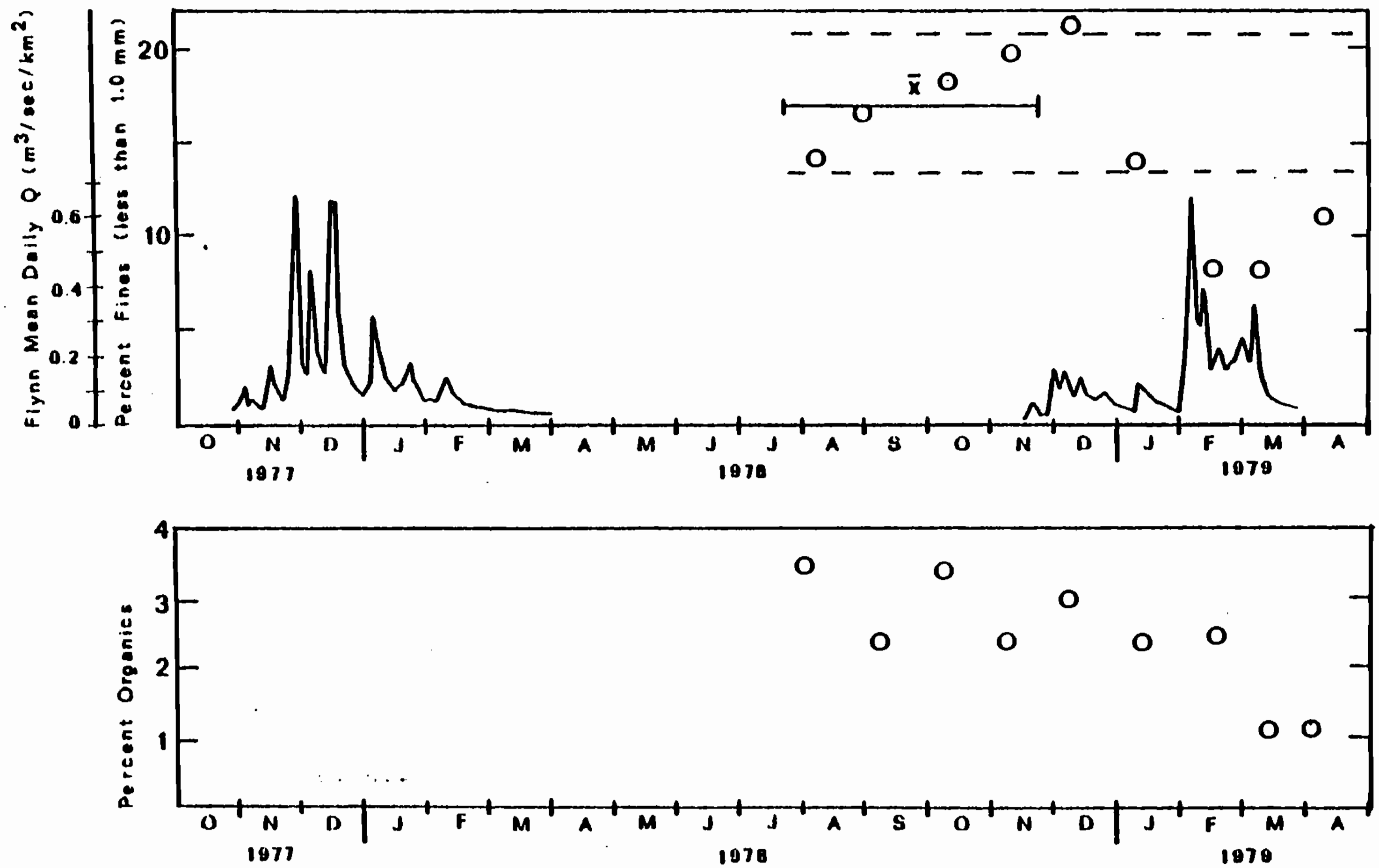

Figure 6. Time trends in percent fine sediment and percent organic matter, by weight, for Deer Creek Plot 2.

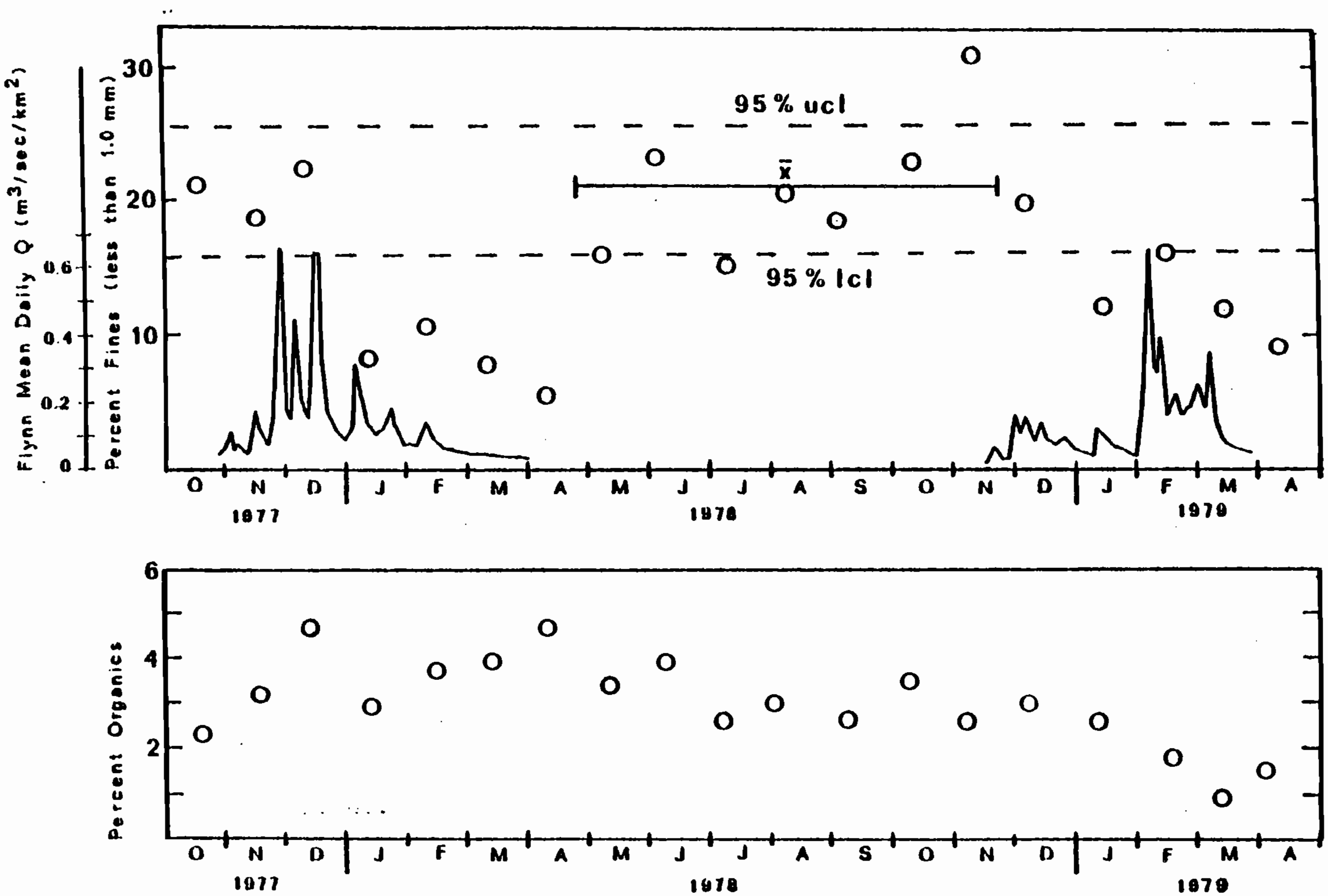

Figure 7. Time trends in percent fine sediment and percent organic matter, by weight, for Flynn Creek Plot 1.

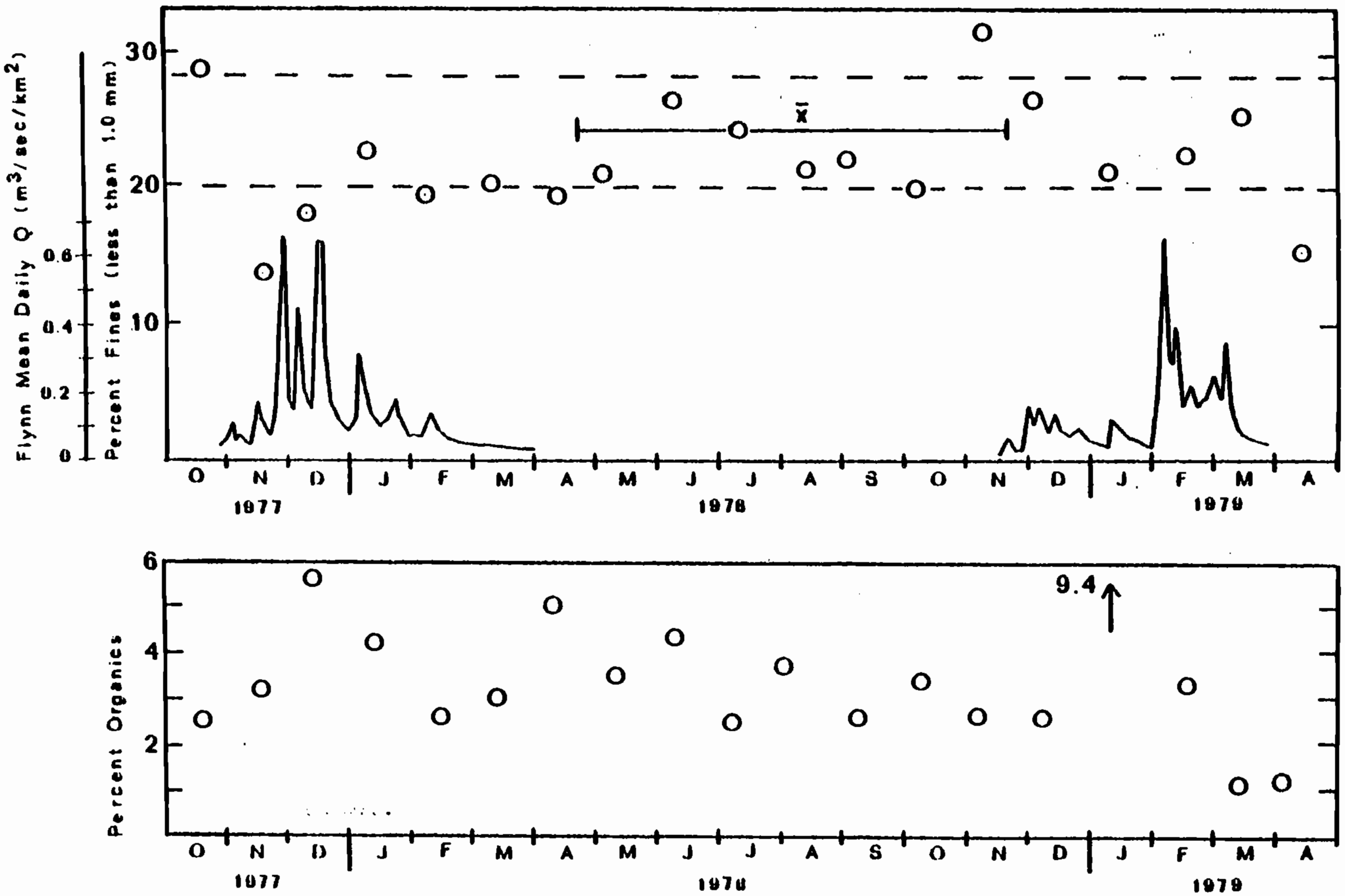

Figure 8. Time trends in percent fine sediment and percent organic matter, by weight, for Flynn Creek Plot 2.

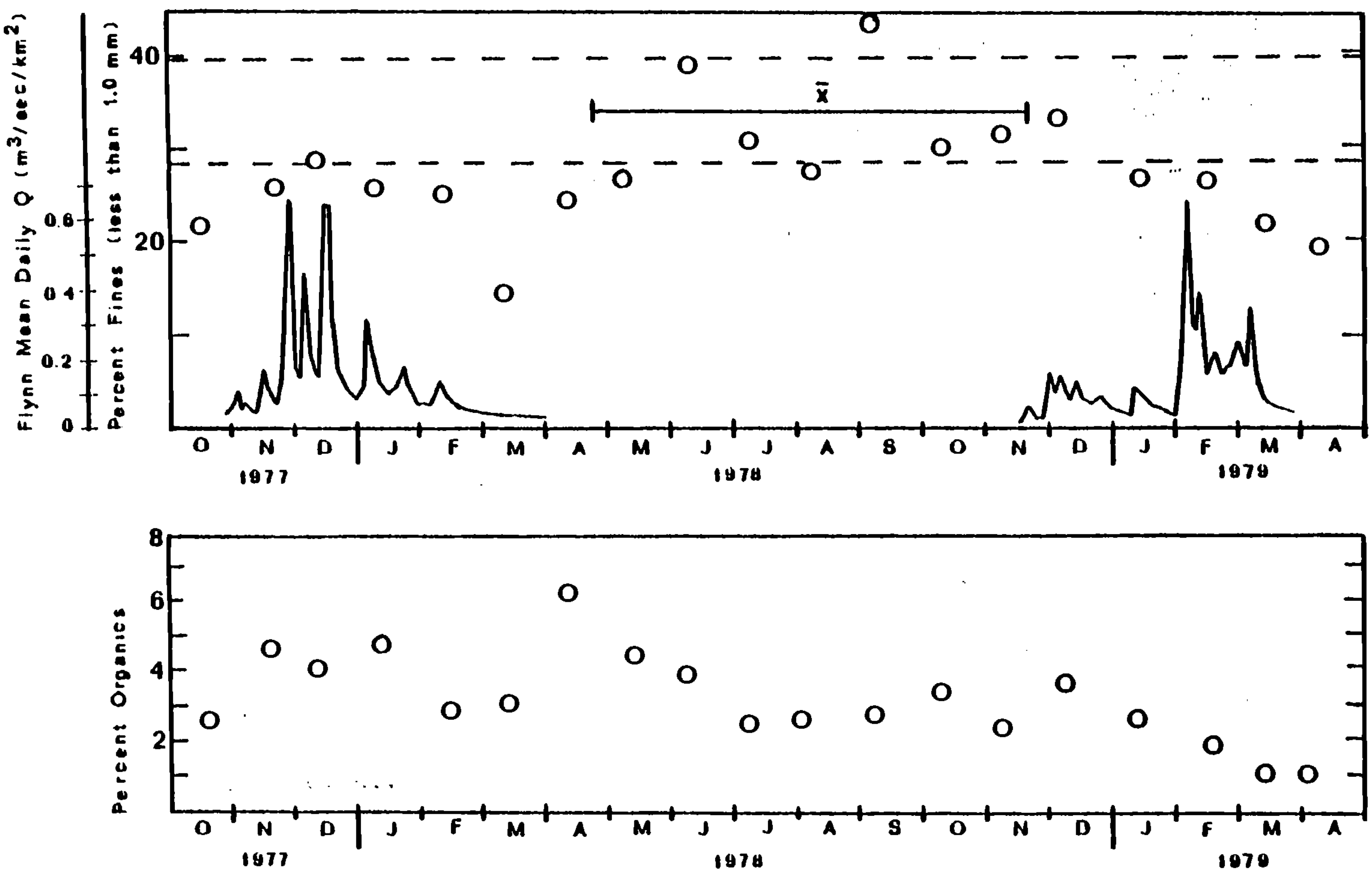

Figure 9. Time trends in percent fine sediment and percent organic matter, by weight, for Flynn Creek Plot 3.

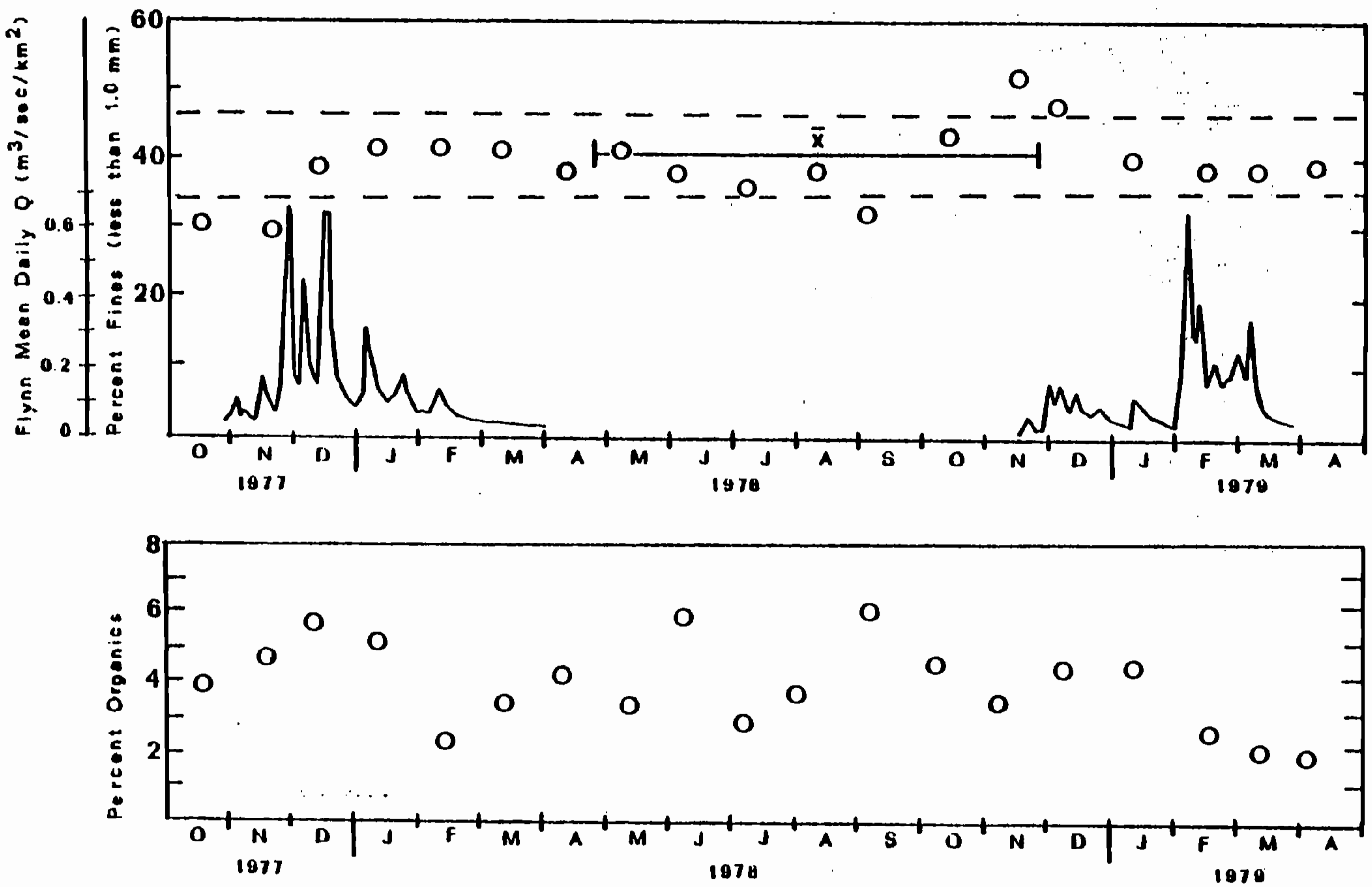

Figure 10. Time trends in percent fine sediment and percent organic matter, by weight, for Flynn Creek Plot 4.

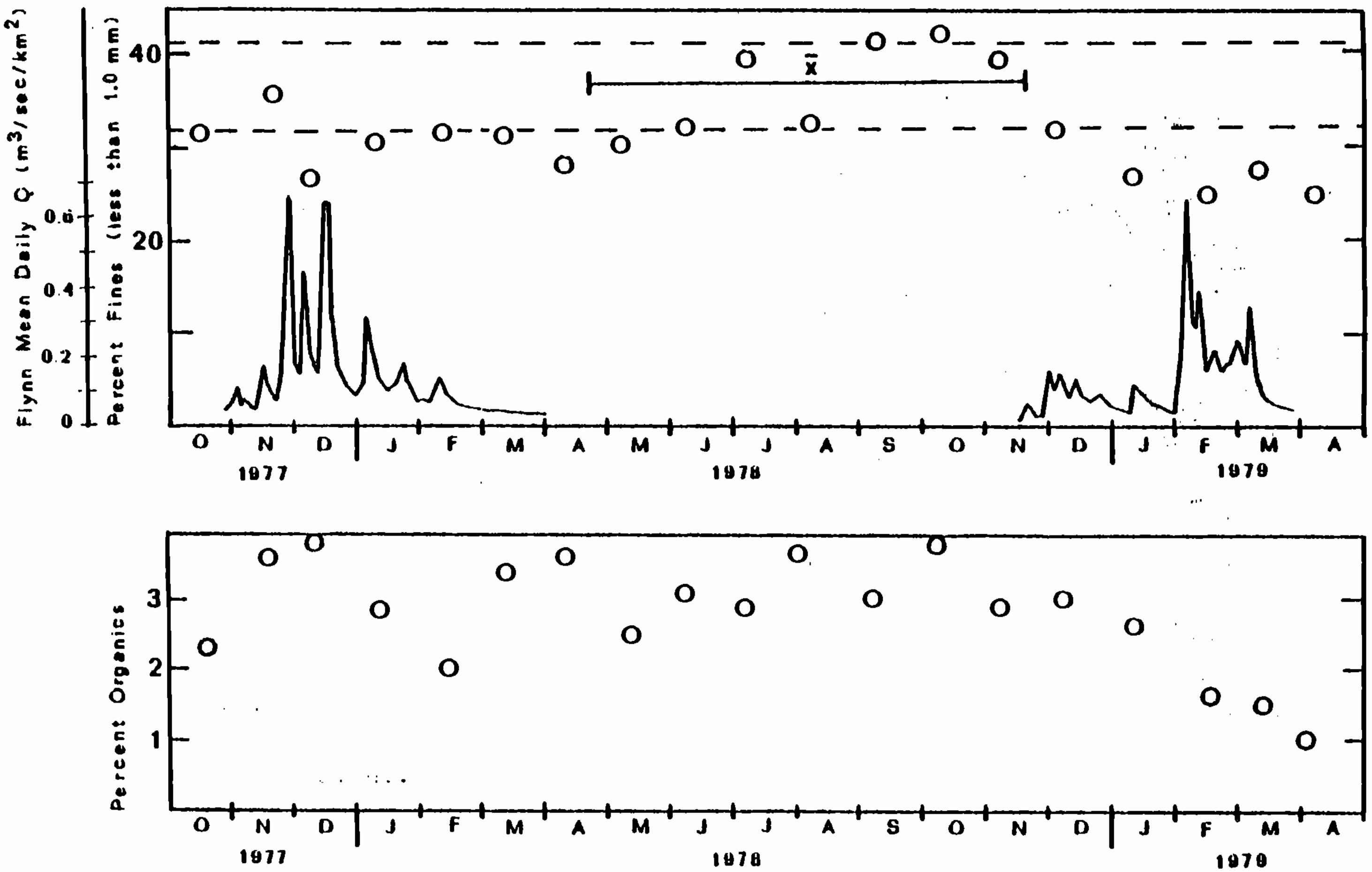

Figure 11. Time trends in percent fine sediment and percent organic matter, by weight, for Meadow Creek Plot 1.

the stream began to divert completely around the sample plot by undercutting a steep cut bank about 10 m high on the far side of one of the cross-section stakes. Since this shift of the channel was undesireable from a sampling standpoint, the debris jam was taken apart by hand and removed from the channel in late January 1978. The stream returned to its normal course through the sample plot, but some of the sediment previously stored behind the debris jam settled into the sample cross section and caused an abrupt increase in bed fines. The fines remained at the high level throughout the summer. These circumstances may not be considered to be completely natural occurrences at this sample plot. However, debris jams do naturally form and break, releasing stored sediment to downstream areas. This sequence of events should not be considered to be entirely artificial. The first few storms of the second winter effectively flushed the fines from this sample plot.

Plot 2 on Deer Creek (Figure 6) seems to exhibit some flushing of fines from the bed with the large storms in February 1979. There also seems to be a gradual increase in fine sediment content in the bed over the course of the summer low flow months.

Plot 1 on Flynn Creek (Figure 7) shows definite flushing of fines from the bed during both high flow seasons. A tree fell into the stream just upstream from the sample plot during the storm of December 15, 1977. The tree diverted the water flow into the bed and caused extensive scour and fill of gravel at this plot. Two large salmon were also observed spawning in this riffle the same month. The fine sediment content of the bed decreased to about half its previous value when it was sampled the next month. Fines seemed to accumulate in the bed at the end of the first winter and were flushed out again with the next storm season.

Plot 2 on Flynn Creek (Figure 8) shows some seasonal variation of fines in the bed. It seems the small storms in November of 1977 flushed fines from the bed and that the larger storms in late November and December 1977 redeposited fines in this plot.

Plot 3 on Flynn Creek (Figure 9) shows some weak indication that fines were flushed from the bed during both high flow seasons. Plot 1 on Meadow Creek (Figure 11) exhibits about the same degree of flushing as Plot 3.

Plot 4 on Flynn Creek (Figure 10) was located immediately upstream from the fish trap. Sampling of bedload transport was carried out at this structure during storm events. The vortex bedload sampler was installed in the summer of 1976 and boards to direct the flow into the concrete channel were placed in front of the fish trap at this time. Plot 4 was sampled twice before the Thanksgiving day storm of 1977, which was the first storm with significant amounts of bedload transport after the installation of the vortex tube. Cross-section measurements indicated that sediment deposited in the plot to a depth of about 10 cm during this storm. The percent fines increased from about 30% to 40% and remained at that high level until the bed was disturbed in

September of 1978. In another study, color coded marbles had been placed in the bed near this sample plot to document the occurrence of gravel bed movement. The bed was partially excavated in September 1978 to attempt to recover some of these marbles. This activity is thought to be the cause of the spurious measurements obtained in September, October, and November of 1978. In order to increase the efficiency of the vortex sampler, a 5 cm high board was placed at the end of the concrete channel in the fall of 1978 to reduce the velocity of flow through the trap. It essentially changed the base level of the stream by 5 cm. The storm of February 18, 1979 deposited another 3 cm of sediment at the plot and the fine sediment content of the bed again leveled off around 40%.

Green Creek

Gravel bed movement with high flows, as indexed by cross-section measurements on five sample plots (Table 7), was much less common on Green Creek than it was on the three other study streams. Although the discharges for the three streams expressed on a per unit area basis are about the same, there were much smaller volumes of flow in Green Creek than the other streams because of the smaller size of the watershed. These smaller volumes of flow are less efficient in initiating gravel bed movement than the flows on the other study streams.

The time series data for the five sample plots (Appendix G) are presented in Figures 12 through 16. The data are presented in essentially

Table 7. Incidence of gravel bed movement and net scour and fill as indexed by cross-section measurements on Green Creek.[a]

	Storm Dates[b]				
Plot	11/19/78	12/ 1/78 12/ 5/78 12/11/78	12/25/78 1/11/79	2/ 7/79 2/10/79 2/18/79	2/28/79 3/ 5/79
1	o	o	o	o	+ –
2	o	o	o	+ –	o
3	o	o	o	+ –	–
4	o	o	o	+ –	–
5	o	o	o	o	o

[a]A (+) indicates net fill, a (–) indicates net scour, a (+ –) indicates that the sample plot was scoured in places and filled in places, and a (o) indicates no measureable change.

[b]Storms are grouped as they occurred between sampling intervals.

the same manner as they were for the other streams with two exceptions. The peak discharges on Green Creek as estimated from the crest gage measurements are displayed in conjunction with the Flynn Creek hydrograph. Also, only the samples for the months of May through October could be used for the calculation of low flow means and confidence limits. The November 1978 samples were taken immediately after the first small freshet of the storm season and could not be included in the low flow data.

Plot 1 on Green Creek (Figure 12) displays some flushing of fine sediment with the storm in early March of 1979. This was the only storm to cause any change in the cross-section measurements at this plot.

Plot 2 (Figure 13) has weak indications of the flushing of fines with the February 1979 storm. Gravel bed movement was also documented to occur at this time.

Plot 3 (Figure 14) shows little or no sign of time trends in the fine sediment content of the bed even though bed movement was documented during the storms in February 1979.

Plot 4 (Figure 15) displays some weak trends in fine sediment content with time. It appears that the storm of November 19, 1979 may have caused intrusion of fines into the bed and that these fines were progressively flushed from the bed after this point in time.

Plot 5 (Figure 16) displays little or no flushing of fines with high flows, but it does seem to show signs of fines intruding during the storm of January 11, 1979.

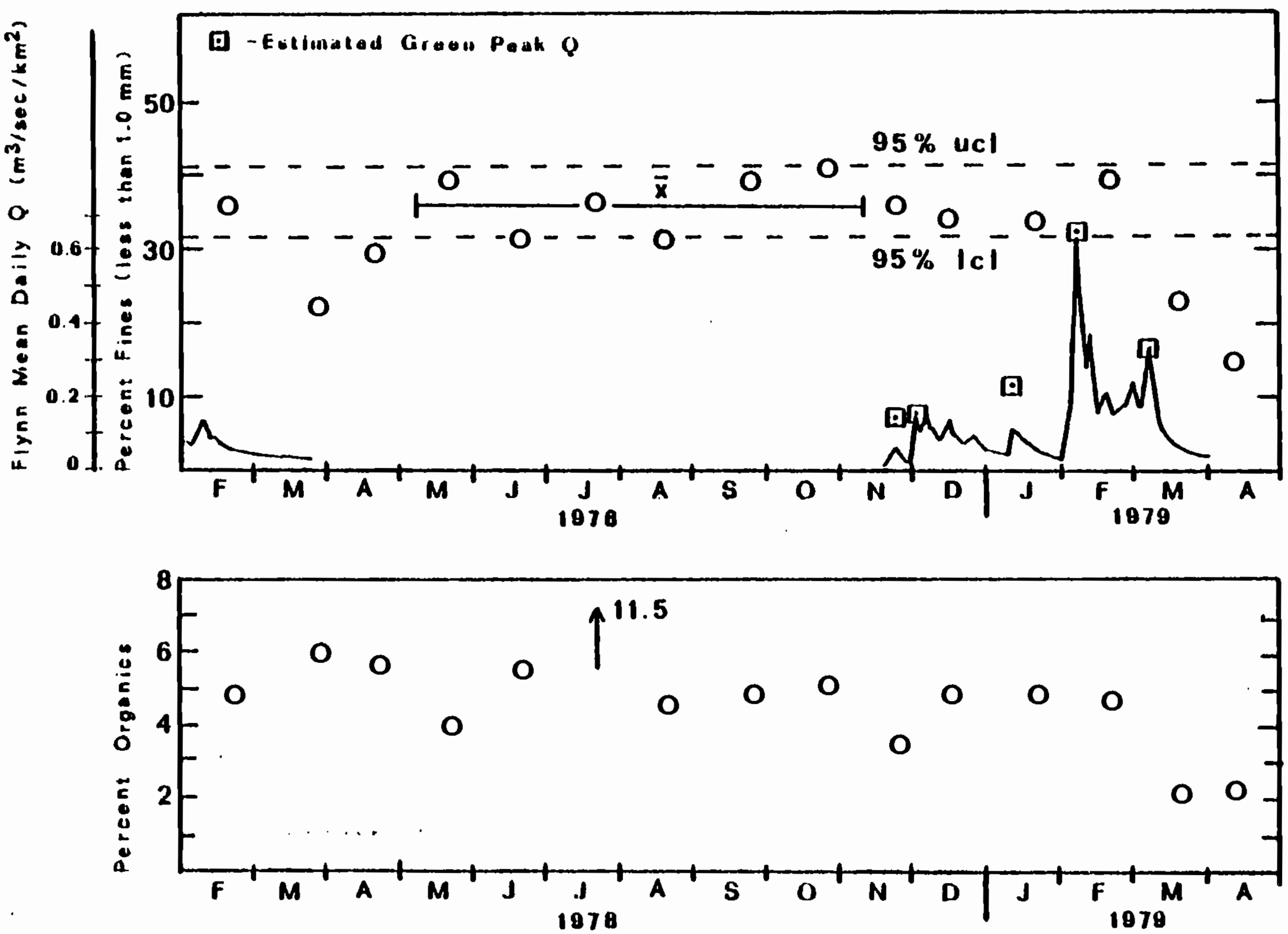

Figure 12. Time trends in percent fine sediment and percent organic matter, by weight, for Green Creek Plot 1.

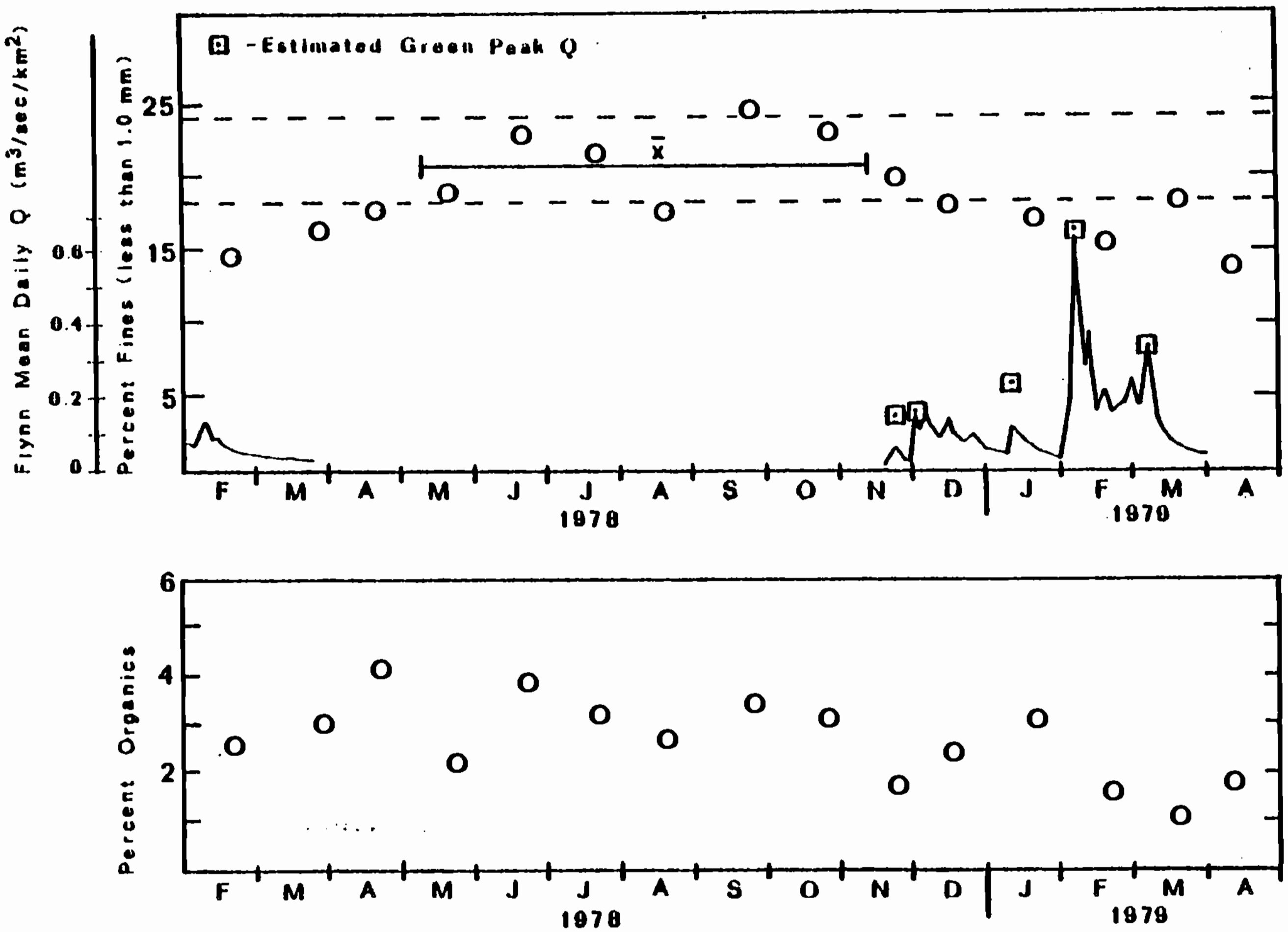

Figure 13. Time trends in percent fine sediment and percent organic matter, by weight, for Green Creek Plot 2.

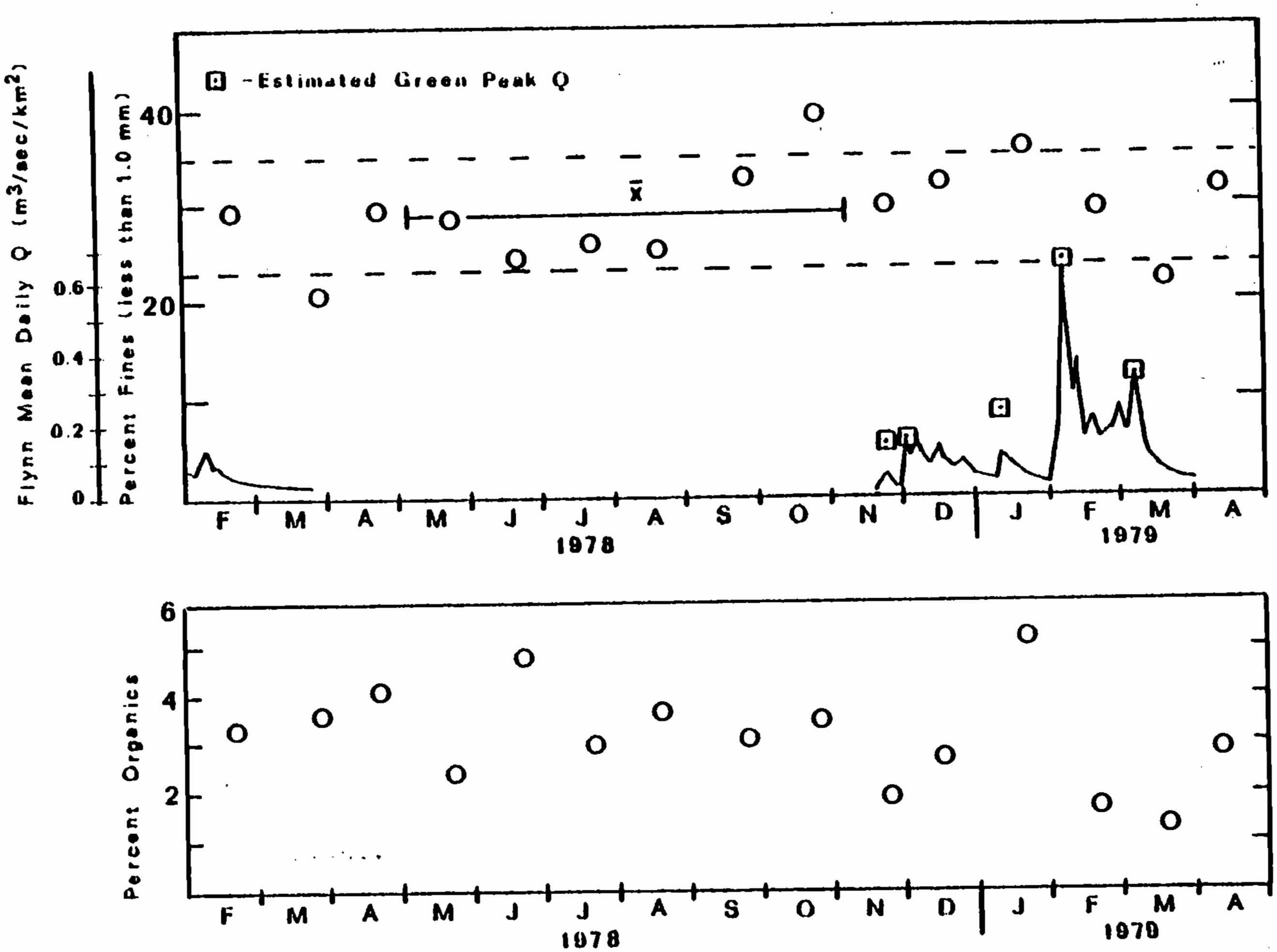

Figure 14. Time trends in percent fine sediment and percent organic matter, by weight, for Green Creek Plot 3.

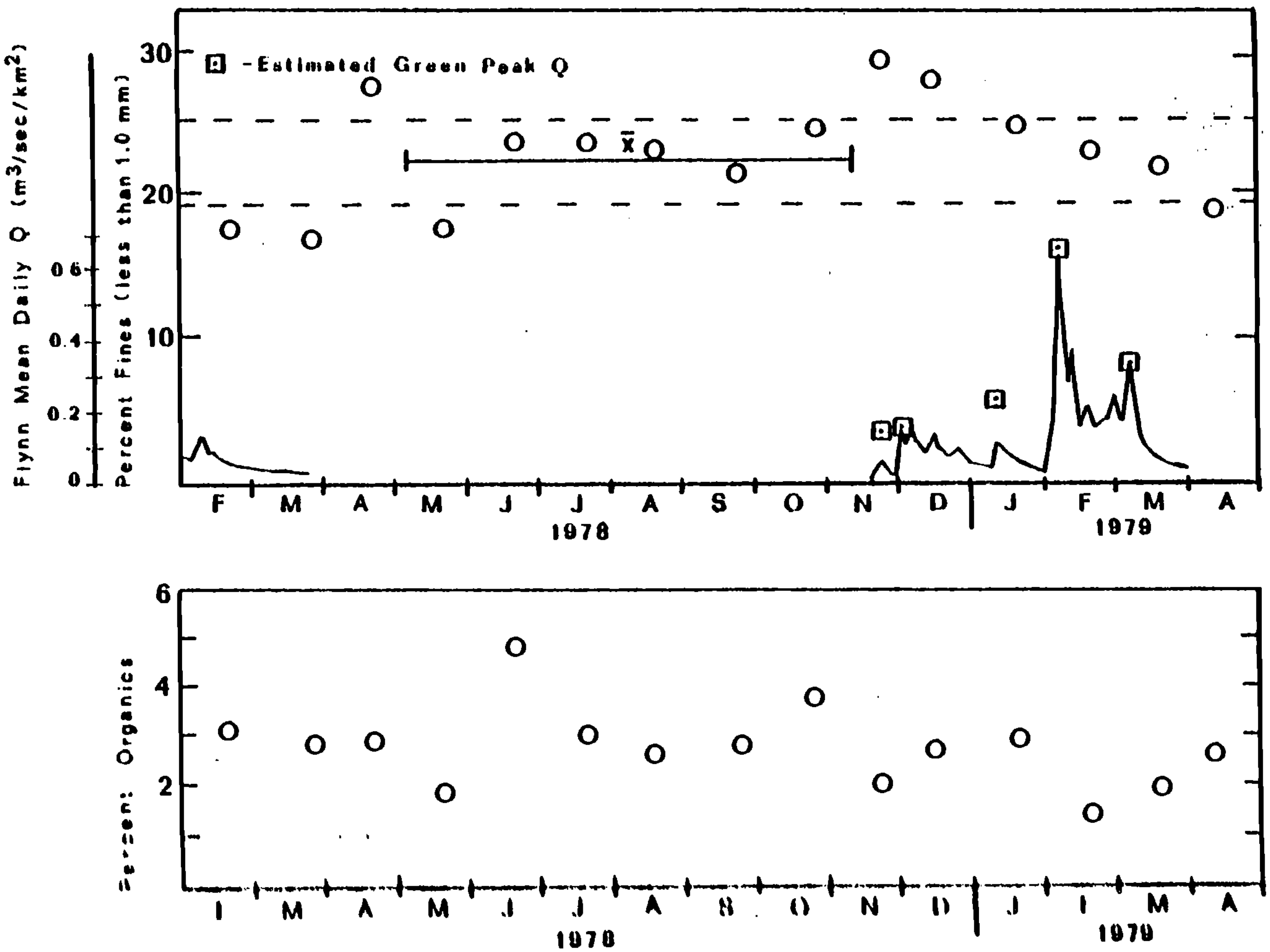

Figure 15. Time trends in percent fine sediment and percent organic matter, by weight, for Green Creek Plot 4.

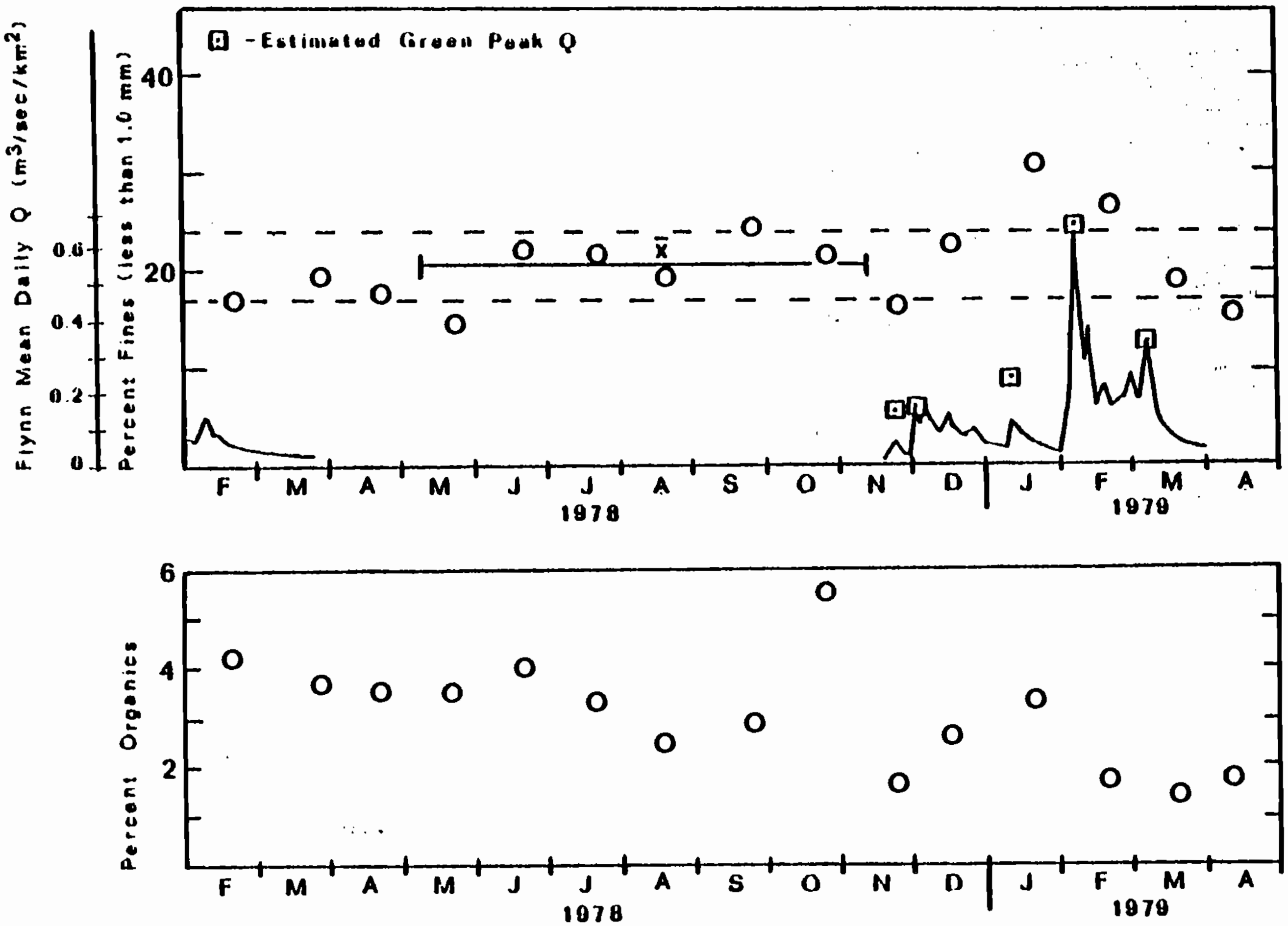

Figure 16. Time trends in percent fine sediment and percent organic matter, by weight, for Green Creek Plot 5.

Discussion

The time series data collected for this study seem to suggest that the flushing of fines during high flows is a random event that occurs in localized areas of the stream. The occurrence and movement of large organic debris also seems to play an important role in influencing the local flow conditions which, in turn, affect the movement of the bed and the flushing of fines.

By examining the interrelationships between the incidence of bed movement as indexed by cross-section measurements (Tables 6 and 7) and the time trends in bed fine sediment content (Figures 4 through 16), one must conclude that the bed must move for fines to be flushed from the gravel. In all cases where the flushing of fines was indicated by the times series data, bed movement was indicated by the cross-section measurements. However, the flushing of fines did not occur in all cases of gravel bed movement.

When one examines the time series graphs, it becomes apparent that the small storms are as effective, and sometimes more effective than the larger storms in flushing fine sediment from the gravel bed. This result was surprising in that the larger storms might be expected to be more efficient in flushing fines because they cause more gravel bed movement than the small storms. It appears, however, that the small storms may move the gravel and redeposit it with little subsequent intrusion of fines during the recession limb of the hydrograph since there are relatively small amounts of sediment in transport. The large storms probably cause larger amounts of bedload movement and redeposition, but they also have large amounts of fines in transport.

Some of the sample plots (eg. Figures 5, 7, 9, and 13) show trends of increasing fine sediment content at the end of the high flow season and even on through the summer (Figures 6 and 10). These trends are difficult to explain, but two possible explanations are offered. Fine sands and smaller material can be observed moving along the stream bed long after a storm event. This material might continue to slowly intrude into the bed for periods of up to two weeks following a freshet. This slow intrusion process may be the reason for the increasing levels of bed fines at the end of the first high flow season. Some of the plots show increasing levels of fines throughout the summer low flow months. Plot 2 on Deer Creek is a prime example of this phenomenon. The trends may be an artificial effect of the variation resulting from the sample technique since all the summer trends are well within the variance induced by sampling alone. It may also be possible that the sandstone rocks weather in place and slowly increase the level of fines as measured over time. The sandstone rocks are typically incompetent and friable. Rocks breaking apart and crumbling in place were often observed on the surface of stream beds during summer low flow months. Dry ravel from the stream banks during the summer months may also be a source of sediment that may be deposited in the gravel bed. These processes might tend to cause a continual change in gravel bed composition during the summer low flow period.

The time series data indicate that the percentage of fine sediment in stream gravel beds is variable in time. This variability needs to be recognized and taken into account in any sampling program. If percent fines in the gravel is to be used as a stream quality criterion, the time of sampling becomes an important consideration. It is suggested that streambed composition be monitored over time and that special emphasis be placed on sampling immediately after storm events. If a stream can only be sampled once, it should be sampled during the low flow period since bed composition is relatively stable during this time. However, if percent fines in the gravel is being used to index the stream quality as a fishery resource, it should be recognized that summer measurements of bed composition may have little bearing on bed composition during the winter high flow months when the anadromous fish eggs are in the gravel.

Temporal Variability in Percent Organic Matter

Percent organic matter content by weight was generally between two and eight percent on all the sample plots. There were occasional outliers in the data, which are represented by arrows pointing beyond the limits of the figure. These outliers were samples that included large sticks that had become trapped in the bed and were left off the graphs to allow for the resolution of the smaller values. There does seem to be a very general trend in that the percent organic matter in most of the sample plots tends to decrease over the course of the summer and through the winter of 1978-79.

The small cores obtained with the carbon dioxide probe may not be large enough samples of the bed for accurately estimating the bed organic matter content. It has also been noted that the exclusion of rocks larger than 50.8 mm in diameter from the samples increased the variance of percent organic matter. Even though samples containing these large rocks were rare, this still may have been a source of variation. Also, the oven in which the samples were ashed was difficult to regulate accurately. Oven temperatures began to deteriorate in September of 1978 and might have caused the general trend in decreasing organic matter content in the samples after this point in time. All these factors, and the possibility that bed organic matter content is naturally highly variable, might explain the large amount of variation and the absence of pronounced seasonal trends in the organic matter data.

Relationship Between Percent Fine Sediment and Organic Matter Content

Several authors have reported strong linear relationships between fine sediment and organic matter content in gravel bed samples. Ringler (1970) reported that the percent organic matter by weight in his samples was directly related to the percentage of fine sediment by weight less than 3.33 mm in diameter ($r^2 = 0.56$). Martin (1976) reported a strong positive correlation between the percentage of fines by weight less than 0.25 mm in diameter and the amount of organics in bed samples.

The relationship between percent fines and percent organics for the time series data was determined after stratifying the data into several groups. Percent organics was regressed against percent fines for the four Alsea watershed study streams for the low flow months of May through September of 1978. A sample from Plot 1 on Deer Creek (June 4, 1978) and another from Plot 2 on Flynn Creek (January 9, 1979) were excluded since they were extreme outliers because they contained large sticks. The resultant relationship is illustrated in Figure 17. Utilizing all the data for the four Alsea watershed study streams resulted in the following relationship:

$$\text{Percent organics} = 0.050\ (\text{Percent fines}) + 1.92 \qquad r^2 = 0.16$$

Again, the same two outliers were excluded from the analysis.

The data on Green Creek for the same five summer months was analyzed in the same manner (Figure 18). An outlier collected in July of 1978 on Plot 1 was excluded from the analysis. Using all the data collected on Green Creek, with the exception of the one outlier, the relationship took the form below.

$$\text{Percent organics} = 0.081\ (\text{Percent fines}) + 1.21 \qquad r^2 = 0.23$$

The above regressions and those in Figures 17 and 18 are significant

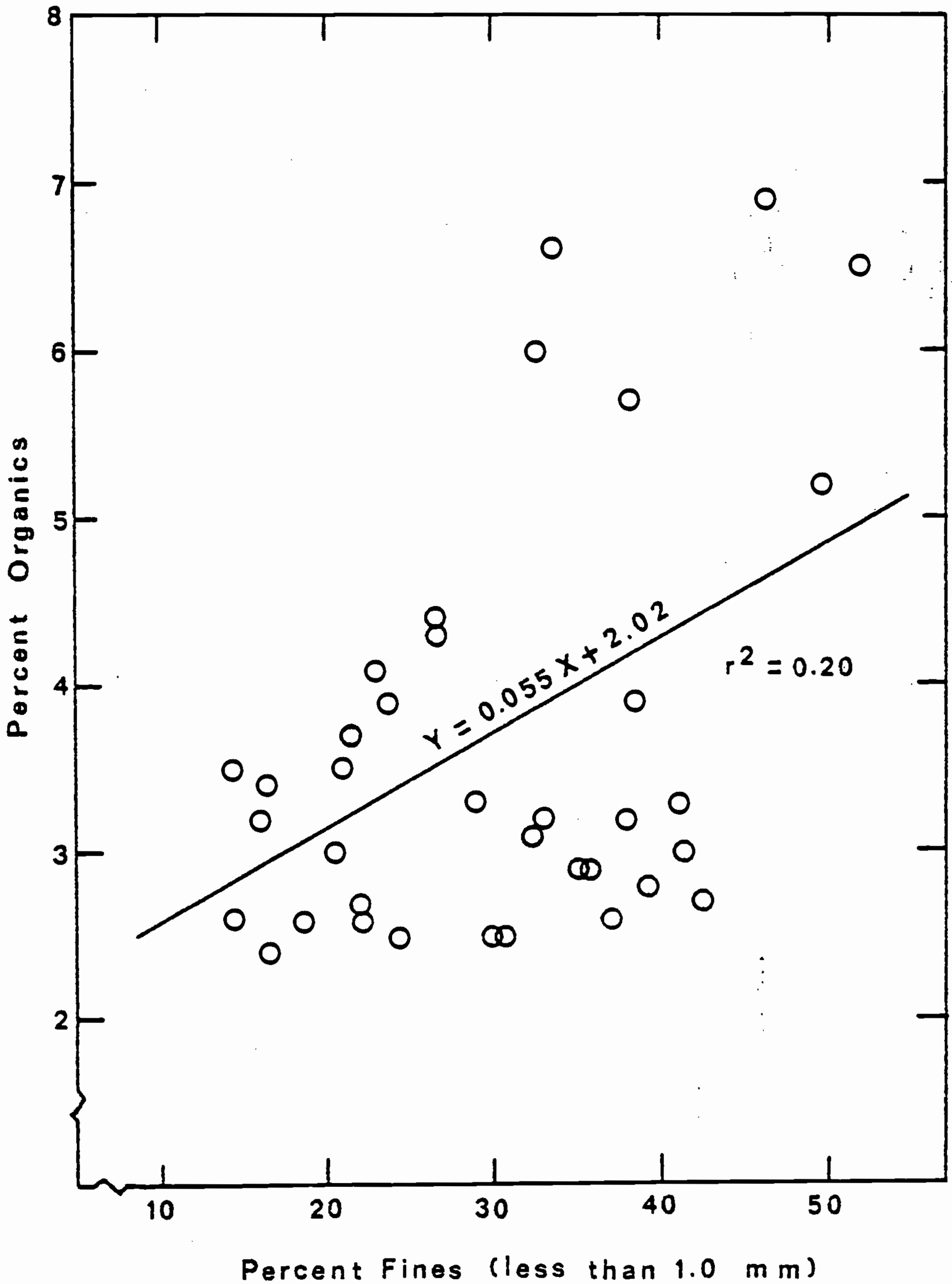

Figure 17. Percent organic matter versus percent fine sediment, by weight, for Alsea watershed streambed samples collected May through September, 1978.

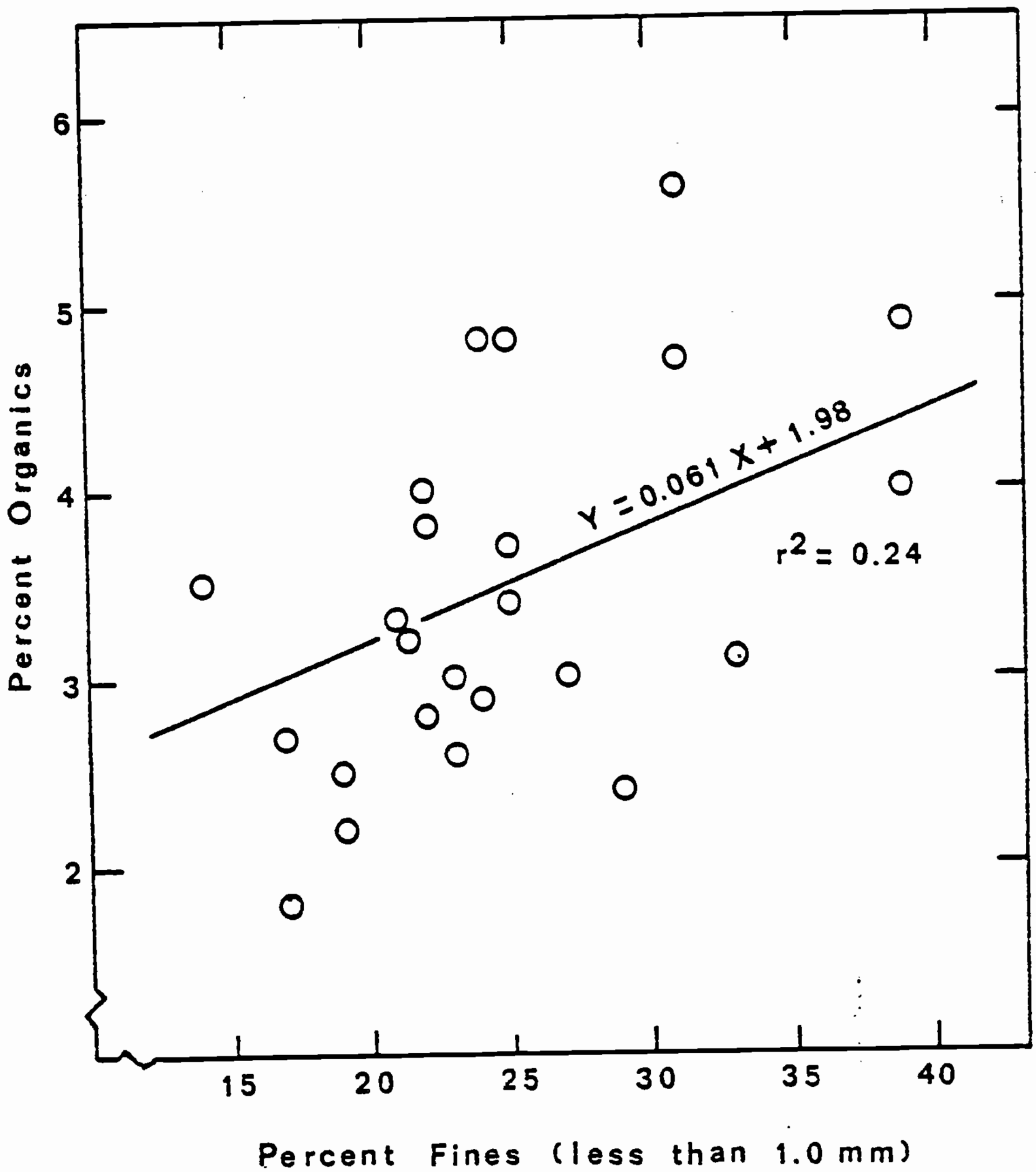

Figure 18. Percent organic matter versus percent fine sediment, by weight, for Green Creek streambed samples collected May through September, 1978.

(95% CL). However, the r^2 values are low, indicating large amounts of scatter about the regression lines. The persistence of statistical significance for the four regressions and the fact that the coefficients for the regression equations are remarkably similar suggest that there is a positive relationship between fine sediment and organic matter content in the gravel bed, albeit a weak one. The fact that Ringler (1970) and Martin (1976) found similar relationship fortifies this conclusion.

These results suggest that riffle areas with large amounts of fine sediment in the bed might also have large amounts of deposited organic material and relatively low intergravel dissolved oxygen levels. This two pronged effect of increased biochemical oxygen demands due to increased organics and low rates of intergravel flow due to increased fines could have an important effect on egg and alevin survival within the gravel bed.

Spatial Variability in Percent Fine Sediment

Variation Between Streams

The mean percent fines less than 1.0 mm for the 21 watersheds sampled in the Coast Range during the summer of 1978 was 19.4%. Percent fines had a standard deviation of 8.3% and ranged from a low of 10.6% to a high of 49.3%. The two totally undisturbed watersheds (samples 1 and 7, Appendix B) had average percent fines of 29.4% and

18.7%. The undisturbed Flynn Creek watershed had the second highest level of percent fines of all the watersheds sampled. The three watersheds that were uncut and only slightly disturbed by ridge roads had average percent fines of 10.6%, 14.0%, and 13.3% (samples 4, 5, and 6, Appendix B).

Comparisons were also made between the five time series study streams. Averages were calculated for all the time series data and for the nitrogen samples, if available (Table 8). No statistical comparisons were made between the streams due to the differences in sample sizes and sampling methods at each creek. Needle Branch and Meadow Creek (Table 8) are represented by only one sample plot in the time series data. Large differences exist in the bed composition between the streams in both the time series data and the watershed data collected during the summer months.

Variation Between Locations Within a Stream

Streambed fine sediment content also varys spatially with a single stream. This in-stream spatial variability was the reason for the collection of three bed samples in each of the streams sampled for the watershed data. It was hoped that the three samples were sufficient to characterize the average bed composition in the 21 sample streams.

The spatial variability of percent fines within a given stream was determined by comparing sample plot means for the time series data (Table 9). These plot averages were compared for both the summer low

Table 8. Average percent fine sediment less than 1.0 mm (by weight) for reaches of five study streams.

	Time Series		Watershed Samples	
	Percent Fines	n	Percent Fines	n
Needle Branch	24.7	19	12.9	3
Deer Creek	29.2	28	16.4	3
Flynn Creek	22.1[a]	57	29.4[b]	6
Meadow Creek	32.1	19	-	-
Green Creek	24.7	75	-	-

[a] Plot number 4 on Flynn Creek was excluded because it was under the ponding influence of the fish trap and the bed composition at this plot is not considered to be representative of the stream as a whole.

[b] Sample number 1 on Flynn Creek (Sample 1, Appendix A) was excluded for the same reasons as above.

Table 9. Average percent fine sediment (by weight) less than 1.0 mm for sample plots, time series data.

Plot	All data		Low flow data[a]	
	Average	n	Average	n
Needle 1	24.7	19	24.1	7
Deer 1	36.1	19	46.1	7
Deer 2	14.7	9	17.3	4
Flynn 1	16.4	19	21.2	7
Flynn 2	22.0	19	23.9	7
Flynn 3	27.9	19	34.0	7
Flynn 4	39.4	19	40.2	7
Meadow 1	32.1	19	36.8	7
Green 1	32.6	15	36.5	6
Green 2	18.6	15	21.3	6
Green 3	29.1	15	29.6	6
Green 4	22.7	15	22.3	6
Green 5	20.5	15	20.4	6

[a]For Needle, Deer, Flynn, and Meadow Creeks, low flow data was taken from May through November, 1978. For Green Creek, low flow data was taken from May through October, 1978.

flow data and all the data for each plot. Statistical tests for the difference in the means between plots on the same stream were conducted (95% CL).

There were significant differences in percent fines between plots 1 and 2 on Deer Creek for both the low flow and total data sets, even though the two plots are separated by a distance of only 10 m. The average percent fines for these two plots, using all the data, are 14.7% and 36.1%. Approximately three-fourths of all the other comparisons made between sample plot means on the same stream indicated significant differences in percent fine sediment content in the beds (95% CL). This spacial variability may occur over a very small area within the stream, as documented by the differences in the two plots on Deer Creek.

As a result of the large spatial variability in percent fines within a channel, a large number of samples may be needed to adequately characterize the bed composition of a stream. If percent fines in the gravel is to be used as a stream quality criterion, specific sampling designs will have to be implemented if reliable measurements are to be obtained.

Variation Within a Riffle

The percent fines and percent organics for 16 samples obtained at a single riffle in Flynn Creek are shown in Table 10. There are statistically significant (95% CL) changes in bed composition in that the

Table 10. Percent fine sediment less than 1.0 mm and percent organic matter, by weight, for a 1.44 m^2 riffle at Flynn Creek.[a,b]

Rows	Columns 1	2	3	4	Row Averages
1 Percent Fines	26.7	21.7	16.7	15.5	20.2
Percent Organics	3.9	3.6	3.1	3.2	3.5
2 Percent Fines	27.4	20.4	18.8	16.0	20.7
Percent Organics	3.4	3.2	3.2	3.5	3.3
3 Percent Fines	32.7	23.7	21.8	18.6	24.2
Percent Organics	3.2	3.2	3.3	3.2	3.2
4 Percent Fines	31.7	23.9	23.3	16.1	23.8
Percent Organics	3.6	3.4	3.1	3.0	3.3
Column Averages					
Percent Fines	29.6	22.4	20.2	16.6	
Percent Organics	3.5	3.4	3.2	3.2	

[a] Columns represent locations across the stream whereas rows represent locations in a downstream direction.

[b] Samples ashed at 350°C for organic matter analysis.

percentage of fine sediment increases slightly in the direction of the flow and there is an even greater increase perpendicular to the direction of flow. No significant changes in organic matter content occurred in either the rows or columns.

It is doubtful that the same trend in percent fines would be detected in all other riffles at Flynn Creek. Time limitations allowed for intensive sampling of only one riffle. However, this analysis does indicate that there may be significant differences in percent fines even within a particular spawning riffle. This third type of spatial variability further complicates sampling design. When only one sample was obtained at a given stream reach, the sample was taken in the center of the stream. This procedure was used for the collection of liquid nitrogen cores on the 21 sample streams.

During the collection of times series samples, the two samples on each plot were taken either from the middle of the bed or one sample from each side of the bed. Similarly, both samples were taken at the cross-section tape, or one upstream and one downstream from the tape. Hopefully, this spatial staggering of the frozen cores would balance any systematic changes in percent fines within a sample plot.

Discussion

Between stream, within stream, and within riffle variations in percent fines create problems in characterizing the composition of a stream bed. If possible, several samples should be taken within each riffle area. This high amount of natural variability might be used as an argument against the use of percent fines in the gravel as a stream quality criterion.

The causes of these three types of spatial variability are speculative. Between streams in the Coast Range, it would seem that differences in erosion rates and sediment delivery, the size and composition of gravel substrate and fine sediments, and the hydraulic conditions of streamflow might cause differences in percent fines. For a given stream, differences in gravel substrate composition and hydraulic conditions of streamflow might be the major causes of variability in bed composition. It is also possible that the amount and size composition of fines in transport might change over a relatively short reach of channel. Within a single stream riffle area, it would seem that the changes in the hydraulic conditions of flow across the riffle would be the primary source of variation in bed composition. It might also be expected that the bed substrate and rates of sediment transport might vary across a given riffle area and cause changes in the amount of fine sediment in the gravel. For example, when sampling bedload transport during high flows with Helley-Smith hand-held bedload samplers, it was noticed that the rates of transport of fine sands was highly variable across the stream cross section (Bill Jackson, 1979. School of Forestry, Corvallis, Oregon, Personal communication). Transport of these sands was often concentrated in one or two areas of the stream bed. This concentration of sediment transport in certain lateral segments of the stream may be a major factor contributing to the variation of fine sediment content within a riffle area.

Factors Affecting Gravel Bed Composition

At least three liquid nitrogen frozen cores were obtained on each of the 21 Coast Range streams sampled during the summer of 1978. The cores were taken to a depth of about 40 cm and were stratified by depth. The fine sediment content in each sample was determined for each depth strata, but only the top 25 cm of the bed is considered in this analysis. A sample depth of 25 cm was chosen for consistency with the time series data and the fact that this is the approximate depth to which anadromous fish deposit their eggs.

Three analyses were performed with these data. The first used all 67 individual samples. The second analysis used averages for the dependent and independent variables collected on each of the three stream sample plots. Finally, the seven samples collected on Flynn Creek were analyzed.

Multiple linear regressions were used to model the percent fines in the stream bed as a function of several independent variables. A model was chosen for each data set by examining the multiple coefficients of determination and the significance of both the overall regression and independent variables. When the final model was chosen, scattergrams of percent fines versus the independent variables were investigated to see if linear relationships existed and if all the assumptions necessary for the development of the model were met. Also, residual plots for each independent variable were examined to see if any transformations were appropriate. In all cases, the assumptions of normality and linearity were met and no data transformations were needed. Analysis of variance tables for each model are in Appendix H.

Model 1 - Individual Sample Plots

The 67 individual samples (Appendix A) were used to develop the first model. The independent variables are listed in order of decreasing significance:

			t-value
Percent Fines =	53.04	(Constant, %)	9.43
	-1.38	(Average watershed slope, %)	-7.72
	+0.03	(Watershed area, ha)	3.73
(1)	+0.24	(Percent Area Time Factor, %)	3.32
	-9.05	(Road density, km/km^2)	-2.79
	+50.05	(Watershed relief ratio, -)	2.41
	Critical t ($\alpha = 0.05$, d.f. = 61)		± 2.00
	$R^2 = 0.54$		

Model 1 accounts for 54% of the total variance in percent fines and is statistically significant (95% CL). It is interesting to note that three watershed variables and two land use variables are significantly related to the percentage of fine sediment in the gravel whereas none of the in-channel variables were significant predictors of percent fines. This fact would suggest that bed composition is controlled by the geomorphology and the land use history of the watershed. Although the interpretation of coefficients in multiple linear regression equations is sometimes tenuous when several variables are used, the significant variables often identify factors which, in this case, may cause variation in bed fines. The coefficients in Model 1 suggest that percent fines in the gravel increase with increasing watershed area, Percent Area Time Factor, and watershed relief ratio. Percent fines is seen to decrease with increasing average slope and road intensity.

The interpretation of the coefficient for the road density variable raises a difficult question about the model. The majority of research shows that increasing road densities on a watershed generally increase the rates of erosion and sediment delivery to the stream which may ultimately increase the level of fine sediment in the gravel bed. Model 1 seems to predict that just the opposite will occur; increasing road densities would decrease the fine sediment content of the bed. Perhaps an interaction between watershed area and road density exists and this interaction produces the negative coefficient. However, the fact that both of the variables are statistically significant indicates that they each supply independent information to the model. Essentially, there seems to be no rational explanation for the negative road density coefficient in Model 1. The negative sign for this coefficient was especially difficult to interpret when compared with the positive Percent Area Time Factor coefficient, which also includes road density.

Model 2 - Watershed Averages

The second model was developed by regressing the average percent fines for each stream against the average values of the independent variables (Appendix B) collected on each watershed. Again, the independent variables are listed in order of decreasing significance:

			t-values
Percent Fines =	41.94	(Constant, %)	5.30
	-1.23	(Average watershed slope, %)	-5.14
	+0.03	(Watershed area, ha)	2.83
(2)	+68.89	(Watershed relief ratio, -)	2.79
	+0.06	(Percent Area Time Factor, %)	2.55
	Critical t (α = 0.05, d.f. = 16)		$\pm$2.12
	$R^2 = 0.66$		

The overall regression and the four independent variables are all significant (95% CL). The model accounts for 66% of the variance in percent fines for the 21 streams. The higher R^2 value for Model 2 as compared with Model 1 suggests that the procedure of averaging the three samples on each stream reduces the variance in the estimate of percent fines in the gravel. Three watershed characteristics and one land use variable were found to predict percent fines. Again, percent fines in the gravel seems to increase with increasing watershed area, watershed relief ratio, and Percent Area Time Factor, and decrease with increasing average watershed slope. The road density variable was not significant in this model. In both Models 1 and 2, average watershed slope is the most significant independent variable. A scattergram of percent fines versus average watershed slope for the 21 watersheds is illustrated in Figure 19.

No in-channel variables were significant predictors of percent fines in either of the two models. All the significant variables were indicators of watershed characteristics, rather than channel characteristics. However, the three significant watershed variables undoubtedly play a major role in determining the channel characteristics within a particular reach of stream. Averaging the values for several plots in each stream reduces the variance in the measure of percent fines by accounting for some of the spatial variability. As a result, Model 2 has a higher R^2 value with one less independent variable than Model 1. For these reasons, Model 2 is considered to be the superior model in terms of quantitatively describing the set of data collected on the 21 watersheds. Model 2 further illustrates that the percentage of fine sediment in the gravel bed is influenced by both the geomorphology and land use history of the watershed.

Models 3 and 4 - Flynn Creek Samples

It was originally hypothesized that in-channel variables would have an important effect on bed composition. However, none of these

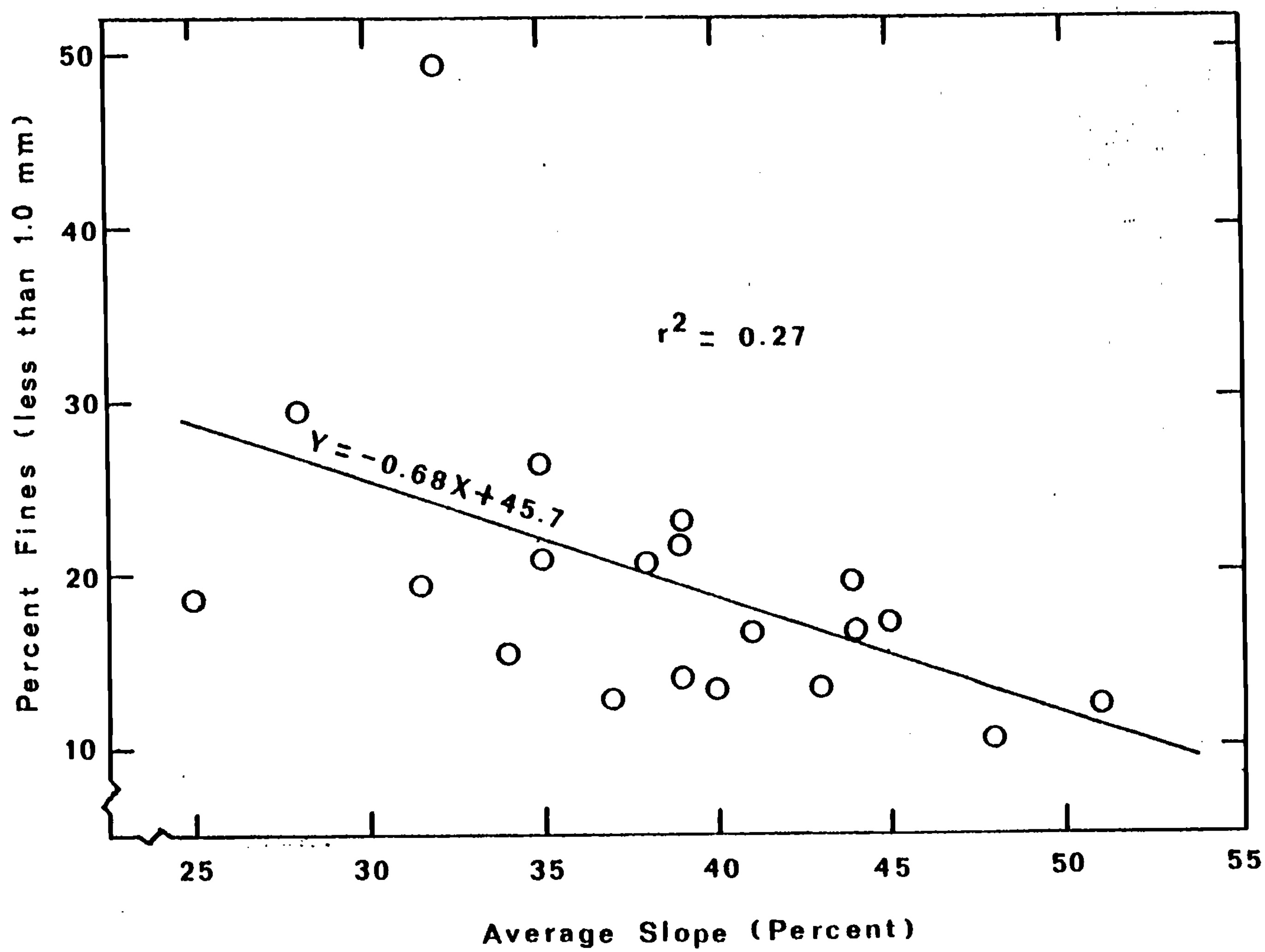

Figure 19. Percent fine sediment (by weight) versus average watershed slope for the 21 watersheds in the Coast Range.

variables were significant in the first two models. The seven samples on Flynn Creek offered a unique chance to test for the effect of in-channel variables while holding all the land use and watershed variables constant. Percent fines for these seven samples (No. 1 through 7, Appendix A) were regressed against the five in-channel variables measured at each plot. Two models were developed:

		t-value
Percent Fines =	-31.04 (Constant, %)	-2.06
	+27.02 (Sinuosity, -)	2.09
(3)	+35.22 (Bankfull stage, m)	1.34
	Critical t (α = 0.05, d.f. = 4)	$\pm$2.78
	$R^2 = 0.82$	

Percent Fines =	-24.94 (Constant, %)	-1.62
(4)	+38.83 (Sinuosity, -)	3.79
	Critical t (α = 0.05, d.f. = 5)	$\pm$2.57
	$r^2 = 0.74$	

Both of the overall regressions are significant (95% CL), however, the sinuosity term in Model 4 is the only significant independent variable in either model. Both independent variables in Model 3 are non-significant (95% CL) despite the significance of the overall regression. The high coefficients of determination (0.82 and 0.74) suggest that the variables of bankfull stage and sinuosity may affect the composition of the stream bed. However, the small sample size used in model development might limit the validity of this conclusion. The fact that neither of the variables are significant when they are both in the equation suggests that there is some interaction between them. According to Model 3, percent fines in the bed increases with increasing sinuosity and bankfull stage.

Discussion

The amount of fine sediment in a stream bed seems to be determined in large part by the intrinsic characteristics of the watershed, such as area, slope, and relief. In both Models 1 and 2, slope and watershed size were the two most significant factors in predicting the percentage of fine sediments in the bed. The fact that percent fines increases with the area of the watershed suggests that the amount of fines in the bed of a stream will generally increase in going from the headwater streams down to the second and third order streams. This conclusion agrees well with observations made in the field.

The difference in the signs for the slope and the relief ratio coefficients in Models 1 and 2 is difficult to reconcile. A possible explanation is that these two variables represent entirely different ways to quantify the landform of a particular watershed. Average slope is a variable that applies to the entire watershed. The relief ratio only quantifies the area along the straight line from the mouth to the highest point on the watershed.

The significance of the Percent Area Time Factor in both models for the 21 streams suggests that the combined effects of road construction and forest harvesting may affect gravel bed composition. The positive sign for this land use variable is interpreted as meaning that higher road densities and larger clearcuts tend to increase the amount of fines in stream gravel beds. The fact that the other land use variables, particularly the percentage of the watershed harvested, were not significant implies that this increase in levels of bed fines accompanying forest harvesting activities is not a permanent change. The Percent Area Time Factor was designed to account for the eventual return of bed fines to background levels with time after disturbance. The flushing of fines from the bed with high flows as documented with the time series data undoubtedly plays an important part in this process.

Within a particular stream, the amount of fine sediment in the gravel bed is controlled largely by the hydraulic conditions of flow as indexed by sinuosity and bankfull stage in Model 3. Changes in sinuosity could have a large influence on the depth and velocity of the flow. Both of these factors are taken into account by the Froude number, which has been found to influence the intrusion of fine sediment into gravel beds (Beschta and Jackson, 1977).

Bankfull stage was a statistically insignificant variable in Model 3, but its presence improved the total explained variance in comparison to Model 4. Stream channels grade or degrade in response to high flows and bankfull stage is an approximate measure of water depth during these high flow events. The positive coefficient for the bankfull stage variable in Model 3 suggests that the percentage of fine sediment in the bed increases with increasing water depth. Similarly, Einstein

(1968) found that the deposition of fine sediment in a gravel bed in an artificial channel also increased with increasing water depth.

Percent Fine Sediment in the Oregon Coast Range

Characteristic or representative levels of fine sediment in gravel beds of streams in the Oregon Coast Range are difficult to determine. The five undisturbed drainages sampled during the summer months had percent fines ranging from 10.6% to 29.4%. These large amounts of natural background variation prohibit making precise estimates of natural levels of fines. The data suggest, however, that streams not impacted by road building and forest harvesting activities should have percent fines within the range of 5% to 30%.

The supply of fine sediments in the Coast Range seems to be sufficient in most streams to completely fill most intergravel pores. Large open intergravel pore spaces, recognizeable as frozen intergravel water in the sample cores, were not common in samples collected during this study. However, clean pore spaces were noticed in sample cores immediately after high flow events. The incidence of intergravel pore spaces in the time series samples was always accompanied by a decrease in fine sediments at that sample plot. However, the interstices of most stream gravel beds in the Coast Range seem to fill with fine sediment by the summer months.

In the Coast Range, the size distribution of the fines and the bed into which they are intruding are such that fines apparently settle to the bottom of the bed without forming a sand seal at the surface. Any paucity in the supply of fines available for intrusion would thus result in clean interstices in the upper portions of the bed.

Since most of the gravel beds in Coast Range streams appear to be "saturated" with fines, it is possible that the percentage of fine sediment is influenced by the size distribution of the gravel substrate. For an ideal sample of uniform spherical particles with an open packing arrangement, it may be shown that porosity is independent of particle radius. However, the frozen cores do not represent ideal samples, nor are the rocks uniform spherical particles. Larger rocks often extend beyond the frozen front of the core. Thus, the size distribution of the gravel substrate might influence the measure of percent fines in the frozen core samples. This effect may be reduced, but not eliminated, by the exclusion of rocks larger than 50.8 mm in diameter.

V. CONCLUSIONS AND RECOMMENDATIONS

The amount of fine sediment in stream gravel beds is highly variable in time and space. The temporal variability in bed fines is largely a result of high streamflow events. Fine sediments are flushed from the gravel during periods of gravel bed movement induced by high flows. The net flushing of fines appears to occur randomly and not throughout the entire length of stream with every freshet.

Percent fines was found to vary between streams, between riffle areas in the same stream, and within the same riffle. These differences in bed fines may be due to differences in the size composition of the gravel substrate and fines, the supply of fines to be intruded into the bed, and the hydraulic conditions of flow.

On a watershed basis, percent fines seemed to be influenced by the geomorphological characteristics of the watershed and its land use history. Multiple linear regression analysis indicated that percent fines was related to the average watershed slope, watershed area, relief ratio, and the Percent Area Time Factor.

For a single stream sampled at several locations, the amount of fine sediment in the bed was related to the stream sinuosity and bankfull stage. Thus, within a given stream, percent fines seems to be influenced by the hydraulic conditions of flow and water depth during high flow events.

The large amount of background variation in levels of intergravel fine sediment precludes the pinpointing of representative levels of percent fines; gravel bed fine sediment content for undisturbed Coast Range streams ranged from about 10% to 50%.

There are large regional differences in streambed and sediment morphology and the application of similar percent fines criteria to all regions would seem inappropriate. The large levels of background variation in this parameter also indicate that sampling error may be a major problem. Streams should be sampled through time and on an event basis, if possible. Sample sites should be selected on bed riffle areas suitable as spawning sites for anadromous fish and several riffles should be sampled in each stream. Standards should be set for lab analysis techniques and the fine sediment content of a bed should be expressed in a consistent manner so that comparisons can be made.

Management Implications

Regression analysis and field observations suggest that gravel bed composition may be influenced by road construction and forest harvesting activities. Increased road densities and larger clearcut areas within the watershed might lead to higher levels of fine sediment within the gravel bed. However, due to the large amounts of background variation in bed composition between streams, percent fines is not a sensitive measure of the land use in a watershed. That is not to say, however, that bed composition is not affected by road construction and forest harvesting activities. Since fine sediment is flushed from the gravel with high flow events, increases in levels of bed fines after disturbance are often temporary if the increased sediment inputs are curtailed. Continued disturbances, however, might cause sustained high levels of bed fines.

The conclusion that forest harvesting activity increases the levels of fine sediment within stream gravel beds is consistent with earlier studies (Burns, 1970; 1972; Ringler, 1970; Moring and Lantz, 1974; Platts and Megahan, 1975). If the objective of a land manager is to harvest timber on a watershed with minimal impacts on the stream environment, erosion and the entry of fine sediment into the stream system must be minimized. Precautions for minimizing stream impacts have been documented (Brown 1972; Moring, 1975b; Oregon State Department of Forestry, 1978). These methods include limiting machine activity in or near the stream channel, minimizing disturbance to the stream bed and banks, minimizing road density, suspending the front end of the log during yarding, and many other precautions that will limit the erosion of soil and the entry of sediment to the stream.

Recommendations for Future Research

The measurement of percent fines may be influenced by the size distribution of a gravel bed substrate. Therefore, percent fines (by weight) in the sample may not be an accurate estimator of the reduction in water filled pore space caused by the addition of fine sediment. Since it is the amount of water filled pore space that is important for fisheries considerations, the relationship between percent fines and available pore space needs to be investigated. Estimates of the water filled pore space in the gravel bed are easily obtainable with the frozen core sampling technique. Perhaps an estimate of water filled pore space might be a more useful stream quality criterion than percent fines in the gravel.

More intensive monitoring of bed composition of streams draining proposed timber sale areas needs to be conducted to quantify the effects of clearcutting and road construction on the amount of fine sediment in the bed. A before and after approach may lend itself to more definite conclusions than sampling streams draining roaded and clearcut watersheds after the fact. Perhaps a variety of both road design and construction techniques and logging methods could be monitored to assess the impacts of different techniques. Since large temporal variation in percent fines was documented in this study, the streams should be sampled at least on a monthly basis.

The model for percent fines developed from the seven samples on Flynn Creek (Model 3) has a relatively high R^2 value (0.82). The small sample size, however, limits the validity of the conclusions drawn from the model. A larger sample size, collected over a wider range of bed composition in Flynn Creek, might be used to verify the model and obtain additional information. A more intensive study within one stream might yield further information relating to the importance of various in-channel characteristics in influencing gravel bed composition.

VI. LITERATURE CITED

Anderson, H. W. 1971. Relative contributions of sediment from source areas and transport processes. pp. 56-63. IN: Krygier, J. T. and J. D. Hall, eds., Forest land uses and the stream environment. Oregon State Univ., Corvallis, Oreg. 252 pp.

Anonymous. 1978. Anadromous fish habitat research. USDA For. Serv., 15 pp.

Badura, G. J., H. A. Legard and L. C. Meyer. 1974. Siuslaw National Forest soil resource inventory. USDA For. Serv., Pac. North West Reg., Portland, Oreg. 139 pp.

Baldwin, E. M. 1974. Geology of Oregon. Edwards Brothers, Inc., Ann Arbor, Michigan. 165 pp.

Beschta, R. L. 1978a. Long term patterns of sediment production following road construction and logging in the Oregon Coast Range. Water Resources Res. 14(6): 1011-1016.

_____________. 1978b. Inventorying small streams and channels on wildland watersheds. pp. 104-113. IN: V. J. LaBau, ed., Proc. National Workshop on Integrated Inventories of Renewable Natural Resources, Jan. 8-12, 1978, Tuscon, Ariz. USDA For. Serv., Gen. Tech. Rep. RM-55. 482 pp.

_____________, and W. L. Jackson. 1977. The intrusion of fine sediments into a gravel bedded channel. Project completion report, Oregon State Univ., Corvallis, Oreg. 57 pp.

_____________, and W. L. Jackson. 1978. The intrusion of fine sediments into a stable gravel bed. J. Fish. Res. Board Can. 36: 204-210.

Bethlahmy, N. 1967. Effect of exposure and logging on runoff and erosion. USDA For. Serv., Res. Note INT-61. 7 pp.

Bishop, D. M. and M. E. Stevens. 1964. Landslides on logged areas in southeast Alaska. USDA For. Serv., Res. Pap. NOR-1. 18 pp.

Bjornn, T. C., M. A. Brusven, M. P. Molnau, and J. H. Milligan. 1977. Transport of granitic sediment in streams and its effects on insects and fish. Forest, Wildlife, and Range Experiment Station, Univ. of Idaho, Moscow, Idaho. 43 pp.

Brown, G. W. 1971. Clearcut logging and sediment production in the Oregon Coast Range. pp. 35-54. IN: Krygier, J. T. ed., Studies on effects of watershed practices on streams. Oregon State Univ., Corvallis, Oreg. 173 pp.

__________. 1972. The Alsea watershed study. Loggers Handbook. 32: 13-25, 127-130.

__________. 1976. Forestry and water quality. School of Forestry, Oregon State Univ., Corvallis, Oreg. 74 pp.

__________, and J. T. Krygier. 1971. Clearcut logging and sediment production in the Oregon Coast Range. Water Resources Res. 7(5): 1189-1199.

Burns, J. W. 1970. Spawning bed sedimentation studies in Northern California streams. Cal. Fish and Game. 56(4): 253-270.

__________. 1972. Some effects of logging and associated road construction on northern California streams. Trans. Amer. Fish. Soc. 101(1): 1-17.

Cederholm, C. J. and L. C. Lestelle. 1974. Observations on the effects of landslide siltation on salmon and trout resources of the Clearwater River, Jefferson County, Washington, 1972-73. Fisheries Res. Ins., Univ. of Wash., Seattle, Wash. 89 pp.

Chemical Rubber Company. 1966. Handbook of Chemistry and Physics. Cleveland, Ohio. Various pagings.

Coble, D. W. 1961. Influence of water exchange and dissolved oxygen in redds on survival of steelhead trout embryos. Trans. Amer. Fish. Soc. 90: 469-474.

Cooper, A. C. 1965. The effects of transported stream sediments on the survival of sockeye and pink salmon eggs and alevin. Int. Pac. Salmon Fish. Com., Bul. 18. 71 pp.

Cordone, A. J. and D. E. Kelley. 1961. The influences of inorganic sediment on the aquatic life of streams. Cal. Fish and Game. 47(2): 189-228.

Dill, L. M. and T. G. Northcote. 1970. Effects of gravel size, egg depth, and egg density on intergravel movement and emergence of coho salmon alevins. J. Fish. Res. Board Can. 27(2): 1191-1199.

Einstein, H. A. 1968. Deposition of suspended particles in a gravel bed. ASCE Journal, Hydraulics Div. 94(HY5): 1197-1205.

Fredriksen, R. L. 1965. Sedimentation after logging road construction in a small western Oregon watershed. pp. 64-74. IN: Proc. Federal Inter-Agency Sedimentation Conference. USDA Misc. Pub. 970. 993 pp.

____________. 1970. Erosion and sedimentation following road construction and timber harvest on unstable soils in three western Oregon watersheds. USDA For. Serv., Res. Pap. PNW-104. 15 pp.

Froehlich, H. A. 1976. The influences of land management activities on landscape stability. Forest Research Laboratory Paper 1291, Oregon State Univ., Corvallis, Oreg. 14 pp.

Garde, R. J., K. A. Ali, and S. Siette. 1977. Armoring processes in degrading streams. ASCE Journal, Hydraulics Div. 103(HY9): 1091-1095.

Garvin, W. F. 1974. The intrusion of logging debris into artificial gravel streambeds. Completion Report, Water Resources Res. Ins., Oregon State Univ., Corvallis, Oreg. 79 pp.

Gibbons, D. R. and E. O. Salo. 1973. Annotated bibliography of the effects of logging on fish of the western United States and Canada. USDA For. Serv., Gen. Tech. Rep. PNW-10. 145 pp.

Guy, H. P. 1964. An analysis of some storm-period variables affecting stream sediment transport. U. S. Geol. Surv., Prof. Pap. 462-E. 38 pp.

Hall, J. D. and R. L. Lantz. 1969. Effects of logging on the habitat of coho salmon and cutthroat trout in coastal streams. pp. 353-375. IN: T. G. Northcote, ed., A Symposium on Salmon and Trout in Streams. Univ. of British Columbia, Victoria, B. C. 388 pp.

Harris, D. D. 1973. Hydrologic changes after clearcut logging in a small Oregon coastal watershed. U. S. Geol. Surv., Jour. of Res. 1(4): 487-491.

____________, and R. C. Williams. 1971. Sediment transport and water temperature characteristics of three small watersheds in the Alsea river basin, Oregon. U. S. Geol. Surv., Circ. 642. 20 pp.

Hess, V. S. 1977. Predicting logging debris accumulation in natural stream beds: a method for forest managers. MS thesis, Oregon State Univ., Corvallis, Oreg. 61 pp.

Hewlett, J. D. and W. L. Nutter. 1969. An outline of forest hydrology. Univ. of Georgia Press, Athens, Ga. 137 pp.

Iwamoto, R. N., E. O. Salo, M. A. Madej, and R. L. Comas. 1978. Sediment and water quality: a review of the literature including a suggested approach for a water quality criterion. U. S. Environ. Prot. Agen., Seattle, Wash. 248 pp.

Ketcheson, G. and H. A. Froehlich. 1977. Hydrologic factors and envirionmental impacts of mass soil movements in the Oregon Coast Range. Project Completion Report, Water Resources Res. Ins., Oregon State Univ., Corvallis, Oreg. 94 pp.

Klingeman, P. C. 1971. Evaluation of bedload and total sediment yield processes on small mountain streams. pp. 59-169. IN: J. T. Krygier ed., Studies on effects of watershed practices on streams. Oregon State Univ., Corvallis, Oreg. 173 pp.

Koski, K V. 1966. The survival of coho salmon from egg deposition to emergence in three Oregon coastal streams. MS thesis, Oregon State Univ., Corvallis, Oreg. 84 pp.

____________. 1972. Effects of sediment on fish resources. Fish. Res. Ins., Univ. of Wash., Seattle, Wash. 36 pp.

____________. 1975. The survival and fitness of two stocks of chum salmon (*Oncorhynchus keta*) from egg deposition to emergence in a controlled stream environment at Big Beef Creek. PhD dissertation, Univ. of Wash., Seattle, Wash. 212 pp.

Lantz, R. L. 1971. Fish population impacts. pp. 246-249. IN: Krygier, J. T. and J. D. Hall, eds., Forest land uses and the stream environment. Oregon State Univ., Corvallis, Oreg. 252 pp.

Linsley, R. M., M. A. Kohler, and L. H. Paulhus. 1975. Hydrology for engineers. McGraw-Hill, Inc., New York. 481 pp.

Martin, D. J. 1976. The effects of sediment and organic detritus on the production of benthic macroinvertebrates in four tributary streams of the Clearwater River, Washington. MS thesis, Univ. of Wash., Seattle, Wash. 63 pp.

McNeil, W. J. 1966. Effect of spawning bed environment on reproduction of pink and chum salmon. USDI Fish and Wildlife Serv., Fisheries Bul. 65(2): 495-523.

____________, and W. H. Ahnell. 1960. Measurement of gravel composition of salmon stream beds. Fisheries Res. Ins., Univ. of Wash., Seattle, Wash. Circ. 120. 6 pp.

____________, and W. H. Ahnell. 1964. Success of pink salmon spawning relative to size of spawning bed materials. USDI Fish and Wildlife Serv., Spec. Sci. Rep., Fish. 469. 15 pp.

Meehan, W. R. and D. N. Swanston. 1977. Effects of gravel morphology on fine sediment accumulation and survival of incubating salmon eggs. USDA For. Serv., Res. Pap. PNW-220. 16 pp.

Megahan, W. F. 1974. Erosion over time on severely disturbed granite soils: a model. USDA For. Serv., Res. Pap. INT-156. 14 pp.

____________, and W. J. Kid. 1972. Effects of logging and logging roads on erosion and sediment deposition from steep terrain. J. For. 70(3): 136-142.

Mih, W. C. 1976. Literature search on restoration of stream gravel for spawning and rearing of salmon species. Wash. State Dept. of Fisheries, Tumwater, Wash. 31 pp.

Milhous, R. T. 1973. Sediment transport in a gravel bottomed stream. PhD dissertation, Oregon State Univ., Corvallis, Oreg. 232 pp.

____________, and P. C. Klingeman. 1971. Bedload transport in mountain streams. ASCE Hydraulics Division Specialty Conference, Univ. of Iowa, Iowa City, Iowa. 16 pp.

Miner, N. H. 1968. Natural filtering of suspended soil by a stream at low flow. USDA For. Serv., Res. Note PNW-88. 4 pp.

Moring, J. R. 1975a. The Alsea watershed study: effects of logging on the aquatic resources of three headwater streams of the Alsea River, Oregon, II, changes in environmental conditions. Fish. Res. Rep. No. 9, Oregon Dept. of Fish and Wildlife, Corvallis, Oreg. 39 pp.

____________. 1975b. The Alsea watershed study: effects of logging on the aquatic resources of three headwater streams of the Alsea River, Oregon, III, discussion and recommendations. Fish. Res. Rep. No. 9, Oregon Dept. of Fish and Wildlife, Corvallis, Oreg. 23 pp.

____________, and R. L. Lantz. 1974. Immediate effects of logging on the freshwater environment of salmonids. Oregon Wildlife Com., Res. Div. Proj. AFS-58, Final Report, Corvallis, Oreg. 101 pp.

____________, and R. L. Lantz. 1975. The Alsea watershed study: effects of logging on the aquatic resources of three headwater streams of the Alsea river, Oregon, I, biological studies. Fish. Res. Rep. No. 9, Oregon Dept. of Fish and Wildlife, Corvallis, Oreg. 66 pp.

Neter, J. and W. Wasserman. 1977. Applied linear statistical models. Richard D. Irwin, Inc. Homewood, Illinois. 842 pp.

Nuttal, P. M. 1972. The effects of sand deposition upon the macro-invertebrate fauna of the river Camel, Cornwall. Freshwater Biology. 2: 181-186.

Oregon State Department of Forestry. 1978. Field guide to Oregon forest practice rules. Fifth revision, State of Oregon, Salem, Oregon. 55 pp.

Osterkamp, W. R. 1978. Bed and bank material sampling procedures at channel geometry sites. U. S. Geol. Surv., Lawrence, Kansas. 20 pp.

Ott, L. 1977. An introduction to statistical methods and data analysis. Duxbury Press, North Scituate, Mass. 730 pp.

Pfankuch, D. J. 1975. Stream reach inventory and channel stability evaluation. USDA For. Serv., Northern Region. 26 pp.

Phillips, R. W. 1965. Effect of fine material on salmon and trout redds. pp. 59-61. IN: Meeting on Erosion and Sedimentation in the Northwest 1964-65 Flood Season. Water Supply and Water Pollution Control subcommittee. Columbia basin interagency committee, Portland, Oreg. 103 pp.

____________. 1971. Effect of sediment on the gravel environment and fish production. pp. 64-70. IN: Krygier, J. T. and J. D. Hall, eds., Forest land uses and the stream environment. Oregon State Univ., Corvallis, Oreg. 252 pp.

____________, and H. J. Campbell. 1961. The embryonic survival of coho salmon and steelhead trout as influenced by some environmental conditions in gravel beds. Pac. Marine Fish. Com., 14th Annual report. pp. 60-73.

____________, R. L. Lantz, E. W. Claire, and J. R. Moring. 1975. Some effects of gravel mixtures on emergence of coho salmon and steelhead trout fry. Trans. Amer. Fish. Soc. 104(3) 461-466.

Platts, W. S. and W. F. Megahan. 1975. Time trends in river bed sediment composition in salmon and steelhead spawning areas: south fork salmon river, Idaho. USDA For. Serv., Intermountain Forest and Range Experiment Station, Ogden, Utah. 5 pp.

Renard, K. G. 1974. Bed material size changes and sediment transport. ASAE Trans., St. Joseph, Michigan. 17(6): 1001-1010.

Ringler, N. H. 1970. Effects of logging on spawning bed environment in two Oregon coastal streams. MS thesis, Oregon State Univ., Corvallis, Oreg. 96 pp.

____________, and J. D. Hall. 1975. Effects of logging on water temperature and dissolved oxygen in spawning beds. Trans. Amer. Fish. Soc. 104 (1):111-121.

Rothacher, J., C. T. Dryness, and R. L. Fredriksen. 1967. Hydrologic and related characteristics of three small watersheds in the Oregon Cascades. USDA For. Ser., Pac. Northwest Forest and Range Experiment Station, Corvallis, Oreg. 54 pp.

Rowe, K., J. A. Barnes, R. Brenne, and K. Ewert. 1978. Statistical interactive programming system (SIPS) command reference manual. Statistical Computing Reprt No. 6. Dept. of Statistics, Oregon State Univ., Corvallis, Oreg. 66 pp.

Sargent-Welch Scientific Company. 1968. Table of periodic properties of the elements. Skokie, Illinois. 2 pp.

Saunders, J. W. and M. W. Smith. 1965. Changes in a stream population of trout associated with silt. J. Fish Res. Board Can. 22(2): 395-404.

Shapley, S. P. and D. M. Bishop. 1965. Sedimentation in a salmon stream. J. Fish Res. Board Can. 22(4): 919-928.

Sheridan, W. L. 1962. Water flow through a salmon spawning riffle in southeast Alaska. UDSI Fish and Wildlife Serv., Spec. Sci. Rep. No. 407. 20 pp.

____________, T. Hoffman, and S. Olson. 1965. A technique for monitoring effects of land use on salmon streams in Alaska. pp. 155-159. IN: Proc. 45th Annual Conf. Western Assn. of State Game and Fish Com., Ankorage, Alaska. 326 pp.

__________, and W. J. McNeil. 1968. Some effects of logging on two salmon streams in Alaska. J. For. 66(2): 128-133.

Sharazi, M. A. 1978. Stream bed characterization variability. U. S. Environ. Prot. Agen., Corvallis, Oreg. 12 pp.

Smedley, S. C., K. E. Dudley, C. C. Larson, D. M. Bishop, W. L. Sheridan, and F. Stevens. 1970. Effects of land use in salmon production. Completion report, Alaska Dept. of Fish and Game, Juneau, Alaska. 8 pp.

Strahler, A. N. 1957. Quantitative analysis of watershed geomorphology. Amer. Geophys. Union Trans., 38: 913-920.

Sutherland, A. J. 1967. Proposed mechanism for sediment entrainment by turbulent flows. J. Geophys. Res. 72(24): 6188-6194.

Swanson, F. J. and C. T. Dryness. 1975. Impact of clearcutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon. Geol. 3: 393-396.

__________, and D. N. Swanston. 1977. Complex mass movement terrains in the western Cascade Range, Oregon. Geol. Soc. Amer., Reviews in Engineering Geology. 3: 113-124.

Swanston, D. N. 1971. Principle mass movement processes influenced by logging, road building, and fire. pp. 29-38. IN: Krygier, J. T. and J.D. Hall, eds., Forest land uses and the stream environment. Oregon State Univ., Corvallis, Oreg. 252 pp.

__________. 1974. Slope stability problems associated with timber harvesting in mountainous regions of the western United States. USDA For. Serv., Gen. Tech. Rep. PNW-21. 14 pp.

__________. 1976. Erosion processes and control methods in North America. USDA For. Serv., Pac. Northwest Forest and Range Exp. Sta., Corvallis, Oreg. 25 pp.

__________, and F. J. Swanson. 1976. Timber harvesting, mass erosion, and steepland geomorphology in the Pacific Northwest. pp 199-221. IN: Donald R. Coates, ed., Geomorphology and Engineering. Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pa. 360 pp.

__________, W. R. Meehan, and J. A. McNut. 1977. A quantitative geomorphic approach to predictin productivity of pink and chum salmon streams in southeast Alaska. USDA For. Serv., Res. Pap. PNW-227. 16 pp.

Tagart, J. V. 1976. The survival from egg deposition to emergence of coho salmon in the Clearwater River, Jefferson County, Washington. MS Thesis, Univ. of Wash., Seattle, Wash. 101 pp.

Vaux, W. G. 1962. Interchange of stream and intergravel water in a salmon spawning riffle. USDI Fish and Wildlife Serv., Spec. Sci. Rep. Fish. No. 405. 11 pp.

Walkotten, W. J. 1973. A freezing technique for sampling stream bed gravel. USDA For. Serv., Res. Note PNW-205. 7 pp.

____________. 1976. An improved technique for freeze sampling stream bed sediments. USDA For. Serv., Res. Note PNW-281. 11 pp.

Walling, D. E. 1977. Assessing the accuracy of suspended sediment rating curves for a small basin. Water Resources Res. 13(3): 531-539.

Wendling, F. L. 1978. Final report on gravel porosity studies along the trans-Akaska pipeline. USDI Fish and Wildlife Serv., Spec. Rep. No. 18. 77 pp.

Yalin, M. S. and G. D. Finlayson. 1972. On the velocity distribution of the flow carrying sediment in suspension. pp. 8-1 to 8-18. IN: H. W. Shen, ed., Sedimentation Symposium to honor Professor H. A. Einstein. Colorado State Univ., Fort Collins, Colorado. Various pagings.

Zimmer, D. W. and R. W. Bachmann. 1978. Channelization and invertebrate drift in some Iowa streams. Water Resources Bul. 14(4) 868-883.

APPENDICES

APPENDIX A

STREAMBED, CHANNEL, WATERSHED, AND LAND USE CHARACTERISTICS FOR 67 LIQUID NITROGEN CORES, OREGON COAST RANGE.

Column Identification	Vairable Description
A	Sample I. D.
B	Percent fines (1.0 mm exc. rocks larger than 50.8 mm)
C	Percent fines (1.0 mm inc. rocks larger than 50.8 mm)
D	Percent fines (2.0 mm exc. rocks larger than 50.8 mm)
E	Percent fines (2.0 mm inc. rocks larger than 50.8 mm)
F	Percent fines (0.84 mm exc. rocks larger than 50.8 mm)
G	Stream order
H	Watershed area (ha)
I	Bankfull stage (m)
J	Stream cross-sectional area at bankfull stage (m^2)
K	Width-depth ratio
L	Stream gradient (%)
M	Sinuosity
N	Watershed relief ratio
O	Average watershed slope (%)
P	Watershed sediment yield ranking
Q	Road density (km/km^2)
R	Amount of watershed harvested (%)
S	Percent Area Time Factor (%)
T	Amount of direct stream disturbance (%)
U	Armor layer average diameter (cm)
V	Average log transformed armor layer diameter (cm)
W	Channel stability rating
X	Basalt present in stream (yes=1, no=0)
Y	Large scale mass movements (yes=1, no=0)
Z	Private timber holdings (yes=1, no=0)
ZZ	Index of uniformity

Appendix A. (Continued)

A	B	C	D	E	F	G	H	I	J	K	L	M
1	53.1	53.1	69.4	69.4	47.0	2	202	.9	5.4	9.0	0.0	1.9
2	31.0	31.0	36.6	36.6	29.0	2	202	.6	1.7	6.0	0.0	1.7
3	29.2	29.2	34.0	34.0	25.0	2	202	.5	2.6	7.3	1.0	1.4
4	46.7	46.7	61.6	61.6	44.0	2	202	.7	2.1	6.8	1.0	1.6
5	17.9	17.9	24.2	24.2	16.0	2	202	.5	2.5	13.1	1.0	1.1
6	23.7	23.7	27.7	27.7	22.0	2	202	.6	2.2	6.4	1.0	1.2
7	27.7	27.7	40.9	40.9	26.0	2	202	.6	1.5	7.0	2.0	1.5
8	12.3	12.3	15.8	15.8	12.0	1	75	.5	1.4	8.0	1.0	1.4
9	16.3	16.3	21.9	21.9	14.0	1	75	.5	1.1	9.9	1.0	1.5
10	10.1	10.1	15.0	15.0	9.0	1	75	.5	.5	4.5	1.0	1.1
11	17.3	17.3	21.8	21.8	16.0	3	304	.6	2.6	6.1	2.0	1.0
12	15.5	15.5	20.1	20.1	14.0	3	304	.3	2.6	5.0	3.0	1.2
13	16.2	16.2	21.1	21.1	15.0	3	304	.6	2.0	7.5	1.0	1.3
14	8.2	4.7	12.3	7.1	6.0	2	247	.9	5.4	10.3	2.0	1.1
15	9.0	5.9	15.0	9.9	7.5	2	247	.6	2.6	12.5	1.0	1.1
16	14.5	14.5	23.1	23.1	14.0	2	247	.5	4.0	11.5	1.0	1.1
17	21.6	7.1	30.3	9.9	20.0	2	373	1.3	5.1	5.7	4.0	1.2
18	11.4	6.7	15.5	9.3	10.0	2	373	.5	3.9	9.5	2.5	1.0
19	9.1	4.5	13.8	6.6	6.0	2	373	1.1	7.1	8.1	3.0	1.5
20	14.9	10.3	18.3	12.6	13.0	2	202	.7	2.5	7.7	2.0	1.3
21	16.8	14.6	20.4	17.6	15.0	2	202	.5	1.5	10.6	3.0	1.2
22	8.1	8.1	11.7	11.7	8.0	2	202	.5	1.6	10.0	1.0	1.2
23	15.6	18.6	23.1	23.1	18.0	2	119	.5	1.4	7.1	.5	2.2
24	20.5	20.5	26.3	26.3	19.0	2	119	.3	1.3	17.0	2.0	1.2
25	17.1	14.6	19.9	19.9	16.5	2	119	.3	1.0	13.0	.5	1.2
26	60.2	60.2	77.4	77.4	56.0	3	234	.5	3.4	6.9	0.0	1.1
27	47.9	47.9	59.3	59.3	44.5	3	234	.7	3.4	7.9	1.0	1.1
28	39.7	39.7	47.4	47.4	37.5	3	234	.5	2.7	11.1	0.0	1.2
29	13.6	14.8	23.7	15.8	17.5	1	67	1.0	2.6	3.5	2.0	1.1
30	24.2	21.3	32.0	28.2	22.5	1	67	1.2	3.5	4.1	4.0	1.1
31	25.1	28.1	32.6	32.6	24.0	1	67	.7	1.9	5.0	3.0	1.2
32	16.4	14.2	21.1	15.2	15.0	1	26	1.0	2.0	4.1	5.0	1.4
33	20.9	19.5	25.9	25.1	19.5	1	26	1.1	3.0	4.3	9.0	1.2
34	13.7	10.9	19.1	15.1	12.0	1	26	.5	1.4	4.0	6.0	1.2
35	27.5	27.5	31.4	31.4	15.5	2	275	.7	3.9	9.5	.5	1.4
36	13.9	12.4	15.1	13.5	13.0	2	275	.8	3.4	5.6	1.0	1.4
37	23.6	23.6	25.4	23.4	20.5	2	275	.9	4.5	11.0	1.5	1.3
38	20.6	20.6	24.2	24.2	19.5	2	251	.7	3.1	8.3	1.0	1.1
39	21.5	21.5	26.9	26.9	19.0	2	251	.7	2.5	7.1	1.0	1.0
40	15.8	15.8	18.2	18.2	14.0	2	251	1.3	5.4	4.9	2.0	1.4
41	21.7	21.7	26.8	26.6	19.5	1	67	.7	1.3	3.9	2.0	1.1
42	14.4	12.4	19.5	15.8	13.5	1	67	.6	1.6	3.6	2.0	1.3
43	14.0	14.0	16.1	15.1	13.0	1	67	.6	1.1	5.0	3.0	1.2
44	13.9	8.3	18.0	10.5	13.0	2	274	1.2	7.5	5.9	3.0	1.0
45	13.2	10.9	18.5	15.2	11.5	2	274	1.2	9.0	7.8	5.0	1.1
46	13.0	9.5	17.3	13.0	11.0	2	274	1.3	5.9	6.7	6.0	1.1
47	10.5	7.0	15.8	10.2	10.0	2	245	1.3	6.1	5.2	2.0	1.1
48	14.3	11.6	18.5	15.0	14.0	2	245	.7	3.2	9.1	1.0	1.0
49	11.7	9.5	16.7	13.5	10.0	2	245	1.2	6.7	7.4	6.0	1.1
50	17.9	17.4	22.3	21.6	17.5	1	46	1.0	4.4	6.2	2.0	1.2
51	10.5	8.4	14.0	10.9	10.0	1	46	1.1	3.3	4.9	3.0	1.1
52	17.1	16.3	20.5	19.5	15.0	1	46	.7	1.5	4.2	3.0	1.1
53	14.4	12.5	19.8	17.3	12.5	2	76	.9	2.1	6.9	3.0	1.0
54	17.1	16.7	23.6	22.9	15.5	2	76	.9	3.5	4.0	3.0	1.1
55	16.7	14.2	22.9	19.6	16.0	2	76	.9	4.0	6.0	5.0	1.1
56	21.3	19.5	24.1	22.1	20.5	2	211	.7	2.5	6.2	1.0	1.1
57	22.0	14.4	25.0	15.4	20.5	2	211	.9	3.7	7.2	2.5	1.1
58	18.8	13.8	22.3	16.3	15.0	2	211	1.1	6.1	8.6	1.0	1.1
59	24.3	24.3	31.8	31.6	22.0	3	537	1.0	6.9	7.6	1.0	1.3
60	33.9	33.6	47.7	47.7	31.0	3	537	.8	4.2	8.5	1.0	1.3
61	20.9	20.9	24.9	24.9	19.5	3	537	1.1	5.1	7.1	1.0	1.3
62	27.5	21.4	31.4	24.4	26.0	2	155	.6	2.0	6.2	3.0	1.3
63	15.4	13.5	18.4	16.2	14.0	2	155	.6	2.4	7.6	2.0	1.3
64	19.4	19.4	21.9	21.9	15.5	2	155	.3	2.5	6.4	3.0	1.5
65	22.1	15.6	26.9	20.2	21.0	1	23	.3	3.6	7.0	2.5	1.1
66	16.6	14.1	22.9	17.2	17.5	1	23	.6	1.5	7.0	4.0	1.1
67	17.5	13.2	22.6	16.8	16.0	1	23	1.1	4.3	4.3	4.0	1.9

Appendix A. (Continued)

A	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	ZZ
1	.12	28	4	0.00	0	0	0	.81	.79	107	0	0	0	9.3
2	.12	28	4	0.00	0	0	0	1.03	.99	107	0	0	0	36.7
3	.12	28	4	0.00	0	0	0	1.34	1.27	107	0	0	0	50.0
4	.12	28	4	0.00	0	0	0	1.35	1.31	107	0	0	0	13.3
5	.12	28	4	0.00	0	0	0	2.17	2.09	107	0	0	0	42.5
6	.12	28	4	0.00	0	0	0	1.71	1.55	107	0	0	0	65.0
7	.12	28	4	0.00	0	0	0	1.98	1.89	107	0	0	0	15.6
8	.13	37	3	3.21	100	123	100	1.70	1.63	76	0	0	1	30.0
9	.13	37	3	3.21	100	123	100	1.57	1.48	76	0	0	1	26.0
10	.13	37	3	3.21	100	123	100	1.52	1.41	75	0	0	1	15.0
11	.14	41	3	1.96	37	85	24	1.61	1.75	83	0	0	0	60.5
12	.14	41	3	1.96	37	85	24	1.74	1.68	83	0	0	0	31.6
13	.14	41	3	1.96	37	85	24	2.46	2.25	83	0	0	0	40.0
14	.28	48	4	1.56	0	60	0	8.55	7.35	83	1	0	0	30.8
15	.28	48	4	1.56	0	60	0	4.02	3.55	83	1	0	0	15.1
16	.28	48	4	1.56	0	60	0	6.46	5.61	83	1	0	0	25.0
17	.19	39	3	.35	0	13	0	8.93	8.33	78	1	0	0	66.7
18	.19	39	3	.35	0	13	0	9.13	7.74	78	1	0	0	30.0
19	.19	39	3	.35	0	13	0	5.46	4.84	78	1	0	0	16.7
20	.17	40	3	2.15	6	65	0	5.39	5.19	99	0	0	0	60.0
21	.17	40	3	2.15	6	65	0	4.14	3.57	99	0	0	0	75.0
22	.17	40	3	2.15	6	65	0	5.97	5.24	99	0	0	0	20.0
23	.07	25	4	0.00	0	0	0	1.73	1.65	109	0	0	0	43.3
24	.07	25	4	0.00	0	0	0	1.22	1.12	109	0	0	0	52.3
25	.07	25	4	0.00	0	0	0	1.95	1.31	109	0	0	0	92.0
26	.25	32	3	4.07	82	197	92	.62	.61	100	0	0	1	7.7
27	.25	32	3	4.07	82	197	92	1.33	1.29	100	0	0	1	16.9
28	.25	32	3	4.07	82	197	92	1.32	1.19	100	0	0	1	30.0
29	.23	39	3	1.91	100	123	100	1.35	1.21	103	0	0	0	63.3
30	.23	39	3	1.91	100	123	100	1.27	1.15	103	0	0	0	36.9
31	.23	39	3	1.91	100	123	100	1.84	1.52	103	0	0	0	55.6
32	.27	45	3	4.35	100	216	100	2.30	1.32	71	0	0	0	57.5
33	.27	45	3	4.35	100	216	100	1.10	1.01	71	0	0	0	68.0
34	.27	45	3	4.35	100	216	100	1.08	.96	71	0	0	0	36.4
35	.13	39	3	1.28	41	59	29	2.53	2.38	105	0	0	0	50.0
36	.13	39	3	1.28	41	59	29	3.20	2.99	105	0	0	0	74.3
37	.13	39	3	1.28	41	59	29	1.09	1.76	105	0	0	0	40.0
38	.16	34	4	2.17	26	90	39	2.56	2.24	96	0	0	0	56.7
39	.16	34	4	2.17	26	90	39	1.79	1.63	96	0	0	0	25.7
40	.16	34	4	2.17	26	90	39	2.05	1.81	96	0	0	0	84.0
41	.20	44	3	3.11	64	160	79	2.83	1.94	97	0	0	0	66.7
42	.20	44	3	3.11	64	160	79	4.45	3.38	97	0	0	0	36.7
43	.20	44	3	3.11	64	160	79	1.90	1.63	97	0	0	0	57.5
44	.19	43	3	1.83	43	87	33	5.29	4.15	87	0	1	0	36.7
45	.19	43	3	1.83	43	87	33	8.72	5.62	87	0	1	0	24.3
46	.19	43	3	1.83	43	87	33	7.25	4.31	87	0	1	0	31.4
47	.15	51	3	2.22	40	116	62	9.42	6.68	87	0	1	0	35.0
48	.15	51	3	2.22	40	116	62	7.39	5.19	87	0	1	0	46.0
49	.15	51	3	2.22	40	116	62	3.45	2.37	87	0	1	0	25.0
50	.12	34	4	3.92	22	159	76	1.77	1.53	94	0	0	0	57.1
51	.12	34	4	3.92	22	159	76	2.61	2.15	94	0	0	0	36.3
52	.12	34	4	3.92	22	159	76	2.04	1.73	94	0	0	0	78.5
53	.26	41	3	3.52	89	180	100	2.22	1.90	95	0	0	1	36.7
54	.26	41	3	3.52	89	180	100	1.47	1.18	95	0	0	1	37.5
55	.26	41	3	3.52	89	180	100	1.14	1.01	95	0	0	1	35.0
56	.15	38	3	2.58	98	132	100	1.76	1.51	103	0	0	0	91.7
57	.15	38	3	2.58	98	132	100	2.10	1.66	103	0	0	0	81.8
58	.15	38	3	2.58	98	132	100	1.42	1.15	103	0	0	0	30.0
59	.10	35	3	2.07	33	94	49	1.20	1.10	129	0	0	0	26.7
60	.10	35	3	2.07	33	94	49	1.11	1.02	129	0	0	0	25.3
61	.10	35	3	2.07	33	94	49	1.86	1.61	129	0	0	0	40.0
62	.16	35	3	2.70	31	121	0	2.64	2.12	88	0	0	0	100.0
63	.16	35	3	2.70	31	121	0	1.87	1.51	88	0	0	0	57.5
64	.16	35	3	2.70	31	121	0	1.40	1.20	88	0	0	0	83.3
65	.32	44	3	1.38	65	97	0	4.99	3.32	88	0	0	0	60.0
66	.32	44	3	1.38	65	97	0	5.59	4.86	88	0	0	0	45.9
67	.32	44	3	1.38	65	97	0	4.46	2.72	80	0	0	0	62.9

APPENDIX B

AVERAGE STREAMBED, CHANNEL, WATERSHED, AND LAND USE CHARACTERISTICS FOR 21 WATERSHEDS, OREGON COAST RANGE.

(The same column identifications apply as in Appendix A)

A	B	C	D	E	F	G	H	I	J	K	L	M
1	29.4	29.4	37.5	37.5	27.5	2	202	.7	2.6	6.2	.9	1.5
2	12.9	12.9	17.6	17.6	11.7	1	75	.5	1.2	5.5	1.0	1.3
3	15.4	15.4	21.0	21.0	15.0	3	364	.7	2.5	6.5	2.0	1.2
4	10.6	6.4	16.5	13.4	9.5	2	247	.5	4.1	11.4	1.3	1.1
5	14.0	6.1	20.0	6.7	12.7	2	373	1.0	5.4	7.6	3.2	1.2
6	13.3	11.0	16.6	14.0	12.0	2	202	.5	2.1	9.4	2.0	1.2
7	16.7	17.9	23.1	22.1	17.9	2	119	.4	1.2	12.4	1.0	1.5
8	49.3	49.3	61.4	61.4	46.0	3	234	.7	3.2	6.6	.3	1.1
9	23.0	20.7	29.4	26.5	21.3	1	97	1.0	2.7	4.2	3.0	1.1
10	17.0	14.9	22.4	19.5	15.5	1	26	.9	2.1	4.3	9.0	1.3
11	21.7	21.2	25.0	24.4	16.3	2	275	.5	3.9	6.7	1.0	1.4
12	19.3	19.3	23.5	23.5	17.5	2	251	.9	3.3	6.6	1.3	1.2
13	16.7	16.0	21.5	20.6	15.3	1	97	.7	1.3	4.2	2.3	1.2
14	13.4	9.6	18.1	13.0	12.2	2	274	1.2	7.5	7.1	4.7	1.1
15	12.3	9.4	17.0	12.9	11.3	2	245	1.0	5.3	7.3	3.0	1.1
16	15.3	14.0	16.9	17.3	14.5	1	45	1.0	3.1	5.1	2.7	1.1
17	16.1	14.5	22.1	19.5	14.7	2	75	.9	2.3	5.6	3.7	1.1
18	20.7	15.5	23.6	15.3	19.7	2	211	.9	4.1	6.0	1.5	1.1
19	26.3	26.3	34.6	34.6	24.2	3	537	.9	5.4	7.6	1.0	1.3
20	20.3	13.1	23.9	20.6	19.5	2	155	.7	2.5	6.7	2.7	1.4
21	19.6	14.6	24.1	18.1	15.2	1	23	.3	3.2	6.1	3.5	1.4

A	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	ZZ
1	.12	26	4	0.00	0	0	0	1.60	1.52	107	0	0	0	37.2
2	.13	37	3	3.21	100	123	100	1.60	1.51	75	0	0	1	23.7
3	.14	41	3	1.96	37	65	24	2.00	1.39	83	0	0	0	44.0
4	.28	48	4	1.59	0	60	0	6.36	5.50	63	1	0	0	23.6
5	.19	39	3	.35	0	13	0	7.51	6.97	78	1	0	0	37.8
6	.17	40	3	2.15	0	85	0	5.17	4.67	99	0	0	0	51.7
7	.07	25	4	0.00	0	0	0	1.63	1.53	109	0	0	0	62.5
8	.25	32	3	4.07	52	197	92	1.09	1.03	100	0	0	1	18.2
9	.23	39	3	1.91	100	123	100	1.49	1.33	103	0	0	0	51.9
10	.27	45	3	4.35	100	216	100	1.49	1.26	71	0	0	0	54.0
11	.13	39	3	1.28	41	59	29	2.54	2.35	105	0	0	0	54.8
12	.16	33	4	4.24	25	90	39	2.13	1.69	96	0	0	0	55.5
13	.20	44	3	3.10	64	160	79	3.01	2.32	97	0	0	0	53.6
14	.19	43	3	1.37	43	87	33	7.10	4.56	87	0	1	0	30.8
15	.15	51	3	2.22	46	115	62	6.75	4.75	87	0	1	0	35.3
16	.12	34	4	3.92	22	159	76	2.14	1.80	94	0	0	0	57.3
17	.26	41	3	3.52	89	130	100	1.61	1.36	95	0	0	1	36.4
18	.15	36	3	2.55	95	132	100	1.76	1.44	103	0	0	0	84.5
19	.10	35	3	2.07	33	94	49	1.39	1.24	129	0	0	0	30.7
20	.16	35	3	2.69	31	121	0	1.97	1.61	55	0	0	0	80.2
21	.32	44	3	1.38	65	97	0	5.13	3.63	88	0	0	0	56.3

APPENDIX C. CORRELATION MATRIX FOR DATA IN APPENDIX A. (The same column identifications apply as in Appendix A).

	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
C	.97																								
D	.99	.96																							
E	.96	.99	.97																						
F	.99	.96	.97	.95																					
G	.35	.35	.35	.35	.34																				
H	.12	.11	.14	.12	.11	.80																			
I	-.12	-.21	-.10	-.20	-.13	-.05	.20																		
J	-.05	-.14	-.02	-.13	-.07	.29	.54	.00																	
K	-.06	-.08	-.06	.08	.04	.44	.35	-.45	.02																
L	-.32	.37	-.30	-.35	-.31	-.40	-.33	.46	.17	-.40															
M	.26	.29	.25	.27	.25	-.03	-.04	-.10	-.11	-.10	-.17														
N	-.05	-.12	-.02	-.09	-.04	-.28	-.36	.23	.06	-.23	.46	-.27													
O	-.52	-.56	-.40	-.52	-.53	-.23	-.06	.41	.20	-.24	.48	-.41	.59												
P	.11	.17	.13	.10	.13	-.02	-.06	-.24	-.16	.33	-.32	.22	-.32	-.53											
Q	-.07	-.04	-.00	-.05	-.05	-.20	-.34	.15	-.13	-.45	.36	-.37	.36	.37	-.42										
R	.03	-.02	.01	.01	.03	-.33	-.43	.16	-.13	-.50	.34	-.25	.44	.35	-.63	.68									
S	-.02	-.01	-.03	-.02	-.01	-.24	-.40	.20	-.12	-.50	.42	-.38	.48	.42	-.51	.96	.70								
T	.03	.05	.03	.05	.04	-.27	-.33	.20	-.10	-.49	.25	-.33	.20	.21	-.39	.77	.06	.01							
U	-.45	-.54	-.41	-.52	-.44	-.04	.22	.32	.49	.11	.16	-.23	.26	.56	-.14	-.21	-.29	-.21	-.35						
V	-.44	-.53	-.40	-.51	-.43	-.01	.26	.27	.43	.17	.10	-.23	.24	.50	-.10	-.26	-.36	-.27	-.40	.97					
W	.44	.40	.41	.47	.43	.39	.37	-.16	-.02	.26	-.52	.17	-.49	-.57	.23	-.31	-.23	-.29	-.09	-.39	-.38				
X	-.24	-.32	-.19	-.28	-.24	.07	.30	.13	.31	.20	-.01	-.11	.20	.26	.15	-.27	-.30	-.31	-.33	.53	.64	-.38			
Y	-.23	-.25	-.21	-.23	-.23	.07	.17	.43	.53	-.01	.24	-.24	-.03	.43	-.20	-.01	-.01	.01	.03	.54	.39	-.19	-.10		
Z	.22	.25	.25	.26	.23	.08	-.20	-.10	-.10	-.11	-.13	-.11	.22	-.08	-.24	.47	.50	.43	.51	-.27	-.26	-.13	-.12	-.12	
ZZ	-.19	-.24	-.30	-.33	-.17	-.22	-.23	-.01	-.16	-.10	.14	-.04	-.10	-.05	-.05	.05	.09	.08	-.01	-.10	-.10	.03	-.21	-.17	-.34

APPENDIX D

PERCENT ORGANIC MATTER (BY WEIGHT) OF FROZEN CORE SAMPLES ASHED AT 310°C AND 550°C

Sample Number	Percent Organics at 310°C	Percent Organics at 550°C	Increase in Percent Organics
1	3.4	5.4	2.0
2	4.7	7.0	2.3
3	2.4	4.1	1.7
4	2.4	4.6	2.2
5	3.1	5.3	2.2
6	2.8	5.5	2.7
7	2.7	4.5	1.8
8	2.7	5.1	2.4
9	2.9	5.8	2.9
10	2.9	5.4	2.5
11	6.5	9.0	2.5
12	2.6	5.5	2.9
13	2.5	4.8	2.3
14	2.5	4.7	2.2
15	2.8	5.5	2.7
16	2.9	5.9	3.0
17	6.6	8.9	2.3
18	3.5	5.6	2.1
19	3.0	5.1	2.1
20	3.7	6.2	2.5

APPENDIX E. PERCENT FINES LESS THAN 1.0 mm (BY WEIGHT) BY DEPTH FOR 59 LIQUID NITROGEN CORES.

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13
0-10 cm	29.0	24.0	42.0	14.0	24.0	40.0	14.0	14.3	6.3	4.3	8.9	11.5	8.4
10-25 cm	32.0	32.0	49.0	20.0	25.0	23.0	11.7	17.8	11.4	8.6	15.7	25.9	12.5
25-40 cm	28.0	26.0	73.0	25.0	20.0	16.0	21.6	10.9	20.0	8.3	19.0	20.1	15.5
Sample	14	15	16	17	18	19	20	21	22	23	24	25	26
0-10 cm	12.1	3.3	20.0	24.6	14.8	51.6	49.0	31.7	18.6	14.4	19.7	14.1	7.9
10-25 cm	16.6	10.1	18.0	16.9	18.9	66.5	47.5	43.4	18.7	31.6	31.6	17.4	29.8
25-40 cm	22.4	14.1	22.8	21.8	17.2	63.9	37.7	15.8	15.6	35.2	19.2	15.1	25.1
Sample	27	28	29	30	31	32	33	34	35	36	37	38	39
0-10 cm	8.8	20.9	8.6	26.1	15.5	16.9	16.1	10.8	15.0	10.9	6.2	11.0	6.8
10-25	17.5	30.7	15.7	22.3	24.4	24.9	24.9	16.9	13.3	16.3	17.1	14.0	12.8
25-40 cm	16.1	18.4	20.0	21.2	23.6	14.0	19.2	12.7	20.9	14.1	14.3	13.5	13.2
Sample	40	41	42	43	44	45	46	47	48	49	50	51	52
0-10 cm	11.0	11.2	14.9	11.8	15.7	10.9	16.2	13.8	23.3	14.7	17.1	17.8	30.9
10-25 cm	15.5	12.0	19.6	10.1	17.9	16.1	17.7	19.1	20.3	26.2	19.7	27.0	34.8
25-40 cm	16.7	12.7	18.5	16.4	40.1	15.6	20.8	13.6	17.6	16.8	20.5	55.2	22.0
Sample	53	54	55	56	57	58	59	Average					
0-10 cm	18.8	20.5	15.7	19.5	19.1	17.2	13.5	17.45					
10-25 cm	21.8	37.2	15.1	19.3	23.6	19.8	19.4	22.28					
25-40 cm	38.5	20.0	18.7	21.0	20.8	32.8	18.8	22.16					

APPENDIX F. TIME TRENDS IN PERCENT FINE SEDIMENT AND PERCENT ORGANIC MATTER FOR NEEDLE BRANCH, DEER CREEK, FLYNN CREEK, AND MEADOW CREEK - OREGON COAST RANGE.

Plot	10/15/77	11/20/77	12/10/77	1/9/78	2/10/78	3/11/78	4/8/78	5/7/78	6/4/78
	Percent fines (by weight) less than 1.0 mm								
Needle 1	27.1	25.6	24.6	31.5	27.4	33.8	21.3	28.8	23.0
Deer 1	28.8	22.7	25.3	19.8	51.6	37.9	45.7	49.7	41.0
Deer 2	-	-	-	-	-	-	-	-	-
Flynn 1	21.5	18.8	22.5	7.4	10.8	7.9	5.3	16.5	23.8
Flynn 2	28.4	13.5	17.7	22.5	19.3	20.2	18.7	21.0	26.7
Flynn 3	21.6	25.4	28.3	25.5	25.0	14.5	24.1	26.7	38.7
Flynn 4	30.6	29.7	39.2	41.7	41.8	40.9	38.7	41.1	38.1
Meadow 1	31.5	35.7	26.7	30.5	31.5	31.1	28.0	30.1	32.3
	Percent organic matter (by weight)								
Needle 1	2.9	3.0	4.0	3.4	3.8	4.9	5.1	3.3	4.1
Deer 1	3.3	3.2	6.7	4.2	7.6	6.5	6.8	5.2	15.7
Deer 2	-	-	-	-	-	-	-	-	-
Flynn 1	2.3	3.2	4.6	2.9	3.7	3.9	4.7	3.4	3.9
Flynn 2	2.5	3.2	5.6	4.2	2.6	3.0	5.0	3.5	4.3
Flynn 3	2.6	4.6	4.0	4.7	2.8	3.1	6.1	4.4	3.9
Flynn 4	3.9	4.7	5.6	5.2	2.3	3.4	4.1	3.3	5.8
Meadow 1	2.3	3.6	3.8	2.8	2.0	3.4	3.6	2.5	3.1

Appendix F. (Continued)

Plot	7/6/78	8/7/78	9/1/78	10/6/78	11/10/78	12/3/78	1/9/79	2/15/79	3/10/79	4/7/9
Percent fines (by weight) less than 1.0 mm										
Needle 1	34.9	15.9	21.9	19.5	24.5	21.8	22.5	23.1	18.7	24.2
Deer 1	52.0	33.7	46.2	47.0	52.9	21.9	21.4	32.1	25.0	31.7
Deer 2	-	14.3	16.7	18.2	19.9	21.4	14.0	8.2	8.2	11.1
Flynn 1	14.3	20.6	18.6	23.6	30.8	19.7	11.8	16.2	12.1	8.7
Flynn 2	24.3	21.3	22.1	19.9	31.9	26.4	21.3	22.3	25.5	14.9
Flynn 3	30.4	37.2	43.5	29.9	31.5	33.0	26.7	26.0	21.9	19.4
Flynn 4	35.7	37.8	32.7	43.5	52.2	48.0	40.0	39.2	39.0	39.7
Meadow 1	39.3	32.8	41.4	42.1	39.4	32.3	27.8	24.1	27.9	24.8
Percent organic matter (by weight)										
Needle 1	2.9	3.7	2.7	3.0	2.5	3.3	2.8	1.8	1.3	1.3
Deer 1	6.5	6.6	6.9	5.3	4.7	4.7	2.9	2.4	2.1	3.0
Deer 2	-	3.5	2.4	3.4	2.4	3.0	2.4	2.5	1.2	1.2
Flynn 1	2.6	3.0	2.6	3.5	2.6	3.0	2.6	1.8	0.9	1.5
Flynn 2	2.5	3.7	2.6	3.4	2.6	2.6	9.4	3.3	1.1	1.2
Flynn 3	2.5	2.6	2.7	3.3	2.4	3.7	2.7	1.8	1.0	1.0
Flynn 4	2.9	3.7	6.0	4.5	3.4	4.3	4.4	2.5	2.0	1.8
Meadow 1	2.8	3.7	3.0	3.9	2.9	3.0	2.7	1.7	1.5	1.0

APPENDIX G. TIME TRENDS IN PERCENT FINE SEDIMENT AND PERCENT ORGANIC MATTER FOR GREEN CREEK - OREGON COAST RANGE.

Plot	2/18/78	3/27/78	4/22/78	5/21/78	6/20/78	7/21/78	8/19/78	9/25/78
Percent fines (by weight) less than 1.0 mm								
1	36.1	22.7	29.6	39.0	31.0	37.2	31.2	39.4
2	14.4	16.8	17.5	18.7	22.7	21.5	17.4	24.7
3	29.1	20.9	29.5	28.6	24.7	27.0	25.1	32.8
4	17.5	16.7	27.6	17.5	23.4	23.2	23.1	21.7
5	17.0	19.3	17.7	14.5	22.0	21.4	19.2	24.1
Percent organic matter (by weight)								
1	4.8	5.9	5.7	4.0	5.6	11.5	4.7	4.9
2	2.6	3.0	4.1	2.2	3.8	3.2	2.7	3.4
3	3.3	3.6	4.1	2.4	4.8	3.0	3.7	3.1
4	3.1	2.8	2.9	1.8	4.8	3.0	2.6	2.8
5	4.2	3.7	3.5	3.5	4.0	3.3	2.5	2.9

Appendix G. (Continued)

Plot	10/27/78	11/24/78	12/16/78	1/23/79	2/20/79	3/22/79	4/12/79
			Percent fines (by weight) less than 1.0 mm				
1	41.0	36.1	34.3	33.9	39.5	23.1	15.1
2	22.9	19.9	18.4	17.2	15.4	18.1	13.9
3	39.3	29.8	32.1	35.6	29.6	22.1	30.2
4	24.8	29.7	27.8	24.7	22.9	21.9	18.5
5	21.3	16.6	22.6	30.9	26.5	19.1	15.7
			Percent organic matter (by wt.)				
1	5.1	3.6	4.9	4.9	4.8	2.1	2.2
2	3.1	1.7	2.4	3.1	1.6	1.1	1.8
3	3.5	1.9	2.7	5.2	1.7	1.3	2.9
4	3.8	2.0	2.7	2.9	1.4	1.9	2.6
5	5.5	1.6	2.6	3.3	1.7	1.4	1.7

APPENDIX H

ANALYSIS OF VARIANCE TABLES FOR MODELS 1 THROUGH 4

Model	Source	Degrees of freedom	Sum of Squares	Mean Square
1	Total	66	6831.38	103.51
	Regression	5	3666.98	733.40
	Error	61	3164.41	51.88
2	Total	20	1386.26	69.31
	Regression	4	914.62	288.66
	Error	16	471.64	29.48
3	Total	6	952.32	158.72
	Regression	2	782.99	391.49
	Error	4	169.33	42.33
4	Total	6	952.32	158.72
	Regression	1	706.58	706.58
	Error	5	245.74	49.15