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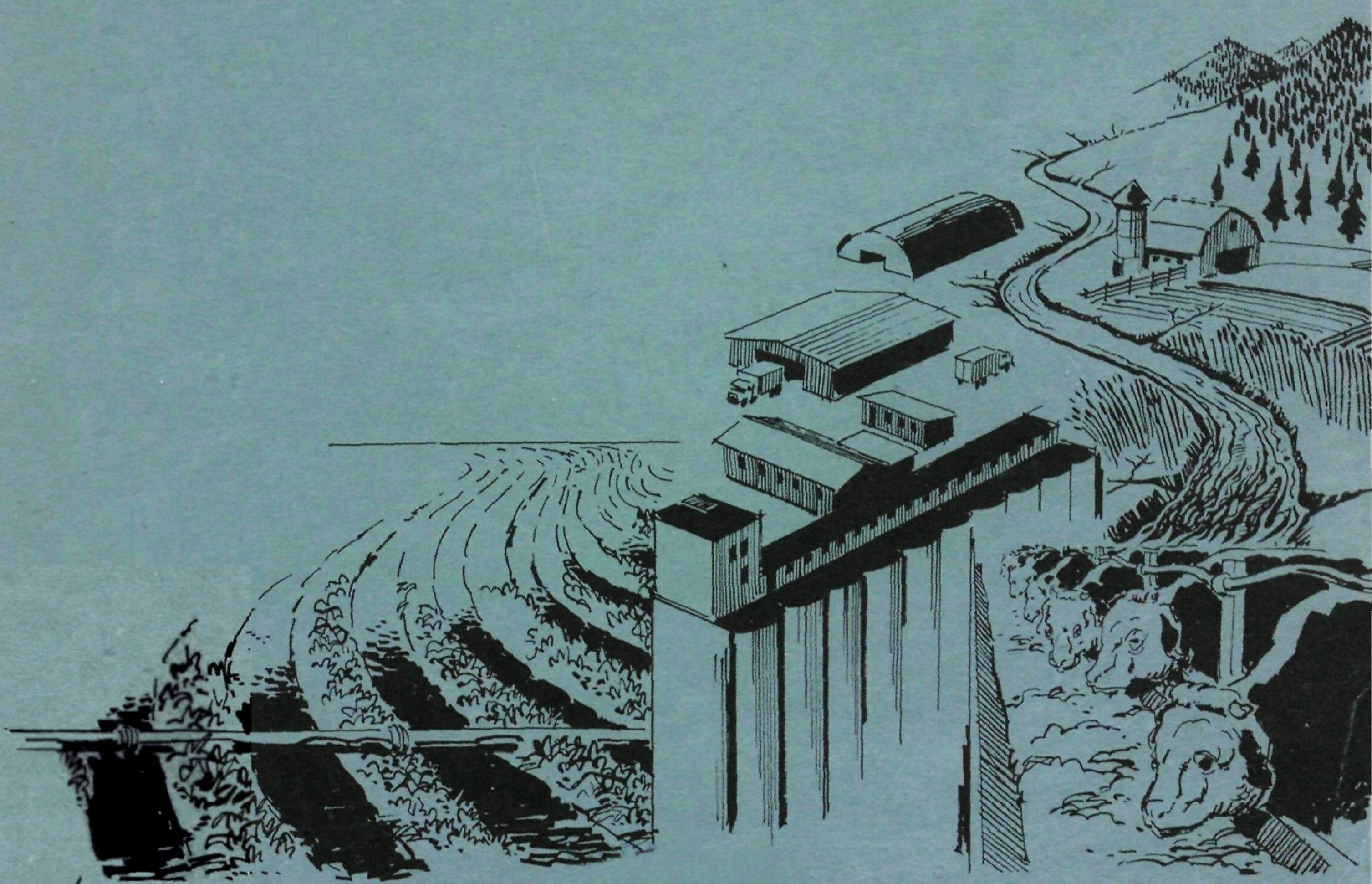
STUDIES ON EFFECTS OF WATERSHED PRACTICES ON STREAMS



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STUDIES ON EFFECTS OF WATERSHED PRACTICES ON STREAMS

by

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for the

ENVIRONMENTAL PROTECTION AGENCY

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EPA Review Notice

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ABSTRACTS

Chapter I - Effects of Clearcutting on Stream Temperature

The purpose of the substudy was to describe the long-term effects of clearcutting timber on two small streams in the Oregon Coast Range.

One watershed contained three small clearcuts; the edges of the clearcuts were generally 100 feet from the main stream, thus providing shade. The second watershed was completely clearcut and most of the main stream was exposed. A third watershed and some uncut subwatersheds were retained as uncut controls. The three watersheds range from 175 to 750 acres.

The diurnal temperature regime was not altered after logging on the watershed with three small clearcuts. The fully clearcut watershed had a maximum diurnal change in temperature of 8°F. before it was logged, but 28°F. after logging.

The maximum temperatures recorded in the 2 years after logging on the patchcut watershed was 60 and 61.5°F.--little different from the control. The maximum temperature on the fully exposed stream after logging was 85°F., a 28°F. increase. All temperature regimes had a trend toward the prelogging condition in subsequent years.

The principal conclusion was that temperature change in these small streams is associated with the degree of exposure to sunlight. The changes in temperature lessen as the area along the stream revegetates.

Streamside strips will minimize temperature change after logging. The decision to leave such strips depends on timber and aquatic values, the degree of temperature change anticipated if timber is removed, and re-establishment rate of streamside vegetation.

Chapter II - Predicting the Effect of Clearcutting on Stream Temperature

The purpose of this study is to present a practical technique for estimating the maximum change in temperature that would result after the shade has been removed from forest streams by clearcutting.

Previous prediction studies by Brown had shown that accurate hourly predictions could be achieved on small streams using energy budget techniques. Solar radiation accounted for over 95 percent of the heat input during the midday period of midsummer and led to the conclusion that a simple technique could be applied in estimating temperature change.

The components of prediction are

$$\Delta T = \frac{A \times H}{D} \times 0.000267$$

where ΔT is the predicted change in temperature; A = surface area in square feet of the stream exposed by clearcutting, excluding isolated pools; H = rate of heat absorbed by the stream in British Thermal Units; D = minimum discharge rate in cubic feet per second.

Application of the method is described in detail.

Chapter III - Heat Loss from a Thermally Loaded Stream

The purpose of this study was to ascertain the way heated streams lose heat as they flow into forests from a clearcut.

Energy budget components were measured using a track and trolley system especially developed for making spatially integrated radiation measurements above small streams. Other measurements included air and water temperature, vapor pressure of the air, and wind speed.

The study site was located downstream from a clearcut in the Cascade Mountains near Roseburg, Oregon. The water temperature reached 80 to 85°F. during midday in the areas of the clearcut.

Energy disposition by radiation, evaporation, convection, and conduction and storage are given for a fully shaded reach below a clearcut, and for a buffer strip within a clearcut. Heat was added to the streams in both cases; amounts were larger where the buffer strip shaded the stream, but in neither case did stream temperature change.

This study confirmed the earlier work on temperature prediction by Brown (1969) that temperature change is closely associated with shade. The hypothesis that shaded zones below clearcuts will cool heated water is questionable. Further, the study showed the effectiveness of narrow buffer strips in controlling water temperature.

Chapter IV - Heat Flow in Stream Beds

The role of the stream bed in heat exchange was studied by measuring thermal conductivities of various bed materials. Thermal gradients were measured in stream beds and cores were obtained for laboratory analysis The study was terminated before these both could be evaluated.

Chapter V - Clearcut Logging and Sediment Production in the Oregon Coast Range

The purpose of this paper was to discover the effect of road building, clearcut logging, and slash burning on suspended sediment production from three forested watersheds in Oregon's Coast Range where precipitation averages 100 inches annually and topography is steep.

Sediment-yield characteristics were monitored for seven years prior to road building and clearcut logging in two of three watersheds; and for four additional years during and after treatment.

On Deer Creek and Needle Branch, mainline roads were built in 1965. In 1966, Deer Creek was clearcut in patches at three locations (about 25 percent cut) and Needle Branch was completely clearcut. Slash in one unit of the patch-cut watershed and in all of Needle Branch was burned. A third watershed was left as a control.

Road building significantly increased sediment yield in both of the treated watersheds. Annual sediment yield increased markedly after logging and burning, and although it declined in subsequent years, was still significantly higher than normal for four years after treatment had been initiated.

During low flow periods (below 5 csm), even the most severe treatment on Needle Branch resulted in only a few days with concentration above 10 ppm.

The results indicate that clearcut logging does not cause major impact on sediment concentrations, but that road building and perhaps burned areas are important sources of sediment.

Chapter VI - Evaluation of Bed Load and Total Sediment Yield Processes on Small Mountain Streams

A facility was developed to study bed-load processes in small gravel-carrying, mountain streams. One portion had a reach subject to natural runoff and one portion had a controllable channel where gravel beds coul be placed. The facility provided data on bed-load transport rates for gravelly mountain streambeds, on limits of scour during storms and on interrelations between the streambed and the suspended sediment load of the stream.

An "armor" layer of coarse gravels at the top surface of the streambed was examined. The layer appeared to protect the streambed from scour until discharges became sufficiently great, after which the bed was set in motion to a depth of several particle diameters. As discharges receded after storms, the armor layer acted as a silt reservoir for the stream.

A major contribution of this research is the development of an effective tool for sampling the bed load of a stream in sediment-yield studies of water quality, turbidity, and watershed practices and their relationship to stream hydraulics.

In large peak discharges, the bed-load at the study area approached 70 percent of the suspended-load transport.

Basic research on bed-load transport rates during storm runoff should continue to extend the tentative results obtained to date, by this study, so as to better assess the effect of logging practices and other watershed practices upon streamflow, sediment transport, and stream channel changes.

This report was submitted in fulfillment of Project 13010EGA under the partial sponsorship of the Environmental Protection Agency.

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CHAPTER I

EFFECTS OF CLEARCUTTING ON STREAM TEMPERATURE

SECTION I

INTRODUCTION

Timber, water, and sport and commercial fish are the principal resources in the Oregon Coast Range. The need for delineating the areas of conflict between logging and utilization of the other resources led to the establishment of the Alsea Logging-Aquatic Resources Study in 1958. The purpose of this broadly interdisciplinary study was to determine the effect of logging on the physical, chemical, and biological characteristics of small coastal streams.

The purpose of this paper is to describe the long-term effects of two clearcuttings on the temperature regime of two small streams in Oregon's Coast Range. One watershed contained three small clearcuts; the edges of the clearcuts were at least 100 feet from the stream. The second watershed was completely clearcut. An earlier report (Brown & Krygier, 1967) described the first-year effect of clearcutting only during the logging operation on the completely clearcut watershed. This report reviews results from a network of eighteen thermograph stations distributed through the watersheds. The observation period extends from two years before logging through the fourth summer after logging.

Temperature is a significant water-quality parameter. It strongly influences levels of oxygen and solids dissolved in streams. Temperature changes can induce algal blooms with subsequent changes in taste, odor, and color of a stream. Warm water is conducive to the growth and development of many species of aquatic bacteria, such as the parasitic columnaris disease. Increased populations of these bacteria may cause fish mortality (Brett, 1956). The growth of fish may be directly affected by water temperature as demonstrated on juvenile coho salmon (Hall, 1968). In short, water temperature is a major determinant of the suitability of water for many uses.

Research has been limited on temperature changes in small streams from land use, although fisheries biologists have long been concerned with the effects that deforestation can produce on water temperature. Meehan, et al., (1969) studied the effects of clearcutting on the salmon habitat of two Southeast Alaska streams. They noted a statistically significant increase in mean monthly temperatures after logging. The maximum increase in average monthly temperature was about 4°F. The increase in maximum temperatures was about 9°F. during July and August.

During a study of logging and southeastern trout streams, Greene (1950) reported that maximum weekly temperatures recorded during May on a nonforested stream were 13°F. higher than those recorded on a nearby forested stream. He noticed also that the maximum temperature dropped from 80 to 68°F. after the nonforested stream meandered through 400 feet of forest and brush cover.

Levno and Rothacher (1967) reported large temperature increases in two experimental watersheds in Oregon after logging. The shade provided by riparian vegetation in a patchcut watershed was eliminated by scouring after large floods in 1964. Subsequently, mean monthly temperatures increased 7-12°F. from April to August. Average monthly maxima increased by 4°F. after complete clearcutting in a second watershed. The smaller increase in the completely clearcut watershed was the result of shade from the logging debris that accumulated in the channel.

Patric (1969) compared the effect of two clearcutting patterns on water quality. Temperatures were unaffected by clearcutting the upper half of one watershed. Clearcutting the lower half of the second watershed increased temperatures up to 7°F.

SECTION II

THE STUDY

Three experimental watersheds are included in the Alsea Logging-Aquatic Resources Study (Figure 1). These watersheds, which vary in size from 175 to 750 acres, are located in Oregon's Coast Range about 10 miles from the Pacific Ocean. Each stream is an important rearing area for coho salmon (Oncorhynchus kisutch Walbam) and coastal cutthroat trout (Salmo clarki clarki Richardson). In its natural condition, the study area was densely forested with Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco) and red alder (Alnus rubra Bong). The study streams were overgrown with salmonberry (Rubus spectabilis Pursh.), vine maple (Acer circinatum Pursh.), and other species. Although annual precipitation is about 100 inches, the summer months are generally hot and dry. Summer streamflow regularly drops below 0.20 cubic feet per second or 0.17 csm (cfs) on Deer Creek, the largest watershed, and to 0.01 cfs or 0.04 csm on Needle Branch, the smallest watershed.

The low summer flows described above may seem insufficient to support salmon. The adults, however, spawn in these streams during the high flows of the winter months. Salmon fingerlings live in these streams during the summer. The fingerlings inhabit pools, many of which become nearly isolated during the late summer. In the fall, the yearling fish migrate to the sea when rains again increase streamflow. Before logging, the number of yearling fish passing through the fish trap to the sea ranged from 1809 to 3175 in Deer Creek, and from 166 to 630 in Needle Branch (Hall and Lantz, 1969).

The study was designed to permit comparison of two different logging patterns. One watershed, Needle Branch (175 acres), was fully clearcut. A second watershed, Deer Creek (750 acres), was patchcut; 25 percent of this area had several clearcut units. The remainder of the watershed was unlogged. In Deer Creek, strips of vegetation were left along the perennial streams. A third watershed, Flynn Creek (502 acres), was left unlogged as a control. Two small subwatersheds in Deer Creek also served as unlogged controls.

Eighteen 7-day thermographs, accurate to 0.5°F., were installed in the three watersheds to evaluate the effect of the cutting (Figure 1). Thermographs were placed below each proposed logging unit and at the junction of each major tributary in Deer Creek so that effects within the watershed could be determined. In Needle Branch, thermographs were distributed within the clearcutting to evaluate the spatial temperature changes occurring in a fully exposed stream. Thermographs were installed in March, 1964. Probes were placed in flowing water deep enough to insure complete coverage throughout the year. The years 1964 and 1965 served as control periods, and 1966-1969 as treatment periods.

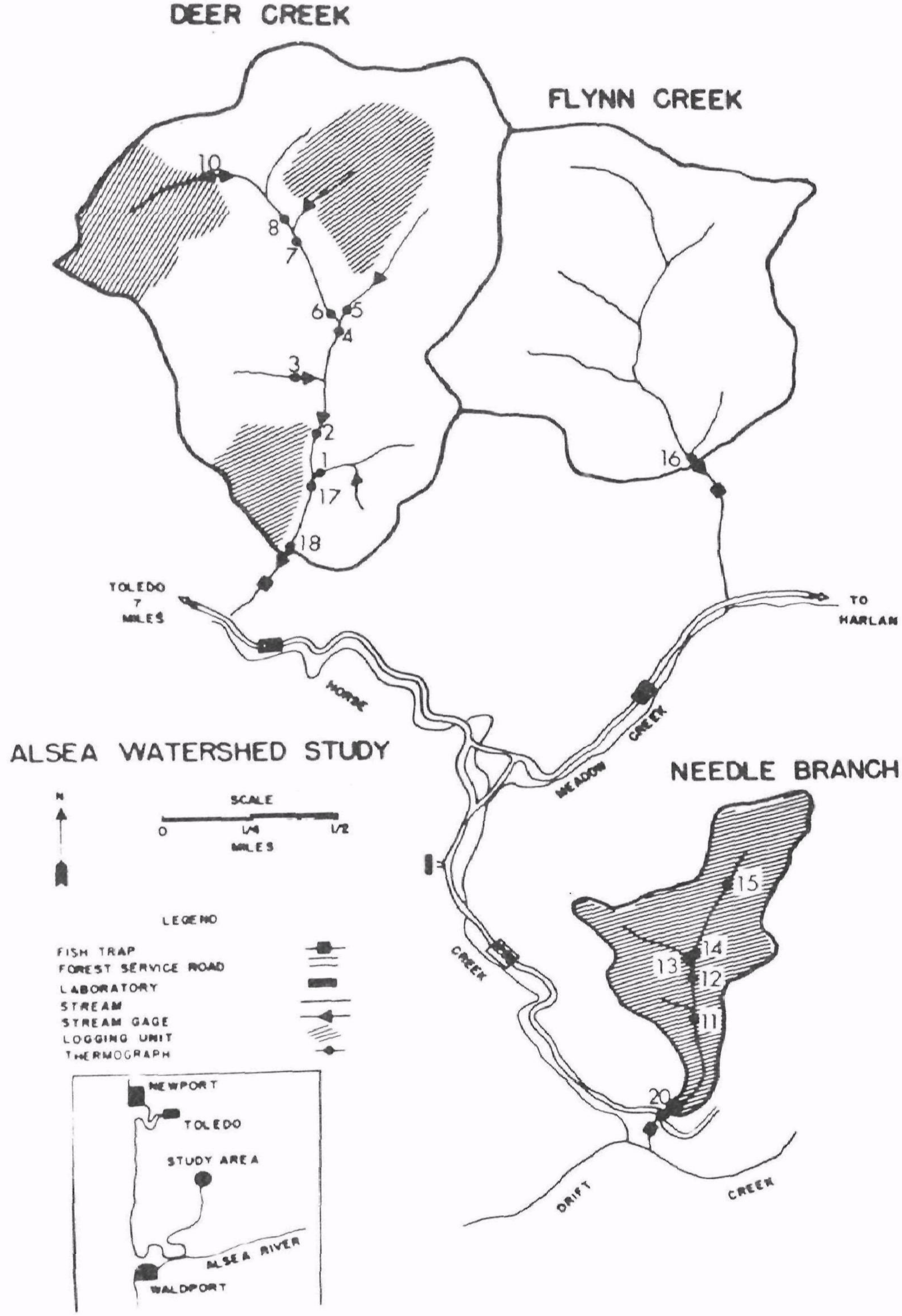

Figure 1. The watersheds of the Alsea Basin logging - aquatic resources study.

Road building was completed in 1965, but, because the roads were built on ridges, little char· occurred that could be interpreted as having any influence on water temperature. Logging began in March, 1966, in both watersheds and was completed in August on Needle Branch and in November on Deer Creek. In October, 1966, the stream in the clearcut watershed was cleared of logging debris. Following clearing, a well-distributed burn removed most logging debris and streamside vegetation. Data reported extend through September, 1969.

SECTION III

RESULTS

The data from this study have been analyzed in two ways. The large changes occurring after clearcutting are presented graphically. The small changes occurring after patchcutting required a statistical analysis to ascertain the significance of these changes. The standard statistical technique of regression could not be used because of the nonrandom effects of climate, the lack of independence between successive daily maxima, and the potential alteration of the variance of seasonal temperature distributions by logging. A stationary time series was developed to circumvent these difficulties (Beck, 1968). Time series techniques are commonly used for analysis of weather data where similar difficulties abound. Jenkins and Watts (1968) describe the application of this technique to several such problems. Our time series compared daily maximum temperatures recorded June 1 - October 1 of the pretreatment years with the daily maxima for the same period during each treatment year. The analysis was applied to data from the control as well as the patchcut watershed to ascertain the effects of climate.

Diurnal Temperature Regimes

The temperature patterns recorded on the days of the annual maximum on the clearcut watershed from 1965 to 1969 are illustrated in Figure 2. The values for 1965 and 1966 occurred at the watershed outlet. The values for 1967, 1968, and 1969 occurred within the cutover unit. A thermograph was installed at 1,000 feet above the outlet in the spring of 1967, after intensive sampling showed that the maximum occurred at this location. This inconsistency in the temperature pattern was the result of incomplete removal of shade from the lower portion of the stream channel after logging and burning. The variation in temperatures recorded at the outlet of the unlogged watershed for the same days is also shown. Minima recorded on the clearcut watershed are about the same as the maxima recorded on the unlogged control. This occurs because travel time through the clearcut watershed is greater than 24 hours during the low flow period. Convection and nocturnal basic radiation are insufficient to cool the water to the same minima measured on the control. The maximum diurnal fluctuation recorded on the clearcut watershed was 28°F. during 1967. The maximum temperature, 85°F. during 1967, represents an increase of 28°F. over the prelogging maximum of 57°F. for 1965. The decline of maximum temperatures after 1967 represents the rapid return of streamside vegetation in this watershed.

The maximum temperatures recorded on the patchcut watershed were 60 and 61.5°F. for 1965 and 1967, respectively. The maximum diurnal fluctuation during both years was 10°F.

A cumulative frequency distribution of the diurnal fluctuations in temperature at the outlet of all three streams from June 1 to

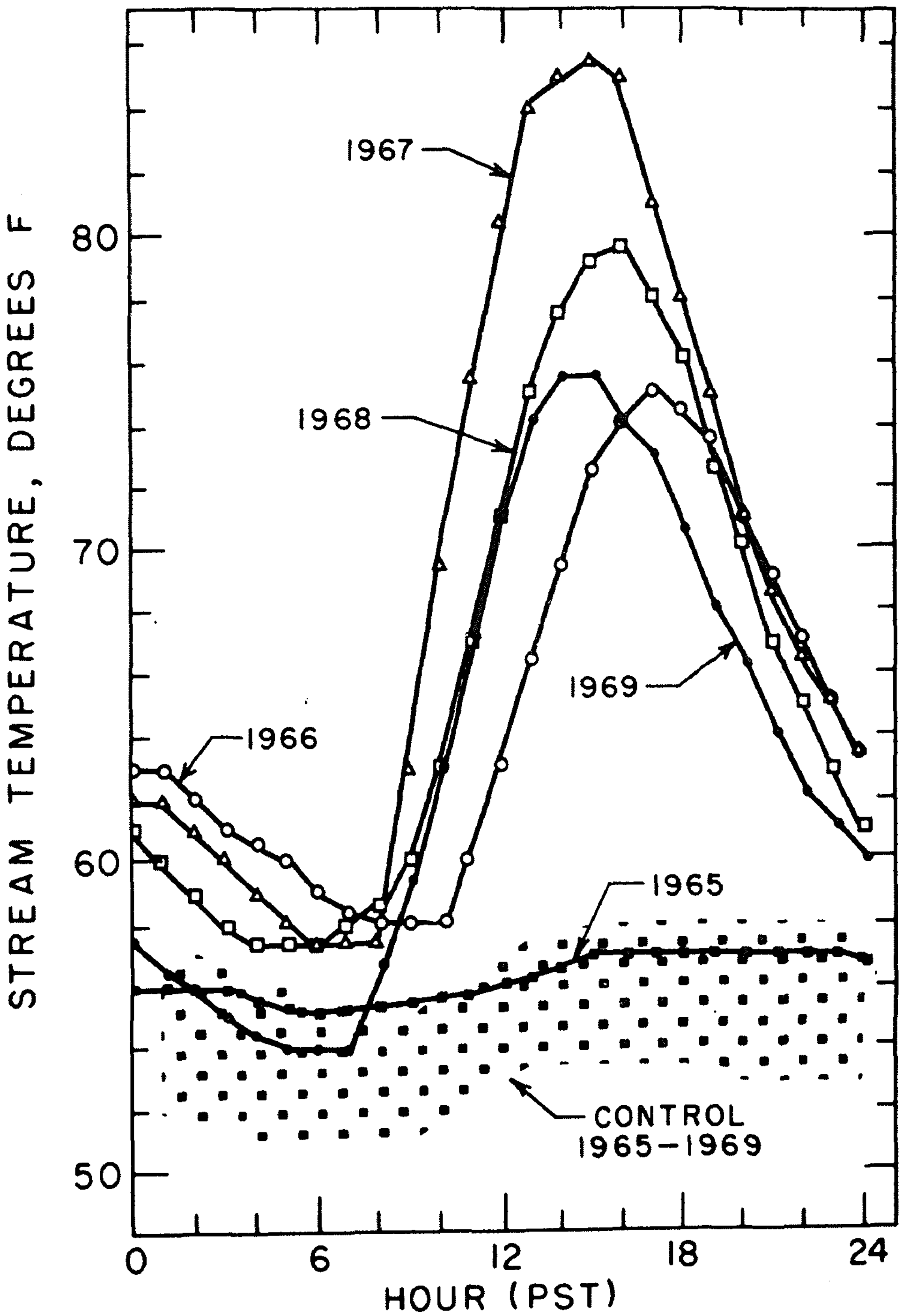

Figure 2. The maximum diurnal change in temperature recorded on the clearcut and uncut control watersheds before (1965), during (1968), and after (1967-1969) logging.

October 1 for the years 1965-1969 is shown in Figure 3. The temperature stability of natural, forested streams is illustrated again in this figure. The maximum fluctuations in temperature before logging in 1965 were 6, 8 and 10°F. on Flynn Creek, Needle Branch, and Deer Creek. These maximum fluctuations were not exceeded on Flynn Creek or at any station within Deer Creek during or after logging. On Needle Branch, the maximum fluctuation of 8°F. was exceeded 28 percent of the time in 1966 and 82 percent of the time in 1967, the year immediately following burning and stream clearance. This percentage dropped to 46 percent in 1968 and 36 percent in 1969, again reflecting the regrowth of streamside vegetation.

The outlet stations are representative of the changes that occurred within each watershed. Temperature fluctuations generally decreased with distance upstream in the patchcut watershed. The most remote station (15) in the clearcut performed similarly to the outlet of Deer Creek.

Monthly Maximum Temperatures

Clearcut. Maximum daily stream temperatures averaged by month for one year before and four years after logging are shown for the outlets of the clearcut and unlogged watersheds in Figure 4. Except for the most remote station (15), the changes recorded at the outlet station are representative of those occurring at the other stations within the clearcut watershed. The highest temperatures again are shown to occur during 1967, the year after stream clearance and slash burning. The mean monthly maximum for July increased from 57°F. in 1965 to 71°F. in 1967. The trend toward the prelogging condition is again shown in this figure.

Patchcut. The frequency diagram illustrates the nearly constant pattern of daily temperature fluctuation recorded on the patchcut watershed throughout the study (Figure 3). A time series was required to determine whether the small increases observed initially were the result of logging or climatic differences between years. The results of the time series are presented in Table 1. Significant changes in the summer maximum temperatures were observed at the outlets on the control and patchcut watershed one year after logging. The larger changes observed on the control indicate that climatic factors, and not the patchcutting, were responsible for this increase. During 1966 and 1968, summer maxima in the stream of the patchcut were nearly the same as those observed before logging. The ten internal stations exhibited smaller changes in temperature than the outlet station. These data show that patchcutting which leaves streamside strips of brush and trees, did not alter temperature patterns of the adjacent stream.

Other inferences about the temperature patterns may be drawn from these data. Clearly, the patterns in summer temperatures of forested streams are relatively constant from year to year. The small differences

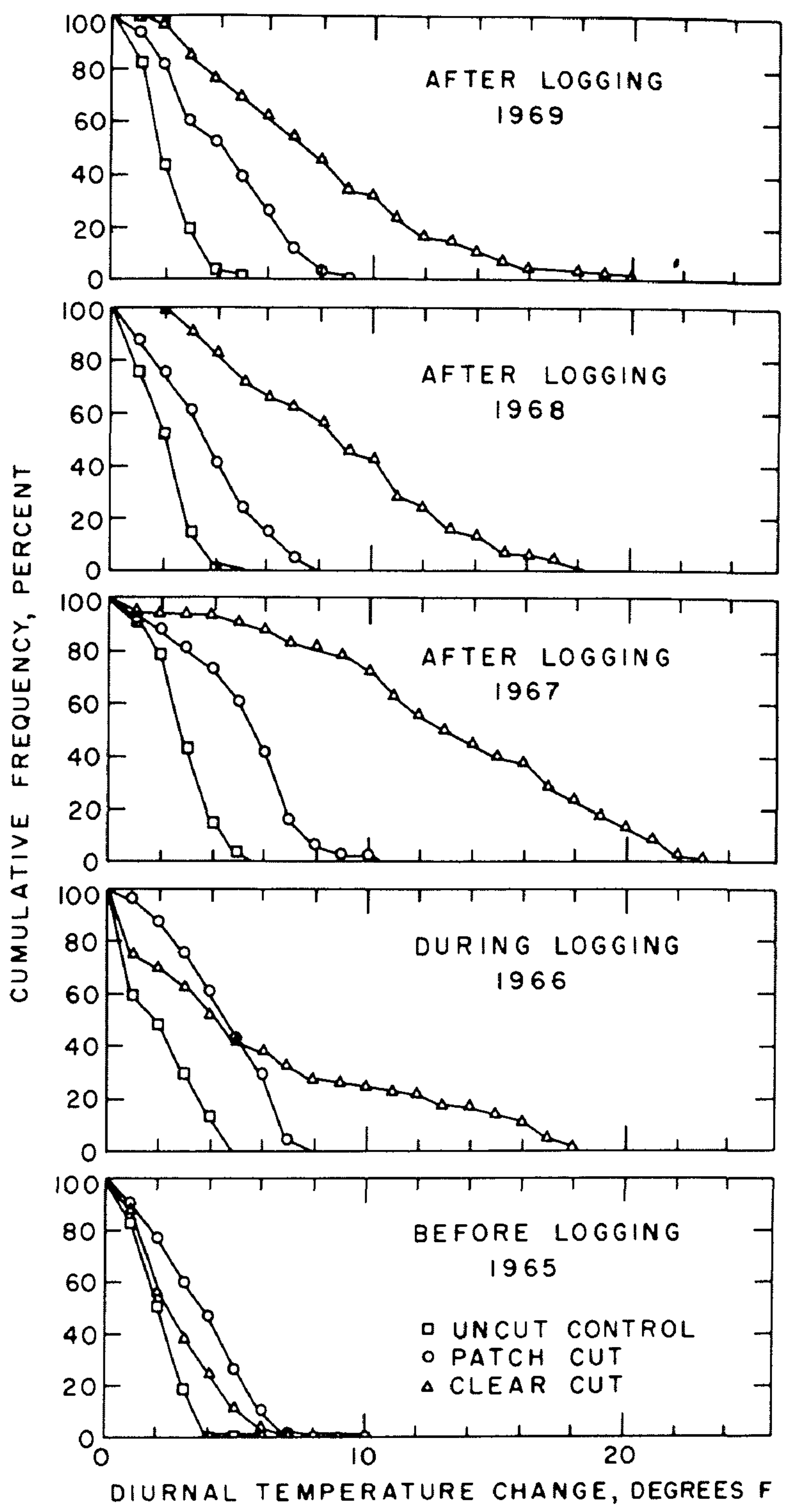

Figure 3. A frequency distribution of diurnal temperature changes on the clearcut, patchcut, and uncut control watersheds before (1965), during (1966), and after (1967-1969) logging.

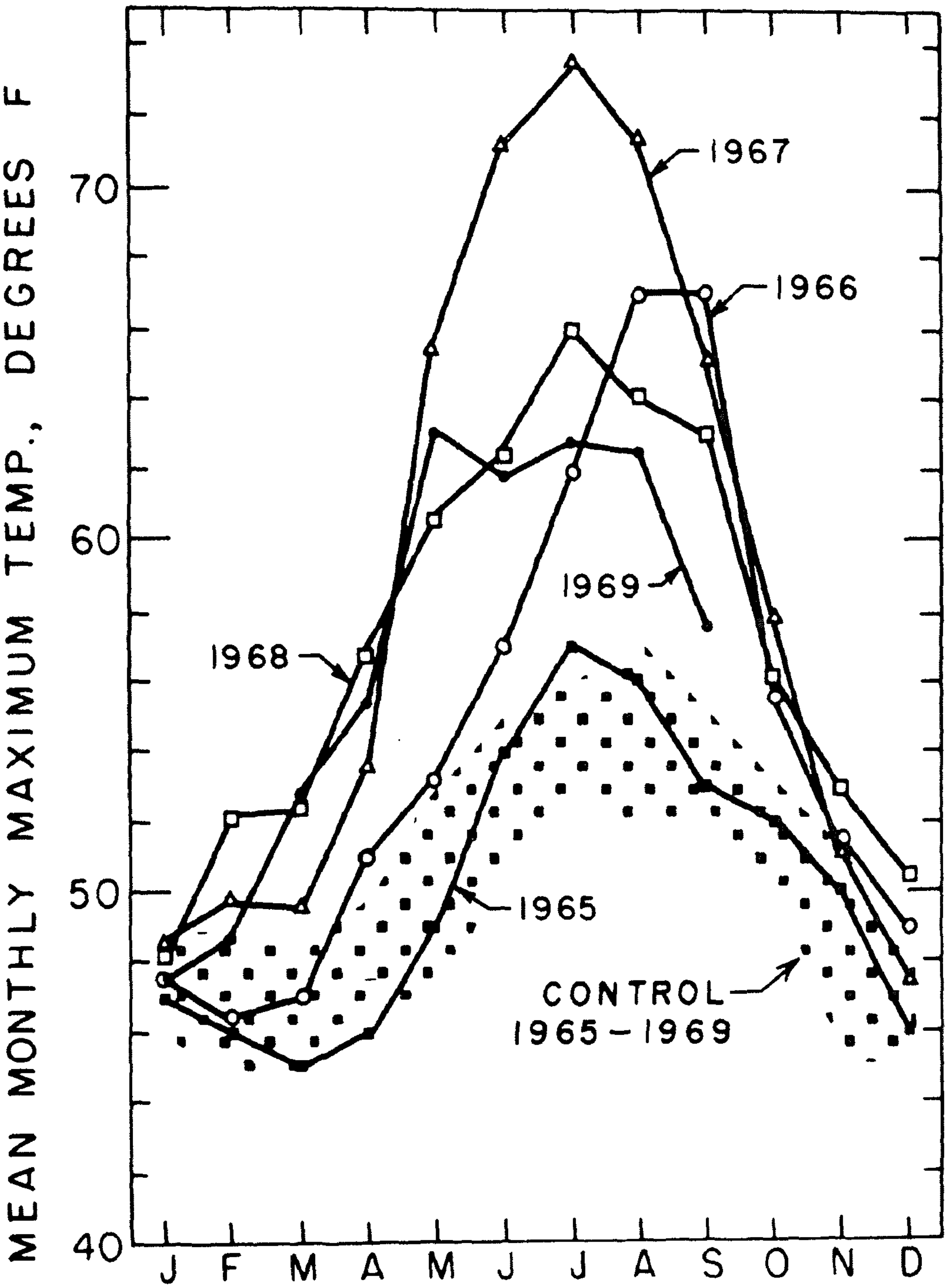

Figure 4. Mean monthly maximum temperatures for the clearcut and uncut control watersheds before (1965), during (1965), and after (1967-1969) logging.

between years listed in Table 1 and the statistical significance of a 2-degree change illustrate little variability in average maximum temperature for a summer.

Table 1. A time series analysis of the difference between daily maximum temperatures of streams before and after patchcutting, for the period of June 1 to October 1.

	Temperature Change, °F.		
Watershed	1966	1967	1968
Flynn Creek (unlogged)	0.8	2.3*	0.3
Deer Creek (patchcut)	0.4	1.9*	-0.4

*Significant at the 5% level of probability.

SECTION IV

DISCUSSION

A detailed description of the hydrologic and atmospheric factors affecting water temperature has been given earlier (Brown, 1969). The most important environmental factor governing temperature change is solar radiation received at the stream surface.

Temperature differences between watersheds and all of the temperature anomalies within the clearcut watershed can be explained in terms of shade differences. The patchcuts on Deer Creek did not produce any significant changes in temperature in the main stream. One-hundred-foot strips of timber were left beside each perennial stream; the amount of shade on the stream surface was essentially unchanged. On Needle Branch, little shade remained after the clearcutting and burning were completed. As a result, large changes in annual and daily patterns of temperature were observed.

The principal cause of high temperature of water following logging is exposure of the stream surface to direct insolation, not the increased soil temperature on the clearcut slopes as has been suggested by Eschner and Larmoyeux (1963). Satisfactory predictions of temperature have been made on Deer Creek and Needle Branch with net radiation as the primary parameter. On these same streams, we found that the maximum rate of net thermal radiation added to the unshaded stream in the clearcut was more than ten times that added to the shaded stream in the patchcut watershed. These differences are reflected in the postlogging temperature patterns of each stream and help explain the temperature stability of most forested streams.

For a given level of solar radiation or heat, stream temperature is inversely proportional to volume. As a result, the temperature patterns of small, shallow streams typical of headwaters regions may be increased significantly by any changes in the solar radiation. Discharge of the stream in the clearcut watershed regularly drops to 0.01 cfs during the hot summer months. Thus, the large changes in temperature recorded after the shade was removed from this stream were to be expected. The flow regime of this small stream is typical of many western Oregon streams that must support salmon and trout during the period of low flow.

Can the results of this study be classified as typical of western Oregon conditions or were they merely caused by unusually hot summers? The maximum temperature of 85°F. recorded for the clearcut and burned watershed is undoubtedly close to the maximum temperature that could occur for this size of clearcut and stream. Because of its small size, the stream responded to each clear day with high temperatures, regardless of the previous day's weather. Even if only one clear, hot day had occurred, this temperature would have been observed. The records of mean monthly temperatures and the frequencies of diurnal change present data for longer periods. The number of days of sunshine, overcast, fog, and rain influence such results. Long-term records of sunshine are not available for the study area. Records at nearby stations, however, indicate that the period of study was not abnormal.

Duration of temperature effects following clearcutting is the subject of continued observation in these experimental streams. The amelioration of temperature is related to the development of shade. As stream bank vegetation becomes re-established, temperatures drop accordingly. In many of the watersheds of the Pacific Northwest, regrowth occurs very rapidly on moist sites. On the basis of our data, it seems that summer maxima may approach prelogging levels within six years after logging has completely exposed the stream if vigorous invasion of such moist-site species as alder, salmonberry, elderberry, and vine maple occurs. The decline of high temperatures noted in Figures 2, 3, and 4 after the 1967 maximum on Needle Branch illustrate this recovery. The stream's temperature patterns are well on the way to returning to the prelogging condition.

Our research reported here and a companion study (Brown, 1969) have illustrated the effect of two patterns of logging on the temperature of small coastal streams and the amelioration of the effect with time. These results, however, have raised several questions about temperature control in the management of fishery, forest, and water resources. Foremost among them is the effect of high temperatures, such as those recorded during 1967 in the clearcut watershed, on fish. Earlier work (Brett, 1952) indicated that, at 27.5°C. (81.5°F.), the time required to induce 50 percent mortality in a population of coho salmon fry is only 70 minutes. But no unusual mortality in coho was observed during this study even though stream temperatures were often above this limit for four to six hours.

The study illustrated the benefit of strips of vegetation alongside small streams for temperature control. The width, density, species composition, and costs incurred when planning streamside strips are only a few of the questions posed by forest managers.

Finally, this study should encourage water resource agencies to engage in further studies of the aquatic habitat in small streams and its relation to land use. Although the temperature changes recorded are defined as thermal pollution in Oregon's current water quality standards, the effect on the coho fishery would suggest that a more precise definition is required. This, of course, will require a better understanding of the response of the aquatic system to temperatures in the lethal and sublethal ranges.

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CHAPTER II

PREDICTING THE EFFECT OF CLEARCUTTING ON STREAM TEMPERATURE

SECTION I

INTRODUCTION

Effects of logging on water yield, peak discharge, and sediment have long been measured and predicted by forest hydrologists. Only recently have researchers and land managers become concerned about the effect of logging on other characteristics of water quality. Considerable attention is now being focused upon water temperature, because of its potential effect on fish populations. In an earlier paper (Brown & Krygier, 1967), the general effect of removing all of the shade from forested streams has been described. How may this information be extended to estimate the effects of clearcuttings of various sizes on other streams? The purpose of this paper is to present a practical technique for estimating the maximum change in temperature that would result after the shade has been removed from forest streams by clearcutting.

TEMPERATURE PREDICTION

The adverse effect of elevated temperature of water on fish and other aquatic organisms led to studies designed to predict changes in temperature. The first efforts were made by engineers concerned with regulation of temperature below large dams (Burt, 1958; Delay & Seaders, 1966). The techniques developed for prediction of temperature on large rivers were subsequently modified by Brown (1969) for use on small streams.

My previous studies (Brown, 1969) showed that accurate, hourly predictions of temperature could be made on small streams using energy budget techniques and on-site meteorological measurements. I found that air temperature and the cooling effect of evaporation were much less important than solar radiation in controlling temperature on small, unshaded streams in the Oregon Coast Range. Solar radiation accounted for over 95 percent of the heat input during the midday period at mid-summer.

Predicting the hourly change in temperature is often unnecessary, however, if the maximum change produced by clearcutting can be assessed. Estimates of the maximum change would be sufficient to permit a prediction of any major change in stream ecology. Hourly prediction of temperature requires experience in micrometeorology and considerable expenditure for equipment.

The simplified temperature prediction technique has been published (Brown, 1970). It also appears below.

The potential effect of a clearcutting on maximum temperatures of a stream may be estimated without extensive meteorological expertise or equipment. Uniform exposure of the stream surface to direct sunlight can often be assumed. If the stream surface is not dappled with spots of sunlight and shade, elaborate systems for sampling solar radiation are not required.

The dominance of direct sunlight also simplifies the prediction technique. Because the maximum change in temperature will no doubt occur during the midday hours on a clear day, predicted rather than measured solar radiation can be used to estimate the heat input for an exposed stream. Topographic shading is also likely to be unimportant during this midday period.

Once this heat input is assessed, the predicted change in temperature (ΔT) can be computed as the ratio of the heat added to the volume of water heated. The heat added to the system is computed as the product of the rate of heat (H) absorbed by the stream, in British thermal units per square foot per minute, and the surface area (A) in square feet of the stream exposed by the clearcutting. Water in isolated pools should not be measured. Neither should moving water in the backwater sections of large pools in the main stream where velocity is zero or directed upstream. The maximum change in temperature will occur when the greatest amount of heat warms the smallest volume of water. This volume is represented by the minimum discharge rate in summer (D) in cubic feet per second. Rates can be used in this ratio because the times during which the rates apply are the same for numerator and denominator. In equation form, this ratio becomes:

$$\Delta T = \frac{A \times H}{D} \times 0.000267 \qquad [1]$$

The constant, 0.000267, converts discharge in cubic feet per second to pounds of water per minute. The temperature change is then in units of Btu per lb of water and thus is equivalent to temperature in degrees Fahrenheit.

The stream surface to be exposed by a proposed clearcutting and the lowest discharge in summer can be measured the year before logging. How, then, may the heat input be estimated?

The amount of heat received from the sun on a clear day depends upon solar angle. Solar angle, in turn, depends upon season, time of day, and latitude. The symmetry of the solar path, however, permits construction of a series of curves that provide hourly values for solar angle on the basis on the sun's angle at solar noon. This information may be obtained with a solar ephemeris (List, 1966, pp. 500-502).

Raphael (1962) converted Moon's (1940) standard curves to determine incoming solar radiation in Btu/ft^2-hr as a function of solar angle. Raphael's values have been multiplied by the appropriate solar angles to provide, in Table 1, an estimation of the total (direct and diffuse) incoming shortwave radiation throughout the day as a function of midday solar angles.

Part of this incoming radiation is reflected. The amount reflected is, again, determined by the sun's angle. Dirmhirn (1964) has presented reflection values from water surfaces for several solar angles. These data are included in Table 2.

The incoming energy in Table 1 is reduced by considering the appropriate solar angle and the reflectivity given in Table 2. The product of this computation is the approximate hourly net solar radiation for given sun angles at solar noon (Figure 1).

Heat may be added to the stream by incoming long-wave radiation. This input, however, is about equal to the back radiation from the water. Subsequent computations recognize these sources of heat gain and loss, but because their net effect is approximately zero, they are not considered directly.

Table 1. Incoming shortwave and diffuse radiation on a horizontal surface, Btu/ft^2-min

Hour		Midday solar angle					
A.M.	P.M.	30°	40°	50°	60°	70°	80°
12		2.42	3.27	4.02	4.63	5.10	5.36
11	1	2.37	3.10	3.87	4.51	4.91	5.18
10	2	1.86	2.77	3.42	4.02	4.45	4.72
9	3	1.31	2.05	2.77	3.27	3.65	3.95
8	4	0.52	1.12	1.77	2.33	2.68	3.02
7	5	0.04	0.29	0.58	1.31	1.49	1.77
6	6	0.00	0.00	0.13	0.45	0.51	0.58

Table 2. Percent reflection from water surfaces, after Dirmhirn(1964).

	Sun angle, degrees									
Radiation	5	10	15	20	25	30	40	50	60	70
	Percent reflection									
Solar	67	40	26	17	12	12	8.5	5	3	2.7
Diffuse sky	17	15.5	14.5	13.2	12.5	11.2	9.3	8	7.4	7.0
Total	84	55.5	40.5	30.2	24.5	23.2	17.8	13	10.4	9.7

The rate of incoming energy is constantly changing (Figure 1). To determine the appropriate rate of energy for the temperature-change equation, we need to know how long the stream will be exposed to the direct rays of the sun. This necessitates measuring the time required for the stream to flow through the proposed clearcutting during the low-flow period--that is, the travel time. Travel time can easily be estimated by observing the time required for a slug of dye to move through the area.

To predict the maximum change in water temperature as the stream flows through the clearcutting, an estimate of the maximum input of heat must be made. This estimate is made by averaging the net radiation about the noon maximum for a given travel time (Figure 2). A 2-hour travel time, for example, would require averaging the incoming radiation from 11:00 a.m. to 1:00 p.m.

A forester may now estimate the maximum change in temperature that a clearcutting would produce. The procedure may be summarized as follows:

1. Mark the upstream and downstream boundaries of the proposed clearcutting.
2. Determine the lowest discharge during the summer and the dates during which it occurs.
3. Determine the surface area of the stream in the proposed clearcutting during the low-flow period.
4. With dye, determine the travel time of the stream through the proposed clearcutting during the low-flow season.
5. From a solar ephemeris, determine the highest sun angle at solar noon for the period of low flow.
6. Enter figure 2 with the appropriate travel time. Move up to the correct curve for the sun angle at solar noon and read the average radiation in Btu/ft^2-min.
7. Compute the predicted maximum change in temperature using Equation 1.

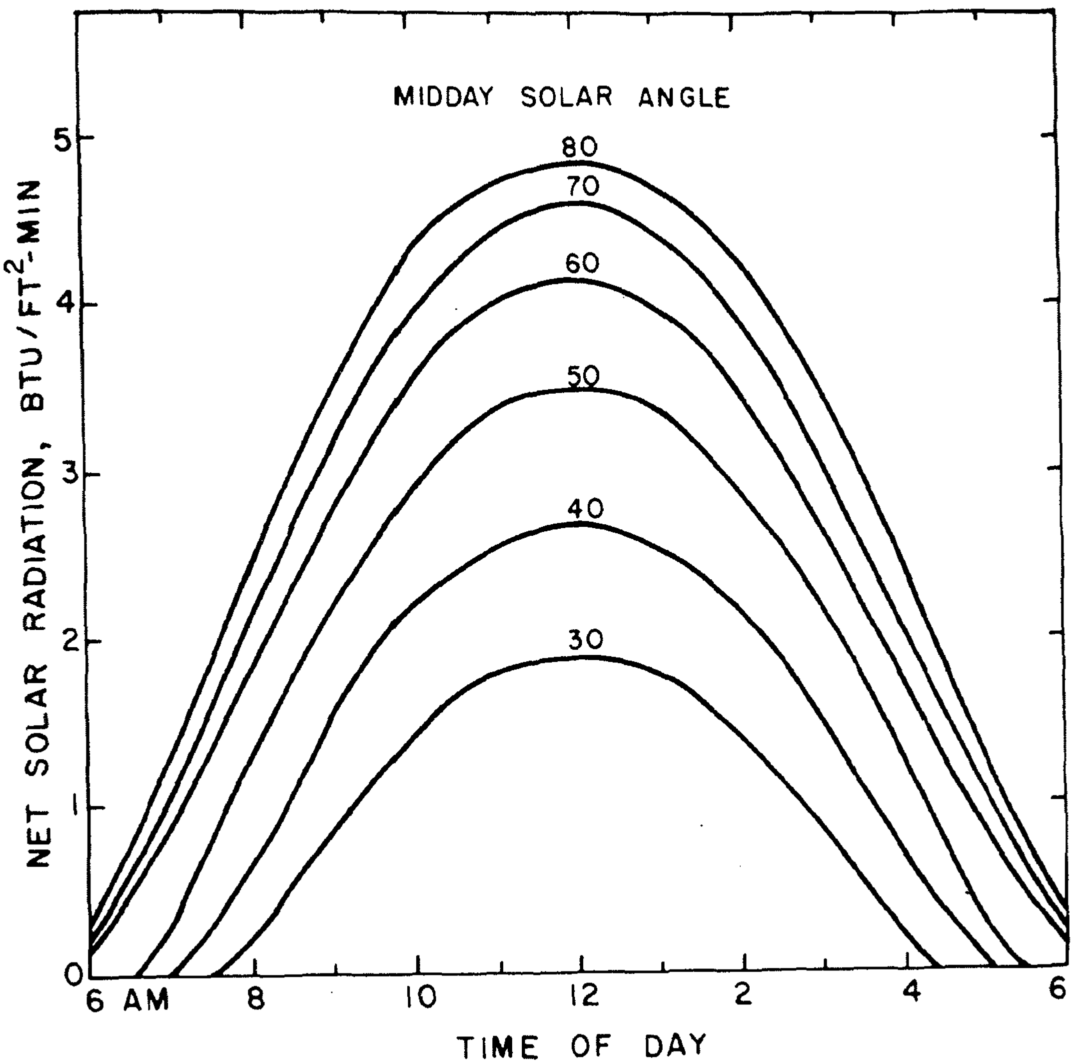

Figure 1. Hourly values for net solar radiation above water surfaces in clear days between latitudes 30N and 50N for several solar paths.

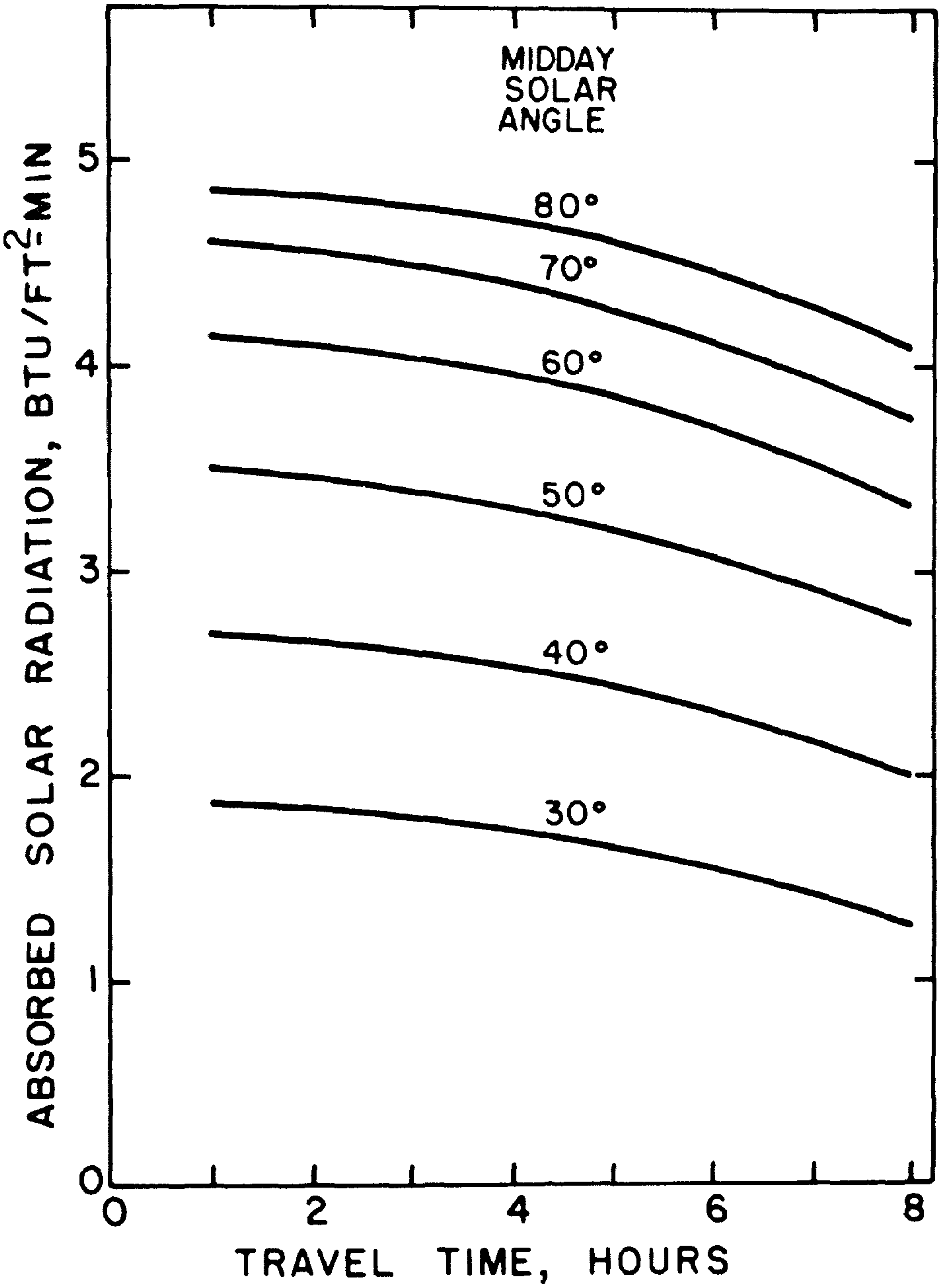

Figure 2. Average net solar radiation absorbed by streams between latitudes 30N and 50N on clear days during several periods of exposure to different solar paths.

SECTION III

DISCUSSION

On a single stream without tributaries, this method will provide estimates of changes in temperature within about 3°F of the true value. The technique was tested on two streams in Oregon bounded by clearcuttings. Temperature changes of 16°F were predicted within 1°F.

This simplified method for predicting stream temperature does have some limitations, however. First, it is assumed that no surface tributaries flow into the section of stream exposed by clearcutting. If such flow occurs, we must estimate the temperature of the inflow and adjust the predicted temperature of the main stream. This adjustment is made with a mixing ratio of the predicted temperatures of the tributary stream (T_t) and the main stream (T_m), weighted by their respective discharges (D_t and D_m). This may be written as:

$$\text{Adjusted temperature} = \frac{(D_t)(T_t) + (D_m)(T_m)}{(D_t) + (D_m)} \qquad [2]$$

The second limitation is that low-flow discharge is assumed constant. Changes in summer discharge could occur because of climatic change, or, if the area logged is large enough, the clearcutting might increase base flow. In some areas, base flow has been increased by 50-75 percent after the entire watersheds have been clearcut. An increase in discharge may be partially compensated by a corresponding increase in surface area that depends upon channel configuration, which would reduce the error in Equation 1. The principal error comes from the low temperature of this unknown volume of groundwater. In areas where hydrologic data indicate the extent of this increase, the effect of groundwater addition may be estimated by treating it as a tributary (Equation 2). Groundwater temperatures may be obtained by making midsummer measurements in auger holes placed in the saturated zone near the stream.

A final limitation is imposed by the assumption of complete exposure of the stream surface to direct sunlight. If considerable overhanging vegetation remains after clearcutting, or if topographic shading occurs, the predicted change in temperature will be too large.

In practice, these limitations are not likely to restrict the application of this method, even though their presence makes the predicted change in temperature too high. Watersheds are seldom clearcut in their entirety today. The most common occurrence probably is exposure of 2,000-3,000 feet of stream, which may eliminate much of the error induced by increasing groundwater discharge. Noting the duration of any topographic shading will permit adjustment of the exposure interval used in Figure 2. Finally, any cooling effect of residual shade after logging may be taken as a "safety factor" in making the temperature-change estimate.

The "quality of our environment" is a popular phrase often used by politicians, conservationists, and others interested in pollution. Responsibility for the quality of the environment extends to everyone. Flood prevention and erosion control have often been listed as a primary justification for our national forests, but forests and foresters have recently been assigned broader roles in maintaining environmental quality. Floods and sediment are no longer the only measure of a forester's effectiveness in controlling water quality. For the first time, national legal criteria have established several characteristics to define water quality.

The Federal Water Quality Act of 1965 required that each state prepare a set of water-quality standards and a plan for their enforcement. The standards include a large number of water-quality characteristics over which the forester has some influence. They include not only sediment, but also dissolved oxygen and water temperature.

The implications of such standards are clear. Foresters have been given legal responsibility for maintaining the quality of the aquatic environment. Furthermore, a yardstick has been adopted that will judge the effectiveness of their efforts.

Temperature prediction has increased meaning under these circumstances. This technique now becomes a tool for the solution of a practical problem. It permits the forester to do an improved job of managing all the resources of the watershed. Temperature prediction will also help him avoid violation of water-quality criteria established in his state. In short, this predictive model will help the forester to meet his growing responsibility in maintaining the quality of our environment.

SECTION IV

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CHAPTER III

HEAT LOSS FROM A THERMALLY LOADED STREAM

Energy balance studies proved invaluable for understanding the processes governing heat exchange on small streams. This technique was also utilized to ascertain the way heated streams lost this heat as they flowed into the forest from a clearcut.

Our earlier work (Brown, 1969) illustrated the importance of the solar flux in temperature prediction. Measuring this flux beneath a highly varied forest canopy required development of some new techniques. A system was developed to spatially integrate solar radiation penetrating the canopy in both time and space.

The system developed for spatially integrating solar radiation is shown in Figure 1. It consists of an aluminum track, track supports, a trolley for moving the sensor along the track, cabling for moving the trolley and transmitting the sensor signal, and a recorder. A strip chart recorder with integrator measures sensor output and integrates it with time and thus space. Aspirated psychrometers, thermocouples, and anemometers were also used to measure components of the energy balance.

Data collection was accomplished with a 25-channel digital data acquisition system (Figure 2). This system permitted us to sample the environment quickly and accurately. All 25 channels were measured within a 30-second period at intervals of one to ten minutes. Sensor output could be measured to within one microvolt. A teletype provided both typewritten and punch-tape records of the measurements. Punch-tape records were later fed directly into a computer for interpretation and analysis.

Data were collected during the summer of 1969. Energy balance measurements were made in the Umpqua National Forest. The study site was located downstream from a clearcut in which water temperature reached 80-85°F. during midday. Additional measurements were made along a stream protected by a buffer of trees separating the stream from a large clearcut.

The result of the energy balance measurements below a clearcut during a typical day is shown in Figure 3. Positive values indicate energy additions to the stream. Negative values represent energy losses. The curve labeled "storage" is the algebraic sum of net radiation, evaporation, convection and conduction.

What this figure tells us is that even in the shade, relatively small amounts of heat are added to the stream throughout the day since the storage function is always positive. Further, we could anticipate that the stream will not cool as it flows into the shade, but continue to increase in temperature at a very slow rate.

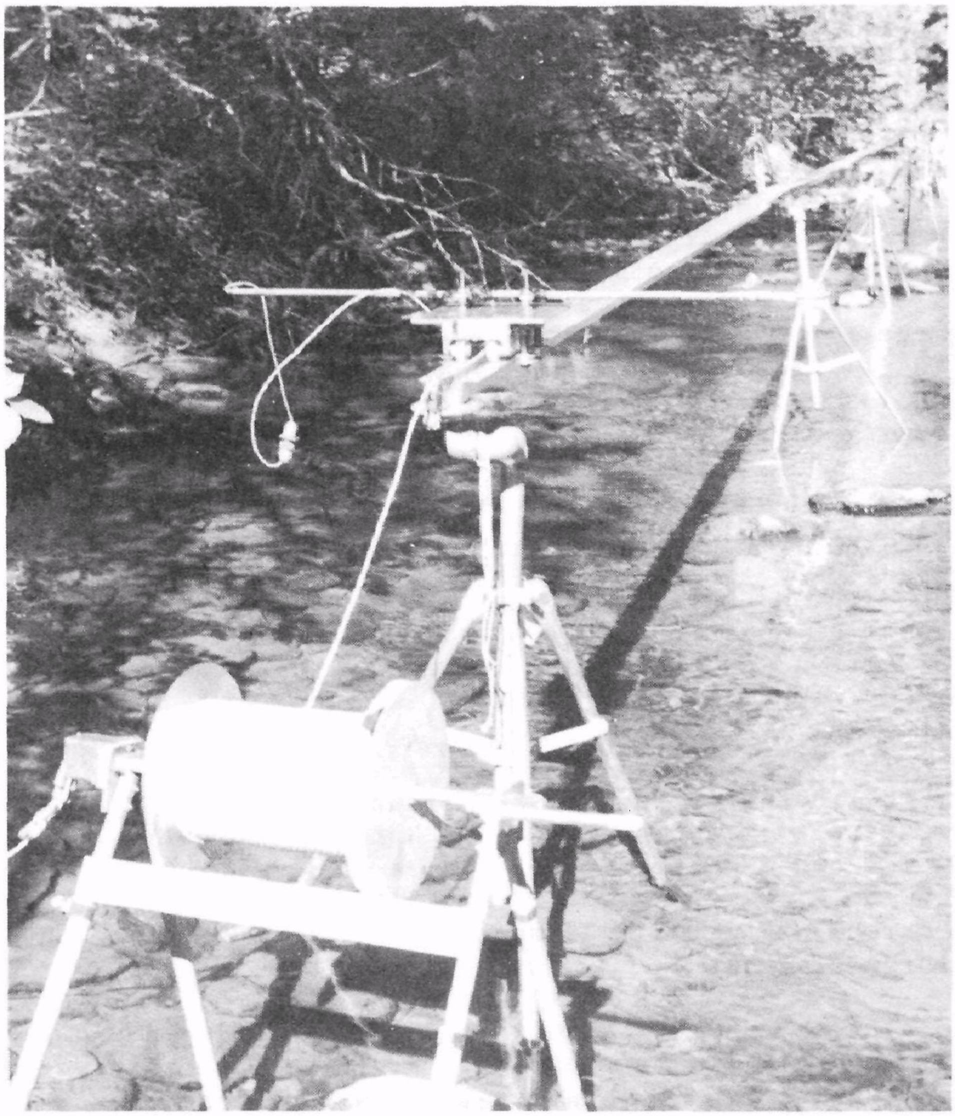

Figure 1. A system for spatially integrating solar radiation.

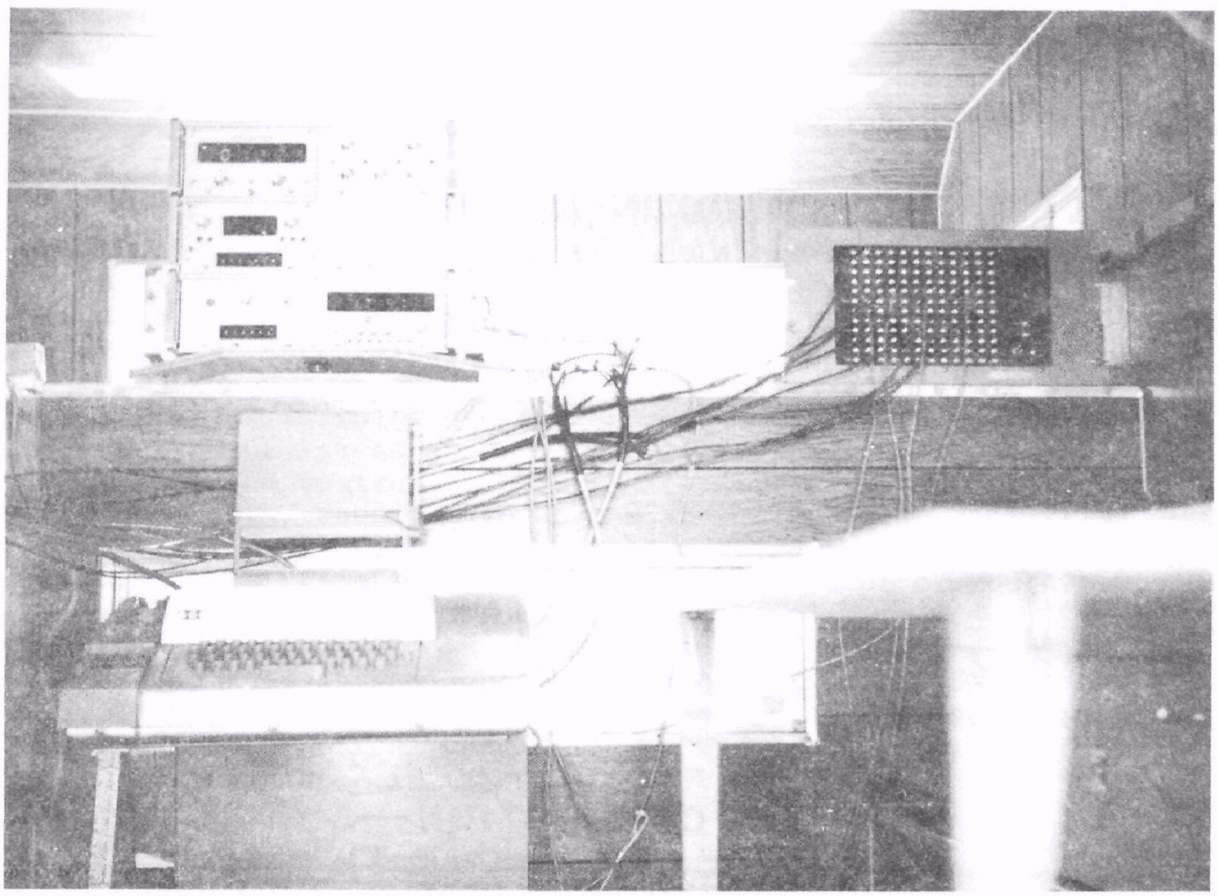

Figure 2. The digital data acquisition system.

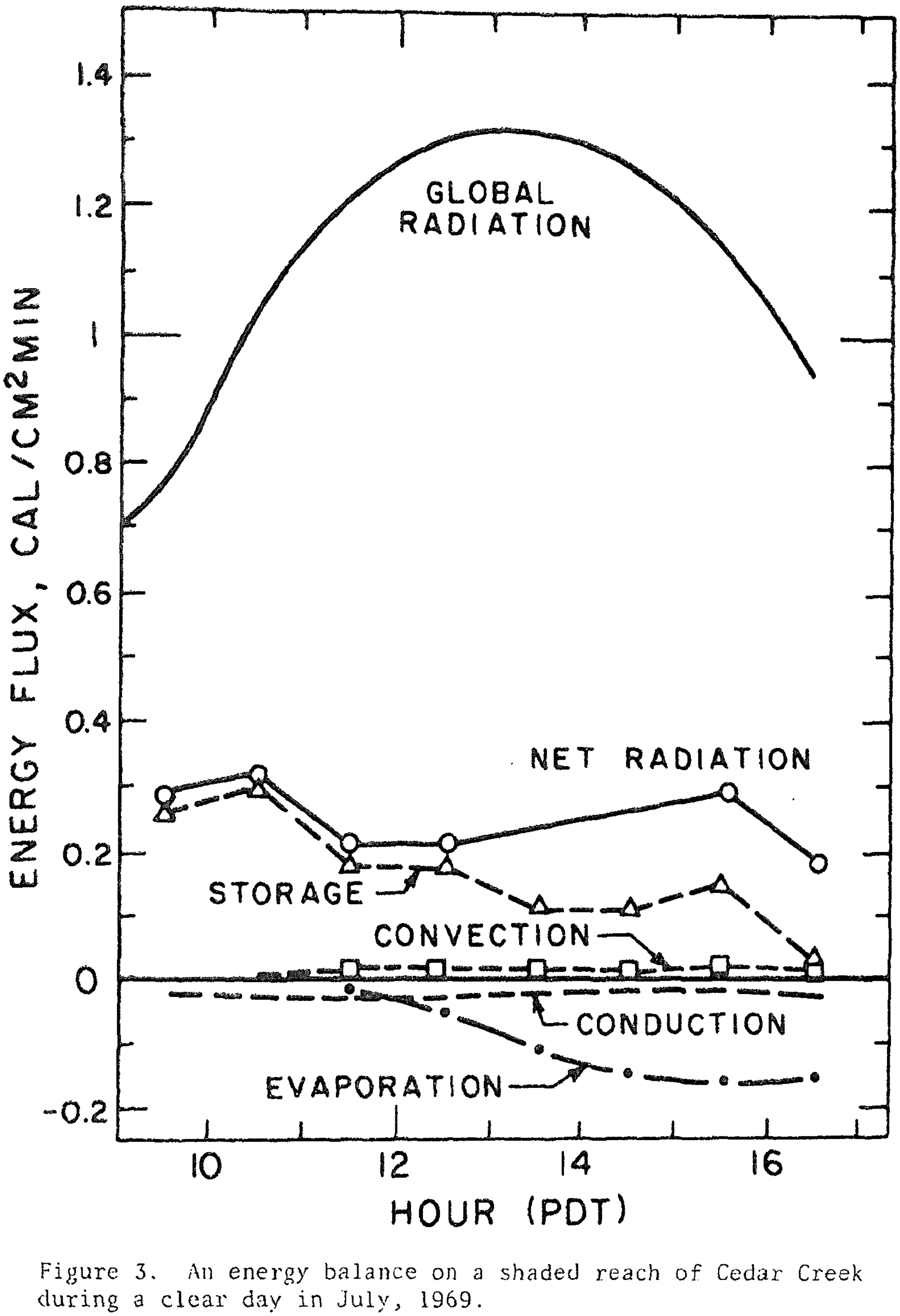

Figure 3. An energy balance on a shaded reach of Cedar Creek during a clear day in July, 1969.

This conclusion is strengthened by thermograph measurements obtained within shaded reaches and studied elsewhere in the Cascades.

The second study evaluated the net radiation absorbed on Little Rock Creek. At this site, the water flowed through a reach shaded by a strip of trees left during a clearcut operation adjacent to the stream. Again this measure of net radiation was made with the device that gave a time and space integration.

The integrated net radiation measured on Little Rock Creek is shown in Figure 4. The net radiation on Cedar Creek observed the previous day and the measured global radiation are also shown. The curve labeled "expected net radiation" is the net radiation that would have been absorbed by both streams had the trees not been present.

The curves show us that the streamside strip on Little Rock Creek is less efficient in reducing net radiation than the uncut block of timber through which Cedar Creek flowed. Considering the potential net radiation, however, its efficiency is remarkable. Thermograph measurements made by Dallas Hughes along this same stretch of stream confirm this efficiency. As he illustrates in another section of this report, the temperature increase through this section was nil.

In very practical terms, then, these measurements have confirmed an earlier hypothesis: as long as the stream surface can be shaded, temperature can be controlled. Further, extremely wide buffer strips are not necessarily required to do the job. The strip on Little Rock Creek was only two trees deep, about 50-75 feet. The volume contained in this strip is estimated at 75 M bd feet or roughly 0.1 percent of the sale volume, from the 55-acre unit.

The hypothesis that shaded zones below clearcuts will cool heated water is questionable. The energy balance and thermograph measurements lead to the very practical conclusion that if cool water is desirable, it should not be heated in the first place.

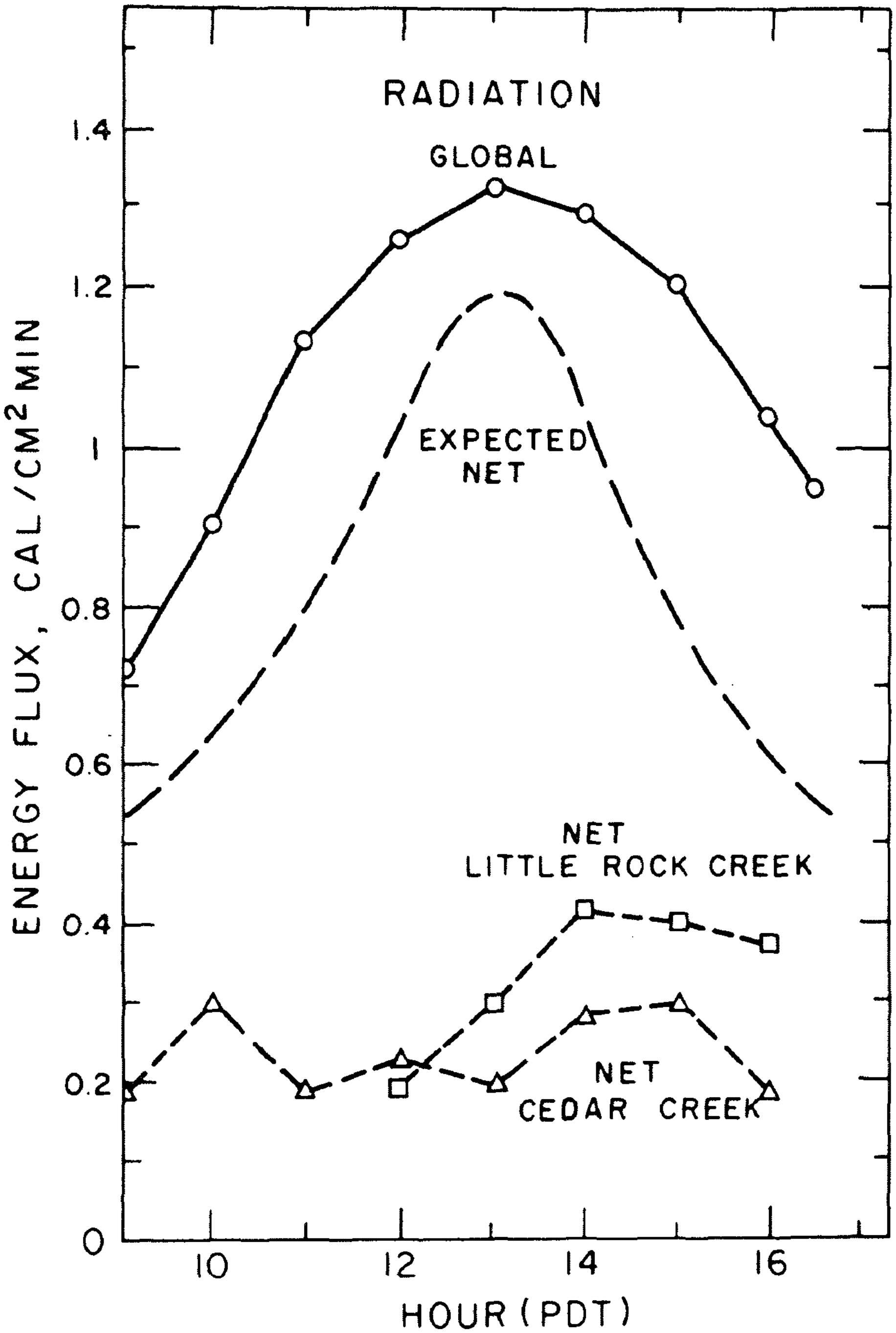

Figure 4. Net all-wave radiation measured in a shaded reach of Cedar Creek and within a shaded buffer strip on Little Rock Creek during clear days in July, 1969.

CHAPTER IV

HEAT FLOW IN STREAM BEDS

The role of the stream bed in heat exchange was attacked through analysis of thermal conductivities of various bed materials. Cores were extracted from selected streams for laboratory analysis of thermal conductivity.

These cores were frozen using a heat-pump technique developed by the Canada Department of Fisheries and utilized successfully by Ringler (1969). Acetone is cooled using dry ice, causing circulation within a pipe penetrating the gravel. The temperature of the acetone is about -79°C. and freezes a core around the pipe. This core can then be extracted and taken to the laboratory for analysis. Importantly, the position of the gravel particles and the composition of the mass is fixed. The device is illustrated in Figure 1.

Thermal conductivity measurements were begun using a device much simpler than that proposed in the original research proposal. A system devised by Wang and Knudsen (1958) and successfully used in predicting thermal conductivity in two phase systems was substituted. It was much simpler in design and much less expensive.

The thermal conductivity device is shown in Figure 2. A heat source is created in the top chamber and a heat sink created in the bottom chamber. A substance of known thermal conductivity (usually water) is introduced into the chamber immediately below the heat source. Heat flow through this chamber is calculated by:

$$Q = K\ A\ \frac{dT}{dL} \qquad [1]$$

where q is the heat flow, K is the thermal conductivity of water, A is the cross sectional area of the chamber, dT is the temperature gradient across the chamber, and dL is the chamber height.

Under conditions of steady state, q out of the chamber containing water will equal q into the chamber containing the material with unknown K. Thus, this unknown K can be determined with the equation above after measuring dT, dL, and A.

Laboratory analysis of cores together with evaluation of thermal gradients measured <u>in situ</u> was scheduled for Year 3. Termination of this grant during Year 2 precluded further work.

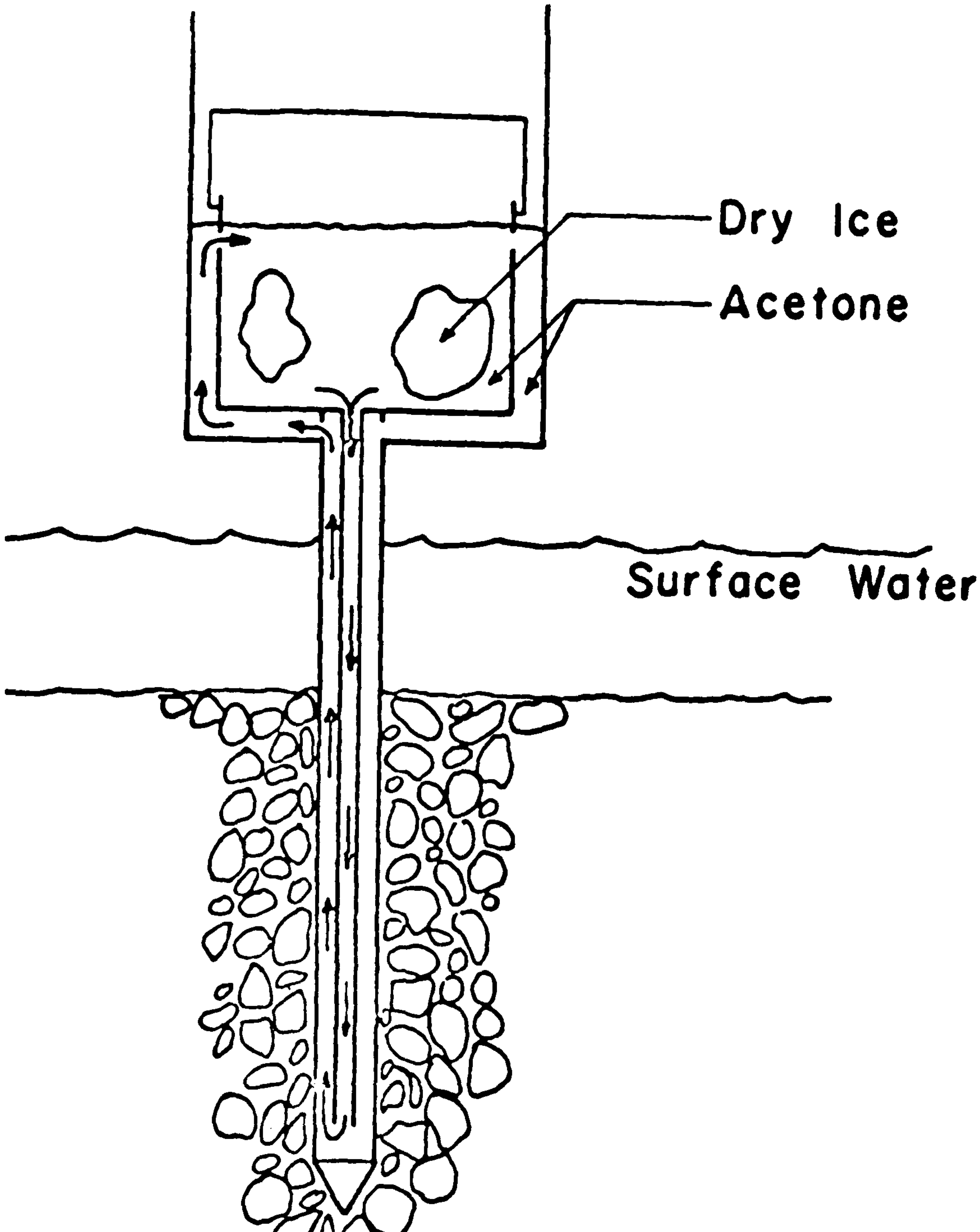

Figure 1. Cutaway view of frozen core sampler in operation. Arrows indicate direction of acetone circulation (After Ringler, 1969).

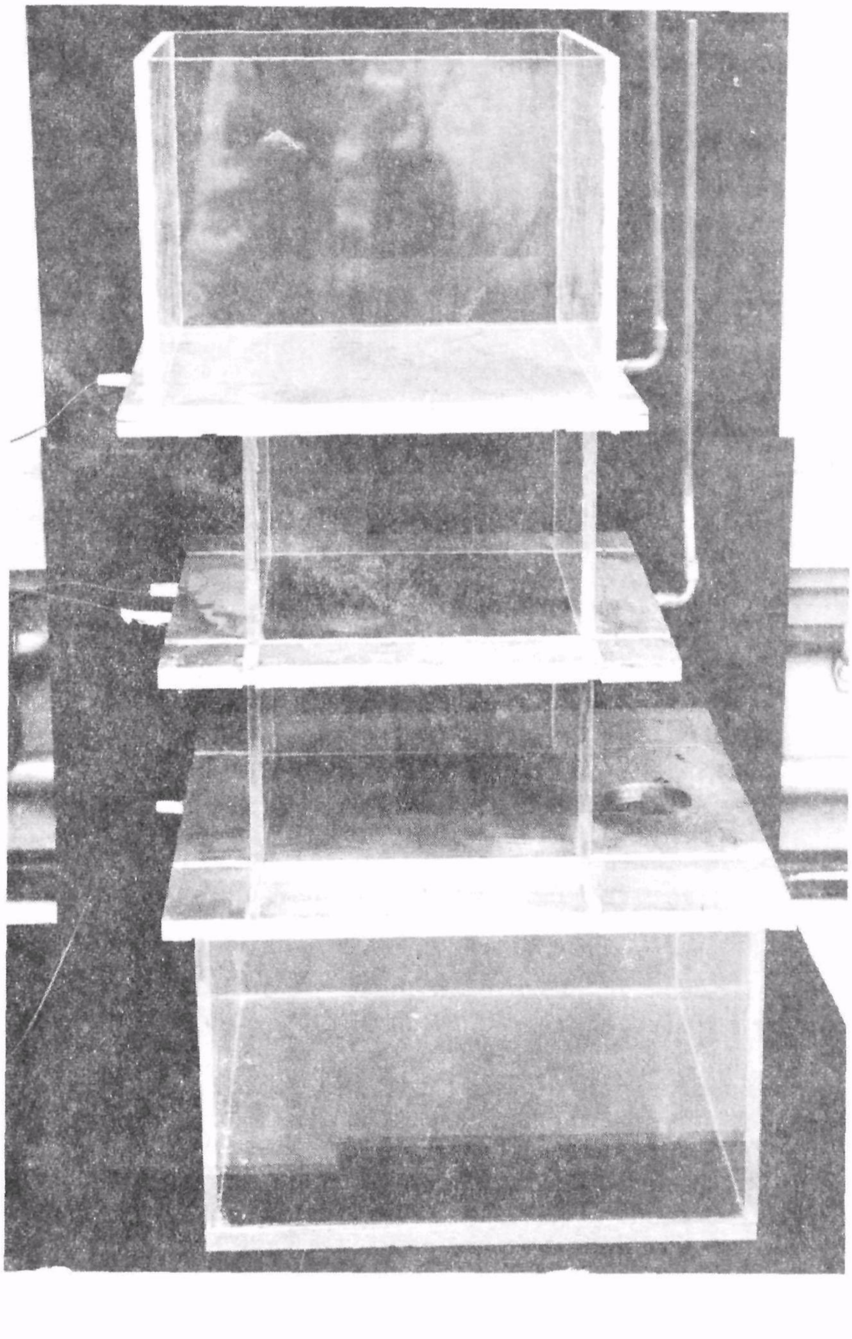

Figure 2. The thermal conductivity chamber.

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CHAPTER V

CLEARCUT LOGGING AND SEDIMENT PRODUCTION IN THE OREGON COAST RANGE

SECTION I

INTRODUCTION

In the Pacific Northwest, commercial forests cover much of the headwaters landscape. Timber harvest in these forests is the predominant land use activity. In Oregon alone, between 500,000 and 700,000 acres are logged annually. Logging is preceded by road construction. Clearcutting is the principal logging technique, followed by slash burning. The change in the appearance of the landscape is dramatic and abrupt. The crucial question from a water quality standpoint is: how does clearcut logging affect erosion and sedimentation in headwater streams? In Oregon, this question is crucial since salmon, steelhead and trout utilize these small streams for spawning and rearing sites.

The purpose of this paper is to describe the effect of road building, clearcut logging, and slash burning on suspended sediment production from three forested watersheds in Oregon's Coast Range where precipitation averages 100 inches annually and topography is steep.

The effects of sediment on fish have been summarized by Cordone and Kelley (1961). Excessive concentrations of suspended sediment (20,000 ppm) can cause gill injury to fish or alteration of behavior patterns. The most significant sediments effects at more typical concentrations occur because of alteration and destruction of bottom organisms, and from indirect influences of sediment deposition on intragravel flow and aeration. Mineral and organic sediments in water or deposited in spawning gravels may cause mortality, delayed development, or poorer condition in salmon and trout (Brannon, 1965; Kramer, 1965; Koski, 1966; Shelton, 1966; Servizi, et al., 1969). Gravel size has been related to the interchange of dissolved oxygen (Cooper, 1965; Oregon Game Comm., 1966; Ringler, 1970). Cooper found that deposition will occur in spawning gravels at moderate concentrations even though velocities are too high to permit deposition on the surface.

Public concern for pollution has led to the establishment of water quality standards. Oregon has now gone beyond interstate standards (Water Quality Act of 1965), and has applied water quality standards to sub-basins with direct intent to control quality of upstream waters (Oregon Dept. of Environmental Quality, 1969). These standards have been set without a full understanding of sediment concentrations or sediment production rates from mountain streams under both natural conditions and conditions influenced by logging operations.

Forest hydrologists have often related sediment production to timber harvest operations in headwater areas. Road construction preceding logging is often the most serious cause of erosion. In the volcanic formations of the Oregon Cascades, sediment yields from three small stee watersheds tributary to the McKenzie River seldom exceeded 200 parts per million (ppm) prior to treatment (Fredriksen, 1965, 1970). Immediately after roads were constructed across one watershed, a peak sediment concentration of 1,780 ppm was observed, 250 times that recorded in a control. This initial effect subsided after two months, but concentrations remained two to three times the level predicted from the control. These results did not include samples from landslide events. In 1961 and 1964, landslides from the roads produced average concentrations about 34 times greater than expected from the pre-treatment relationship. Mean annual sediment yield including bed load was 8,000 tons/mi^2-yr in a nine-year period, 109 times the loss from an undisturbed control watershed.

At Castle Creek, in California, where the primary influence was roads, average sediment concentrations and loads from a 4-mi^2 watershed increased five-fold in the first year, from 64 ppm to 303 ppm, or from 935 tons/mi^2-yr to 4,600 tons/mi^2-yr. Concentrations and yield declined to twice the normal rate in the second year (Rice and Wallis, 1962; Anderson and Wallis, 1963). In the Idaho granitic batholith, roads associated with jammer logging (a high-density road system), produced highly variable sediment yields from three logged watersheds of 12,400, 8,900, and 89 tons/mi^2 in one season (Copeland, 1965). Neighboring drainages without roads in this area of highly erodible granitic soil produced no sediment; high yields in watersheds with roads were attributed to inadequate cross drains.

The effects of the logging operation are often difficult to separate. In many erosion studies, the sediment contribution caused by road construction, skid trails, and logging are measured together. One such study at Fernow Experimental Forest in West Virginia reported an average turbidity of 490 ppm (Jackson Turbidity Units) during tractor logging. One year later average turbidity dropped to 38 ppm; two years later it was only 1 ppm. Another study at this forest illustrated the importance of planning logging operations. On a well planned logging operation, the maximum turbidity was only 25 ppm. An adjacent watershed was logged without any plan or direction and maximum turbitities of 56,000 ppm were recorded (Reinhardt and Eschner, 1962).

Sediment sampling before, during, and after clearcut logging was conducted in Maybeso and Harris River Valleys in southeastern Alaska (Meehan et al., 1969). No significant change could be detected in the concentrations, possibly due to inadequate sampling. Sheridan and McNeil (1968) found small increases in the percentage of fine sediments deposited in the stream gravels after logging in this same area. The probable source of this sediment was debris avalanches which were common in clearcut areas.

Fredriksen (1970) reported that on a watershed that was clearcut over a period of three years with a sky-line system, and thus without roads, concentrations were only modestly affected during logging. Mean concentration during storm periods remained below 10 ppm until slides, triggered by the record storms of 1965, brought about 800 tons of soil and rock material into the channel. Most of this material remained trapped by logging debris.

Controlled slash burning is a common practice following clearcutting in the Pacific Northwest. Very little information exists about the effect of controlled burning on sediment production from forests. Burning following logging with the sky-line system described above was also reported by Fredriksen (1970). Resulting sediment concentrations during two subsequent years ranged from 100-150 ppm and were 67 and 28 times those recorded on an undisturbedwatershed during the same period. Fredriksen noted that sediment had been trapped in the logging debris and was released only after burning.

SECTION II

THE STUDY

In 1958, Oregon State University began a cooperative study of the effects of logging on water quality and fishery resources of three small watersheds in Oregon's Alsea Basin. These watersheds are located about 8 miles south of Toledo and about 10 miles from the Pacific Ocean (Figure 1). The watersheds were forested with Douglas-fir and alder. Mean elevations are between 740 and 1,000 feet. Mean slopes range from 25 to 50 percent. The maritime climate produces a mean annual precipitation of about 100 inches. Summers are dry, however, and most of the rainfall occurs between November and April. The soils are derived from the Tyee sandstone formation. Over 80 percent of the soils are from either the Slickrock or Bohannon series. The Slickrock soils are derived from sandstone colluvium and are fairly deep. The Bohannon series, a shallow, stony soil, is derived from the sandstone residuum. Both series are moderately stable.

The sediment yield characteristics of the watersheds were monitored for seven years prior to treatment, from 1958 to 1965. Suspended sediment was measured at the mouth of each watershed and at six small stream gages in Deer Creek. The gages at the mouth of each watershed are operated by the U.S. Geological Survey and integrate the effects of land use on each watershed. The small gages in Deer Creek are operated by Oregon State University's School of Forestry. These gages were installed in 1963 to evaluate the effect of each cutting unit on the tributaries within the Deer Creek watershed.

Logging roads were constructed into Deer Creek and Needle Branch between March and August, 1965. Flynn Creek, a 500-acre watershed, served as a control and remained in its natural condition throughout the study. Sediment samples were collected during the winter of 1965-66 to evaluate the effect of roadbuilding. Logging began in March, 1966, and ended in November of that year. Needle Branch, a 175-acre watershed, was fully clearcut; Deer Creek, a 750-acre watershed, was 25 percent clearcut with three small units (Figure 1). The effects of these three units were measured at four weirs. The 138-acre watershed above weir II was 30 percent clearcut. The 100-acre watershed above weir III was 65 percent clearcut. Weir IV measures the runoff from a 39-acre watershed that was 90 percent clearcut. Weir VI measures the combined effect of the upper watersheds; its 572 acres were 25 percent clearcut.

The slash on Needle Branch was burned in October, 1966. The upper units of Deer Creek remained unburned; the lower unit was lightly burned in October, 1966. Sediment sampling on Needle Branch the following winter reflected the combined effect of roadbuilding, logging and slash burning. Sediment measurements at the six stations within Deer Creek permitted evaluation of the first two effects; the U.S.

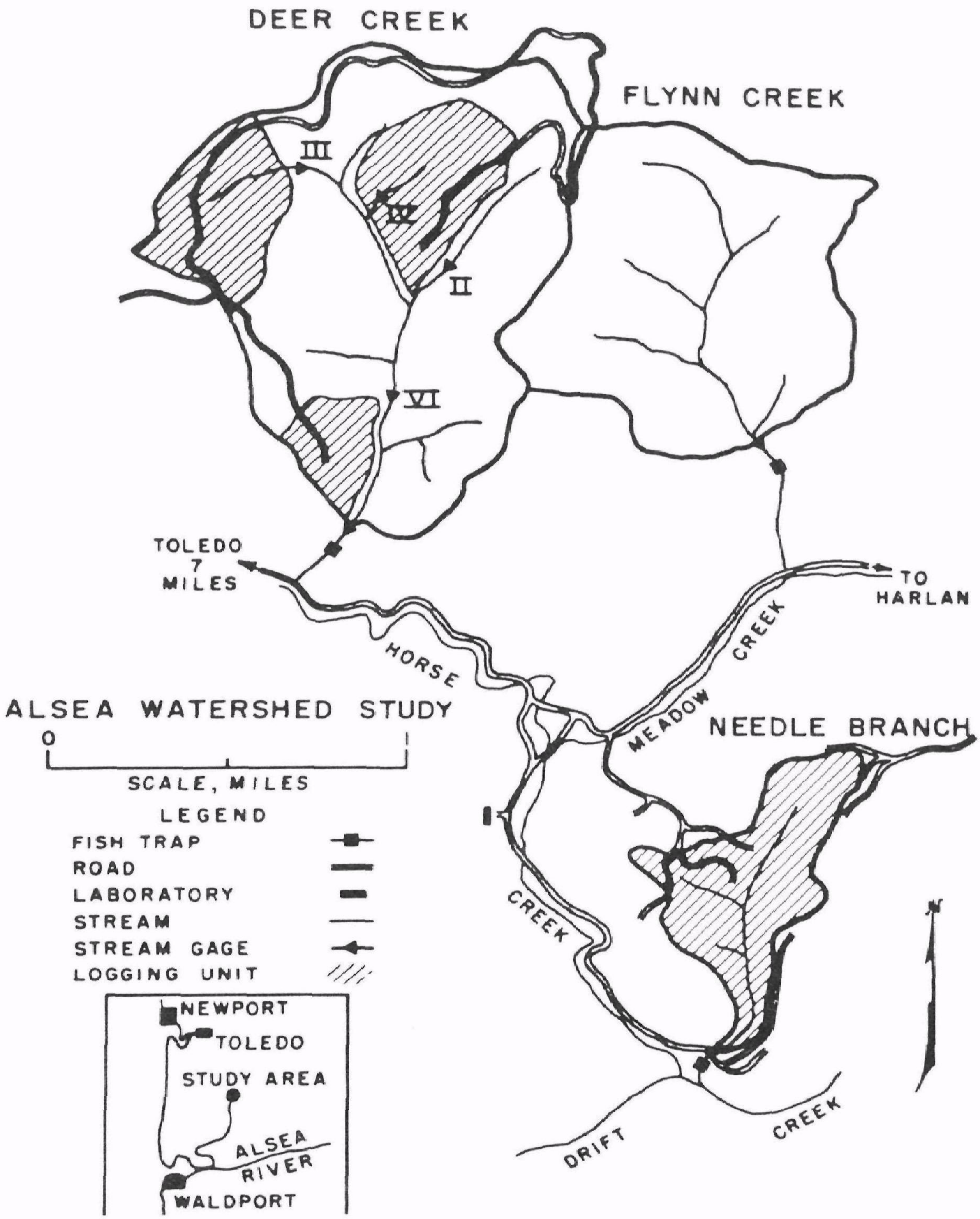

Figure 1. The study watersheds and sediment sampling stations in the Alsea Watershed Study.

Geological Survey samples included the effect of burning the lower unit. Sediment sampling continued through the 1967-68 and 1968-69 storm seasons. Sediment yields will be monitored for several more years.

Routine suspended sediment concentrations in parts per million were obtained daily at the U.S. Geological Survey weirs by Oregon Game Commission personnel. During storms, samples were taken at more frequent intervals to ascertain sediment loads as stream levels changed. At the small weirs within Deer Creek samples were taken only during storm periods.

SECTION III

CHANGES IN ANNUAL SEDIMENT LOAD

Two analyses were run on the suspended sediment data; analysis of total annual load and analysis of suspended sediment concentration. Changes in annual sediment load for the three watersheds were estimated using an averaging technique designed to reduce the variation in sediment associated with a changing streamflow regime. It has been well documented in streamflow studies conducted concurrently with these sediment studies that timber harvest produced significantly increased volumes of streamflow on both treated watersheds (Harper, 1969; Hsieh, 1970).

A long-term flow-duration curve was used to estimate annual sediment yields based on the flow regime during an average year. The procedure used in this averaging technique was as follows. First, six years of data from the calibration period were used to estimate the long-term flow-duration characteristics of each stream. Next, a relation between mean daily sediment concentration and mean daily discharge at each of the three weirs was developed for each year of the study. Finally, the sediment concentration-discharge relationship was combined with the mean flow-duration curve for each weir to obtain the mass of sediment carried in each flow class. Summing these values provided estimates of total annual sediment yield from each watershed. Thus, this technique assumed that the flow each year was equal to the long-term mean in volume and distribution. This normalized the effect of abnormal years by reducing the variation in sediment yield associated with annual differences in discharge. The sediment yields thus attained provide an indication of the average expectancy of a change associated with the treatments. The normalized annual sediment yield from each of the treated watersheds was then compared to that of the control with regression analysis. A similar analysis technique has been described by Anderson (1954).

Annual sediment yields are shown in Table I for each watershed. Included are both normalized, or weighted, yields and "actual" yields provided from the annual sediment-hydrograph analyses reported by the U.S. Geological Survey. Regressions comparing normalized annual sediment yield on Flynn Creek, the control, with that of each treated watershed are illustrated in Figures 2 and 3. Only the upper 95% confidence limits (CL) are calculated, since there is no reason to suspect that treatment would reduce sediment yield.

Annual sediment yields were highly variable during the pretreatment period. There was a three-fold difference between the minimum and maximum annual yields on each watershed during this period, even using normalized values.

Roadbuilding significantly increased sediment yield in Deer Creek,

Table I

Total Annual Sediment Yield in Tons Per Square Mile

Computed from U.S. Geological Survey Records

Water Year	Flynn Creek		Deer Creek		Needle Branch	
	Normalized	Actual	Normalized	Actual	Normalized	Actual
1959	92	66	114	82	74	49
1960	105	50	81	77	96	40
1961	172	258	193	286	98	180
1962	136	84	178	97	201	115
1963	212	127	285	160	161	115
1964	223	209	231	199	181	187
1965	337	1237	308	1040	129	422
1966	246	300	577	740	270	365
1967	136	137	251	213	570	904
1968	92	59	101	84	372	490
1969	123	139	162	162	279	517

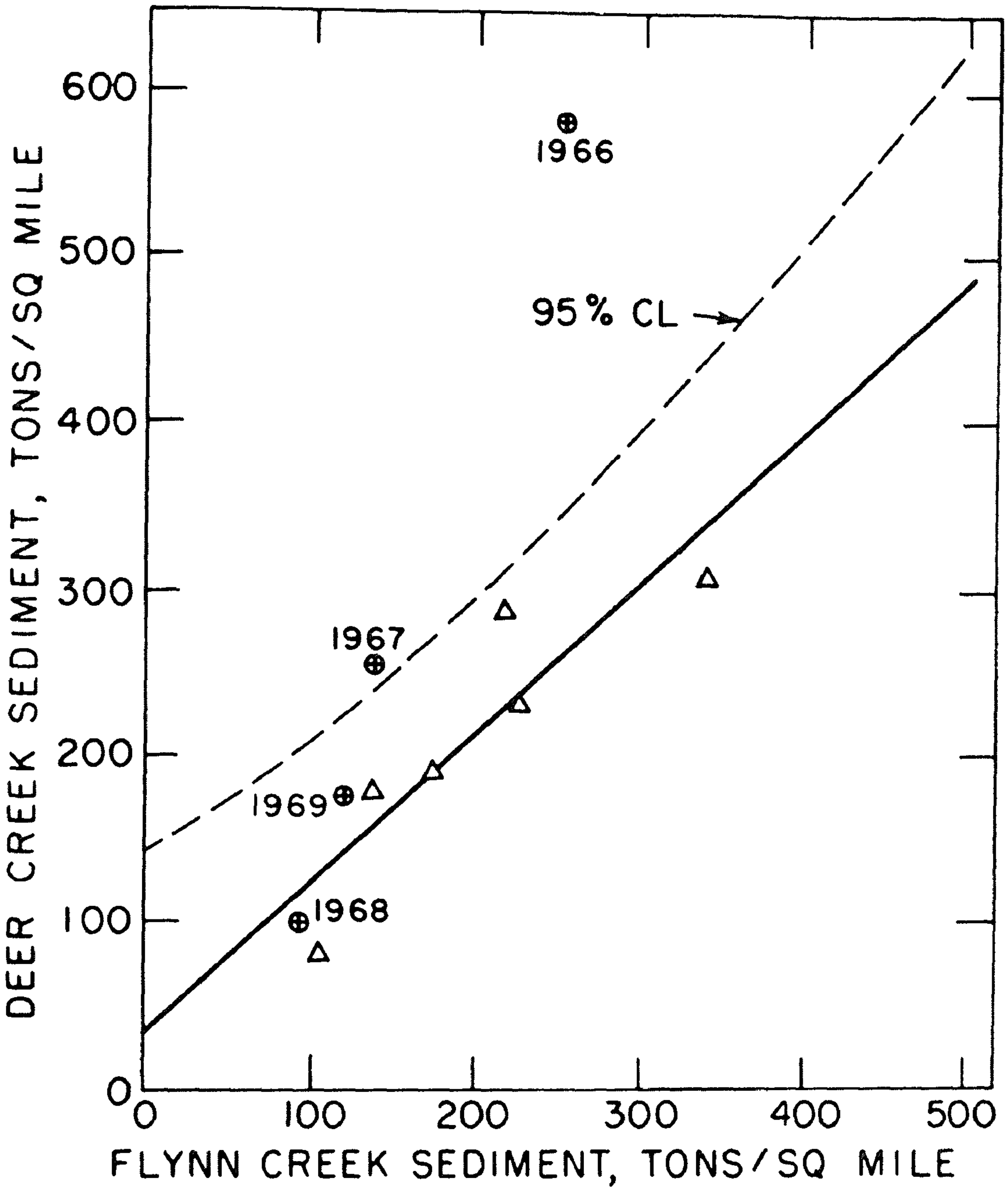

Figure 2. A comparison of normalized annual sediment yield from Flynn Creek (unlogged) and Deer Creek (patchcut) for seven years prior to treatment. Comparative yields after road building (1966) and logging (1967-1969) are shown in relation to the 95 percent confidence limit about the pretreatment regression.

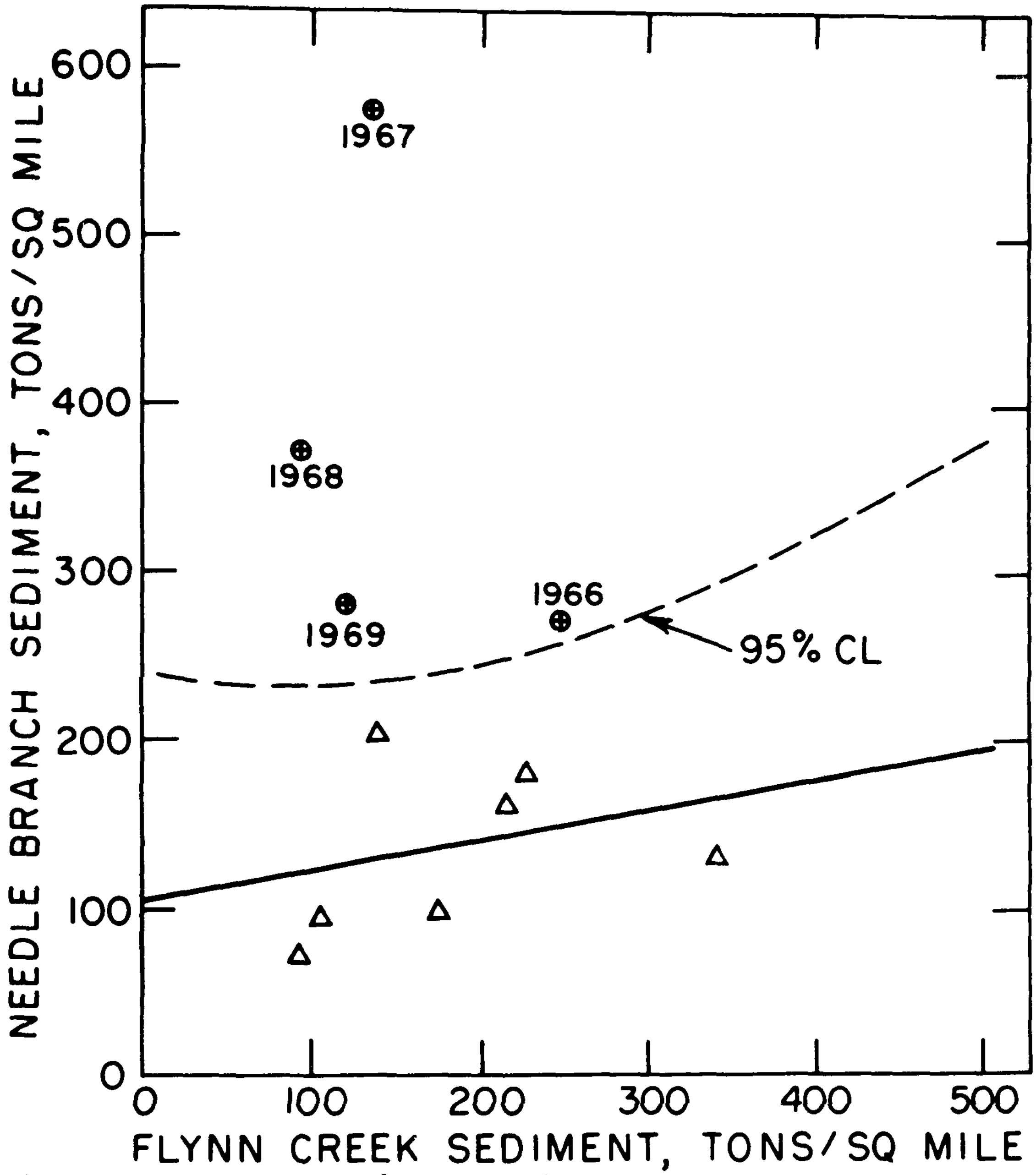

Figure 3. A comparison of normalized annual sediment yield from Flynn Creek (unlogged) and Needle Branch (clearcut) for seven years prior to treatment. Comparative yields after road building (1966) and logging and burning (1967-1969) are shown in relation to the 95 percent confidence limit about the pretreatment regression.

the patchcut watershed during the 1966 water year. One road slide produced a sediment yield of 347 tons, or 40 percent of the non-normalized yield, for the 1966 water year.

The increase in annual sediment yield after roadbuilding in Needle Branch was also statistically significant at the 95% level. Road drainage or erosion of side cast materials along roads seem the most likely sources of this increase. No large road slide occurred in Needle Branch.

The annual sediment yield observed during the first year after logging in Deer Creek (1967) was significantly higher than during the control period. This yield may include materials deposited by the large slide the previous year. During the two post-logging water years of 1968 and 1969, sediment yields returned to prelogging levels.

Annual sediment yields in Needle Branch increased markedly immediately after the watershed was logged and burned. The normalized sediment yield increased four-fold over the pretreatment mean. The normalized yield on the control watershed dropped to three-fourths of its pretreatment mean during this year. The annual sediment yield declined during the following years as vegetation returned, but yields remained higher than before logging and burning.

SECTION IV

CHANGES IN SEDIMENT CONCENTRATION

A second analysis compared the instantaneous concentrations of sediment during storms with the streamflow at which the samples were obtained. This was done both before and after roadbuilding and logging. Understanding how sediment concentration varies with watershed treatment is of great significance, since most of the new water quality standards for sediment are related to this value, and not annual yield.

Regressions comparing instantaneous sediment concentration with the streamflow observed when the sediment sample was taken were prepared for each sampling station. It was necessary to segregate the concentration data into two groups for these analyses since the sediment-streamflow relationship for rising stages was significantly different from that observed for falling stages at all sampling sites. A similar procedure has been used by Fredriksen (1970). The correlation coefficient (r) was generally much higher for rising stage data. All of the concentration analyses therefore utilize only rising stage data. Rising stage data were further segregated to include only storm data with discharges greater than 5 csm.

Simultaneous samples of sediment concentration and discharge were fitted to a regression equation of the form.

$$\log S = a + b \log D \qquad [1]$$

where S is the sediment concentration, D is the discharge measured when the sediment sample was obtained, and _a_ and _b_ are regression constants.

Evaluating the differences in sediment concentration resulting from watershed treatment proved a difficult task. Sample sizes tend to be unequal. Variations in the sediment concentration-discharge equation can also occur because of annual changes in runoff pattern. Two additional types of variation may be imposed by treatment: clearcutting may not only change the variation in sediment concentration, but the variation in discharge as well. Thus, the assumption of orthogonality in the individual degrees of freedom test may not apply. This means that the standard test for interaction between regression equations may not be appropriate.

The test statistic selected to circumvent this difficulty was:

$$F^2_2 = \frac{SSB_p - (SSB_1 + SSB_2)}{SSA - (SSA_1 + SSA_2)} \qquad [2]$$

where SSp is the error sum of squares obtained by combining or pooling the sediment concentration-discharge data for the pretreatment period (1) and each treatment year (2) for each watershed (A or B), SS_1 is the error sum of squares for the pretreatment period, SS_2 is the error sum of squares for the post-treatment period. Watershed A represents the control watershed, Flynn Creek, and watershed B represents either of the treated watersheds, Deer Creek or Needle Branch.

Mean streamflow and sediment concentrations are shown in Table II for the U.S. Geological Survey weirs and in Table III for the small weirs within Deer Creek for each year of the study. Only two years of pretreatment data were used in this analysis since more data were not available from the small weirs in Deer Creek. Notation of a significant increase is the result of testing regressions with equation (2) above and not by simple tests on the mean values.

Some interesting differences appear in the conclusions which can be drawn from analysis of separate samples and from analysis of annual yield. In Deer Creek, the road slide in 1966 produced an increased annual yield that was significant at the 95% level. The relative significance dropped in the analysis of sediment concentration. The increase was not significant at 95%, but rather 90%. The following water year, 1967, annual yield was still significantly higher than the pretreatment period at the 95% level. The comparison of sediment concentrations during the 1967 water year with those during the control period revealed no significant differences. The reason for this discrepancy is that there was a significant shift in the sediment-discharge relationship of the control watershed during this year.

It is quite likely that the shift in the sediment concentration-discharge relationship of the control occurred as a result of the 1964-1965 floods, and was produced by residual materials deposited during those major events. Prior to the floods, the maximum suspended sediment concentration recorded on Flynn Creek, the control, was 682 ppm compared to 969 ppm recorded on Needle Branch. During the flood, the maximum Flynn Creek concentration was 2,050 ppm compared with 476 ppm on Needle Branch. Most of the pools in Flynn Creek were filled with sediment (Williams, 1965). Thus, the control watershed responded differently to the same storm event than did the other two watersheds which were treated the following year. Anderson (1968, 1970) has noted the dissimilar responses of other watersheds to the same large event. He has also shown that materials deposited during these events provide a sediment reservoir for many subsequent years. Thus, the classical concept of a single "control" watershed for sediment studies of this type may not always be valid.

The same pattern appears on Needle Branch. The difference during the first water year after logging, 1967, is even more profound. A five-fold increase in mean sediment concentration was not significant at the 90% level because of the upward shift in the sediment-discharge regression of the control watershed during this same year. The

Table II

An Analysis of Simultaneous Sampling of Suspended Sediment Concentration and Streamflow at U.S. Geological Survey Stations During Rising Stages and Discharges Greater Than 5 CSM

Station	Water Year	Sample Size	Sediment Concentration (ppm) Range	Mean	Streamflow (cfs) Range	Mean
Flynn Creek (control)	1964-65	72	1- 205	194	4.2-148	32
	1966	64	1- 718	128	4.2- 66	22
	1967	28	38- 439	148	4.2- 69	32
	1968	18	32- 256	109	11 - 44	26
	1969	17	1- 200	57	7 - 44	20
Deer Creek (patch cut)	1964-65	71	1-1610	267	6 -204	58
	1966	66	1-6960	337*	6 -115	32
	1967	32	53- 670	233	20 -105	59
	1968	20	35- 345	115	10 - 46	40
	1969	49	6- 381	90	8 - 76	37
Needle Branch (clear-cut)	1964-65	88	1- 969	116	1.6- 45	13
	1966	68	1- 892	179*	1.6- 27	9
	1967	89	1-6300	589	1.6- 25	11
	1968	44	20-7670	640**	1.9- 32	10
	1969	38	70- 738	280**	3.1- 24	12

* Significant increase at 90% level.
** Significant increase at 95% level.

Table III

An Analysis of Simultaneous Sampling of Suspended Sediment Concentrations and Streamflow at Stations Within Deer Creek During Rising Stages and Discharges Greater than 5 CSM

Station	Water Year	Sample Size	Sediment Concentration (ppm) Range	Sediment Concentration (ppm) Mean	Streamflow (cfs) Range	Streamflow (cfs) Mean
Deer Creek II	1964-65	55	1-716	70	1.0- 34	0.8
	1966	15	2-178	32	1.0- 9	3.7
	1967	14	3-242	67	1.0- 30	11.3
Deer Creek III	1964-65	54	1-793	79	0.8- 19	3.7
	1966	15	1-410	117	1.2- 18	4.9
	1967	14	4-194	72	0.8- 18	7.1
Deer Creek IV	1964-65	20	1- 99	15	0.3- 10	1.7
	1966	14	1- 10	2	0.3- 8	1.8
	1967	13	1- 8	4	0.3- 7	2.0
Deer Creek VI	1964-65	33	3-462	88	4.5-136	16
	1966	21	1-720	127*	4.5-108	20
	1967	19	1-366	122	6 - 84	33

* Significant increase at 90% level.

increase on Needle Branch is significant at about 87%, but the difference in statistical significance is still surprising.

The comparison of changes in sediment concentration for the small weirs in Deer Creek is shown in Table III. Roadbuilding produced significant changes only at Station VI. Station III, immediately below the road slide, showed no increase in sediment concentration because samples were not taken during this event. Logging did not produce significant increases in sediment concentration at any of the sampling stations in Deer Creek.

A frequency distribution of mean daily sediment concentration during low flow periods is shown in Table IV. Mean daily flow less than 5 csm occurred during 60-70% of the year on these coastal watersheds. Even with the severe treatment given Needle Branch during the 1967 water year, mean daily concentrations were less than 10 ppm during about 97% of these low-flow days. These data substantiate the fact that in mountain watersheds the majority of the sediment load is carried during a few large storms. The best indication of treatment effect is shown in the increased maximum concentration at low flow on Needle Branch from water years, 1966 through 1969. The pattern is similar to that of sediment yield shown in Table I.

Table IV

A Frequency Distribution of Mean Daily Suspended Sediment Concentrations During Days with Mean Flow Less Than 5 CSM

Station	Water Year	Concentration Class (ppm) 0-5	5-10	10-20	20-30	>30	Maximum Conc. (ppm)	Days/Year With Flow <5 CSM
		% Days <5 CSM By Class						
Flynn Creek	1959-65	91.9	5.4	2.1	0.3	0.3	26	231
	1966	84.4	11.0	4.2	0.4		21	263
	1967	97.4	2.2	0.4			13	237
	1968	98.1	1.1	0.4	0.4		26	267
	1969	92.8	6.8	0.4			12	251
Deer Creek	1959-65	89.3	7.7	2.5	0.3	0.2	28	237
	1966	84.7	11.5	3.4	0.4		28	261
	1967	77.1	16.7	1.2	3.8		52	240
	1968	79.3	17.9	0.8	0.4	1.6	53	257
	1969	89.4	4.6	4.2	0.9	0.9	37	216
Needle Branch	1959-65	94.4	4.7	0.8	0.1		15	235
	1966	89.8	9.0	0.4	0.4	0.4	74	256
	1967	96.6	0.8	1.4	0.4	0.8	220	238
	1968	93.2	2.4	2.0		2.4	413	250
	1969	93.4	3.5	1.3	1.4	0.4	230	230

SECTION V

DISCUSSION

The results of this intensive study of sediment yield and land use clearly illustrate the effect of several forest management practices on water quality. The influence of roads on sediment yield has again been demonstrated by this study, substantiating the conclusions drawn by Fredriksen (1970). The road system in Deer Creek, for example, was conservatively located, constructed, and used. The roads were located near the ridges. They entered the watershed from the back of the ridges, thus minimizing the road mileage within the watershed. The roads were well gravelled and were not used during the winter months. Even with these precautions, one slide occurred and its effect was quite significant. A large volume of material still remains trapped behind a log jam in the upper part of the watershed, providing a potential source for additional sediment yield at some later date.

About 1.5 miles of road were constructed within Needle Branch. This, together with the landings for logs, exposed mineral soil over about 7% of the watershed. This undoubtedly was the source of sediment in water year 1966.

High-lead logging alone did not produce amounts of sediment significantly different from those in the calibration period. This result also coincides with those observed elsewhere (Fredriksen, 1970; Lull and Satterlund, 1963; Meehan, et. al., 1969; Packer, 1967). The maximum sediment concentration observed at weir IV in Deer Creek was less than 20 ppm. The watershed was 90 percent clearcut, but unburned. This can be compared with a maximum sediment concentration of over 7,000 ppm observed after logging and burning in Needle Branch.

Slash burning is a common management practice in the Pacific Northwest following clearcutting. Arguments both for and against burning are numerous. A review of this controversy is clearly beyond the scope of this paper. The sediment data collected during this study, however, indicate the effect of this practice on water quality.

The slash fire in Needle Branch was extremely hot; mineral soil was exposed through most of the watershed. High sediment yields could be expected where mineral soil is subjected to over 100 inches of rain during a six-month period.

The cause of increased sediment yield after logging in Deer Creek is somewhat obscure and may be the result of interacting factors. The sediment contribution of the two upstream clearcuts, as indicated by changes in their sediment concentration-discharge regressions, was not significant. Downstream, two possible sources of sediment exist. Materials which accumulated in the stream channel as a result of the road slide the previous year may have accounted for part of the noted increase. The mean sediment concentration at station VI in Deer Creek, though not statistically significant, remained high implicating some residual source. A second downstream source of sediment may have been the clearcut furthest downstream, which lies between Station VI and the U.S. Geological Survey station. This clearcut was lightly burned after logging, which could have contributed to an increase in sediment yield.

The data indicate that sediment yields should approach pretreatment levels 5-6 years after complete clearcutting and burning. Two important concepts must be understood about this recovery. First, these results pertain to a case study conducted in an area where vegetation grows rapidly and returns to unoccupied sites very quickly. Exposure time for mineral soil is thus minimized. Second, it is essential to remember that erosion is significant for both terrestrial and aquatic habitats. Although the supply of sediment from the slopes may decline rapidly, the presence of this material in the stream gravels may persist. Such an accumulation of fine materials in spawning gravel can significantly reduce the emergence of salmonid fry (Hall and Lantz, 1969).

What inferences can be drawn from the data about sediment sampling or monitoring? This question is a crucial one, not only from the point of view of studying sediment transport processes, but from a water quality control aspect as well. The Oregon water quality standards (Oregon Department of Environmental Quality, 1969) for example, specify that no activities will be permitted which cause "any measureable increases in natural stream turbidities when natural turbidities are less than 30 Jackson Turbidity Units (JTU) or more than a 10 percent cumulative increase in natural stream turbidities when stream turbidities are more than 30 JTU..."

The important question that must be answered is how to obtain the best standard of comparison. What, in other words, is a "natural" sediment concentration for small streams? Our data indicate that rather large annual variations in the sediment-discharge relationship can occur on undisturbed watersheds. Variations between watersheds may also be large. Variation in the sediment-discharge relationship is stage-dependent. A much better correlation between sediment concentration and discharge was observed during rising stages. This leads to the conclusion that a great deal of experience, together with an intensive, rigidly standardized sampling scheme based on flow regimes is required before a judgment with a precision of 10% can be made.

Our ability to make accurate judgments about changes in the sediment concentration-discharge relationship in this study would have been greatly improved by replicating the control. The assumption that neighboring watersheds respond in similar fashion to similar events, regardless of magnitude, is certainly questionable. It would seem then, that any sediment monitoring system would require more than one control for comparison.

A further constraint in sediment sampling or monitoring is imposed by the influence of a few large storms on annual sediment yields. If these events are not sampled adequately or are missed, conclusions about the treatment effect are likely to be erroneous. This problem is compounded by the treatment itself, which imposes a greater variation on the sediment-discharge relationship, particularly at high flows. Thus, monitoring a specific stream to detect a 10% change in sediment concentration will require more than just a few random samples.

We have shown that clearcut logging may produce little or no change in sediment concentrations in small streams. The greatest changes were associated with the roadbuilding operation that preceded logging and the controlled slash burning afterward. We have also shown that unless these changes are large, it may be very difficult to separate man-caused changes in sediment concentration from those imposed by natural variation, particularly if very large events occur within the measurement period.

SECTION VI

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CHAPTER VI

EVALUATION OF BED LOAD AND TOTAL SEDIMENT YIELD PROCESSES ON SMALL MOUNTAIN STREAMS

SECTION I

INTRODUCTION

Scope and Purpose

The purpose of this phase of the research has been to develop a fundamental grasp of the physical processes involved in sediment movement in small mountain streams. Particular emphasis has been given to the bed-load processes which may cause great quantities of gravel to be disturbed and transported during periods of storm runoff. At such times the amount of silt also carried by the stream may become much higher, partly attributable to what might be called a "silt reservoir" effect of streambed gravels--whereby silt is trapped and collected in the gravel bed when the bed is undisturbed and is released by the bed when the protective gravels are dislodged and moved by the flowing water.

It is common in studies of watershed practices to develop correlations between stream discharge and various modes of sediment yield, such as suspended sediment yield or total sediment yield. Development of such correlations depends upon field sampling of the flow and measurement of trapped sediments, both of which have deficiencies of many types, including infrequency of sampling. Because the transport rate of suspended particles is principally a function of the availability of particles for transport, rather than any physical relationship with streamflow, the correlation diagrams typically exhibit a great deal of scatter. Nevertheless, if sufficient data are obtained the effect of a watershed practice upon suspended load can often be reliably detected. The total sediment yield, however, is much less reliably and more difficultly determined in most instances and therefore is often omitted from studies of watershed practices. The total load consists of both the suspended load and the bed load. Considerable research on bed-load transport has shown a definite physical relationship between rate of transport and stream discharge (unlike the situation for suspended load). Unfortunately, the application of known relationships becomes questionable for small mountain streams with coarse gravel beds, shallow flow depths, and frequent riffles and pools. Consequently, the alternative approach to bed-load measurement by trapping sediment in pools above weirs (or similar techniques) is often resorted to. The results are unsatisfactory for several reasons, which include loss by flushing out during very high runoff, compaction of sediment, and an overly long time increment between measurements--such that the transport may be estimated for a particular runoff hydrograph, but is not sufficiently related to the individual discharges which make up that hydrograph (i.e., the transferability of results remains uncertain).

With an awareness of the difficulties in assessing watershed practice effects upon total sediment yield, this phase of the research was established to seek a clearer understanding of the bed-load processes for small mountain streams. The immediate scope of the study has been to develop an instrumented reach of stream to conduct detailed investigations of bed-load and total-load transport for natural or controlled streamflow conditions. The broader scope of the study has been to apply the research findings to identification of the effects of watershed practices upon the stream environment downstream of the disturbed watershed.

Relation to Water Quality Problems

Turbidity, along with temperature, dissolved oxygen, and other key parameters, is an important determinant of water's quality. Hence, use of the term "silt pollution" has become commonplace where the turbidity of streams by unnatural causes has had any adverse (or suspected adverse) effects on use of that water for whatever purpose, including its aesthetic use, by man or other organisms.

Sedimentation and increased turbidity of streams are common consequences of road building, logging, agricultural land use, mining, sand-and-gravel operations, and urban development in all parts of the nation. These problems are especially severe in regions of steep topography, such as the mountainous states of the West. They are perhaps most critical in the Pacific Northwest, where abundant rainfall and extensive forests result in widespread logging and severe watershed erosion--where the observer in an airplane can see miles of uncut forests drained by clear blue-green streams or see patches of logged forests drained by chocolate-colored sediment-laden streams--where clear and muddy tributaries join and flow together to the sea in a growing river of silt-polluted water.

In time, nature may have a chance to heal the scars on the watershed. But meanwhile, any changes in sediment production alter the substrate of streams and estuaries and, consequently, the biology and fishery resources of those areas. Similarly, water withdrawals from silt-laden streams for municipal, industrial, and agricultural uses are adversely affected, which leads to greatly increased costs for water treatment. Water-oriented recreational activities also suffer from muddy waters.

The role of the streambed in controlling the quality of water flowing over it may be appreciable. A watershed practice could have a significant effect upon the composition of material in the streambed and thus exert its influence upon the stream environment long after the initial removal of sediment or organic material from the watershed by storm runoff. At times, a gravel streambed may provide in nature much the same filtration effect upon fine particulate matter as does a sand filter in a water treatment plant. Subsequent storm runoff might be sufficient to disturb the gravel bed and permit a return of those fine particles to the flowing stream. This could compound any problem already present due to other material carried from upstream by the runoff. Furthermore, the watershed practice might increase flood runoff and cause greater disturbance of the streambed.

Although fine sediments and organic matter may be the chief offenders of water quality in streams draining timbered watersheds, sorbed toxic materials might also occur downstream because of applications of herbicides. Toxic materials likewise may be found downstream of some mining and agricultural operations. Also, an extensive literature deals with analogous problems with radionuclides on large streams. Hence, the types of pollutant material which may be temporarily stored in the gravel pores of a streambed are quite varied and not merely confined to fine sediments.

SECTION II

OBJECTIVES

Broad Objectives

The broad objectives of this phase of the research were to:

1. develop a better understanding of the sediment transport mechanisms in small rough-bottomed streams;
2. relate sediment transport to watershed conditions and land use; and
3. relate sediment transport to stream water quality.

These objectives were complementary to other phases of this research in developing a fuller understanding of the effects of watershed practices upon streams.

Specific Objectives

The detailed objectives of this phase of the research were to:

1. obtain measures of bed-load movement for a variety of steady and transient flow conditions in order to better evaluate:

    (a) the relationship between stream hydraulics and bed-material movement for coarse bed materials, especially for transient conditions.

    (b) the applicability of existing theories for evaluation of bed-load movement of coarse gravels subject to steady and variable discharges.

    (c) the effect of heterogeneity of bed-material on the transport of smaller particles present in the bed.

    (d) the depth of scour of coarse bed materials in mountain streams and the influx or efflux of silt particles from the gravel pores.

    (e) the factors influencing gravel bar formation in mountain streambeds.

2. evaluate the relationships between total sediment yield, suspended-sediment yield, bed-material disturbance, and land use based upon information obtained in achieving the first objective.

3. apply the knowledge gained under the first and second objectives to evaluate the total sediment load from the Alsea Experimental Watersheds and thus to evaluate the effects of land use on water quality.

Timetable to Achieve Objectives--Curtailment of Project

The objectives for this phase of the research were established for accomplishment with a three-year program. Principal activities scheduled for the first project year were to be literature reviews, facilities design, and facilities construction. The second and third years were to be devoted to concurrent field experiments and data analyses, and the third project year was scheduled to conclude with data evaluation and interpretation and the preparation of a detailed report. The work was to be conducted by a faculty principal investigator, a Ph.D. candidate developing his thesis along the general lines of the project, and several aides to assist with field and office work.

Curtailment of the project at the end of the second project year has made it impossible to complete several elements of the research included in the original objectives. However, in connection with some research objectives, a sufficient amount of data and/or insights have been obtained to permit at least some tentative conclusions to be drawn. Therefore, such conclusions have been made where sufficient sound evidence is available, together with adequate time for careful evaluation and interpretation.

SECTION III

EXPERIMENTAL APPROACH

General Aspects

This phase of the research was designed to provide answers to some critical questions on sediment yield processes and related stream hydraulics for rivers transporting a broad range of particle sizes. Emphasis was placed upon both the coarse particles (gravels), which determine the general streambed features and provide a "silt reservoir" in their intragravel void spaces, and the fine particles, which often constitute some type of pollutant through adverse effects upon water quality. Here the term "silt" is being used rather loosely, for descriptive purposes, to indicate fine particles in the stream which usually are carried in suspension when in motion and which may be found in the intragravel void space of an undisturbed streambed.

Previous research on suspended sediment yield from logged areas has indicated the need for a sediment model that defines the following:
1. the relationship of suspended sediment load to bed-load transport and to total sediment yield;
2. the relationship of total sediment yield to land use;
3. the hydraulic factors influencing movement of gravels and boulders of various sizes along the streambed;
4. the magnitude of bed-material transport during
   (a) steady-state stream conditions
   (b) transient (storm) stream conditions;
5. sediment yield related to a range of logging practices.

The present research was planned to develop such a model during a three-year project period. Because the frequent storm-flood event is crucial in introducing large quantities of fine sediment into the streamflow, this transient condition was given particularly detailed examination.

The total sediment load of a stream consists of (1) the bed load of material which moves at the streambed and is similar in size to particles making up the bed, and (2) the suspended or wash load of smaller particles carried throughout the entire water profile of the stream. The suspended-load particles do not represent an important percentage by weight of the streambed's composition. Nevertheless, such particles occupy the pore spaces among the coarse particles which comprise the bed and thus significantly affect the pore water quality of the bed. The streamflow may easily carry large quantities of this suspended load; hence, the wash load is limited only by the availability of small particles in the watershed, streambanks, and streambed, all of which are, in turn, significantly affected by watershed practices. Conversely, the amount of bed-material load is governed by the ability of the flow to transport it, rather than by availability of particles in the watershed. Here, too, watershed practices may have a significant effect by altering flood discharges (as has been demonstrated on the Alsea watersheds). Thus, the total sediment load of a stream is influenced by watershed practices, but the influence may differ for the wash load and bed-material load which make up this total load.

In most watershed studies, only the suspended load has been measured. The measured load was then related to land use. This approach has, of necessity, been utilized for studies on mountain streams because classical theories of bed-load movement were derived principally for streams with sandy bottoms or for equilibrium flow conditions. Bed-load theories for equilibrium transport of coarse gravels and boulders have many limitations, and none is universally applicable.

In short, the effect of land use on the erosion process and on water quality was assumed previously to be reflected in suspended sediment yields, without consideration of the effect of land use on the hydraulic processes ultimately responsible for sediment transport in mountain channels. Particularly concerning movement of large gravel, such assumptions were the only recourse in studies of the effect of land use on water quality.

Therefore, the general approach taken in this research regarding the problem of total sediment yield was to measure total yield in such a manner that the two distinct sediment-transport modes could be separately determined. Further, the process of sediment transport was analyzed in terms of its controlling hydraulic factors and the degree of disturbance of the streambed.

Planned Approach for Three-Year Project Period

Detailed examination of bed-load transport, suspended-sediment transport and total sediment yield was to be conducted at the Oak Creek facilities especially developed for this purpose. The bed-load process was to be analyzed in terms of its controlling hydraulic factors. Both transient and steady-state conditions were to be used. The degree of disturbance of the stream bed during transport was to be established.

Completion of this part of the project was expected to permit consideration of a wide range of sediment-related questions which comprise the remaining objectives. For example, a realistic (bed/load)/(suspended-load)/total-load) sediment model might then be formulated and related to the changed hydraulic characteristics below logged areas. This would identify the effects of logging on the sediment processes. The findings would also permit an examination of the utility of predictive techniques for relating land-use effects to water quality.

The effect of logging on sediment production from forested watersheds was to be determined from sediment data obtained at the Alsea experimental watersheds, where different logging practices were applied on several sub-basins for this purpose.

Extensive data on streamflows and sediment transport (suspended load and approximate total load) have been collected over several years, up to the present. Logging on two of the Alsea experimental watersheds occurred in 1966; the third watershed serves as a "control" for comparative studies. The analyzed data, together with information on streambed scour and deposition, was to be related to sediment transport processes. Hydraulic characteristics of the Alsea streams and composition of the streambeds were to be determined for use in determining sediment transport conditions below different logged areas.

The fate of released sediment and the nature of resulting problems also were to be determined at the Alsea watersheds, as well as at the Oak Creek watershed. Inferences were to be drawn in part from data on streambed siltation and in part from other sediment data obtained at the Alsea. Inferences were also to be made from relevant published research, so as to expand the applicability of this research.

Changes in hydraulic characteristics of streams downstream of logged areas were to be determined from data and observations at the Alsea watersheds. Supporting information published by other researchers was to be utilized also.

Finally, the research findings were to be evaluated from the viewpoint of suggesting possible watershed practices to minimize or avoid adverse water-quality problems with silt and related pollutants so as to protect the stream environment.

Modified Approach Due to Curtailment of Project

No major modifications in experimental approach were made at the Oak Creek facilities concerning those experiments dealing with sediment transport during naturally varying streamflows. However, the number of experiments conducted under controlled streamflows was greatly reduced to permit more time for data work-up and analysis.

Only a limited amount of data regarding bed-load materials in the Alsea Experimental Watershed was gathered because of the time reduction for this research.

SECTION IV

DEVELOPMENT OF OAK CREEK RESEARCH FACILITIES

Oak Creek, draining McDonald Forest in the Coastal Range just five miles west of the Oregon State University campus, offers several hundred feet of stream channel suitable for research purposes. The vegetation, terrain, stream profile, streamflows, and streambed composition are typical of many Pacific Northwest streams which provide spawning gravels for anadromous fish and which drain watersheds subject to logging. Access roads conveniently parallel the stream over most of its length. Because of these suitable stream characteristics and the great convenience for conducting research, a portion of Oak Creek was developed to facilitate study of sediment-transport processes in small mountain streams. Facilities were developed at two nearby reaches of the creek; the downstream reach was left essentially in its natural state and the upstream reach modified to permit water diversion into a concrete channel.

Instrumented Natural Stream

The downstream reach provides a 500-foot instrumented portion of the natural channel for study of sediment transport as a result of natural storm runoff. A schematic diagram of the reach and facilities is shown in Figure 1. Both the bed load and the suspended load of the stream can be measured. Depth of streambed scour and deposition can be determined as well as any significant changes in the features of the streambed and stream banks. Most of this reach has been improved only by clearing overhanging bank vegetation, channel debris, and some overbank vegetation to improve access and permit the use of surveying techniques in data acquisition.

Along this natural test reach, cross-sectioning stations were established at 12.5-foot intervals to permit study of changes in streambed and bank topography. Metal pins embedded in concrete mark the far ends of each cross-section.

Staff gages were mounted at seven locations along the reach to allow determination of water surface slopes and energy gradients over segments of the reach in conjunction with other experimental observations.

At the downstream end of the study area are several devices to permit the collection of streamflow and sediment transport data. Progressing in the downstream direction (Figure 1) these include: (1) an access bridge for work during major floods; (2) a plank bridge for stream-gaging moderate flows and for obtaining suspended sediment samples with a hand sampler (DH 48); (3) a support structure for the intake tube to an automatic sampling system for determining the integrated suspended sediment transport over extended periods; (4) intakes to a stilling well and the stilling well and water-level recorder (Type F) for obtaining a continuous record of river stage;

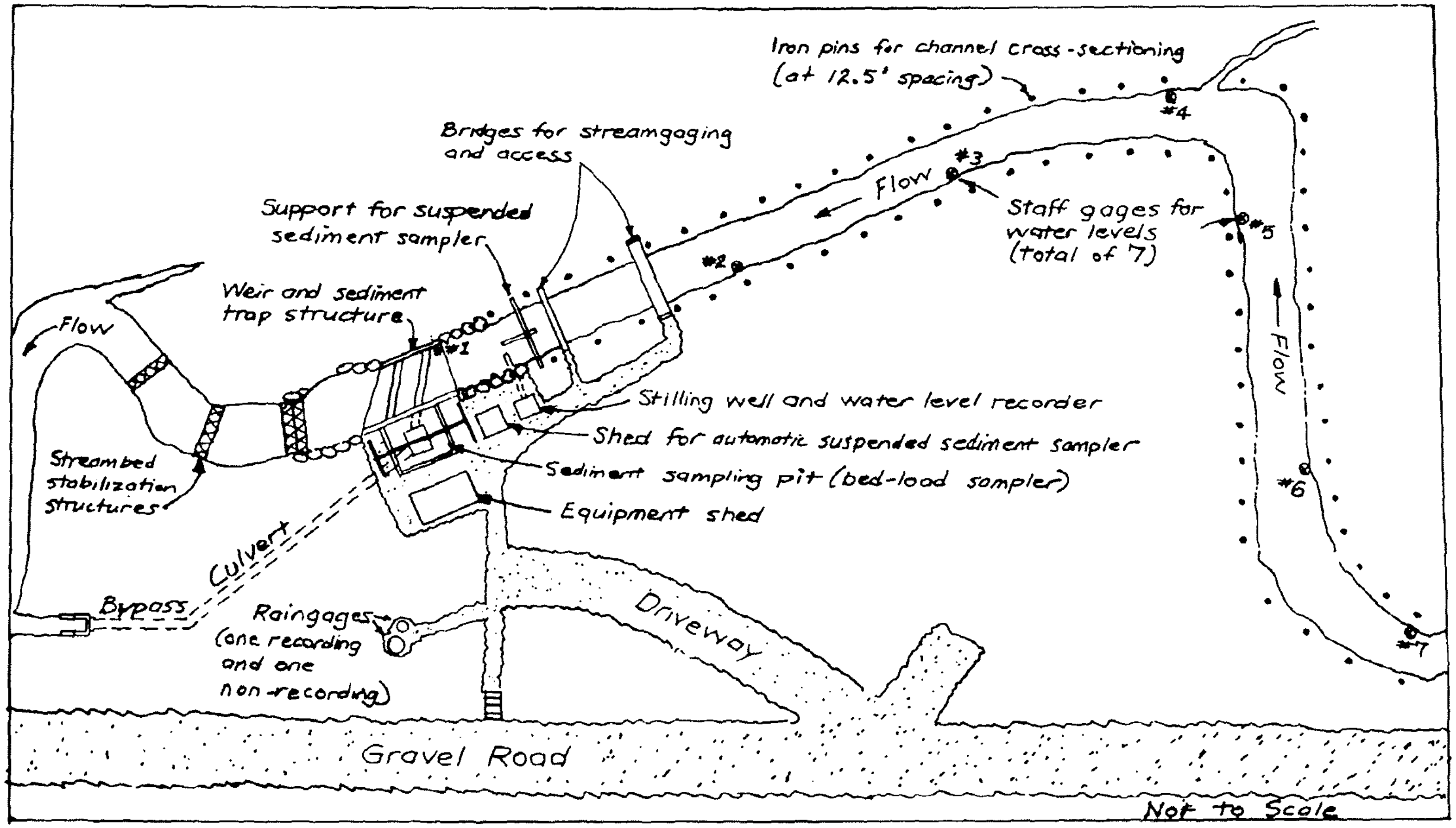

Figure 1. Schematic view of research facilities at instrumented reach of Oak Creek.

(5) the instrument house for the automatic suspended-load sampler (connected to the stilling well so that sampling frequency is a function of stage); and (6) a broad-crested weir into which a bed-load sampler has been incorporated. The broad-crested weir acts as a control for water level at the stilling well to provide a constant stage-discharge relation for the reach. The bed-load sampler is of unique design, using a vortex principle to remove the bed load from the channel into a sampling box, after which the withdrawn water (only a small fraction of the total streamflow) is returned to the stream via a bypass line. Control gates for the sampler permit continuous or discrete sampling of the entire bed load passing this section of the stream. Detailed information on the features of the weir/trap structure is presented in the next section because of the potential utility of such a device for other sediment research.

The Vortex Bed-Load Sampler

During the literature review on sediment sampling, before the design of the Oak Creek research facilities, it was thought that a bed-load trap for in-stream sediment collection might be devised with features similar to those used in some of the large flumes in various hydraulic laboratories. However, a vortex tube sand trap described by Robinson (1962) for excluding unwanted sediment from irrigation and other canals appeared to have possibilities for adaptation as a bed-load sampler. Because there was not much hydraulic and sediment information for Oak Creek upon which to base a careful design, a rough correspondence to Robinson's design criteria was attempted instead. Subsequent operation of the bed-load sampler indicated no major difficulties (although several minor changes might be incorporated into any future sampler). The resulting vortex-type bed-load sampling system is shown in plan view and cross-sectional views in Figure 2.

In designing the vortex bed-load sampler, doubts existed as to the capability of the vortex flume for handling coarse gravel and cobbles up to six inches in diameter (major axis). Therefore, a second trough was placed two feet downstream of and parallel to the vortex flume to act as a backup trough. Large material escaping from the vortex presumably would fall into this trough, where it could be collected. By use of the two troughs, the hope was to have a 100 percent efficient bed-load trap. Hindsight indicates that the second trough was unnecessary insofar as the coarse bed-load material was concerned. All particles larger than No. 4 sieve size (U.S. Standard Series) in diameter (3/16 inch) were trapped and held by the vortex for all streamflows--none reached the backup trough when the vortex trap was operated. As particle size became smaller in the sand range, the trap efficiency decreased and became dependent upon streamflow, according to inferences made from the data on bed-load transport. Thus, at flows greater than 40 cubic feet per second (cfs) the trap efficiency became very low for material of less than the No. 50 sieve size (0.297 millimeter) and as the flow decreased the trap

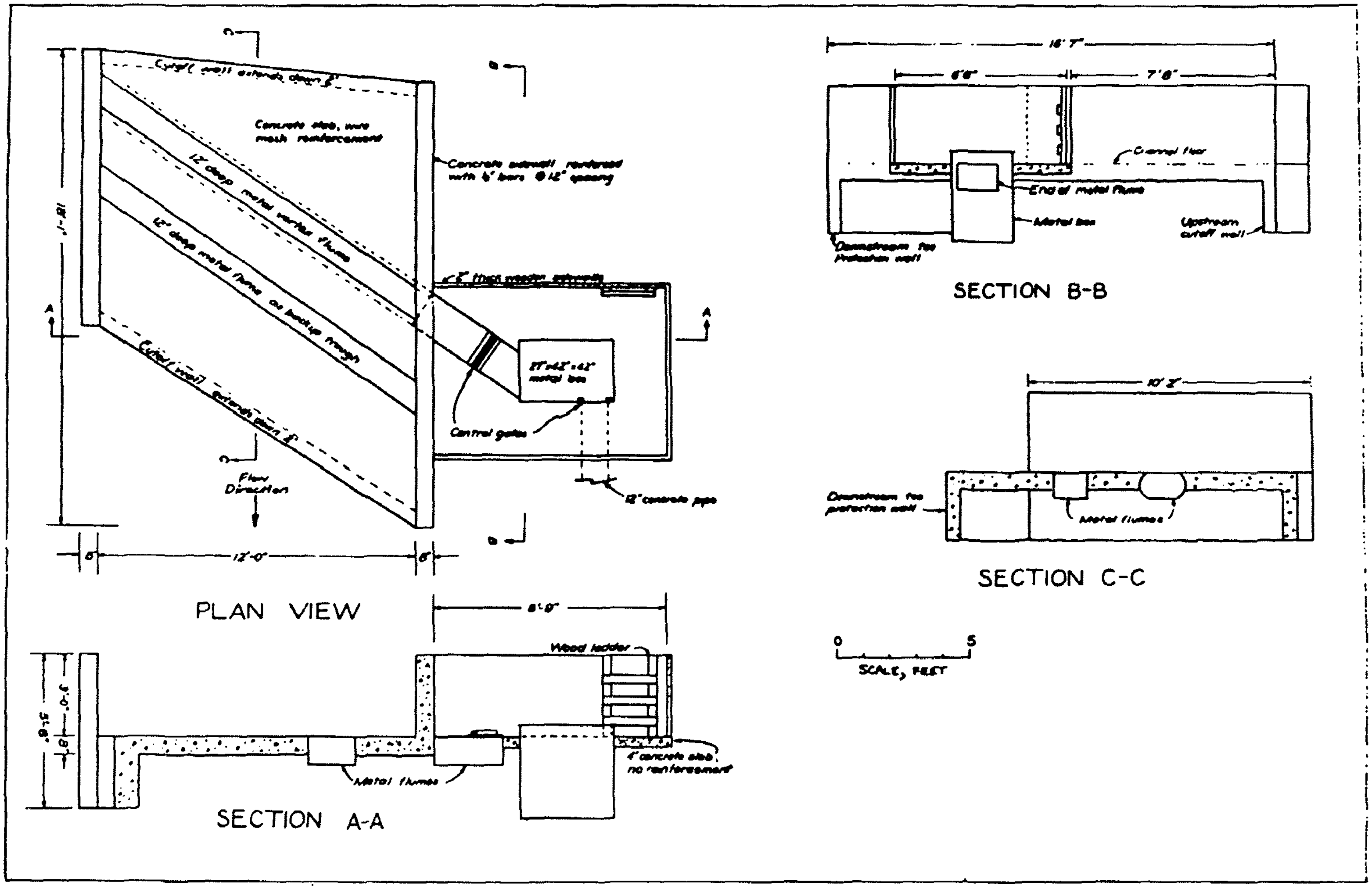

Figure 2. Broad-crested weir and vortex-type sediment sampling system (weir/trap structure).

efficiency increased. This same tendency was exhibited in various degrees for other particle sizes ranging from those passing the No. 4 sieve to those retained on the No. 200 sieve (0.074 millimeter). Particles finer than 0.074 millimeter were trapped in such small amounts that the trap efficiency for silt-sized and smaller particles was believed to be virtually zero. The trap efficiencies of less than 100 percent indicated for the finer fraction of bed load are believed to be explained by the turbulence of flow in the vortex, such that the finer particles were temporarily placed in suspension and thrown back out of the vortex flume or carried past the trap and into the bypass line.

The vortex flume and backup trough have an angle of orientation of almost 60 degrees to the direction of flow. The orientation was determined as much by tree roots in the streambanks as by the criterion of 45 degrees recommended by Robinson.

The vortex flume is placed horizontally and has its upstream and downstream edges at the same level. In cross-sectional shape the bottom is flat and 12 inches wide, but the sidewalls are curved and have a maximum width of 18 inches. The top opening is 12 inches wide. Total depth of the flume is 12 inches. The shape was selected for easy fabrication. The total flow length of the vortex flume is 19.5 feet, and the length of opening in the concrete channel floor is 14.5 feet. A vortex develops readily at all stream stages when the control gates are opened.

The backup trough is horizontal with upstream and downstream edges at the same level. It has a square 12-inch by 12-inch cross-sectional shape.

The concrete channel floor, in addition to holding in place the two sampling troughs, acts as a broad-crested weir and helps stabilize the stage-discharge relation at the stilling well. However, operation of the vortex causes a backwater curve that changes the stages for a short distance upstream. Consequently, either a correction curve or a dual rating curve is required to convert the water-level data to the corresponding discharges--both when the vortex bed-load sampler is open for use and when it is closed. Placing the stilling well a greater distance upstream could avoid or minimize this problem.

The vortex flume leads from the stream to a work pit having a concrete floor at the same level as the channel floor. This pit greatly increases the ease of collecting samples. Flat metal plates with handles serve as control gates in the work pit to regulate the vortex flow. The vortex flume opens into a deep metal box, or sampling trap, in the floor of the work pit. A smaller sample box can be placed in position at the vortex exit within the sampling trap to catch the bed load as it decelerates upon leaving the vortex flume.

Sample boxes are raised from and lowered into the sampling trap by means of a chain hoist attached to a pulley and supported by a hoist frame. The hoist frame also permits shifting the sample box to higher ground outside the work pit, where the sample can be stored or transferred to containers for subsequent laboratory analyses.

After the bed load has been deposited in the sampling box, the water drawn into the sampling area is returned to the stream by a return pipe. Because of local topographic features, a 100-foot line of 12-inch-diameter culvert pipe was used. Under different circumstances a shorter "bypass" or return line would be equally effective. The difference in energy head across the bypass culvert depends upon river stage and has a mean value of approximately three feet.

Operational experience has shown that most of the bed load drops into the sample box. However, sufficient turbulence occurs in the sampling trap so that some of the fine sand deposits in the bottom of the trap instead of collecting in the sample box. Subsequent collection of this sand poses no special problems other than time loss and some inconvenience. An improvement would be the use of a sampling trap large enough to use larger sampling boxes and to achieve a greater reduction in water velocity and turbulence.

Performance characteristics of the vortex bed-load sampler are illustrated by Figures 3, 4, and 5. Figure 3 shows the varying capacity of the vortex system as a function of river discharge (and hence indirectly of upstream energy head). No accurate data were obtained on the tail-water level at the bypass outlet, however, to relate vortex flow to differential energy head. But the system appears to be regulated principally by "inlet control" at the entry to the culvert from the sampling pit. At streamflows of less than 2.35 cfs, the vortex diverted the entire creek (Figure 4). The strength of the vortex increased considerably with increasing streamflow and water stage. At intermediate stream depths, a distinct breaker of white water occurred directly over the downstream edge of the vortex flume. At highest stages, the stream surface was generally wavy (suggesting critical-flow conditions) and the breaker was no longer visible, although a strong vortex could be felt if one stood in the flume in wading boots. The vortex always exhibited sufficient strength to transport any material carried into it by the streamflow (except when the vortex flume was completely filled with gravel after occasional periods of non-operation during unexpected storm runoff). From Figure 4 it may be seen that the vortex handled an increasing quantity but a decreasing proportion of the total flow as the river discharge increased. For example, at 40.9 cfs (the largest flow at which streamgagings were conducted both upstream and downstream of the weir/trap structure for the purpose of developing a rating curve of the vortex system) 8.1 cfs or 20 percent of the streamflow was diverted through the vortex. During discharges exceeding 150 cfs, the vortex flow was estimated to not exceed 15 cfs (i.e., 10 percent

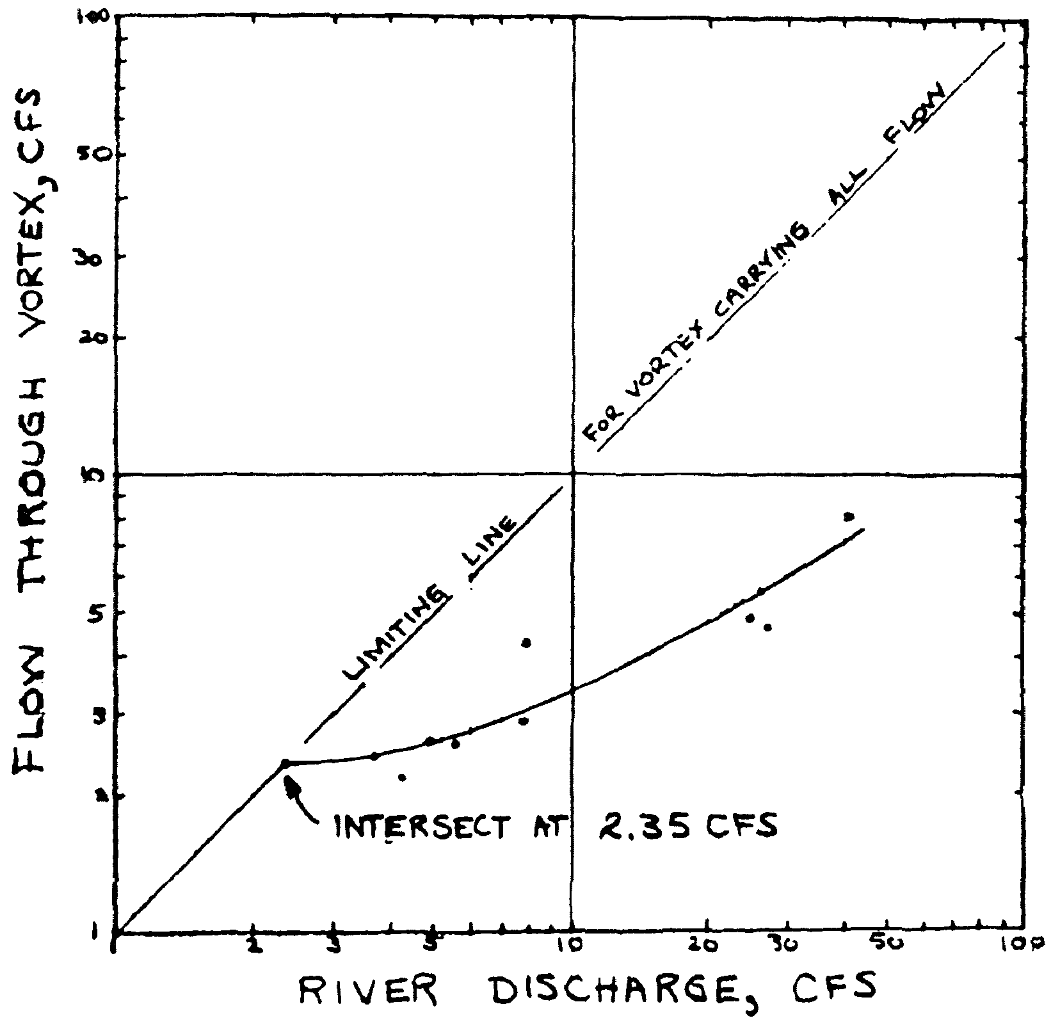

Figure 3. Discharge capacity of the vortex bed-load sampler.

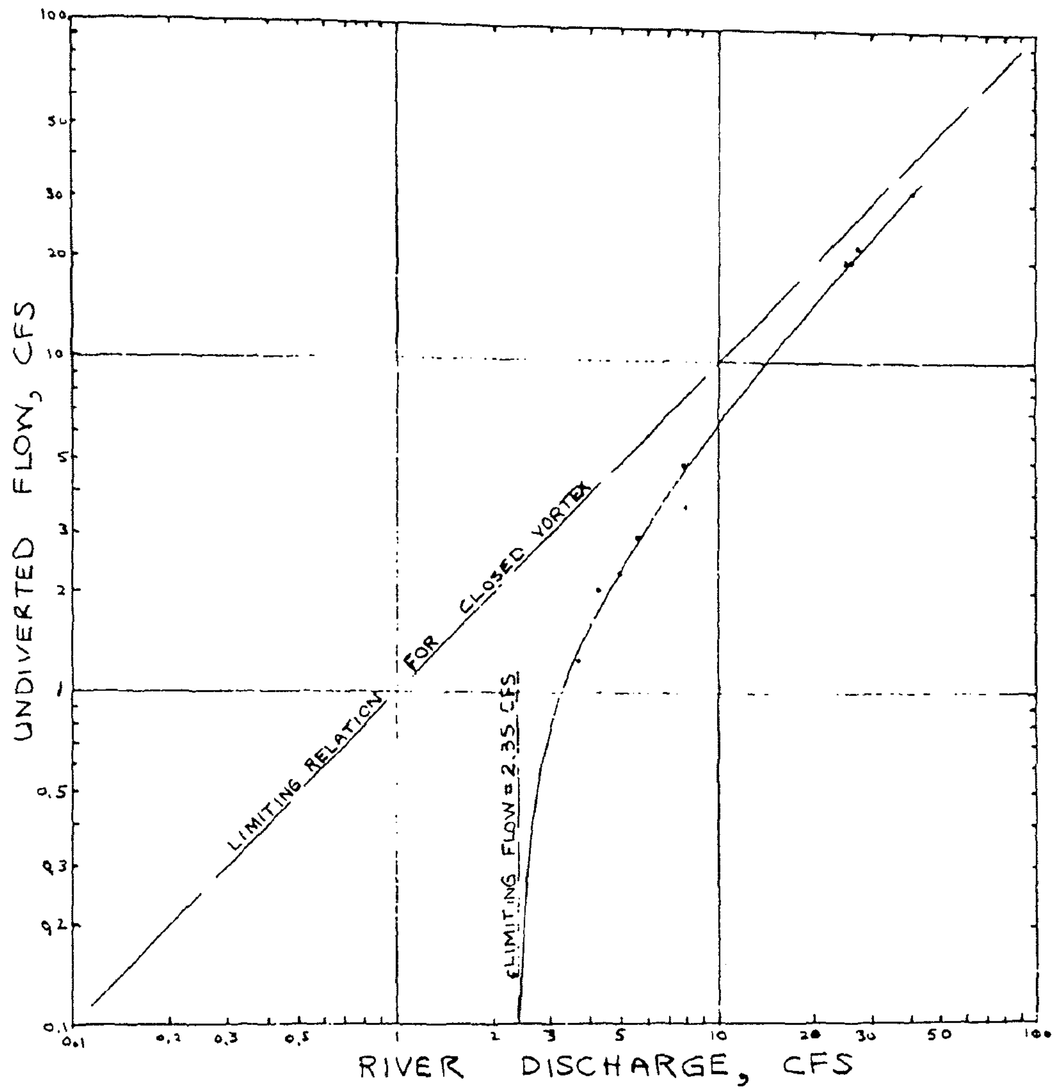

Figure 4. Flow across weir/trap structure during operation of vortex bed-load sampler.

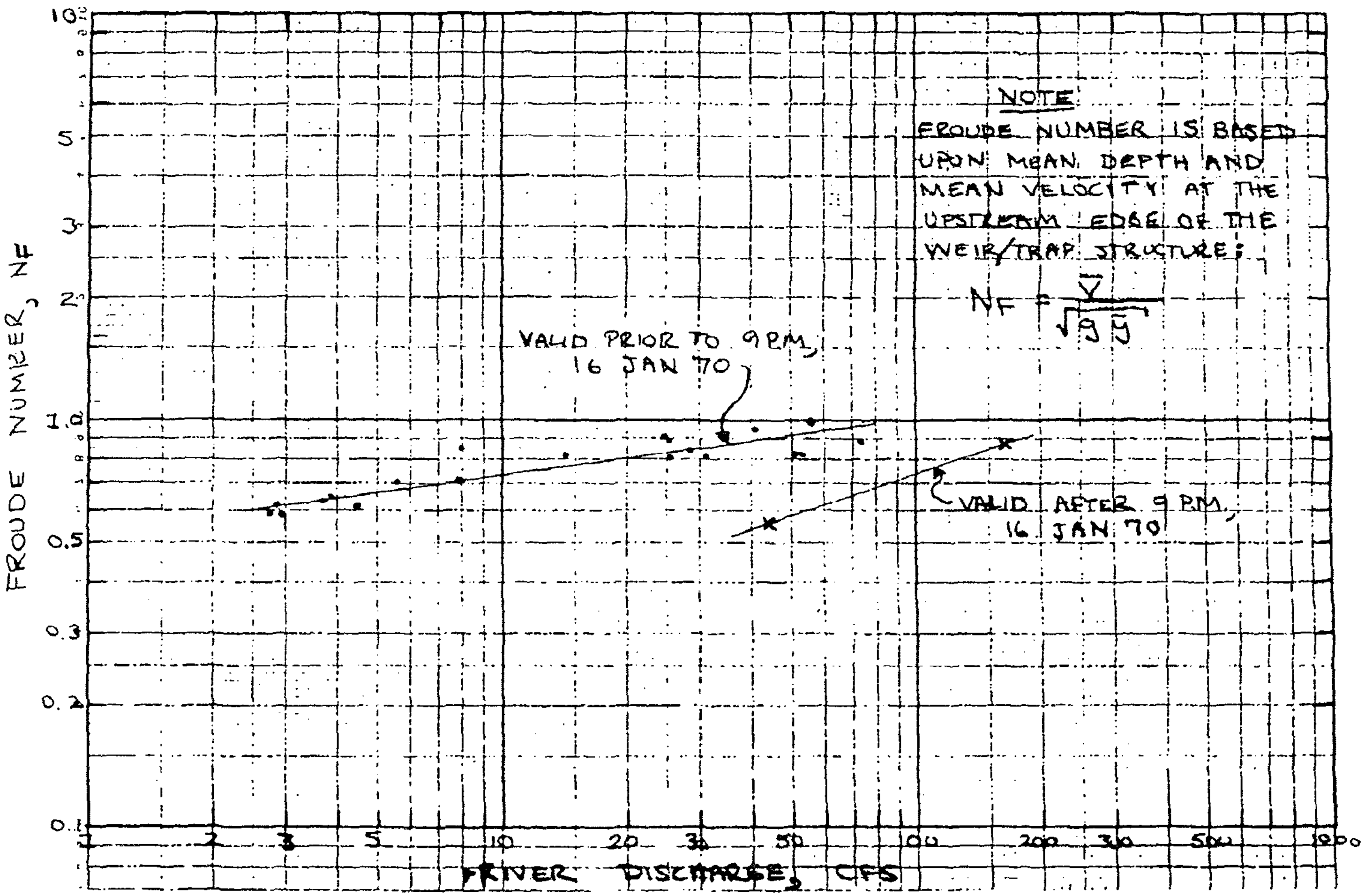

Figure 5. Variation of Froude number with discharge during operation of the vortex bed-load sampler.

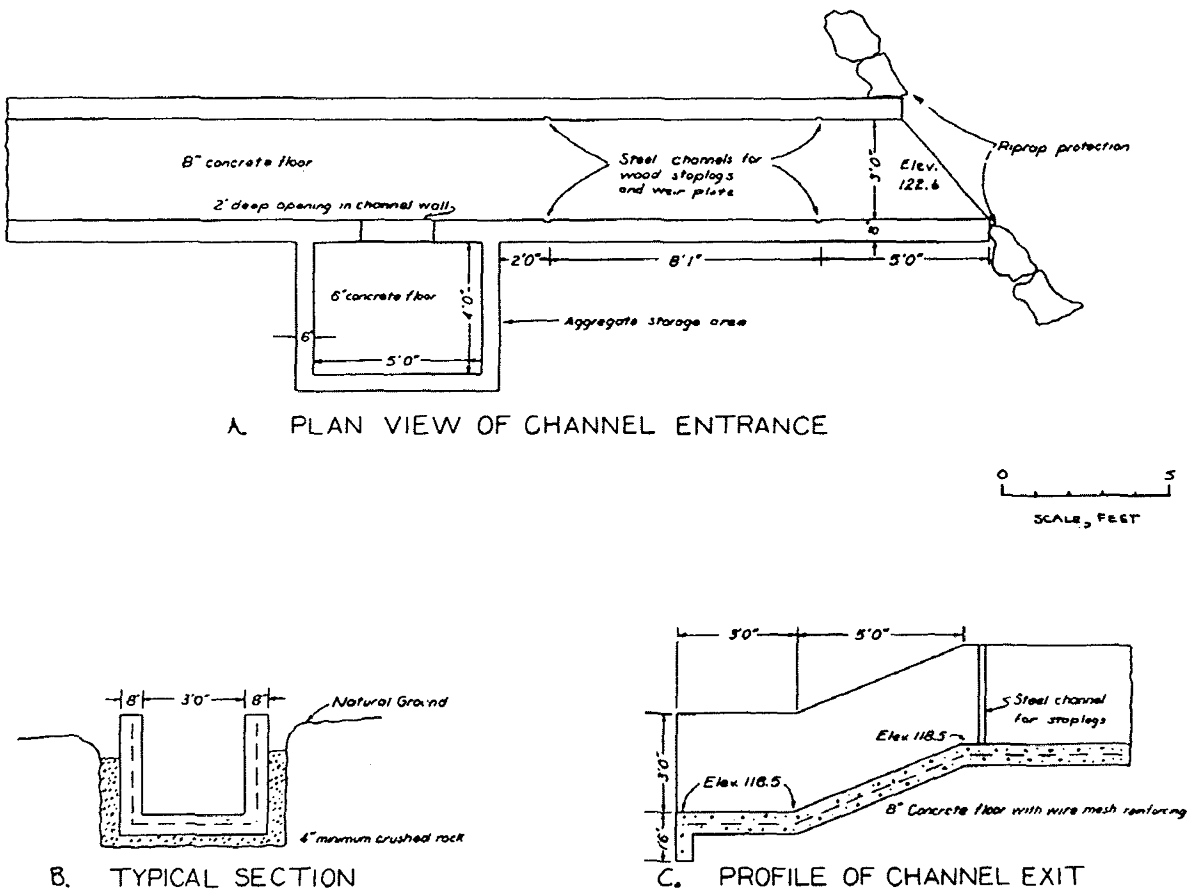

Figure 7. Detail views of concrete channel.

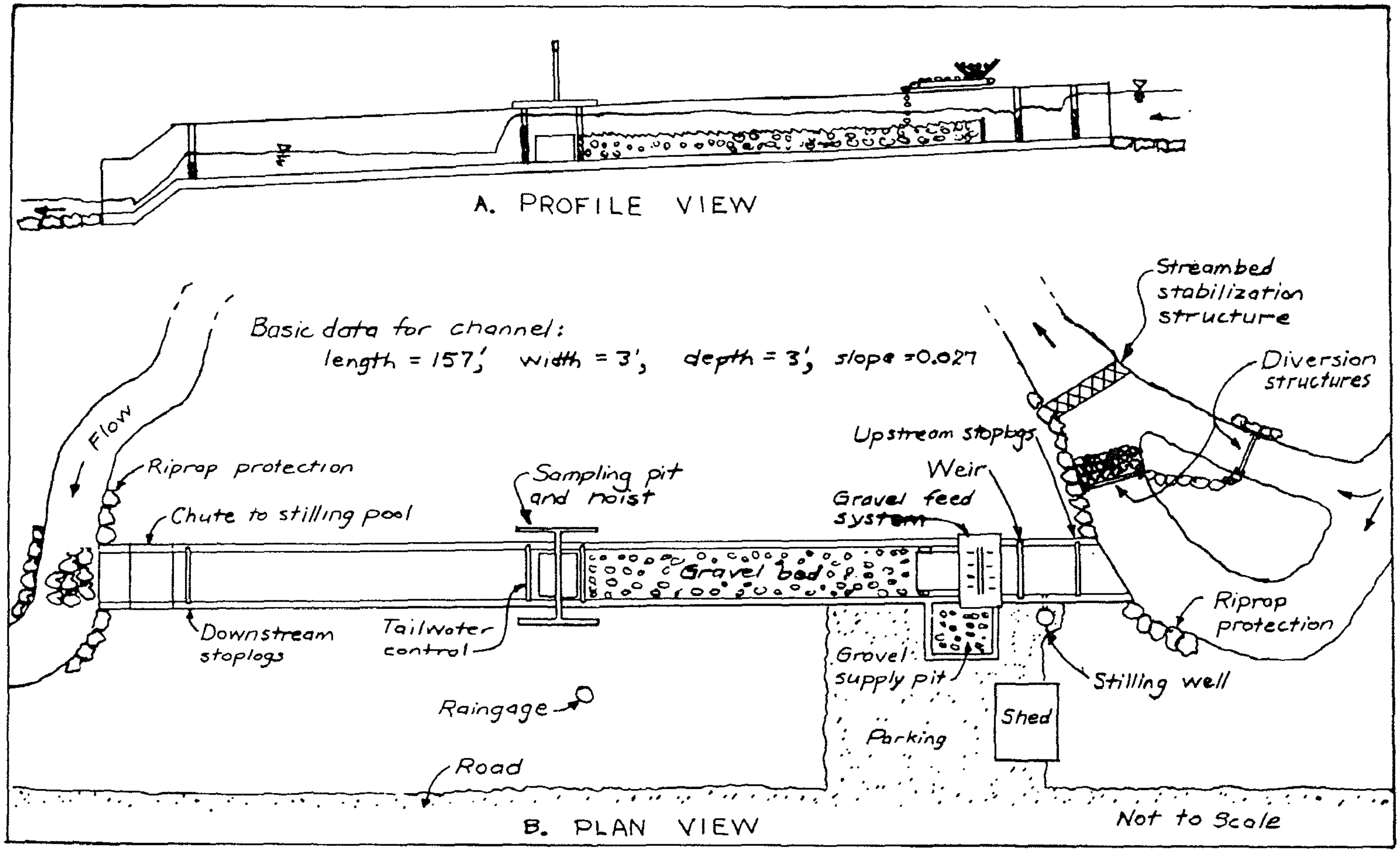

Figure 6. Schematic views of instrumented concrete channel.

or less of the total river flow). For comparison, Robinson (1962) indicates a flow removal of from 5 to 15 percent of the total flow as a criterion for successful operation with sand.

In Figure 5, the variability of Froude number (the mean flow velocity divided by the square root of the product of gravitational acceleration (g) and mean depth of flow) with streamflow is shown. The Froude number is calculated for the cross-section just upstream of the vortex flume. A shift in the location of the control point for the stage-discharge relationship occurred during the night of January 16 and accounts for the different lines in Figure 5. During periods of bed-load transport, the Froude number ranged from 0.6 to slightly less than 1.0, which indicated sub-critical flow approaching the vortex trough. The shift in control point and corresponding reduction of Froude number at a given discharge caused a change in trap efficiency for sand-sized particles, as will be discussed later.

Instrumented Concrete Channel

A short distance upstream of the instrumented "natural stream" research area, a 157-foot concrete research channel lies across a large meander loop of Oak Creek. The channel is three feet wide by three feet deep. A diversion structure at the upper end of the reach permits control of the flow entering the concrete channel. This facility permits controlled experiments of bed-load transport and related phenomena for placed streambeds of selected material and for simulated storm runoff and other regulated flows.

Schematic representations of the research facilities in this reach of Oak Creek are shown in Figure 6. Details of the concrete channel are presented in Figure 7.

The diversion structures consist of wooden plank dams supported between pairs of steel channels embedded in concrete. The structure nearest the channel (see Figure 6) rests on a low dam of broken concrete riprap sealed with a plastic sheet. Low ground between the diversion structures is similarly dammed by broken concrete and a plastic sheet. A trash rack upstream of the diversion structures prevents branches and logs from entering the concrete channel.

Stoplogs may be placed near the upstream entrance to the concrete channel to exclude or regulate streamflow through the channel. (The diversion structures also provide such regulation, but with much less control.) A short distance downstream, additional stoplog slots accomodate a sharp-edged weir of adjustable height. A stilling well alongside the concrete channel indicates water levels upstream of the weir by means of a pipe connection through the channel wall. A point gage in the stilling well allows measurement of water levels for use with a rating curve to obtain the discharge rate through the channel.

Gravel beds of selected material sizes are placed in the channel over lengths that may be varied by end walls at different stoplog slots along the channel length (e.g., see the profile view in Figure 6). The tailwater level and depth of flow over the gravel also can be regulated with stoplogs in the slots near the downstream end of the gravel bed. Although the slope of the concrete channel is fixed at 0.027 feet/foot, the initial slope of a gravel bed can be varied considerably by its manner of placement in the channel.

Bed-load transport is measured at a sediment trap at the downstream end of the gravel bed. A sampling box fits snugly into a trap area between two sets of stoplogs to accomplish this. The sample box can be removed by a chain hoist and pulley attached to a hoist frame, as at the downstream reach, and the sample collected for subsequent analyses.

Gravel can be fed to the streambed at its upstream end at a steady, adjustable rate. This is done by a V-shaped supply trough above a power-driven conveyor belt. A gravel storage area alongside the trough permits replenishing the supply material as required.

Elevations of the gravel bed and water surface are determined with movable point gages. Stations of known elevation at 1-foot intervals along the full length of the channel facilitate these measurements.

SECTION V

EXPERIMENTAL PROCEDURES AND METHODOLOGY

The general procedures and methods followed in conducting experiments on sediment-yield processes at Oak Creek are described briefly in the following paragraphs. Where applicable, standard techniques were followed and are, therefore, not explained in great detail.

Streamflow

Continuous records of stream discharge were needed to convert individual observations of sediment transport rate into estimates of sediment yield. A water-level recorder installed in a stilling well near the weir/trap structure gave a continuous record of water stage, which was related to discharge through a series of streamflow gagings by conventional measurement techniques using standard and small current meters (Gurley Price, Gurley Pygmy, Ott C1 Small, and Neyrpie Midget) at gaging sites near the stilling well. From these observations a rating curve was developed so that continuous streamflow data could be obtained. Streamgagings were conducted over as full a range of discharges as possible and with sufficient frequency to detect any changes in the stage-discharge relationship attributable to shifting control points for the flow.

Supplemental measurements were obtained concurrently with several of the stream gagings. Among these were observations of the effect upon water stage of the operating status of the vortex bed-load sampler (whether open or closed). Also, simultaneous or nearly concurrent measurements were made at the downstream end of the weir/trap structure and at the gaging station just upstream to determine the vortex discharge at various streamflows.

Hydraulic gradients along the instrumented reach of Oak Creek were determined at the times of most streamgagings. This was accomplished from observations of water stages at seven staff gages along the channel spanning sub-reaches with differing hydraulic characteristics. The energy gradients along the instrumented reach could also be determined from the data on water surface slope and from estimates of velocity head based on streamflow data.

Suspended Load

Suspended sediment loads were sampled by two techniques--periodic hand sampling and composite automatic sampling. Individual samples were collected near the stilling well by means of a DH 48 hand sampler. These samples were integrated with respect to depth and lateral position in the stream cross-section, but were discrete with respect to time. For composite automatic sampling, a specially constructed sampler was used, patterned after a similar sampler developed at the Forestry Sciences Laboratory, U.S. Forest Service, Corvallis. A sampling tube extended from a framework, which held it in the stream, to an instrument house, which contained a pump, solenoid-activated valves, sample container, timer, power supply, and switches for controlling sampling frequency. Upon activation, the pump removed all "old" water from the sampling tube before the sample was taken. A float in the stilling well was connected to a counterweight in this instrument house so that different switch circuits were opened or closed as water stage changed, thus varying the sampling interval between 10 minutes at highest stages and 12 hours at lowest stages. All samples for any period of days were composited in a 20-gallon bottle.

The collected samples were analyzed for suspended solids concentration using filtration with 0.45 micron Millipore filters. Standard procedures were followed.

Bed Load

The field procedures followed to obtain bed-load samples with the vortex bed-load sampler evolved with experience in operating the sampler. At first, the sampler was operated continually. However, the samples occasionally could become completely filled at times of abrupt streamflow increase if no operator was present (e.g., during the middle of the night). On such occasions, the rate of sediment transport into the trap was uncertain. Furthermore, considerable effort was required to completely clean the sampler before further sampling.

The procedure eventually followed was to keep the vortex gates closed at all times except when obtaining bed-load samples. At such times, the vortex flume and backup trough first were checked and any sediment deposits cleaned out. The trap gates then were opened for a variable sampling period. When the streamflow was high, several minutes of sampling were sufficient to nearly fill the sample box, at which time the gates again were closed. Times and water stages at the stilling well were noted upon opening and closing the gates. As soon as the partly filled sample box had been removed and an empty box put in its place in the sampling trap, the gates would be opened again. Any material deposited in the vortex trough during the brief period when the gates were closed would be included in this subsequent sample, with respect to both the sediment amount and the time period for the subsequent sample. In this respect, then, the bed-load sampling could be done continuously, if desired. When the bed-load transport rate was low, the material collecting in the sample box would be checked periodically for size and amount before deciding whether to close the gates for sampling. Ideally, samples were sought which would correspond to a fairly constant stream discharge during the sampling interval, and the sampling interval desired would be a small segment of time on the rising or falling limb of a runoff hydrograph.

Samples of bed load were carefully transferred from the sample boxes to 5-gallon buckets and given identity numbers before being taken to the laboratory. On one occasion where the vortex had been left open overnight and the entire sampling trap had filled with sediment, the material was randomly split and only a known fraction of the sample was taken to the laboratory for analysis.

In the laboratory, the entire sample first was ovendried at about 150°C (the controls on this large oven could not be adjusted to lower temperatures). Then the dried sample was processed through a series of sieves, using mechanical vibration, to determine both the total dry weight of the sample and the particle size distribution of the sample (based on dry weight of sample retained between successive sieves). The sieve screens conformed to the U.S. Standard Series in the size of the mesh openings. A listing of the complete set of sieves used is given in Table 1, together with the equivalent diameter of the smallest particle retained on each sieve. Sieving was facilitated by first passing the dried sample through the sieves ranging from No. 4 to 2 inches in mesh. The fraction retained on the 2-inch sieve was then checked for material coarser than 3-inch and 4-inch sizes. Similarly, the fraction passing the No. 4 sieve was analyzed with the series of screens from No. 8 to No. 200. If the amount of material passing the No. 4 sieve was too great to be held in the smaller screens, this fraction of the sample was first split before resieving.

Bed Materials in Instrumented Reach

Samples were collected of surface and subsurface sediments in the streambed to characterize these materials. The majority of samples were obtained in several locations where channel cross-sectioning stations were established. Others were obtained away from the stations if some distinct feature existed, such as the rapid local down cutting of a gravel bar, which left a vertical cut through the bar upon recession of streamflow. Many of the samples consisted of collecting the surface layer of sediment. However, in some locations sets of samples corresponding to adjacent vertical zones were obtained.

Laboratory analyses of the samples included particle-size distributions of the bed material, based upon sieving the ovendried samples as already described, and weight distributions of individual particles within each sieve-size range. The shapes of individual particles within each sieve-size range were determined by measuring the major, minor, and intermediate diameters of each particle with calipers.

Specific gravity tests were made on a composite sample of streambed particles to determine the representative specific gravity of bed material from Oak Creek and any possible variability in this value as a function of particle-size range. Specific gravities of the smaller particles were determined by standard procedures with a pycnometer, or volumetric flask. Gravel coarser than No. 4 sieve in

Table 1

SIEVE SERIES AND EQUIVALENT PARTICLE DIAMETERS FOR ANALYSIS OF SEDIMENT SAMPLES IN STUDY (1)

Sieve Size	Approx. size of sieve opening	
	Inches	Millimeters
4-inch	4	101.6
3-inch	3	76.2
2-inch	2	50.8
1 1/2-inch	1.5	38.1
3/4-inch	0.75	19.05
3/8-inch	0.375	9.52
No. 4	0.1875	4.76
No. 8	0.0937	2.38
No. 16	0.0469	1.19
No. 30	0.0234	0.595
No. 50	0.0117	0.297
No. 100	0.0059	0.149
No. 200	0.0029	0.074

(1) U.S. Standard Series sieve sizes used.

size was analyzed for specific gravity using a wire basket suspended in water and following accepted procedures.

Changes in Channel Topography

During the initial field surveying and mapping before the development of sediment research facilities, several control points of known elevation (arbitrary datum) were established, some of which were adjacent to the instrumented reach of Oak Creek. During development of the facilities, pairs of cross-sectioning stations were established at 25-foot intervals along the axis of the stream. Metal pins were embedded in the ground and held with concrete at the outer ends of each cross-section for permanent reference. Subsequently, additional cross-sections were established half-way between the existing ones, giving a 12.5-foot average spacing of sections. The purpose of the cross-sections was to provide fixed locations for periodic resurveying of the channel to map the streambed and banks, and determine any changes in shape because of erosion and sedimentation.

Such mapping of the channel was conducted on several occasions using conventional surveying techniques. Elevations were obtained at all "break-points" in shape across each cross-section. A surveyor's level, leveling rod, and steel measuring tape were used. At the time of the first detailed survey, elevations were obtained at numerous points between cross-sections for the purpose of completing a detailed map.

Depth of Scour and Deposition

The depths of streambed scour and deposition during floods were studied by means of buried "scour" balls as well as through the cross-sectional surveying already described. The scour balls were of two types: punctured ping pong balls of neutral buoyancy and buoyant stryofoam balls of the same size as ping pong balls. Each type was installed in vertical arrangement in the streambed and the point of burial referenced to the metal pins of nearby cross-sections for later relocation.

To place the balls in the streambed, a solid rod and concentric hollow pipe were first driven into the bed to a depth of over one foot. The rod was then removed, leaving only the pipe sleeve. For the punctured ping pong balls, a fishing weight with attached colored line was dropped down the pipe such that the line would trail out in the water to facilitate later relocation of the buried balls. The numbered balls were then sunk into the pipe until they extended from the top of the fishing weight to the top of the streambed. The depths of the bottom and top balls were noted so that the positions of all balls in the column (about a dozen balls, typically) could be determined. The pipe sleeve was then removed from the bed and a small amount of sand placed over the top ball at the streambed surface. During floods, any scour that occurred would remove one or more of the ping pong balls, depending upon the depth of scour, which would then move downstream toward the vortex trap along with other bed-load material.

The styrofoam balls, because of their buoyancy, would rise to the stream surface at that instant when scour developed to the depth of burial of such a ball. Each ball had a separate fishing weight as its anchor. The anchors were all placed in the bottom of the pipe sleeve and covered by some sediment. Individually numbered balls were buried with some gravel and much slack fishing line between them so that one ball rising to the water surface would not pull the other balls out of the hole. During floods, if scour was sufficient to disturb any of the styrofoam balls, they would pop to the surface and an observer making a periodic inspection of the test reach would, hopefully, see the balls and note their presence and identification number.

The depth of maximum scour during flood periods and any subsequent redeposition as flood strength weakened were both determined. To accomplish this, the collection of scoured balls as described above was supplemented by relocation of the burial points during low water between floods and excavation down to the top ball. The depth of excavation indicated the depth of redeposition and the identity number of the top remaining ball indicated the depth of maximum scour. The balls were then carefully covered to the pre-excavation level.

Painted-Gravel Experiments

Painted gravel was used to study the distance-of-travel and time-of-travel of large bed-load material. The gravel used for these experiments was taken from the analyzed material collected from Oak Creek during early bed-load sampling. The sizes of the particles ranged from 3 inches to 3/16 inch in nominal diameter. A yellow paint similar to that applied for highway marking was applied by hand brush. The individual rocks then were numbered and weighed. The prepared gravel then was dropped into the stream from above the water surface so that the particles would come to rest on the streambed in as natural an orientation as they could be placed. During and after periods of storm runoff, inspections of the stream were made to locate the painted gravel, and the positions and rock numbers were recorded. Some problems were experienced in making these inspections: it was necessary to wait until storm runoff receded and the water cleared before the streambed became visible again; the paint tended to wear off rapidly because of abrasion at the time of bed-load transport; and painted gravel tended to become buried beneath the surface of the bed as a result of bed-load transport of these and other particles.

Period of Intensive Field Work at Instrumented Reach

In the fall of 1969, preparatory work was completed for winter sediment-yield observations. Detailed mapping of the channel bed and banks was followed by installation of several scour balls. All sediment sampling apparatus was set up, as well as related equipment for obtaining precipitation and streamflow information.

Sediment was sampled during December, January, and February when streamflows were sufficient to disturb the streambed. Depth of scour and deposition and of changes in channel topography also were determined periodically during this period. By April, spring streamflows clearly were no longer sufficient to transport gravel, so no further field work was done at the instrumented reach.

Research Activities at the Concrete Channel

Graded river-run gravel from the Willamette River was placed in the concrete channel to create a plane gravel bed of fairly uniform particle size. The commercial gravel used ranged from 3/4 to 1 1/2 inches, although some finer and coarser material was present.

Movement of this artificial streambed was studied under a range of transient and steady-state flow conditions. Particular focus of these initial experiments was upon incipient motion of the particles, scour patterns, and tendencies for any development of a natural protective "armor" layer at the surface of the bed. This information was sought to give greater insight to the bed-load observations made in the natural study reach and the basic mechanisms involved.

The data obtained during the late winter and early spring of 1970 are rather tentative in their applicability at the moment. Several additional experiments are required when streamflow again becomes sufficient to transport gravel. Therefore, no firm conclusions have been drawn from the data obtained in the concrete channel. Because of this, any further discussion of experimental procedures and methods at the concrete channel is omitted from this report.

SECTION VI

HYDROLOGIC CHARACTERISTICS OF OAK CREEK STUDY REACH

The Oak Creek Drainage Basin

The Oak Creek Basin used for this study lies almost entirely in McDonald Forest, which is managed by Oregon State University's School of Forestry. The forest lands lie on the eastern edge of the Coastal Range. The drainage basin above the weir/trap structure is outlined in Figure 8, which also gives the general location of the basin with respect to Corvallis and Oregon State University.

The drainage area tributary to the weir/trap structure is approximately 2.8 square miles. This land ranges in elevation from 480 feet (MSL) at the structure to 2,178 feet at the highest ridge fringing the basin.

Most of the drainage basin lands are covered with young-to-mature Douglas fir. Various other tree species occur, including Oregon white oak, grand fir, western yew, western redcedar, western hemlock, Oregon ash, red alder, and bigleaf maple. Some clearcutting, thinning, and replanting have taken place on the watershed in the past. Natural open meadows also occur in the basin.

The soils of the drainage basin vary in depth from a few inches or less in steep areas to several feet in the alluvial deposits along the lower portions of Oak Creek near the research facilities. Infiltration rates are quite high because of a well-developed forest litter and root system in all vegetated areas.

The subsoil zone consists of fractured and weathering bedrock, which is principally sedimentary and basaltic in origin. Outcroppings of this fractured and weathered bedrock along the channel provide the source material for bed-load transport in Oak Creek. (The alluvial portions of the lower part of the basin allow long-term storage of this material as the channel changes in position over the years.)

Precipitation During Field Studies

During sediment sampling, Oak Creek streamflow was very responsive to changes in rainfall intensity at times when the watershed was thoroughly wet from antecedent rainfall. This sensitivity to rainfall was particularly evident during part of December 1969, most of January 1970, and part of February 1970, because of the heavy rainfall over several days in those periods. These long "steady" rains exhibited considerable variation in intensity, which caused the stream level and discharge to fluctuate considerably during many 24-hour periods.

The seasonal variation in rainfall at the Oak Creek drainage basin can be seen from Table 2. Data from the Hyslop farm northeast of Corvallis have been included in this table to extend the Oak Creek data back into early fall, 1969. The two precipitation stations are

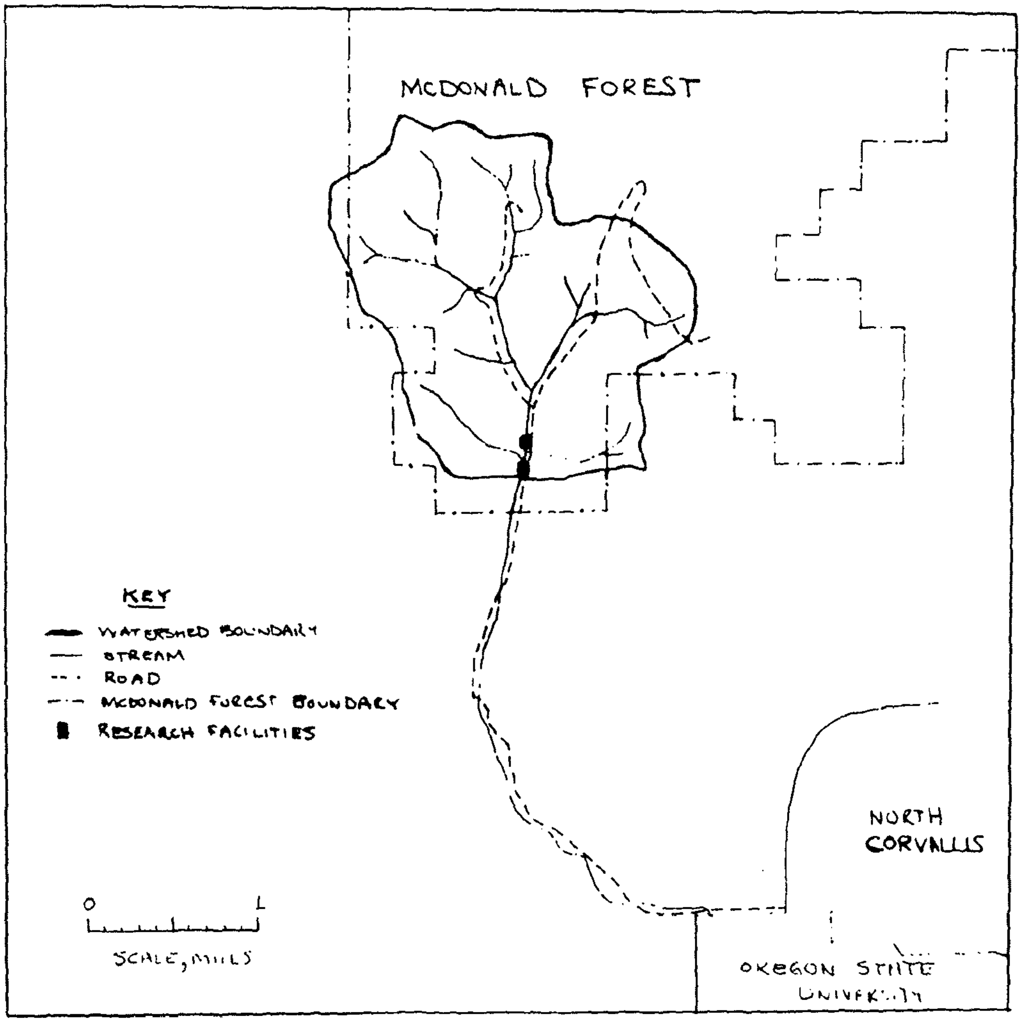

Figure 8. Location map for Oak Creek sediment research facilities.

Table 2

MONTHLY RAINFALL TOTALS DURING FIELD STUDIES

Month	Corvallis Precipitation (1)	Oak Creek Precipitation (2)
Aug 1969	Trace	---
Sept	3.62	---
Oct	3.91	---
Nov	2.86	---
Dec	11.59	12.08
Jan 1970	15.51	17.45
Feb	5.97	5.28
Mar	2.29	2.46
Apr	2.66	3.91
May	1.12	1.62

(1) Measured at Hyslop farm near Corvallis; elevation 225'.

(2) Measured adjacent to research facilities; elevation 490'.

generally similar in broad rainfall characteristics, as can be noted by a comparison of the concurrent records from December through May. Most of the rainfall through early December was intercepted by vegetation or utilized on the basin to recharge soil moisture. Similarly, much of the rainfall on the basin after the end of February was used to recharge soil moisture or lost to the atmosphere by evapotranspiration.

Daily precipitation values near the basin from December through February are shown in Table 3. Data from the Hyslop farm were used because of the consistent time of daily observation. The daily rainfalls at Hyslop farm did not differ importantly from those observed at the Oak Creek gages.

Two major storm periods occurred in December 8-14 and 20-23. In the first period, 5.64 inches of rain fell at Oak Creek rain gages from noon on the eighth until 5 p.m. on the fourteenth, and considerable sediment transport took place in the stream. During the second storm, an inch of rain fell at Oak Creek during the night of the twentieth and morning of the twenty-first and also caused considerable sediment movement in Oak Creek.

January precipitation in Corvallis was the greatest in 89 years of record. By inference, this also was true at Oak Creek. Bed-load transport occurred in the stream on several occasions because of particularly heavy, extended rainfall. The more important periods included 8-9, 12-14, 15-20, and 22-27.

In February, the principal storm resulting in bed-load transport in Oak Creek caused heavy rainfall on 15-16.

The variability of rainfall intensity during a storm period and its resulting effect upon Oak Creek discharge are shown in Figure 9. The period 12-20 January is illustrated because of the large streamflows. The rate of change of cumulative rainfall at the recording rain gage (the slope of the curve at any point of tangency) gives the intensity of rainfall. Rainfall intensity was quite changeable, and during low-intensity rainfall the streamflow tended to recede. Each period of sustained high-intensity rainfall was marked by an abrupt rise in streamflow with corresponding effect on sediment movement. Rainfalls of about 3/4 inch in less than four hours on January 16 and 19 led to the two maximum streamflow peaks of the winter season.

Streamflow During Field Studies

Rating curves were developed for water stage and discharge at the Oak Creek weir/trap structure, based on numerous streamgagings at differing flows. Instead of a single rating curve, two rating curves were required, because of a shift in control point during the flood on January 16-17 (Figure 9). At that time, the bed-load transport past the vortex sampler was so great that continuous operation of the

Table 3

DAILY RAINFALL TOTALS DURING WINTER 1969-70

Date	Total rainfall, inches, for 24 hrs to 8 am of date shown [1] December	January	February
1	-	-	.29
2	-	-	.01
3	-	-	.03
4	.19	.13	-
5	.01	-	.02
6	.12	-	1.14
7	.09	-	.25
8	.29	.04	-
9	.57	.86	-
10	.22	.84	-
11	.42	.03	-
12	2.37	.52	-
13	.35	.47	.20
14	1.17	.50	-
15	.02	.50	.05
16	.22	.45	1.93
17	.24	1.80	1.73
18	.41	.79	.21
19	.14	.54	-
20	.35	.98	-
21	1.30	.57	-
22	.02	.75	-
23	1.18	1.51	-
24	.32	.74	-
25	.11	1.73	-
26	.59	.54	-
27	.20	1.02	-
28	.67	.08	.11
29	.02	-	
30	-	.10	
31	-	.02	

(1) Data from Hyslop farm near Corvallis used because of consistent time of daily observation. Source: U.S. Weather Bureau, E.S.S.A., "Climatological Data, Oregon" December, 1969; January, 1970 - February, 1970.

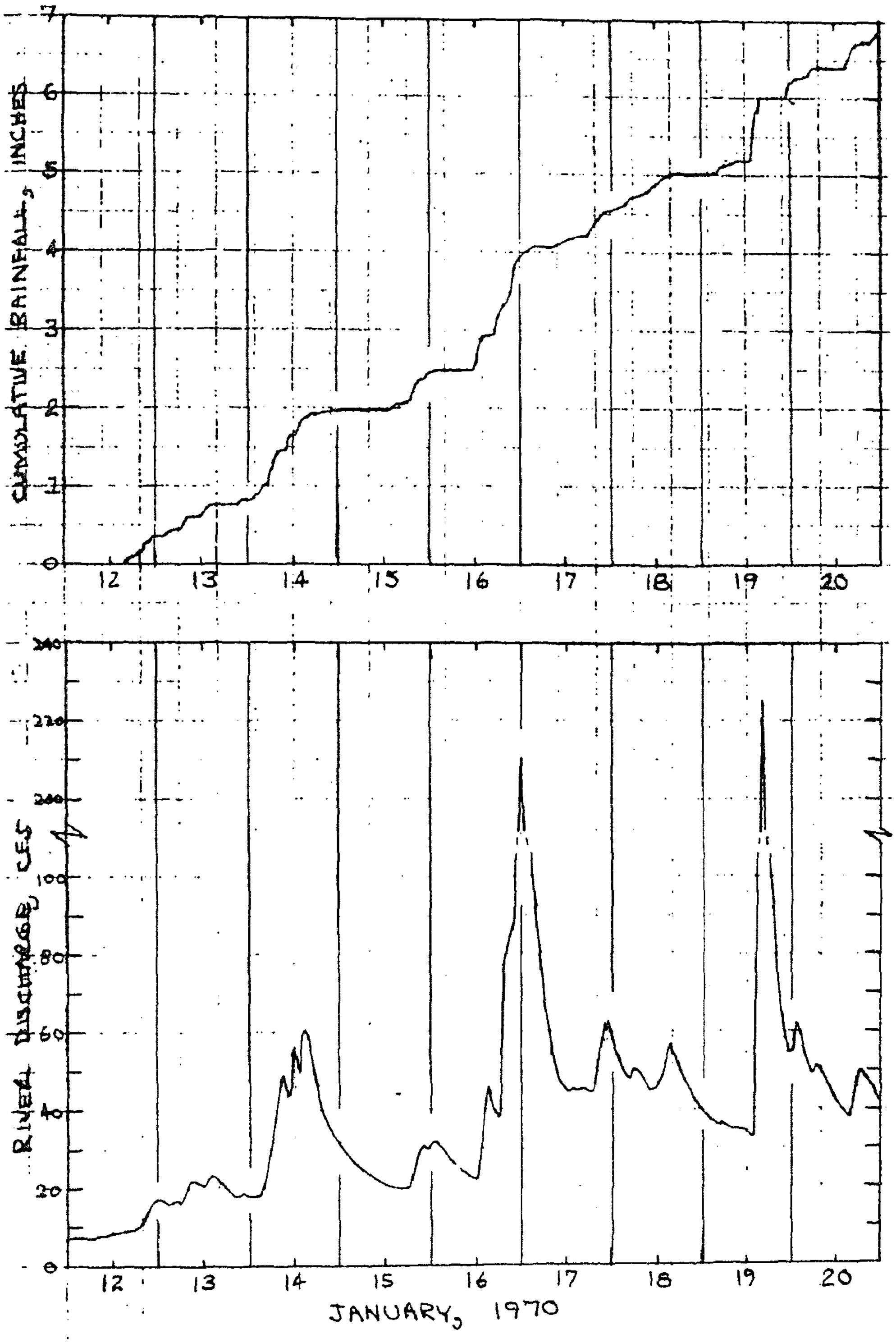

Figure 9. Rainfall and streamflow at Oak Creek weir/trap structure in mid-January, 1970.

sampler was not possible. After the vortex flume and sampling trap had completely filled with gravel, large quantities of material moved past the structure and deposited immediately downstream at an emergency bed stabilization structure. (This structure had been placed during the December 11-12 storm runoff because of excessive scour from interception of all bed load by the vortex sampler.) The numerous storms in January made reshifting the control point back to the weir/trap structure impractical, and hence two rating curves were required. Rating curve No. 1 covers the period through January 16, 9 p.m., and rating curve No. 2 covers the study period since that time. The rating curves are shown in Figure 10.

Before January 16, the vortex trap was frequently open, even when no bed-load transport occurred. Therefore, a correlation curve was developed to evaluate the effect of vortex operation upon water stage at the stilling well. This effect is portrayed in Figure 10 by use of a dual rating for curve No. 1--one line for the vortex operating (open) and another for the vortex trap closed.

Potential extreme floods were of great interest and concern, both for sampling and for protection of the research facilities. Therefore, a flood frequency analysis for the drainage basin was made according to U.S. Geological Survey procedures and information on Western Oregon given in Water Supply Paper 1689 (U.S.G.S., 1964). The estimate is approximate only, as the average annual runoff was unknown and local orographic effects could cause this and other parameters to differ in value from those at nearby stations used by the Geological Survey in its regional analysis. The estimated once-in-50-years flood is shown in Figure 10 for comparison with the rating curves at the Oak Creek facilities. Also shown is the estimated mean-of-annual-floods (or mean annual flood). Both are indicated by a range of discharge values rather than a single value because of the approximations involved in their estimate. The largest observed discharge during the study period, 225 cubic feet per second (cfs) on January 19, is also noted in Figure 10. This runoff would appear to be on the order of a once-in-20-years event. This runoff was influenced by very wet antecedent conditions, which included a peak discharge of 210 cfs three days earlier, on January 16 (Figure 9).

The hydrograph of mean daily discharges spanning the winter field study period at Oak Creek is shown in Figure 11. Fall runoff until December was low and quite stable, as response to fall rainfall was very slight. Streamflow during the period of no record was similar to that before and after (the water stage recorder and other equipment were removed from the field for protection during a brief hunting season). The periods of major runoff corresponded to those of major storms, as described earlier. Bed-load sampling occurred during these periods and streambed surveying took place between these periods. Spring flows continued to recede with only minor rises after March (not shown in Figure 11).

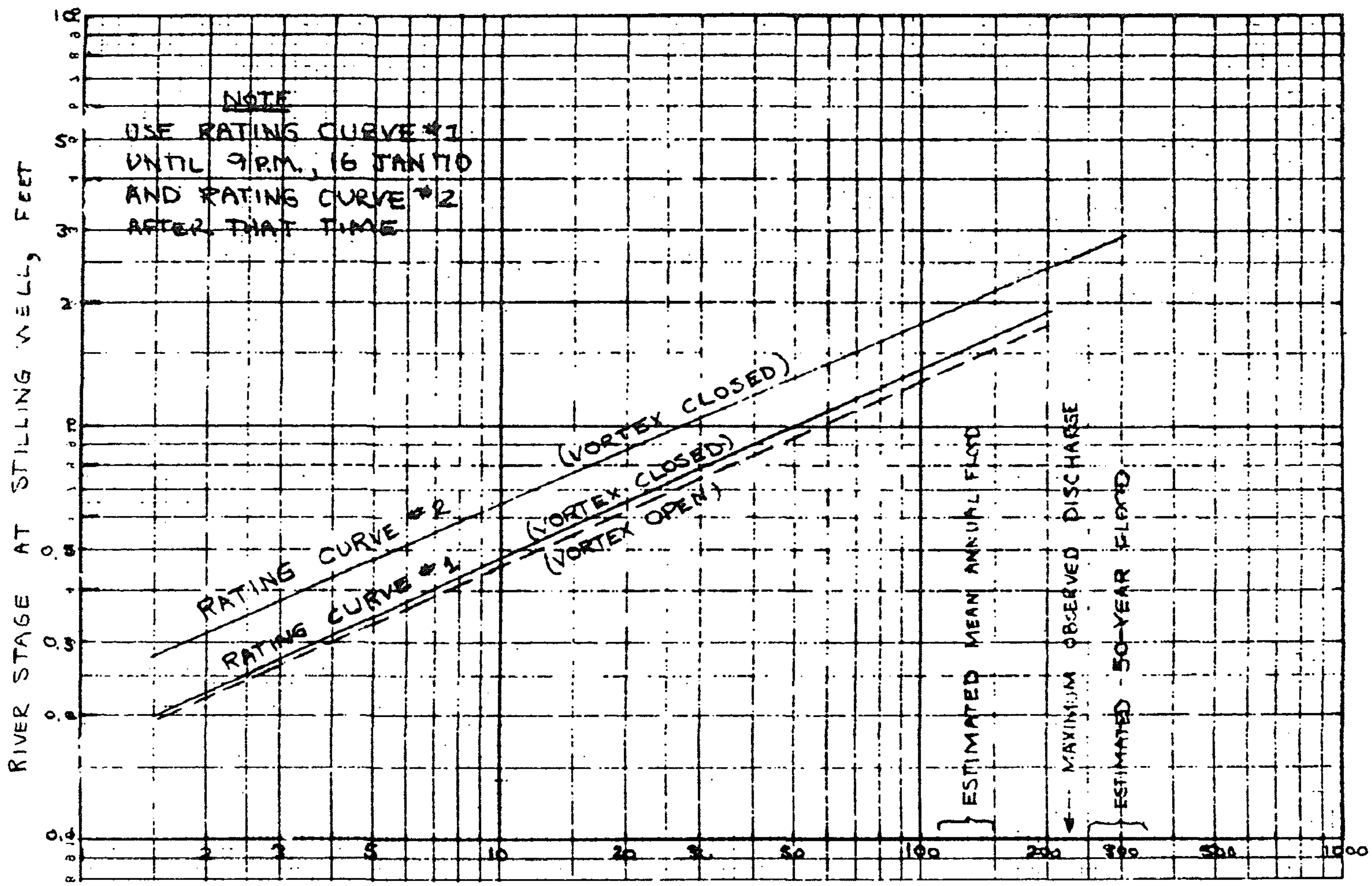

Figure 10. Rating curves for Oak Creek at the weir/trap structure.

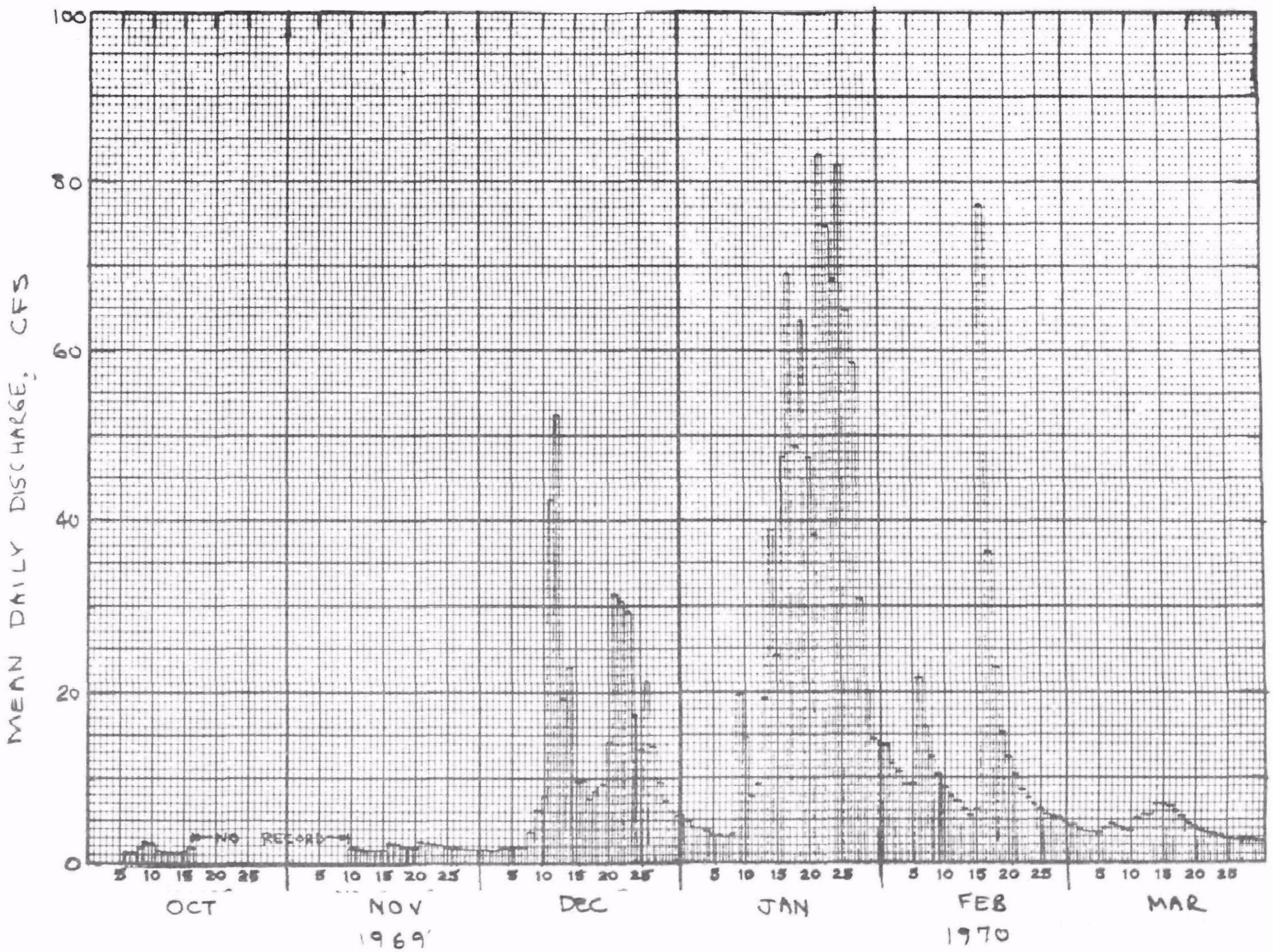

Figure 11. Mean daily discharge at Oak Creek weir/trap structure during 1969-70 field studies.

The hydrograph of mean daily discharge at Oak Creek has certain limitations in portraying streamflow variations for so small a basin. For example, the hour at which peak discharge occurs may greatly influence the average daily runoff value. More importantly, the maximum dailydischarges at Oak Creek during floods are much smaller than the maximum instantaneous discharges at peak flow. Therefore, the relative magnitudes of flood peaks can be disguised in hydrographs that are based on daily values. Thus, from Figure 11, the three greatest daily peak flows of the winter occurred on January 22 and 25 and on February 16, respectively (in particular, they were larger than the daily flows on January 17 and 19). However, the instantaneous peak flows on the first three dates mentioned (158, 182, and 175 cfs, respectively) were smaller than for the latter two floods (210 and 225 cfs, respectively). Hence, daily flow values can be misleading regarding instantaneous flood peaks.

Segments of the instantaneous discharge hydrographs during periods of bed-load sampling will be presented in a later section and are not given here.

Hydraulic Characteristics of Reach

Some idea of the velocities experienced in the Oak Creek study can be obtained from velocities measured during streamgagings. During large flows, the velocity was frequently 7-8 feet per second (fps) at 0.2 depth below the water surface and 5-6 fps at 0.2 depth above the streambed in water of about 2-foot depth. The largest point velocity observed was 8.71 fps. Velocities in the test reach away from the gaging station were smiilar in magnitude, although some pools had slower flow and one steep portion of the channel had velocities that may have exceeded 10 fps on occasion. Velocities also were locally high in the vicinity of tree-root obstructions at the channel banks during times of flood runoff.

The mean velocities at the gaging station cross-sections are shown as a function of discharge in Figure 12. By extrapolation, the largest average velocity experienced at these sections during the study period is estimated to have been about 7.5 fps, for which the point velocities may have approached 10 fps near the channel center and water surface. In Figure 12A, the natural channel upstream of the weir/trap structure exhibits a flatter velocity-discharge curve than at the structure (Figure 12B). This is attributable to the widening of cross-section with increasing stage at the upstream location, whereas the sidewalls of the weir/trap are vertical. The shift in control to a more downstream position on January 16 is reflected in Figure 12B by lower velocities at a given discharge after that date. This is because of a greater depth of flow at the structure afterwards caused by the new backwater conditions extending upstream from the control point. The effect of vortex operation upon nearby velocities can also be seen from Figure 12B. With the vortex sampler operating, the flow becomes

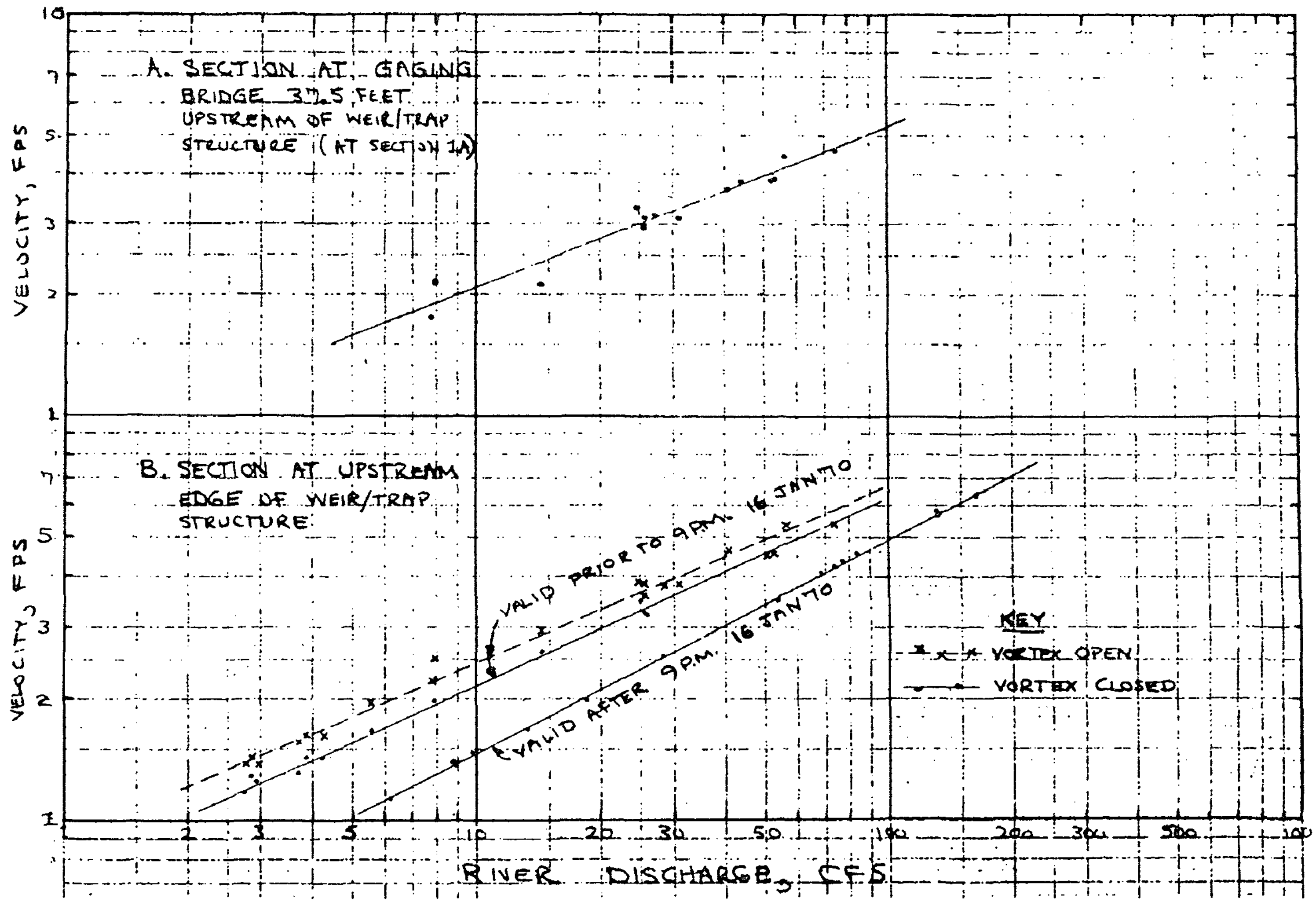

Figure 12. Variability of velocity with discharge at Oak Creek streamgaging sections.

shallower and swifter near the vortex trough. Froude numbers for this flow were presented earlier, in Figure 5.

Additional hydraulic properties at the gaging section upstream of the weir/trap structure are presented in Figure 13. Because channel width only increases slightly with discharge at the gaged flows, the mean flow depth and the cross-sectional area are related by a nearly constant factor. At flows greater than gaged at this section, the cross-section widens abruptly so that the logarithmically linear relationships of Figure 13A and 13B would become curved at higher discharges.

Manning's "n" at this cross-section (a measure of channel roughness) was about 0.035 and appeared to decrease slightly as water stage and discharge increased. This variation is attributable to differences in bed and bank composition. The local streambed consists of gravel across the full bottom width of the channel, but the banks are a mixture of finer soils with some gravel and offer a smoother surface to the flow than does the streambed.

The overall channel slope for a 2,600-foot reach of Oak Creek that includes the study area was 1.81 percent, or 0.0181 feet/foot. Considerable local variability was noted over short distances, because of numerous riffles and pools. The stream profile in this part of the creek did not exhibit any concavity, but instead had irregular variations. The stream profile was determined by means of a survey line along the main thread of low-water flow.

The average hydraulic gradient across the instrumented test reach during the study period was 1.39 percent (0.0139 feet/foot), or somewhat less than that for the 2,600 feet of channel spanning this reach. This figure was based upon observations on 20 occasions during streamgagings which covered a large range of discharge (3-164 cfs) and included rising, falling, and steady flow conditions. Observations were made at seven staff gages located along the channel. The spacing of staff gages and the mean hydraulic gradients observed between staff gages are summarized in Table 4. The mean hydraulic gradient for the steep, straight subreach between staff gages 6 and 7 was more than twice as great as the mean gradients of flatter subreaches 1-2 (straight) and 5-6 (winding somewhat around tree roots along the subreach). Extreme variations in hydraulic gradient were generally within 30 percent of the mean value for the subreaches. Over the entire reach, the hydraulic gradients observed did not deviate by more than five percent from the mean value. At very low flows, numerous riffles were exposed along the test reach and caused local drops in the hydraulic gradient.

As noted earlier, velocities were variable along the channel. Therefore, the energy gradients along the reach for subreaches were not identical with the hydraulic gradients given. Nevertheless, mean velocities were sufficiently similar so that the hydraulic gradients offer

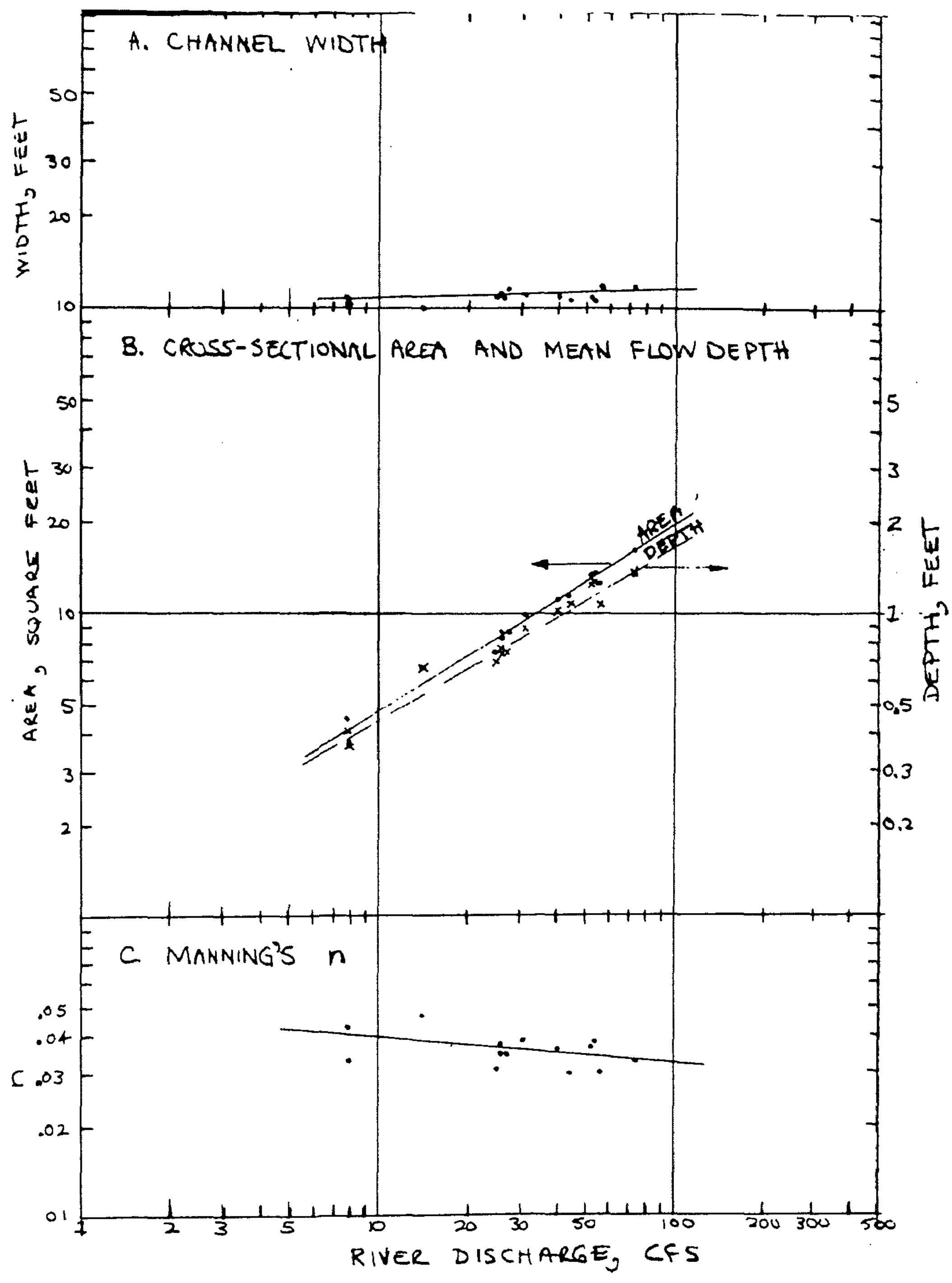

Figure 13. Variability of hydraulic parameters with discharge at Oak Creek streamgaging section upstream of weir/trap structure.

Table 4

MEAN HYDRAULIC GRADIENTS FOR STUDY REACH

Staff Gage Number	Flow Distance to weir/trap feet	Incremental Length, feet	Mean Incremental Hydraulic Gradient, feet/foot	Mean Hydraulic Gradient feet/foot
1	0			
		95	0.0087	
2	95			
		65	0.0124	
3	160			
		51	0.0171	
4	211			0.0139
		70	0.0166	
5	281			
		81	0.0092	
6	362			
		72	0.0217	
7	434			

reasonable estimates of the energy gradients for the subreaches and a very good estimate of the mean energy gradient for the entire study reach.

SECTION VII

CHANGES IN CHANNEL TOPOGRAPHY

Organization of Data Collection

Changes of channel shape caused by scour and deposition in the study reach of Oak Creek were detected through a sequence of surveys at cross-sectioning stations and intermediate points. The surveying included streambed elevations and bank elevations extending well above the highest water level during the winter, so as to note any bank caving that might have occurred. Survey data on net changes of channel topography were supplemented by information on maximum depth of scour during the interval between surveys, as determined from buried scour-ball devices.

The locations of metal reference pins and cross-sections used to evaluate changes in stream topography are given in Figure 14. Stations identified by number only were established in early fall, 1969, and station numbers followed by the letter A were added at the end of December.

The positions of buried scour balls are also shown in Figure 14. These positions were chosen randomly to avoid any human bias in their selection (a coin-flipping system was developed for selection of position along and across the channel). Most of the scour balls were installed in fall, 1969. A few additional installations were made in February, 1970. Figure 14 also shows the locations of the seven staff gages used for determining water levels and hydraulic gradients for the subreaches. Approximate edge-of-water lines for frequent high streamflows are indicated, although at the highest streamflows observed there was some overbank flow along the left bank from station 11A to 16A (up to eight feet farther from the stream center than shown in Figure 14) and flow in a higher overflow channel behind the right bank from Station 12A to 15.

At low streamflows, numerous riffles were exposed. These changed in position somewhat as a result of intervening storm runoff, as did the location of the low-flow channel. The low-flow channel as it appeared in early fall, 1969, is shown in Figure 14.

Data collection was organized to span periods of storm runoff. The specific dates and the intervening runoff-conditions are summarized in Table 5. Initial topographic surveying and mapping and the installation of scour-ball devices was completed in the fall, before stream rises of any significance occurred (Figure 11). A considerable amount of sediment transport took place during the storm runoff of December 11-12, and a topographic survey was carried out on December 21, after recession of streamflow from that storm period and as rains began to cause a new rise in streamflow. After this new storm runoff and a lesser storm immediately thereafter, another topographic survey and a

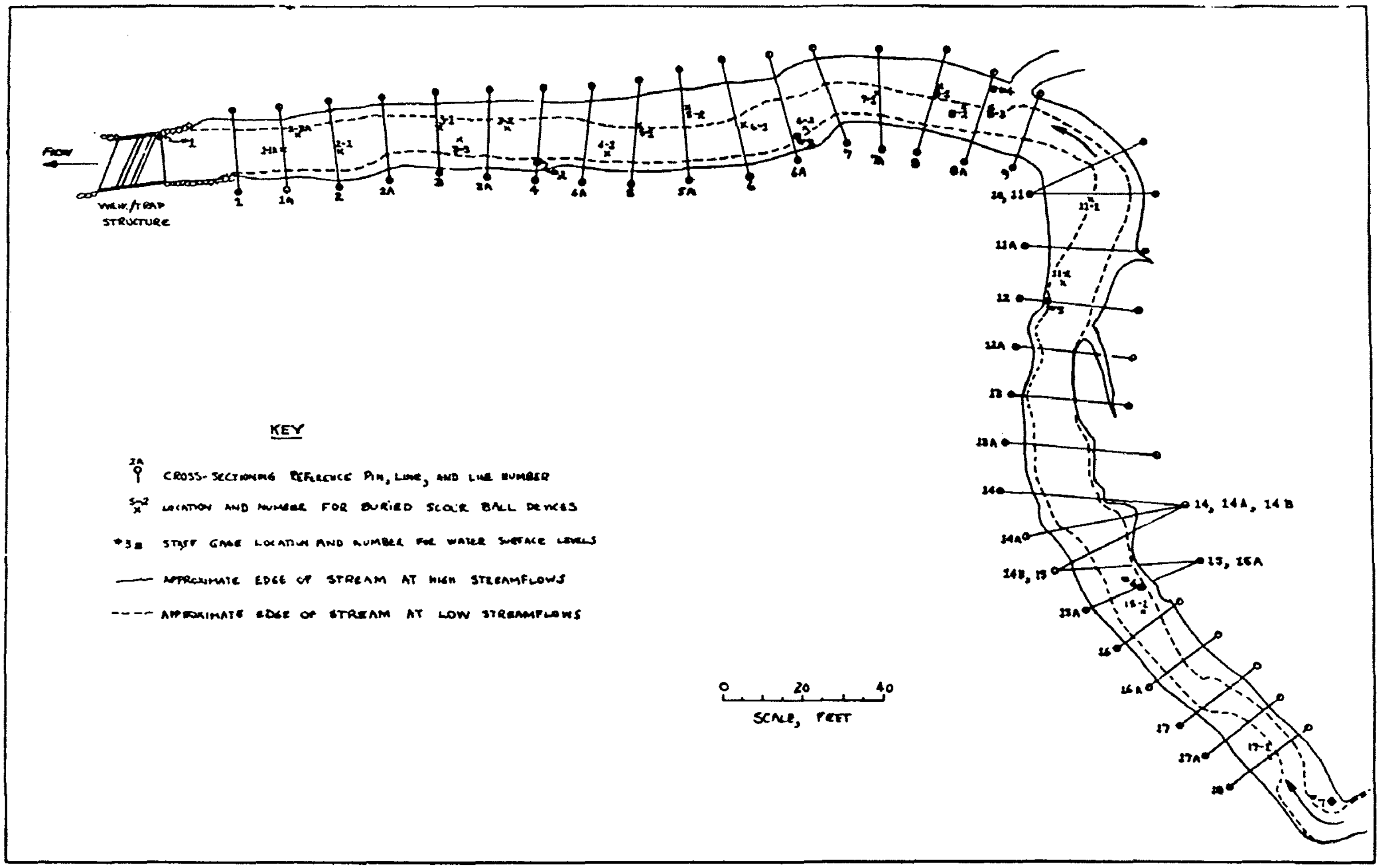

Figure 14. Locations of cross-sectioning stations, scour ball devices, and staff gages.

Table 5

TIMES OF COLLECTING DATA ON SCOUR AND CHANGES IN CHANNEL TOPOGRAPHY, 1969-70

Date of Cross-Section Survey	Date of Scour Ball Survey	Remarks
5 Oct	Nov	Fall baseflow period
21 Dec		Survey after single large storm-runoff event
31 Dec	31 Dec	Survey after two storm-runoff events
31 Jan		Survey after numerous storm-runoff events
	14 Feb	Survey after numerous storm-runoff events
21 Feb	21 Feb	Survey after single large storm-runoff events
24 Mar		Supplemental survey

survey for scour-ball devices was conducted on December 31. The continual storm runoff during January prevented any topographic surveying until January 31, and was followed on February 14 with a survey for scour balls buried in the streambed. The storm runoff of February 16-18 was followed by additional topographic and scour-ball surveys. Supplemental topographic details were obtained on March 24, by which time it was clear that no additional bed-load transport could be expected for the season.

Net Seasonal Changes

The net changes in channel topography caused by storm runoff during the winter bed-load transport season can best be examined by a comparison of maps prepared from the October and February-March topographic surveys. Contour maps for these surveys are presented in Figures 15 and 16, respectively. The contour interval selected for presentation is 0.1 foot (working maps of survey data were first prepared with a 0.5-foot contour interval).

Pools or "holes" in the streambed can be identified in Figures 15 and 16 near channel bends and constrictions caused by tree root systems. One pool also occurs near section 2A in an otherwise wide, straight reach (Figure 15). This is caused by a large fallen branch wedged against the upstream edge of a tree and partly buried in the streambed, so as to act like a weir and also to cause debris to lodge occasionally. Riffles and shallow flow occur along the central portion of the channel between the pools except at higher stages, when even these shallow areas are covered by over two feet of water.

In Figure 17, the topographic maps of Figures 15 and 16 have been superimposed and the net seasonal changes determined. Supplemental data from cross-sectioning surveys and scour-ball devices also have been incorporated in Figure 17. The approximate channel width over which streambed disturbance and bed-load transport took place has been estimated and indicated in this figure. Zones where net scour or net deposition occurred over the winter are shown, as well as zones where bed load was transported but no net change in streambed elevation was detected.

The importance of tree root systems as stabilizing agents for the channel platform can be noted from Figure 17. Near sections 6-7, tree roots have maintained an outside edge of the low-flow channel in spite of high-velocity flood flows that strike the trunks and send "bow-waves" downstream. Even more notable is the narrow, deep channel between tree-stabilized banks in the vicinity of sections 12-14, where no bank scour was evident. The limited deposition that occurred in the pools here may have been caused by a raising of backwater because of accumulation of gravel at the bend downstream (particularly near sections 11A-12).

Cohesive banks offered a great deal of channel stability in a manner analogous to tree root systems. For example, upstream of section 16

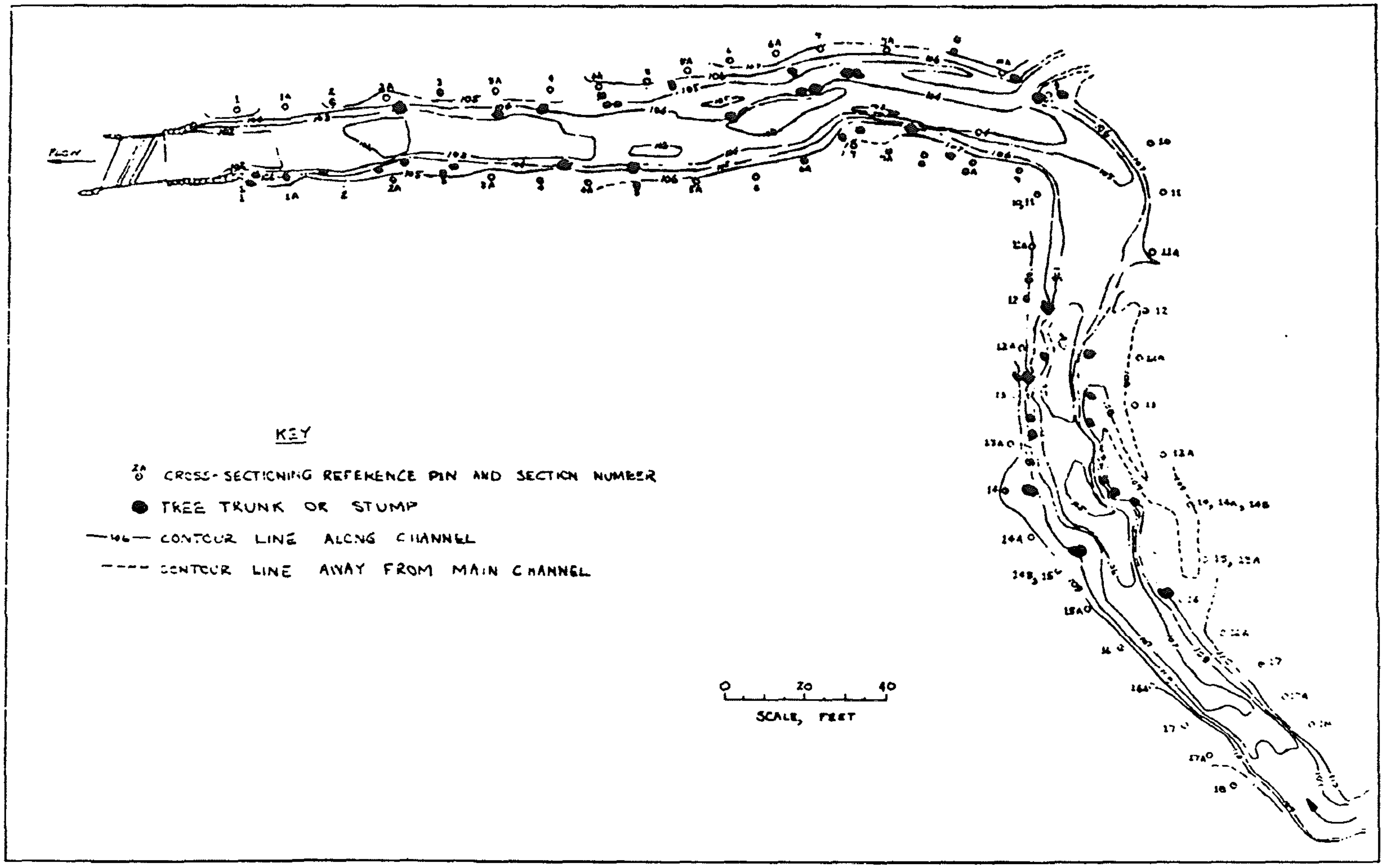

Figure 15. Channel topography in October 1969, before winter bed-load transport.

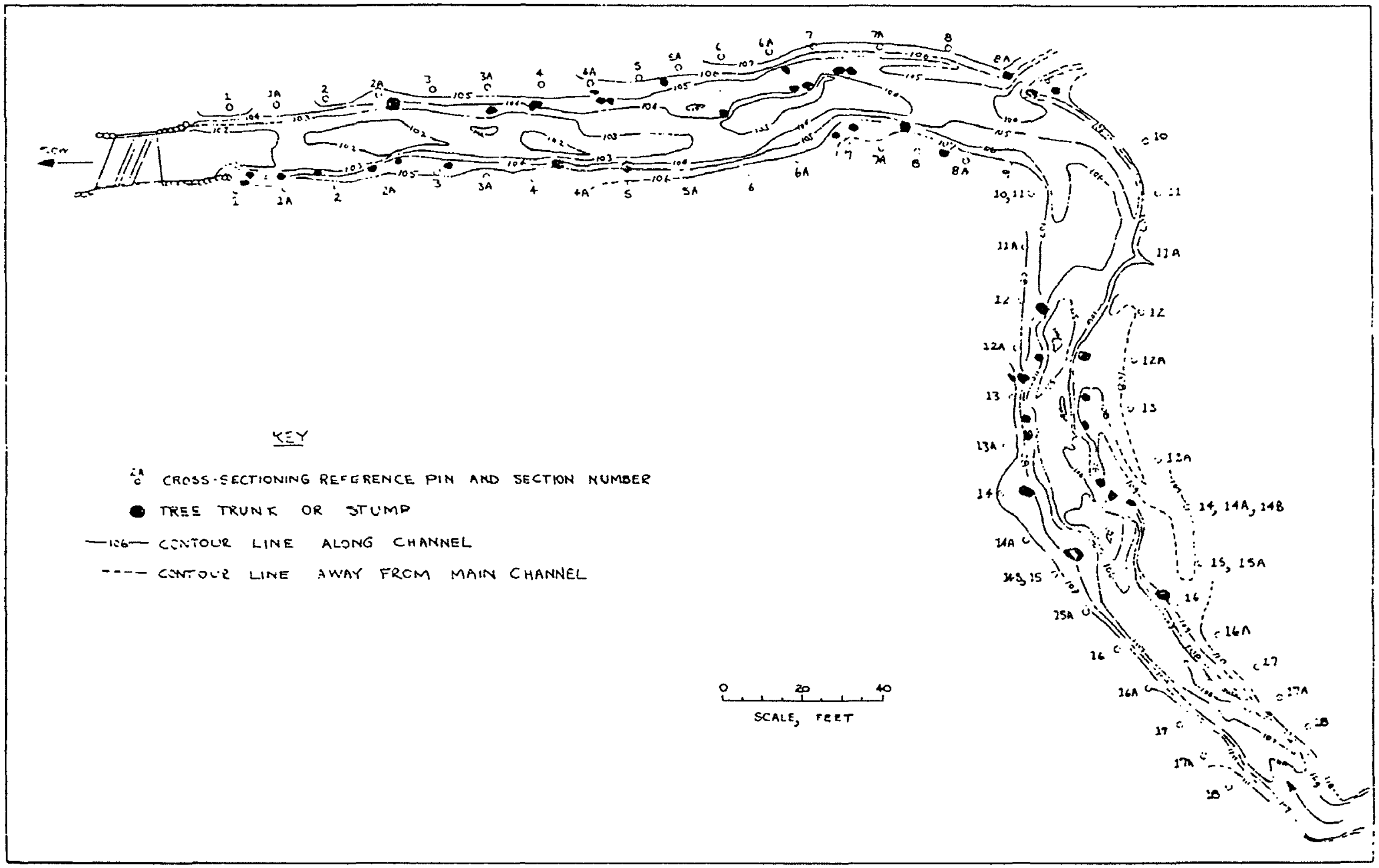

Figure 16. Channel topography in late February 1970, after winter bed-load transport.

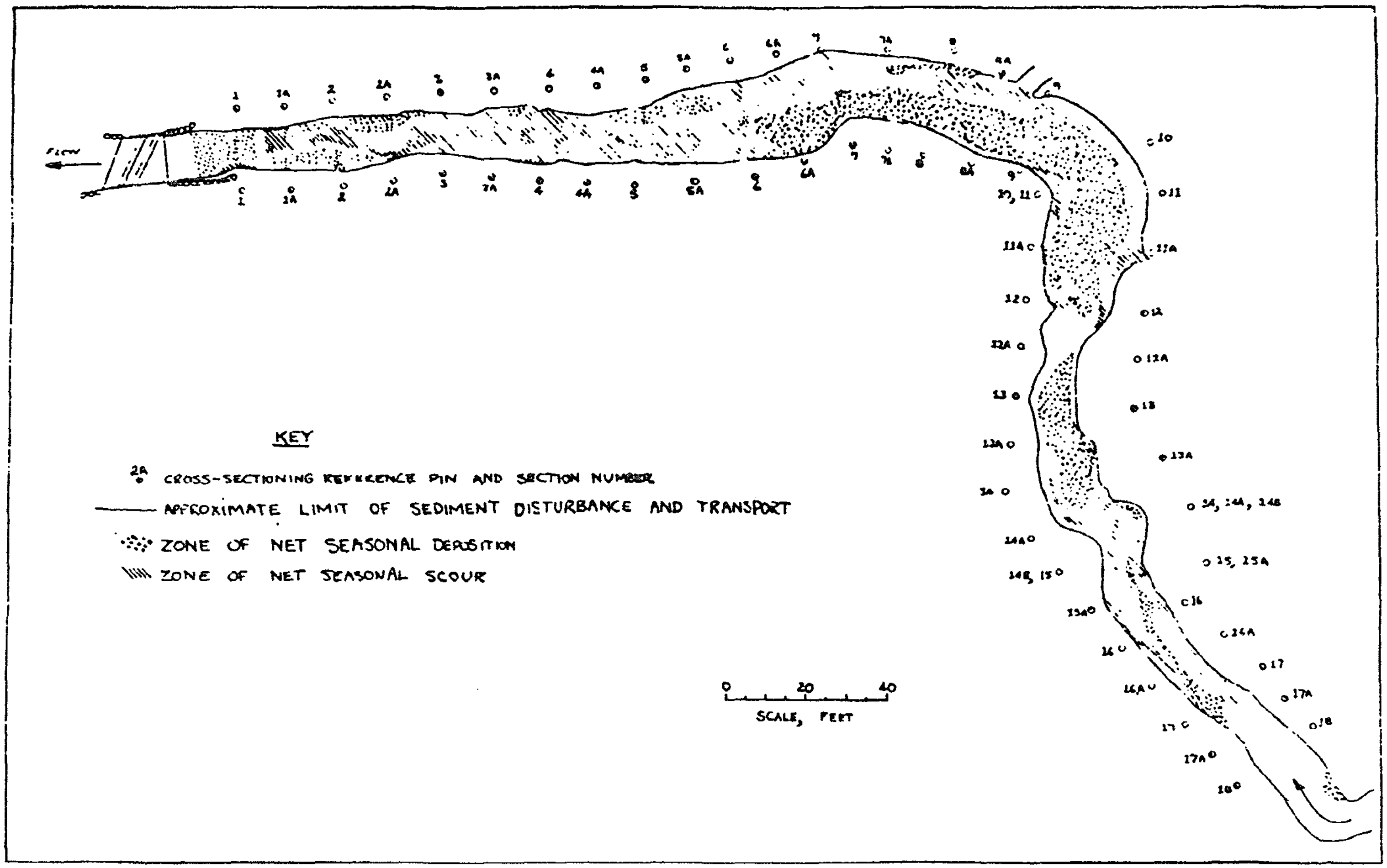

Figure 17. Net seasonal changes in channel topography, October 1969 to late-February 1970, due to winter bed-load transport.

the banks are more cohesive than they are from section 16 downstream. As a consequence, bank scour was minimal between sections 16 and 18, even though considerable scour of the gravel streambed took place (streambed degradation appeared to take place in an upstream-progressing direction here). The bank scour that did occur took place adjacent to the bed, rather than higher on the steep bank, and was presumably caused by abrasion by gravel rather than shear forces exerted by the water. Upstream of the study reach, local zones of cohesive material extend across the streambed and appear to be quite stable in spite of frequent scouring and abrading by storm runoff and bed-load transport.

Near section 14A-15 a weak right bank (looking downstream) which had been subject to erosion before the winter of 1969-70 was subject to severe caving during this winter as a result of additonal erosion. This resulted after debris clogged a trash rack (1/2 inch pipes of 1-foot spacing) near section 14 in mid-December and was subsequently washed out. When the debris dam formed, some local scour occurred at the trash rack and more than a foot of gravel deposited a short distance upstream in the backwater of the debris dam. (The trash rack had been installed to keep leaves, bark, and branches from entering the vortex bed-load sampler, with the intention of cleaning the trash rack frequently during early winter storm runoff to prevent its clogging. However, the overnight runoff of December 11 caused clogging when no one was present.) The new gravel deposit forced erosive flows against the already weak bank. The trash rack was then removed and subsequent local scour after mid-December removed not only the recent gravel deposit but also much of the caved bank.

The channel bend between sections 8 and 12 was subject to considerable modification during the extensive bed-load transport of January. The point bar on the inside of the bend built outward as well as upward at this time (over a foot of fill--see data on scour balls at location 11-1, in Table 6). Some bank scour on the inside bank occurred but the most pronounced scour took place at the outside of the bend, as deposition on the point bar forced the current to erode the outer bank. The effects of deposition and scour at the bend apparently extended downstream for a short distance, causing an altered flow alignment. This is shown by some deposition in the main channel and some scour in an "overbank" portion of the stream within the higher banks between sections 6 and 8A.

The lower straight section of the study reach reflected some tendency toward non-uniformity of cross-sectional depth above section 3A and a tendency toward greater uniformity of cross-sectional depth downstream of section 3A. The actual depths of net scour or deposition were not very great (see cross-sectional figures, in the following section).

Sequential Changes at Cross-Sections

The cross-sectional surveys at each of the sections on the dates indicated in Table 5 give a description of the progressive changes in channel topography. By comparison of the surveys at a section, additional insights to the net seasonal change and perhaps some further idea of the processes involved can be obtained.

The cross sections have been grouped for presentation, based upon the observed net seasonal changes indicated in Figure 17. Figure 18 shows changes in shape at sections 1 through 4, all in the straight lower end of the study reach. Figure 19 and 20 show changes at sections 5 through 8A, where the flow winds slightly among trees. The cross sections in Figure 21 (section 9 through 11A) describe changes at the large bend midway in the study reach. Sections 12 through 13A, in Figure 22, show the cross-sectional changes which took place in this deep, narrow pool zone. In Figure 23, the changes are given for sections 14 through 15A, near some extensive bank caving. Finally, Figure 24 indicates the changes of shape at sections 16 through 18, in the steep, narrow, upper portion of the study reach.

The accuracy of the cross-sectional survey work presented in these figures should be mentioned at this point. The accuracy was about 0.1 foot for horizontal and vertical positioning. Occasional difficulties in identifying breaks in side slopes because of vegetation were compensated for by comparison of successive field survey notes. The elevations of adjacent points in the streambed varied by as much as 0.2 foot, depending upon whether the leveling rod rested upon or alongside some of the larger gravel. Therefore, the rod was placed at what appeared to be the mean level of the bed surface whenever such problems arose.

Sections 1 (Figure 18) and 1A (not shown) exhibited little change in bed elevation between surveys, although a slight net seasonal accretion occurred (as also noted in Figure 17). Sections 2 (Figure 18) and 2A (not shown) experienced localized scour and deposition which, at a given spot, seemed to alternate from one survey to the next. As at the downstream sections, the total net change was not very large. Section 3 (Figure 18) underwent scour over its full bed width during the early December storm runoff and lesser alternating scour and deposition thereafter, for a modest net seasonal scour. The sequential changes observed at section 3A (not shown) were even slighter. Sections 4 (Figure 18) and 4A (not shown) exhibited alternating scour and fill from one survey to the next, with heaviest scour during the January runoff.

In Figure 19, the changes of shape at section 5 were small in each period. At section 5A the central part of the channel had a net January scour of up to 1.2 feet and February fill of 0.9 feet as part of a net seasonal scour of only a few tenths of a foot. Appreciable (1-foot) scour at the left edge of section 6 (Figure 19) in December and some bank scour at the right bank in January suggested some

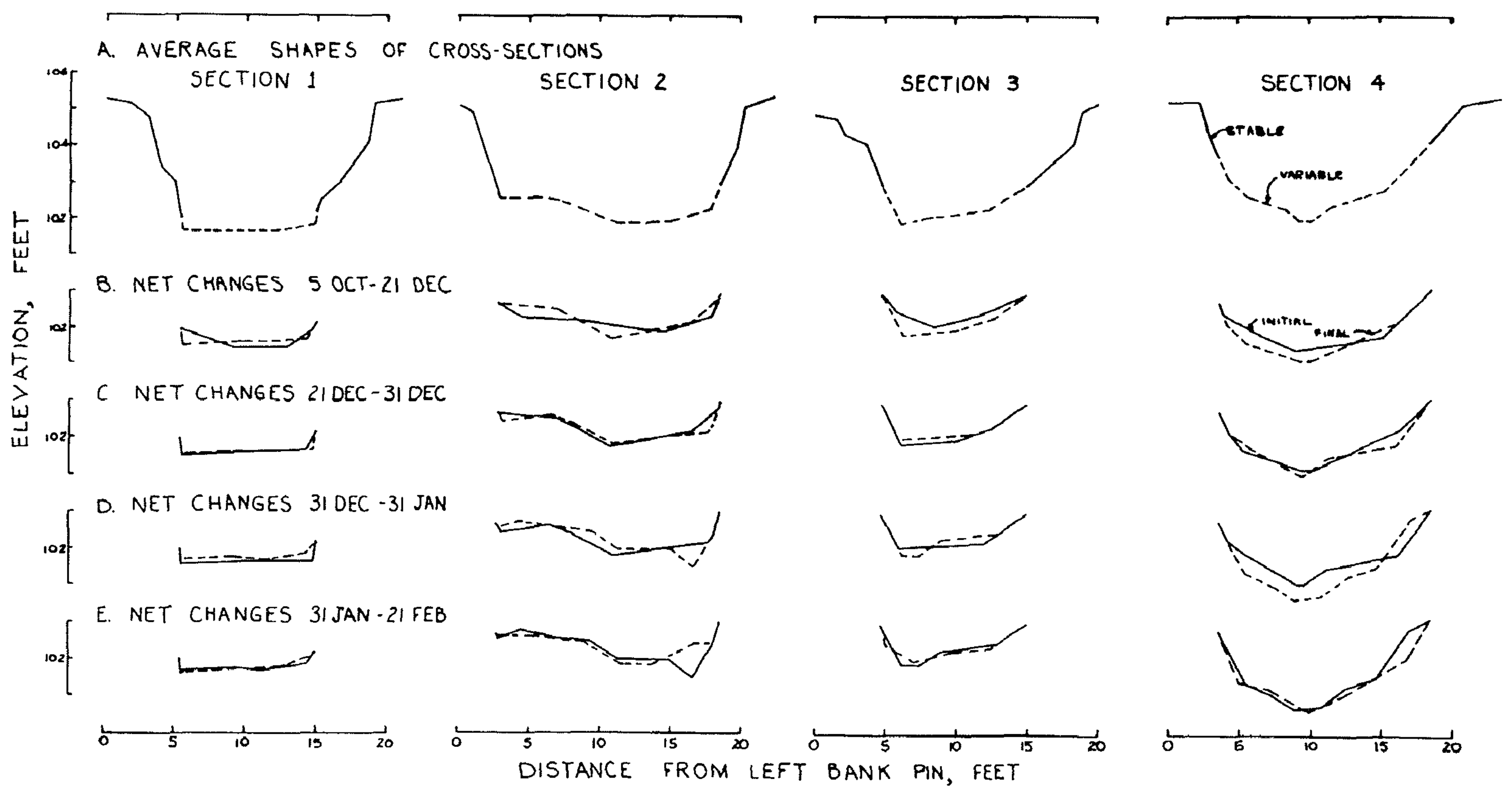

Figure 18. Sequential changes in cross-sectional shape at sections 1-4, winter 1969-70.

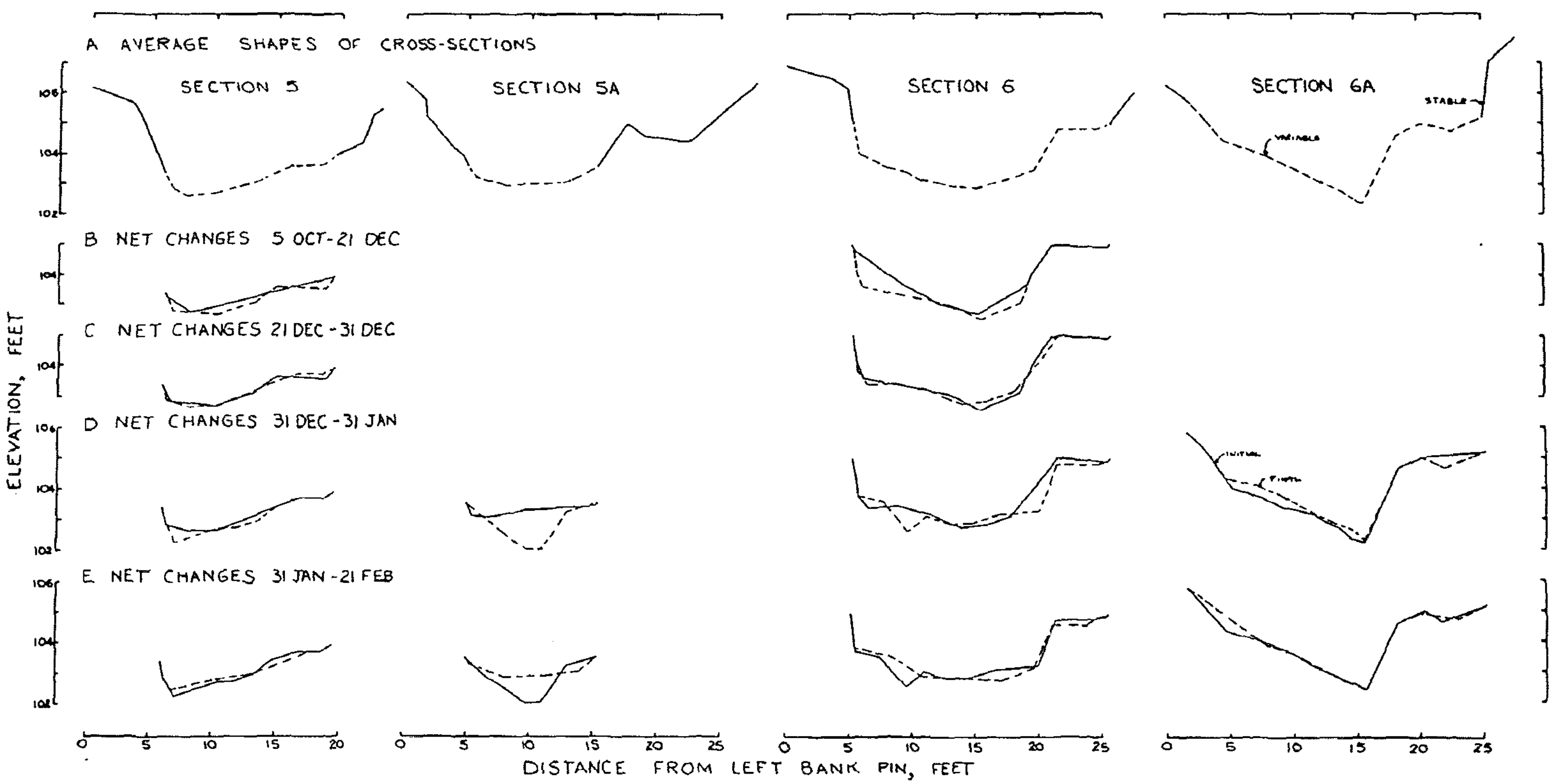

Figure 19. Sequential changes in cross-sectional shape at sections 5-6A, winter 1969-70.

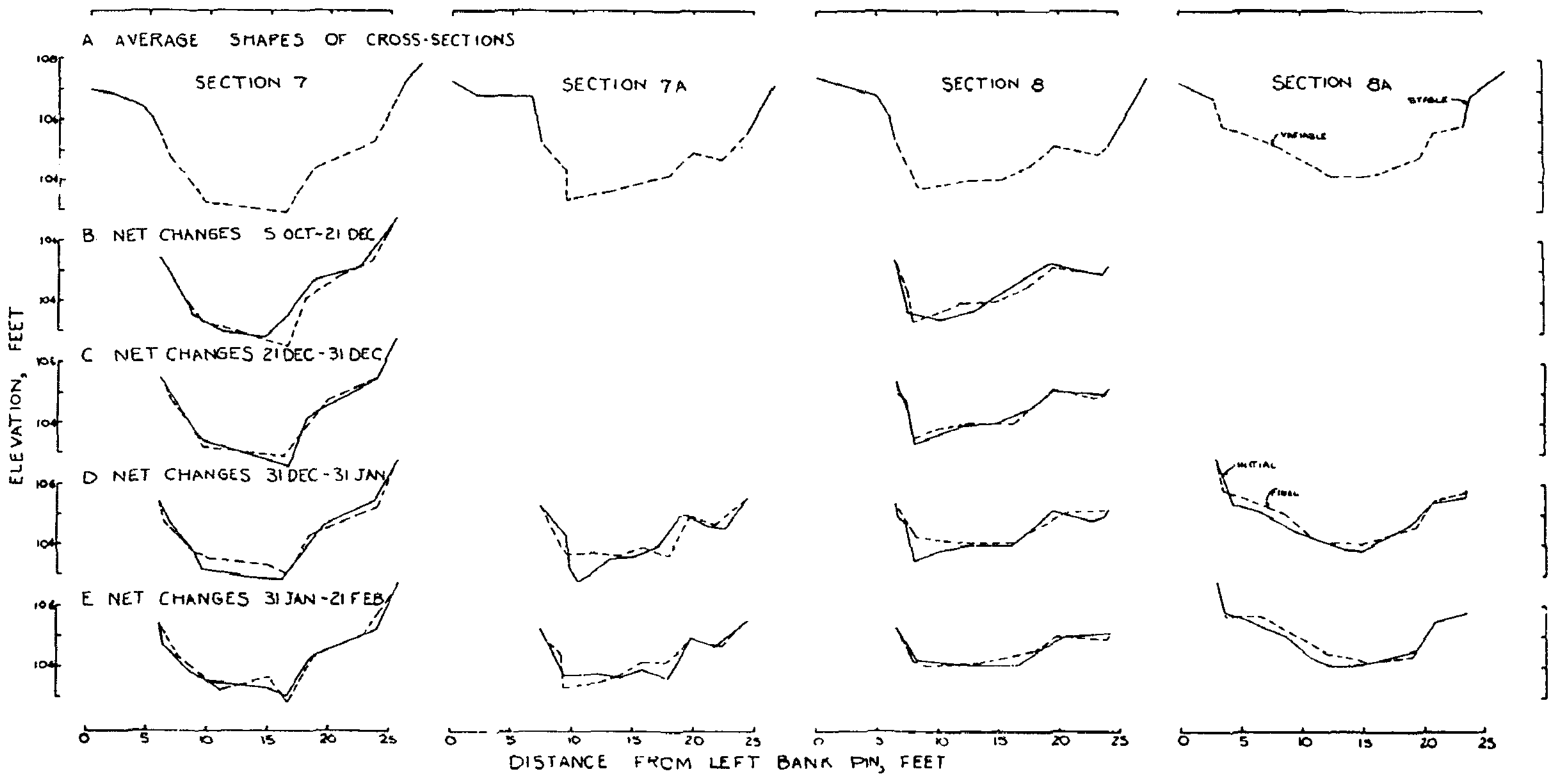

Figure 20. Sequential changes in cross-sectional shape at sections 7-8A, winter 1969-70.

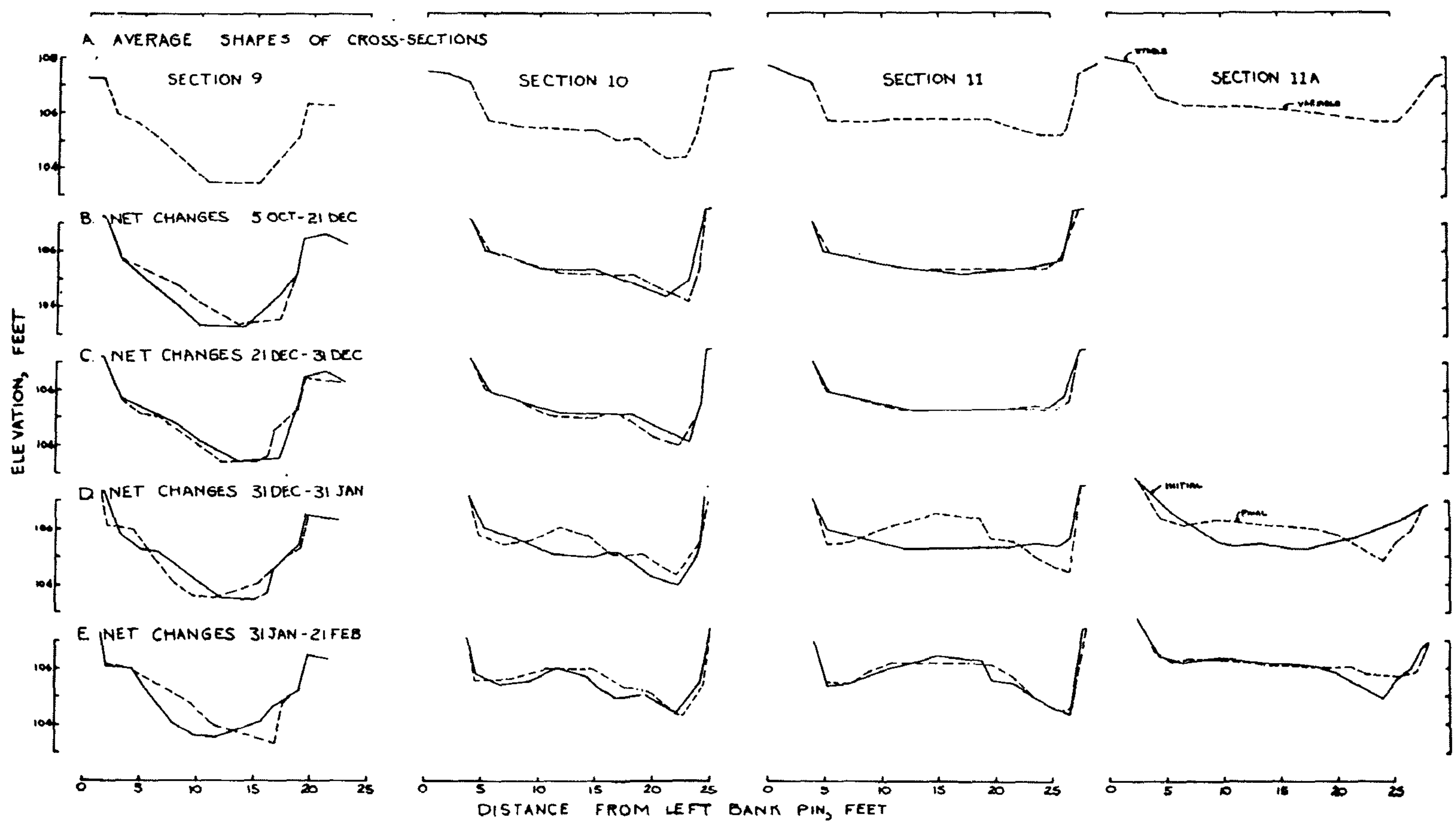

Figure 21. Sequential changes in cross-sectional shape at sections 9-11A, winter 1969-70.

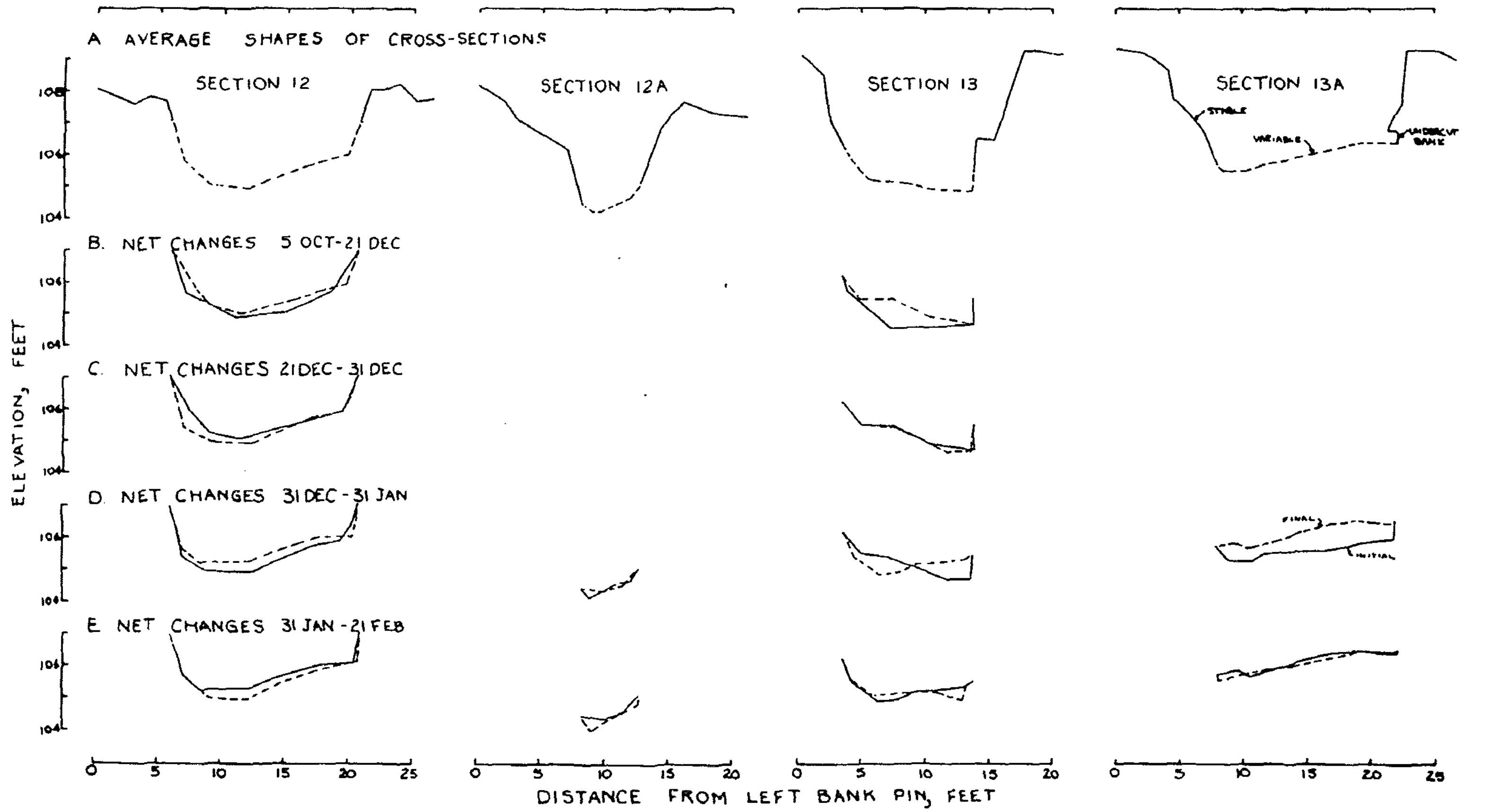

Figure 22. Sequential changes in cross-sectional shape at sections 12-13A, winter 1969-70.

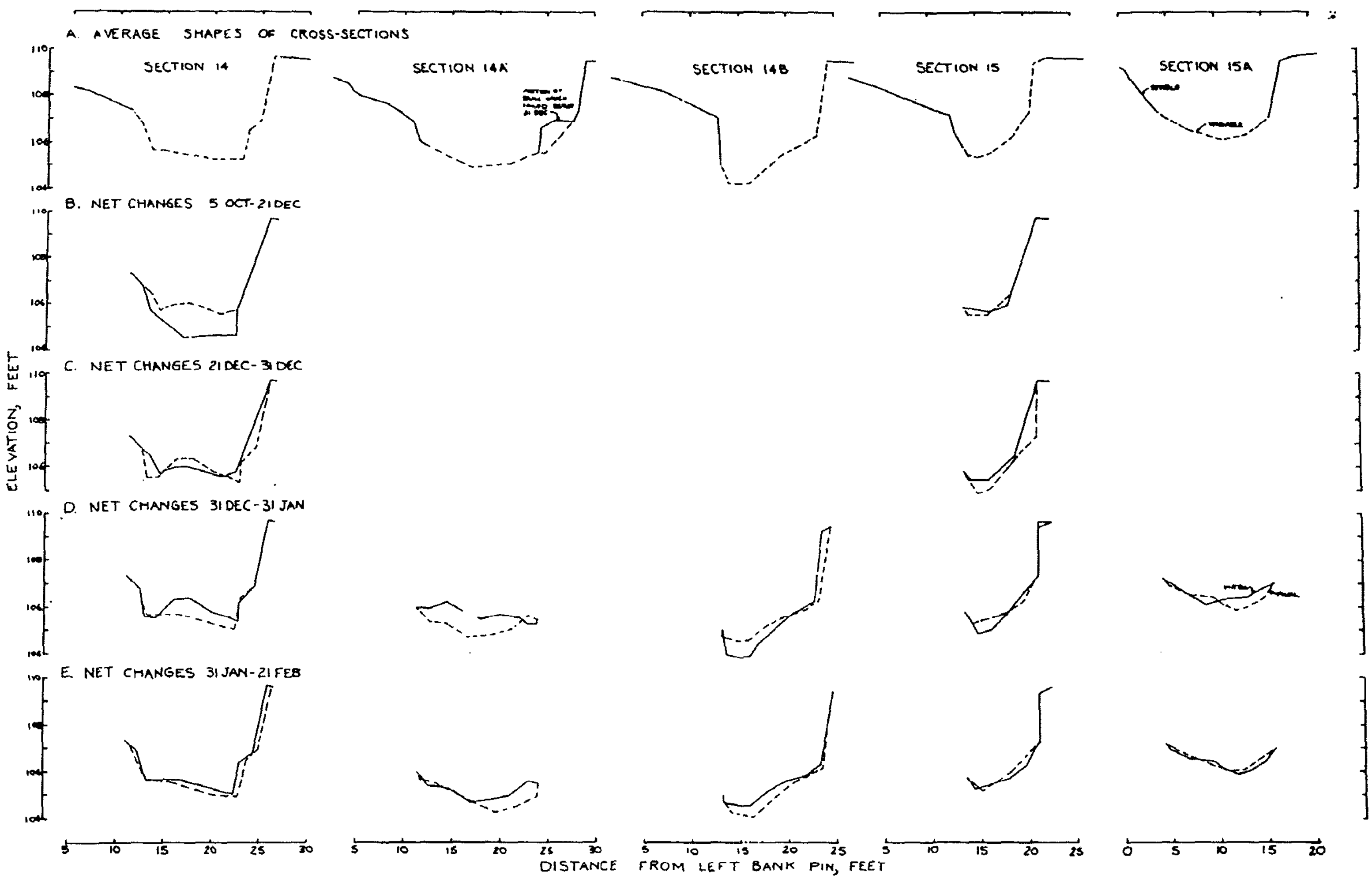

Figure 23. Sequential changes in cross-sectional shape at sections 14-15A, winter 1969-70.

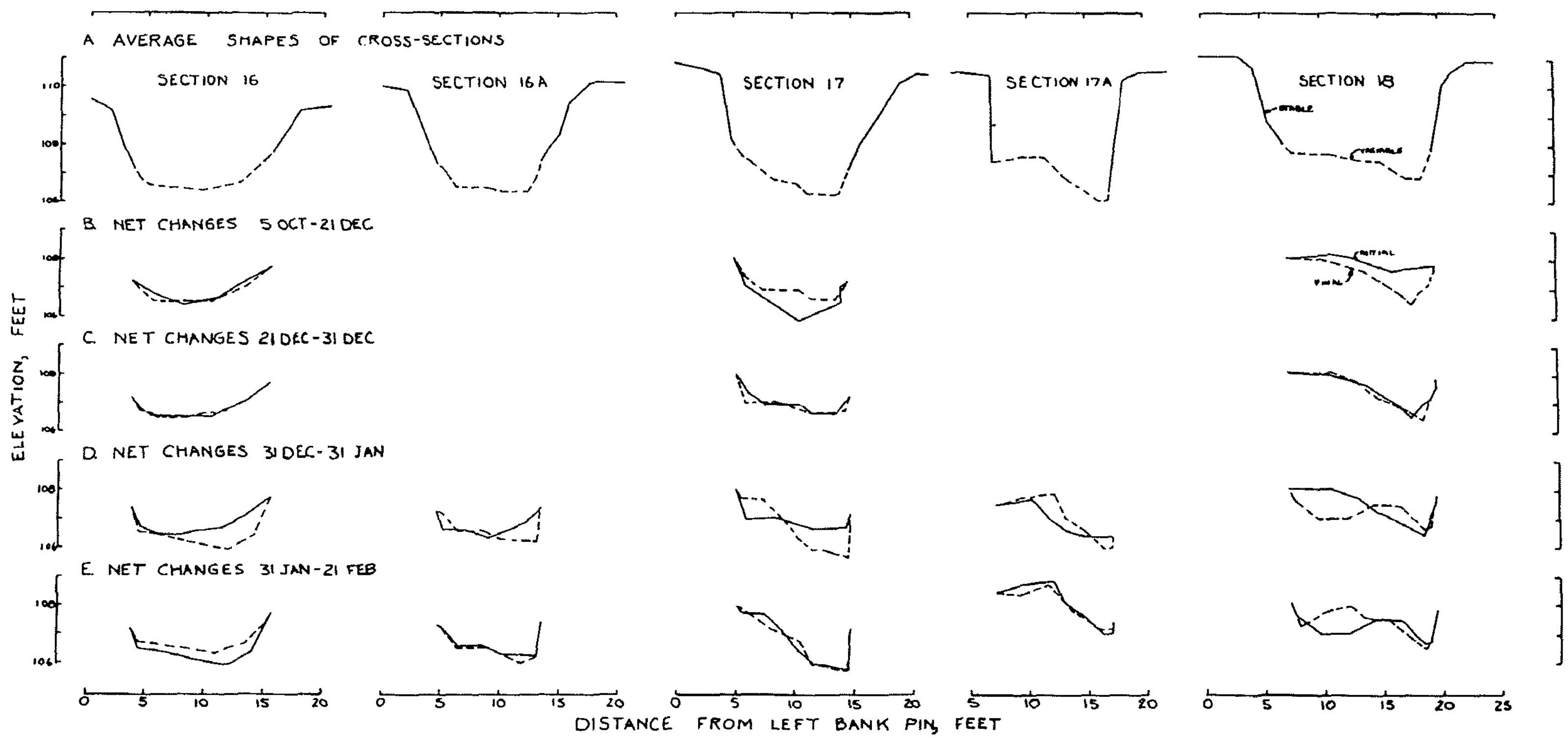

Figure 24. Sequential changes in cross-sectional shape at sections 16-18, winter 1969-70.

realignment of the main thread of storm runoff past this section. This realignment was also reflected by slight local scour and fill at section 6A and heavy deposition in an eddy zone where flow separates from the left bank just upstream of 6A (Figure 17).

Sections 7 through 8A (Figure 20) experienced alternating scour and fill between surveys, which resulted in net deposition near the left bank as a result of flow realignment because of growth of a point bar just upstream. The flow realignment also caused local net scour at these sections.

The growth of the point bar, illustrated in Figure 21, initially occurred with deposition at the lower end, near section 9, and some erosion of the outer bank over its full length (sections 9-11A). The January storm runoff caused the bar to build most notably at its upper end, near sections 11 to 11A. February runoff then caused additional deposition at the lower end of the bar.

Upstream of the bend, the narrower, deep sections 12 and 12A (Figure 22) experienced minor scour and fill between surveys and practically no net seasonal change. The greatest incremental change observed at section 12 was about 0.3 feet of scour in late December near the left bank. At section 13(Figure 22) the net seasonal deposition was small compared to the fill in early December, because of subsequent alternating scour and fill. Section 13A (Figure 22) received a deposition of about 0.5 foot in January as part of the net fill there.

At section 14 (Figure 23), in the midst of a fairly mild-sloped reach (Table 4), a foot of deposition occurred in early December near the trash rack whereas little net change took place at section 15. Subsequently, some erosion of the right bank occurred at and between these sections; also, alternating scour and fill took place at the bed. The incremental scour at section 14A in January amounted to one foot in some places as the deposit behind the trash rack site was eroded. Much of this material was probably redeposited at the upstream end of the point bar (Figure 21).

In the upstream portion of the study reach, both scour and fill occurred at given locations during different parts of the winter. At section 16 (Figure 24) the incremental changes were minimal until January, during which scour occurred up to a foot in depth. Some refilling took place here during the February storm runoff. Similar January and February events occurred to a lesser degree at section 15A (Figure 23), but at section 16A (Figure 24) slight scouring continued into February. The early December flood caused up to a foot or more of scour at section 18 (Figure 24), near a log buried in the streambed, and up to a foot of deposition at section 17 Thereafter, the cross-sectional shape began to alter from section 16A to 18 and become relatively deeper along the right bank. This change was not as progressive at section 18 as further downstream, as may be noted from the foot of scour over the left half of section 18 during January, which tended to give the cross section a less one-sided appearance.

The sequential changes of shape at the several cross sections shown in Figures 18-24 illustrate the dynamic nature of this gravel streambed. Short-term changes often differed from seasonal changes. In fact, at some sections the magnitude of short-term change far exceeded the net seasonal change, because of somewhat compensatory changes from flood to flood. As was particularly evident near the point bar, some changes in channel topography set off a "chain-reaction" of events. Build-up of the bar caused greater scour of the opposite bank, which led to further buildp-up of the bar and modified flow aligment downstream of the bar. Bank vegetation, most notably tree trunks and roots, held the banks against this modified flow alignment wherever it grew. In the absence of such vegetation, the channel banks and streambed downstream of the point bar underwent scour and deposition in response to the modified flow alignment. In steeper reaches, the flow energy was directed more at reworking the streambed than at attacking the channel banks (sections 16-18), but in flatter reaches, bank attack was noted (near sections 14-15).

Maximum Depth of Scour and Redeposition

The extreme depths of scour during a period at selected points in the streambed were detected by relocating previously buried ping pong balls at the end of that period, a technique similar to that used by Leopold and others with buried chains (Leopold, Wolman and Miller, 1964). The depth of excavation needed to find the topmost of the remaining ping pong balls and determine its position number (the basis for measuring maximum scour) also gave the amount of redeposition that followed this maximum scour. The technique required shallow, slowmoving, clear flow at the time of relocation surveying for its successful application in Oak Creek.

Table 6 summarizes the survey data on scour-ball devices, indicating the top ball found at each location and its amount of streambed cover at the installation date and at up to three subsequent dates (Table 5). Data for 19 of 33 scour-ball locations are given. At the other 14 locations (and sometimes at the 19 locations as well) it was not possible to relocate the scour devices at surveys made after installation because of adverse streamflow conditions, scour of all devices (but no recovery at the bed-load trap), or for other reasons. The 19 scour-ball locations are shown in Figure 14.

Table 7 presents an interpretation of maximum scour and redeposition at the 19 scour-device locations, based upon the survey data from Table 6 and information on installation depths of balls at each location.

The styrofoam balls at locations 1-3A, 2-1, 3-1, and two other locations (not given in Tables 6 and 7) were of only limited value. Abrasion

Table 6

SURVEY DATA FOR SCOUR BALL DEVICES, WINTER 1969-1970.

Location Number	November Top Ball	November Cover, Feet	31 Dec Top Ball	31 Dec Cover, Feet	14 Feb Top Ball	14 Feb Cover, Feet	21 Feb Top Ball	21 Feb Cover, Feet
1-1A	--	---	--	---	13	0.05	8	0.4
1-3A(1),(2)	5	0.5						
2-1(1)	5	0.1	3	(?)			none	---
3-1(1),(3)	5	0.2						
3-2	11	0.2			9	0.4	9	0.3
3-3	--	---	--	---	14	0.05	10	0.4
4-1	12	0.1	11	0.1				
5-1	18	0.4	18	0.05	18	0.05	18	0.05
5-2	18	0.05			16	0.1	16	0.1
6-1(4)	12	0.05						
6-2	13	0.05			13	0.8	13	0.9
7-1	14	0.05	14	0.4				
8-1	17	0.2	17(?)	0.2	14	0.2	14	0.35
8-2	14	0.05	10	0.3				
8-3(5)	13	0.05	7	0.1				
11-1	12	0.1	10	0.2	10	1.3		
11-2	13	0.05	10	0.2				
15-1	11	0.2			10	0.4	10	0.5
17-1	14	0.05	11	0.3			6	0.8

(1) Styrofoam "pop-up" balls buried at this location; punctured ping pong balls buried at all other Locations.

(2) Found number 5; date of scour unknown.

(3) Found styrofoam ball here on 7 Feb. with number abraded; date of scour unknown.

(4) Found number 10; date of scour unknown.

(5) Found number 13 in bed-load trap on 12 Dec; found number 4 downstream of bed-load trap on 7 Feb.

of the styrofoam by the bed load tended to remove the identity numbers as scour reached each ball. Debris caught the strings holding some of the balls, occasionally (together with abrasion from the bed load) causing the lines to snap and the styrofoam balls to be carried downstream. Consequently, it was not always possible to know which styrofoam ball had been scoured out of the bed or at what time and portion of the hydrograph such scouring took place.

The ping pong balls at locations 1-1A and 3-3 were not installed until February 14. Hence, they only give data on one storm runoff event, that of February 16.

At location 1-1A, the scour during the February 16 storm runoff extended 0.6 foot below the pre-flood surface of the bed, followed by 0.4 foot of redeposition. Thus, a net degradation of the streambed of 0.2 foot occurred, although triple this depth of the bed actually was reworked near this location by the storm runoff. The net changes during this runoff at the adjacent cross sections 1 and 2 (Figure 14 and 18) were also slight, although it is reasonable to believe that a similarly greater degree of bed reworking occurred there. Hence, the net seasonal changes in this portion of the stream, shown in Figure 17 and from the overall trends in Figure 18, can be assumed to greatly underestimate the extent of extreme scour and deposition--because of the compensating nature of these two processes during individual runoff events.

A styrofoam ball from location 1-3A was recovered to indicate scour of at least 0.5 foot in that area. The date of this scour is unknown. However, this depth of scour supports the observations made regarding the general vicinity of location 1-1A that a fairly stable bed position may still permit a considerable depth of bed disturbance during storm runoff.

The styrofoam balls at location 2-1, near section 2, were placed to a total depth of 1.1 foot, with the top two balls near the surface (their position was disturbed during installation). The net changes based on seasonal (Figure 17) and storm-runoff (Figure 18) periods were modest and suggested a slight net deposition. Yet the bed was disturbed to a total depth of at least 1.1 foot during the season. This further supports the conclusion that bed disturbance may greatly exceed net bed changes during a runoff period.

Data from location 3-2 provide additional evidence of bed disturbances to greater depths than indicated by net seasonal changes in bed position. At location 3-3 this was also true during the February 16 runoff, when little net change in bed level occurred (about 0.1 foot of scour in mid-channel between sections 3 and 4; Figure 18), yet over one-half foot of scour took place before redeposition began or the bed load ceased moving and began to rebuild a stationary bed.

Table 7.

SCOUR AND DEPOSITION INDICATED BY SCOUR BALL DEVICES, WINTER 1969-1970

Location Number	December runoff Scour, Feet	December runoff Refill, Feet	January Runoff Scour, Feet	January Runoff Refill, Feet	February 16 Runoff Scour, Feet	February 16 Runoff Refill, Feet
1-1A	---	---	---	---	0.6	0.4
1-3A[1]		(at least 0.5 ft scour on unknown date)				
2-1[1]		(at least 1.1 ft scour below initial bed over season)				
3-1[1]		(at least 0.2 ft scour by 7 Feb.)				
3-2		(scour 0.42 ft; refill 0.4 ft)			(net scour 0.1 ft)	
3-3	---	---	---	---	0.53	0.4
4-1	0.22	0.1				
5-1	0.35	0	0	0	0	0
5-2		(scour 0.27 ft; refill 0.1 ft)			0	0
6-1		(at least 0.3 ft scour on unknown date)				
6-2		(net fill 0.75 ft)			(net fill 0.1 ft)	
7-1	0	0.35				
8-1	(no net change)		0.53	0.2	(net fill 0.15 ft)	
8-2	0.5	0.3				
8-3	0.65	0.1	(at least 0.5 ft additonal scour by 7 Feb.)			
11-1	0.34	0.2	(net fill 1.1 ft)			
11-2	0.41	0.2				
15-1		(scour 0.3 ft; refill 0.4 ft)			(net fill 0.1 ft)	
17-1	0.29	0.3	(scour 0.9 ft; refill 0.8 ft)			

(1) Styrofoam "pop-up" balls buried at this location; punctured ping pong balls buried at all other locations.

The depth of bed disturbance during December storm runoff was slight at locations 4-1, 5-1, and 5-2. The channel bar at locations 5-1 and 5-2 appeared to be quite stable in spite of regular submergence during storm runoff, as indicated in Figure 17 by very minor net seasonal changes (see also Figure 19).

The amount of scour in the deeper flow near this stable bar was uncertain, but at least 0.3 foot of scour took place at location 6-1 at some unknown date.

At the protected eddy area of location 6-2, net deposition was evidenced over the winter runoff season (Figure 17). Occasional scour may have occurred after initial deposition, but it was never sufficient to reach the topmost buried ball. The deposition during December and January consisted of sand and fine gravel, but the net additional deposit in February was coarser. Such areas might well serve as storage zones for transported material until such time as flow alterations upstream reduce the protected nature of the area and permit further disturbance and transport of the deposited material.

At location 7-1, in the main flow channel, about one-third foot of deposition took place as part of a more extensive seasonal aggradation of the streambed in this zone, below the large bend and point bar (Figure 20).

Streambed disturbance was quite noticeable at locations 8-1, 8-2, and 8-3, situated in a zone subject to net seasonal scour (Figure 17). Data indicated that extreme scour extended to greater depths than reflected by net short-term changes (Figure 20), again supporting conclusions drawn from scour ball observations made downstream.

The large amount of deposition on the point bar began in January (Figure 21) and was reflected by 1.1 foot of accumulated gravel at location 11-1 in that month. Previously, a small amount of net scour took place at 11-1 and 11-2. The gravel that deposited on the point bar was generally coarse; it was probably of nearly the same size as transported throughout the study rock. The pore space below the top gravel was partially filled with sand, and a great deal of filtering of fine particles probably occurred there during recessions of storm runoff.

As elsewhere, the dual processes of scour and refill during flood periods are illustrated by data from location 15-1. Net seasonal deposition did not preclude scour at this point.

Perhaps the greatest relative differences between extreme scour and net short-term change of bed level are shown by data from location 17-1. Here, the bed appeared to undergo a net scour of 0.1 foot during January-February storm runoff, although the bed was actually disturbed and reworked to almost 10 times that depth. This offers further evidence of the dynamic nature of a seemingly stable streambed.

SECTION VIII

SUSPENDED SEDIMENT LOAD

Observed Concentrations

Several discrete samples (with respect to time) of the suspended load were obtained with the DH 48 hand sampler during January and February runoff. The suspension concentrations and stream discharges at the times of sampling are shown in Table 8. A broad range of flows was sampled, although no samples were obtained at the highest stages because of the press of time to conduct bed-load samplings and stream gagings during the brief periods of highest discharge.

The individual samples obtained with the hand sampler were originally intended to supplement the continuous automatic sampling. However, failure of the system's timer in cold weather rendered the samples obtained with the automatic system completely unreliable until a suitable replacement timer was obtained in February. Thereafter, no important stream rises occurred and the data reported in Table 8 from the automatic system represent only the spring recession flows with their minimal suspended load.

Four storm runoff events are represented by the data in Table 8. During the first, second, and fourth of these periods, only the runoff crests and recession limbs were sampled. The first two samples collected on the afternoon of January 9 actually straddled a slightly larger peak discharge (36 cfs). The first sample collected on January 14 was obtained about three-quarters of an hour after the stream crested at 60.3 cfs. However, the sample for February 16 was obtained 4 1/2 hours after the stream had crested at 175 cfs, and hence did not reflect the maximum suspended solids concentration of that runoff event. (It is assumed here that the maximum suspended solids concentrations occurred on the rising limb near crest stage or at about crest stage and not on the falling limb of the hydrograph.)

Sampling of the third runoff event of Table 8 included the rising limb as well as the falling limb of the hydrograph. The concentration of the second sample of January 17 appears to be in error, but no justification could be found for discarding it, so it has been included. (As will be seen in Figure 25A, this data point does not contribute worse scatter than do other data points.) The 1 a.m. sample on Jnauary 17 was obtained an hour after the peak discharge of 210 cfs and perhaps may roughly indicate the maximum turbidity of the stream under present watershed conditions of land usage, because of the relative infrequency of occurrence of such a large peak (on the order of a once-in-twenty-years event).

When discharge is plotted versus the corresponding suspended sediment concentration, considerable scatter may be expected because of the lack of a precise physical law to govern this relationship.

Table 8

OAK CREEK SUSPENDED SEDIMENT CONCENTRATIONS, WINTER 1969-1970

Date	Time	Discharge, cfs	Suspended Sediment Concentration, mg/l
9 January	13:43	35	204
9 January	14:50	35	166
9 January	20:18	28	49
10 January	9:30	13	9
14 January	15:42	60	147
14 January	17:00	50	111
14 January	23:15	34	28
15 January	11:15	21	7
16 January	15:25	45	25
16 January	16:45	40	96
17 January	1:00	138	417
17 January	9:15	52	75
17 January	11:00	46	52
17 January	12:55	44	195(?)
16 February	17:00	80	86
17 February	12:10	35	23
19 Feb - 16 Mar[(1)]		8	5
16 Mar - 8 Apr[(1)]		3	< 2

(1) Obtained with composite automatic sampler; all other samples obtained with DH 48 hand sampler.

Figure 25A shows this scatter for the discrete and composite samples of Table 8. The data have been fitted with a somewhat arbitrary line of relation (the fit was made by eye rather than by a least squares analysis), to show the general behavior of suspended load concentrations as a function of streamflow. At about 30-40 cfs, the suspended sediment concentrations begin to increase rapidly as discharge increased. Interestingly, an independent analysis of bed-load transport as a function of discharge in Oak Creek suggested that significant transport was initiated at about this same range of flows. This strongly suggests the close relation of the suspended load to the behavior and condition of the streambed.

Suspended Sediment Transport Rate

The estimated line of relation of suspended load concentration versus discharge can be converted into various equivalent relations to describe the rate of suspended sediment transport. The parameter used to describe this rate in this study is shown in Figure 25B and might be termed a "unit" suspended sediment transport rate--i.e., the transport rate of suspended sediment in pounds per hour for a unit of stream discharge (for one cubic foot per second). This is almost a dimensionless parameter and would become one upon division by the specific weight of water and use of a seconds-to-hours conversion factor. This parameter was originally selected in analysis of the bed-load transport rate and is used here to provide an analogous relation for the suspended load.

From Figure 25B, note that a unit of discharge carries approximately 70 lb/hr of suspended solids at 100 cfs. For comparison, about 30 lb/hr of bed load are moved by a unit of discharge in Oak Creek at this streamflow (to be discussed in a following section).

Once a relationship such as that in Figure 25B has been developed, it may be readily applied to storm runoff hydrographs to estimate the total suspended sediment yield as a result of a runoff event. This has been done for Oak Creek with three storm runoff periods having differing magnitudes of peak discharge. Similar calculations were also made for the bed load, and the results were combined to estimate the fraction of total sediment load that is transported by bed-load processes. The results conclude the following section on bed-load transport, so no further discussion will be presented here.

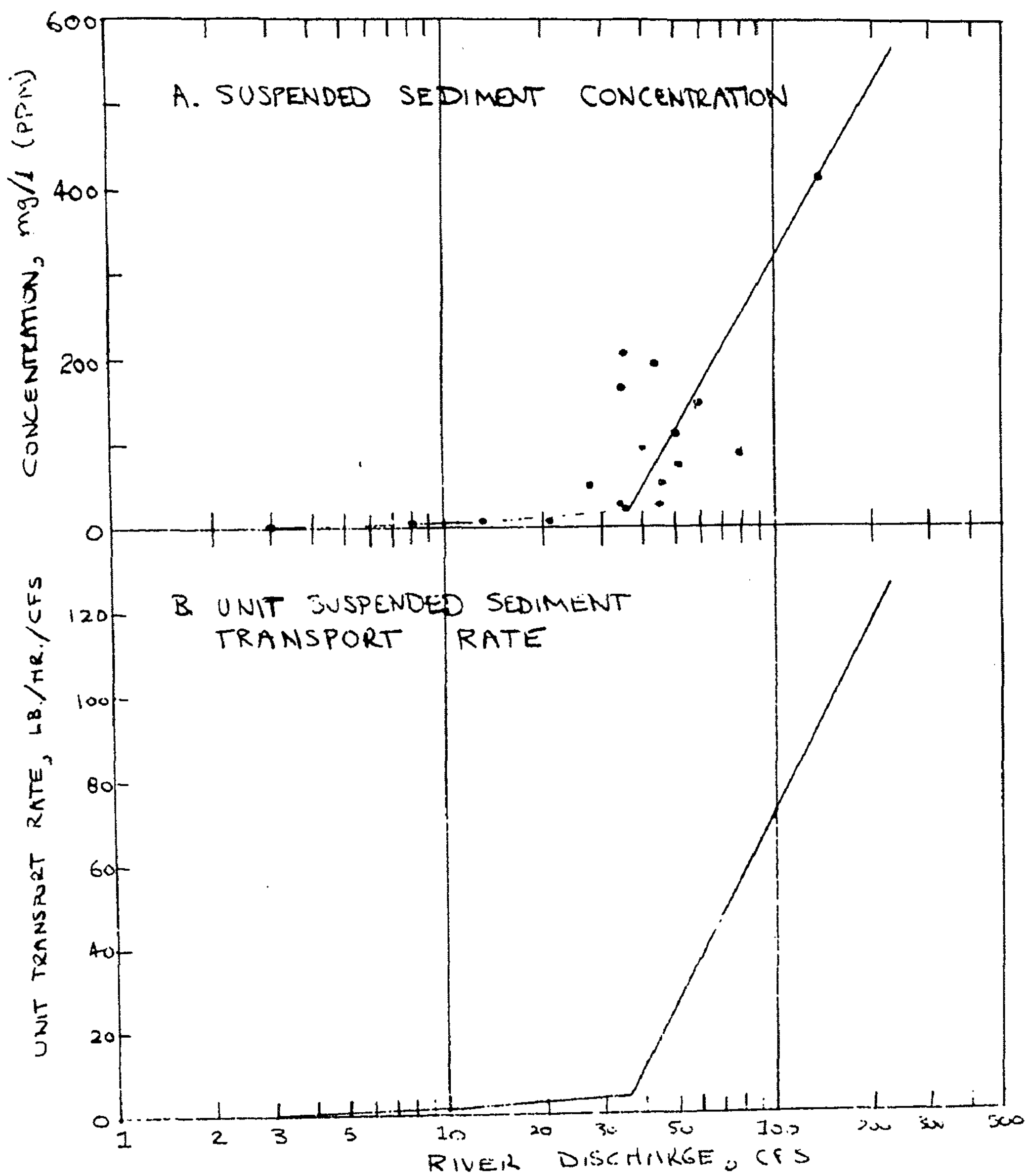

Figure 25. Suspended sediment concentration and unit transport rate as functions of discharge.

SECTION IX

BED-LOAD TRANSPORT

The primary purpose of this research has been to obtain a usable understanding of the changes in total sediment yield from a drainage basin with changes in land use. As stated previously, a study of the bed-load transport process in a typical mountain stream (Oak Creek) was made to obtain insights and data describing the hydraulic and morphological factors that influence the movement of bed material.

This section of the report gives the pertinent results of a review of the literature on sediment yield, of measurements made on bed movement and bed materials at the Oak Creek instrumented study reach, and of measurements made of the bed material in one of the Alsea Experimental Watersheds (Deer Creek). A comparison of bed-load discharge and suspended load discharge is also made.

Sediment Yield From Watersheds

At the start of this study, a review of the literature on sediment yield from watersheds was made to obtain information on the changes of sediment input to a stream channel with changes in land use in the watershed.

The yield of sediments from a watershed can be considered to involve two processes: one on the land surface that transfers sediment to a stream channel, and one in the stream that transports the sediment out of the watershed. The transfer of sediment to a stream consists of three elements, which can act in combination or alone: (1) local and sheet erosion by overland flow; (2) mass movement into the stream channel; and (3) direct erosion by the stream. Roehl (1962) reports that in the Southeastern United States sheet erosion represents 66-100 percent and channel erosion 0-34 percent of the total erosion. No information was found in the literature that quantifies the importance of mass movement of earth materials in the delivery of sediment to stream channels. However, the geologic literature suggests that mass movements are quite important in mountainous areas and that infrequent landslides can deliver very large quantities of sediment to streams. Therefore, mass movements might be important in some instances even though no data on the relative importance of mass movements in comparison to water erosion were found in the literature.

Numerous studies have been made to determine watershed factors that affect the total sediment yield process. One equation relating watershed variables to erosion is that developed by Smith and Wischmeier (1957) for agricultural areas in the Midwestern United States. The Smith and Wischmeier equation is of the form

$$X = (I)\ (\underline{K})\ (LS)\ (C)\ (P), \qquad \text{Eq. 1}$$

where X = annual soil loss (erosion), I = erosive potential rainfall factor, K = soil erodibility, LS = topographic factor, C = cropping-management factor, and P = conservation practice factor.

This equation suggests that sediment yield is a function of: (1) amount of rainfall and the time distribution of rainfall; (2) soil type and geology; (3) topography and geomorphology; and (4) land use.

Hence, the equation could be rewritten as

$$X = x \text{ (rainfall, soil, geology, topography, land use).} \qquad \text{Eq. 2}$$

Anderson (1954) developed a somewhat analogous equation for sediment yield from forested watersheds in western Oregon. His is a regression equation with many empirical terms but, in essence, it can be restated as:

$$Y = y \text{ (runoff, drainage area, bank erosion, soil type, geology, slope, land use, snow-rain factor),} \qquad \text{Eq. 3}$$

where Y is the total sediment yield from a watershed. The snow-rain factor takes into consideration the effect of snow or a rain-snow situation upon the runoff process. The runoff factor is a function of a rainfall, drainage area, soil type, geology, topography, and snowpack. Hence, Equation 3 can be rewritten as:

$$Y = y \text{ (rainfall, soil type, geology, topography, land use, snow-rain factor, drainage area, bank erosion).} \qquad \text{Eq. 4}$$

A comparison of Equations 2 and 4 suggests that erosion in forested mountain areas is a function of (1) rainfall, (2) soil type and geology, (3) topography, (4) land use, and (5) snow-rain factor, and that the transport of the sediment from the watershed is a function of (1) drainage area and (2) bank erosion. For a given watershed, the factors that can be influenced by land management practices are land use, bank erosion, and over a long period of time, soil type.

Equation 4 can be considered to include a set of erosion terms (identified by the symbol X from Equation 2, but with rainfall assumed to include the snow-rain factor) and a set of sediment transport terms and can be written as:

$$Y = y \text{ (X, drainage area, bank erosion)} \qquad \text{Eq. 5}$$

Furthermore, it is convenient to regard the sediment yield problem as one where material, once eroded, must be either redeposited in the watershed or transported from the watershed.

Roehl (1962) has presented a procedure to estimate the "sediment delivery ratio" based on watershed parameters. He defines the sediment delivery ratio as "the percentage relationship between the sediment yield at a specified measuring point in a watershed and the gross, or total, erosion occurring in the watershed upstream from the point." The sediment delivery ratio was found to be a function of drainage area, ratio of basin relief to length, and a factor that is a function of the density of drainage channels. The density of drainage channels is strongly influenced by the soil type and geology. From the definition of sediment delivery ratio, it would appear reasonable to include bank erosion as one of the influencing factors. Hence, we can write

$$SDR = f\text{ (soil type, geology, topography, drainage area, bank erosion)}, \qquad \text{Eq. 6}$$

where SDR is the sediment delivery ratio.

Equation 6 may be combined with Equation 4 and 5, giving

$$Y = y\ (X,\ SDR) \qquad \text{Eq. 7}$$

The resulting equation expresses total sediment yield from a watershed as a function of the total watershed erosion and the transport capability for removing these erosion products (as expressed by the sediment delivery ratio).

The equations as presented above obviously give only qualitative relationships based on quantitative data--yet, there are certain unexplained factors. One of these is the method of measuring the total sediment yield from a watershed. The total load of material moving in a stream usually is divided into bed load and suspended load and the only part measured is that in suspension. On smaller watersheds, the measurement technique often used is to induce turbulence into the flow such that part of the bed load will be suspended at the sampling point. If the bed material is fine sand, this technique may be reasonably good. But if the material is coarse sand or gravel, the material either will not be suspended by the turbulence or will not be sampled--because errors in sampling increase as the particle size increases (Love and Benedict, 1948). In larger streams, the bed load is often not measured in any way. This means that the process of erosion will place material in a stream that will be transported by the stream but not included as part of the sediment yield by the measurement techniques.

In determining his equation for sediment delivery ratio, Roehl used data on sedimentation in a reservoir to determine the sediment yield from a watershed. The amount of sediment in a reservoir was measured and divided by the trapping efficiency of the reservoir to obtain the estimated total sediment yield. Unfortunately, trap efficiencies of reservoirs are based on sediment measurements that usually do not represent the total sediment transported from a watershed. Consequently, neither reservoir surveys nor sediment sampling will give reliable estimates of the sediment yield from a watershed unless the bed load is measured.

As an illustration, assume that the sediment delivery ratio varies with drainage area as shown by Roehl and as reproduced in Figure 26. As is shown, the sediment delivery ratio decreases rapidly as the drainage area increases. For an illustrative drainage area of 6 square miles, only 20 percent of the material eroded will be carried out of the watershed, which means that 80 percent is redeposited in the watershed to be eroded again when there is another storm. If the assumed gross erosion has been accurately determined, then this example suggests three possibilities:

1. once eroded, sediment will move on the land surface until reaching a stream or be redeposited on the land surface as overland flow diminishes;
2. deposition occurs in the stream channel and results in net aggradation of the channel (but much of the available literature, including Roehl's paper, indicates that channel erosion is common in upland areas); and
3. the estimate of total sediment yield is too low because the bed load usually is not known.

Both sheet erosion and channel sediment transport will include material that is being carried at the "bed" of the flowing water. For a stream, this is the bed load and for sheet flow, this is really bed load, although no such distinction of the separate components of sediment transport is made for sheet flow. In each instance, as the flow recedes the "bed" material will redeposit and be at rest. If this redeposition material is transported again with the next storm runoff and is classified again as part of the gross erosion, this results in only a low percentage of the gross erosion products being carried out of a watershed in any one storm.

The main reason for discussing the ideas presented above is to suggest that an understanding of the process of bed-load transport is important in understanding erosion on a watershed and in quantifying the amount of sediment yield from a watershed.

<u>Oak Creek Bed Material</u>

In the fall of 1969, before any storm runoff, the bed materials were sampled in the instrumented natural study reach of Oak Creek. The samples were taken at previously established cross sections (Figure 14). All but one of the samples were of armor material at the surface of the streambed and were made with the object of obtaining data on the size of material that forms the boundary of the flowing water. One sample was also taken of the material just below the surface layer.

The technique used in sampling the bed material in the study reach was to obtain representative surface material at the center of the stream and at the quarter points of a given cross section. These samples were then combined to form a sample for the cross section. To do this at each point, a bucket with the bottom cut out was set on the bed and all material within it exposed at the surface was collected. The

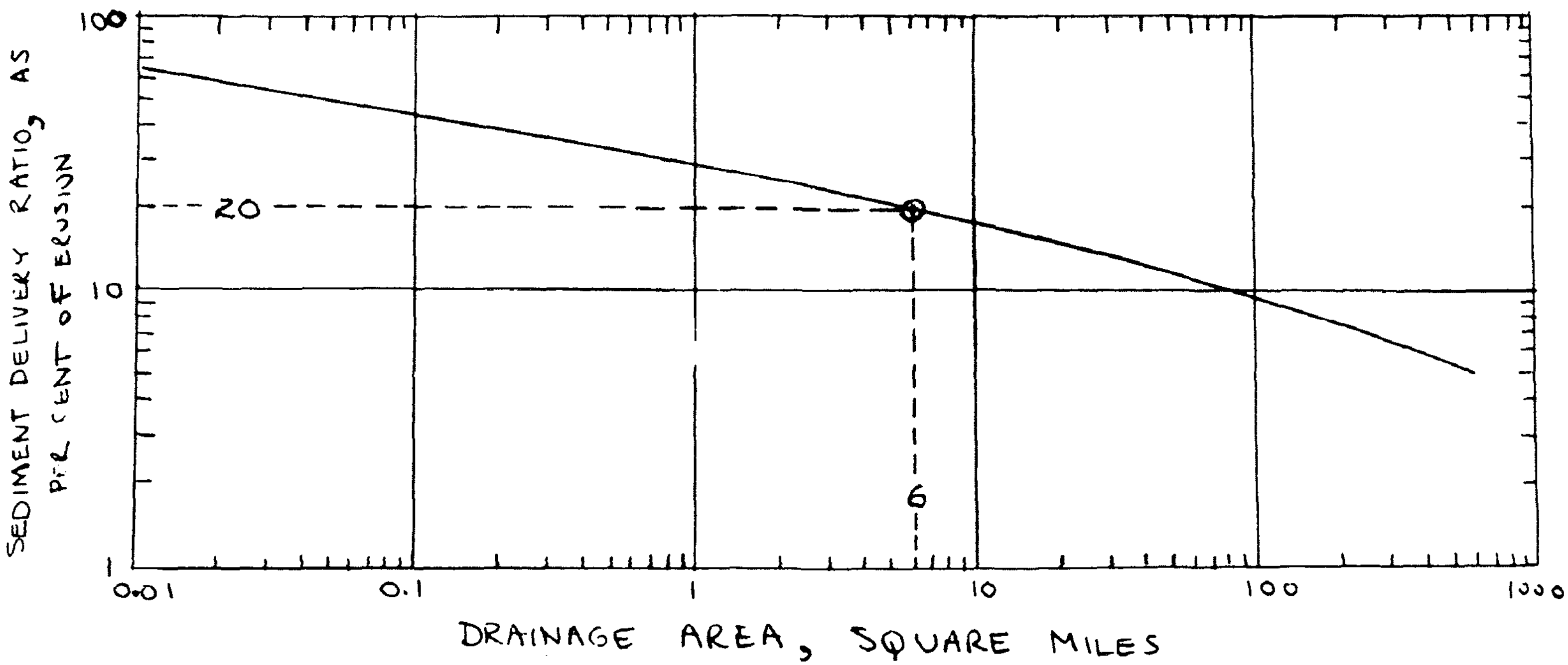

Figure 26. Sediment delivery ratio as a function of basin size (adapted from Roehl, 1962, Figure 2).

diameter of the bucket opening was 8+ inches, for an area of about 0.4 square foot per sample point and 1.2 square feet per cross section. Some fines (small sand and silt-size particles) were washed off the larger particles and lost if the sample point was located in the water.

Particle-size analyses were made with this bed material. The results of these analyses are presented in Table 9. The table gives the fraction (by weight) of each cross-sectional sample retained on each of several sieves. (For oblong particles, the size measured by a sieve analysis is the intermediate dimension of the particle.)

The mean particle size (size for which 50 percent of the sample by weight is smaller--designated as D_{50}) for the surface layer at each cross section is also given in Table 9. These values were obtained from particle gradation curves for each sample (i.e., from graphs of percentage of sample passing each sieve versus sieve opening size, the latter being assumed equivalent to particle diameter). The gradation curves for the samples with the smallest and largest mean particle sizes, those for samples at sections 9 and 12 respectively, are presented in Figure 27. These illustrate the typical gradation of the surface (armor) layer throughout the study reach, because of little variation in the mean values of particle size from section to section. If the mean particle sizes at the sections are averaged, a mean size of surface material for the entire reach can be estimated. This value was found to be 2 1/4 inches.

Of some interest is the variation of mean grain size of the streambed surface with distance along the study reach. A plot of the mean particle size for each cross section versus location along the channel is given on Figure 28A. As shown, there is some irregular variation with distance, but there may be a slight tendency for the mean particle size to decrease with distance downstream. In this reach, the smallest observed mean size at a cross section was 1 3/4 inches at section 9, located in a pool (Figure 15) and the largest was 2 3/4 inches at section 12, located near the upstream edge of a bar. For comparison, a sample of the armor material located near a debris dam about 1,000 feet downstream of the study reach had a mean diameter of 1 3/4 inches, which tends to add support to the idea that the mean particle size of streambed particles decreases with distance downstream.

Figure 28B shows the variation of the surface layer fraction 1 1/2 inches or coarser in size with distance along the channel. The variation is considerable. Yet, the suggested limits of this variation indicate a decrease in the coarse fraction in the downstream direction, again supporting the idea that particle size of streambed materials decreases with distance downstream.

Another important aspect is the variation of the size gradation of

Table 9

PARTICLE SIZE DISTRIBUTIONS FOR OAK CREEK BED MATERIAL FORMING THE SURFACE LAYER IN THE STUDY REACH, FALL 1969

Sieve Size	Fraction of sample retained by indicated sieve at the given sampled cross-section											
	3	4	5	6	7	8	9	10 1/2 (1)	12	13	14	15
3 - in.	0.200	0.085	0.111	0	0.070	0	0	0.098	0.119	0	0.279	0
2 - in.	---	0.552	---	---	---	---	---	---	---	---	---	---
1 1/2 - in.	0.782	0.699	0.686	0.561	0.787	0.683	0.611	0.679	0.863	0.625	0.625	0.862
3/4 - in.	0.926	0.920	0.919	0.886	0.931	0.885	0.897	0.858	0.964	0.942	0.846	0.971
3/8 - in.	0.962	0.979	0.978	0.970	0.967	0.965	0.970	0.935	0.991	0.986	0.926	0.997
No. 4	0.977	0.996	0.992	0.987	0.980	0.986	0.986	0.964	0.998	0.994	0.963	0.999
No. 8	0.983	0.999	0.996	0.994	0.988	0.994	0.989	0.980	0.999	0.997	0.969	0.999
No. 16	0.989	0.999	0.997	0.998	0.992	0.996	0.993	0.988	0.999	0.999	0.990	0.999
No. 30	0.994	0.999	0.998	0.999	0.996	0.998	0.996	0.993	0.999	0.999	0.996	0.999
No. 50	0.997	0.999	0.999	0.999	0.999	0.999	0.998	0.996	0.999	0.999	0.998	0.999
No. 100	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.998	0.999	0.999	0.999	0.999
Pan	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Mean Particle size at Cross-section, inches	2 1/2	2 1/4	2 1/4	2 1/4	2 1/2	2 1/4	1 3/4	2	2 3/4	2 1/2	2 1/2	2 3/4

(1) Midway between sections 10 and 11.

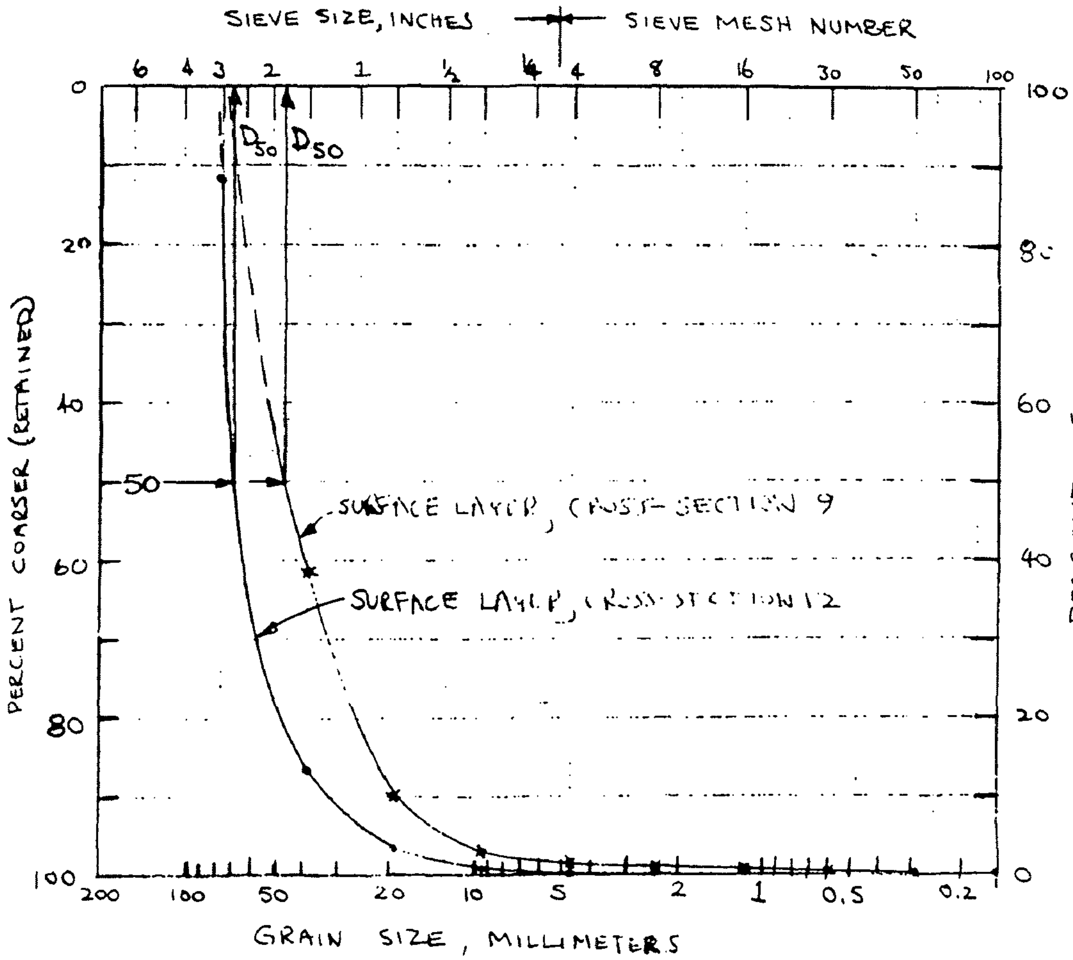

Figure 27. Typical particle gradation curves for the bed surface in Oak Creek study reach, fall 1969.

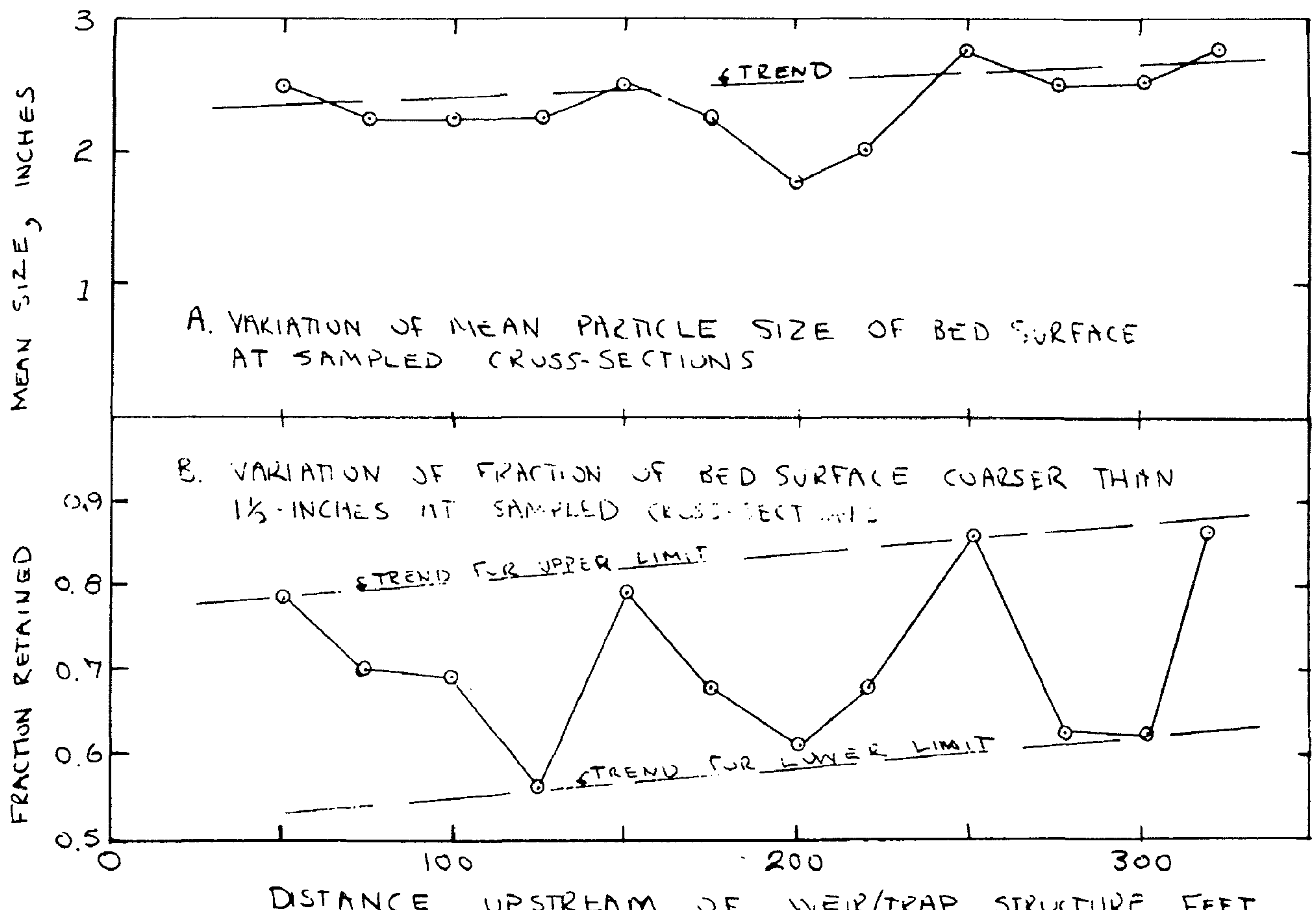

Figure 28. Variation of mean size and coarse fraction of streambed surface layer with location along Oak Creek study reach, fall 1969.

the bed material with depth below the bed surface. One sample was taken of the material below the surface layer at cross section 15. The data are given in Table 10 and on Figure 29A. In addition, a sample was taken from a bar that had deposited behind a fallen tree and debris dam about 1,000 feet downstream of the instrumented channel. The debris dam subsequently failed abruptly during a flood and part of the bar was eroded, which lowered the water level and exposed a cut cross section of the bar to a depth of over a foot below its surface layer. Samples of this surface layer and of the material below it were taken without losing the fines (because there was no flow to contend with). The results of the sieve analysis are given in Table 10 and on Figure 29B.

As is shown in Table 10 and Figure 29, there is a significant difference between the surface layer and the material below. Furthermore, there is little difference in material composition for the first and second six inches of bed below the surface at the downstream bar. Similar observations by other investigators of coarse surface layers overlying vertically well-mixed (but finer) streambeds have given rise to the terms "armor layer" and "protective pavement" to describe such surface layers. Their existence appears to be quite common when dealing with gravelly streams. They offer an added measure of protection against bed-load transport until the flow increases sufficiently to disturb them.

Streambed materials, like other earth materials, can be described by an index or coefficient of uniformity, derived from the particle size gradation curve. This index is defined as the ratio of that particle size such that 60 percent of the sample is finer to that particle size such that 10 percent of the sample is finer (i.e., $U = D_{60}/D_{10}$). Data on the uniformity of selected samples from Oak Creek are given in Table 11. The index of uniformity for the armor is between 2.3 and 2.8, but that for the material below the armor layer is between 5 and 8. Hence, the armor layer is considerably more uniform (a lower index value) in its size range than is true for the material beneath the surface.

Another important consideration is the variation of particle weights within each of the size ranges. Data on this are given in Table 12. The data indicate a wide range of weight for a given sieve size. There is also considerable overlap of particle weights from the larger grains of one size range to the smaller grains of the next-larger size range. The weight of a "representative sphere" also was calculated for each size range, based upon the geometric mean (representative) particle diameter for each size range. These calculated weights of the equivalent spheres compare favorably with the measured median particle weights of each fraction, which suggests the equivalent weight may be as good as any other single weight in representing the weight of any given set of particles. However, the variance of particle weight is very large and probably quite important in understanding the transport and armoring processes. The calculated weight for the No. 4 sieve size range is much less than the median

Table 10

VARIATION OF STREAMBED PARTICLE SIZE DISTRIBUTION WITH DEPTH BELOW BED SURFACE, OAK CREEK, FALL 1969

Sieve Size	Fraction of Sample Retained by Indicated Sieve at Sampling Location: Section 15		Downstream Bar (1)		
	Surface	Subsurface (2)	Surface	1st 6 inches	2nd 6 inches
3 in.	0		0	0	0
2 in.			0.390	0.076	0.135
1 1/2 in.	0.862	0	0.624	0.197	0.263
3/4 in.	0.971	0.426	0.958	0.576	0.623
3/8 in.	0.997	0.695	0.998	0.785	0.813
No. 4	0.999	0.860	1.000	0.905	0.933
No. 8	0.999	0.893		0.951	0.978
No. 16	0.999	0.928		0.973	0.990
No. 30	0.999	0.992		0.986	0.995
No. 50	0.999	0.996		0.995	0.998
No. 100	0.999	0.998		0.997	0.999
Pan	1.000	1.000		1.000	1.000
Mean Particle Size at Location, mm. (inches)	68 (2 3/4)	16	45 (1 3/4)	22	24

(1) This bar is about 1,000 feet downstream of the study area.

(2) Approximately the first three inches of streambed below the surface layer.

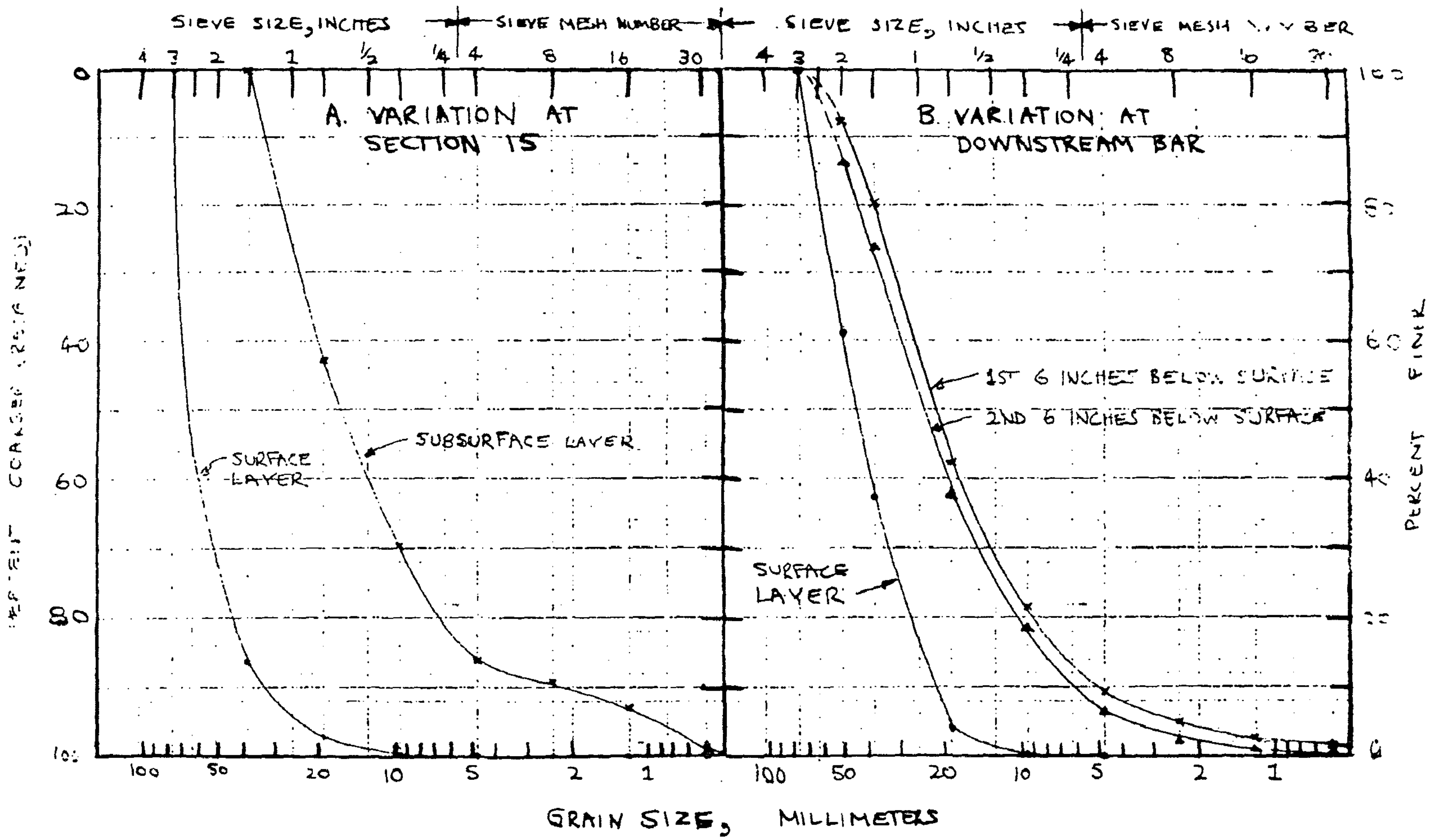

Figure 29. Variation of size gradation of bed material with depth below bed surface, Oak Creek, fall 1969.

Table 11

UNIFORMITY OF OAK CREEK BED MATERIAL
AT SELECTED LOCATIONS, FALL 1969

Property of particle size gradation curve	Values at Indicated Locations						
	Section 9	Section 12	Section 15		Downstream Bar		
			Surface	Subsurface	Surface	1st 6 inches	2nd 6 inches
$D_{60}^{(1)}$	52	73	70	20	51	25	30
$D_{10}^{(2)}$	19	31	30	2.5	21	4.8	6
$U^{(3)}$	2.74	2.36	2.33	8.0	2.43	5.2	5.0

(1) Size such that 60 percent of sample particles are smaller.

(2) Size such that 10 percent of sample particles are smaller.

(3) $U = D_{60}/D_{10}$

(Note: if $U_1 > U_2$, then sample 1 is less uniform than sample 2)

Table 12

VARIATION OF PARTICLE WEIGHTS WITHIN GIVEN SIZE RANGES FOR OAK CREEK ARMOR LAYER, FALL 1969

Sieve Retained on	Representative Particle Diameter, Millimeters (1)	Weight of Equivalent Sphere, grams (2)	Particle Weights		
			Maximum, grams	Median, grams	Minimum, grams
3 - in.	88	1,020	1,465	936	552
2 - in.	62	360	766	318	169
1 1/2 - in.	44	127	234	134	69
3/4 - in.	27	29.2	70.6	19.3	3.8
3/8 - in.	13.5	3.7	12.9	2.8	0.89
No. 4 (3)	6.7	0.45	2.03	0.99	0.77

(1) The representative particle diameter is the geometric mean of the sieve on which the particles are retained and the next larger sieve (which the particles were able to pass through).

(2) The equivalent sphere is based upon the representative particle diameter for that size range and its weight is calculated assuming a specific gravity of 2.85 for the grains (based on laboratory measurements).

(3) Data for this size range were based upon a single sample at an exposed bar downstream of the study reach; all other data represent composited samples.

weight, probably because the lighter particles had been removed from the armor layer so that the measured weights are not representative of the full range of particles between No. 4 and 3/8-inch, even though the calculated weight is.

Oak Creek Bed-Load Transport

This section reports the results of bed-load measurements made at Oak Creek in the winter of 1969-70 using the vortex bed-load sampler. Considerable experience had to be gained in operating the installation and at the same time collecting samples for use in the sediment yield analysis. Therefore, the data reported here are the results of measurements made in the process of learning how to operate the installation and represent only those data taken at time intervals when the discharge was reasonably constant. Measurements made over other time intervals when the discharge varied widely were not considered usable because the effective discharges for such situations were not known.

Mechanical analyses of the 14 bed-load samples for which the effective discharges could be determined reliably are summarized in Table 13. Also shown are several useful measures of particle size distributions, obtained from the gradation curves for each sample. These include the average (D_{50}) particle diameters, the indices of uniformity (based on D_{60} and D_{10}), indications of bed roughness (D_{65}), and indications of maximum particle size (D_{95}). In each instance the subscript refers to the fraction of the sample finer than the indicated size. Considerable variation in all of these measures is evident in this table. These values can be related to stream discharge and bed-load transport rate, as may be seen by comparison with data in Table 14 and as discussed in subsequent paragraphs.

Bed-load transport data are summarized in Table 14. The indicated discharges are the mean or effective values for the sampling intervals. A descriptive column in the table indicates the manner in which the hydrograph was varying during each sampling period. The total bed-load transport rate at each sampling period is reported, followed by a breakdown giving transport rates for various size fractions of the bed-load.

Data from Tables 13 and 14 are presented in Figures 30A, 30B, and 30C to show the variation with stream discharge of total bed load, bed load coarser than 1 1/2 inches, and bed load coarser than No. 4 sieve size (4.76 mm.), respectively. In Figure 30, no data adjustments were made for bed-load sampler efficiency. Lines of "visual best fit" were drawn through the unadjusted data points. The total bed-load transport, in Figure 30A, at 130 cfs was estimated during the large storm runoff event that transported more bed load than the sampling installation could handle. The estimate was made on the basis of the rate at which the vortex trough filled after being partly cleared and is considered to be a good estimate of the possible range of the

Table 13

PARTICLE SIZE DISTRIBUTIONS FOR BED-LOAD SAMPLES, OAK CREEK, WINTER 1969-1970

Sieve Size	Fraction of sample retained by indicated sieve for sample of given identity number													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
3 - in.		0.00	0.001		0	0		0	0	0	0	0	0	
2 - in.		0.006	0.074		0.121	0.025	0	0.080	0.046	0.065	0.022	0.023	0.007	0
1 1/2 - in.		0.028	0.195	0	0.141	0.081	0.097	0.194	0.136	0.101	0.056	0.072	0.036	0.006
3/4 - in.	0.0	0.117	0.555	0.034	0.252	0.301	0.272	0.512	0.442	0.230	0.239	0.333	0.279	0.010
3/8 - in.	0.054	0.194	0.739	0.060	0.358	0.468	0.358	0.697	0.646	0.421	0.432	0.560	0.516	0.285
No. 4	0.070	0.285	0.818	0.093	0.428	0.509	0.414	0.792	0.762	0.584	0.535	0.672	0.647	0.532
No. 8	0.116	0.419	0.870	0.176	0.520	0.563	0.500	0.860	0.837	0.699	0.641	0.748	0.740	0.652
No. 16	0.238	0.677	0.930	0.432	0.660	0.707	0.666	0.933	0.922	0.850	0.821	0.849	0.867	0.773
No. 30	0.454	0.887	0.976	0.682	0.810	0.845	0.820	0.978	0.976	0.947	0.944	0.931	0.964	0.871
No. 50	0.762	0.965	0.992	0.832	0.897	0.914	0.919	0.992	0.993	0.981	0.982	0.965	0.991	0.921
No. 100	0.919	0.966	0.996	0.923	0.951	0.963	0.927	0.996	0.997	0.992	0.992	0.983	0.996	0.955
Pan	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
D_{50}, Millimeters	0.52	2.00	22.5	0.96	2.78	6.50	2.40	20.0	16.3	7.20	7.20	12.5	10.4	5.20
D_{60}, Millimeters	0.74	2.70	26.0	1.20	6.80	13.0	6.00	24.0	21.0	10.0	11.0	18.0	14.0	7.20
D_{10}, Millimeters	0.17	0.54	1.80	0.18	0.28	0.32	0.38	1.50	1.40	0.90	0.84	0.84	0.98	0.42
$\breve{U} = \frac{D_{60}}{D_{10}}$	4.35	5.00	14.4	6.66	24.3	40.6	15.9	16.0	15.0	11.1	13.1	21.4	14.3	17.1
D_{65}, Millimeters	0.78	3.40	30.0	1.40	10.0	17.0	12.0	28.0	23.0	14.7	13.0	20.0	17.0	8.00
D_{95}, Millimeters	11.0	33.0	56.0	12.7	70.0	43.0	44.0	56.0	51.0	55.0	40.0	42.0	37.0	18.0

Table 14

SUMMARY OF BED-LOAD TRANSPORT DATA, OAK CREEK, WINTER 1969-1970

Sample Identity Number	Stream Discharge, cfs	Water Stage Trend	Bed-Load Transport, lb./hr.					
				For Fraction Coarser than Indicated Sieve				
			Total	1 1/2 - inch	No. 4	No. 16	No. 30	No. 50
1	19.0	Varying	0.050	0	0.004	0.012	0.023	0.038
2	49.4	Rising	26.05	0.73	7.42	17.63	23.10	25.13
3	71.0	Falling	441.36	85.88	360.09	410.66	430.69	437.88
4	23.3	Rising	1.22	0.0	0.11	0.52	0.83	1.01
5	33.6	Rising	7.06	0.88	2.66	4.40	5.50	6.22
6	32.9	Falling	3.90	0.36	2.26	2.98	3.40	3.62
7	20.3	Falling	1.01	0.10	0.42	0.67	0.83	0.93
8	54.0	Falling	100.65	19.50	79.70	93.92	98.46	99.88
9	50.0	Falling	82.93	11.26	63.19	76.50	80.93	82.33
10	39.4	Falling	5.67	0.58	3.31	4.82	5.37	5.56
11	44.0	Falling	77.26	4.32	41.36	63.45	72.98	75.87
12	46.5	Falling	466.06	33.32	313.36	395.72	433.80	449.66
13	45.0	Rising	173.05	6.17	112.03	150.08	166.80	171.48
14	34.8	Falling	14.11	0.08	7.50	10.90	12.28	12.99

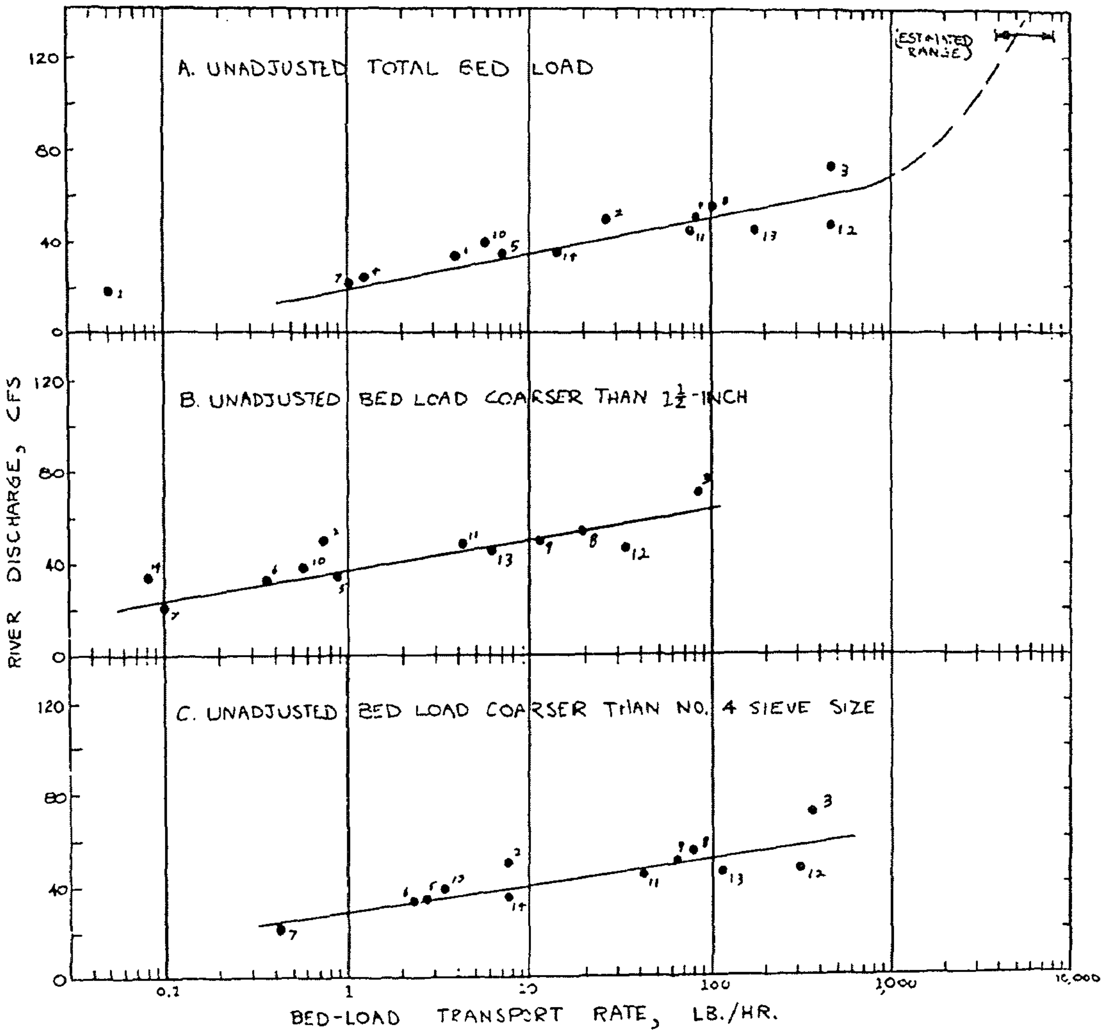

Figure 30. Unadjusted bed-load transport curves, Oak Creek, winter 1969-70.

bed-load discharge when the flow rate is 130 cfs. For comparative purposes, the three curves of Figure 30 are superimposed, with data points omitted in Figure 31.

Figure 30 shows considerable scatter of the data. Furthermore, the convergence, as discharge increases, of the lines of best fit for total bed-load transport and transport of particles coarser than No. 4 sieve size implies that the fraction of the total bed load smaller than No. 4 sieve size (represented by the gap between the converging lines) decreases toward zero with increasing transport rate, which is not reasonable. Consequently, the bed-load data were critically examined to find an explanation for this seeming inconsistency regarding the transport of sand-size material.

To obtain some idea of the transport rate of the sand-size material, graphs of the bed-load transport rate for grains smaller than No. 4 sieve size and No. 30 sieve size (0.595 mm.) were made (Figure 32). As shown, there are two possible lines through the data--one that includes the low-flow samples plus data for the early-winter samples and another through the low-flow data and the late-winter samples. The probable reason for this difference is that the stage-discharge relationship had changed on January 16 and the Froude number was lower for the later samples (Figure 5). The trap efficiency of the bed-load sampler for small particles appears to be related to the Froude number. Field observations indicated a higher degree of turbulence as the Froude number increased, which would tend to cause suspension of an increasingly higher percentage of the sand and silt-size particles. If it is assumed that the lower lines in Figure 32A and 32B represent higher trap efficiencies than do the upper lines (since the lower lines indicate greater transport at a given discharge than do the upper lines), then it appears that trap efficiencies were higher for samples 11, 12, 13, and 14 than for other samples collected at high streamflows. In fact, sample 11 was obtained on January 16 as the rating curve was shifting toward lower Froude numbers. Using Figure 32, the data can be adjusted to obtain a better estimate of the true bed-load transport and also some idea of the efficiency of the sediment trap for the sand-size particles. To do this, Froude numbers were calculated for each sample, based on Figure 5. Relative trap efficiences were also calculated with the assumption that the lower curves of Figure 32 correspond to maximum trap efficiency. From these calculations, a diagram of trap efficiency versus Froude number was prepared (Figure 33).

The curve of Figure 33 shows a marked decrease in the trapping efficiency for small particles as the Froude number increases much above a value of 0.83.

Based on Figure 32, adjustments of the bed-load tranport rates for samples 2, 3, 8, 9, and 10 were made to obtain a better idea of the "true" transport rate. The revised estimates of the total bed-load

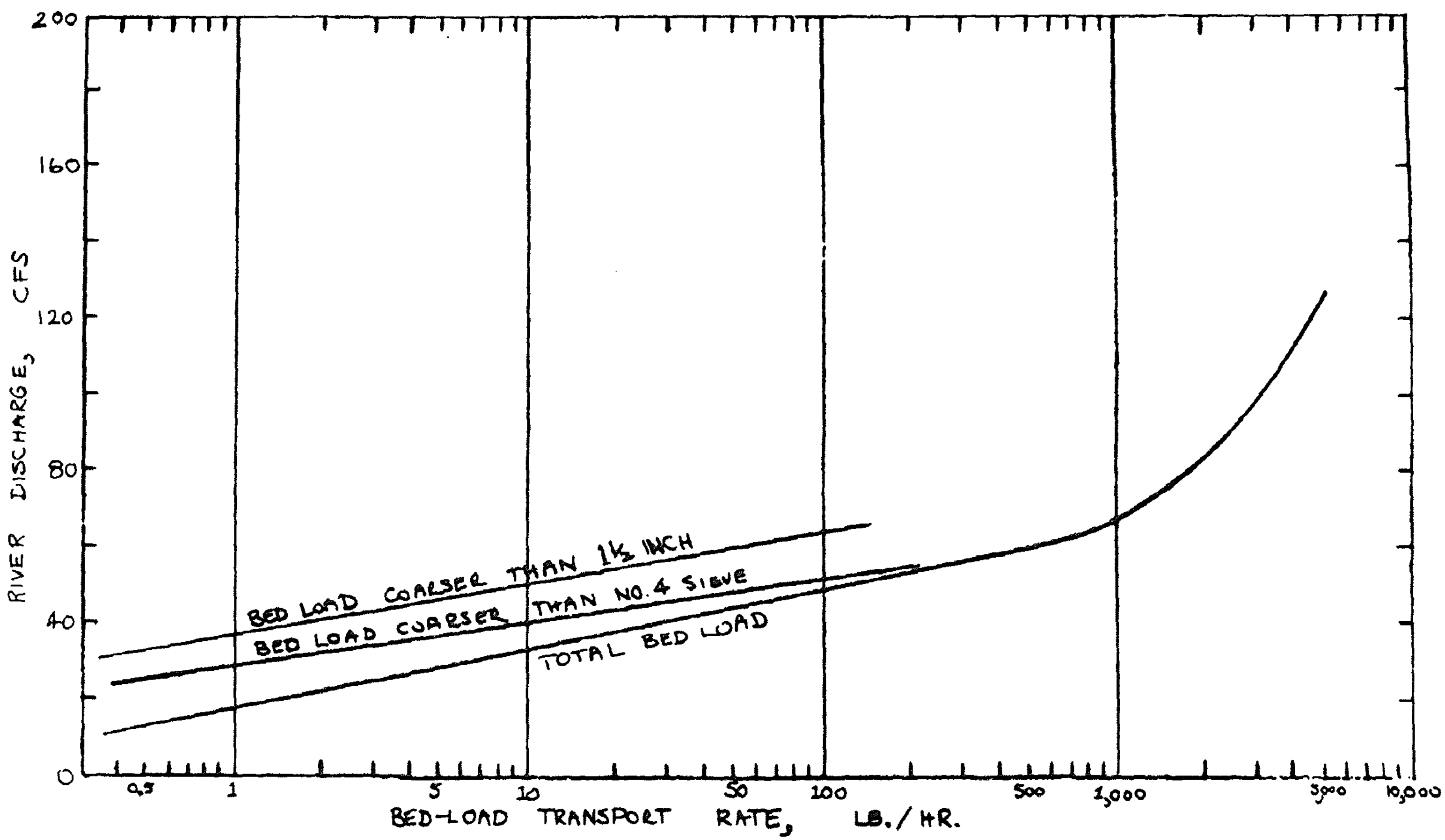

Figure 31. Superimposed unadjusted bed-load transport curves, Oak Creek, winter 1969-70.

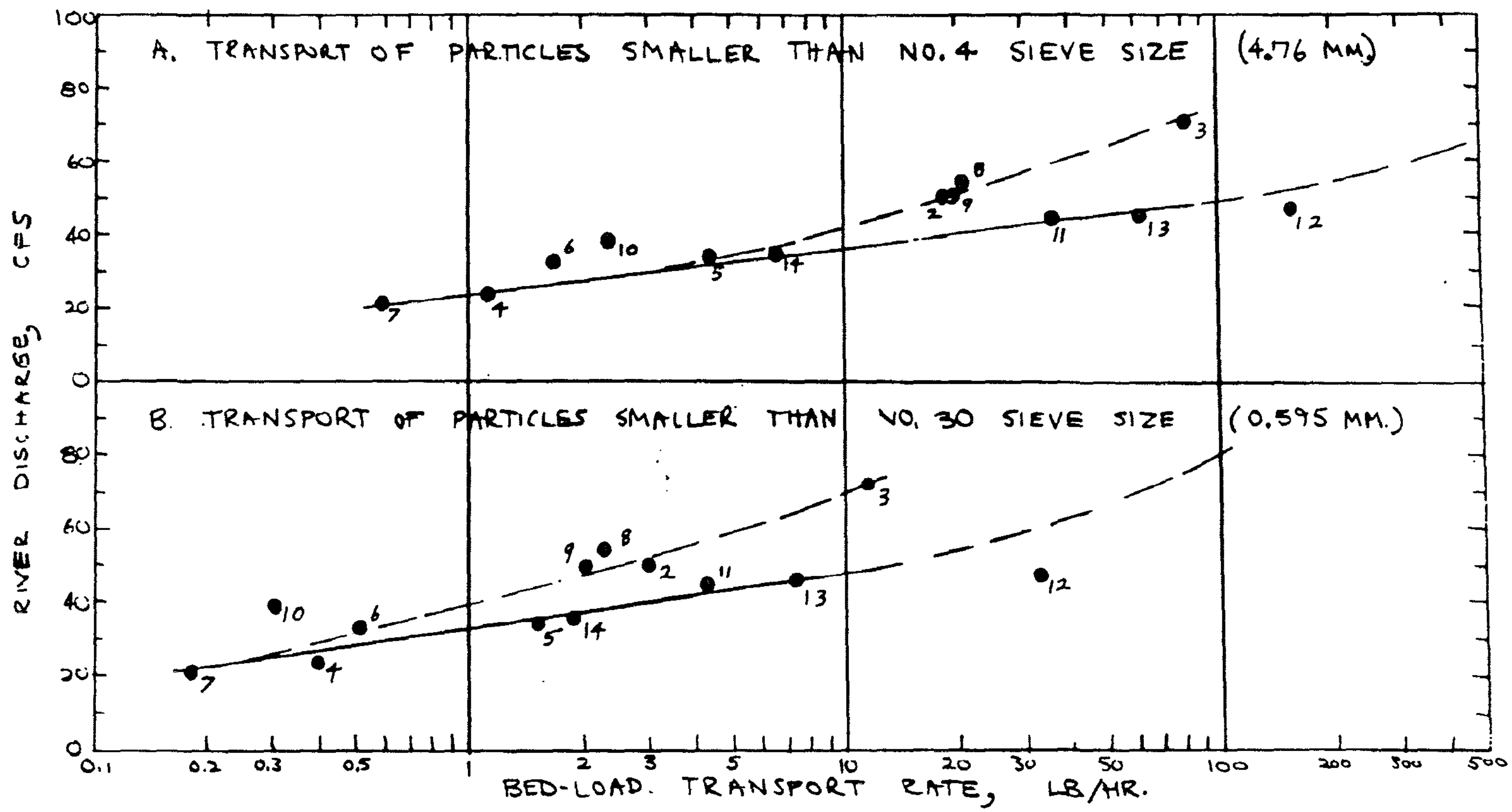

Figure 32. Bed-load transport for sand-size material, Oak Creek, winter 1969-70.

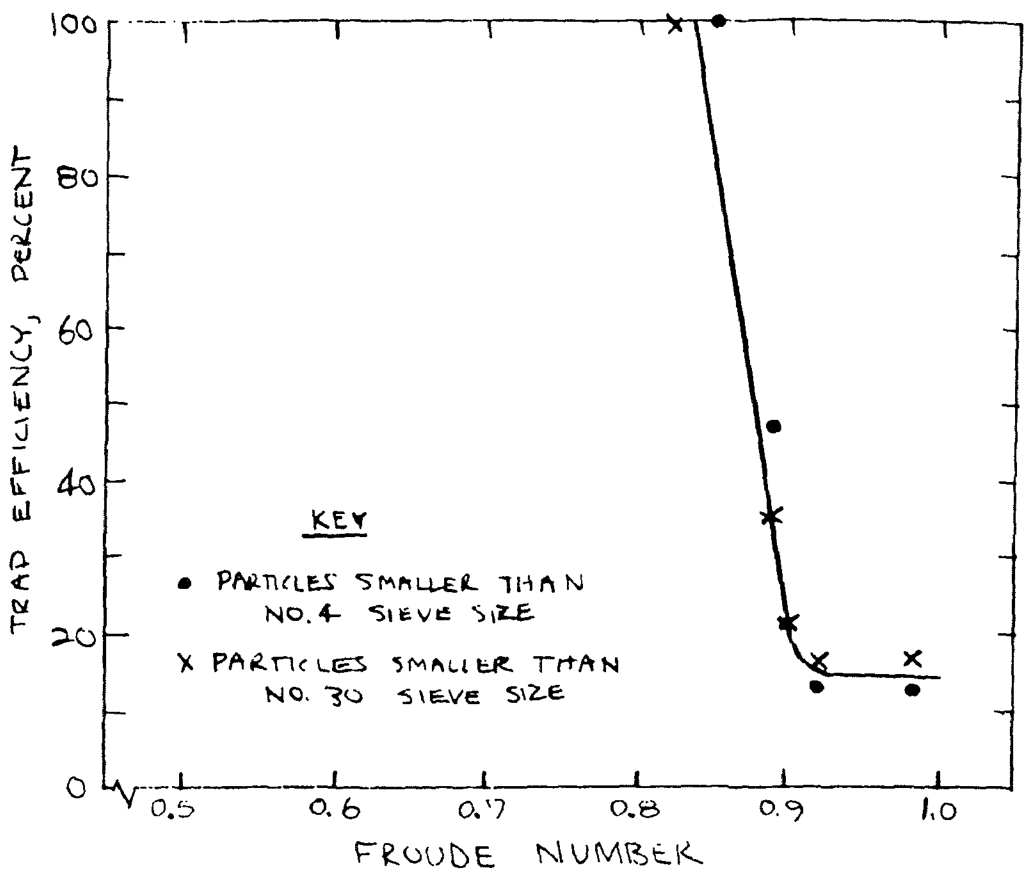

Figure 33. Trap efficiency for sand-size bed-load material, Oak Creek, winter 1969-70.

transport rate for the five samples are given on Table 15 and the adjusted total bed-load transport rates are plotted on Figure 34. In comparison with the unadjusted data of Figure 30A, the scatter is much reduced. Sample 12 still appears to have a bed-load transport rate that is too high for the discharge. Sample 12 was collected just after a period when the vortex and backup troughs were filled and then cleaned out just before opening the sampling gate. Opening the gate probably caused material temporarily stored upstream of the trap (deposited in the backwater of the filled troughs) to scour out because of increased shear velocities at the streambed. (Normally, material would not be stored upstream of the trap in such a manner, but deposition of material in the troughs and on the downstream edge of the weir/trap structure had raised the effective bed level. These deposits were removed, which lowered the bed level before the gates were opened.) If the plotted location of sample 12 is assumed wrong on Figure 34, the appropriate correction to make, based upon the argument of excessive scour because of adjustment of bed level, would reduce the bed-load transport and draw the plotted point closer to the curve.

The curve for the adjusted total bed-load transport rate is superimposed on the curves for bed-load transport of material coarser than 1 1/2 inch and No. 4 sieve size in Figure 35. It is evident that the convergence of the unadjusted data of Figure 31 has been accounted for by the correction for trap efficiency of sand-size particles.

The data for adjusted total bed-load transport in Oak Creek have been rearranged in Figure 36 to present the "unit" bed-load transport rate, or transport rate per unit of discharge (1 cfs), as a function of streamflow. This curve can be conveniently used to estimate the total bed-load transport during a storm-runoff period (see discussion in a following section).

The adjusted data on total bed-load transport are presented on an arithmetic scale in Figure 37, in comparison with the logarithmic scale used in Figure 34. This form of plotting permits an estimate to be made of the critical discharge for initiation of bed-load transport. This was done on Figure 37 by extending the linear portion of the bed-load transport curve to the ordinate axis at zero bed-load transport. The critical discharge for incipient motion was found to be 43 cfs.

This critical discharge would be relative to the armor layer, which has a fairly uniform particle size (low index of uniformity). Using this discharge with a channel slope of 0.009 ft/ft from Table 4, channel width and depth from Figure 13, and approximate mean particle diameter of 2 1/4 inches (57 mm) from Table 9, an estimation of the critical shear stress was made and compared to data given in Figure 6-11 (p. 170) of the text by Leopold, Wolman, and Miller (1964). A

Table 15

ADJUSTMENT OF BED-LOAD TRANSPORT DATA FOR TRAP EFFICIENCY OF SAND-SIZE MATERIAL, OAK CREEK, WINTER 1969-1970

Sample Identity Number	Total Bed-Load Transport, lb / hr		Bed-load Transport for Material Smaller than No. 4 Sieve Size, lb / hr	
	Measured	Adjusted	Measured	Adjusted
2	26.0	127	18.6	120
3	441	1059	81.3	699
8	101	331	21.0	251
9	82.9	183	19.7	120
10	5.7	17.7	2.4	14

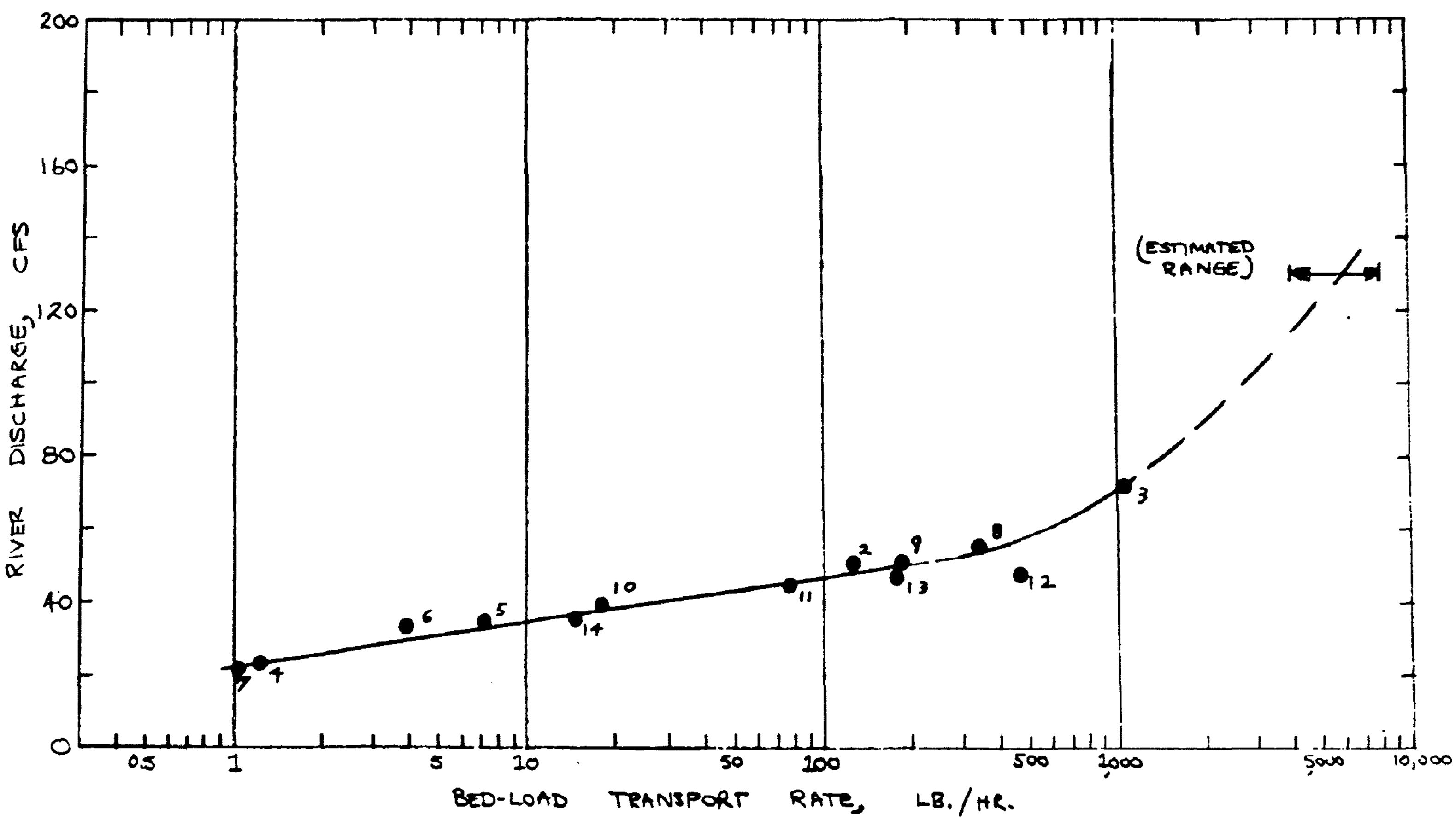

Figure 34. Adjusted total bed-load transport rate, Oak Creek, winter 1969-70.

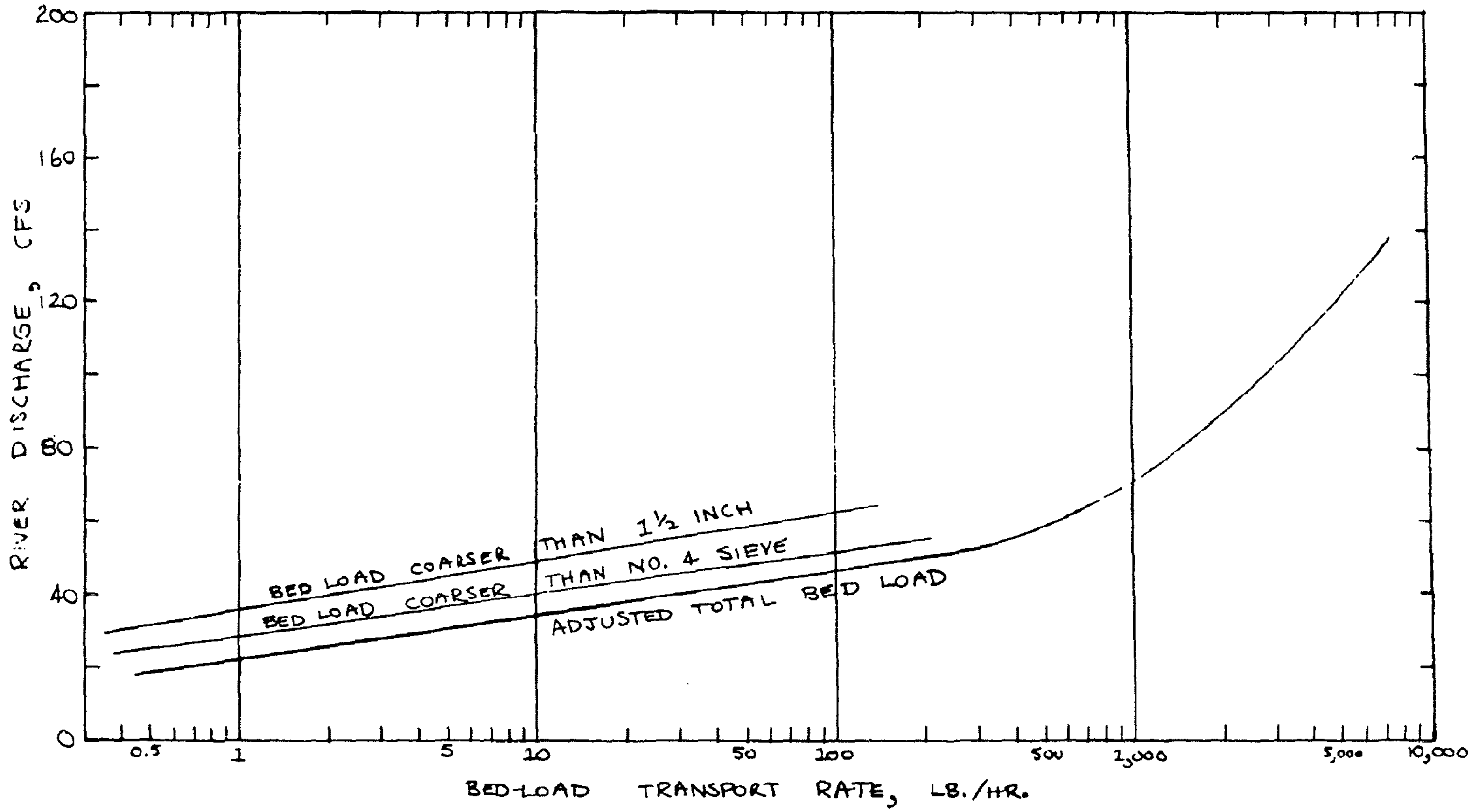

Figure 35. Superimposed adjusted bed-load transport curves, Oak Creek, winter 1969-70.

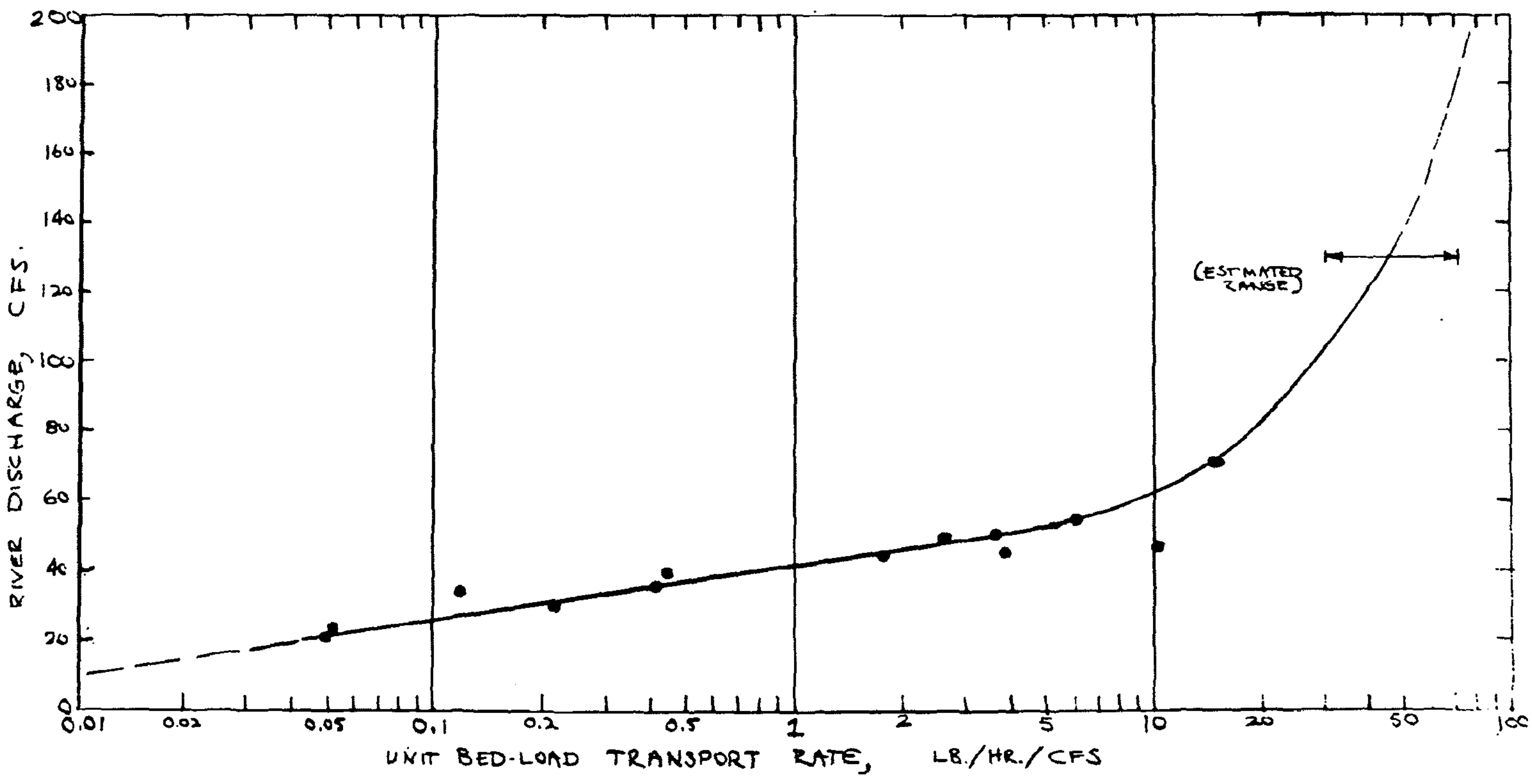

Figure 36. Unit bed-load transport rate as function of discharge, Oak Creek, winter 1969-70.

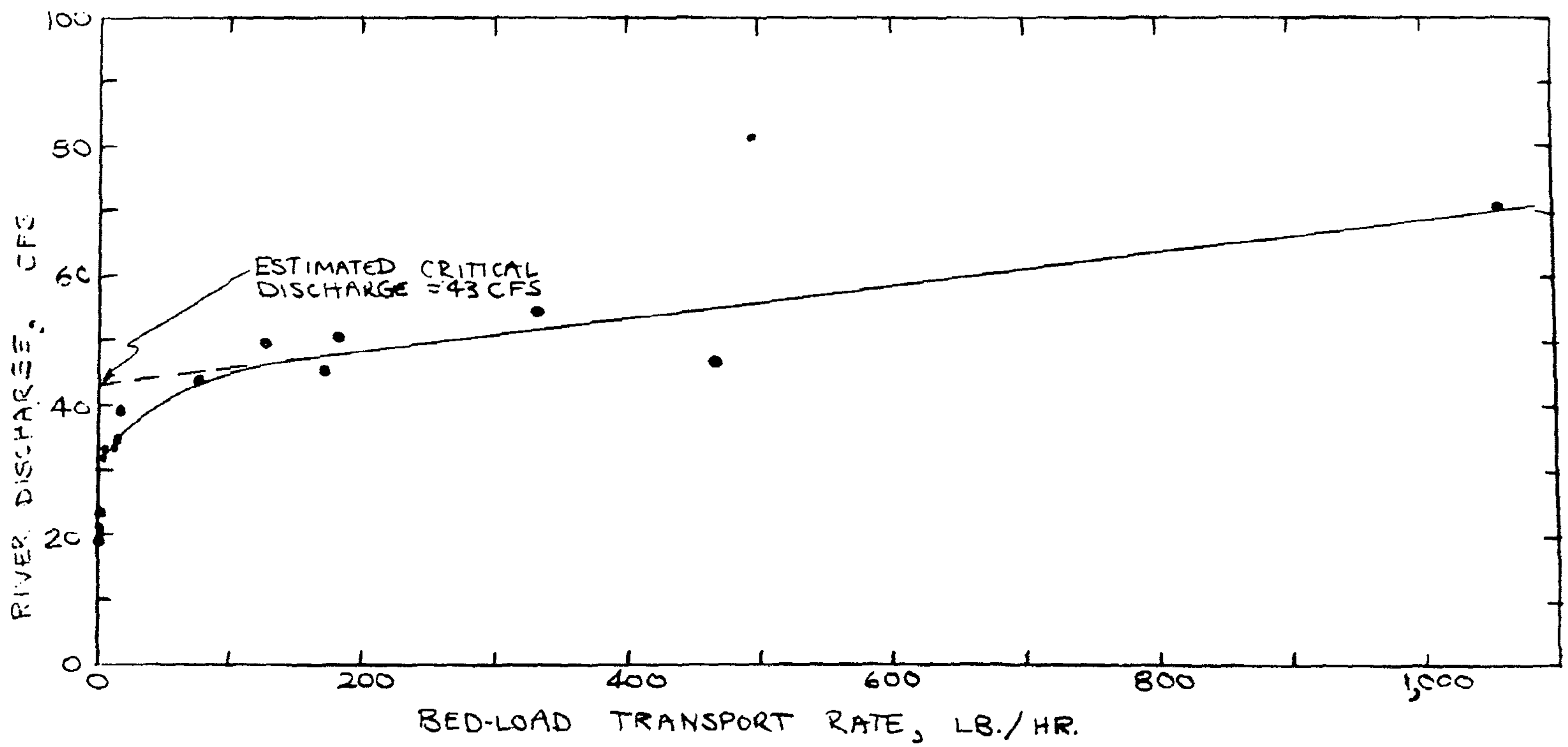

Figure 37. Estimated critical discharge to initiate bed-load transport near Oak Creek weir/trap structure.

portion of that figure has been reproduced in Figure 38 with the calculated point for Oak Creek armor material added (a calculated critical shear stress of about 0.6 pound per square foot). The plotted point from the Oak Creek data lies well within the range of other data shown in the figure.

Several measures of particle size were given in Table 13 for the bed-load samples. These characterizing diameters and derived parameters are plotted in relation to their corresponding bed-load transport rates in Figure 39. The diagrams are based on the measured data, and are in error because they lack any trap efficiency correction. Even with these errors, certain tentative conclusions for Oak Creek bed-load can be drawn. These are:

1. The mean size of the bed-load (D_{50}) increased with transport rate to a limiting value of about 14 mm (0.55 inch). (The points above the line would shift to the right and down after correction for trap efficiency.) In comparison, the mean size of the material below the armor layer was estimated to be about 20 mm (Table 10). Hence, the bed load was "finer" than the streambed from which it derived.
2. Except at low transport rates, the index of uniformity was in the range 10 to 20. In comparison, measurements of the bed material indicated the armor layer had a uniformity index of 2.3 to 2.8 and the bed material a uniformity index of 5 to 8. Hence, the bed load was less uniform than the streambed.
3. The D_{65} size also approached a constant value of from 20 to 30 mm. Although D_{65} is considered an index of bed roughness, its exact significance for moving material is uncertain.
4. The maximum size as indicated by D_{95} did not increase with transport rate but reached a constant value of from 40 to 60 mm.

At this point, no further conclusions can be made without further analysis (of the type planned for the third year of the original project).

Oak Creek Painted Gravel Experiment

To obtain some idea of the distance that individual particles move in Oak Creek during a period of high flow, a collection of rocks was painted yellow and placed in the stream. They were located on a bar at the upper end of the instrumented reach (at section 18). In this experiment, five nominal sizes were used: 2 inch, 1 1/2 inch, 3/4 inch, and 0.19 inch (No. 4 sieve size). Each particle was weighed and all were placed in a group on the surface of the streambed. Upon placement, the smaller particles tended to fall between the particles of the natural armor layer.

On 16-17 February 1970, an isolated storm-runoff event took place that moved bed material. After the flow subsided, a reconnaissance was made to locate the yellow rock. A summary of the results of the experiment is presented in Table 16. Graphs of the distance moved

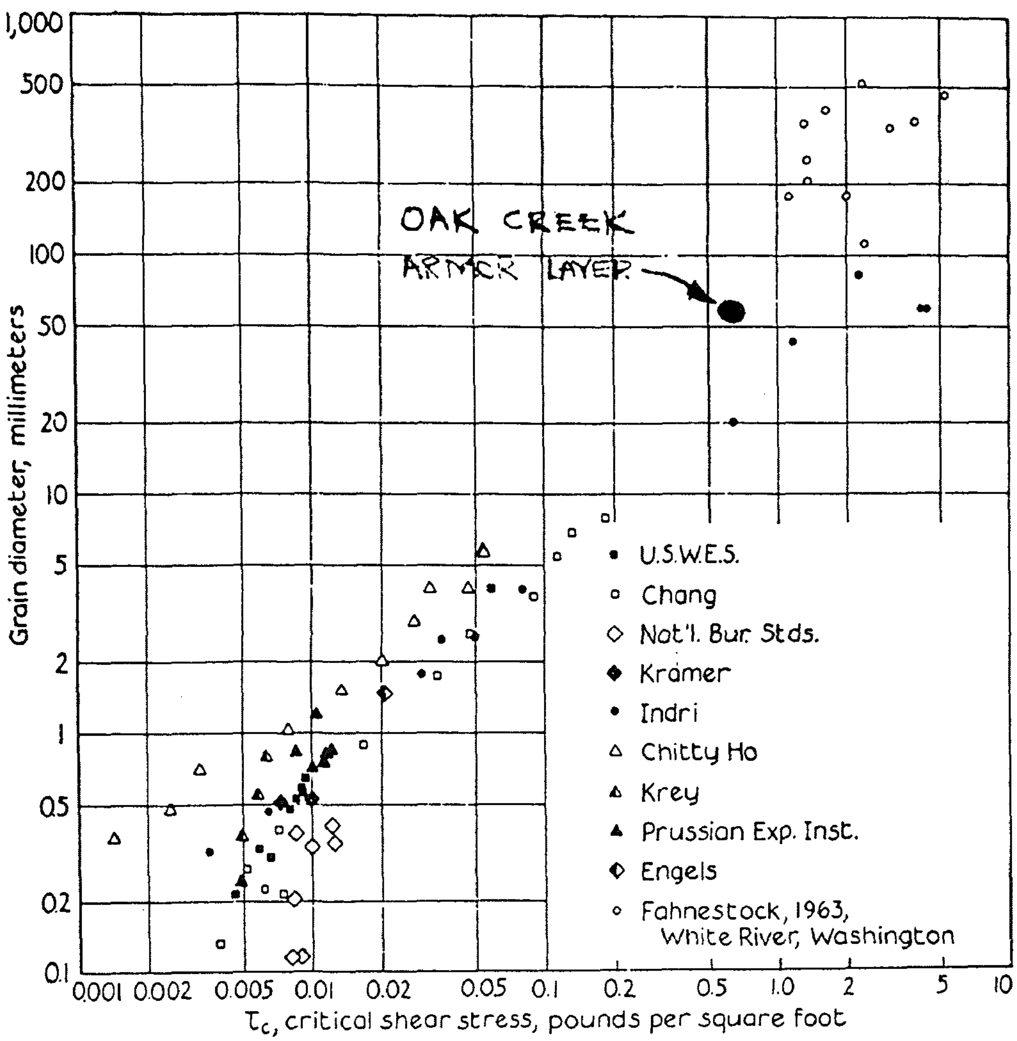

Figure 38. Laboratory and field data on criticalshear stress required to initiate movement of particles (after Leopold, Wolman and Miller, 1964, Figure 6-11, p. 170).

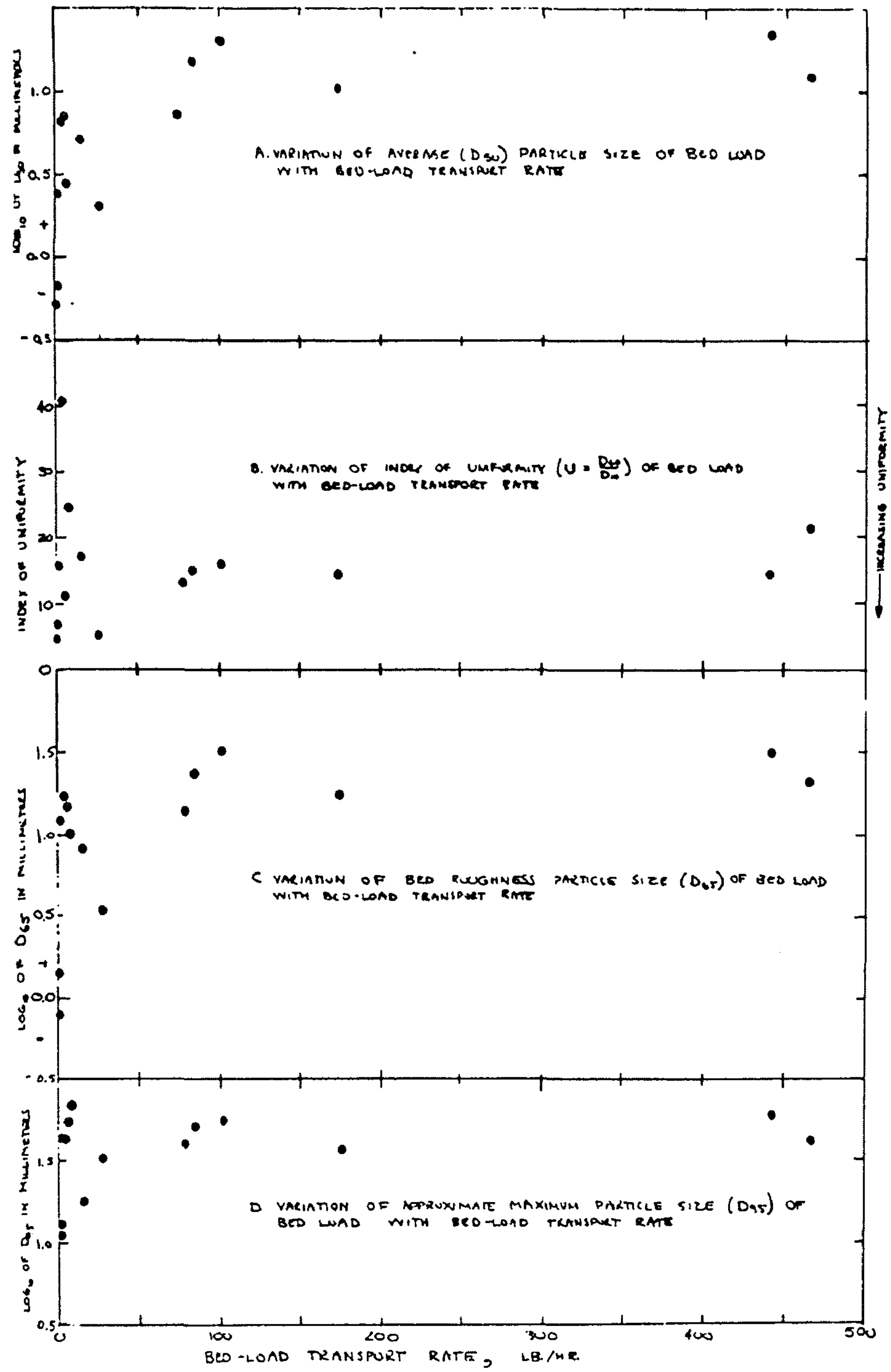

Figure 39. Variations in characterizing particle sizes for bed-load samples as function of bed-load transport rate, Oak Creek, winter 1969-70.

Table 16

PAINTED-GRAVEL EXPERIMENT, OAK CREEK, 16-17 FEBRUARY 1970

Particle Size, Inches	Fraction of Sample		Mean Weight, gm		Distance Moved, feet(1)	Particle Velocity, ft/hr(2)
	Moved	Recovered	Placed	Recovered		
2	0.83	0.42	370	276	160	6.7
1 1/2	0.75	0.33	146	144	160	6.7
3/4	0.92	0.33	44	50	112	4.7
3/8	0.92	0.25	6.6	6.6	125	5.2
0.19	1.00	0	0.7	---	?	?

(1) The mean distance moved for all recovered particles of the indicated size which actually did move.

(2) Calculated assuming that particles only moved at discharges exceeding 40 cfs, based on critical discharge for incipient motion discussed in connection with Figure 37. The time interval for such movement was 24 hours.

and the probability of movement are given in Figure 40 as a function of particle weight.

Because of the low percentage of particles recovered, very little information on the distance moved can be extracted from the data. The data suggest that the larger particles move farther and faster than the smaller particles. The smaller particles were found on the bottom of pools and the larger particles on bars or transitions between bars and pools. This fact suggests that the larger particles are carried rapidly through pool areas, but the smaller particles may deposit in such pools and be protected from further disturbance. The grain-size data for the streambed support this observation, as the bed was somewhat finer in composition in pools than on bars.

Another interesting result shown in Figure 40 is that the probability of movement increases as the particle size decreases (for the flow condition at the site where the rocks were placed), even though some of the smaller particles were "protected" by the larger particles.

Importance of Bed Load in Total Sediment Yield

Sufficient information on sediment transport at Oak Creek was obtained to develop some rather tentative relations for suspended-load and bed-load transport. These were presented in Figures 25B and 36, respectively. From these two curves, a third relationship can be derived that expresses the ratio of bed-load to suspended-load transport rate as a function of streamflow. This relationship is presented in Figure 41. The ratio increases with discharge toward some limiting value, which suggests that at quite large flows the bed load approaches but does not quite match the suspended load in magnitude. At very small flows, the ratio becomes very small as the bed load approaches zero.

To obtain some idea of the importance of bed load during a storm runoff event, three runoff events were selected that exhibited low, intermediate, and high peak discharges. The curves in Figures 25B and 36 were used to estimate the total amount of sediment transported past the gaging station during the runoff event. The hydrographs used are shown in Figures 42A, 42B, and 42C. A summary of the results obtained is given in Table 17.

The data in Table 17 suggest that the bed load is of minor importance for low-peak runoff events, but that the importance of the bed load increases as the peak discharge increases. This relation suggests that a change in land use that would increase only the peak flow would also increase the importance of the bed load. An increase in bed-load transport, even for a couple of years, could result in stream-channel changes that would persist long after the peak flows had returned to the previous levels.

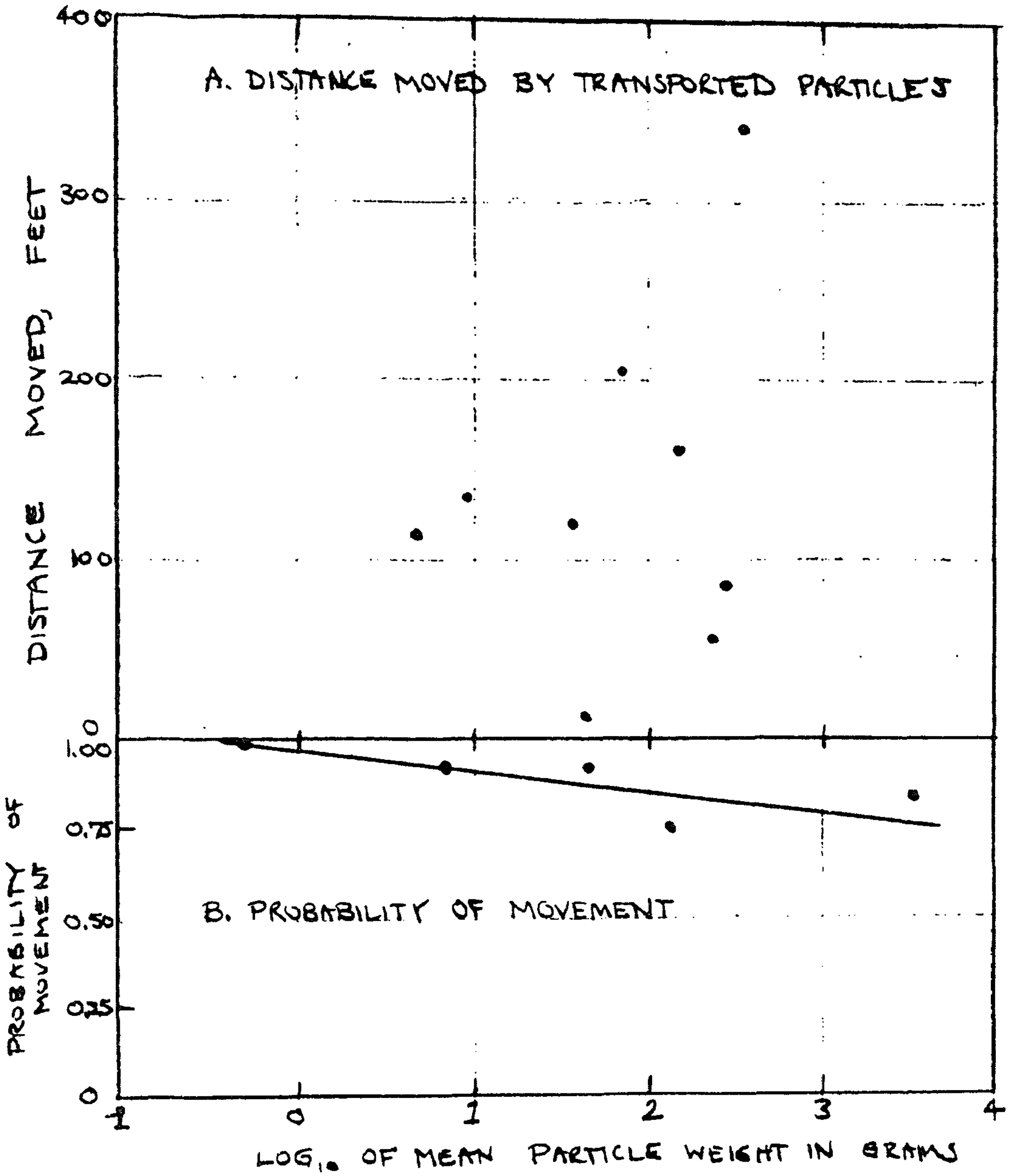

Figure 40. Distance moved and probability of movement in painted-gravel experiment, Oak Creek, 16-17 February 1970.

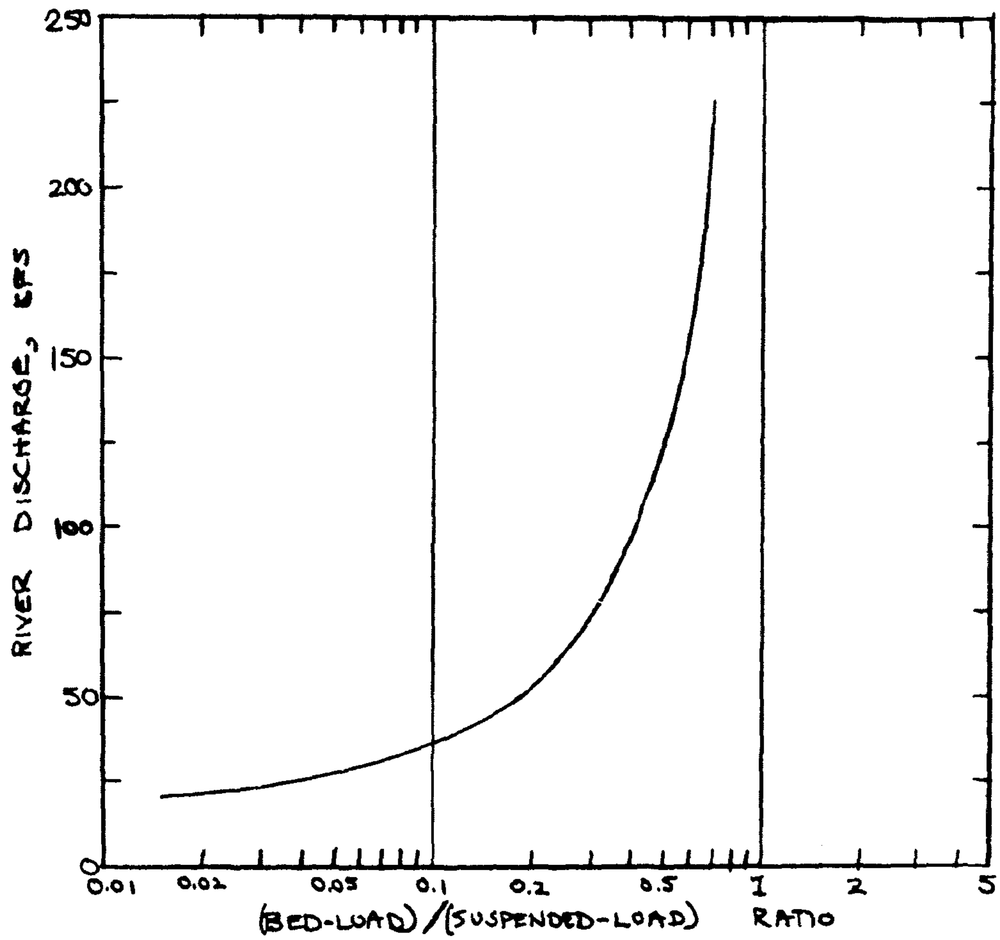

Figure 41. Bed-load/suspended-load relation as function of discharge, Oak Creek, winter 1969-70.

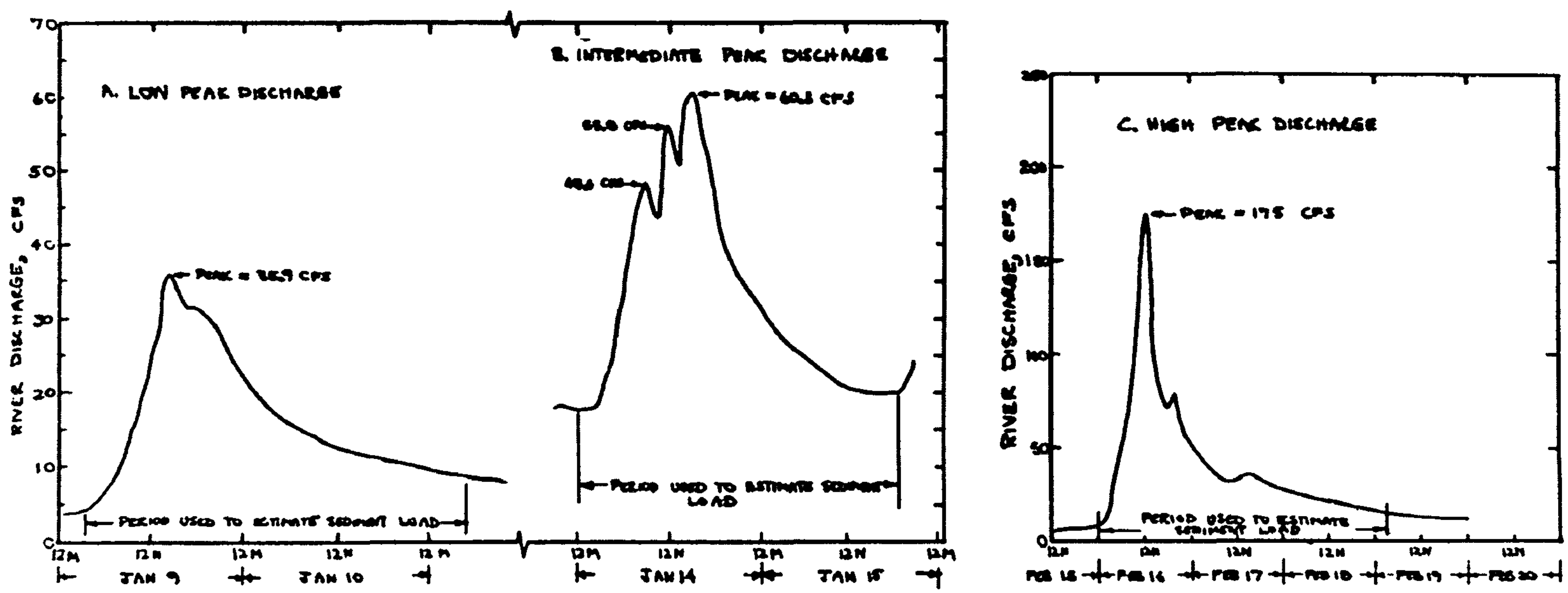

Figure 42. Hydrographs used to estimate sediment yield, Oak Creek, winter 1969-70.

Table 17

BED LOAD, SUSPENDED LOAD, AND TOTAL SEDIMENT YIELD FOR STORM-RUNOFF PERIODS, OAK CREEK, WINTER 1969-1970

Peak Discharge, cfs	Bed-Load Transport, lb.	Suspended-Load Transport, lb.	Total Sediment Yield, lb.	Percent of Total Yield as Bed-Load	Bed-Load / suspended-Load Ratio
36 (low peak)	24	2,400	2,424	<1	0.01
60 (intermediate peak)	3,070	18,430	21,500	14	0.17
175 (high peak)	50,800	142,900	193,700	26	0.36

SECTION X

BED MEASUREMENTS, ALSEA EXPERIMENTAL WATERSHEDS

Dear Creek Streambed Materials

Because considerable work has been done to measure suspended sediment discharges in the Alsea experimental watersheds, it was thought desirable to obtain some idea of the bed materials in an alluvial area on one of the basins. Therefore, a portion of Deer Creek was sampled. Sampling was done where the creek flows through an open meadow area and in a reach of the stream where the sediment sizes and type (except at one sampling location) are controlled by the stream itself and not by the movement of material into the channel by mass movements. The one exception (the sampling section where hydraulic flows do not control the sediment properties) was just upstream of a "channel-control" reach where mass movement into the stream is possibly important. This section (18+00) had numerous boulders in the stream and the bordering valley slopes are steep close to the stream. All of the samples were obtained on low bars at bends in the stream, with similar locations used at each bar to provide consistent sampling for later comparisons of data.

The sampling technique was to use an apparatus similar to the one described by McNeil and Ahnell (1964). The procedure was to set a 6-inch-diameter pipe on the bed surface, remove the armor layer and save it in a separate sample bag, and then sample the bed material to a depth of about eight inches. The material was removed from the pipe into a concentric holding barrel welded to the pipe and the pipe was advanced into the streambed as the material was removed. Using this procedure, little material was lost and any lost material was probably smaller than No. 100 sieve size. Because the sample of armor material collected at each point with the 6-inch pipe was too small for reliable analysis, additional samples were composited to increase the sample size, all such samples being obtained from the armor layer adjacent to the main sampling location.

Particle-size data for the samples collected from Deer Creek are presented in Table 18. Graphs of mean particle size and of the variation of the fraction of bed material coarser than 3/4 inch as a function of distance are presented in Figure 43.

The sampled bed materials have an upper size limit of less than three inches. A distinct difference is evident between the materials in the surface layer of the streambed and those beneath. Except at station 18+00, there is a distinct tendency for particle size to decrease in the downstream direction. Presumably this trend is attributable to particle breakdown during periods of bed-load transport--the sedimentary-type rock at the Alsea basins does not appear to produce gravel as durable as that from the sedimentary and basaltic rock in the Oak Creek watershed. The increase in particle size at station 18+00

Table 18

DEER CREEK STREAMBED MATERIALS IN SELECTED ALLUVIAL AREAS.

	Fraction of Sample Retained by Indicated Sieve at Sampling Location											
	18+00		28+00		36+76		37+00		43+34		44+00	
Sieve Size	Armor Layer	Sub-Surface(1)	Armor Layer	Sub-Surface	Armor Layer	Sub-Surface	Armor Layer	Sub-Surface	Armor Layer	Sub-Surface	Armor Layer	Sub-Surface
3-in.	0	0	--	--	0	--	--	--	--	--	--	0
2-in.	.1645	.0969	--	--	.1501	0	0	--	--	0	0	.1641
1 1/2-in.	.2751	.0969	0	0	.3564	.0903	.1422	0	0	.1769	.3020	.2135
3/4-in.	.7718	.3411	.3756	.0907	.8840	.2635	.6483	.2928	.8241	.3856	.7786	.4906
3/8-in.	.9660	.5559	.5990	.3092	.9636	.4649	.8751	.5145	.9229	.5290	.9233	.6720
No. 4	.9928	.7167	.7304	.4807	.9852	.6457	.9469	.6519	.9568	.6506	.9652	.7952
No. 8	.9963	.7948	.8191	.5871	.9937	.7586	.9749	.7359	.9763	.7532	.9790	.8408
No. 16	.9970	.8346	.8664	.6541	.9962	.8183	.9832	.7916	.9858	.8315	.9843	.8608
No. 30	.9974	.8692	.9133	.7228	.9972	.8733	.9872	.8477	.9911	.8959	.9890	.8878
No. 50	.9980	.9429	.9751	.8924	.9985	.9618	.9937	.9543	.9951	.9528	.9941	.9558
No. 100	.9988	.9872	.9939	.9670	.9994	.9885	.9973	.9859	.9974	.9812	.9973	.9855
Pan	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.000
D_{50}, MM	30	4	16	4	38	8.5	27	10	25	11	30	18
D_{65} MM'	36	9.6	20	8	39	17	31	16	30	21	35	28
D_{60}, MM'	35	7.6	18	6.8	39	14	30	15	28	18	34	22
D_{10}, MM'	14	0.24	0.88	0.27	18	0.55	8	0.38	11	0.58	12	0.65
U(2)	2.5	32.6	20.5	25.2	2.16	25.4	3.75	39.5	2.55	31.0	2.84	33.8

(1) Sampled to a depth of 8 inches after removal of armor (surface) layer.

(2) $U = D_{60} / D_{10}$

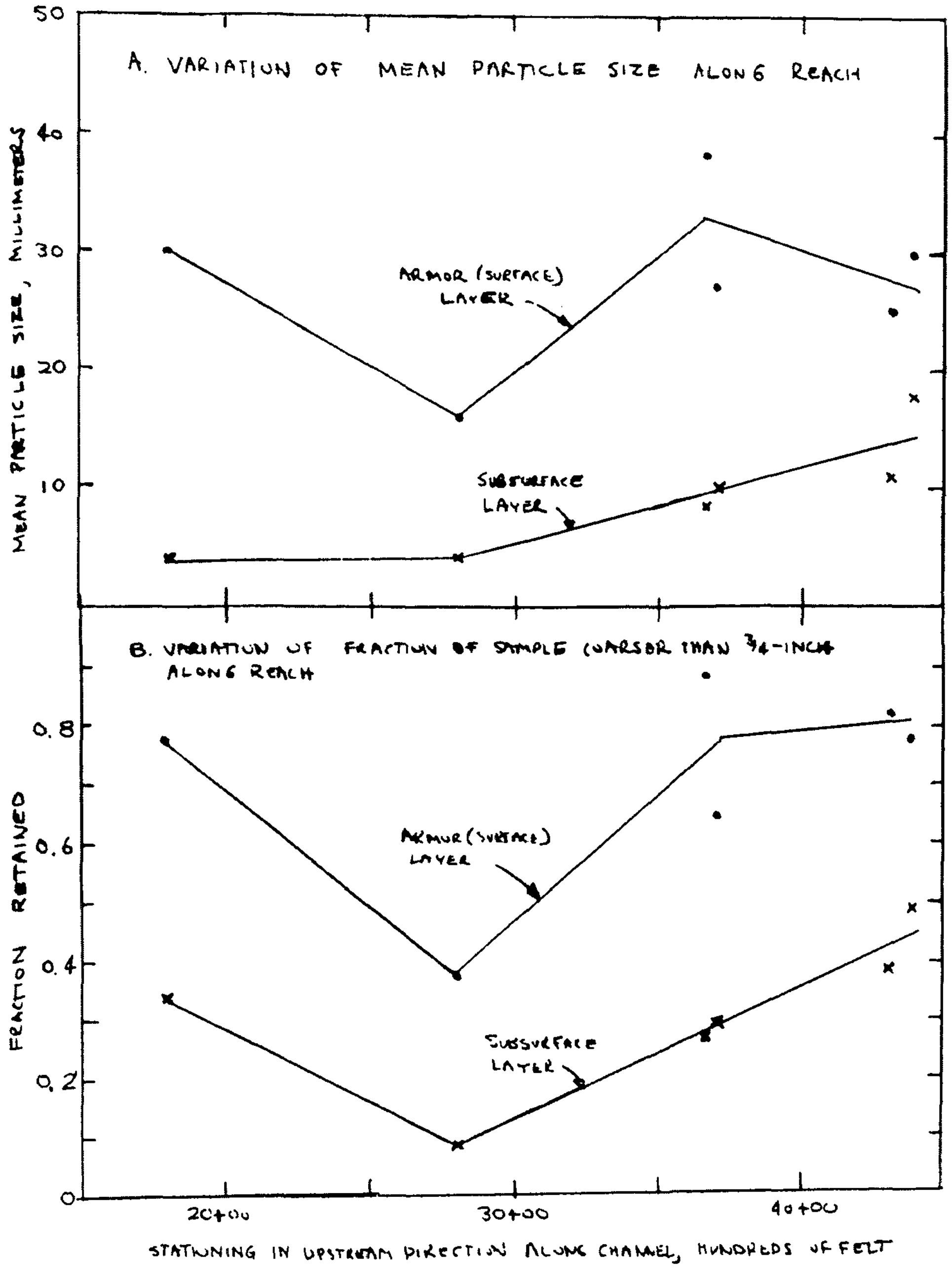

Figure 43. Streambed material characteristics, selected alluvial portions of Deer Creek.

may be attributable to mass movements of sediment adjacent to the channel, which locally contributes large particles to the streambed.

Implications of Oak Creek Data for Deer Creek

Deer Creek has an armored streambed but with somewhat smaller surface material than for Oak Creek. The fact that the Deer Creek streambed has such an armoring indicates that in such reaches of the creek a critical discharge must be reached before general bed-load transport of an appreciable magnitude. Comparatively more of the bed material at the sampled Deer Creek reaches is in the sand-size range. Therefore, the armor layer in Deer Creek may exert a stronger controlling effect upon the suspended load at high streamflows, when the finer bed material may actually move in suspension. Further examination is required of the Alsea experimental basins and of data already collected before other implications of Oak Creek research can be offered with adequate confidence.

SECTION XI

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APPENDIX

The Alsea Watershed Study was launched as a broadly interdisciplinary undertaking and formed the backdrop for most of the work reported here. The Alsea Project is a case study utilizing experimental watersheds located in the Oregon Coast Range. Many investigators, agencies, and members of the University staff attempted to pool resources to study not only land use but also the physical, chemical, and biological effects of logging operations in an area where timber, water, and fisheries are all important resources.

The effort reported here is only part of a progression of work already reported from the Alsea and related studies. Some of this published research is to be found referenced at the end of the chapters.

This report clearly shows the shift in research from the case study approach, such as for temperature and sediment effects of logging, to that of studying pertinent processes. The type of research contribution each has made is clearly seen. The case studies on water temperature provided orders of magnitude of specific treatment effects, while process studies provided insight for more universal adaptation and prediction. Both were complementary. Water temperature related to cover conditions is currently being studied by Dr. Brown under another grant from the Environmental Protection Agency.

A similar research approach was undertaken with sediment production and land use. First the case study was undertaken, then a shift to a study of processes to provide predictions in small streams and watersheds. This proved to be a far more difficult undertaking. The original proposal for the work contained in this report was for a three-year period; hence, the report should be examined in this context. Dr. Hall's work on biological effects of water temperature changes was terminated and then transferred from the conjunctive effort and therefore will be reported elsewhere. Discontinuance of financial support for the sediment project at the end of the second year also prevented accomplishment of all original objectives, yet substantial contributions are reported.

Chapters I and II have been published elsewhere and Chapter V will appear in a national journal in the near future.

The project leaders of the studies undertaken, Drs. Brown, Hall, and Klingeman, undertook to meet their objectives diligently. The results reported here along with corollary efforts should contribute in a major way to our understanding of environmental change from logging the watersheds of small streams.

James T. Krygier
Principal Investigator

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Chapters I and V were authored by Dr. George W. Brown and Dr. James T. Krygier, School of Forestry, Oregon State University; Chapters II, III, and IV were by Dr. George W. Brown; and Chapter VI was authored by Dr. Peter C. Klingeman, School of Engineering, Oregon State University.

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*Water Pollution Sources

27 *Abstract*

A number of studies were undertaken related to effects of clearcut logging on water quality and the process affected in small streams.

Water temperature studied before and after logging was increased significantly where stream cover was removed. Energy balances of small streams were measured and predictive models were developed.

Road building significantly increased sediment yield in clearcut and patch cut watersheds. Logging itself was not an important sediment contributor.

Methods for sampling bed load and suspended sediment were developed. Bed load constituted 70 percent of suspended load during peak discharges.

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