GLACIER RUNOFF AND
SEDIMENT TRANSPORT AND DEPOSITION
EKLUTNA LAKE BASIN, ALASKA

by Timothy P. Brabets

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Water-Resources Investigations Report 92-4132

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
acre-foot (acre-ft)	1,233	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per day [(ft^3/s)/d]	0.02832	cubic meter per second per day
ton, short	0.9072	megagram
ton per square mile (ton/mi^2)	0.3503	megagram per square kilometer
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter
million gallons per day (Mgal/d)	0.04381	cubic meter per second

degree Fahrenheit ($^\circ$F)	$^\circ C = 5/9 \times (^\circ F\text{-}32)$	degree Celsius ($^\circ$C)

Other abbreviations in this report are:

g/cm^3, gram per cubic centimeter
mg/L, milligram per liter

Sea level:

In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929), a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

Two streams in the Eklutna Lake basin, the East Fork Eklutna Creek and the West Fork Eklutna Creek, provided more than 80 percent of the water to Eklutna Lake during the period of study, 1985-88. The East Fork Eklutna Creek drains an area of 38.2 square miles, of which 7.6 square miles are glaciers; the West Fork Eklutna Creek drains an area of 25.4 square miles, of which 12.2 square miles are glaciers.

For water years 1986, 1987, and 1988, total runoff ranged from 43 to 53 inches in the East Fork Eklutna basin and from 55 to 58 inches in the West Fork Eklutna basin. More than 75 percent of the runoff from the East Fork Eklutna basin and more than 85 percent of the runoff from the West Fork Eklutna basin occurred from June to September. The principal components of runoff were snowmelt (52-64 percent), rainfall (27-33 percent), and icemelt (6-19 percent).

From 1985-87, total annual sediment load transported past the East Fork and West Fork Eklutna Creek gaging stations ranged from 22,300 to 36,500 tons and from 46,700 to 54,600 tons, respectively. Bedload constitutes between 14 and 26 percent of the total sediment transported past the East Fork station and between 7 and 10 percent of the total sediment transported past the West Fork station. Most of the suspended sediment was composed of silt and clay; most of the bedload consisted of coarse sand and fine gravel.

Eklutna Lake has an active storage capacity of 138,000 acre-feet at a water-surface altitude of 860.00 feet above sea level. Sedimentation in the lake is characterized by delta progradation and river plume dispersion. Coarse sediment accumulates at a rate of about 5 acre-feet per year near the delta of the lake and suspended sediment accumulates at a rate of 74 acre-feet per year throughout the lake. A distinct interflow (density current) is present in the lake from late June through September.

Two U.S. Geological Survey computer-based models were used in this study: the Precipitation-Runoff Modeling System (PRMS) and a storage frequency model. Although PRMS was able to predict the amount of icemelt, it underpredicted daily runoff. The storage frequency model indicates that at an outflow rate of 450 cubic feet per second, the probability of the storage capacity of Eklutna Lake being exceeded is less than 10 percent, and that May and June are the months when the capacity would most likely be exceeded.

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INTRODUCTION

In March 1974, Congress authorized the Metropolitan Anchorage Urban Study (MAUS) to identify and solve the water and related land resources problems and development needs of the Anchorage metropolitan area. One finding of MAUS was the lack of a developed and dependable water supply for the projected future population of the Municipality of Anchorage (U.S. Army Corps of Engineers, 1979). The MAUS further recommended that diversion of water from Eklutna Lake (fig. 1) would be the most feasible solution to solving Anchorage's long-term water-supply problem. Thus, in 1984 construction began on a $200 million project to bring Eklutna Lake water to Anchorage. This project consisted of a 32-mile gravity-feed pipeline system, two energy-recovery stations, a water-treatment plant and clearwell, and an 8,500-foot tunnel. The project was completed in 1988.

Communities along the Eklutna pipeline such as Peters Creek, Chugiak, and Eagle River will most likely use Eklutna Lake water by the year 2000. Also, it is expected that water use in the Anchorage area will increase, placing additional demands on the municipality's public-water supply. Although the hydrologic data that were available during the MAUS study provided sufficient information to indicate that Eklutna Lake would provide enough water for the near future, some more specific questions remained. For example, the rate and volume of runoff from the glacierized and snow-covered areas of Eklutna Lake basin vary both seasonally and annually, which would affect operation of a water-supply reservoir. Additionally, glacier-fed streams have high concentrations of suspended sediment during the snowmelt and icemelt seasons, which would require special operating procedures for a water-treatment plant supplied by the lake. Sedimentation on the lake bottom could reduce the storage capacity of the lake.

Thus, in 1985, the U.S. Geological Survey, in cooperation with the Municipality of Anchorage, began a 4-year study of the glacial runoff and sedimentation characteristics of Eklutna Lake.

Purpose and Scope

This report contains the results of the study of the Eklutna Lake basin. The study had the following objectives: (1) to determine the timing and amount of runoff from rainfall, snowmelt, and icemelt; (2) to determine the amount of sediment that enters Eklutna Lake and how the sediment (both suspended and bed) moves into, within, and out of Eklutna Lake; and (3) to determine the storage characteristics of Eklutna Lake.

Methods of Study

To accomplish the study objectives, the following approach was taken. Intensive field work was done on Eklutna Glacier. This included digging snow pits on the glacier to determine snow density and water equivalent at various locations and at different times. Stakes were installed at different locations on the glacier (plate 1) to allow measurement of melt and accumulation of ice and snow. A climatological station was installed on the glacier (plate 1) to collect solar radiation, air temperature, precipitation, wind speed, and wind direction data. These data were also used to define the accumulation and melting characteristics of snow and ice on Eklutna Glacier and surrounding glaciers and snowfields.

Streamflow information (U.S. Geological Survey, 1986-89) was collected at the major inflow streams to Eklutna Lake: East Fork Eklutna Creek (gaging station No. 15277600) and West Fork Eklutna Creek (gaging station No. 15277800) (plate 1). The data were used to determine the quantity of water that enters Eklutna Lake and the storage characteristics of
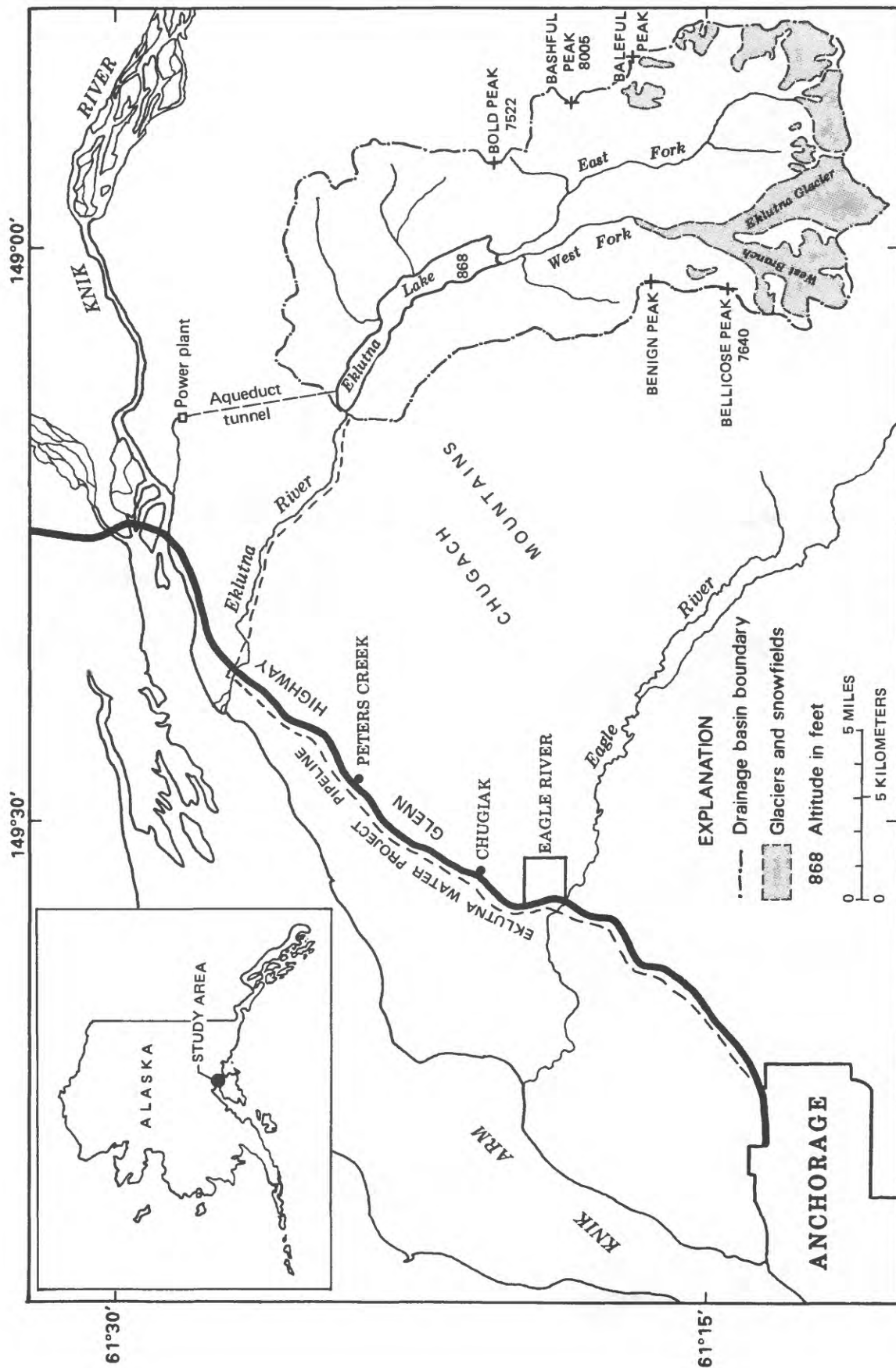
Figure 1.--Eklutna Lake and vicinity.

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the lake. Precipitation and air temperature data were also collected at these stations to detect climatological differences between the two basins and at different altitudes. Bedload and suspended-sediment data were collected to determine the total quantity of sediment entering Eklutna Lake.

Bathymetric profiles of Eklutna Lake were made to determine lake volume and to locate sediment deposition areas (deltas, channel deposits, areas of uniform sediment deposits). Light-transmissivity profiles were made to identify and delineate density plumes within the lake. Lake levels were monitored at a site (plate 1) (station No. 15278000) and were used in storage analysis. Historical information, such as inflow, lake levels, and water use, was also available from the Eklutna Power Plant and from the Alaska Power Authority (now named the Alaska Energy Authority).

DESCRIPTION OF STUDY AREA

Watersheds

The Eklutna Lake drainage basin is approximately 120 mi^2 in size (plate 1). Eklutna Lake (fig. 2) is a long, narrow, deep, glacially formed lake. Near the lower end of the lake, an intake structure and tunnel divert water from the lake to the Alaska Power Administration's Eklutna Power Project and the Municipality's Eklutna Water Project. The lake surface altitude annually ranges from 825 to 870 ft above sea level.

Two watersheds account for more than half of the Eklutna Lake drainage basin. The East Fork Eklutna Creek basin is 38.2 mi^2 in size, of which approximately 20 percent consists of glaciers (fig. 3). The West Fork Eklutna Creek basin is 25.4 mi^2 in size, of which about 50 percent consists of glaciers (fig. 3). Numerous small drainages, generally less than 5 mi^2 in size, constitute the remainder of the Eklutna Lake drainage.

Figure 2.--Eklutna Lake, 1987.

Surficial Geology

Both the East Fork and West Fork Eklutna basins lie entirely within the Chugach Mountains and are developed primarily in structurally complex and variably metamorphosed sedimentary and igneous rock. The topography is rugged and the glaciers are surrounded by cliffs and gullies. Vegetation in the West Fork basin is sparse whereas vegetative cover is somewhat greater in the lower part of the East Fork basin flood plain.

Alluvial deposits, consisting chiefly of gravel and sand, are present at the south end of Eklutna Lake and at the mouths of various tributaries along the lake (plate 1). Colluvial deposits, which have accumulated on slopes primarily through the action of gravity and running water, are present locally along the

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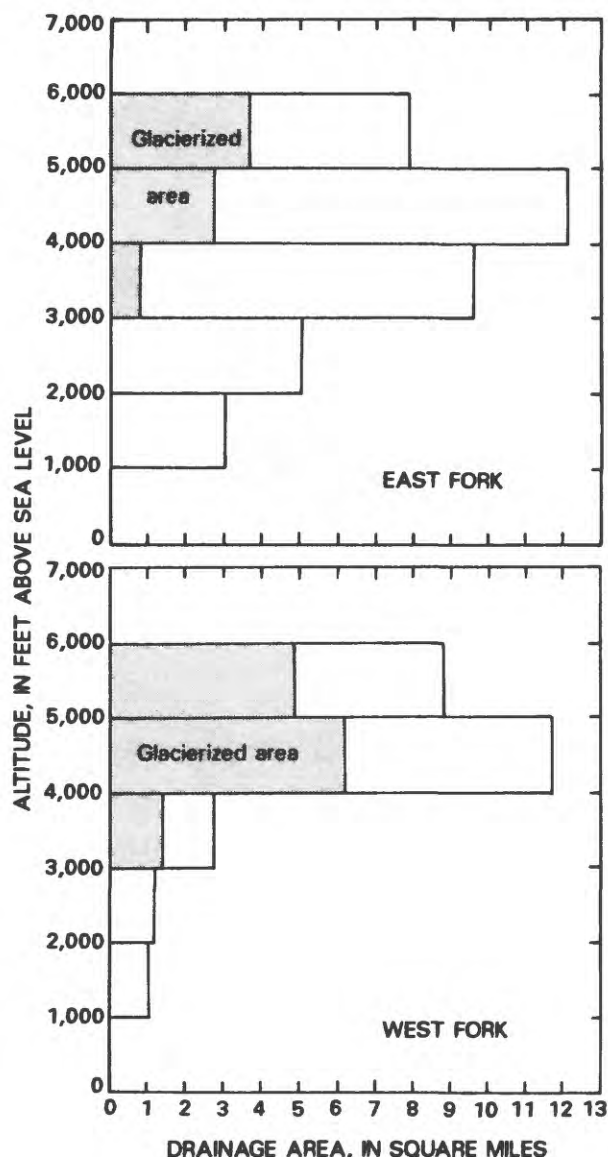
Figure 3.--Area-altitude distribution of
the East Fork and West Fork
Eklutna Creeks basins.

steep slopes in the East Fork and West Fork
Eklutna basins (plate 1). Rock glaciers and
their deposits are common in high-level cir-
ques. Thick glacial, glaciolacustrine, and gla-
cioalluvial deposits are found only in the
Eklutna River valley downstream from
Eklutna Lake.

Because surficial deposits are thin and
because impermeable bedrock dominates the

basin, ground-water storage in the study area
is probably minor. Also, runoff from these
basins from rain, snowmelt, or icemelt is
expected to be rapid because little or no infil-
tration would occur.

Surficial geology (plate 1) was mapped
between 1965 and 1988, mainly from interpre-
tation of 1:40,000 scale aerial photographs
taken in 1957 and by field investigations.
Topographic maps that were based on this
aerial photography were used to determine the
drainage areas and glacier areas of the East and
West Fork Eklutna Creeks.

Glaciers

Glaciers are located in both the East Fork
and West Fork Eklutna Creek basins. A series
of small, steep glaciers cover about 20 percent
of the East Fork basin (fig. 4). These glaciers
originate at peaks at about 6,000 ft altitude and
terminate at about 3,000 ft.

Eklutna Glacier (fig. 5) covers about 50 per-
cent of the West Fork basin. The glacier is cur-
rently about 8 mi long; its source is the slopes
of peaks at about 6,000 ft altitude. In 1957, the
terminus was at about 1,200 ft (Field, 1975);
during field observations in 1988, it was at
approximately 2,400 ft. The terminus has
retreated about 1 mi in 30 years. The equilib-
rium line altitude (ELA) was estimated to be at
4,000 ft in 1957. During the study period, the
ELA remained at approximately this same alti-
tude.

Eklutna Lake

Eklutna Lake occupies an elongated, gla-
cially steepened depression dammed by a
recessional terminal moraine of Eklutna Gla-
cier (Karlstrom, 1965). This glacial lake is fed
primarily by inflow from the East Fork and
West Fork Eklutna Creeks. Two seasons char-
acterize Eklutna Lake: (1) summer, when the
lake is ice-free and when most of the water and

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Figure 4.--Headwaters of East Fork Eklutna Creek, 1987.

sediment enter the lake, and (2) winter, when the lake and most of the inflow streams are frozen, when little or no flow enters into the lake, and when the fine sediment particles that are still in the water column slowly sink to the bottom as vertical fallout. The length of the winter season may equal or exceed that of the summer season.

In terms of thermal classification, Eklutna Lake is a dimictic lake. During the summer season, June to September, the lake becomes thermally stratified: warmer water overlies colder water (fig. 6A). As the lake water circulates, the water temperature becomes isothermal from fall to early winter (fig. 6B). Then in winter (late December to early March) the lake becomes inversely stratified: colder water overlies warmer water. In spring, the water becomes isothermal and the process repeats itself.

The morphometry of Eklutna Lake is given on table 1. The lake is long (6.5 mi), narrow (0.85 mi), and deep (average depth, 120 ft) (fig. 7). The combined flow of the East Fork and West Fork Eklutna Creeks is highly seasonal (fig. 8A) and thus the corresponding lake level has a large annual variation (fig. 8B).

GLACIER MASS BALANCE

The difference between accumulation and ablation (melting) at a given location on a glacier is called the "ice balance" or "mass balance" at that point (Mayo and others, 1972). If the mass balance averaged over the glacier is positive, the glacier increases mass by storing water. Conversely, if the mass balance averaged over the glacier is negative, the glacier loses mass as meltwater, evaporation, and calving. Mass changes observed on a glacier's surface usually are not immediately reflected in the volume of runoff from the drainage basin, mainly because of the storage characteristics of the glacier.

Figure 5.--Eklutna Glacier, 1965.
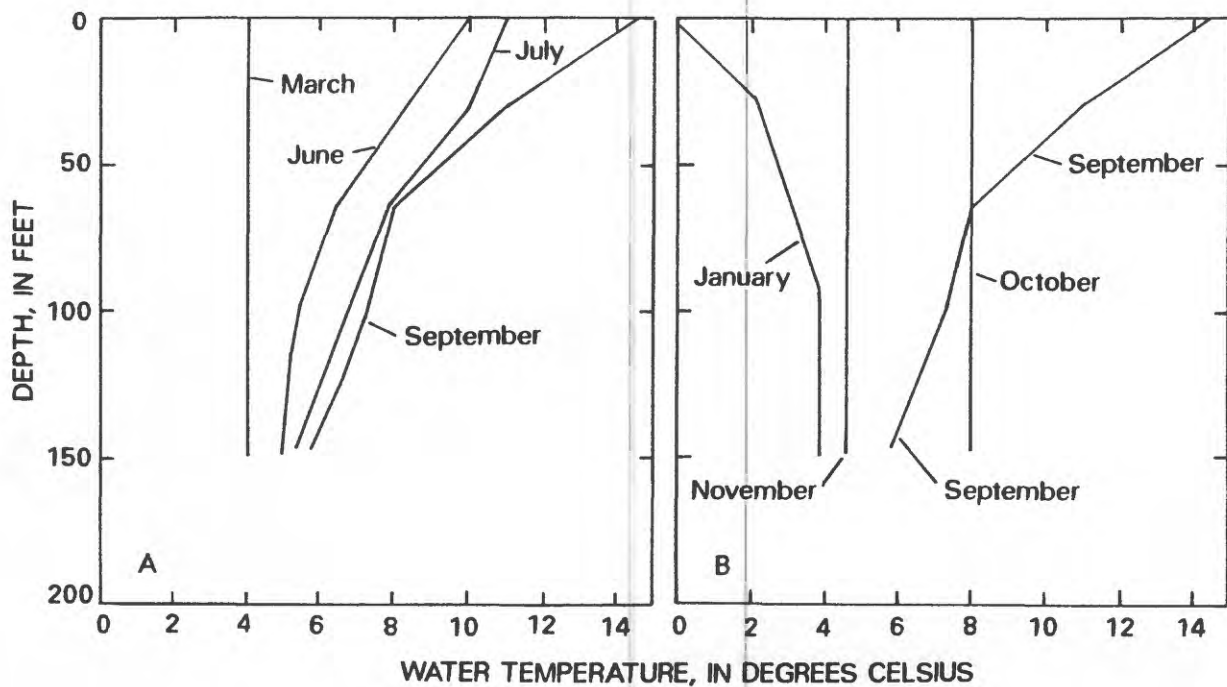
Figure 6.--Water temperature profiles of Eklutna Lake showing: A, summer stratification and B, winter inverse stratification.

**Table 1.--Morphometry of Eklutna Lake
at 860.00 feet water-surface altitude**

Lake characteristic	Value	Unit
Area	4.94	square miles
Volume	366,048	acre-feet
Length	6.50	miles
Mean depth	120	feet
Maximum depth	200	feet
Mean width	0.85	mile
Maximum width	1.1	mile
Shoreline	16.0	miles
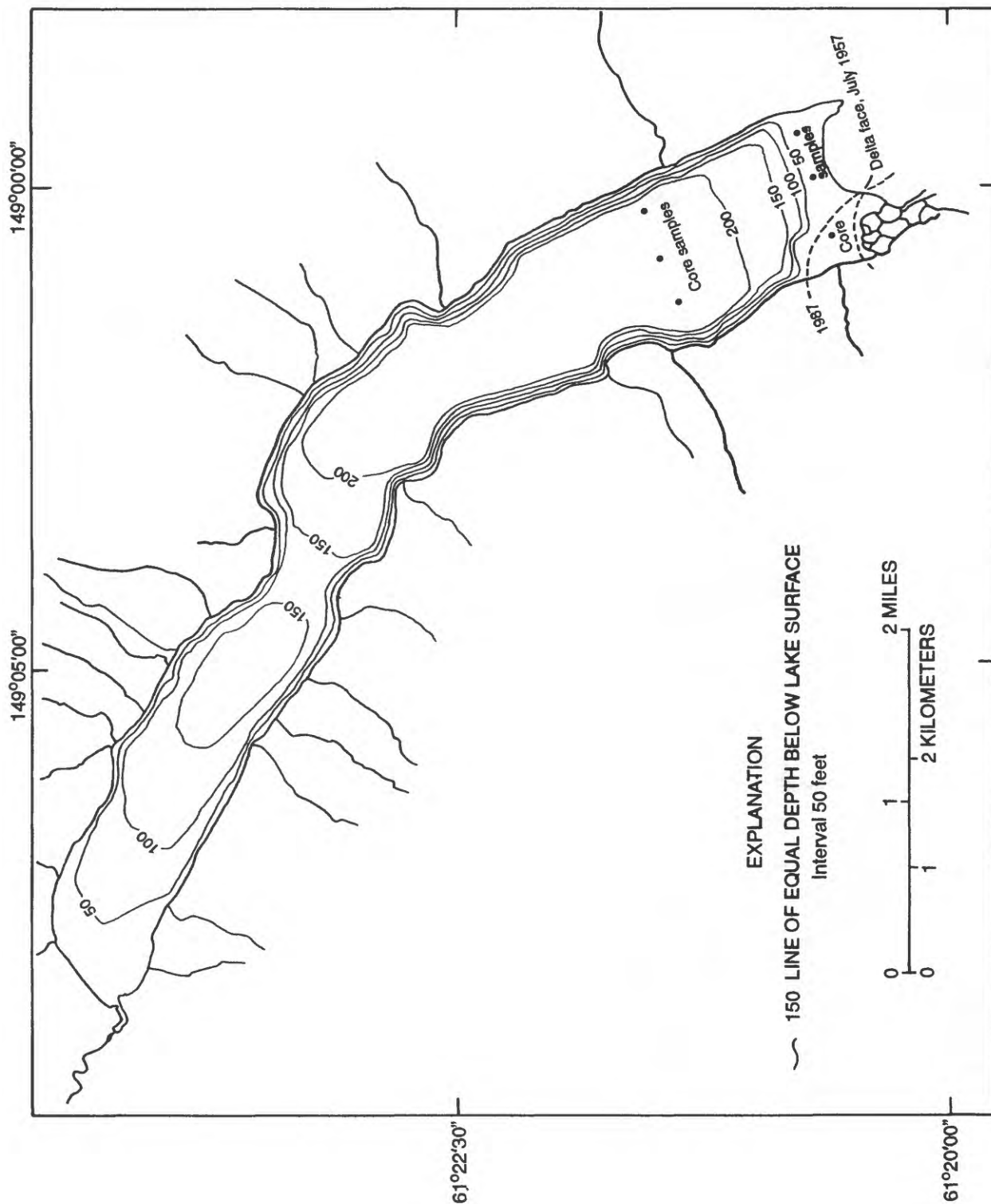
Figure 7.--Bathymetry of Eklutna Lake and locations of core samples.

EXPLANATION

—150— LINE OF EQUAL DEPTH BELOW LAKE SURFACE
Interval 50 feet

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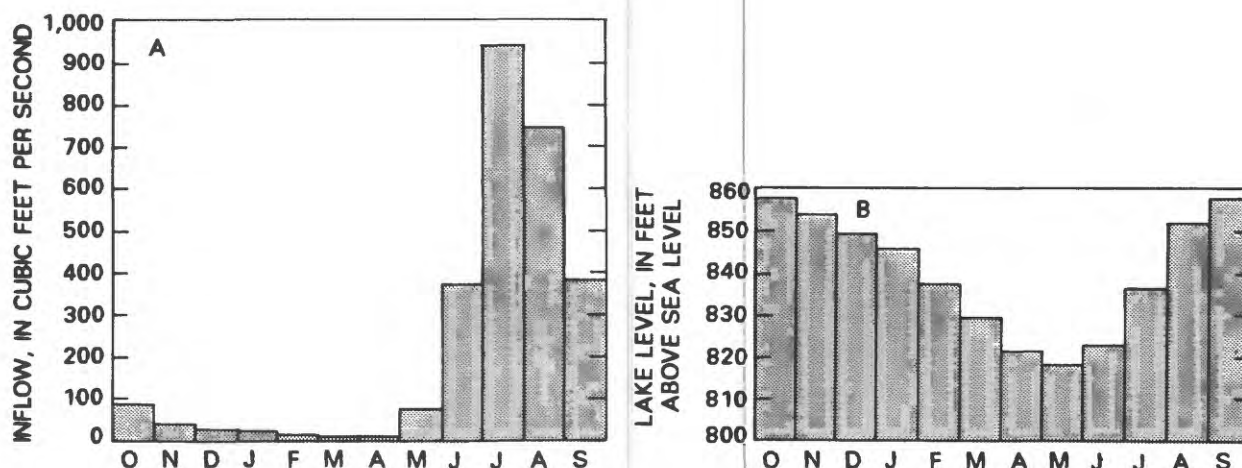
Figure 8.--Characteristics of Eklutna Lake, 1986 water year, showing: A, monthly inflow; and B, monthly lake level.

Accurate measurements of snow accumulation, rainfall, snowmelt, and ice ablation are required to determine the mass balance of a glacier. Although measurements of snowmelt and ice ablation are relatively simple and can be made with a high degree of accuracy, measurements of precipitation are difficult. Thus, in averaging these measurements over the glacier surface to determine the mass balance, some errors will be unavoidable.

For this study, estimates of the errors in mass balance measurements of Eklutna Glacier were made using methods described by Pelto (1988), Meier and others (1971), and Tangborn and others (1977). These authors estimated errors in mass balance for both the accumulation zone and ablation zone on the basis of factors such as variation in snow density, variation in ice density, stake settling, and sampling density. Total errors in mass balance ranged from -0.33 to 0.98 ft; a value of 0.6 ft was assumed for this study.

Snow accumulates on Eklutna Glacier and the surrounding glaciers from late September to mid-April. Pits were dug at various altitudes on the glacier and at different times of the year to determine the current year's snow density characteristics (table 2). During the

Table 2.-- Snow density at various altitudes on Eklutna Glacier

[g/cm³, grams per cubic centimeter]

Date	Density (g/cm³)	Altitude (feet)	Location (plate 1)
6-12-85	0.50	4,000	Stake A
6-12-85	.49	4,400	Stake B
6-12-85	.52	4,650	Stake C
6-13-85	.46	4,850	Stake D
6-13-85	.42	5,600	Stake E
7-18-85	.55	4,650	Stake C
8-30-85	.59	5,600	Stake E
8-30-85	.59	4,850	Stake D
6-27-86	.52	4,350	Stake F
3-18-87	.39	4,000	Stake A

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4-year study period, the density did not differ significantly with altitude, but it did differ seasonally. The lowest value of snow density measured was 0.39 g/cm^3, in mid-March. In June, the average density increased to approximately 0.50 g/cm^3, which would be expected because of compaction of the snowpack. In late August, the average density increased to 0.59 g/cm^3.

Accumulation of snow and ablation of ice and snow from Eklutna Glacier were estimated by measurement of stakes placed in the glacier surface (plate 1) and by additional probing of the snowpack. The accumulation/ablation values obtained at the stakes were then integrated over the entire glacier. No similar measurements were made on the series of small glaciers in the East Fork Eklutna Creek basin. However, because these glaciers are north facing and are at approximately the same altitude as Eklutna Glacier, it was assumed that their accumulation and ablation characteristics would be similar to those of Eklutna Glacier.

On the basis of probing and observations in snow pits, snow accumulation on Eklutna Glacier increases with higher altitude. Averaged over the glacier, snow amounts were similar during the 1985-87 water years (table 3). However, the 1988 water year was an exceptional snow year -- the average of 100 in. water equivalent of the snowpack was almost twice as much in any of the previous 3 years.

The rate of snow ablation was generally equal over the glacier surface from June to mid-July (fig. 9). From mid-July to the end of September, ablation rates appeared to vary with altitude. Ablation of snow and ice for the 4-year study period ranged from 47.0 in. to 78.3 in. water equivalent for snow and from 5.0 in. to 9.1 in. water equivalent for ice (table 3). The amount of icemelt in 1988 was the lowest measured during the study period and is probably due to the thick snowpack that covered the glacier during that spring.

Table 3.-- Mass balance measurements on Eklutna Glacier, 1985-88

[All values in inches of water equivalent, except accumulation area ratio]

Water year	Snow accumulation	Snow ablation	Ice ablation	Net change	Accumulation area ratio
1985	55.3	47.0	7.4	+1.0	0.58
1986	58.0	63.0	8.3	-13.3	.60
1987	54.8	54.0	9.1	-8.3	.60
1988	100.0	78.3	5.0	+16.7	.75
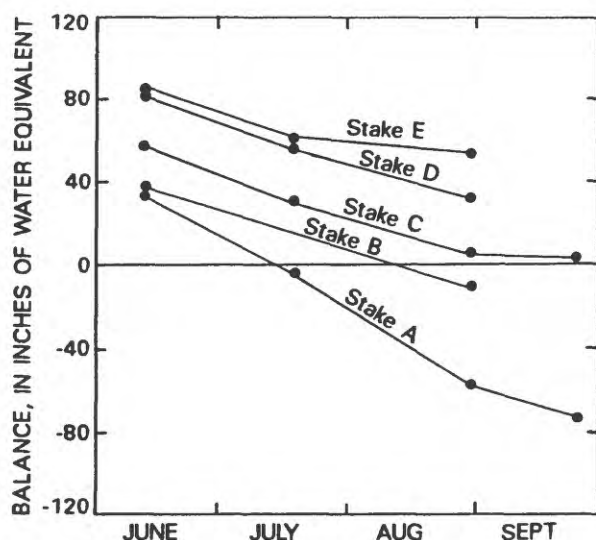
Figure 9.--Ablation of snow and ice on
Eklutna Glacier,1985 water year.

In summary, the mass balance calculations of Eklutna Glacier made during the 1985-88 water years, given the errors associated with these calculations, indicate no significant changes to Eklutna Glacier. As an additional check, the accumulation area ratio (area of accumulation/total area), abbreviated AAR, was determined for Eklutna Glacier for the period of study (table 3) and ranged from 0.58 to 0.75. Previous work by Meier and Post (1962) indicated that a land glacier with an AAR between 0.5 and 0.8 is neither advancing nor retreating.

GLACIER RUNOFF

Glaciers store an enormous amount of water in the form of ice. This feature alone makes any drainage basin containing glaciers both unique and complex. The release of this water is highly dependent on the energy supplied by solar radiation and air temperature (Meier, 1969). A hot summer will cause rapid melting and high runoff, whereas a cool summer will have low runoff.

Runoff from glacier-fed rivers is strongly influenced by the glacier behavior. For example, during a single year, the mass of a glacier may increase, decrease, or remain the same.

When a glacier decreases (negative mass balance), the basin will yield more water than a similar basin without glaciers. A growing glacier stores and thus withholds some water from the normal runoff in the stream. Even if a glacier is in equilibrium, most of the meltwater will be released during a fairly short summer season. The peak runoff from glaciers occurs later than that from lower altitude, non-glacier areas (Meier and Tangborn, 1961).

The extra water withheld by the glaciers may affect the amount of runoff from the basin. For example, Fountain and Tangborn (1985) found that in certain years the water yield from a glacierized basin was 20 to 30 percent higher than the water yield from a non-glacierized basin.

Streamflow Characteristics

The hydrograph of stream discharge provides a good picture of its flow characteristics. Discharge hydrographs for the East Fork and West Fork Eklutna Creeks (fig. 10) show distinct diurnal fluctuations. The low flow of the day usually occurs in the mid-morning and the high flow occurs in the evening, reflecting the time lag between melting of snow and ice and the arrival of the resulting meltwater at the gaging station.

Annual hydrographs (figs. 11-12) indicate that from about the end of October until April or early May, flows steadily declined in both basins. A noteworthy difference between the two streams is that the East Fork Eklutna Creek is characterized by a ground-water base flow component. During the study period, base flows kept this stream ice-free in winter whereas no flow occurred in West Fork Eklutna Creek. Rising temperatures in May initiate snowmelt and consequent runoff throughout the basins, and near the end of June the melt increases to a maximum. Annual peaks in streamflow occur during July and August when glacial melt and storm runoff coincide. Streamflow declines during September and October as air temperatures cool, and snowmelt and icemelt decrease. Occasional peaks are due to storms in late fall.

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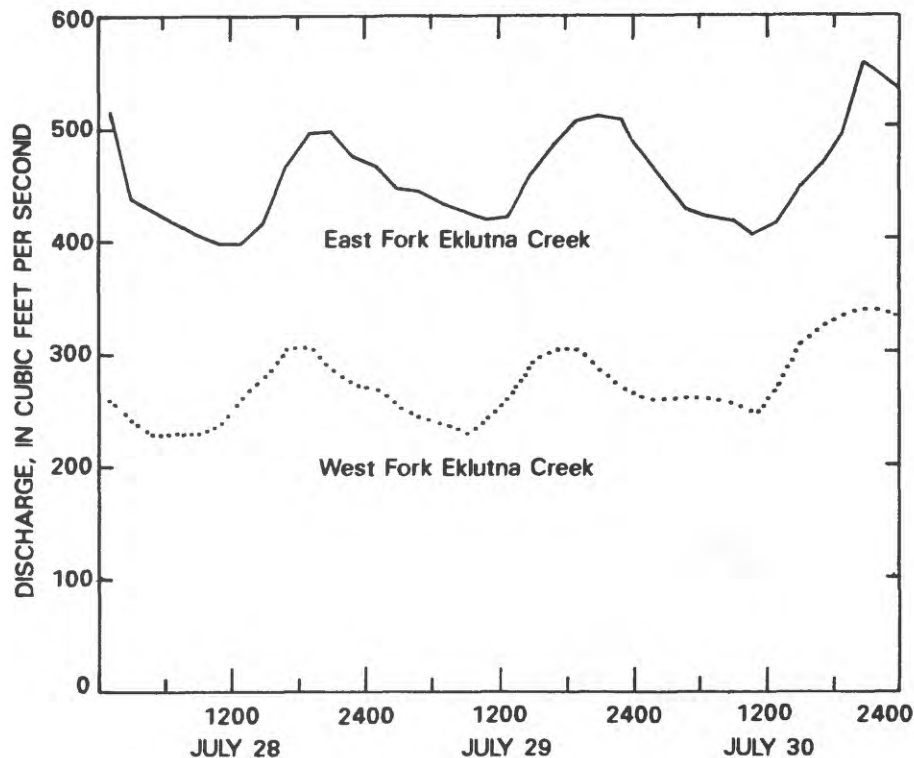
Figure 10.--Streamflow of East Fork and West Fork Eklutna Creeks,
July 28-30, 1985.

Runoff Components

Although the East Fork basin is larger than the West Fork basin, comparison of unit runoff (figs. 13-14) indicates more runoff from the latter basin. During the June-to-September periods of the 4-year study, runoff from the East Fork basin (20 percent glacierized) ranged from 34.13 to 44.28 in., while runoff from the West Fork basin (50 percent glacierized) ranged from 43.34 to 55.79 in. Over an entire water year, more than 80 percent of the total runoff in the East Fork basin occurs from June through September, while more than 90 percent of the total runoff in the West Fork basin occurs during these 4 months. During May, runoff from the East Fork accounts for about 5 percent of the total yearly runoff, whereas runoff in the West Fork basin accounts for about 1 percent of the total runoff. The difference in

runoff between the two basins during May is probably because snowmelt in the West Fork basin is accumulating in the snowpack or draining through the glacier, instead of becoming immediate runoff.

In water years 1985, 1987, and 1988, June-to-September runoff from the West Fork basin was approximately 10 in. higher than that from the East Fork basin. In water year 1986, runoff was approximately 20 in. higher in the West Fork basin than in the East Fork basin. Two possible causes for this significant difference are: (1) the heavy precipitation that was localized on Eklutna Glacier did not occur in the East Fork basin (table 4), and (2) air temperatures in the West Fork basin in July and August average approximately 2 °F warmer than those in the East Fork basin, which may have caused increased icemelt.

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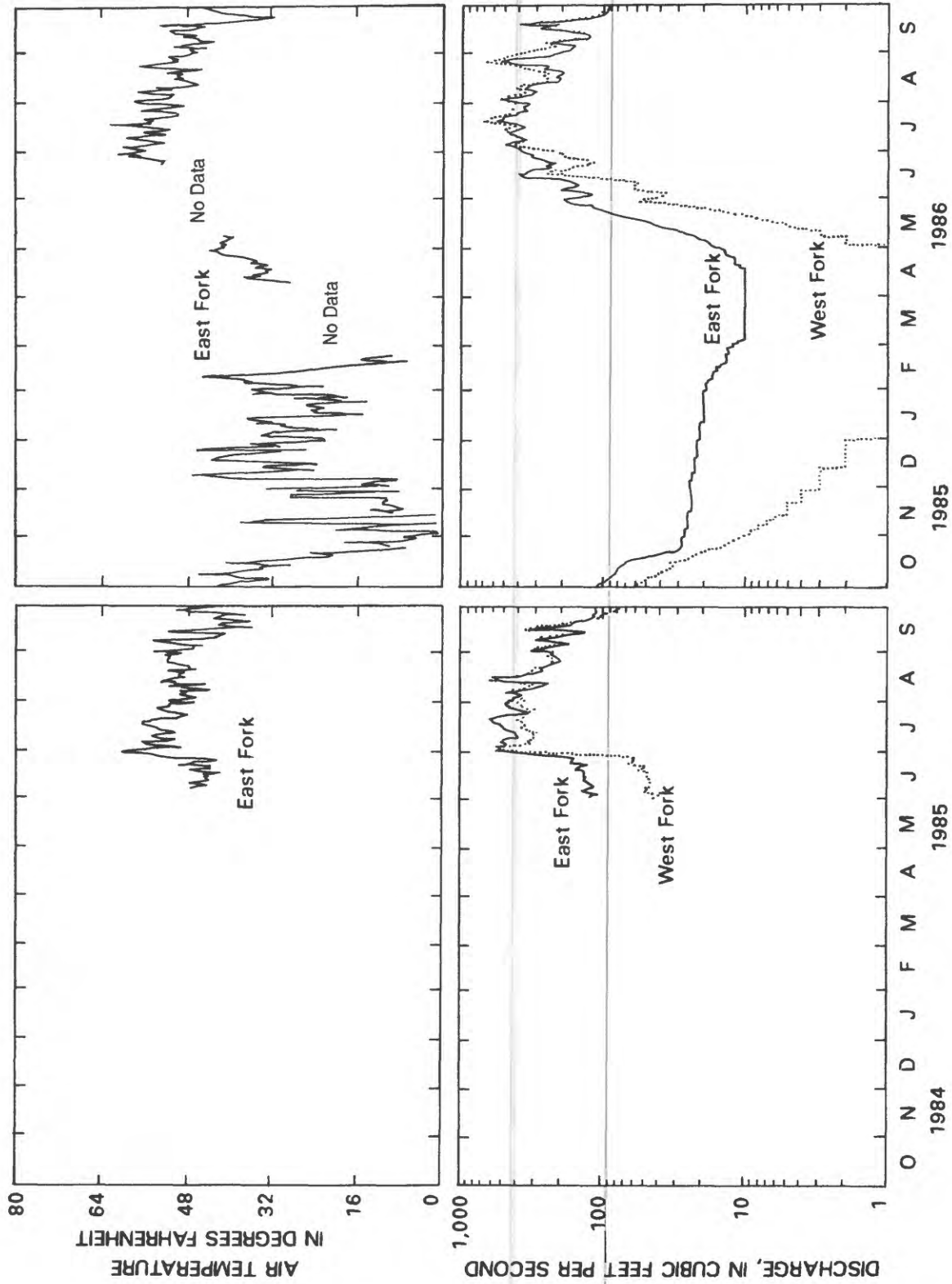
Figure 11.--Daily streamflow and air temperature for East Fork and West Fork Eklutna Creeks, 1985 and 1986 water years.

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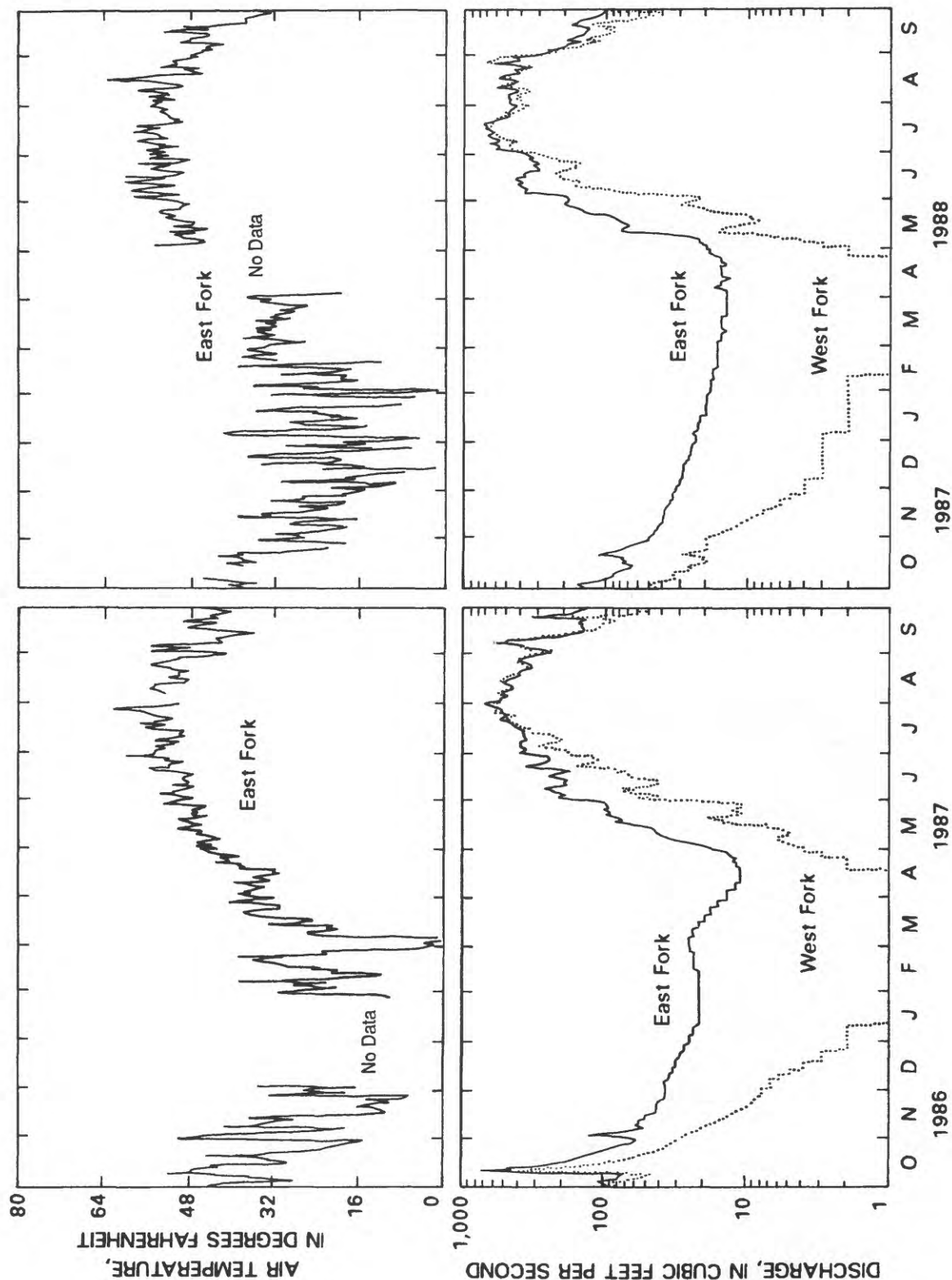
Figure 12.--Daily streamflow and air temperature for East Fork and West Fork Eklutna Creeks, 1987 and 1988 water years.

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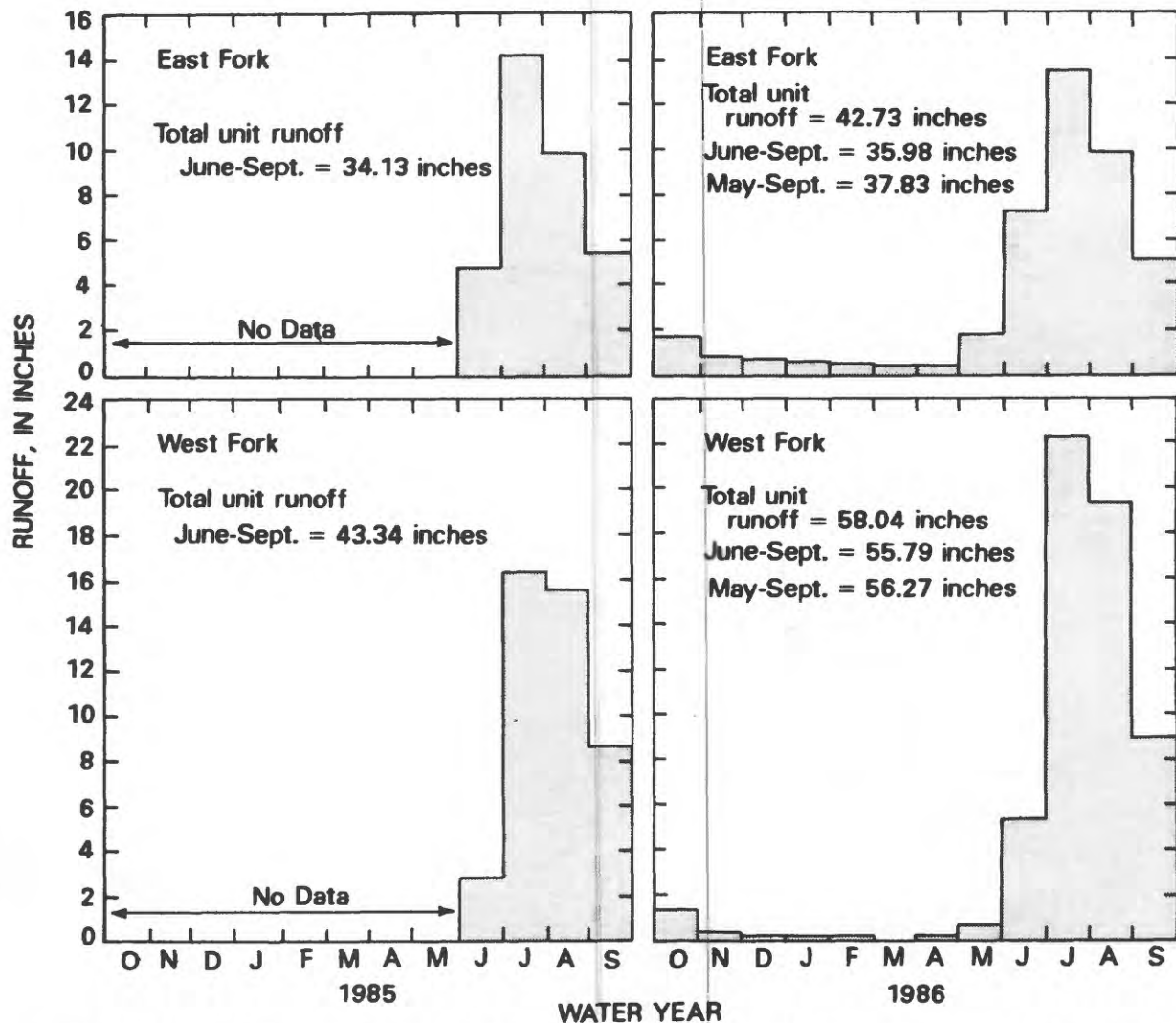
Figure 13.--Monthly runoff for East Fork and West Fork Eklutna Creeks, 1985 and 1986 water years.

The hydrologic balance, which is the difference between inflow (mostly precipitation) and outflow (mostly runoff) was determined for the East Fork and West Fork Eklutna basins for the period June to September. Balances were based on the following assumptions:

1) The discharge measured at the two gaging stations was considered to be the most accurately measured of the variables, which also included icemelt, snowmelt, and rainfall.

2) From analysis of the streamflow discharge for East Fork Eklutna Creek, a ground-water component of 1.6 in. was estimated and used for this station. A ground-water component of 0.0 in. was used in balance calculations for West Fork Eklutna Creek.

3) Icemelt for the West Fork basin was assumed to be equal to the icemelt estimated for Eklutna Glacier (table 3). For the glaciers in the East Fork basin, it was assumed that the icemelt characteristics were the same as those for Eklutna Glacier. Thus, the quantity of icemelt was computed by dividing the
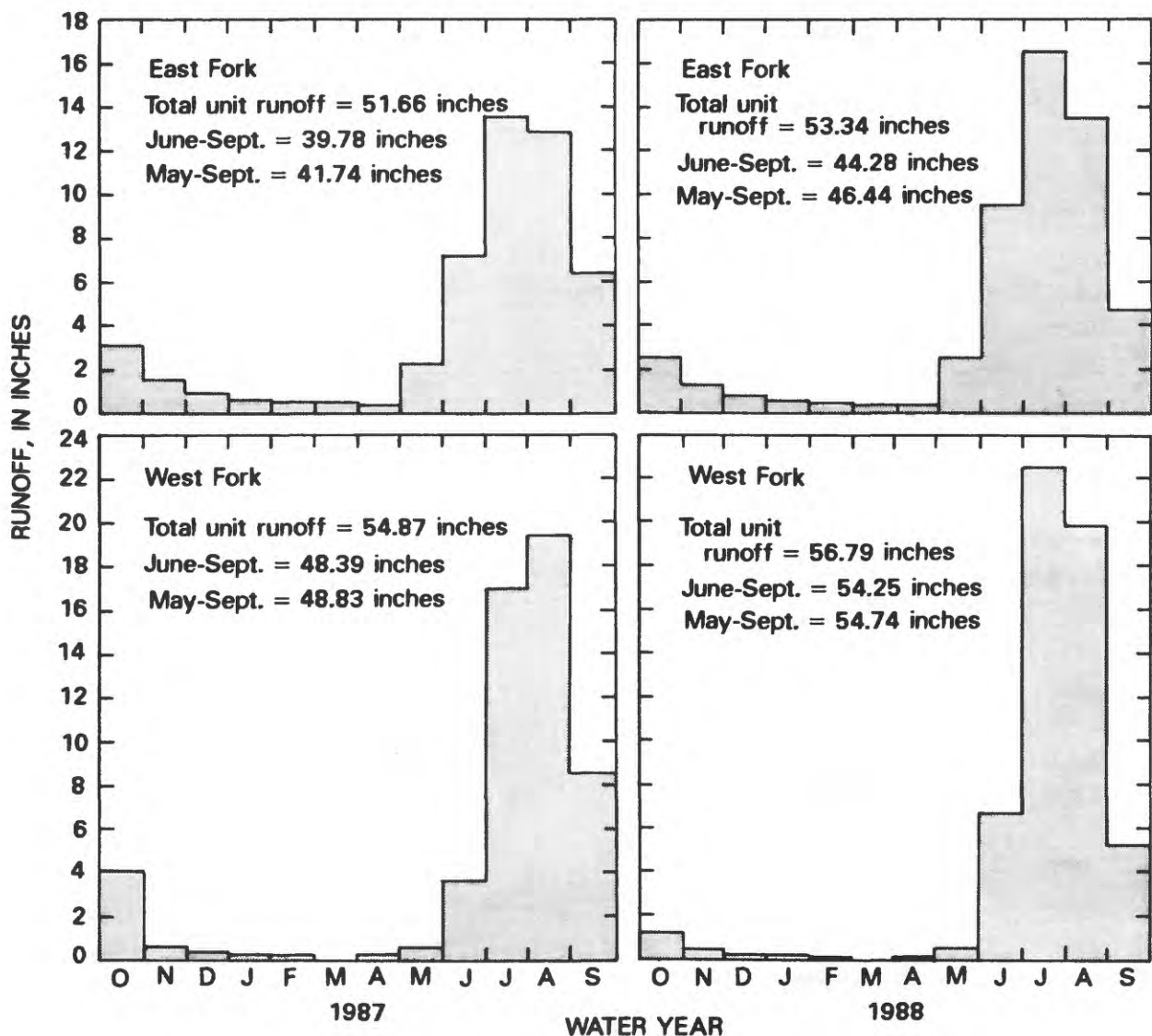
Figure 14.--Monthly runoff for East Fork and West Fork Eklutna Creeks, 1987 and 1988 water years.

area of the glaciers in the East Fork basin below the ELA by the area of Eklutna Glacier below the ELA, and then multiplying this number by the icemelt from Eklutna Glacier. It was assumed that all icemelt from both basins became runoff that was measured as discharge at the corresponding gaging station.

4) Runoff caused by snowmelt and rainfall was

assumed to increase with a decrease in altitude (fig. 15).

5) Evaporation losses were assumed to be negligible.

Hydrologic balances of the two basins indicate that glacier icemelt contributes between 9 and 19 percent of the flow in the West Fork basin and between 6 and 13 percent of the flow

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Table 4.-- Precipitation measured in the Eklutna Lake basin, 1985-88

[Number below site name is altitude in feet above sea level;
all table values are in inches;   ---, no data available]

Year and month	Eklutna Creek		Eklutna Glacier (4,000)	Eklutna Power Plant (350)
	East Fork (1,050)	West Fork (1,050)		
1985				
June	---	---	---	1.15
July	0.08	0.26	0.82	.98
August	.61	---	4.11	3.57
September	2.29	3.00	4.07	4.22
1986				
June	---	---	---	.76
July	1.64	2.28	6.02	3.85
August	1.19	1.93	6.20	2.33
September	1.10	2.61	5.96	3.46
1987				
June	.77	1.21	---	2.13
July	1.92	2.04	3.72	1.34
August	1.78	1.75	2.40	2.40
September	2.88	4.87	8.20	2.70
1988				
June	.78	1.04	.97	2.61
July	.67	1.33	.86	2.08
August	1.45	2.11	7.54	2.53
September	.96	2.33	---	2.01
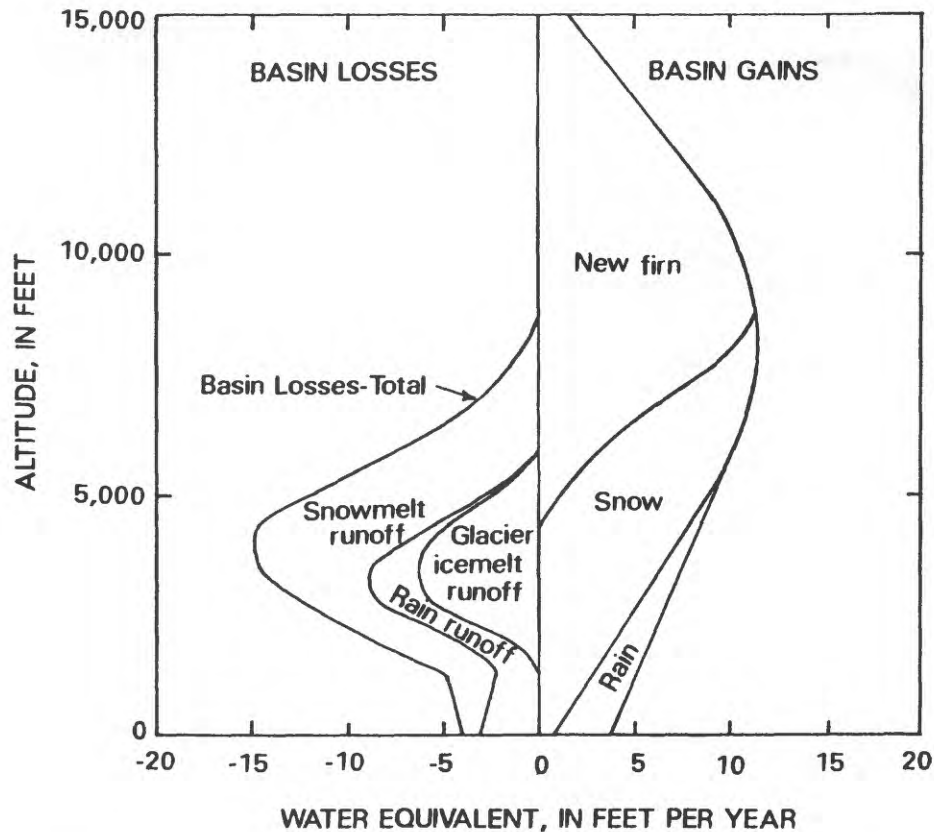
Figure 15.--Altitude distribution of precipitation as rain and snow,
accumulation, icemelt, snowmelt, and runoff for a glacier
in southcentral Alaska (modified from Mayo and Trabant, 1979).

in the East Fork basin (table 5). Snowmelt and rainfall account for most of the runoff in both basins. Although the estimate for icemelt runoff is considered to be fairly accurate, the estimates for snowmelt and rainfall runoff are considered to be quite variable. The reasons for this variability are: (1) the lack of detailed snowmelt and rainfall data for both basins and (2) the difficulty in determining the quantity of snowmelt and rainfall that actually becomes runoff.

Runoff Prediction

Methods of predicting runoff from glacierized basins range from simple to complex. The simplest models relate snowmelt to air temper-

ature: the most commonly used index is mean daily air temperature in excess of 32 °F. The temperature index method (Anderson, 1973) has the advantage that few data are needed. However, this method does not account for the increasing density of the snowpack or the decrease in the snow-surface albedo as the melt season progresses and it assumes that all snowmelt becomes runoff. More complex models incorporate detailed energy balances and internal flow routing through the glacier. However, internal glacier drainage is poorly understood and experimental verification of internal drainage theories is difficult (Young, 1985). Despite these limitations, two methods (one simple, one complex) were tested to determine their applicability in this study.

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Table 5.-- Estimated distribution of unit runoff of the West Fork and East Fork Eklutna Creeks, June to September, 1985-88

Water year and component	West Fork		East Fork	
	Unit runoff (inches)	Percent of total	Unit runoff (inches)	Percent of total
1985				
Icemelt	7.4	17	4.1	12
Snowmelt	24.3	56	19.0	56
Rainfall	11.6	27	9.2	27
Ground water	0.0	0	1.6	5
Total	43.3		33.9	
1986				
Icemelt	8.3	15	4.6	13
Snowmelt	29.0	52	19.2	53
Rainfall	18.5	33	10.6	29
Ground water	0.0	0	1.6	5
Total	55.8		36.0	
1987				
Icemelt	9.1	19	5.1	13
Snowmelt	25.2	52	21.6	54
Rainfall	14.0	29	11.5	29
Ground water	0.0	0	1.6	4
Total	48.3		39.8	
1988				
Icemelt	5.0	9	2.8	6
Snowmelt	34.5	64	27.9	63
Rainfall	14.7	27	12.0	27
Ground water	0.0	0	1.6	4
Total	54.2		44.3	

Statistical Relations

Statistical regression techniques were used to estimate daily discharge for June 1 to September 30 by using the log-transformed daily discharge, air temperature, and rainfall data collected in the East Fork Eklutna and West Fork Eklutna basins. The regression analysis produced the following equations:

East Fork Eklutna Creek:

$$EFQ = 33.9(HDD)^{.86} \ (1+PRECIP)^{.074}$$

Number of observations =248
Coefficient of determination = .49
Standard error of estimate (percent) = 40

West Fork Eklutna Creek:

$$WFQ = 22.4(HDD)^{.96}(1+PRECIP)^{.040}$$

Number of observations = 248
Coefficient of determination = .49
Standard error of estimate (percent) = 45

where   EFQ   is daily discharge for East Fork Eklutna Creek, in cubic feet per second;

        WFQ   is daily discharge for West Fork Eklutna Creek, in cubic feet per second;

        HDD   is heating degree days (equals average temperature for the day minus 32 °F); and

        PRECIP   is precipitation, in inches.

The relatively low coefficient of determination, high standard error of estimate for these two equations, and inspection of figures 16 and 17 indicate that this method would not give reliable results. This is due to the fact that the equations are attempting to describe a fairly complex hydrologic system.
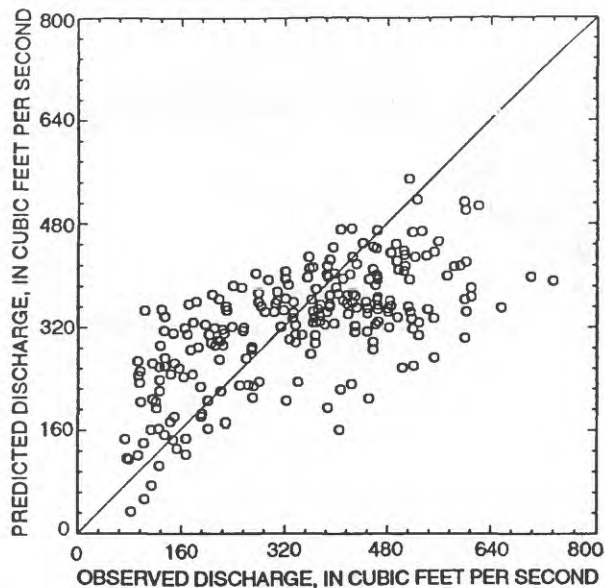
Figure 16.--Observed daily mean streamflow and daily mean streamflow predicted from statistical equations, June to September 1985-88, East Fork Eklutna Creek.

Figure 17.--Observed daily mean streamflow and daily mean streamflow predicted from statistical equations, June to September 1985-88, West Fork Eklutna Creek.

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Precipitation-Runoff Modeling System

The Precipitation-Runoff Modeling System (PRMS) was developed to evaluate the effects of various combinations of precipitation, climate, and land uses on surface-water runoff (Leavesley and others, 1983). The concept of PRMS is to partition a watershed into units--referred to as hydrologic response units (HRU's)--on the basis of similar characteristics such as slope, aspect, vegetation type, soil type, and precipitation distribution. Thus, for this application, PRMS would enable one to partition the glaciers in the East Fork and West Fork basins into the ablation and accumulation zones, modify the water equivalent of the snowpack using the snow density data collected, and adjust for the differences in precipitation (both snow and rain) with altitude. Temporal changes in watershed characteristics can also be modeled.

Input variables required to run PRMS are physical and hydrologic data for each HRU of the watershed, daily precipitation, maximum and minimum daily air temperature, and daily solar radiation. Using the input data, PRMS simulates processes such as evapotranspiration, snowmelt, and runoff on a daily basis.

Some limitations in applying PRMS to this study were: (1) it does not account for the internal drainage system of a glacier; (2) it does not have a mechanism to account for the enlarging ablation zone during the summer months; and (3) it does not simulate icemelt. However, a very simplified technique was used to determine icemelt and is outlined as follows using certain output variables from PRMS (Leavesley and others, 1983).

1) Determine the net shortwave radiation:

$$SWN = SWRD * (1.0 - ALB) * TRNCF,$$

where   SWRD   is the computed short-wave radiation received (langleys);

ALB   is the albedo of the ice surface, assumed to be 0.4; and

TRNCF   is the transmission coefficient for the vegetation canopy over the snowpack, assumed to be 1.0.

2) Determine the net longwave radiation:

$$LWN = (1.0 - COVDNW)*[(EMIS*AIRN)-SNON] + COVDNW*(AIRN - SNON),$$

where   COVDNW   is the winter cover density of the predominant vegetation above the snowpack, assumed to be 0.0;

EMIS   is the emissivity of air, assumed to be 0.76;

AIRN   is the longwave energy emitted from a perfect black body at the average air temperature for the 12-hour period (cal); and

SNON   is the longwave energy emitted from the snowpack surface at the surface temperature for the 12-hour period (cal).

AIRN and SNON are computed using the Stefan-Boltzmann law (Leavesley and others, 1983, p. 43).

3) Determine the latent and sensible heat:

$$CEN = CECN(MO)*TAVC,$$

where CECN(MO) is a parameter for
month MO, assumed
to be 10; and

TAVC is the mean air
temperature for the
12-hour period (C).

The total energy balance CALN is then determined by summing SWN, LWN, and CEN. Icemelt is then computed by CALN/203.2, where 203.2 is the number of calories required to melt 1 in. of water-equivalent ice at 0 °C. The total icemelt for the glacier areas was then determined by integrating the value of daily icemelt over the ablation area. Because PRMS does not account for an increasing ablation zone, an average value was used.

The East Fork and West Fork basins were delineated into their respective HRU's (fig. 18).

WEST FORK

EAST FORK

N

⌢⌢⌢ Glacier

—··— Hydrologic response unit boundary

0   1   2   3 MILES

0   1   2   3 KILOMETERS

Figure 18.--West Fork and East Fork Eklutna Creek basins partitioned into hydrologic response units.

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Using streamflow, climatological, and physical characteristics of the basins as input, initial runs of PRMS were made. The values of the physical properties were based on typical values outlined by Leavesley and others (1983) and on general hydrologic knowledge of the these two basins. As expected, changes in soil moisture or ground-water properties did not have any significant effect in model output. Output was most sensitive to changes in temperature lapse rates and in precipitation coefficients. Thus, for the remaining simulations, these values were adjusted within reasonable limits until the best fit between observed and simulated discharge was reached. A rigorous calibration and sensitivity analysis was not done because of the previously mentioned limitations of the PRMS in simulating runoff from glacierized basins.

No attempt was made to calibrate observed and simulated discharge for the 1985 water year because of the computational procedures of PRMS and the beginning of the data set (June 1, 1985). The period of icemelt was based on stake ablation data. For 1986 and 1987, the icemelt period lasted from July 1 to September 1, while in 1988 it lasted from July 20 to September 1.

Daily discharges predicted by PRMS (figs. 19-20) generally follow the trends of the observed discharges for the East Fork and West Fork Eklutna Creeks. Simulated peak discharges are sharper and higher and occur sooner than the observed peak discharges. These features are most likely because PRMS does not account for the internal drainage of glaciers. In general, agreement between observed and simulated daily discharge is closer for West Fork than for East Fork Eklutna Creek. This is probably because the West Fork basin includes Eklutna Glacier and bedrock and is not difficult to partition into HRU's. The larger East Fork basin includes several small

glaciers and has some ground-water flow, making it more difficult to partition.

The quantity of icemelt simulated by PRMS agrees reasonably well with the calculated quantity for both the East Fork and West Fork Eklutna basins (table 6). This indicates that the previously mentioned equations for determining icemelt are reasonable. Comparing the observed and simulated discharges on an average monthly basis (table 7) indicates that the differences in simulated and observed values are smaller for June and September, when glaciers are normally not producing any water, than for July and August, when glaciers release most of their water from storage. PRMS underpredicts the quantity of runoff, even after accounting for the icemelt, for July and August (table 7).

Limitations apply to both methods tested for predicting runoff. However, although it is more complex, it is believed that PRMS is a more accurate method for simulating runoff from glacierized basins. Its ability to partition a watershed into distinct units, to distribute precipitation on the basis of altitude, and to account for changes in snowpack allows an accurate description of a watershed in mathematical terms. For PRMS to simulate runoff from glacierized basins still more accurately, more development of the model is needed in representing the storage and release of water from a glacier's internal drainage system.

SEDIMENT TRANSPORT AND DEPOSITION

The transport of material eroded from a streambank or along the streambed depends on several factors. The streamflow velocity of bed slope usually determines the size and quantity of material transported. These variables change throughout the course of the stream so that uneven beds can form as a result of scour in one part of the stream and deposition in another part.
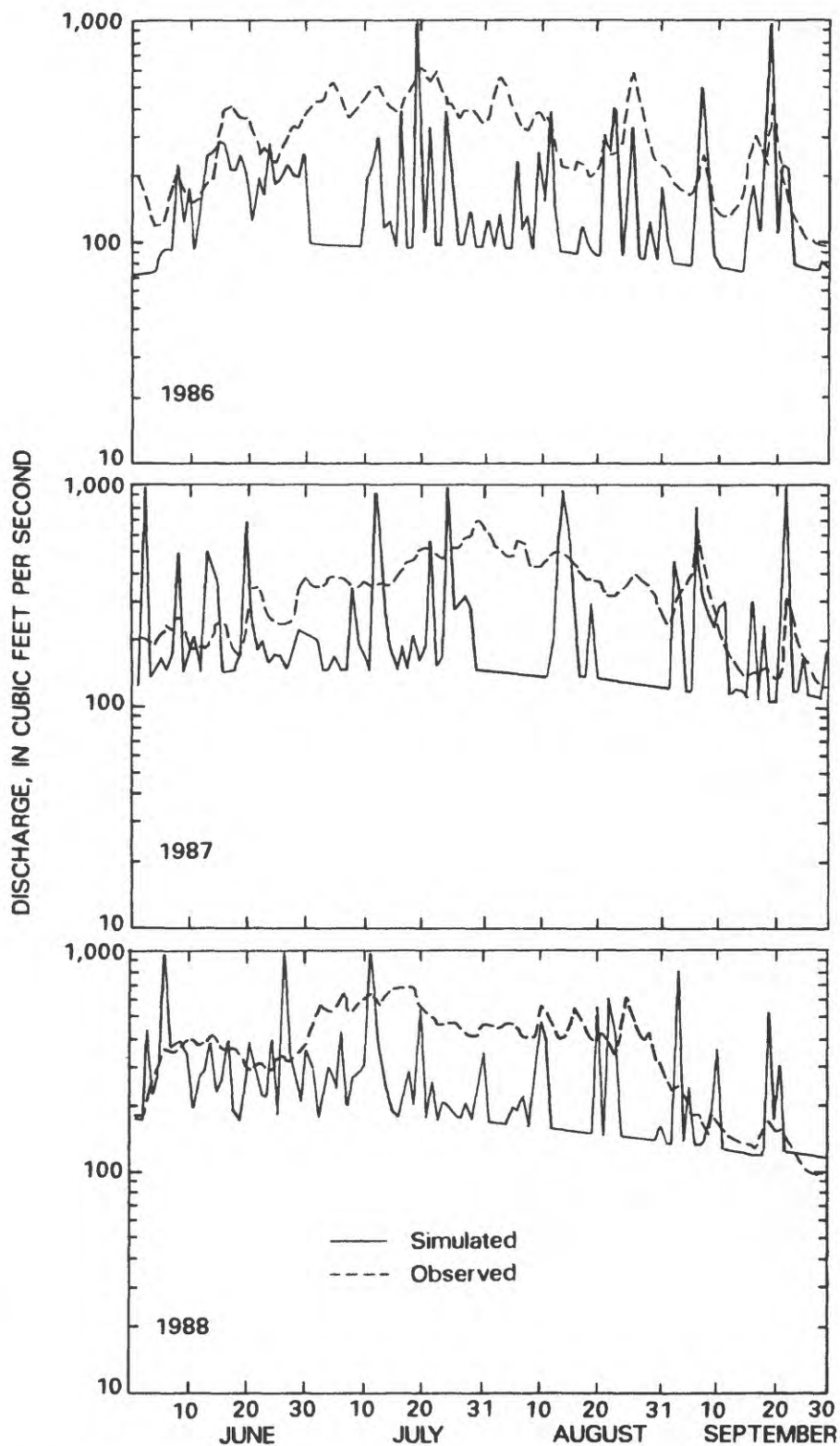
Figure 19.--Observed daily mean streamflow and daily mean streamflow
simulated from the PRMS, June to September 1986-88,
East Fork Eklutna Creek.

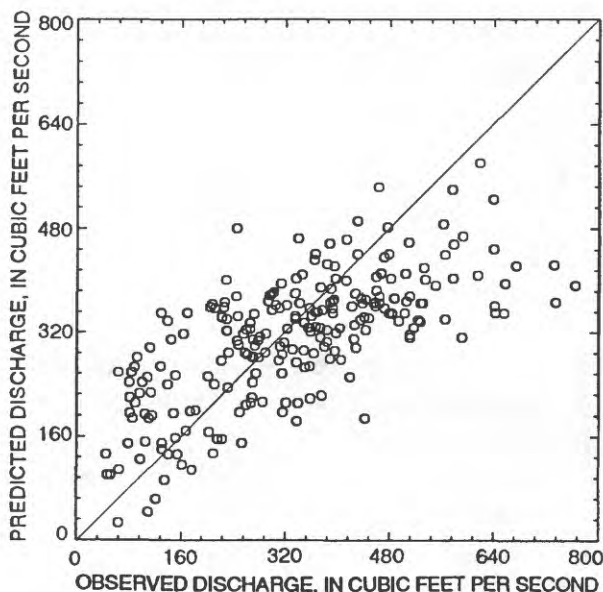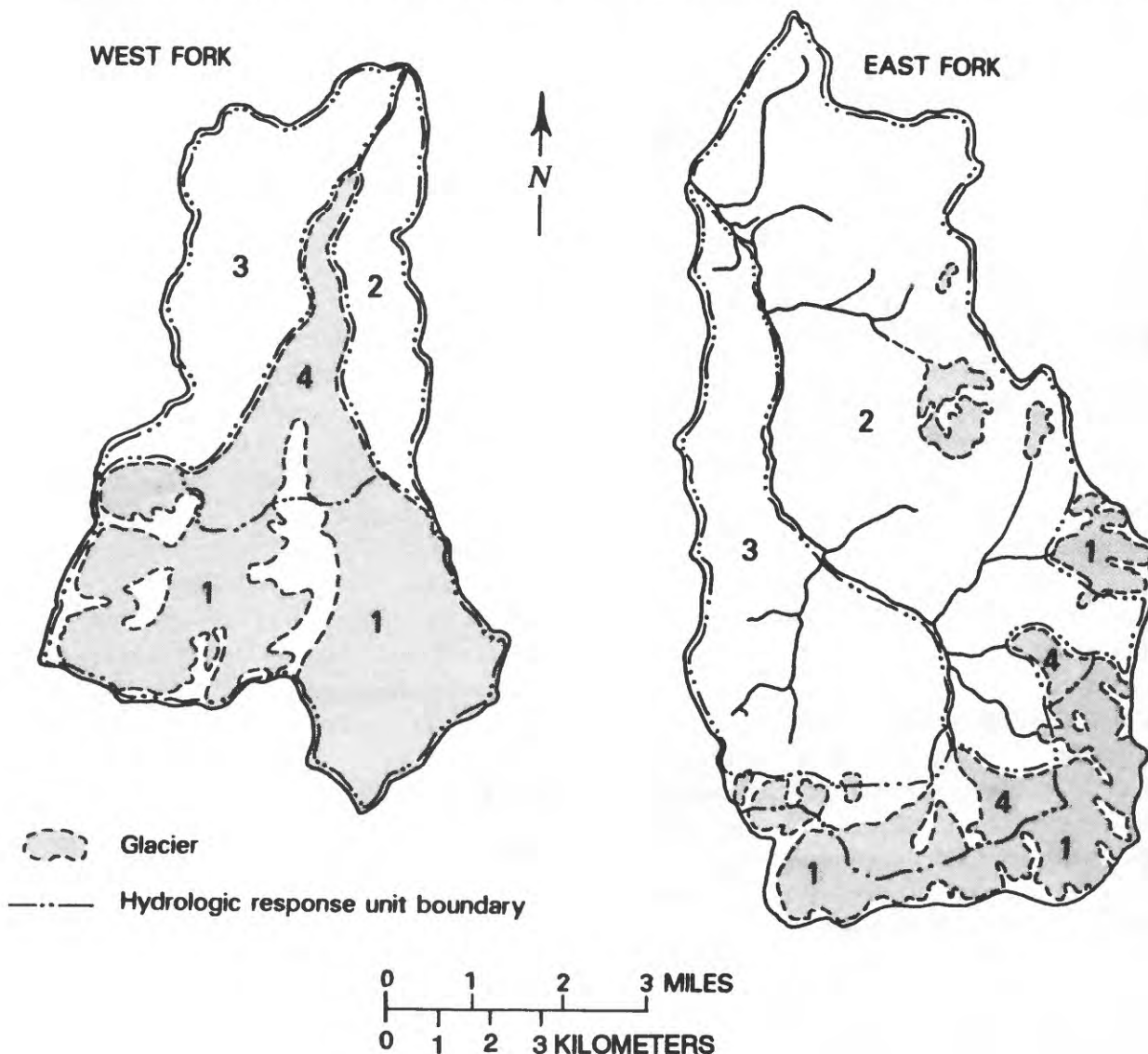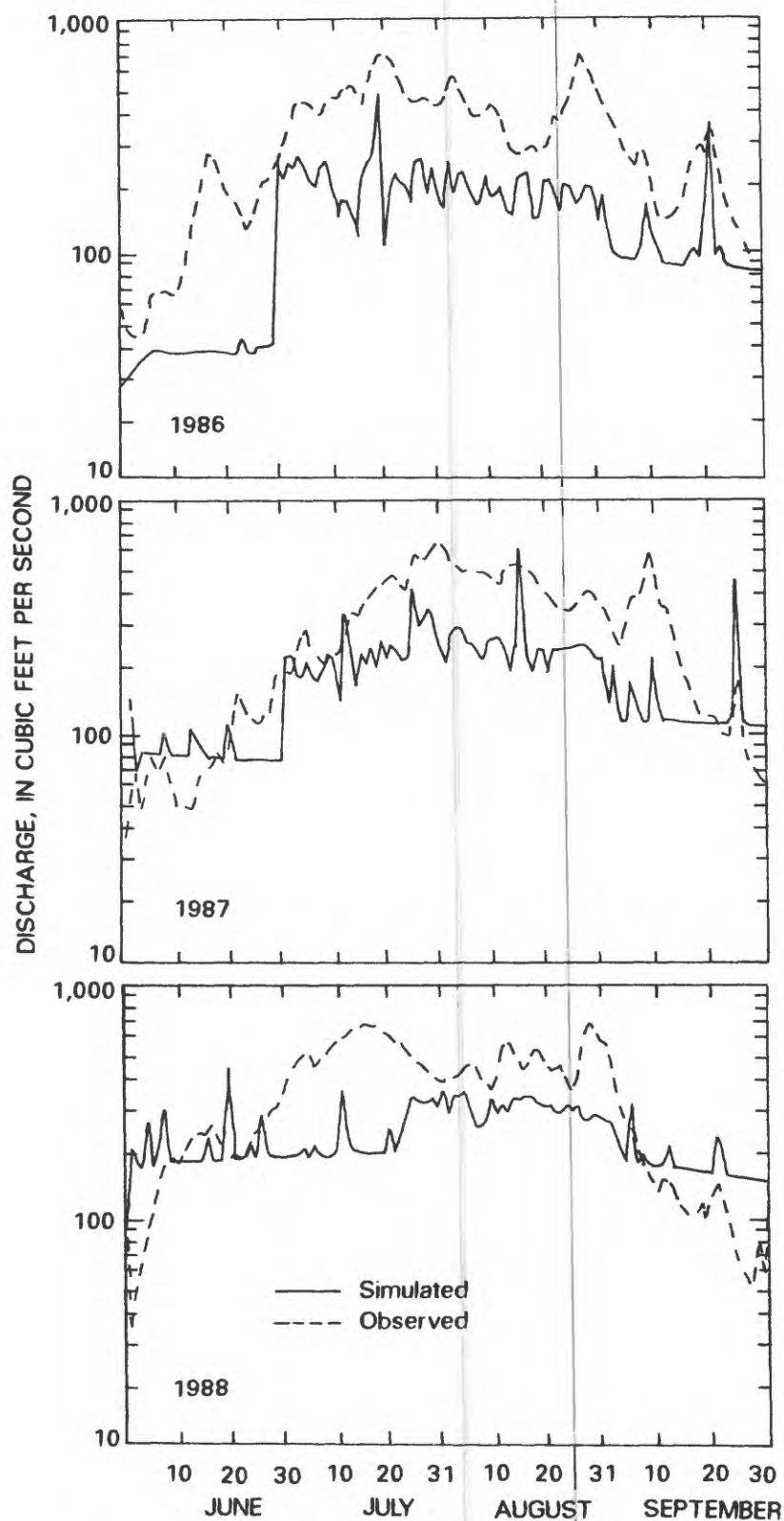Figure 20.--Observed daily mean streamflow and daily mean streamflow
simulated from the PRMS, June to September 1986-88,
West Fork Eklutna Creek.

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Table 6.-- Calculated and simulated icemelt for East Fork and West Fork Eklutna Creeks, June to September, 1986-88

[Values in inches; PRMS, Precipitation-Runoff Modeling System]

| Water year | East Fork icemelt | | West Fork icemelt | |
	Calculated (table 5)	Simulated (PRMS)	Calculated (table 5)	Simulated (PRMS)
1986	4.6	4.5	8.3	9.5
1987	5.1	4.4	9.1	10.5
1988	2.8	1.9	5.0	5.5

Table 7.-- Observed and simulated average monthly discharges for East Fork and West Fork Eklutna Creeks, June to September 1986-88

[Values in cubic feet per second]

| Year and month | East Fork discharge | | | West Fork discharge | | |
	Observed	Simulated	Difference	Observed	Simulated	Difference
1986						
June	248	176	+72	123	35	+88
July	451	264	+187	490	224	+266
August	327	203	+124	422	180	+242
September	180	178	+2	204	118	+86
1987						
June	235	263	-28	84	82	+2
July	444	357	+87	379	231	+148
August	425	255	+170	437	247	+190
September	227	284	-57	197	134	+63
1988						
June	326	340	-14	154	182	-28
July	548	287	+261	494	314	+180
August	445	280	+165	437	277	+160
September	162	186	-24	118	166	-48

Similarly, the rate and quantity of sedimentation in lakes are not uniform. Sediment deposition can vary with the seasonal inflow of streams and with fluctuations in lake currents. For example, in cold climates, spring and summer runoff can flush large quantities of sediment into a lake. These sediments will then be distributed throughout the lake, depending on the lake's currents. In winter, when discharge is relatively low and lakes are ice covered, no sediment accumulates.

Streams

Sediment in streams is transported in suspension and as bedload. Suspended sediment consists of fine particles, usually clay or silt, that are transported in a stream while being held in suspension by the turbulence of flowing water. Bedload consists of coarse sediment, usually sands, gravels, and larger particles, that is transported on or near the streambed.

Suspended-sediment samples were collected at East Fork and West Fork Eklutna Creeks by automatic samplers and correlated with manually collected samples. Samples were collected three times daily in the summer during the 1985-86 water years and twice daily in the summer during the 1987 water year. Samples were also taken at times of discharge measurements in winter.

Bedload was sampled at approximately 2-week intervals during summer seasons of the 1985-87 water years. The samples of bedload were collected using a sampler (Helley and Smith, 1971) designed for collecting coarse material (0.062 - 76.2 mm). Sampling time, number of sampling points, stream width and depth, and weight of dry sediment were recorded as a basis for calculating bedload discharge. Trap efficiency of the sampler was assumed to be 1.0. Characteristics of the sampler and procedures to obtain representative samples have not been fully evaluated. In the interim, the U.S. Geological Survey follows a provisional method of obtaining samples at about 20 equally spaced verticals based largely on field tests by Emmett (1979).

Suspended-Sediment Discharge

In late May, as air temperatures begin to rise above freezing at higher altitudes, glacial meltwater begins to contribute to the streamflow and a corresponding increase in silt-clay concentration occurs. This causes the stream to take on the turbid, milky appearance that is characteristic of glacier-fed streams. Virtually all the sediment in a given year is transported past the gaging sites from this time until the beginning of October, when air temperature decreases and streamflow declines.

The daily sediment concentrations of the East Fork (fig. 21) and West Fork (fig. 22) Eklutna Creeks followed the same patterns and trends as streamflow, but their fluctuations are more pronounced. Twenty-nine suspended-sediment samples were analyzed for sand/fines analysis (>0.062 mm). For the East Fork Eklutna Creek the samples averaged 76 percent finer than 0.062 mm and for the West Fork Eklutna Creek samples averaged 80 percent finer than 0.062 mm. Thus, most of the suspended load consists of silt-clay particles with some fine sand. Water/sediment relations that were developed between suspended-sediment transport rate and water discharge for the two sites (fig. 23) showed that for a given discharge, more suspended sediment will be transported past the West Fork site.

The suspended-sediment load for the period June 1 to September 30 for the 1985-87 water years was computed for the East Fork and West Fork basins. Suspended-sediment loads were computed from the mean daily discharge
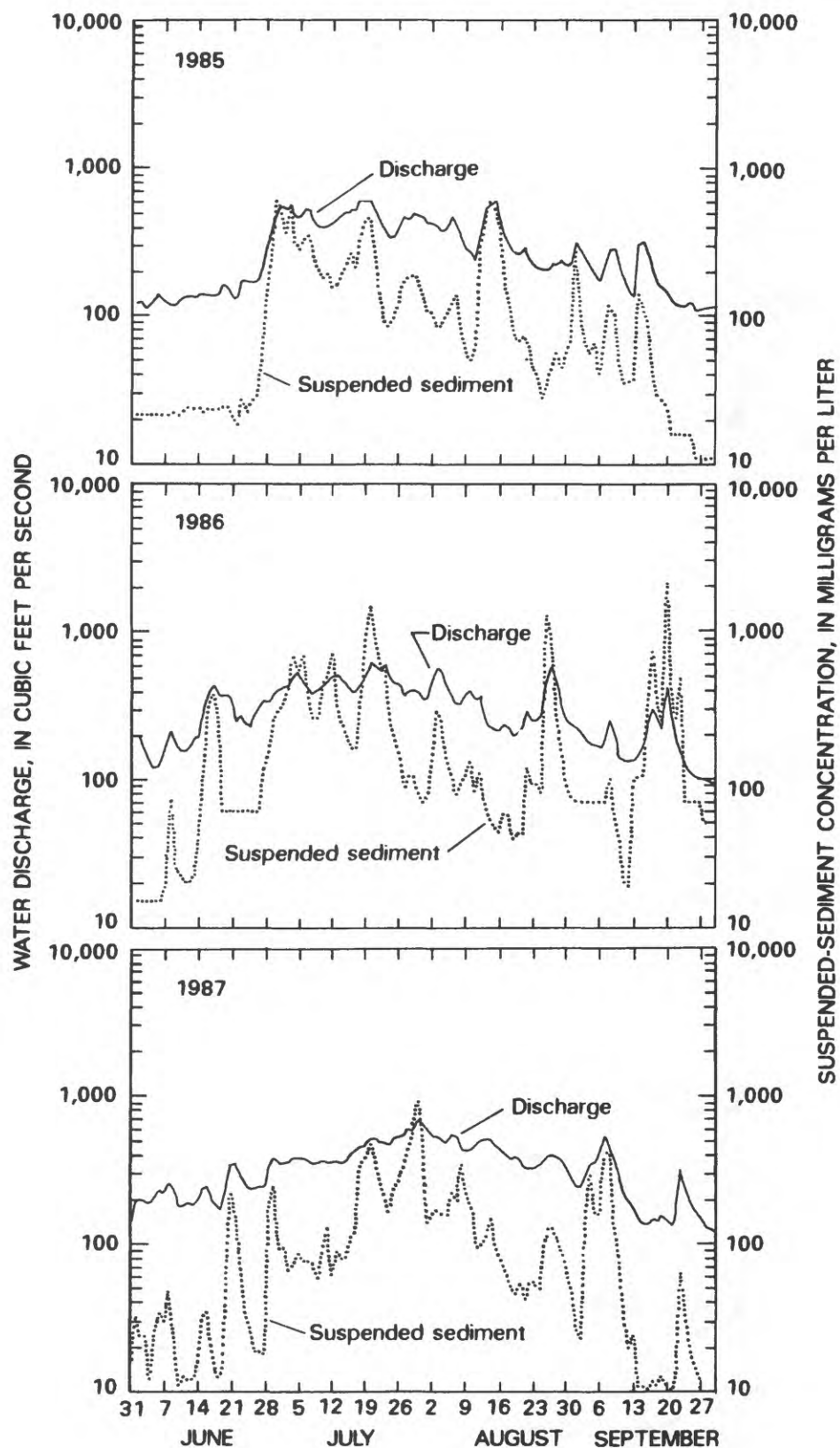
Figure 21.--Daily mean streamflow and suspended-sediment concentration,
June to September 1985, 1986, and 1987, East Fork Eklutna Creek.

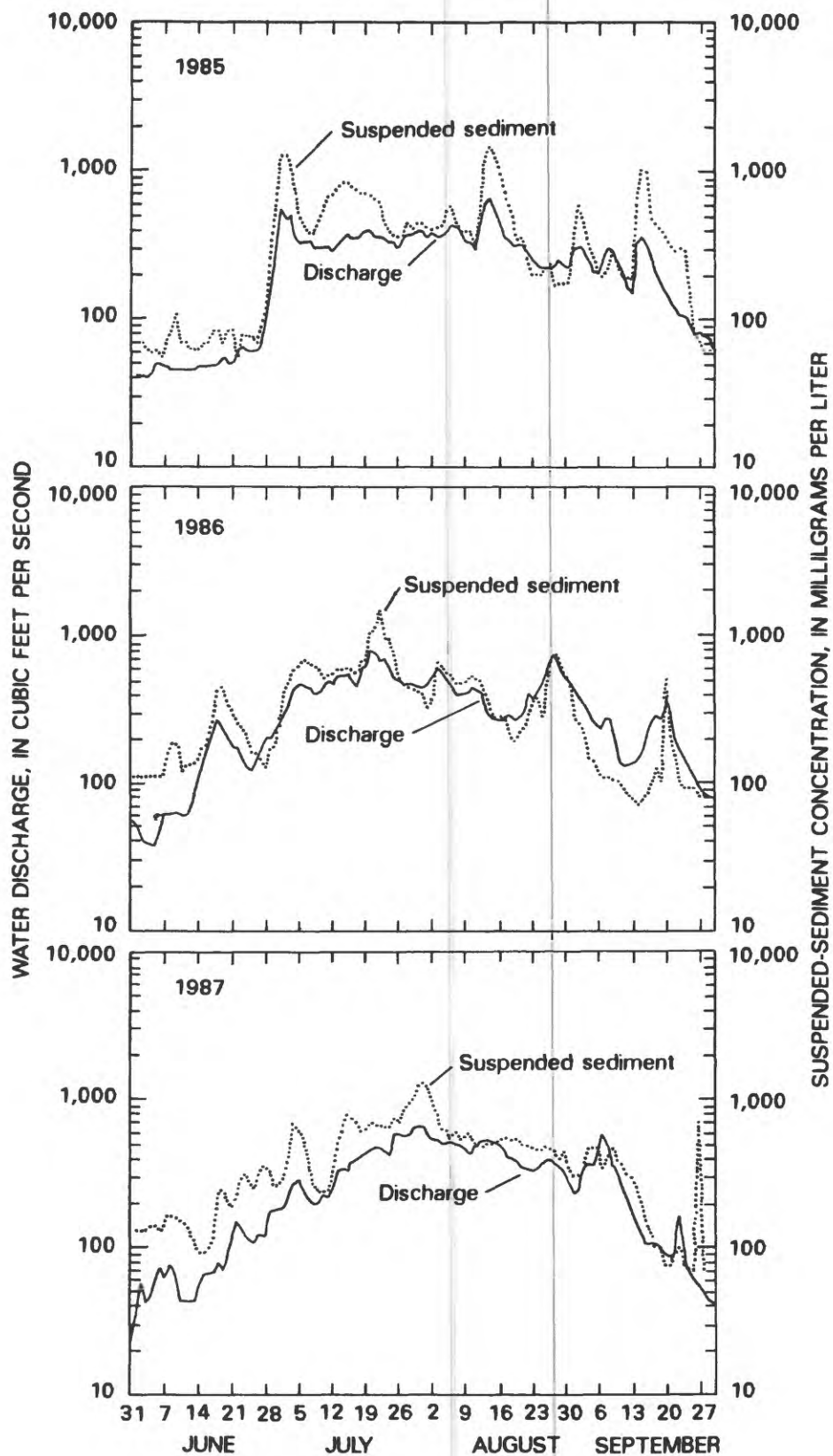Figure 22.--Daily mean streamflow and suspended-sediment concentration,
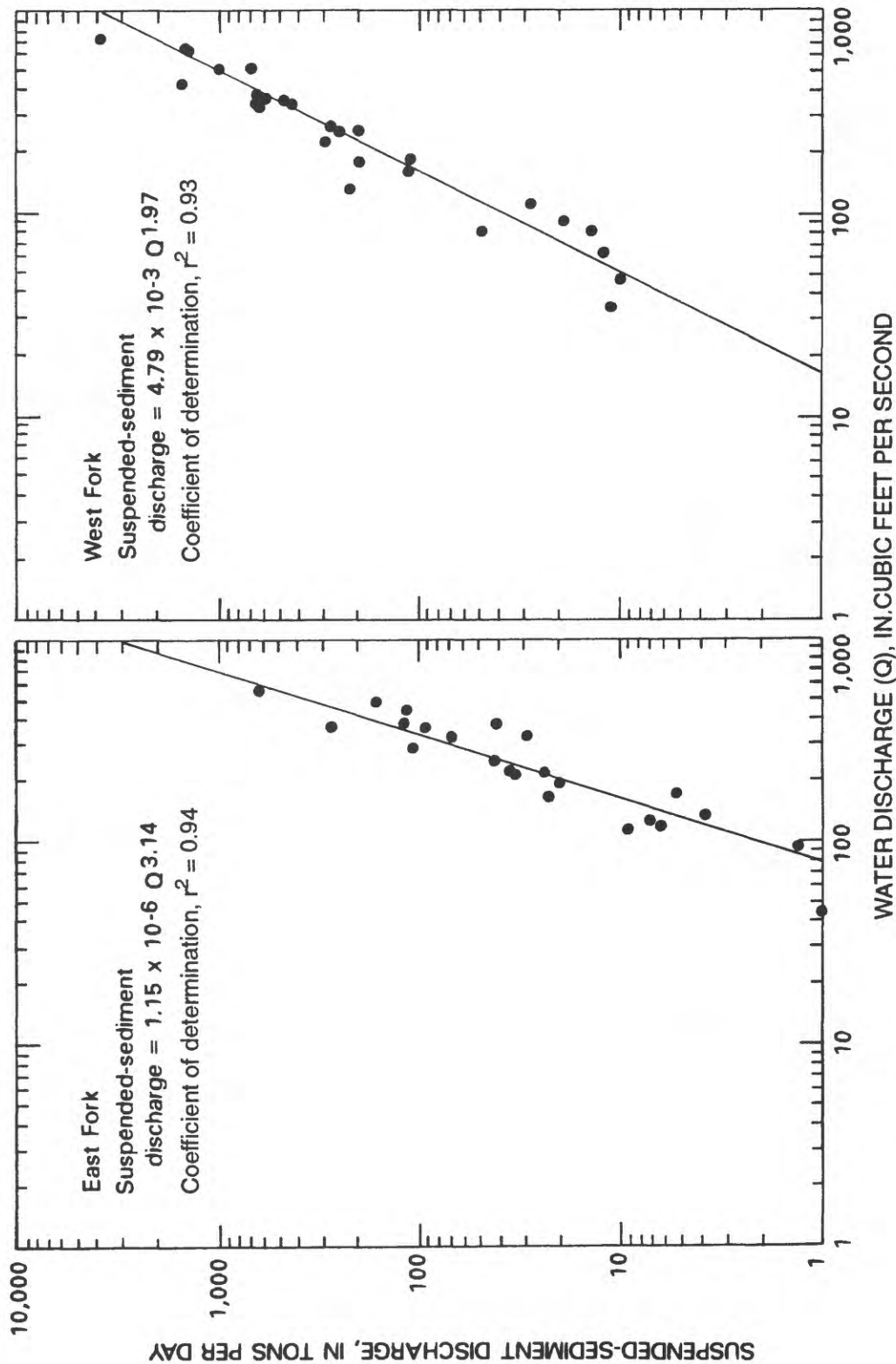June to September 1985, 1986, and 1987, West Fork Eklutna Creek.

30

Figure 23.--Suspended-sediment discharge and water discharge for East Fork and West Fork Eklutna Creeks.

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and mean daily suspended-sediment concentration using the method described by Porterfield (1972). The sum of the loads for this period is assumed to represent the annual load, because of low discharge and sediment concentration from October 1 to May 31. Suspended-sediment transport ranged from 17,400 to 30,200 tons at East Fork Eklutna Creek and from 42,900 to 49,600 tons at West Fork Eklutna Creek (fig. 24). Compared on the basis of a yield (tons per square mile), the West Fork basin (50 percent glacierized) contributes sediment at a rate approximately two to three times greater than does the East Fork basin (20 percent glacierized).

Bedload Discharge

Bedload transport is a process characterized by extreme variability both temporally and spatially. On a temporal basis, bedload may range from zero to about four times the actual average bedload of a stream even when the flow is constant (Hubbell, 1987). Significant spatial variability also occurs because bed material commonly will move only within part of the active channel. Thus, an individual bedload sample may provide no more than the roughest estimate of the actual average bedload transport.

The average particle size of bedload was slightly higher than 2 mm (fine gravel) for both the East Fork and West Fork streams. The median particle size (D_{50}) of bedload (fig. 25) varied from very coarse sand to fine gravel for both streams. More sand is transported at higher discharges in both streams.

The statistical relations between bedload transport rate and water discharge for the two sites (fig. 26) are not as accurate as the relation of water discharge to suspended-sediment transport (fig. 23). This indicates that bedload discharge is influenced by factors other than water discharge. These factors could include the hydraulic conditions of the stream, the time lag between movement of bed material and runoff, or the efficiency of the Helley-Smith sampler. However, the equations for both sites are similar, which indicates that for a given discharge, approximately the same amount of bedload is transported past both sites.

The total bedload for the East Fork and West Fork Eklutna Creeks was estimated using the shift-control method of Colby (1956). In this subjective method, judgement is used to decide whether or not the transport curves in figure 26 should be shifted to pass through or near each individual measurement. Although subjective, the method is considered the most reliable one available. Bedload transported from June 1 to September 30 during the 1985-87 water years ranged from approximately 4,900 to 6,300 tons at East Fork Eklutna Creek and from approximately 3,800 to 5,000 tons at West Fork Eklutna Creek (fig. 27). It is assumed that the total load for this period also represents the annual total. Given the sampling limitations mentioned above and the computation procedures, the total bedload transported past each site during the 1985 and 1986 water years was approximately equal. In 1987, more bedload was transported past the East Fork gage. A possible explanation for this difference may be the influence of a flood that occurred in 1986. The resulting floodwaters may have resupplied the channel with material that was then transported during 1987.

The total annual sediment load (suspended sediment plus bedload) transported past the East Fork Eklutna Creek gage from 1985-87, ranged from 22,300 to 36,500 tons. At the West Fork Eklutna gage, the total annual sediment load transported ranged from 46,700 to 54,600 tons. Bedload constitutes between 14 and 26 percent of the total sediment transported past

SUSPENDED-SEDIMENT LOAD, IN TONS

28,000
26,000
24,000
22,000
20,000
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0

JUNE   JULY   AUG   SEPT
1985

JUNE   JULY   AUG   SEPT
1986

JUNE   JULY   AUG   SEPT
1987
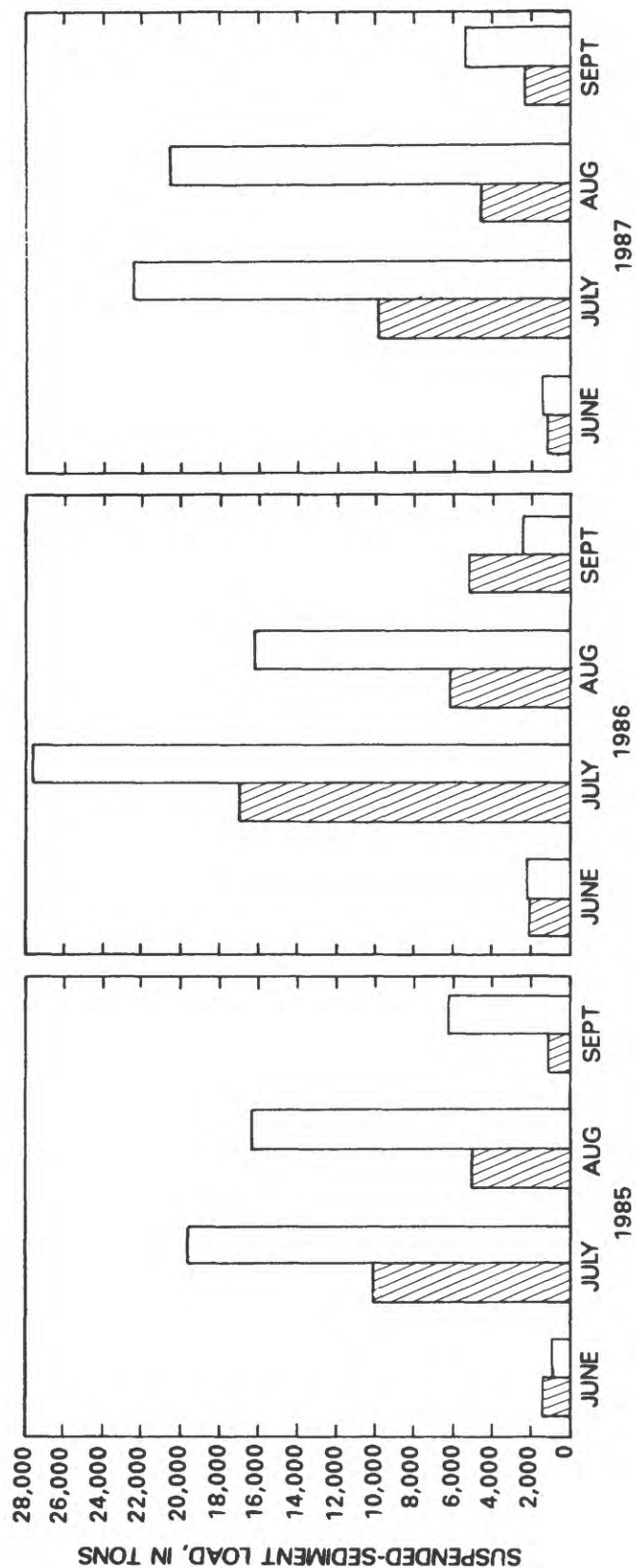
EXPLANATION

	EAST FORK		WEST FORK
YEAR			
1985	Total Suspended Load = 17,400 tons		Total Suspended Load = 42,900 tons
1986	Total Suspended Load = 30,200 tons		Total Suspended Load = 48,400 tons
1987	Total Suspended Load = 17,700 tons		Total Suspended Load = 49,600 tons

Figure 24.--Suspended-sediment loads for East Fork and West Fork Eklutna Creeks,
June to September 1985, 1986, and 1987.

33
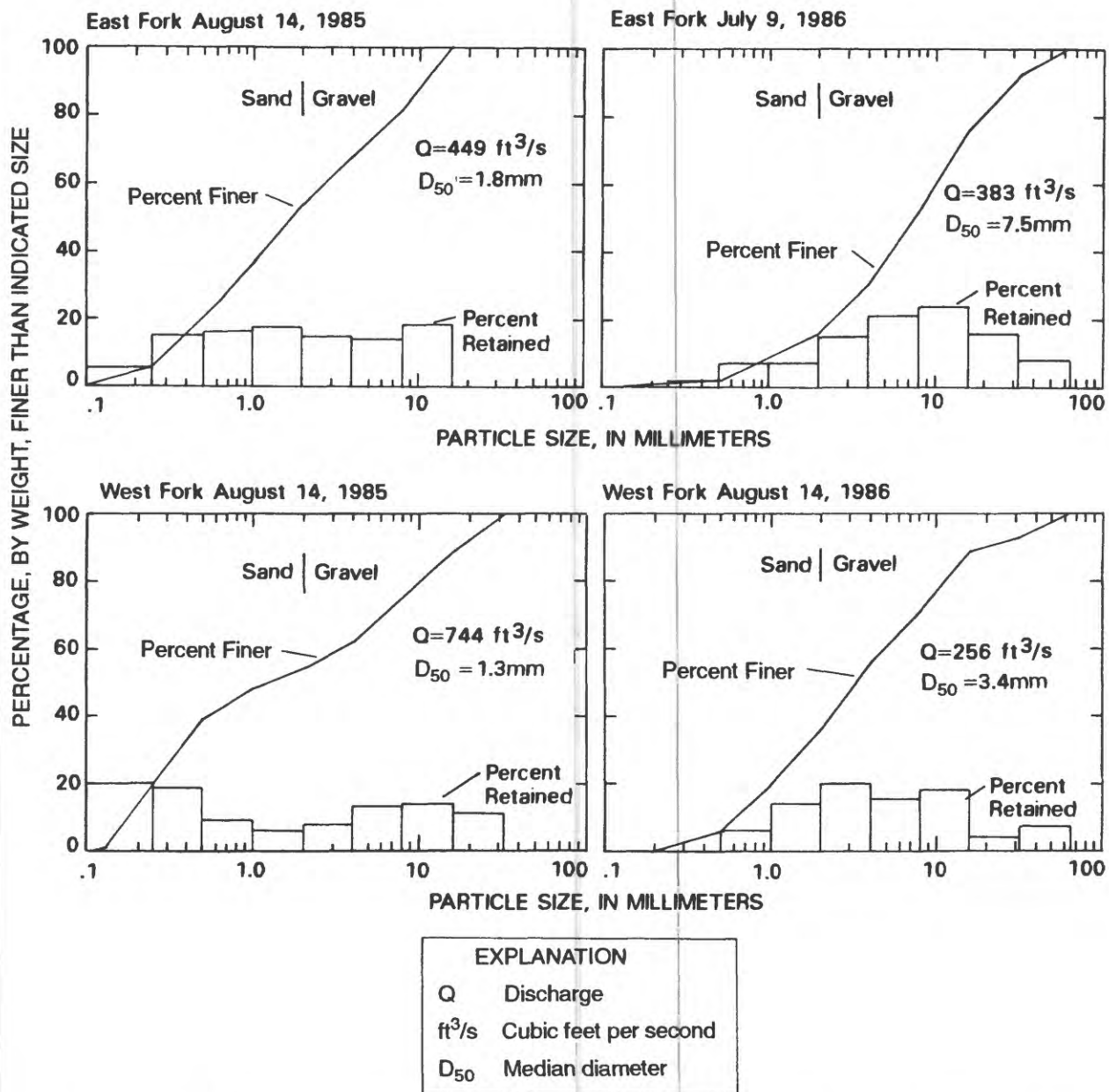
Figure 25.--Particle-size distribution and median diameter of bedload for East Fork and West Fork Eklutna Creeks.
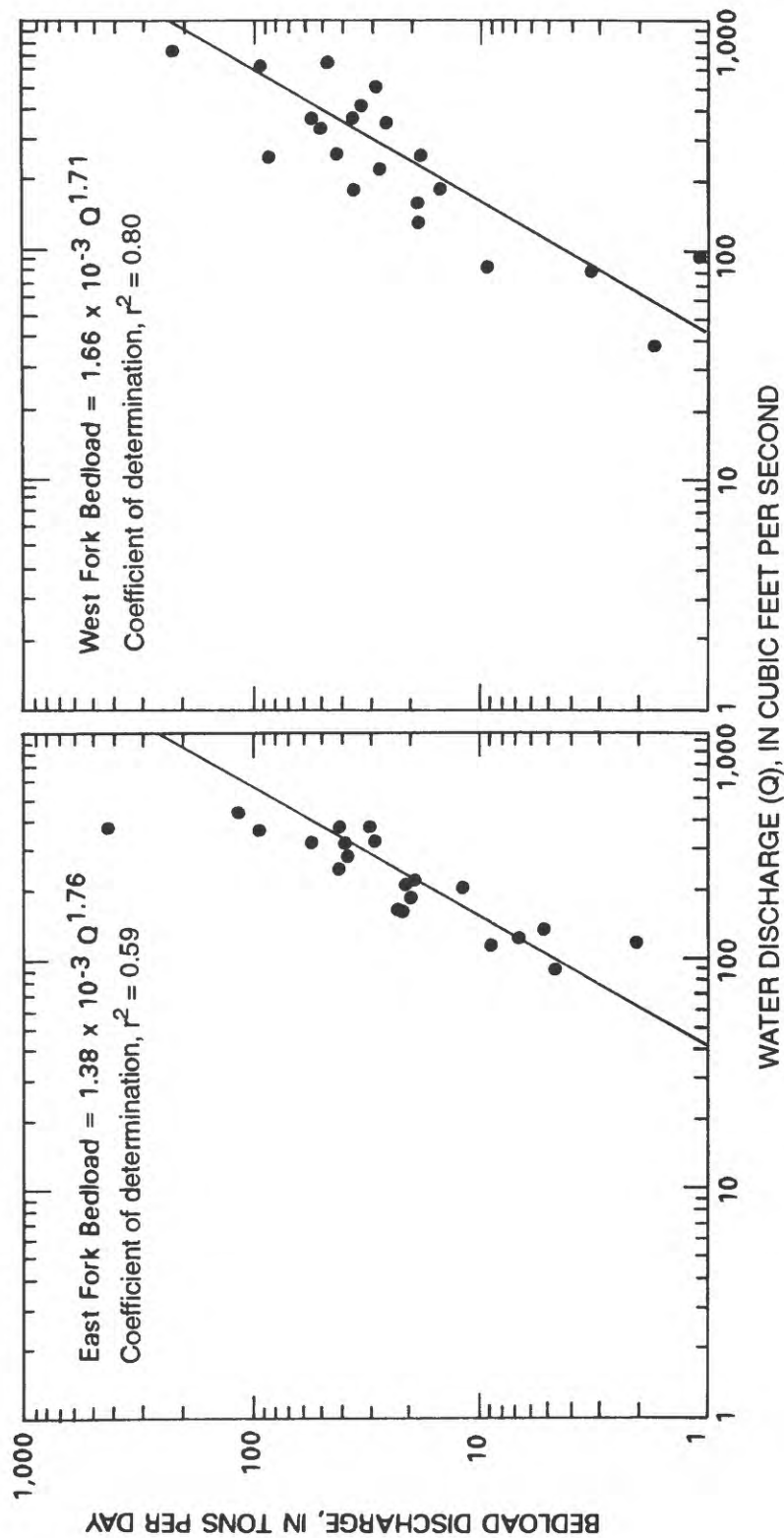
Figure 26.--Bedload discharge and water discharge for East Fork and West Fork Eklutna Creeks.
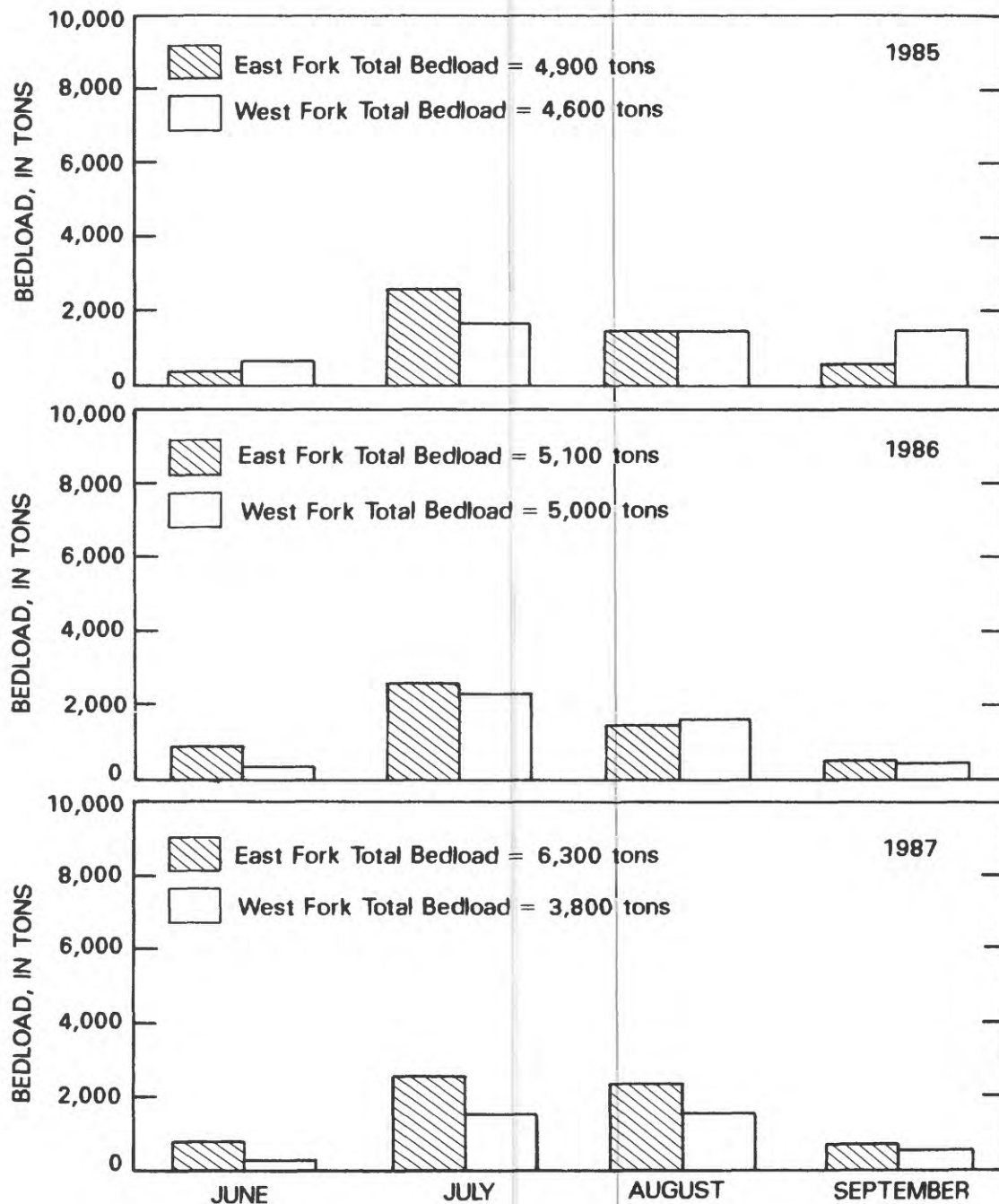
Figure 27.--Bedload for East Fork and West Fork Eklutna Creeks, June to September 1985, 1986, and 1987.

the East Fork gage and between 7 and 10 percent of the total sediment transported past the West Fork gage.

Eklutna Lake

Eklutna Lake has two primary sedimentation processes: (1) delta progradation and (2) river plume dispersion. Delta progradation is the buildup and movement of sediment at the mouth of an inflow stream caused by the sudden decrease in water velocity. River plume dispersion involves the transport and deposition of medium- and fine-grained particles by the plume of river water as it moves through the lake.

Delta Progradation

Hydraulic conditions change at the mouth of the inflowing stream that enters Eklutna Lake (plate 1). This stream, which is the combined flow of the East Fork and West Fork Eklutna Creeks, undergoes a rapid decrease in velocity. The stream's coarse sediment load (mostly the bedload) is deposited and the delta that is formed is composed of three layers: a "topset" layer, a "foreset" layer, and a "bottomset" layer (fig. 28). The topset layer consists of sediment deposited on the top surface of the

advancing delta, which is continuous with landward alluvial deposits. The foresets are inclined layers of sandy material deposited upon or along an advancing and relatively steep frontal slope. The bottomset is fine-grained material (usually silt and clay) deposited slowly on the bed of a quiescent body of water (U.S. Geological Survey, 1977).

The approximate extent of the delta of Eklutna Lake was determined from bathymetric profiles and core samples (fig. 7). This location was then compared with the approximate location of the delta in 1957, which was inferred by aerial photography taken that year. Comparison of the two locations indicates that the delta front has not advanced a significant amount.

As another way of examining the movement of the delta front, an accumulation rate of material was determined as follows:

1) The total bedload entering Eklutna Lake was assumed to equal the sum of the bedload past the East Fork and West Fork gaging stations. This gives a total of approximately 10,000 ton/yr.
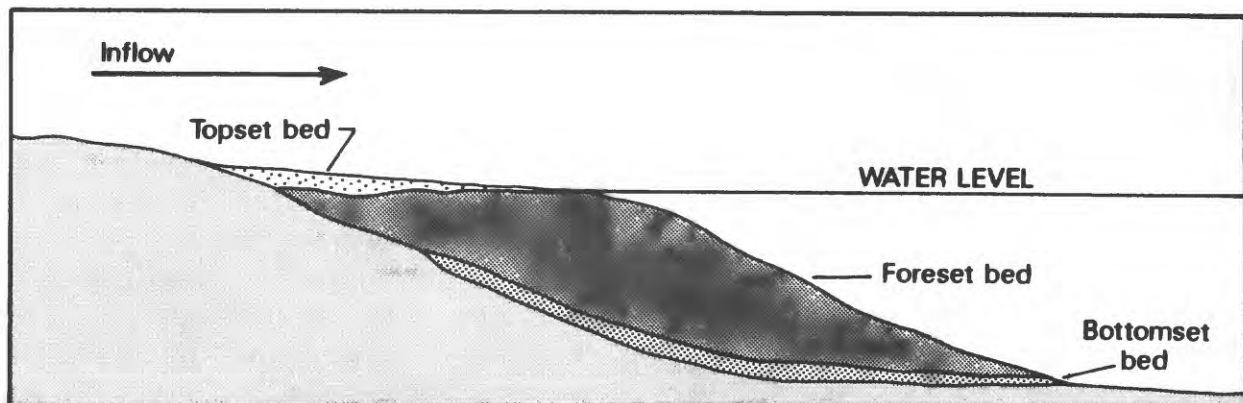
Figure 28.--Types of sediment layers formed by inflow to Eklutna Lake.

2) On the basis of work by Lara and Pemberton (1963), the density of the bedload was estimated to equal 100 lb/ft^3. The accumulation rate was then determined by converting 10,000 ton/yr to a volume based on the unit weight of 100 lb/ft^3. This yields a value of approximately 5 acre-ft/year, which is considered a low rate of accumulation for this study area.

River Plume Dispersion

When the combined inflow of the East and West Fork Eklutna Creeks enters Eklutna Lake, the finer size material (silt and clay) is not deposited in the delta area but rather continues to move through the lake as a plume and eventually is deposited on the bottom of the lake. This type of plume, commonly referred to as a "density" or "turbidity" current, is defined as a current that carries fine-grained sediment in suspension (Friedman and Sanders, 1978). The density of this current depends on the concentration of suspended sediment and on the water temperature, and is usually different from that of the receiving lake water. The density current will then move into and through the lake as either an overflow, interflow, or underflow of lake water.

The location and extent of the density current in Eklutna Lake was determined by measuring transmissivity. Transmissivity is a function of light transmitted through a given path length relative to the total incident light and is expressed in percentage. Thus, transmissivity is inversely related to turbidity.

In October, the transmissivity measurements indicated a slight underflow (fig. 29A). This would be expected because the lake water has warmed through the preceding summer and fall (isothermal) and the incoming glacier-fed streams are colder than the lake. By spring (fig. 29B), the lake water is still isothermal except for the top layer, and no plume is evident. At this time the lake water is clearest (highest transmissivity), reflecting the fact that many of the fine particles have settled to the bottom of the lake. By the end of spring and first part of summer, the lake may be characterized by small overflow (fig. 29C). However, when the major inflow to Eklutna Lake occurs from the end of June through August, a distinct interflow occurs (fig. 29D). It is during this period that most of the fine-grained suspended sediments enter Eklutna Lake and that transmissivity values are lowest. In mid-September, the process repeats itself when inflow begins to decrease and the lake is completely mixed.

Rate of Sediment Accumulation

The proportion of sediment retained in Eklutna Lake--called its "trap efficiency"--has been estimated at 97 percent (Coffin and Ashton, 1986). Assuming that the total amount of sediment entering Eklutna Lake is the sum of the sediment transported past the East Fork and West Fork Eklutna gages, an average total of approximately 76,000 ton/yr remains in the lake.

Another way of representing the accumulation rate is on a volume basis. This is determined by dividing the amount of sediment that enters the lake by the unit weight of the sediment. For Eklutna Lake, the unit weight was determined from the six core samples (fig. 7) by obtaining the dry weight of each sample and the volume of the core it occupied. The average unit weight of these samples was 47 lb/ft^3. The accumulation rate was then determined by converting 76,000 ton/yr to a volume based on a unit weight of 47 lb/ft^3, yielding a value of approximately 74 acre-ft/yr.
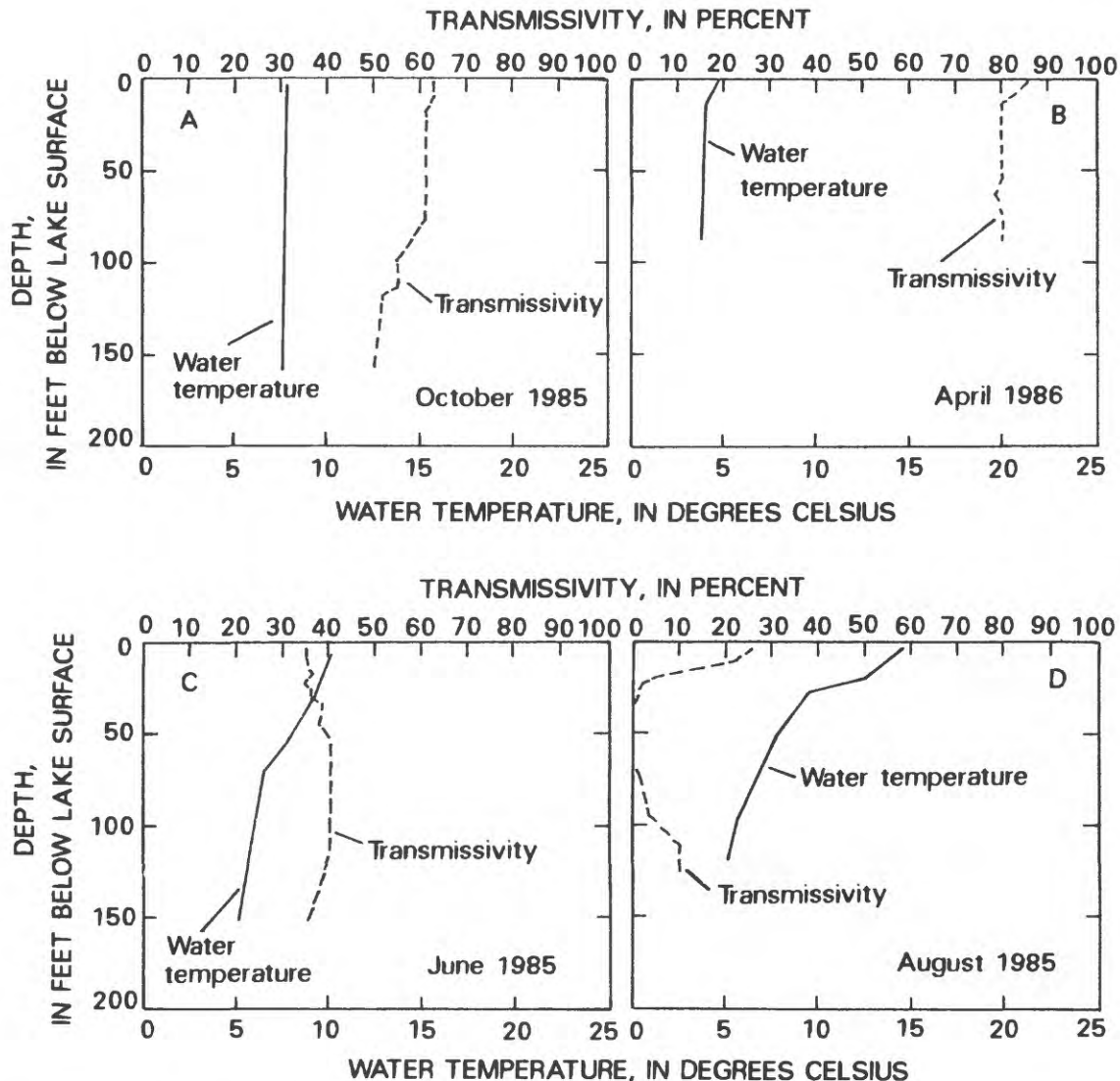
Figure 29.--Profiles of density current in Eklutna Lake at various times showing:
A, underflow; B, no density current; C, overflow; and D, interflow.

WATER STORAGE IN EKLUTNA LAKE

The intake that supplies water to the Eklutna Power Plant and the Eklutna Water Project is at altitude 814.00 ft above sea level. Any volume of water above this altitude is often referred to as the "active storage." The active storage of Eklutna Lake, computed by the Alaska Power Administration, ranges from 0 acre-ft at 814.00 ft to 191,807 acre-ft at 875.90 ft (table 8). The active storage determined from a bathymetric survey of Eklutna Lake made in 1986 at altitude 860.00 ft was 145,400 acre-ft. Because this volume is within 5 percent of the

computed value, it is assumed that the values in table 8 are accurate.

The standard equation used in storage analysis is $I - O = \Delta S$, where I is inflow, O is outflow, and ΔS is change in storage. Storage of Eklutna Lake was analyzed to determine the inflow characteristics of the lake by using (1) the outflow records provided by the Eklutna Power Plant, (2) the lake altitudes to determine changes in storage capacity (table 8), and (3) the inflow from the East and West Fork Eklutna Creeks. This analysis (table 9) indicates that most of the inflow occurs in July and

Table 8.--Active storage of Eklutna Lake

[Water-surface altitude in feet above sea level; data from the Alaska Power Administration]

Water surface altitude	Storage at tenths of a foot (acre-feet)									
	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
814	0	282	564	846	1,128	1,409	1,691	1,973	2,255	2,537
815	2,819	3,102	3,385	3,667	3,950	4,233	4,516	4,799	5,081	5,364
816	5,647	5,931	6,215	6,498	6,782	7,066	7,350	7,634	7,917	8,201
817	8,484	8,770	9,054	9,339	9,623	9,908	10,193	10,477	10,762	11,046
818	11,331	11,616	11,902	12,187	12,473	12,758	13,044	13,329	13,615	13,900
819	14,186	14,472	14,759	15,045	15,331	15,617	15,904	16,190	16,476	16,763
820	17,049	17,336	17,623	17,910	18,197	18,484	18,771	19,058	19,345	19,632
821	19,919	20,206	20,496	20,781	21,069	21,356	21,644	21,931	22,219	22,506
822	22,794	23,082	23,370	23,658	23,946	24,234	24,523	24,811	25,099	25,387
823	25,675	25,963	26,252	26,540	26,829	27,117	27,406	27,694	27,983	28,271
824	28,560	28,849	29,138	29,427	29,716	30,005	30,294	30,583	30,872	31,161
825	31,450	31,739	32,029	32,318	32,608	32,897	33,187	33,476	33,766	34,055
826	34,345	34,635	34,925	35,215	35,505	35,795	36,085	36,375	36,665	36,955
827	37,245	37,535	37,826	38,116	38,407	38,697	38,988	39,278	39,569	39,859
828	40,150	40,441	40,732	41,023	41,314	41,605	41,897	42,188	42,479	42,770
829	43,061	43,353	43,644	43,936	44,228	44,519	44,811	45,103	45,395	45,686
830	45,978	46,270	46,563	46,855	47,148	47,440	47,733	48,025	48,318	48,610
831	48,903	49,196	49,490	49,783	50,077	50,370	50,664	50,957	51,251	51,544
832	51,823	52,132	52,427	52,722	53,016	53,311	53,606	53,900	54,195	54,489
833	54,784	55,080	55,375	55,671	55,967	56,262	56,558	56,854	57,150	57,445
834	57,741	58,038	58,335	58,631	58,928	59,225	59,522	59,819	60,115	60,412
835	60,709	61,007	61,305	61,603	61,901	62,198	62,496	62,794	63,092	63,390
836	63,688	63,987	64,286	64,585	64,884	65,183	65,483	65,782	66,081	66,380
837	66,679	66,979	67,279	67,580	67,880	68,180	68,480	68,781	69,081	69,381
838	69,681	69,982	70,284	70,585	70,887	71,188	71,489	71,791	72,092	72,394
839	72,695	72,998	73,300	73,603	73,905	74,208	74,511	74,813	75,116	75,418
840	75,721	76,025	76,328	76,632	76,935	77,239	77,543	77,846	78,150	78,453
841	78,757	79,061	79,366	79,670	79,975	80,279	80,584	80,888	81,193	81,497
842	81,802	82,107	82,413	82,718	83,023	83,328	83,634	83,939	84,244	84,550
843	84,855	85,161	85,467	85,774	86,080	86,386	86,692	86,998	87,305	87,611
844	87,917	88,224	88,531	88,838	89,145	89,452	89,759	90,066	90,373	90,680
845	90,987	91,295	91,603	91,911	92,219	92,526	92,834	93,142	93,450	93,758
846	94,066	94,375	94,684	94,992	95,301	95,610	95,919	96,228	96,536	96,845
847	97,154	97,464	97,773	98,083	98,393	98,702	99,012	99,322	99,632	99,941
848	100,251	100,562	100,872	101,183	101,493	101,804	102,115	102,425	102,736	103,046
849	103,357	103,668	103,980	104,291	104,603	104,914	105,226	105,537	105,849	106,160
850	106,472	106,784	107,097	107,409	107,722	108,034	108,347	108,659	108,972	109,284
851	109,597	109,910	110,224	110,537	110,851	111,164	111,478	111,791	112,105	112,418
852	112,732	113,047	113,361	113,676	113,990	114,305	114,620	114,934	115,249	115,563
853	115,878	116,194	116,510	116,825	117,141	117,457	117,773	118,089	118,404	118,720

Table 8.--Active storage of Eklutna Lake--Continued

Water surface altitude	Storage at tenths of a foot (acre-feet)									
	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
854	119,036	119,353	119,670	119,987	120,304	120,620	120,937	121,254	121,571	121,888
855	122,205	122,523	122,841	123,159	123,477	123,795	124,114	124,432	124,750	125,068
856	125,386	125,705	126,025	126,344	126,664	126,983	127,302	127,622	127,941	128,261
857	128,380	128,901	129,221	129,542	129,863	130,183	130,504	130,825	131,146	131,466
858	131,787	132,109	132,431	132,753	133,075	133,397	133,719	134,041	134,363	134,685
859	135,007	135,330	135,654	135,977	136,300	136,623	136,947	137,270	137,593	137,917
860	138,240	138,565	138,889	139,214	139,539	139,863	140,188	140,513	140,838	141,162
861	141,487	141,813	142,139	142,465	142,791	143,117	143,444	143,770	144,096	144,422
862	144,748	145,075	145,403	145,730	146,058	146,385	146,713	147,040	147,368	147,695
863	148,023	148,352	148,681	149,010	149,339	149,668	149,997	150,326	150,655	150,984
864	151,313	151,643	151,974	152,304	152,635	152,965	153,296	153,626	153,957	154,287
865	154,618	154,950	155,282	155,614	155,946	156,278	156,611	156,943	157,275	157,607
866	157,939	158,273	158,606	158,940	159,274	159,607	159,941	160,275	160,609	160,942
867	161,276	161,611	161,947	162,282	162,618	162,953	163,288	163,624	163,959	164,295
868	164,630	164,967	165,304	165,641	165,978	166,315	166,653	166,990	167,327	167,664
869	168,001	168,340	168,679	169,018	169,357	169,695	170,034	170,373	170,712	171,051
870	171,390	171,731	172,072	172,412	172,753	173,094	173,435	173,776	174,116	174,457
871	174,798	175,141	175,484	175,827	176,170	176,512	176,855	177,198	177,541	177,884
872	178,227	178,572	178,917	179,262	179,607	179,952	180,297	180,642	180,987	181,332
873	181,677	182,024	182,371	182,719	183,066	183,413	183,760	184,107	184,455	184,802
874	185,149	185,498	185,848	186,197	186,547	186,896	187,245	187,595	187,944	188,294
875	188,643	188,995	189,346	189,698	190,049	190,401	190,753	191,104	191,456	191,807

Table 9.-- Change in storage, outflow, and inflow for Eklutna Lake, 1985-88

Year and month	Change in storage (acre-feet) ΔS	Outflow (acre-feet) O	Combined inflow East Fork and West Fork Creeks (acre-feet) I	Inflow not accounted for (acre-feet)	Percentage of inflow accounted for by East and West Fork
1985					
June	- 4,044	20,299	13,360	2,895	82
July	+50,046	11,677	50,950	10,773	82
August	+40,074	8,821	41,120	7,775	84
September	+16,994	12,592	22,750	6,836	76
October	-11,901	20,299	5,430	2,968	65
November	-13,303	17,053	1,877	1,873	50
December	-15,897	20,246	1,569	2,780	36
1986					
January	-20,225	23,161	1,311	1,625	45
February	-20,977	22,630	907	746	55
March	-22,207	23,300	627	466	57
April	-25,846	28,849	1,298	1,705	57
May	+7,394	287	4,409	3,272	57
June	+21,587	5,418	22,040	4,965	82
July	+57,874	6,890	57,860	6,904	89
August	+32,531	15,970	46,070	2,431	95
September	+7,037	20,520	22,870	4,687	83
October	-3,726	25,260	15,680	5,854	73
November	-13,097	20,641	4,139	3,405	55
December	-13,631	19,665	2,290	3,744	38
1987					
January	-19,531	23,645	1,491	2,623	36
February	-18,560	20,944	1,334	1,050	56
March	-25,647	26,723	1,280	204	86
April	-17,723	19,844	835	1,286	40
May	+8,489	34	4,593	3,930	54
June	+26,393	0	19,010	7,383	72
July	+51,688	12,936	50,650	13,974	78
August	+48,356	17,445	53,020	12,781	80
September	+10,259	20,937	25,220	5,976	81
October	-12,446	24,364	6,970	4,948	58
November	-11,436	20,642	2,909	6,297	32
December	-24,358	19,665	1,898	6,591	22
1988					
January	-24,111	27,597	1,403	2,083	40
February	-17,376	20,352	1,033	1,943	35
March	-13,122	16,182	902	2,158	29
April	- 9,988	14,202	944	3,270	22
May	-10,629	26,603	5,841	10,133	36
June	+20,111	22,025	28,610	13,526	68
July	+61,410	19,944	64,110	17,244	79
August	+33,771	30,198	54,250	9,719	85
September	- 5,716	30,126	16,680	7,730	68

August, and that the West Fork and East Fork Eklutna Creeks contribute a large part (80 percent) of water to Eklutna Lake. During winter and spring months, the amount of inflow to the lake is negligible. Most of the inflow is probably derived from ground water.

With the completion of the Eklutna Water Project, Eklutna Lake now serves two purposes: power generation and water supply. Inspection of the operation records of the Eklutna Power Plant (1966-88) indicates that the average outflow of Eklutna Lake is 306 $(ft^3/s)/d$. The yearly average outflow has been as high as 388 $(ft^3/s)/d$ and monthly outflow has been as high as 520 $(ft^3/s)/d$. The Municipality of Anchorage at present could draw 54 $(ft^3/s)/d$ (35 Mgal/d) from the lake and as much as 108 $(ft^3/s)/d$ (70 Mgal/d) if the treatment plant were expanded.

To determine if there will be an adequate supply of water for both purposes, a storage frequency analysis was done using a model developed by Glover (1984). The model first determines whether the total monthly inflow follows a normal, log-normal, Gumbel, Pearson, or log-Pearson distribution using the methods outlined by Riggs and Hardison (1973). A cumulative probability of inflow function is then developed for each month. Conventional flow routing ($I - O = \Delta S$) is done to generate 12 sets of data points relating initial storage, final storage, and total monthly inflows. Applying the routing relations to the inflow functions produces a transition probability matrix for each month, which defines the chance of reservoir storage changing from any level to any new level. Finally, a system of probability equations is written that describes the final storage probabilities for each month in terms of initial storage probabilities and the monthly transition matrix. By operating the program with a given set of storage capacities and outflow rates, a set of risks of failure are

calculated as the probability of exceeding the available storage capacity.

Input data to the model consist of inflow discharge, outflow rate, and storage capacity. For this study, inflow discharge was assumed to be the change in storage plus outflow. Additionally, the user must specify the number of storage layers. The number of layers used to divide the lake storage can have an effect on the error of the analysis and thus the procedure used was to run the model with different numbers of layers to insure that reasonable answers resulted.

Several runs of the storage frequency model were made using different withdrawal rates. The analyses showed that the months of May and June would have the highest probabilities of storage capacities being exceeded (table 10). Probabilities are relatively low (10 percent) that the storage capacity will be exceeded unless withdrawal rates exceed 450 ft^3/s.

SUMMARY AND CONCLUSIONS

Glacier mass balance, runoff, sediment transport and deposition, and lake storage characteristics in the Eklutna Lake basin were studied. Significant findings are:

1) Mass balance measurements made on Eklutna Glacier from 1985 to 1988 did not indicate any significant changes in the glacier. The accumulation area ration (AAR) for each year during the study indicates that the glacier is in an equilibrium state.

2) Two main streams flow into Eklutna Lake: the East Fork Eklutna Creek drains a 38.2-square-mile basin which is 20 percent glacierized (7.6 square miles), and the West Fork Eklutna Creek drains a 25.4-square-mile basin which is 50 percent glacierized (12.2 square miles).

Table 10.-- Risks of failure to supply withdrawal rates during the year at Eklutna Lake

[ft^3/s, cubic feet per second.]

With-drawal rate (ft^3/s)	Jan.	Feb.	Mar.	Apr.	May	June	July (percent)	Aug.	Sept.	Oct.	Nov.	Dec.
360	0.01	0.1	0.3	1.2	3.1	2.6	0.2	0	0	0	0	0
410	.04	.3	1.2	3.6	8.0	5.6	.4	0	0	0	0	0
450	.1	.5	1.8	4.9	9.8	7.5	.8	0	0	0	0	0
500	.4	1.3	3.7	7.7	13.0	14.9	3.1	0	0	0	0	0
550	.8	2.4	5.8	10.8	16.4	17.4	3.6	0	0	0	0	0.2

3) Daily discharges from both the East Fork and West Fork Eklutna Creeks show a distinct diurnal fluctuation: the low flow of the day occurs in mid-morning and the high flow of the day occurs in the evening.

4) During the 1986, 1987, and 1988 water years, between 77 and 84 percent of the total runoff from the East Fork Eklutna Creek basin occurred from June 1 to September 30. The principal components of runoff during this period were snowmelt (53-63 percent), rainfall (27-29 percent), and icemelt (6-13 percent).

5) During the 1986, 1987, and 1988 water years, between 87 and 96 percent of the total runoff from the West Fork Eklutna Creek basin occurred from June 1 to September 30. The principal components of runoff during this period were snowmelt (52-64 percent), rainfall (27-33 percent), and icemelt (9-19 percent).

6) A USGS flow model, the Precipitation-Runoff Modeling System, simulated the general discharge trends of the East Fork and West Fork Eklutna Creeks. The model's computational scheme for determining icemelt appears reasonable; however, more development in the model is needed to represent a glacier's drainage system.

7) From 1985-87, total yearly sediment transported by the East Fork Eklutna Creek ranged from 22,300 to 36,500 tons, while total yearly sediment transported by the West Fork Eklutna Creek ranged from 46,700 to 54,600 tons. Bedload constitutes between 14 and 26 percent of the sediment for East Fork Eklutna Creek and between 7 and 10 percent of the sediment for West Fork Eklutna Creek.

8) Two sedimentation processes characterize Eklutna Lake: delta progradation and river plume dispersion. At the delta area, coarse

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sediment is accumulating at a rate of about 5 acre-ft/yr, while the finer sediments are accumulating at a rate of 74 acre-ft/yr. A distinct interflow plume is present in the lake from late June through August.

9) Eklutna Lake has an active storage ranging from 0 to 190,000 acre-ft. Approximately 80 percent of the water that enters Eklutna Lake is from the East Fork and West Fork Eklutna Creeks.

10) A storage frequency analysis of Eklutna Lake indicates that May and June are the months when the storage capacity of the lake will most likely be exceeded. However, the probability of storage being exceeded during these months is less than 10 percent at a withdrawal rate of 450 ft^3/s.

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GLOSSARY

Ablation - Melt of snow, firn, or ice.

Accumulation area ratio (AAR) - The area of accumulation of a glacier divided by the total glacier area.

Annual balance - The change in thickness of a glacier at a point from October 1 to September 30. Water equivalent depth is used throughout.

Average annual balance - The integrated annual balance over the glacier surface divided by the glacier area.

Bottomset bed - Fine-grained material (usually silts and clays) slowly deposited on the bed of quiescent body of water and which may in time be buried by foreset beds and topset beds.

Delta - A deposit of sediment formed where moving water (as from a stream at its mouth) is slowed by a body of standing water.

Density current - A highly turbid and relatively dense current which usually moves along the bottom of a body of standing water. Also referred to as a turbidity current.

Equilibrium line altitude (ELA) - The line on a glacier that divides the area of positive annual balance (high altitude) from the area of negative annual balance (low altitude). This is at approximately 4,000 ft on the Eklutna Glacier.

Firn - Snow that has survived at least one summer.

Foreset bed - Inclined layers of sandy material deposited upon or along an advancing and relatively steep frontal slope. A foreset bed progressively covers a bottomset bed, and in turn is covered by a topset bed.

Internal accumulation - The process of liquid water freezing within a glacier. This happens in two ways. First, water left as capillary water at the end of summer freezes during winter. Second, the first water to penetrate the glacier freezes in the underlying cold snow and firn (Trabant and Mayo, 1985).

Topset bed - A layer of sediments deposited on the top surface of an advancing delta which is continuous with the landward alluvial plain.