

Selected Papers in the Hydrologic Sciences 1986

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United States
Geological
Survey
Water-Supply
Paper 2290



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Edited by Seymour Subitzky

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DEPARTMENT OF THE INTERIOR
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PREFACE

Selected Papers in the Hydrologic Sciences is a new journal-type publication presenting timely results on hydrologic studies derived from the Federal research program and the Federal-State cooperative program of the U.S. Geological Survey, which is aimed at meeting widespread public and professional interests of the hydrosience community. Also included may be results of some studies done on behalf of other Federal agencies.

This third issue of the *Selected Papers* series, comprising 13 topical papers, addresses a range of topics including model simulation of ground- and surface-water systems, hydrogeochemistry, limnology, and selected physical and chemical techniques for hydrologic studies.

As a journal-type publication, *Selected Papers* is intended to serve as a forum that encourages dialogue between readers and authors. Discussion from *all* members of the hydrosience community is welcomed. A discussion section for readers' comments and authors' replies is included in each issue. Such dialogue for this issue will be open until June 1986. Address comments to Editor, *Selected Papers in the Hydrologic Sciences*, U.S. Geological Survey, 444 National Center, Reston, Virginia 22092.

A handwritten signature in cursive script, reading "Seymour Subitzky".

Seymour Subitzky
Editor

SI and Inch-Pound Unit Equivalents

International System of Units (SI), a modernized metric system of measurement. All values have been rounded to four significant digits. Use of hectare (ha) as an alternative name for square hectometer (hm²) is restricted to measurement of land or water areas. Use of liter (L) as a special name for cubic decimeter (dm³) is restricted to the measurement of liquids and gases.

Multiply SI units	By	To obtain inch-pound units
Length		
micrometer (μm)	0.000 039 37	inch (in)
millimeter (mm)	0.039 37	inch (in)
centimeter (cm)	0.393 7	inch (in)
meter (m)	3.281	foot (ft)
	1.094	yard (yd)
kilometer (km)	0.621 4	mile (mi)
Area		
centimeter ² (cm ²)	0.155 0	inch ² (in ²)
meter ² (m ²)	10.76	foot ² (ft ²)
	1.196	yard ² (yd ²)
	0.000 247 1	acre
hectometer ² (hm ²)	2.471	acre
kilometer ² (km ²)	0.386 1	mile ² (mi ²)
Volume		
centimeter ³ (cm ³)	0.061 02	inch ³ (in ³)
milliliter (mL)	0.061 02	inch ³ (in ³)
liter (L)	61.02	inch ³ (in ³)
	0.035 31	foot ³ (ft ³)
	33.82	ounce, fluid (oz)
	2.113	pint (pt)
	1.057	quart (qt)
	0.264 2	gallon (gal)
meter ³ (m ³)	35.31	foot ³ (ft ³)
	1.308	yard ³ (yd ³)
	264.2	gallon (gal)
	0.000 810 7	acre-foot (acre-ft)
kilometer ³ (km ³)	0.239 9	mile ³ (mi ³)
Mass		
microgram (μg)	0.000 015 43	grain (gr)
gram (g)	0.035 27	ounce, avoirdupois (oz avdp)
kilogram (kg)	0.002 205	pound, avoirdupois (lb avdp)

Multiply SI units	By	To obtain inch-pound units
Mass per unit volume		
microgram per liter (μg/L)	0.000 058 41	grain per gallon (gr/gal)
milligram per liter (mg/L)	0.058 41	grain per gallon (gr/gal)
Mass or volume per unit time (includes flow)		
gram per minute (g/min)	0.035 27	ounce (avoirdupois) per minute (oz/min)
milliliter per minute (mL/m)	0.033 82	ounce (fluid) per minute (oz/min)
	0.035 31	foot ³ per second (ft ³ /s)
liter per second (L/s)	15.85	gallon per minute (gal/min)
meter ³ per second (m ³ /s)	35.31	foot ³ per second (ft ³ /s)
	15 850	gallon per minute (gal/min)
meter per second (m/s)	3.281	foot per second (ft/s)
meter per day (m/d)	3.281	foot per day (ft/d)
Transmissivity		
meter ² per day (m ² /d)	10.76	foot ² per day (ft ² /d)
Force per unit area		
kilopascal (kPa)	0.145 03	pound-force per inch ² (lbf/in ²)
kilogram per meter ² (kg/m ²)	0.204 8	pound-force per foot ² (lbf/ft ²)
kilogram per meter ³ (kg/m ³)	0.624 6	pound-force per foot ³ (lbf/ft ³)
Temperature		
degree Celsius (°C)	Temp °F=1.8 temp °C+32	degree Fahrenheit (°F)
Specific conductance		
microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25 °C)	1.000	micromho per centimeter at 25 degrees Celsius (μmho/cm at 25 °C)
millisiemens per meter at 25 degrees Celsius (mS/m at 25 °C)	1.000	millimho per meter at 25 degrees Celsius (mmho/m at 25 °C)

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Recent Growth of Gulkana Glacier, Alaska Range, and its Relation to Glacier-Fed River Runoff

By Lawrence R. Mayo and Dennis C. Trabant

Abstract

A hydrologically important shift in climate within the past decade is indicated for the Alaska Range, a glacierized region of relatively high river runoff rates. From 1910 to 1976 Gulkana Glacier thinned and receded. Water released from glacier storage during this period augmented river runoff. Since 1976 the glacier has thickened in the accumulation zone, has thinned slightly in the ablation zone, and is approaching a state of glacier mass and ice-flow equilibrium. The long recession is apparently ended. Recent moraines indicate that all other glaciers in the Alaska Range behaved similarly, which suggests that climatic variations affecting Gulkana are widespread.

River flow from the Alaska Range increased during the recent period of glacier growth, suggesting that this growth was caused by increased precipitation. The hypothesis that glacier growth in the Alaska Range could signal a period of diminished streamflow is not supported.

INTRODUCTION

Glaciers of the Alaska Range, without a known exception, have receded during the past century, leaving conspicuous ice-cored moraines. Sellmann (1962, p. 31) illustrated the magnitude of the large retreat at Gulkana Glacier using comparative photographs taken in 1910 and 1952 (fig. 1).

Anderson (1970, sheet 3) estimated that approximately 5 percent, $50 \text{ m}^3/\text{s}$, of the Tanana River flow since 1910 was derived from glacier ice storage loss. Harrison and others (1983, p. 101–102) measured similar ice losses from 1949 to 1980 at an unnamed glacier 70 km west of Gulkana. They concluded that ice loss contributed 13 percent of the Susitna River discharge during the measurement period from 1949 to present.

Two scenarios of possible responses of glacier-fed river runoff to glacier growth in the Alaska Range were suggested by Bowling (1983). If glacier growth occurs by increased airflow from arctic regions, diminished glacier melting and precipitation would produce less streamflow. Conversely, if glacier growth occurs by increased airflow from the Pacific Ocean, glaciers would grow as a result of increased snow precipitation. At the same time runoff would increase due to increased melting and precipitation.

This scenario is already known to occur at Wolverine Glacier in south-central Alaska (Mayo and Trabant, 1984).

Therefore, measurements of whether glaciers in the Alaska Range are continuing to recede or growing, continuous monitoring of glacier-fed rivers, and interpretation of the causes of fluctuations are critical to understanding long-term trends in water supply and potential hydro-power.

GULKANA GLACIER ALTITUDE DATA

Glaciers in the Alaska Range have been observed for a relatively short period. The longest and most complete set of observations available is for Gulkana Glacier (lat 63.3°N ., long 145.5°W .). Péwé and Reger (1983, p. 110) determined the dates of recent advances of Gulkana from lichenometric and geological evidence. They concluded that the last advance, during what is often referred to as the "Little Ice Age", culminated between 1875 and 1900.

F.H. Moffit obtained the first known photographs of Gulkana Glacier in the summer of 1910 (fig. 1). These photographs show the ice margins to be close to the position of the latest advance dated by Péwé and Reger. The 1910 altitude profile of the lower part of the glacier (fig. 2) was interpreted by comparing the photographs with detailed topographic maps.

The first altitude measurements of the glacier were made by the U.S. Geological Survey as part of the national mapping program. The Gulkana Glacier part of the Mt. Hayes, Alaska, topographic maps was produced by photogrammetric techniques from stereo aerial photographs taken in 1949.

In 1960, Rutter (1961, plate 1) prepared a topographic map of Gulkana Glacier from plane-table surveys. A resurvey by us of a monument (Station "M") left by Rutter and Sellmann (Sellmann, 1962, pl. 3) indicates that the altitudes reported by Rutter are 11.78 m too high. Therefore, we have subtracted 12 m from the altitudes reported by Rutter.

In 1973, we remeasured the longitudinal profile by theodolite surveys, and in 1975 we initiated a program of



1910



1952

Figure 1. Photograph of Gulkana Glacier in 1910 by F.H. Moffit. U.S. Geological Survey photographs 423–424, July 15, 1910. Photograph from the same location in 1952 by T.L. Péwé (photographs 666–668, July 12, 1952).

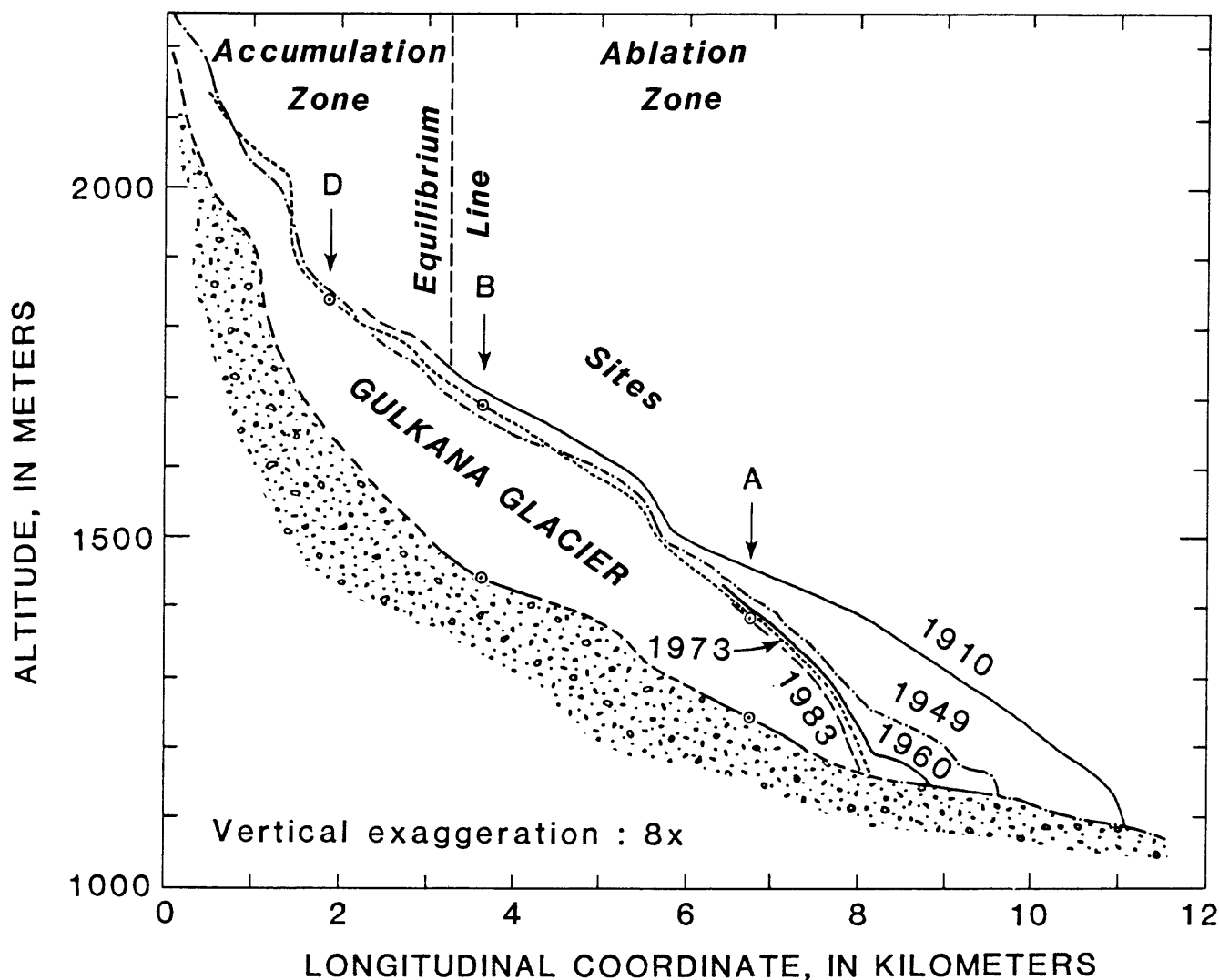


Figure 2. Longitudinal profiles of Gulkana Glacier from 1910 to 1983. Positions of seasonal altitude measurement sites A, B, and D are indicated by arrows. The glacier bed altitude was measured at two sites along the center line by low-frequency radar techniques.

precise altitude measurements several times a year at three fixed locations along the glacier centerline (table 1, fig. 3). The altitude of the glacier bed (fig. 2) was measured in 1976 by low-frequency mono-pulse radar techniques.

The accuracy of altitude information has increased steadily with time. The 1910 photographs cannot be interpreted with more confidence than ± 30 m. The 1949 aerial photogrammetry is generally considered accurate within about ± 15 m altitude, except in the snow-covered areas where the errors are usually larger. The 1960 map probably has an accuracy of ± 5 m after the -12 m correction is applied. The 1973 centerline survey has an accuracy of about ± 1.0 m. Finally, the seasonal altitude measurements made repeatedly since 1975 at fixed coordinates have an accuracy of ± 0.1 m.

Interpretation of the Altitude Profiles

Glaciers that end on land advance or recede due to fluctuations in climate and flow instabilities. Post (1969, p. 232) classified Gulkana as a surging glacier on the basis of its moraine patterns, suggesting that Gulkana can advance due to both causes.

The 1910 photographs of Gulkana show the glacier to be fairly smooth, not crevassed by surging. Other smaller glaciers shown in the 1910 photographs (fig. 1) were also much thicker than in 1952. Therefore, the advance is interpreted to have been controlled primarily by climate. A minor flow instability, or glacier pulse, may have modified the extent of this advance.

There is no evidence, such as push moraines or deformed medial moraines on the glacier surface, to indicate that Gulkana Glacier has surged since 1910. The

Table 1. Sea level-scale local coordinates (in meters) for reference monuments and measurement sites at Gulkana Glacier

Name of site	X	Y	Z
Moore -----	6882.55	7663.62	2089.45
Slim -----	5523.92	7085.96	1909.56
Pass -----	5508.45	8560.38	1908.51
No -----	4435.04	7674.12	1761.42
Yes -----	4451.60	7657.95	1756.93
Rotor -----	2858.27	7405.42	2090.21
IGY -----	1490.10	5981.82	2000.76
"M" -----	4618.34	3854.13	1449.25
"M" (Sellmann, 1962) -----			1461.03
Downdraft -----	2806.95	4795.99	1599.13
Army -----	4713.65	3042.53	1677.40
Péwé -----	1933.74	1619.33	1151.75
Site A -----	3944.10	4293.80	
Site B -----	4847.60	7237.70	
Site D -----	6118.00	7200.10	

surge- and pulse-induced medial moraine patterns on the glacier surface near the terminus at the present time are judged to be remnant from flow instabilities that occurred during the 19th century. Thus, surging probably has not modified the longitudinal profile or the terminus position of Gulkana during this century.

From 1910 to 1949, Gulkana thinned an average of 100 m in the lower part of the ablation zone of the glacier (see fig. 2). The terminus retreated 1.6 km. The upper part of the glacier thinned much less. Moraines at the equilibrium line are only 20–30 m above the present ice surface.

By 1949, the lowest 1.5-km section of the glacier had become nearly stagnant. The convex profile above the 8.2-km longitudinal coordinate (see fig. 2) suggests that glacier flow in 1949 was replenishing part of the ice loss due to ablation; that is, it appeared then that the climate could support a glacier length of approximately 8.0 km.

The 1960 map of Gulkana Glacier (Rutter, 1961, pl. 1) shows that the glacier had thinned and retreated a small amount from 1949, but without any other major changes.

By 1973 the glacier had retreated to a length of 8.2 km, had lost almost all of the stagnant ice tongue, and had regained a convex longitudinal profile near the terminus. Small differences in the profiles in the accumulation zone of the glacier from 1949 to 1973 are probably due to inaccuracies in mapping snow surfaces from the 1949 aerial photography. No net gain or loss is indicated in the accumulation zone during this period. The fact that only insignificant quantities of stagnant ice remained near the terminus in 1973 and that the glacier had regained a convex profile near the terminus indicated that the glacier

would not recede much farther. Thus, the glacier was, even then, approaching a size, flow regime, and profile of equilibrium with climate and mass balance conditions.

Detailed Study from 1975 to Present

In 1975 we began a series of seasonal measurements of snow and ice balance, glacier motion, and glacier surface altitude at three sites, one in the accumulation zone (site D, fig. 3), one near the equilibrium line (site B), and one in the ablation zone (site A). Precise altitude measurements of the glacier surface and base of the seasonal snow pack (fig. 4) are measured at horizontally fixed locations at each of these three measurement sites. Surveys are made by techniques developed to ensure that errors due to meteorological variations in atmospheric refraction are adequately corrected (Mayo and others, 1979; Mayo and Trabant, 1982).

In the accumulation zone (site D), the glacier surface altitude decreased from 1975 to 1976 then alternately increased and decreased from 1976 to 1979 but showed an overall gain. From 1979 to 1983, the rate of new firm accumulation continuously exceeded the submergence flow of the glacier. As a result, the glacier thickened 2.4 m. Thus, 1976 was the date of the end of glacier thinning in the accumulation zone as indicated at this site.

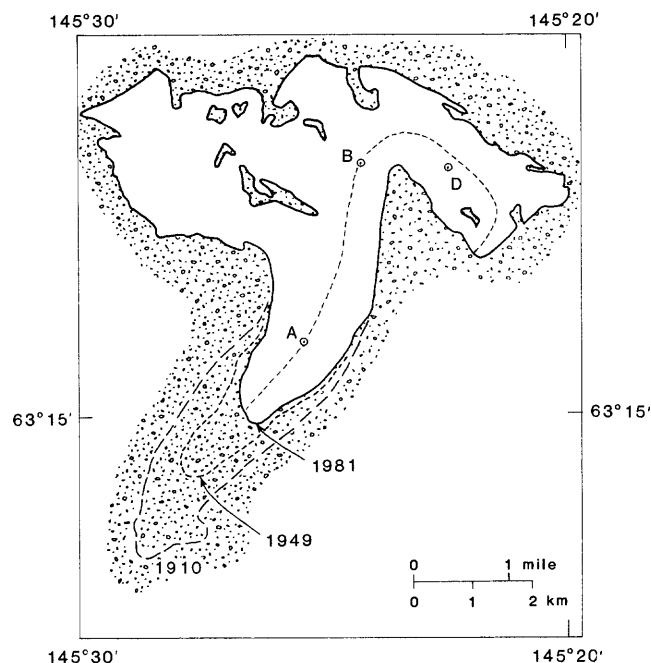


Figure 3. Map showing locations of the terminus, centerline profile, and altitude measurement sites (A, B, and D) on Gulkana Glacier. The glacier position in 1910 was mapped by Rutter (1961). The 1949 position was mapped by the U.S. Geological Survey, Mt. Hayes (A–3 and B–3), Alaska, topographic maps.

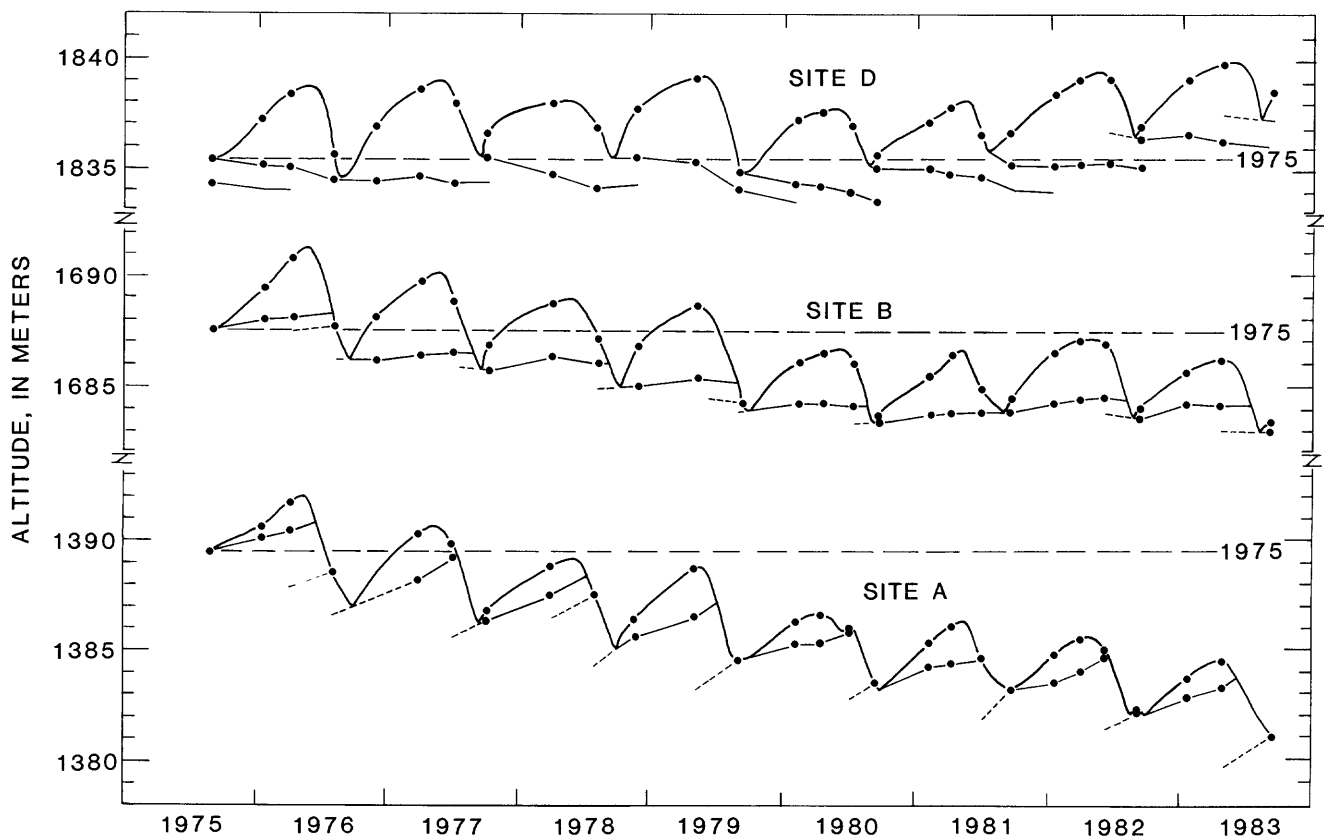


Figure 4. Graph showing changes in altitude from 1975 to 1983 at three measurement sites on Gulkana Glacier. The locations of the sites are shown on figure 3. The altitude of the summer surface, the base of the seasonal snow pack, is also shown. The rate of change of altitude of the base at the summer surface and the dashed lines indicate the rate of emergence of ice relative to the glacier surface.

At site B, 1.0 km below the equilibrium line, 4.2 m of thinning occurred from 1975 to 1980. But since 1980 continuous thinning has ceased, and alternate thickening and thinning has produced only 0.5 m of further thinning.

Lower in the ablation zone, at site A, thinning has been continuous from 1975 to the present time, at an average rate of 1.0 m/yr. The greatest thinning rate, 2.5 m/yr, occurred in 1976.

Closely spaced altitude measurements along cross and longitudinal profiles in 1973 were remeasured in 1985 to determine whether or not single points on a glacier are representative of larger areas. Site A thinned 12.8 m, and the cross profile thinned an average of 13.3 m. Site B thinned 8.1 m, and the cross profile there also thinned 8.1 m. We conclude that single points on Gulkana are representative of large areas.

The three altitude measurement sites represent unequal parts of the glacier. Site A represents 3.8 km²; B, 4.1 km²; and D, 11.6 km². The area-weighted seasonal altitude changes of the glacier surface (fig. 5) indicate that the glacier mass reached a minimum in 1980 and has

grown since that time. Thus, there was a 4-yr lag from the time when thickening was detected locally at site D and when the glacier began growing.

SUMMARY OF GLACIER REGIME

The climatic regime in the Alaska Range from about 1875 to 1976 caused continual ice loss from Gulkana and other glaciers of the central Alaska Range. In 1949, when Gulkana Glacier was first mapped, a considerable amount of ice had been lost since the 1910 photograph was taken, and only a remnant of the previously extended ice tongue remained.

Since 1976 the glacier has thickened in the accumulation zone, beginning slowly but increasing to an average of 0.6 m/yr from 1979 to 1983. The effects on glacier flow from this thickening have propagated down-glacier, reducing the rate of thinning in the upper part of the ablation zone from 0.8 to 0.1 m/yr. The lower part of the glacier is still thinning at an average rate of 1.0 m/yr. The glacier speed at site A has increased from 20 m/yr in

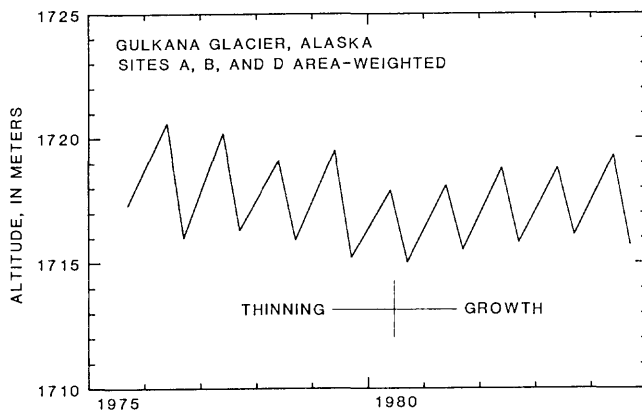


Figure 5. Graph showing glacier-averaged maximum and minimum altitude of the surface of Gulkana Glacier based on measurements at three sites from August 1975 to August 1984.

1961 (Sellmann, 1961, pl. 3) to 27 m/yr in 1983. We expect in the near future that the effects of thickening in the accumulation zone will increase the ice flow sufficiently to stabilize the lower part of the glacier.

Thus, the period in which glacier runoff exceeded precipitation ended by 1980, and the century-long recession of the Gulkana Glacier terminus is about to end. The glacier mass is, at this time, approximately but not exactly stable with climate. The glacier is still slightly over-extended in length, and the glacier flow has not yet adjusted fully. We anticipate that Gulkana Glacier will recede less than 100 m more. If the ice volume in the accumulation zone continues to increase, the glacier will eventually readvance as a consequence of the present climatic regime.

An important question remains. Did Gulkana Glacier recede until it became adjusted to the prevailing climate of this century, or did the climate change about 1976? The fact that the glacier is now becoming thicker in the accumulation zone, at the same time the glacier gradient and speed are increasing, rather than simply stabilizing at a fixed height indicates that a glaciologically significant shift in climate did occur, at least for a decade.

Whether or not Gulkana is "representative" of other glaciers in the Alaska Range is critical to the problem of understanding the hydrology of the Alaska Range in general. Recent, unvegetated, ice-cored moraines high above Gulkana and other valley glaciers in the area indicate that the response of these other glaciers to variations in climate during the past century has been similar to that of Gulkana and that the knowledge gained at Gulkana does have transfer value over the entire central and eastern Alaska Range region.

RUNOFF FROM GLACIERS

The long-term regime of glacier-fed rivers may change in ways that are linked indirectly to climate because glaciers control a large part of the river flow. For example, Harrison and others (1983, p. 102) proposed that the part of river flow derived from ice storage loss is a resource that cannot be relied on for the future. For the Susitna Basin (fig. 6), the site of two proposed large hydropower projects (Watana and Devils Canyon), their studies indicate that more than 13 percent of the total measured flow for the period of record came from glacier ice losses in the basin and, therefore, is of economic significance and possibly may not be available in the future.

There are three processes by which the glacier runoff could decrease in the future. First, if glaciers diminish in size through time, runoff could gradually decrease. Second, if glaciers grow due to a climatic cooling without increases in precipitation, then less melt runoff is available. And third, if precipitation decreases, then the rainfall component of runoff could decrease.

A related ambiguity exists regarding glacier changes. Glaciers can cease declining and begin growing due either to decreases in temperature, which would cause corresponding decreases in river flow, or to increases in precipitation, which would cause increases in streamflow. If glacier regime and glacier-fed runoff are measured simultaneously for a period in which climatic shifting occurs, the ambiguity can be resolved and the controlling climatic variable identified.

Gulkana Glacier runoff flows into the Tanana River, which has been gaged since 1962 (see map, fig. 6). Other adjacent basins with glaciers have also been gaged.

The variability of annual runoff measurements can be smoothed to show the time trend of runoff (fig. 7). The method we use involves weighting the measurement for each previous year in the past by a number in the half-life decay series. A problem with this solution is that the variability of the smoothed values is greater early in the series because fewer terms are considered. To solve this, a series of average values (the average of the first five years) is entered arbitrarily for the unmeasured five years prior to the beginning of measured values. The half-life weighted time series smoothing is calculated by:

$$\bar{X}_t = \frac{\sum_{i=1}^t 0.5^{(t-i)/p} D_i}{\sum_{i=1}^t 0.5^{(t-i)/p}}, \quad (1)$$

where \bar{X}_t is the t th weighted mean value of the series, i is the index of summation, t is the sequence number in the time series, p is the half-life period, 5 years in this case, and D is the measured or estimated value.

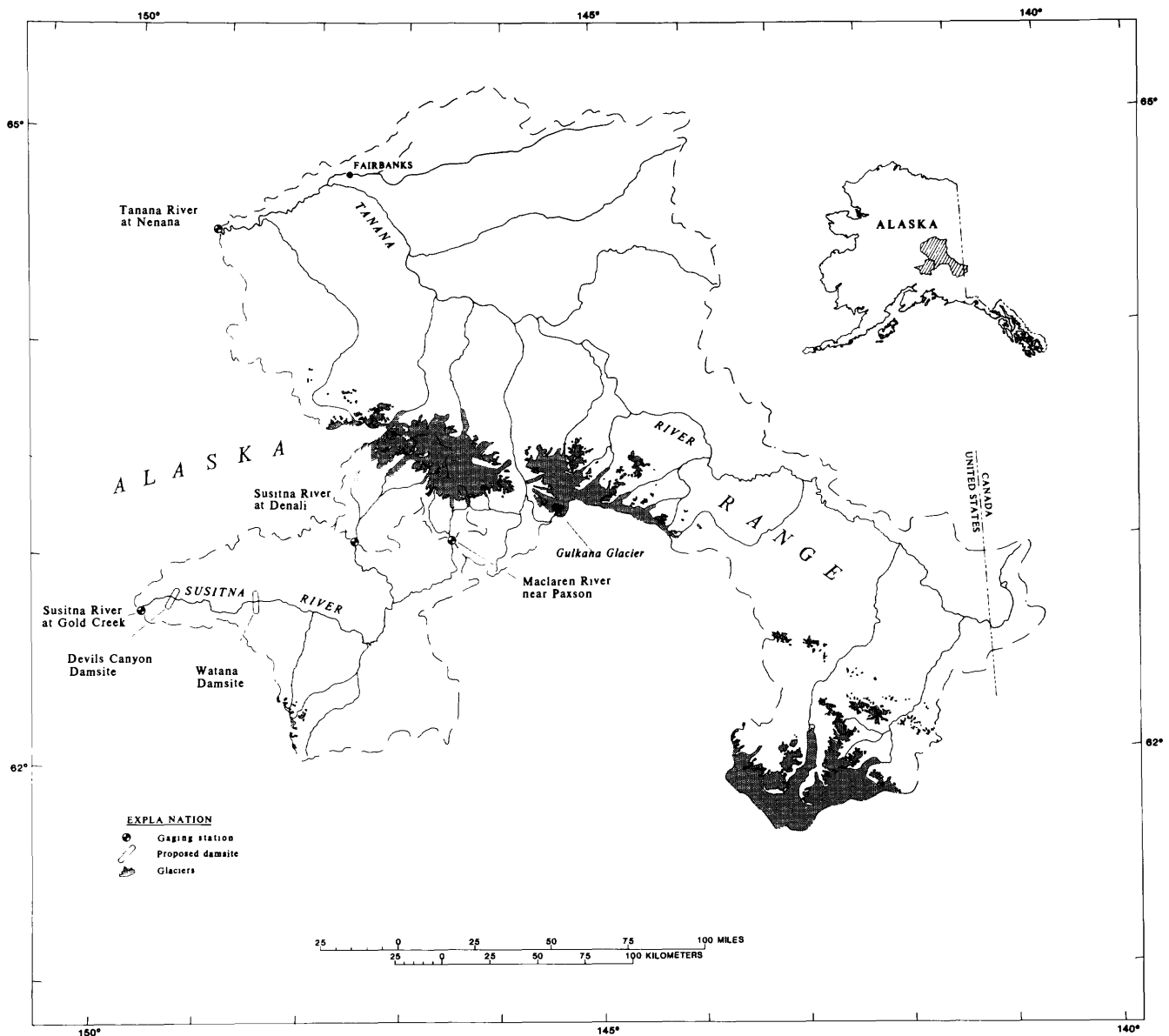


Figure 6. Map of gaged, glacierized basins in central Alaska with measurements of sufficient duration to calculate trends in runoff.

Estimates are useful, as stated above, for decreasing the variability for the first part of the sequence and also for years with missing data.

In general, runoff from glacierized basins in the Alaska Range has gradually increased during the past 10 to 15 years.

RELATION OF CLIMATE, GLACIER REGIME, AND RIVER RUNOFF

The recent period of increasing runoff is the same period during which Gulkana Glacier is known to have

changed from recession to growth. Thus, the mass balance trend of Gulkana, and likely of other glaciers in the Alaska Range, is shown to be in phase with measured runoff trends in the region. This is the key information required to unravel the previously stated ambiguity. Had the glacier grown due to cooler temperatures from arctic air masses, the contribution to streamflow from ice storage loss would have decreased, and total runoff would have decreased. Even though the glacier and non-glacier components of runoff have not been analyzed separately, the data indicate that the dominant climatic factor controlling glacier mass balance and runoff variations over periods of years in the Alaska Range is precipitation from

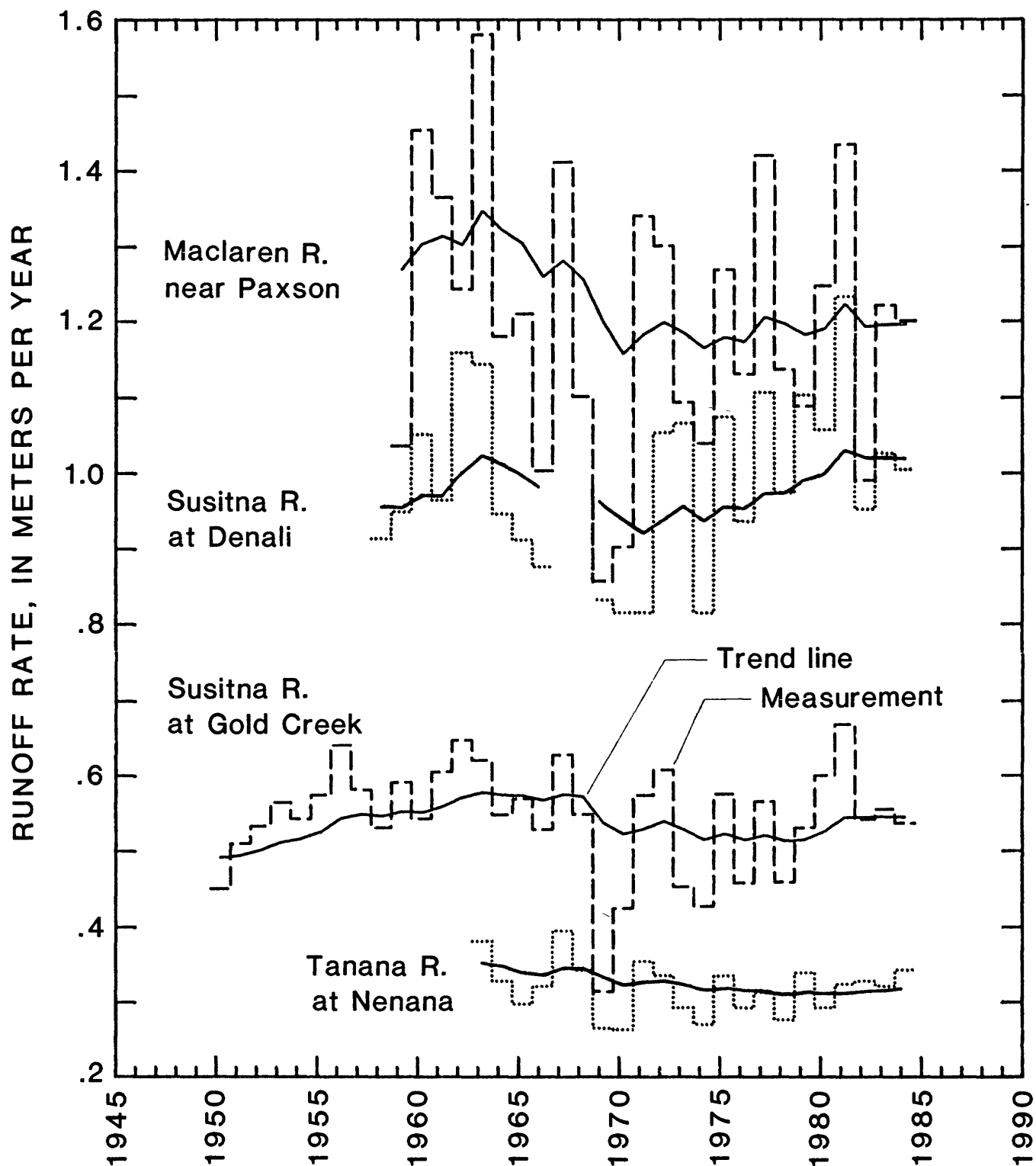


Figure 7. Graph showing measured runoff and runoff trends at four glacier-fed rivers flowing from the Alaska Range. See text for method of calculation of the trend line.

the Gulf of Alaska, probably coupled with smaller variations in temperature. This long-term response is opposite to the seasonal response, in which glacier runoff is related primarily to temperature.

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