GLACIER MASS BALANCES AND RUNOFF
IN THE UPPER SUSITNA AND MACLAREN RIVER BASINS, 1981-1983

FINAL REPORT

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June 1985

ABSTRACT

Mass balance measurements have been made on the major glaciers at the headwaters of the Susitna and Maclaren Rivers during 1981, 1982 and 1983. The primary purpose of the work has been to estimate the amount of water originating from this 790 km^2 glacierized area, in connection with the development of water forecast models for the proposed Susitna hydroelectric project. The study has been at the reconnaissance level, since only one measurement stake per 50 km^2 has been monitored. Annual balances, when summed over the three year measurement period, were estimated at +0.1 ± 0.6 m water equivalent. Average runoff due to the melting of ice, firn and snow was about 1.3 m/yr, as estimated by monitoring melt on the glacier surfaces. Average rain runoff was about 0.25 m/yr, as estimated from rain gauge data. This is probably a lower limit on rainfall runoff. Overall, the glaciers produced about 1.5 ± 0.3 m/yr of water. This is compared to 0.95 m/yr for the unglacierized portion of the basin above the Denali Highway and 0.59 m/yr from the basin as a whole above the Susitna River gauge at Gold Creek for the same period. This suggests that precipitation in the glacierized portion of the basin is about 2.5 times greater than the basin as a whole. The 5.7% and 7.1% glacierized areas above the proposed Devil Canyon and Watana dam sites produced about 15% and 17% of the water at the respective sites. It is estimated that nearly 75% of the melt water originating from glaciers ran off in July and August, while the remaining 25% was distributed between May, June, September and October.

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ACKNOWLEDGEMENTS

It is a pleasure to acknowledge that this report has been the result of the efforts of many people. For the field efforts, credit is due especially to Carl Schoch of R & M Consultants and Clifton Moore of University of Alaska, but we also acknowledge the contributions, at times almost herculean, of Steven and Randy Bergt and Elizabeth Senear. Helicopter support was supplied by Air Logistics. Cooperating companies or agencies have been R & M Consultants, Acres American Inc., Harza-Ebasco Joint Venture, North Pacific Aerial Surveys, the Alaska Power Authority, and the State of Alaska Division of Geological and Geophysical surveys. We are particularly grateful to Steven Bredthauer of R & M for his advice and perspective, to colleagues at University of Alaska, especially Carl Benson, and to Lawrence Mayo, Dennis Trabant, and Rod March at the U.S. Geological Survey. The latter three colleagues have helped with ideas concerning snow accumulation and metamorphism, and mass balance in general. Finally, financial support has been from subcontractors of the Alaska Power Authority, the Division of Geological Surveys, and the University of Alaska.

I. INTRODUCTION

This is a report summarizing the glacier balance data obtained for the glaciers of the Susitna basin in 1981, 1982 and 1983, and the implications for the amount and timing of runoff produced by those glaciers. The immediate objective has been to obtain an assessment of the effect of glaciers on basin water supply, to aid in the development of water forecast models for the proposed Susitna hydroelectric project (Figure 1).

The reason water from glacierized portions of the basin has been singled out for special attention is that it has several unique properties. First and most obvious, its influence is several times greater than might be suggested by the 7% or so areal coverage above the proposed Watana dam site, because it originates at high elevation where precipitation is high. Second, there is no simple relationship between winter precipitation on glaciers and summer runoff, which makes seasonal prediction of runoff from glacierized areas a difficult task, one for which there are few analogies from unglacierized basins. On the positive side, runoff from glacierized basins shows reduced variability with meltwater from glaciers being abundant in clear weather when water from rain is not. Krimmel and Tangborn (1974) and Fountain and Tangborn (1985), working in Washington state and southeastern Alaska, have found minimum variability to occur at 36% glacierization (Fountain and Tangborn 1985). Chacho (personal communication, 1985), working in south-central and interior Alaska, finds that variability reaches a minimum from about 5% to 70% glacier cover, but variability for any given percent glacierization can vary considerably. And third, evaporative losses are very small and in fact usually found to be negative (Patterson, 1969; Sharp, 1960).

The complex relationship between precipitation and runoff for glacierized basins is due to the unique storage processes which occur in these basins.

Although storage of winter snow well into the succeeding summer is familiar enough for unglacierized mountain basins, glaciers store some of the winter snow for hundreds of years, releasing each year not only some of the previous winters' accumulated snow, but ice melt that originated as snow many years earlier. In the long run this ice melt tends to be replenished by glacier flow, but in a given year there is generally no positive correlation between winter snow accumulation and summer runoff; in fact the correlation, if any, is generally negative. Heavy snows lead to the late appearance of underlying low-albedo glacier ice and therefore lower runoff. These phenomena are aspects of glacier storage of solid precipitation. Storage of liquid water within glaciers also occurs, both in early summer, when a sizeable fraction of the surface melt, or rain, is stored and released later in the year (Paterson, 1981; Tangborn and others, 1975; Stenborg, 1970), and from year to year which is usually released as jökulhlaups (Björnsson, 1977; Hodge, 1974).

Storage by glaciers is the source of errors that have sometimes been made in estimates of long-term water availability from stream flow records (Bezinge, 1979). The errors have been due to failure to take into account the component of runoff from secular decrease in glacier volume, which is usually due to warm temperatures over the period of stream flow record. Glaciers are extremely sensitive to temperature; a one degree change in summer temperature may lead to significant volume change (Tangborn, 1980; Meier, 1965; Ahlmann, 1953).

In the work reported here the so-called glaciological method was used to assess the effect of the Susitna basin glaciers on water supply. This method is indirect in that glacier balance, or the accumulation and ablation of mass over the glaciers' surfaces, is monitored at several points, and the water production at the termini of the glaciers is estimated from the results, rather than measured directly. With the exception of Eureka Glacier, which straddles the eastern boundary of the basin, and the small glaciers of the Talkeetna Mountains to the south, all major glaciers of the basin were studied (Figure 2). The total area of glacierization is about 790 km^2, or 7.1% of the total basin area above the proposed Watana dam site. Limitations on the interpretation of the data are imposed by the very sparse coverage (3 measurement points per glacier), and perhaps more important, by the short time span (1981 to 1983) of the data.

Three previous reports describe earlier phases of the work, including thermal and flow regimes of the glaciers, the effect of surges on sediment and water supplies, and the effect of long term glacier volume change (R & M and Harrison, 1981; R & M and Harrison, 1982; Harrison and others 1983). In this report all the balance data are presented, and reduced in a consistent fashion. As stated above, this report is primarily concerned with the determination and timing of glacier runoff, and the mass balance of the glaciers for the 1981-1983 period over which data were collected. The results are summarized in Section IV, which is self-contained and can be read directly by the reader not concerned with the intervening details.

II. MASS BALANCE

(1) Introduction and Terminology

The glaciological method, as already noted, was used to assess the water supply from the Susitna basin glaciers. This method employs a network of stakes drilled into the glacier surface. Melt and accumulation are monitored at each stake. These point changes in water equivilant thickness are then extrapolated over the glacier surface. Melting of snow and ice, when integrated over the hydrologic year, is called the annual ablation, and the discussion of its determination would fulfill the major objectives of this report. However, the discussion is broadened to include data relating to accumulation of snow as well.

Having embarked upon this slightly more ambitious program, a certain amount of terminology is required. Mass balance, measured by the glaciological method, concerns the gain or loss of mass of a glacier, and its distribution over the glacier and over time. The four balance definitions most important for this report are as follows:

1. Annual balance, the balance at a specified point on a glacier during the hydrologic year (1 October to 30 September). Units of water equivalent thickness are used throughout.
2. Annual ablation, the total ablation (which consists of snow, firn and ice melt) at a point during the hydrologic year.
3. Winter season balance, the balance at a point from 1 October to 14 May.
4. Summer season balance, the balance at a point from 15 May to 30 September.

These four quantities, which are defined at a measurement point, can be converted to total volume quantities by integration over the glacier surface, in which case they are usually divided by the total area of the glacier and termed "average annual balance", "average annual ablation", "average winter season balance" and "average summer season balance". The average annual balance is a measure of the "health" of a glacier, as it represents the mass gain or loss in a given hydrologic year. The algebraic sum of average annual ablation and rainfall runoff is approximately equal to total annual runoff. Annual ablation is not the same as average summer season balance because the upper reaches of a glacier might accumulate summer snow, so the summer season balance can be less than, or even the opposite sign from, annual ablation there. This terminology applies in the "fixed date" system of balance description (Anonymous, 1969). In the "stratigraphic" system of balance description, the maximum and minimum glacier volume in a given year are defined as the winter and summer balances, respectively (Anonymous, 1969). This report uses winter season balance and summer season balance as approximations to winter and summer balances. These are only approximations because maximum and minimum glacier mass does not necessarily occur on 14 May and 30 September, respectively. The complex terminology reflects the suprisingly complex processes involved in accumulation and ablation of glacier mass. Mayo and others (1972) presented a good discussion of the complexities involved in mass balance determinations and terminology.

Some further background is needed. Snow that has survived a summer of ablation is "firn". In the fixed date system, the line on the glacier where annual balance is zero is the "equilibrium line". It is the boundary between the "accumulation zone" (annual balance > 0) and the "ablation zone" (annual balance < 0). The stratigraphic boundary between firn and new snow in the upper glacier, or the ice-snow boundary in the lower, is the "summer surface". Sometimes summer surfaces from one year or several years can be identified from snow stratigraphy studies in the accumulation zone. This was attempted on the first visit to the glaciers in 1981; subsequent measurements have been made on stakes drilled into the surfaces of the glaciers.

Great care is necessary in the interpretation of stake or stratigraphic measurements, because snow that melts at the surface is not necessarily available for runoff, even after some delay. This is because refreezing may take place, even to depths exceeding that of the most recent summer surface (Benson, 1962). The process depends critically upon the thermal regime of the glacier, which is one reason that glacier temperature, measured in 1981 at one site, is relevant to glacier hydrology. Melt or rain water frozen on an ice surface is called superimposed ice. Water also freezes in snow and firn (Bazhev, 1973), a process that is sometimes called "internal accumulation". A discussion by Trabant and Mayo (1984) points out that there are actually two processes involved in its formation; the freezing in early summer of downward percolating water and the freezing in winter of the irreducible capillary water remaining in the firn.

When the term "mass" balance is used by glaciologists, "mass" usually means the mass of solid phase H_2O. This is sometimes confusing, because it is known that a great deal of liquid H_2O is also stored in glaciers, particularly in the first part of the melt season (Tangborn and others, 1975; Stenborg, 1970) and is released later either gradually or catastrophically. As with ice storage, liquid storage may be unequal to zero in a given year (Hodge, 1974).

(2) Point Balance Measurements

Balance at a point on a glacier was measured primarily by monitoring the position of the surface with respect to a stake set into the glacier and maintained throughout the year. Snow density was measured as a function of depth and used to convert the stake measurements to water equivalent balances. Three stakes were placed on each of the major glaciers, one in the ablation zone at about 1000 m elevation, one near the equilibrium line at about 1500 m, and one in the accumulation zone at about 2000 m (Figure 2). The stake data were supplemented by probing to the summer surface, where it could be identified this way. Measurements were made in both April or May, and late August or early September, and sometimes in mid summer.

Snow pits were dug to the most recent summer surface at representative stakes in spring. Stratigraphy, snow temperature, and snow density were measured in these pits. In spring 1981, the first year of the work, snow stratigraphy was used to estimate the 1980-81 winter snowpack and the 1980-81 winter balance. Snow density was estimated from samples taken from pit walls, and from samples taken from the surface with thin-walled core tubes. Density was measured in the 1981 and 1982 snow pits from 500 ml snow samples taken from the pit walls every 0.50 m and assumed to be representative of the 0.50 m interval. The cumulative thickness of ice lenses was also measured and density was corrected accordingly. In 1983 the same procedure was used except samples were taken every 0.10 m. Cores, taken from the surface, were 54 mm in diameter and 1.5 m long. Often several cores had to be taken in each hole to complete a snowpack sample.

Table I summarizes density data gathered on the Susitna glaciers between 1981 and 1983. Mean snowpack density, which is of primary concern when calculating the water content of a given snowpack, is tabulated for late spring, mid summer and early fall and for each field season. The density shown for early fall is for the late summer snow only; the previous winter's snow is not included in early fall snow density determinations. The data listed in Table I are averaged both over depth and elevation. While mean snowpack density did not change significantly with elevation, density-depth relations did. Almost invariably snowpacks above the equilibrium line showed increasing density with depth and snowpacks below the equilibrium line showed decreasing density with depth. The change in density with depth was greatest in the surficial third of the high elevation snow packs and greatest in the basal third of the lower elevation snowpacks. These relations are more clearly illustrated in Figure 3. The density relations at high elevation can be explained by compaction; the low altitude relations are caused, at least in part, by the formation of a depth hoar.

The data in Table I show the spring snowpack mean density to lie consistently around 400 kg/m^3. The mid-summer data are limited but the measured density of roughly 500 kg/m^3 seems reasonable considering the late spring 400 kg/m^3 snowpack is wet then. The late summer-early fall densities can vary considerably depending upon when the new snow accumulates. In late August of 1981 a very wet snowfall had a density of about 380 kg/m^3. Density of the September 1982 and September 1983 snowfalls was not measured. These relatively minor snowfalls had been on the ground for several weeks before their depth was measured and were therefore assumed to have a density of 250 kg/m^3.

For the mass balance calculations a density of 400 kg/m^3 was used for spring snowpacks, 500 kg/m^3 was used for snow that was still present after mid-summer, 400 kg/m^3 was used for the late summer snowfall of 1981, and 250 kg/m^3 was used for the fall snow of 1982 and 1983. Ice density was assumed to be 900 kg/m^3 as is standard practice in glaciological investigations.

Superimposed ice, formed on the lower part of the glacier from downward percolating water as discussed earlier, was not studied in the field. However, rough estimates of the amount of ice were made from earlier temperature measurements in Black Rapids Glacier (Harrison and others, 1975) located just east of the Susitna basin. Spring temperatures, measured in the ice just before infiltrating water reaches it through the overlying snow, characterize the strength of a "cold reservoir" which is available for freezing of downward percolating water. These temperatures were used to estimate the amount of superimposed ice that could form. The result is 0.3 to 0.4 m of water equivalent, which, although large, is probably an upper limit. Mayo (pers. comm.), in 20 years of mass balance work on Gulkana Glacier, has never observed this much superimposed ice.

The formation of superimposed ice would not significantly affect the estimates of total ablation, and therefore of runoff. If some snow had melted and refrozen as superimposed ice, this quantity would have been tabulated as glacier ice melt rather than snow melt, but the total melt quantity would be the same. Winter season balance estimates could be affected by superimposed ice, but the glaciers were visited early enough in 1982 and 1983 that little melt is thought to have occurred. However, in 1981 melting occurred early, and the field measurements late, and there was little snow on the lowest parts of some glaciers when they were visited. A lower limit on the winter season balance was therefore all that was obtained from that year. Attempts to estimate the magnitude of the effect on winter balance from snow course data are described in R & M and Harrison (1981) but no corrections are included in this compilation.

Superimposed ice forms only in the lower, essentially impermeable areas of a glacier, but an analogous phenomenon called internal accumulation occurs in higher areas. Its physical basis was discussed earlier. Because the higher areas are permeable, freezing can take place to considerable depth. If the freezing was confined to the snow above the most recent summer surface, and if the density of this snow was monitored, the effect should lead to no serious errors in balance determination. However, freezing may occur deeper, within the firn accumulated from previous years, where it may be impractical to make density measurements. This quantity of internal accumulation was estimated by the method of Trabant and Mayo (1985), which employs an empirical relationship between internal accumulation and the late spring temperature at the summer surface. This temperature was determined from snow pits. The data and results are summarized in Table II.

(3) Balance-Time and Balance-Elevation Curves

The evolution of water equivalent thickness was estimated at each measurement point from the snow and ice accumulation and ablation data, the density data, and the internal accumulation estimates. The results permit balance-time curves to be drawn for each measurement point from spring 1981 to fall 1983 (Figure 4). From these curves balance-elevation curves can be constructed for any desired time interval. Summer season (15 May to 30 September), winter season (1 October to May 14) and annual (1 October to 30 September) balance-elevation curves are shown in Figure 5.

(4) Average Balances

Average balances were found by integrating the point balance measurements over the glacier surfaces, and dividing by their total surface areas. A standard method was used. The balance elevation relations of Figure 5 were multiplied by an areal distribution function describing the distribution of glacier area with elevation, surface elevation then becoming the single variable of integration. The areal distribution functions were obtained by planimetry from 1:63,360 USGS topographic maps, using a 152 m (500 feet) contour interval. At low elevations, the areas were divided into debris covered and clean sections. Ablation under the debris covered areas was assumed to be one half that of clean ice at the same elevation (Nakawo and Young, 1981; Fujii, 1977; Østrem, 1959). Percent debris cover for each glacier and elevation found is given in Table III. At high elevations only the areas shown in white on the maps were included. The results are shown in Figure 5 next to the balance-elevation curves. The procedure is open to criticism as discussed later. The results of these integrations are given in Table IV.

All tributaries, surrounding small glaciers and perennial snow patches were assumed to behave in a manner similar to that of the main glaciers. They were divided according to river drainage (Figure 2). The area-elevation relations of each were determined and added to the areas of the main glaciers; these areas are included in the Figure 5 plots. Susitna Glacier, with its more complex tributary system, was the only exception to this procedure. Complete accumulation/ablation data were obtained on its Turkey and Northwest tributaries in 1981 and on Turkey tributary in 1982. The balance-elevation relationships on those tributaries were used to calculate their individual mass balances.

The accuracy of the mass balance of Susitna Glacier in 1983 is limited because the only reliable accumulation data for that year were collected in the large north facing basin on the main tributary. If this stake, and the other two on the main glacier are used to calculate annual balance for 1981, which we were forced to do for 1983, the result is -0.09 m water equivalent rather than -0.30 m. This is a difference of 0.21 m water equivalent or 57 x 10^6 m^3 of water. It should be noted that this uncertainty has little effect on estimated glacier runoff for that year. The balance relations on the lower reaches of the glacier, where nearly all the melt and therefore from which most of the runoff occurs, are relatively unaffected by this lack of accumulation data. Rather, the amount of replenishment in the upper reaches is affected, which is a reflection of the general health of the glacier that year, not the melt or runoff.

(5) Eureka Glacier

Eureka Glacier presents a problem because it straddles the drainage divide between the Susitna and Delta River basins (Figure 2). Its balance characteristics were assumed to be similar to those of Maclaren Glacier. It was further assumed that 60% (24 km^2) of its area lies within the Susitna basin.

(6) Error

There are many uncertainties in a mass balance investigation such as this. They fall into two categories, those associated with the measurements at each point, such as density, snowpack thickness, superimposed ice, elevation, etc. and those associated with extrapolations of the points over the glacier area. The former, point balance error, was estimated by squaring the uncertainty in each measurement that contributed to a balance, summing the squares and taking the square root. The results are given as error bars on the balance-time data points in Figure 4. These errors were transferred to the balance-altitude plots of Figure 5. In general the errors are small compared to the balance changes between measurements.

The elevation of each stake and the distribution of area with altitude were taken from USGS 1:63,360 series topographic maps, which are based on 1949, 1954 and 1956 aerial photography. Based on the photogrammetrically determined surface elevation change on East Fork Glacier (R & M and Harrison, 1981) and the work by Post (1960) on Susitna and other surging-type glaciers in the region, a 100 m elevation error was assigned to the lower elevation stakes, 75 m to the middle stakes and 50 m to the upper stakes. These errors are shown as vertical bars on the balance-elevation plots of Figure 5. Although the glaciers have lost considerable mass since 1949, it is not safe to assume that elevation uncertainty can only be in the form of an elevation loss. Surge type glaciers build a reservoir of ice at high elevation prior to a surge, and deplete it during a surge. Both Susitna and West Fork Glaciers surged before the maps were made, so their upper basin elevations should be higher than the map elevations. As noted earlier, at high elevations only the areas shown as white on the USGS maps were counted as glacierized. This must lead to a small underestimate in effectively glacierized areas, since most of the snow falling on the steep slopes at high elevations is probably avalanched onto the glaciers.

How accurately a given stake represents the area it samples can be estimated qualitatively by comparing stake data to the more extensive probe data. The point balance data from probes for the winters of 1980-81, 1981-82 and 1982-83 are shown in Figure 6. In general the probe data agree well with stake data up to about 2000 m (Figure 5). Above 2000 m probe data generally show greater winter balance than stake data. Often at high elevation there is no hard summer surface to probe to, which results in less accurate estimates of winter snowpack. Consequently, stake data were considered to provide more reliable data for these high elevation areas.

The error introduced by extrapolating the balance-elevation curve to high elevation is probably large. The curves were drawn in such a way as to peak and level off at the elevation of the topographic saddles in each glacier's basin. This error is buffered by the fact that very little glacier area lies above about 2500 m, where the error due to extrapolation is greatest (Figure 5).

The stake and elevation errors, when combined, allow the balance-elevation curves, as a whole, to shift both with respect to elevation and with respect to balance. If these curves are shifted to the extreme end of both the elevation error bars and balance error bars the effect is to increase or decrease the balance at any point by an amount that is greater than just the uncertainty in the balance at that point. For the winter season balance this overall error is about 0.20 m water equivalent; for the annual balance it is about 0.40 m water equivalent, and for the summer season balance it is about 0.50 m water equivalent. If the winter, annual and summer balance-elevation curves are shifted, as a whole, by these respective amounts, the average balances shift by approximately the same amount. It is felt that these error estimates are conservative for the point balances and realistic for the average balances, the latter of which are subject to the extrapolation errors discussed previously.

III. GLACIER RUNOFF

When compared to nearby unglacierized areas, glaciers tend to produce large quantities of runoff. The Susitna glaciers are no exception. During 1981, 1982 and 1983 the runoff per glacierized area was roughly 2.5 times that of the unglacierized basin above Gold Creek and 1.5 times that of the surrounding basin above the Denali Highway. Glacier runoff comes from three sources: snow melt, firn and ice melt, and rain. A comparison of each of these components to the total water flow through each gauge site during 1981, 1982 and 1983 (USGS) can be found in Tables V and VI and Figure 7.

Before discussing each of these water sources, we emphasize that glacier runoff is not the sum of the summer balance and summer precipitation because the high elevation precipitation falls as snow. This summer snow has two effects. First, it makes the average summer ablation less negative and second, not all the precipitation that falls in a given summer leaves the basin that same year.

(1) Snow Melt

By the definitions discussed earlier, all winter snow that falls below a glacier's equilibrium line melts the following summer. This is the average winter balance below the equilibrium line. Some snow melt also occurs above the equilibrium line, but the quantity is obscured by summer accumulation at the higher elevation stakes. This higher elevation snow melt had to be estimated from melt rates at lower elevation stakes where summer accumulation does not occur.

Melt rate decreases with increasing elevation to the point where all melt is absorbed by the glacier as internal accumulation. Trabant and Mayo (1984) place this melt/internal accumulation equality at roughly 2100 m in the central Alaska Range. Using this elevation as the point above which no runoff comes, and all low and mid elevation ablation data, the melt rate versus elevation plot of Figure 8 was developed. From this curve the average melt per year, in excess of that absorbed by internal accumulation, can be estimated at any elevation. The total snow melt above the equilibrium line is approximated by integrating this balance-elevation relation over the area between the equilibrium line and 2100 m.

The total snow melt is the sum of the winter balance below the equilibrium line and the calculated amount of melt from above. This total, for each stream gauge and year is listed in Table V.

(2) Firn and Ice Melt

The firn and ice melt is the amount of melt produced below the equilibrium line in excess of the past winter's snowpack. It is the total melt below the equilibrium line minus the average winter balance below the equilibrium line. This quantity for each year and stream gauge is listed in Table V. It should be noted that significant firn melt only occurs during years with exceptionally hot summers and/or low winter accumulation. Under these conditions the equilibrium line is pushed to an unusually high elevation, thereby exposing previous years' firn.

The firn and ice melt is the water that makes glacierized basins different from unglacierized basins. It is the precipitation that fell in decades past, metamorphosed and was then transported to lower elevation. It provides, at least on the short term, a very large reservoir of solid water available for melt. The quantity of melt depends almost entirely upon summer, rather than winter meteorological conditions and, therefore, has about the same predictability as summer rain.

(3) Rain

A rain gauge has been maintained by R & M Consultants on a west facing slope above the confluence of the Northwest tributary and the main Susitna Glacier at 1430 m elevation since 20 July 1981. The data from this gauge are listed in Table VIIa. The data in Table VIIa were supplemented by linear regression using precipitation data at Talkeetna Airport. The 9 months for which there are complete data on Susitna Glacier were used in the regression ($r^2 = 0.86$). The resulting regression equation is

$$P_s = 1.65\ P_T - 36.5 \text{ mm}$$

where

P_s = precipitation on Susitna Glacier(s) in mm

P_T = precipitation measured at Talkeetna Airport in mm

The supplemented data set appears in Table VIIb. Comparison of field notes to the dates that precipitation fell at Talkeetna Airport allowed the establishment, with reasonable certainty, that the calculated precipitation did indeed fall as liquid on at least part of the glacier area. For example, if the September 1982 (a month for which rainfall was calculated) data are exmained in Figures 4a and 4d it is reasonably clear that no snow had accumulated by late September at 1460 m (Figure 4a) but some definitely had accumulated at 1670 m (Figure 4d).

Above 1600 m, summer precipitation almost invariably falls as snow on nearby Gulkana Glacier (Mayo, pers. comm.). Assuming, for the case of the Susitna Glaciers, that all summer precipitation below 1600 m falls as rain, and all summer precipitation above 1600 m falls as snow, and assuming the catch efficiency of the R & M rain gauge to be 100%, and ignoring precipitation-elevation gradients, the average liquid precipitation on the glaciers can be determined by multiplying the rainfall in Table VIIb by 0.37 since only 37% of the basin's glacier area lies below 1600 m. The results of this calculation are shown graphically in Figure 7. It should be pointed out that this is probably a lower limit on rainfall runoff since the catch efficiency of the gauge is unknown.

(4) Evaporation

It is known from surface energy balance studies that "net" condensation, the difference between condensation and evaporation, plays a significant role in the surface energy budget of a glacier (Paterson, 1969; Sharp, 1960). Data from a number of glaciers indicate that the energy input from "net" condensation varies from near zero to about 30% of the total energy used for summer melt. However, because the ratio of the heat of vaporization to the heat of fusion is about 7.5, the upper limit of 30% in energy converts to one of 4% in mass. In other words, the ratio of total melt water to condensed water is usually less than 4%, which was considered negligible. What is interesting is that condensation almost invariably exceeds evaporation in glacierized areas.

(5) Timing of Runoff

On the average, runoff from glacierized basins in Alaska peaks in late July or early August (Chapman, 1982). This is when the air is warm, most precipitation falls as liquid, insolation is still relatively high, and a large amount of low-albedo glacier ice is exposed. If storage of early summer melt water by the glaciers is ignored, the proportional monthly melt runoff can be approximated by adding the water equivalent melt at all stakes for a given month and dividing by the melt at all stakes for the summer as a whole. This could not be done for each year owing to lack of mid-summer data, especially in 1983. Rather, all stakes that had enough data to allow resolution of monthly proportions were used in the analysis. Stakes that showed net accumulation were omitted.

The melt distribution as calculated by this method comes out to 4%, 20%, 42%, 30% and 4% for May, June, July, August and September respectively. For comparison, the average monthly flows at Phelan Creek, a 70% glacierized basin 40 km east of Susitna basin, were 1%, 15%, 40%, 33%, 9% and 2% for May, June, July, August, September and October during the 1967-1978 period of record. Comparison of these percentages shows a larger Susitna spring melt than Phelan Creek runoff, which is probably at least partly due to spring melt storage in the Phelan Creek glaciers. Since such storage is a well-known and documented fact from other glaciers (Patterson, 1981; Tangborn and others, 1975; Stenborg, 1970), we have used the Phelan Creek data to distribute the monthly melt from the Susitna Glaciers, even though it is a different basin and the data are for different years. The results are shown in Figure 7.

IV. DISCUSSION AND CONCLUSIONS

The primary objective of the work described in this report has been to assess the impact of high-elevation glacierized areas on the flow of the Susitna River above Gold Creek. Melt and snow accumulation data obtained on the glacier surfaces in 1981, 1982 and 1983 were used for the analysis. The interpretation of the data serves three purposes; first, to produce an estimate of the amount of water produced by different sources in the glacierized areas; second, to provide an estimate of the timing of its runoff; and third, at least in principle, to assess glacier volume change over the three year period. Volume change estimates over a longer period, from 1949 to 1980, have been crudely estimated by Clarke (1985) and R & M and Harrison (1981). The most recent estimates by Clarke (1985) indicate that on the order of 3-4% of the Susitna River discharge at Gold Creek has been from secular decrease of glacier volume for this period.

The conclusions of this report can be listed as follows:

(1) During 1981, 1982 and 1983 roughly 34% of the flow from above the Denali Highway originated on the 25% (790 km^2) glacier cover, and about 13% of the Susitna River flow at Gold Creek originated on the 4.9% glacier cover above that gauge (exclusive of the glaciers in the Talkeetna Mountains) (Table VI). Of the approximately 1.5 m/yr flow from the glaciers, 0.49 m/yr came from snow melt, 0.79 m/yr came from ice and firn melt and about 0.25 m/yr came from rain. Runoff from the rest of the basin above the Denali Highway was about 0.9 ± 0.2 m/yr; runoff from the basin above the Denali Highway as a whole was 1.1 ± 0.2 m/yr (Table VI); flows through the Susitna at Denali, Maclaren near Paxson and Susitna at Gold Creek gauges were 1.1 ± 0.2 m/yr, 1.2 ± 0.2 m/yr and 0.59 ± 0.06 m/yr (Table VI), respectively.

For comparison, the smaller and better-studied Phelan Creek drainage, 70% glacierized and 40 km to the east, produced about 2.02 m/yr from 1967 to 1979 (Mayo, 1984).

(2) If the average monthly runoff from 1967-1978 for Phelan Creek is taken as representative for the 1981-1983 melt runoff from the Susitna Glaciers, the resulting flow distribution is 1%, 15%, 40%, 33%, 9% and 2% for May, June, July, August, September and October (Figure 7).

(3) For 1981, 1982 and 1983 the average annual glacier balances (in m water equivalent) were -0.05 ± 0.40 m, -0.15 ± 0.40 m and + 0.26 ± 0.40 m, respectively (Table IV). Based on these data, which average to a gain of + 0.02 m/yr, it is tempting to say the glaciers were in approximate

equilibrium for these years, but the error is so large that this cannot be said with much confidence.

(4) Accumulation varies considerably from glacier to glacier. Generally the winter precipitation gradients are the same throughout the basin, about 1.2 ± 0.1 mm water equivalent/m elevation, based on winter accumulation, but each glacier's accumulation-elevation line is shifted vertically with respect to the accumulation axis (Figure 6 a-c). This shift ranges over about 0.5 m water equivalent, Maclaren Glacier being invariably the highest, Turkey tributary the lowest, East Fork and Susitna main branch close to Turkey and West Fork closer to Maclaren. Upon closer examination East Fork and the main tributary of Susitna have nearly identical winter precipitation gradients, even down to local accumulation fluctuations (Figure 6c). This is probably due to similarities in basin geometry (Figure 2). Also, as might be expected, this variability in accumulation is reflected in the equilibrium line elevations (Table VIII). The greater the accumulation, the lower the equilibrium line.

The limitations of this study need to be borne in mind. With only one measurement point per 50 km^2, it can at best be considered a reconnaissance level study compared with the mass balance studies done on many other glaciers. An even more serious problem may be its short (3 year) duration, which has given but little perspective into the year-to-year variability of the water supply from glaciers. Based on experience elsewhere, it seems safe to assume that in a drought year such as 1969, water from ice and firn melt is much more important, both in relative and absolute terms, than over the period of this study. Finally, no attention has been given to the problem of understanding, or seeking a correlation with, the meteorological factors responsible for glacier water supply.

REFERENCES

Acres American Inc., 1982. Susitna hydroelectric project; feasibility report. Final draft report for the Alaska Power Authority, Anchorage, AK. 8 Vols.

Ahlman, H. W., 1953. Glacier variation and climate fluctuations. American Geographical Society, New York, New York.

Anonymous, 1969. Mass balance terms. J. Glaciol., V. 8, no. 52, p. 3-7.

Bazhev, A. B., 1973. Infiltration and runoff of meltwater on glaciers. IASH 95, p. 245-250.

Benson, C. S., 1962. Stratigraphic studies in the snow and firn of the Greenland Ice Sheet. SIPRE Research Report 70, 93 p.

Bezinge, A., 1979. Grande Dixence et son hydrologie, la collection de donneés hydrologiques de base en Suisse, Association suisse l'ameńagement des eaux. Service hydrologique national, 19 p.

Björnsson, H., 1977. The cause of jökulhlaups in the Skafta´River, Vatnajökull. Jökull, V. 27, p. 71-78.

Chapman, D. L., 1982. Daily flow statistics of Alaskan streams. NOAA Technical Memorandum NWS AR-35, 57 p.

Clarke, T. S., 1985. Glacier Runoff, Balance and Dynamics in the Upper Susitna River Basin, Alaska. M. S. thesis, University of Alaska, Fairbanks, in preparation.

Fountain, A. G., and W. V. Tangborn, 1985. The effect of glaciers on stream flow variations. Water Resources Research. V. 21, no. 4, p. 579-586.

Fujii, Y., 1977. Field experiment on glacier ablation under a layer of debris cover. J. Japanese Soc. of Snow and Ice. V. 39 (Special Issue) p. 20-21.

Harrison, W. D., L. R. Mayo and D. C. Trabant, 1975. Temperature measurements on Black Rapids Glacier, Alaska, 1973. In: G. Weller and S. A. Bowling, eds., *Climate of the Arctic*. Geophysical Institute, University of Alaska, Fairbanks, Alaska, p. 350-352.

Harrison, W. D., B. T. Drage, S. Bredthauer, D. Johnson, C. Schoch and A. B. Follett, 1983. Reconnaissance of the glaciers of the Susitna basin in connection with proposed hydroelectric development. Annals of Glaciol., V. 4, p. 99-104.

Hodge, S. M., 1974. Variation in the sliding of a temperate glacier. J. Glaciol., V. 13, no. 68, p. 205-218.

Krimmel, R. M. and W. V. Tangborn, 1974. South Cascade Glacier, the moderating effect of glaciers on runoff. Western Snow Conference, 1974, p. 9-13.

Mayo, L. R., 1984. Glacier mass balance and runoff research in the U.S.A. Geogr. Ann., V. 66A, no. 3, p. 215-227.

Mayo, L. R., M. F. Meier, and W. V. Tangborn, 1972. A system to combine stratigraphic and annual mass-balance systems: A contribution to the International Hydrological Decade. J. Glaciol., V. 11, no. 61, p. 2-14.

Meier, M. F., 1965. Glaciers and climate. In: H. E. Wright and D. G. Frey, eds., The Quaternary of the United States. Princeton University Press, Princeton, New Jersey, p. 795-805.

Nakawo, M. and G. J. Young, 1981. Field experiments to determine the effect of a debris layer on ablation of glacier ice. Annals of Glaciol. V. 2, p. 82-91.

Østrem G., 1959. Ice melting under a thin layer of moraine, and the existance of ice cores in moraine ridges. Geogr. Ann., V. 41, no. 4, p. 228-230.

Paterson, W. S. B., 1969. The Physics of Glaciers. Pergamon Press, New York N.Y., 250 p.

Paterson, W. S. B., 1981. The Physics of Glaciers, 2nd ed. Pergamon Press, New York, N.Y., 380 p.

Post, A. S., 1960. The exceptional advances of the Muldrow, Black Rapids and Susitna Glaciers. J. Geophys. Res., V. 65, p. 3703-3712.

R & M Consultants and W. D. Harrison, 1981. Alaska Power Authority Susitna Hydroelectric Project; task 3 - hydrology; glacier studies. Report for Acres American, Inc., Buffalo, N.Y., 30 p.

R & M Consultants and W. D. Harrison, 1982. Alaska Power Authority Susitna Hydroelectric Project; task 3 - hydrology; glacier studies. Report for Acres American, Inc., Buffalo, N.Y., 22 p.

Sharp, R. P., 1960. glaciers. University of Oregon Press, Eugene, Oregon. 78 p.

Stenborg, T., 1970. Delay of runoff from a glacier basin. Geogr. Ann., V. 52A, p. 1-30.

Tangborn, W. V., 1980. Contribution of glacier runoff to hydroelectric power generation on the Columbia River. Acad. Sci., USSR, Section of Glaciology, Data of Glacier Studies, Pub. 39, p. 62-67 and 140-143.

Trabant, D. C. and L. R. Mayo, 1985. Effects of internal accumulation on five glaciers in Alaska. Annals of Glaciol., V. 6, in press.

Tangborn, W. V., R. M. Krimmel, and M. F. Meier, 1975. A comparison of glacier mass balance by glaciological, hydrological and mapping methods, South Cascade Glacier, Washington. IAHS 104, p. 185-196.

U.S. Geological Survey. Water resources data, Alaska, 1981, 1982 and 1983.

Table I. Snow pack density (kg/m^3), averaged over both depth and elevation, for different times of the year on the Susitna glaciers. The underlined number is the number of stations occupied during the indicated time period. The number next to it is the total number of samples used in calculating the mean density. A sample is one complete snowpack density determination, either by core or snow pit. The number of samples is always greater than or equal to the number of stations because often several samples were taken at the same station. Error shown is one standard deviation where the data points are average snowpack density. That is, the error reflects density variations over the glacier's area rather than density variations with snow depth.

Snowpack Density in kg/m^3

	Snow Pit Data			Core Data		
	1981	1982	1983	1981	1982	1983
May	370 ± 20 10/10	420 ± 20 4/4	390 ± 10 5/5	410 ± 80 35/65	390 ± 40 3/3	390 ± 10 3/12
Late July	-	-	-	530 ± 40 7/13	-	-
Late August	-	-	-	380 ± 50 3/7	-	-

Table II. Internal accumulation based on late spring firn surface temperature (method from Trabant and Mayo, 1985).

Glacier	Date	Elevation (m)	Firn Temperature (°C)	Internal Accumulation (meters water equivalent)
West Fork	May 1981	1950	-3	0.12*
	5/23/82	1950	-8	0.30
	5/8/83	1980	-4	0.16
Susitna Main Tributary	5/26/81	2010	-3	0.12
	5/17/82	2010	-7.5	0.28
	5/5/83	2010	-5.2	0.20
Turkey Tributary of Susitna	5/23/81	2290	-6	0.23
	5/15/82	2200	-8	0.30
	5/6/83	2040	-5.6	0.21
Northwest Tributary of Susitna	May 1981	2350	-6	0.23*
East Fork	5/28/81	1950	-1	0.04
	5/20/82	2050	-6	0.23
	4/28/83	2060	-3.0	0.12
Maclaren	5/29/81	1950	-3	0.12
	May 1982	2010	-6	0.23*
	5/1/83	2030	-2.0	0.08

*These firn temperatures were not measured. They had to be estimated from other temperatures at similar altitudes and snow depths.

TABLE III. Percent debris cover in each elevation band on each glacier in the upper Susitna River basin. Area for each elevation band is shown graphically in Figures 5a-f.

Elevation Interval	West Fork	Susitna Main Branch	Susitna Turkey Tributary	Susitna Northwest Tributary	East Fork	Maclaren
763-915 m	100%	100%	-	-	71%	-
915-1067	91	92	-	-	19	37%
1067-1220	63	48	-	-	10	18
1220-1372	42	21	-	20%	10	23
1372-1525	22	3	27%	14	8	13
1525-1677	6	0	23	6	2	0
1677-1830	0	0	0	5	0	0

Table IV.

Average Winter Season Balance (meters water equivalent)*

Glacier	1981	1982	1983
West Fork	+0.86	+0.78	+0.93
Susitna	+0.73	+0.65	+0.78
East Fork	-	+0.77	+0.78
Maclaren	+0.83	+1.14	+1.07
Average	+0.80	+0.81	+0.89

*1 October-14 May

1981-1983 Average: +0.83 m/yr

Average Summer Season Balance (meters water equivalent)*

Glacier	1981	1982	1983
West Fork	-0.87	-1.02	-0.81
Susitna	-1.03	-0.87	-0.38
East Fork	-	-0.97	-0.69
Maclaren	-0.52	-1.00	-0.70
Average	-0.85	-0.96	-0.63

*15 May-30 September

1981-1983 Average: -0.81 m/yr

Average Annual Balance (meters water equivalent)*

Glacier	1981	1982	1983
West Fork	-0.01	-0.24	+0.12
Susitna	-0.30	-0.22	+0.40
East Fork	-	-0.20	+0.09
Maclaren	+0.31	+0.14	+0.37
Average	-0.05	-0.15	+0.26

*1 October-30 September

1981-1982 average: +0.02 m/yr

Table V. Annual water yield from snow melt, firn and ice melt, and rain from the Susitna basin glaciers during 1981, 1982 and 1983.

Year	Stream Gauge	Glacier Snow Melt m/yr	Firn and Ice Melt m/yr	Total Glacier Melt m/yr	Glacier Rain Runoff m/yr	Total Glacier Runoff m/yr
1981	Maclaren River at Denali Highway	0.54	0.42	0.97	0.33	1.3
1981	Susitna River at Denali Highway	0.43	0.93	1.2	0.33	1.7
1981	Susitna River at Gold Creek	0.45	0.83	1.3	0.33	1.6
1982	Maclaren River at Denali Highway	0.64	0.51	1.1	0.25	1.4
1982	Susitna River at Denali Highway	0.45	0.95	1.4	0.25	1.7
1982	Susitna River at Gold Creek	0.49	0.86	1.3	0.25	1.6
1983	Maclaren River at Denali Highway	0.70	0.36	1.1	0.17	1.2
1983	Susitna River at Denali Highway	0.49	0.77	1.3	0.17	1.4
1983	Susitna River at Gold Creek	0.53	0.69	1.2	0.17	1.4
Average	Maclaren River at Denali Highway	0.63	0.43	1.1	0.25	1.3
Average	Susitna River at Denali Highway	0.46	0.88	1.3	0.25	1.6
Average	Susitna River at Gold Creek	0.49	0.79	1.3	0.25	1.5

Table VI. This table gives a detailed breakdown of how the runoff from glaciers compares to total runoff. The first four columns refer to total runoff and area above the given stream gauge. The middle three columns refer to glacier melt runoff. The last three columns refer to both glacier melt runoff and glacier rain runoff. The years in parenthes below each stream gauge refer to the time period over which averages were taken. Runoff from the two dam sites, (5) and (6), do not strictly compare because streamflow data are for a different time period than glacier data.

Stream Guage	Basin Area above Stream Guage	Average Annual Flow	Specific Runoff	Glacier Area	Glacier Snow, Firm and Ice Melt Runoff			Glacier Melt and Glacier Rain Runoff		
	km^2	m^3/s	m/yr	km^2/%	m/yr	m^3/s	%	m/yr	m^3/s	%
(1) Maclaren River at Denali Highway (1981-1983)	730	28.3	1.22	160*/22	1.07	5.44	19	1.32	6.7	24
(2) Susitna River at Denali Highway (1981-1983)	2460	83.6	1.07	628/25	1.34	26.8	32	1.59	31.7	38
(3) Total flow from above Denali Highway [sum of (1) and (2)] (1981-1983)	3190	112	1.10	790*/25	1.29	32.2	29	1.54	38.4	34
(4) Susitna River at Gold Creek** (1981-1983)	15,950	299	0.59	790*/4.9	0.06	32.2	11	0.08	38.4	13
(5) Watana Dam Site** (1949-1981 synthesized flow)***	~11,100	224	-	790*/7.1	-	32.2	14	-	38.4	17
(6) Devil Canyon Dam Site** (1949-1981 synthesized flow ***	~13,800	258	-	790*/5.9	-	32.2	12	-	38.4	15

*Area is not known accurately because Eureka Glacier straddles the drainage divide.
**Numbers do not include glaciers in the Talkeetna Mountains.
***From Acres American, 1982

Table VIIa. Rainfall collected by an R & M rain gauge during 1981, 1982 and 1983 at 1430 m elevation next to Susitna Glacier. Data are listed in mm.

	1981	1982	1983
April	N/A	16.6*	13.0
May	N/A	26.0	2.6***
June	N/A	103.8	18.8****
July	N/A	194.2	50.8
August	300.2	78.6	242.0
September	66.7	0.4**	108.0
October	N/A	N/A	3.4
TOTAL	366.9 mm	419.6 mm	438.6 mm

*April 14-30 **September 1-2 ***May 1-10 ****June 14-30

Table VIIb. Summer precipitation on the Susitna Glaciers during 1981, 1982 and 1983. In general, summer precipitation abov- [illegible]00 m elevation falls as snow (Mayo, pers. comm.) [illegible] nce only 37% of the glacier area lies below 1600 m [illegible] ation quantities must be multiplied by [illegible] te rainfall runoff from glaciers

	1981	19	
April	N/S	N/S	
May	11*	26	[illegible]*
June	183*	104	38*
July	330*	194	51
August	300	79	242
September	67	279*	108
October	N/S	N/S	N/S
TOTAL	891 mm	682 mm	455 mm

*Precipitation approximated by linear regression with Talkeetna Airport data ($r^2 = 0.86$).

Table VIII. Approximate equilibrium line elevations

	1981	1982	1983
West Fork	1650	1675	1650
Susitna Main Tributary	1775	1850	1700
Turkey Tributary	1950	1825	-
Northwest Tributary	1925	-	-
East Fork	-	1825	1775
Maclaren	1625	1675	1625

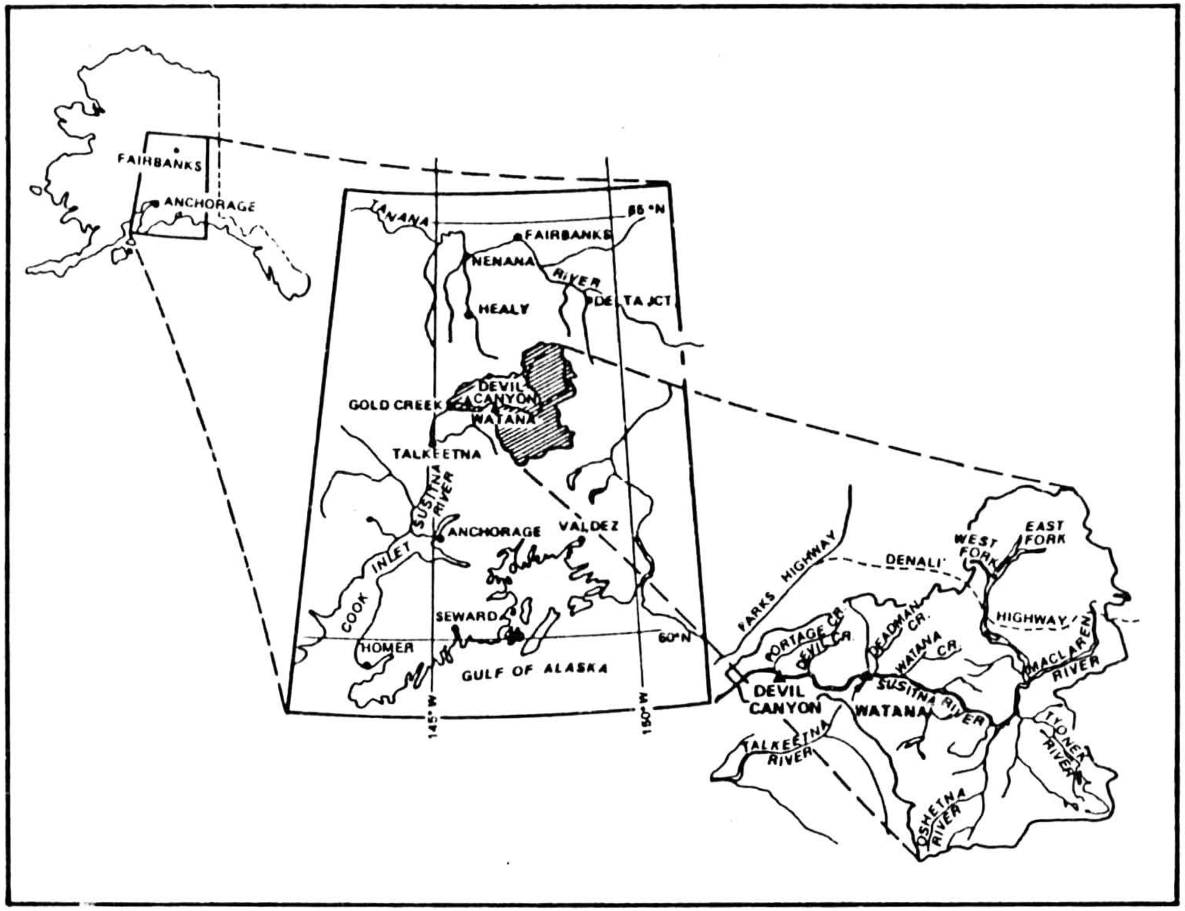


Figure 1. Location map (From Acres American, 1982).

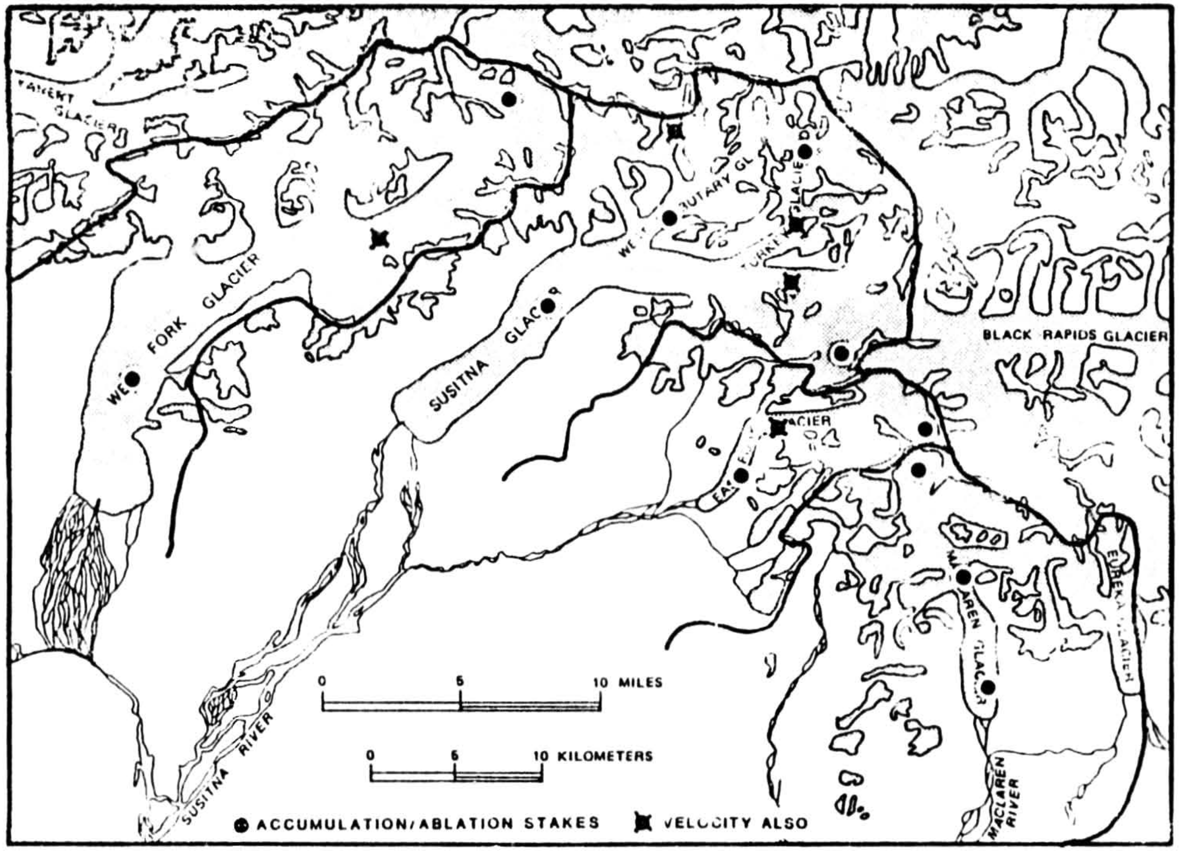
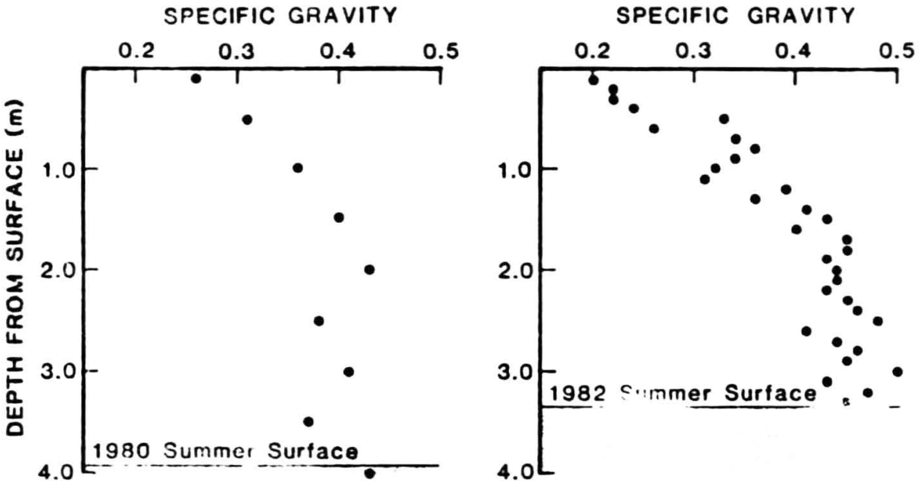
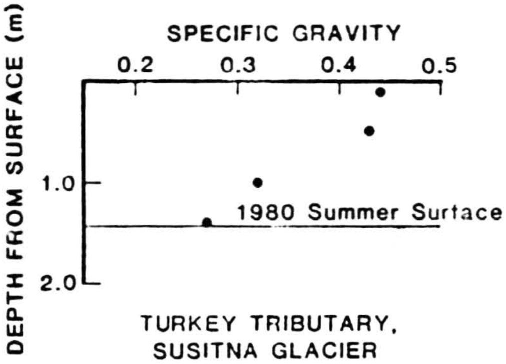


Figure 2. Glacier names and locations, stake locations, and drainage divides (Adapted from Harrison, 1983).



NORTHWEST TRIBUTARY,
SUSITNA GLACIER
2350 m Elevation
22 May 1981

EAST FORK GLACIER
2060 m Elevation
28 April 1983



TURKEY TRIBUTARY,
SUSITNA GLACIER
1670 m Elevation
13 May 1981

Figure 3. Snowpack density variations with depth and elevation. Note that the top two figures depict accumulation area snowpacks, and the bottom figure depicts an ablation area snowpack.

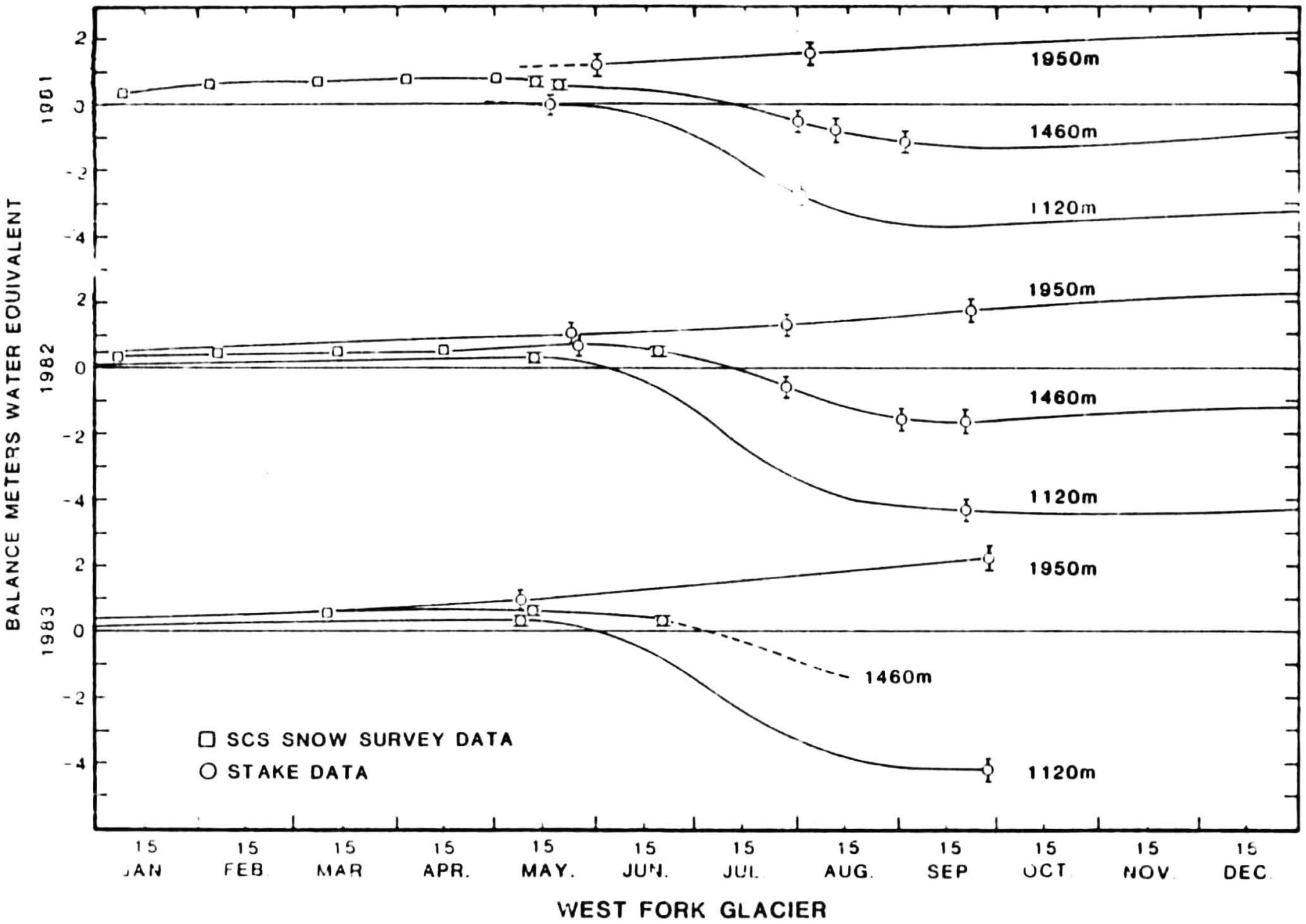


Figure 4a. Balance-time relations on West Fork Glacier.

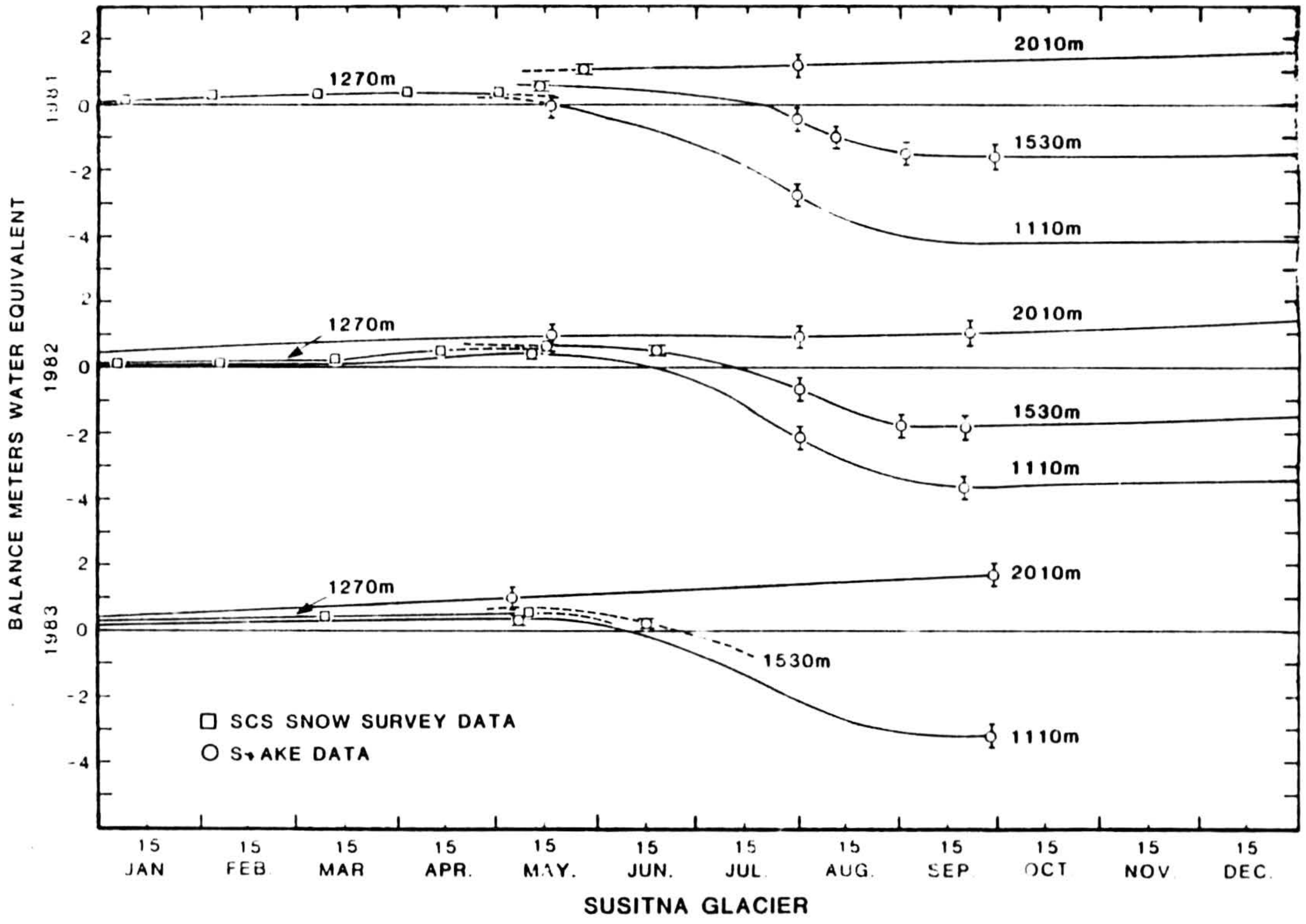


Figure 4b. Balance-time relations on Susitna Glacier.

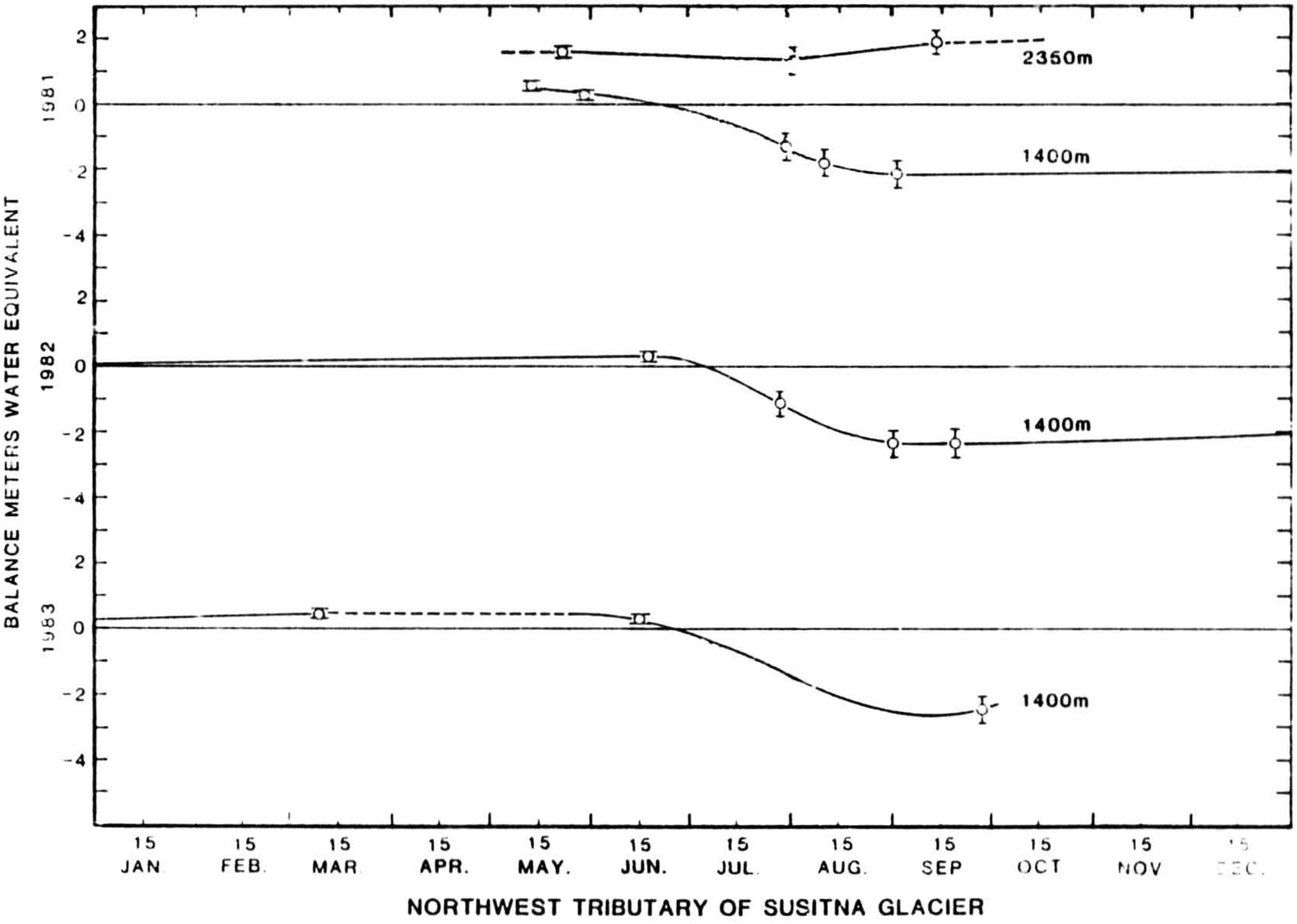


Figure 4c. Balance-time relations on Northwest tributary of Susitna Glacier.

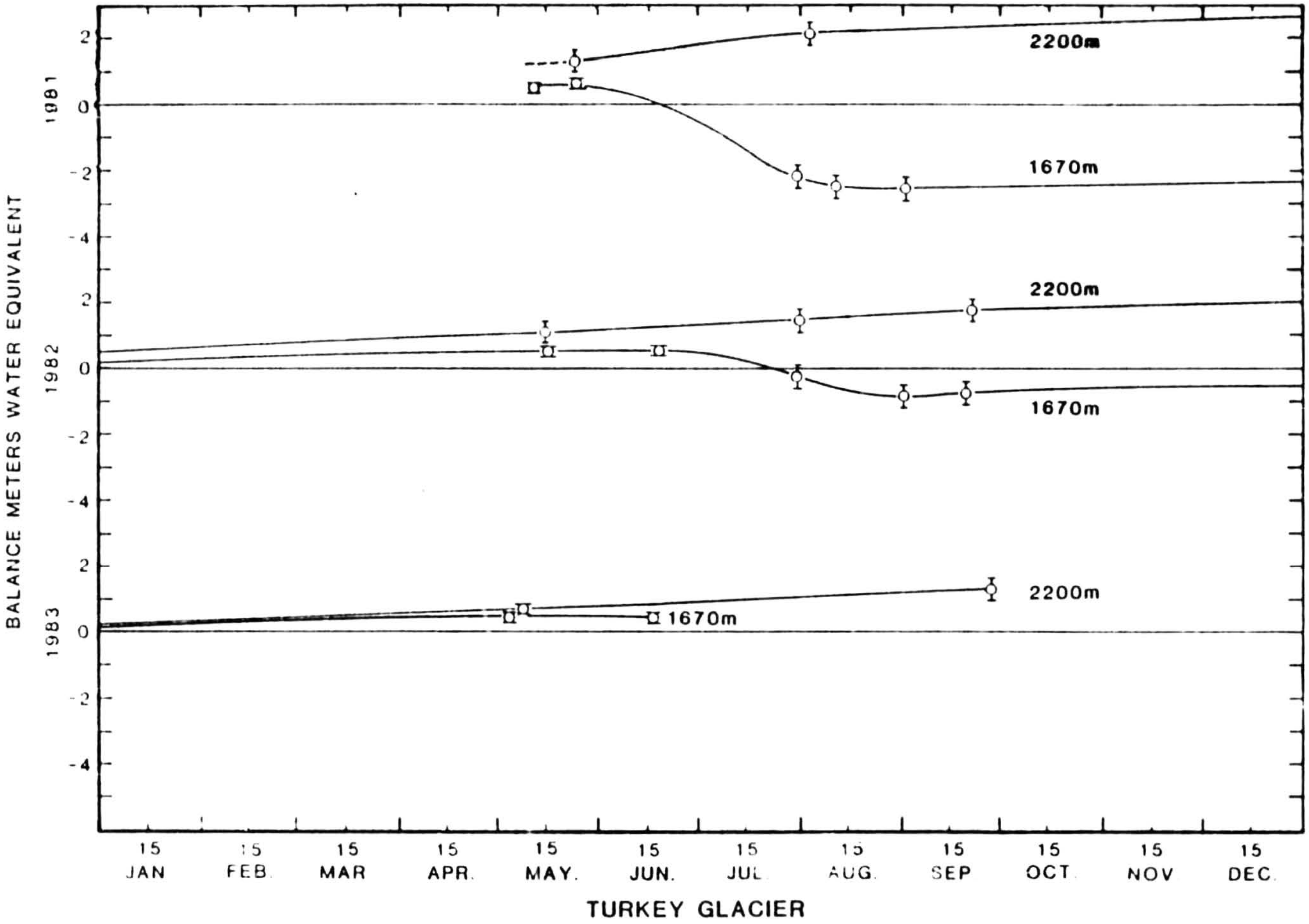


Figure 4d. Balance-time relations on Turkey Tributary of Susitna Glacier.

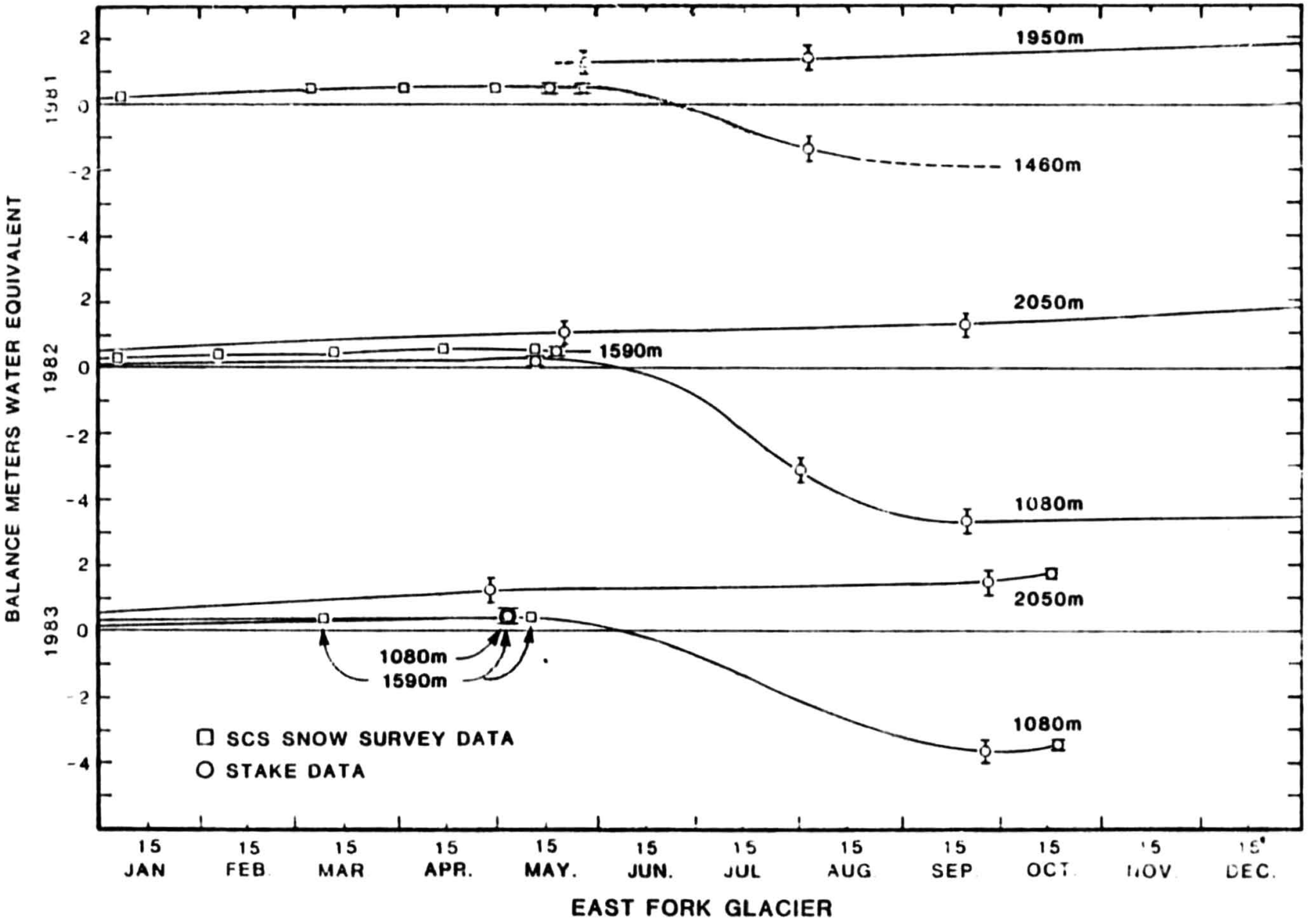


Figure 4e. Balance-time relations on East Fork Glacier.

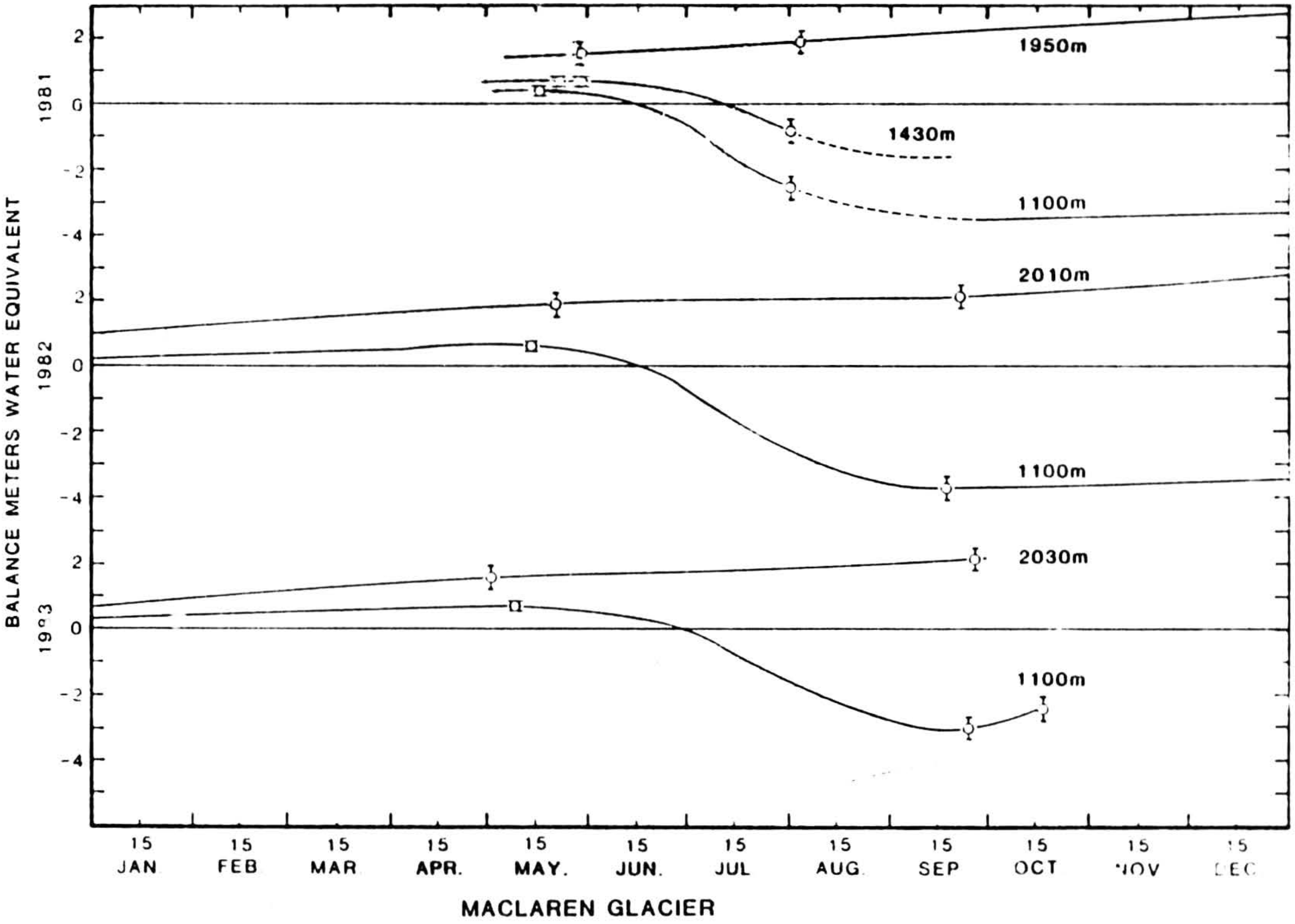


Figure 4f. Balance-time relations on Maclaren Glacier.

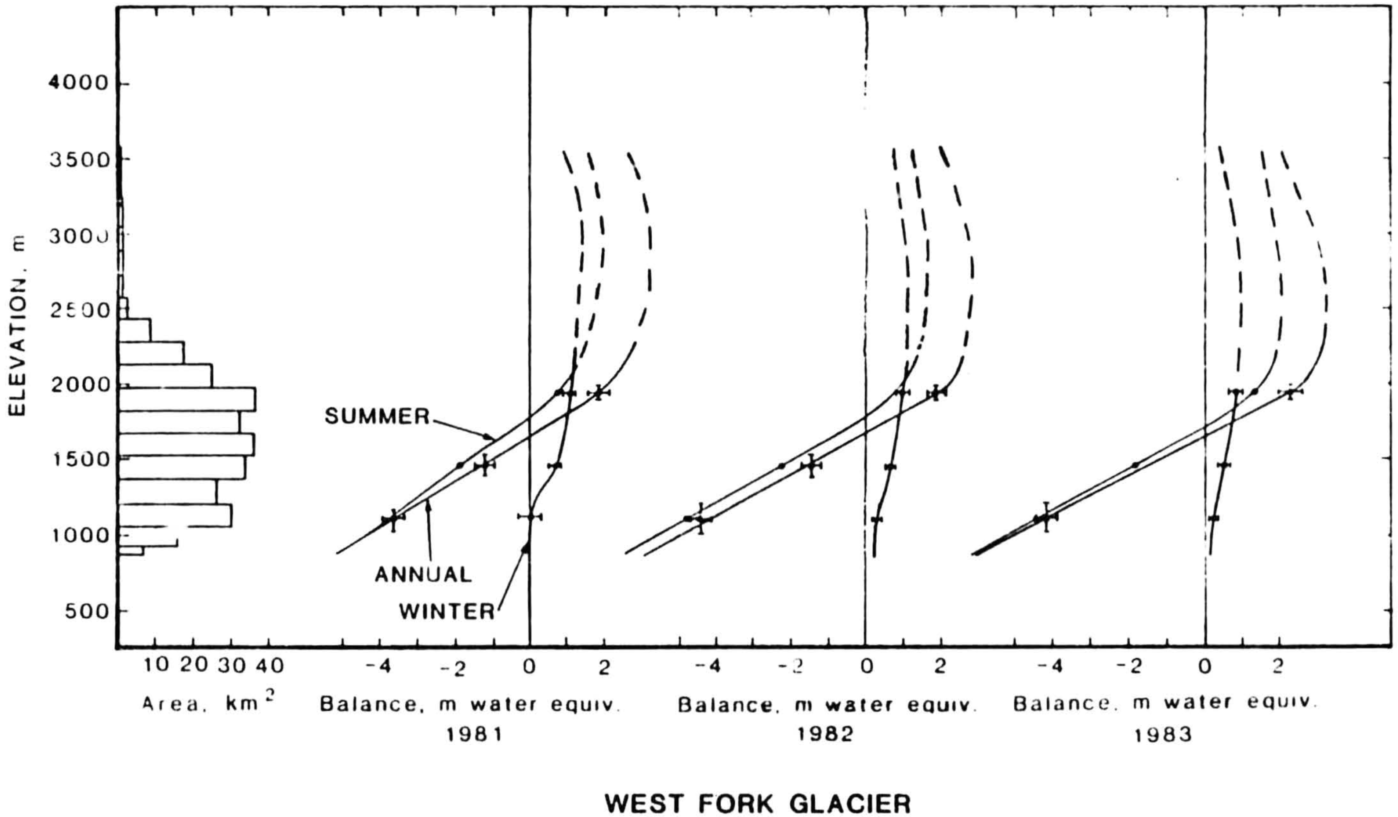


Figure 5a. Balance-elevation and area-elevation relations for West Fork Glacier.

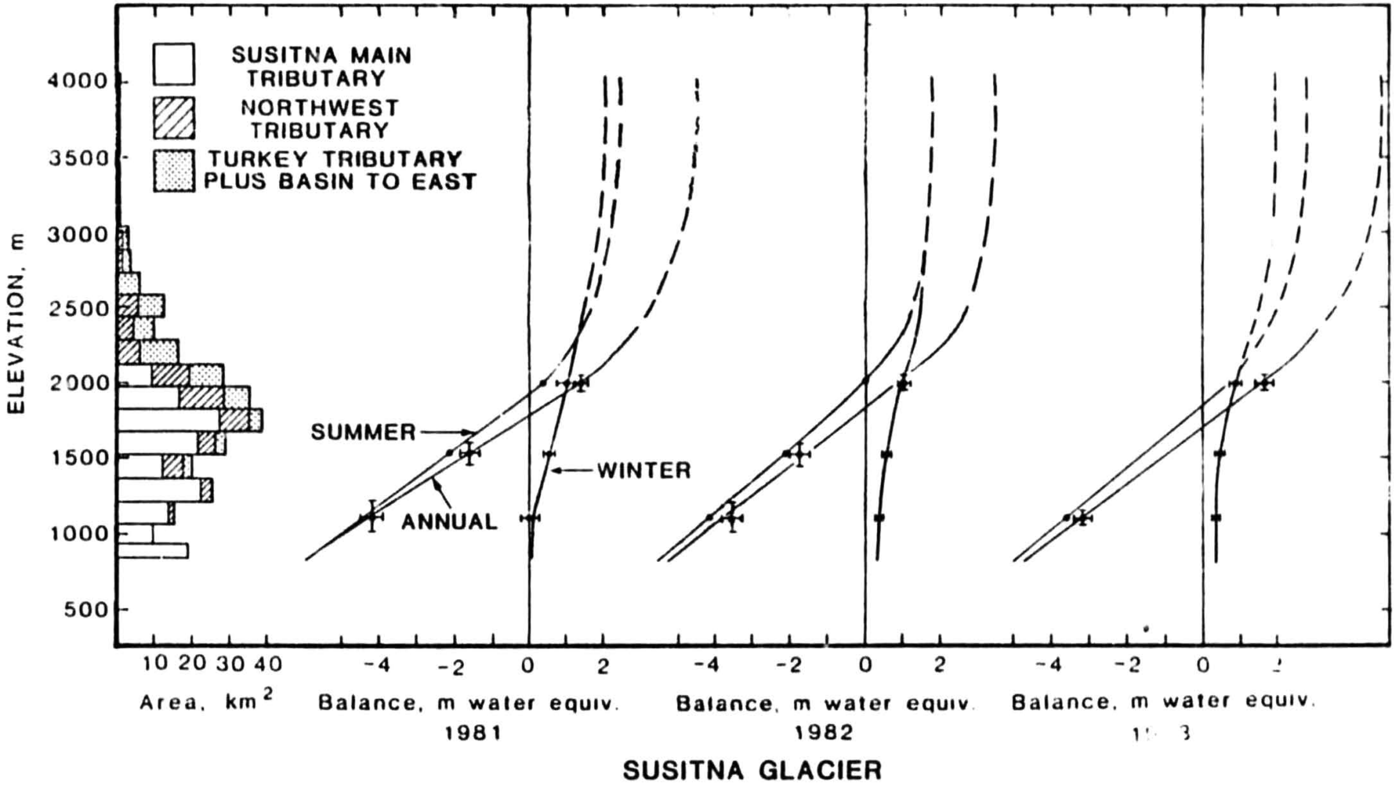


Figure 5b. Balance-elevation and area-elevation relations for Susitna Glacier.

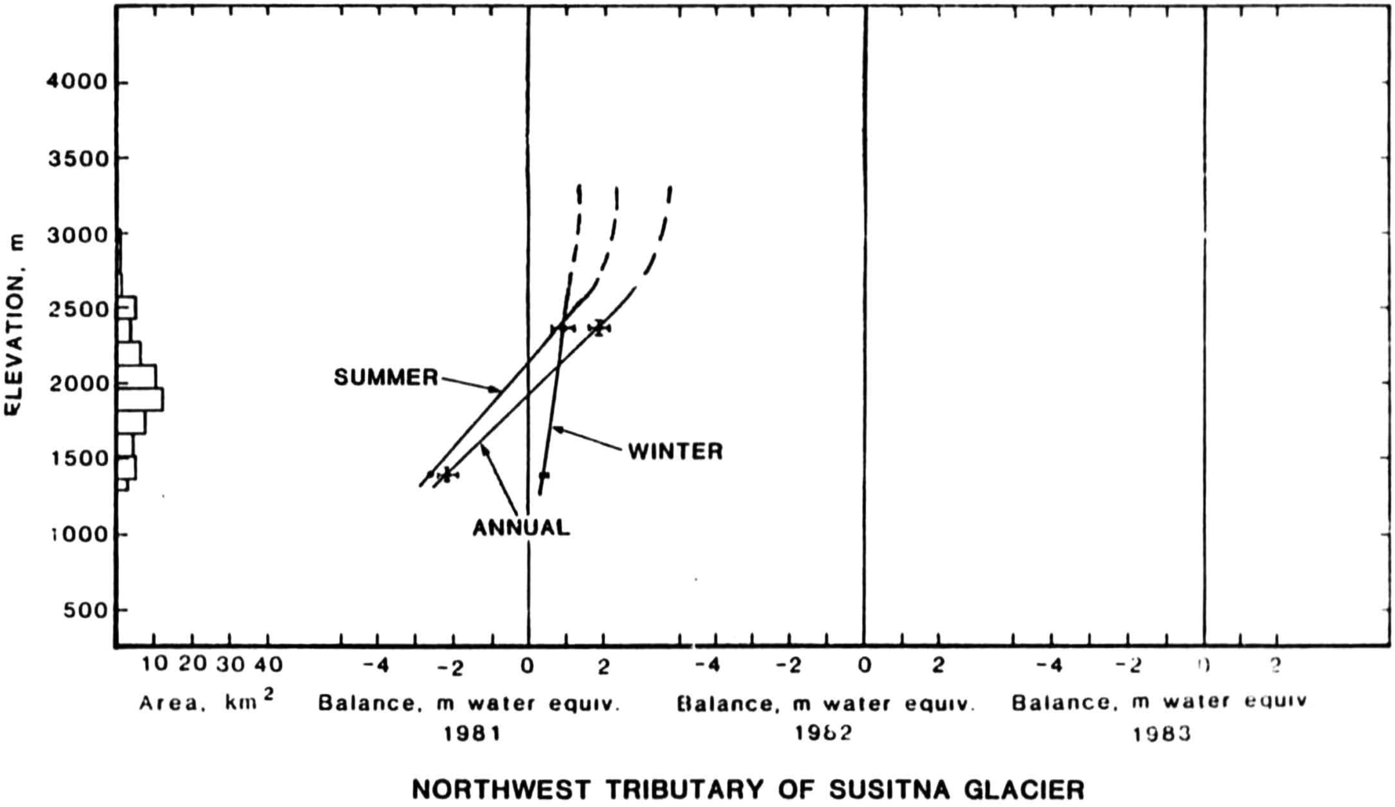


Figure 5c. Balance-elevation and area-elevation relations for Northwest tributary of Susitna Glacier.

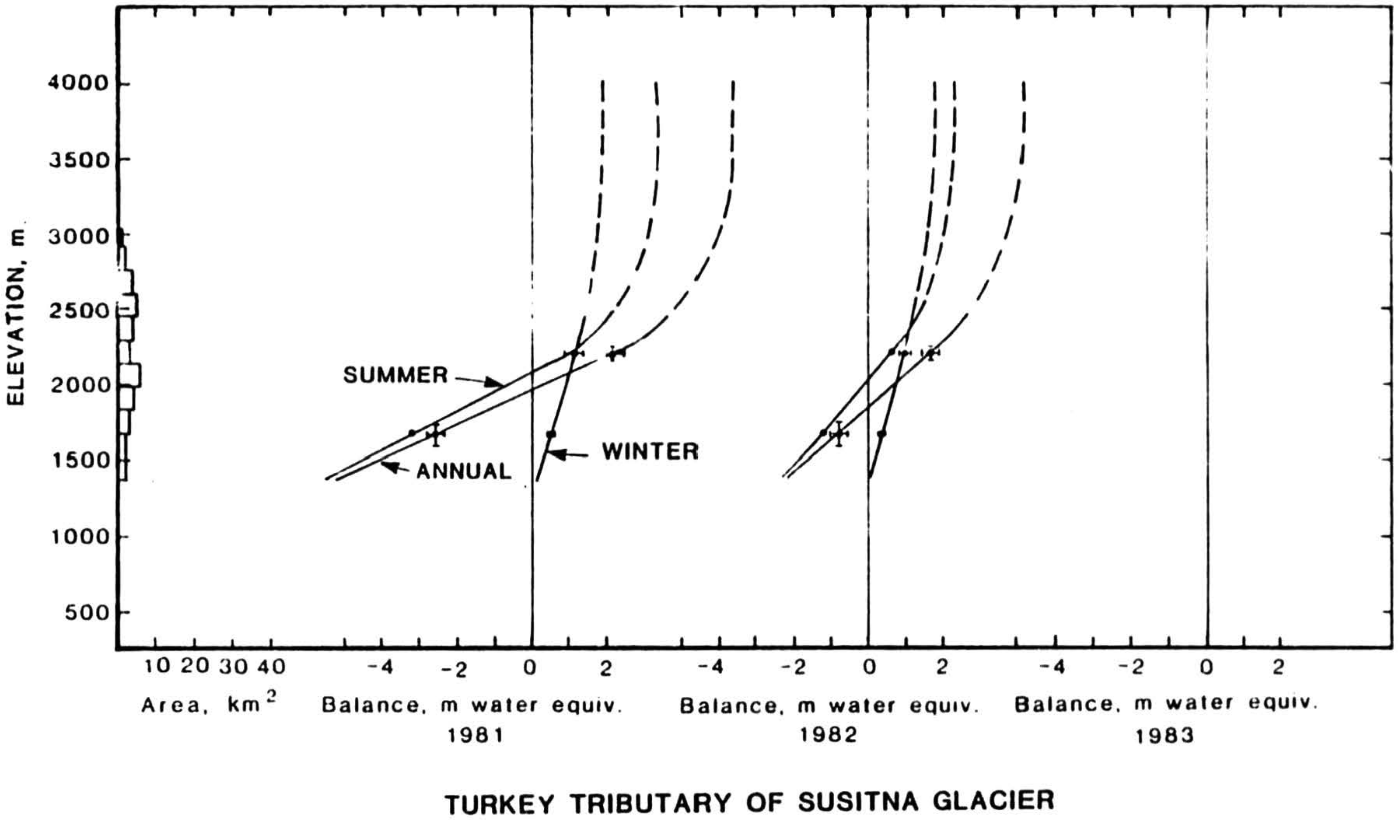


Figure 5d. Balance-elevation and area-elevation relations for Turkey tributary of Susitna Glacier.

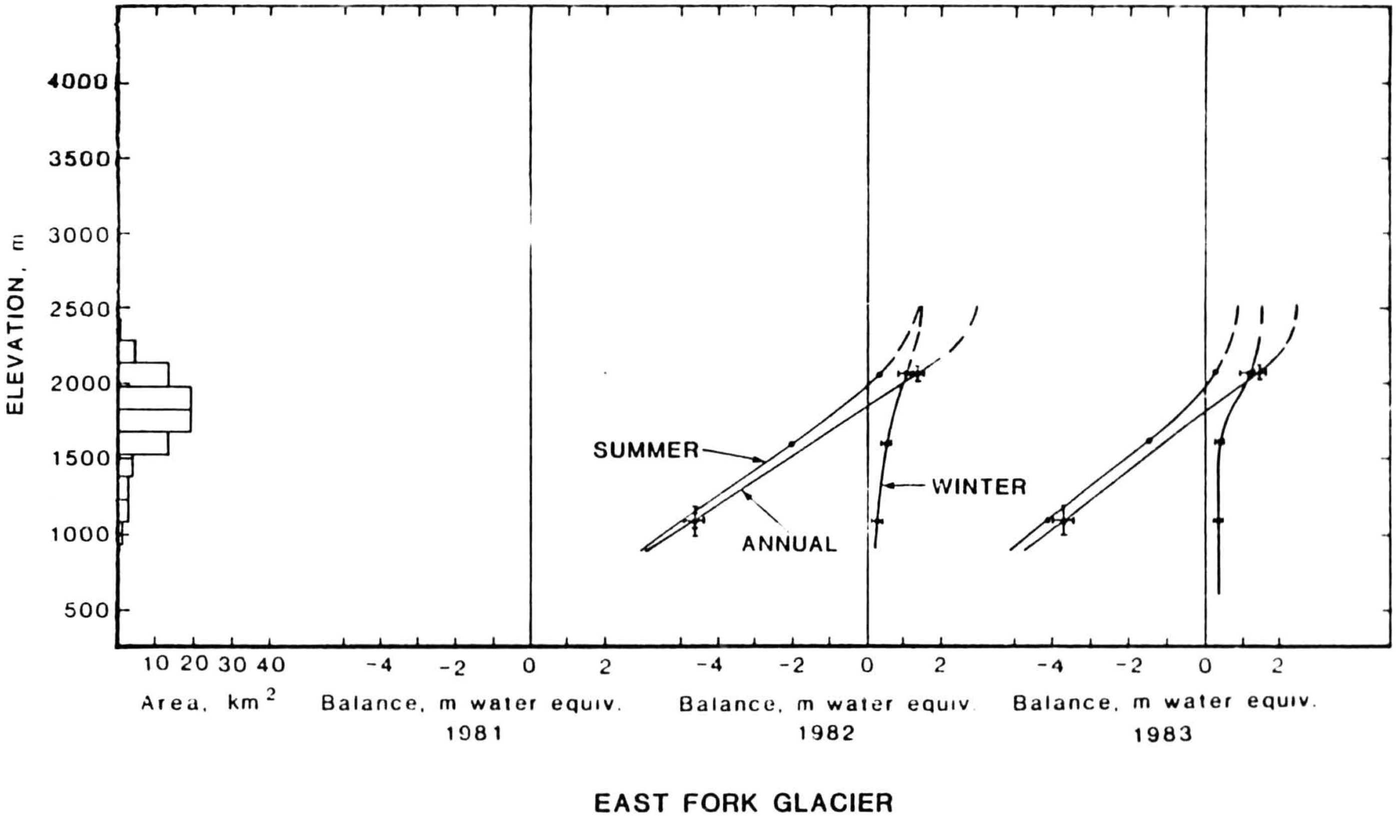


Figure 5e. Balance-elevation and area-elevation relations for East Fork Glacier.

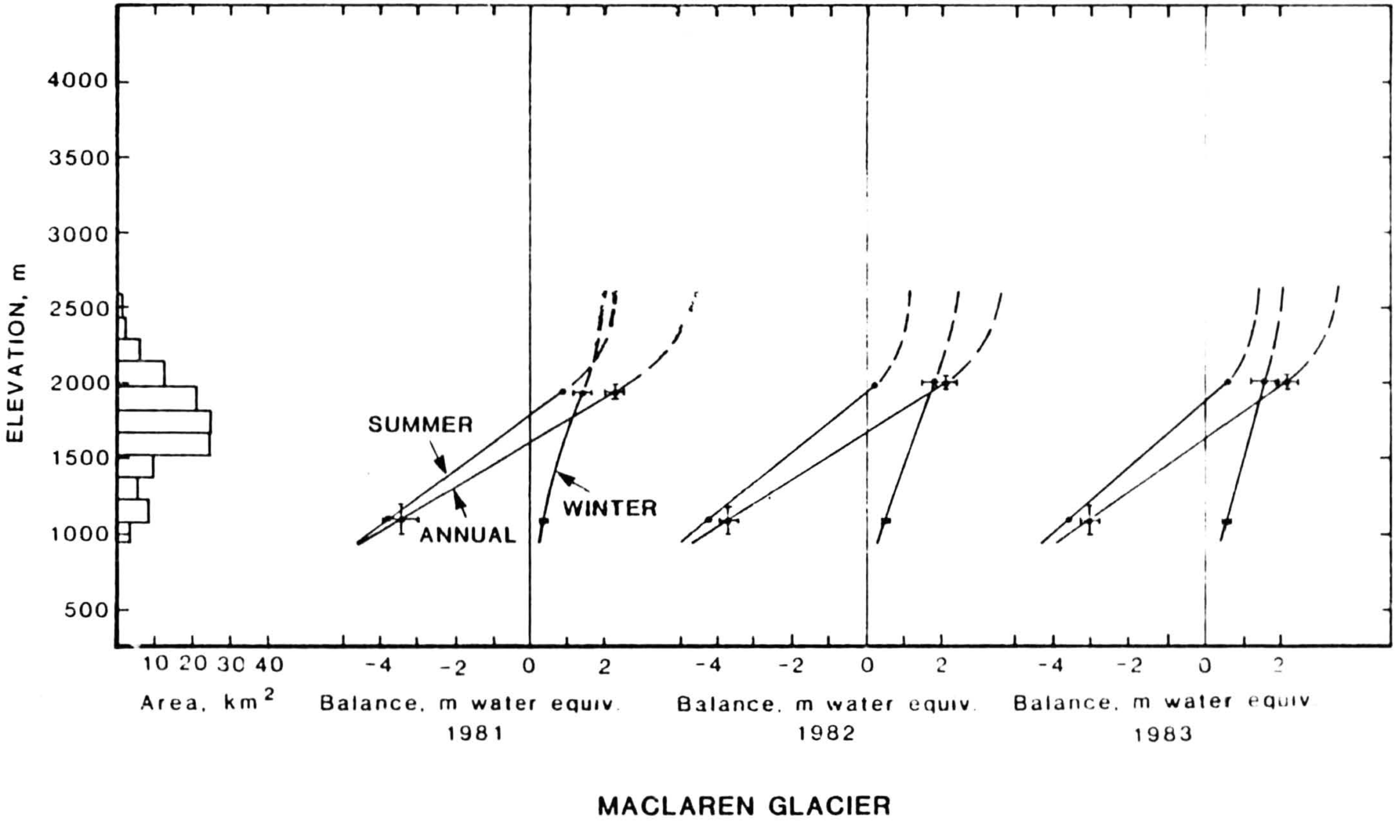


Figure 5f. Balance-elevation and area-elevation relations for Maclaren Glacier.

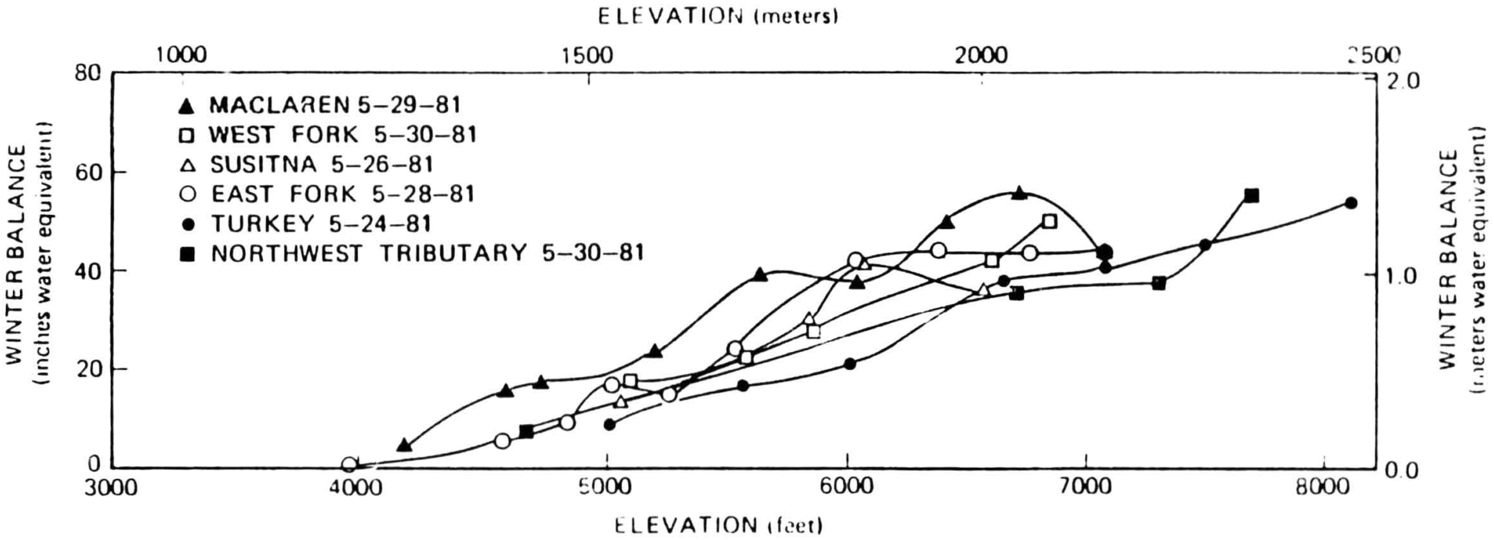


Figure 6a. Winter accumulation for 1980-1981 as determined from snow pack data.

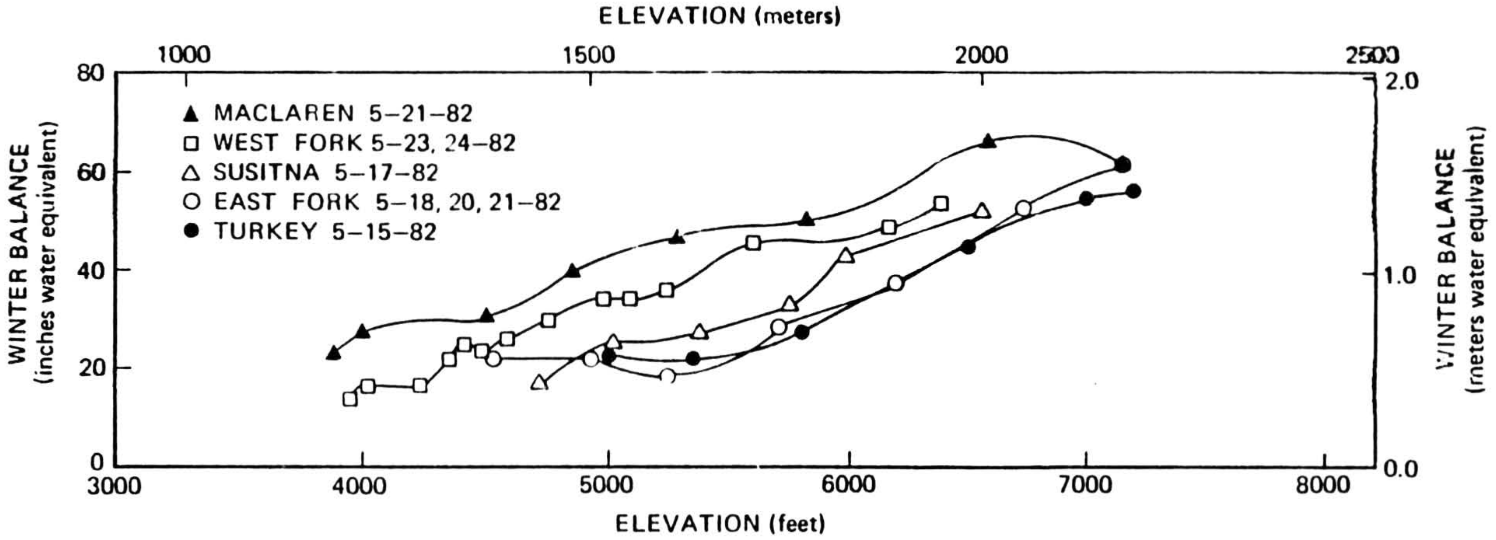


Figure 6b. Winter accumulation for 1981-1982 as determined from snow pack data.

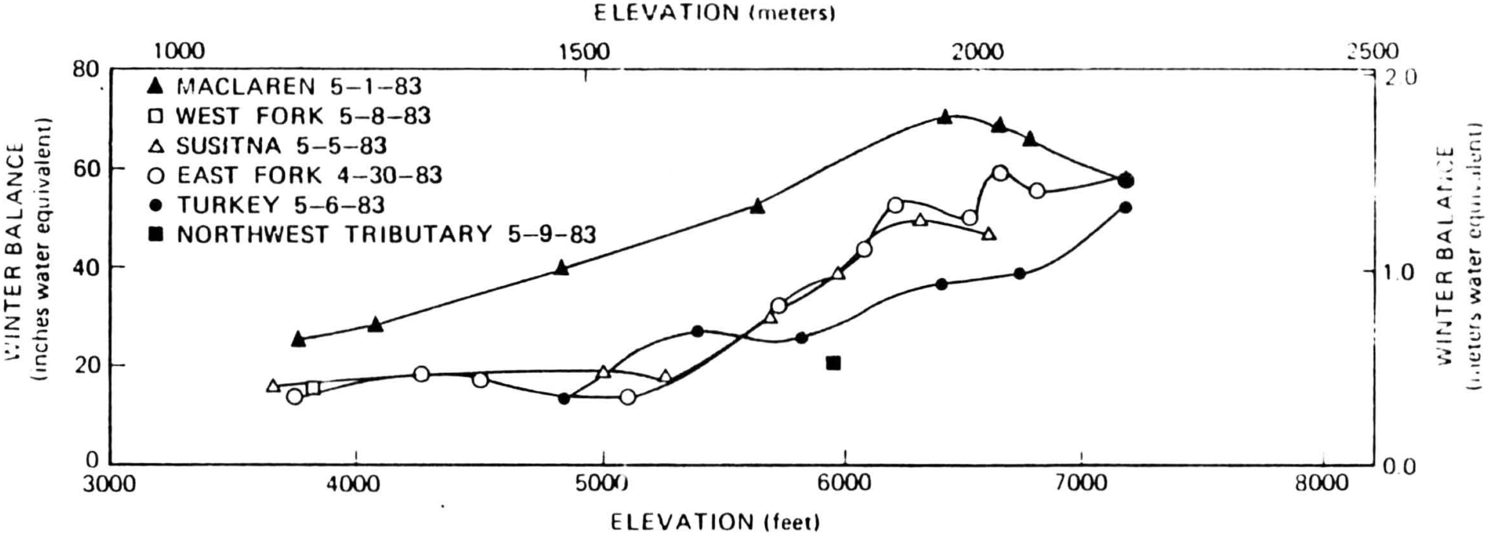


Figure 6c. Winter accumulation for 1982-1983 as determined from snow pack data.

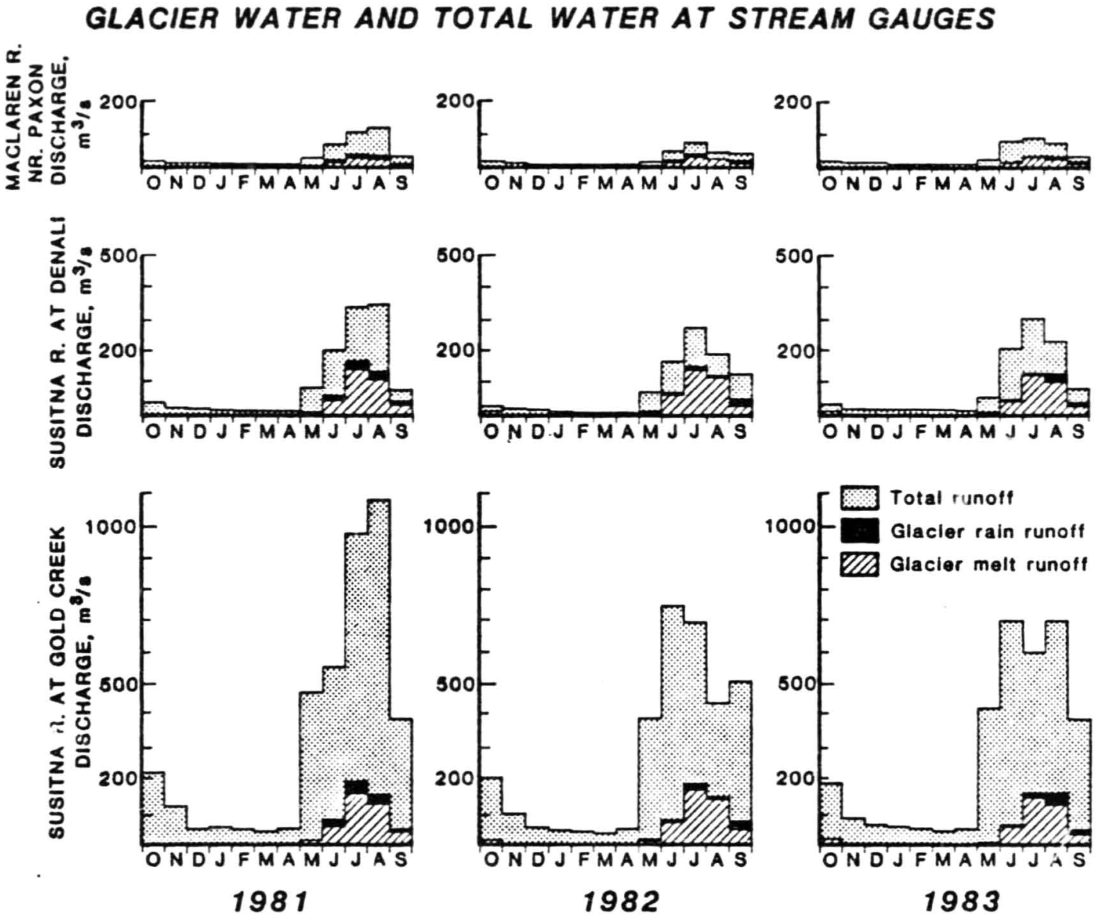


Figure 7. Runoff from glaciers compared to total runoff at stream gauges on the Susitna and Maclaren Rivers.

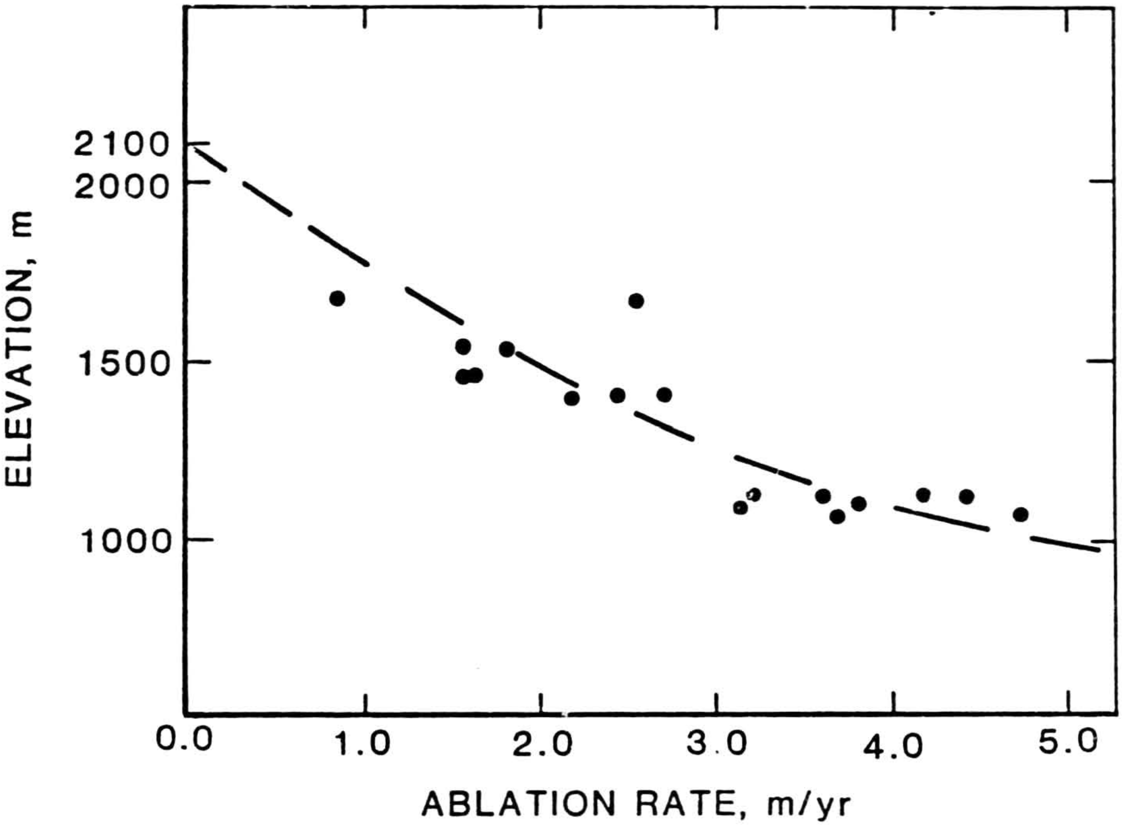


Figure 8. Ablation per year, in excess of that used for internal accumulation, versus elevation. Ablation is given in meters of water equivalent.