Combined Ice and Water Balances of Maclure Glacier, California, South Cascade Glacier, Washington, and Wolverine and Gulkana Glaciers, Alaska, 1967 Hydrologic Year

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ICE AND WATER BALANCES AT SELECTED GLACIERS IN THE UNITED STATES

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By Wendell V. Tangborn, Lawrence R. Mayo, David R. Scully, and Robert M. Krimmel

ABSTRACT

Combined ice and water balances were measured in the 1967 hydrologic year (October 1–September 30) on four glaciers in western North America ranging in latitude from 37° to 63° N. This hydrologic year was characterized by heavier than normal winter precipitation in California and Washington and abnormally dry winter conditions in coastal Alaska. In summer the western conterminous states were abnormally dry and central and southern Alaska experienced very wet conditions.

Maclure Glacier (lat 37°45′ N., 3,650-m (metres) mean equilibrium line altitude) had an above normal winter balance of 3.46 m and a positive annual balance of 1.05 m (metres of water equivalent).

South Cascade Glacier (lat 48°22′ N., 1,900-m mean equilibrium line altitude) had a winter balance of 3.28 m, slightly above average. Above normal summer ablation resulted in a final annual balance of −0.58 m, slightly more negative than has been the case for the past decade.

Wolverine Glacier's (lat 60°24′ N., 1,200-m mean equilibrium line altitude) winter balance was 1.17 m, considerably below normal; the annual balance was −2.04 m.

Gulkana Glacier (lat 63°15′ N., 1,700-m mean equilibrium line altitude) had a winter balance of 1.05 m, approximately normal for this glacier; the final annual balance was −0.30 m.

INTRODUCTION

The purpose of the International Hydrological Decade (1965–74) is to increase the understanding and to promote the efficient use of the Earth's freshwater supply. Seasonal snowpacks and glaciers account for approximately three fourths of the Earth's freshwater; thus a good understanding of the processes involved in the accumulation and ablation of glaciers and snowpacks is essential to account for their role in the hydrologic cycle. An objective of the glaciologic portion of the IHD is to better understand the ice, water, and heat balances of glaciers (UNESCO/IASH, 1970).

Studies on the four glaciers covered in this report are part of the United States' contribution to the IHD program of combined heat, ice, and water balances of selected glacier basins. In the first report of this series (Meier and others, 1971), the hydrologic years 1965 and 1966 were covered along with the description and regional setting for each glacier. This paper reports the results of the 1967 hydrologic year for these glaciers. Information essential to the understanding of terminology in this report is presented in the first report of this series and in a report on glacier mass balance terminology (Meier and others, 1971; Mayo and others, 1972).

WEATHER DURING THE 1967 HYDROLOGIC YEAR

The weather along the west coast of North America during the 1966–67 accumulation season (October 1966 through May 1967) was notable for two reasons. First, persisting low pressure troughs from lat 30° to 50° N. in the east Pacific during November, December, January, and April caused an increased westerly flow of moist Pacific air and produced extremely high precipitation in California and above normal precipitation in Washington and other Western States. North of this intense cyclonic activity a blocking ridge of high pressure extended from the mid-Pacific often into the Aleutians. This high pressure system replaced the usual low pressure storm track in this region. The resulting flow created unusually dry conditions in coastal Alaska from November through May.

During the summer ablation season, conditions were nearly reversed. A strong ridge of high pressure developed over the Rockies in July, causing subnormal precipitation and high temperatures along the Western Coastal States. Conversely, an Arctic low persisted throughout most of the summer, directing cold air flow and a southwesterly current of warm moist Pacific air from a low pressure cell in the Bering Sea produced extremely heavy precipitation in central and southern Alaska (U.S. Department of Commerce, 1967).

MEASUREMENT SYSTEM

The problem of making accurate measurements on glaciers to balance properly the solid and liquid input and output to the hydrologic system is well known (Schytt, 1970; Stenborg, 1970; Björnsson, 1971; Tangborn and others, 1975). Accurate surface measurements of precipitation and ablation are difficult to obtain over large, rugged areas of glacier-clad mountains. Measurements of outflow (runoff) are usually considered more accurate but important hydrologic information is masked by the space and time integration of streamflow. The glacier interior and bottom are poorly known regions in which measurements are difficult. The water flow and storage in a glacier is complicated by the fact that ice and snow permeability is strongly affected by the presence and passage of water; thus one cannot apply the simple laws of flow and storage in porous media. The result is that glaciologic and hydrologic events in a glacier basin are usually nonsynchronous and attempts to relate them directly, without a complete understanding of the glacier's internal drainage system, lead to serious errors. Relating ice and water balances over a year avoids some but not all of the errors.

In this report, the results of the ice and water balance measurements made on four glaciers are presented but no attempt is made to interpret the water transmission and storage in the glaciers. Discrepancies between the glaciologic and hydrologic measurements which occur could be due either to errors in the data or to the delay of stored water. In general, these measurements are not accurate enough to detect, with any certitude, subtle changes in liquid storage within the glaciers as was done on South Cascade Glacier in 1970 (Tangborn and others, 1975).

The glaciologic measurements to obtain ice and snow balance values follow the *combined annual and stratigraphic system* defined earlier (Mayo and others, 1972). All reported balances, precipitation, and runoff are water equivalent values. It is important to remember that mass changes as observed on a glacier's surface are not necessarily immediately reflected in stream discharge from the glacier and drainage basin. The result is a complex and highly variable relationship between ablation, glacier storage, and runoff.

MACLURE GLACIER

DESCRIPTION

Maclure Glacier (lat 37°45′ N., long 119°16′ W., fig. 1) is a small cirque glacier near the crest of the Sierra Nevada in Yosemite National Park, California. This glacier is 0.5 km long and covers an area of 0.2 km^2; the mean ELA (equilibrium line altitude) is 3,650 m. Runoff from the 0.97 km^2 basin flows into the Tuolumne River, which flows west into the San Joaquin Valley of California.

FIELD PROGRAM

The study at Maclure Glacier began in October 1966 with the construction of a combination gaging station–shelter hut, air temperature and precipitation instrumentation, and the commencement of mass balance measurements. No streamflow record was obtained prior to May 24, 1967; however, it is estimated less than 5 percent of the total runoff occurred from October 1, 1966, to May 24, 1967. Air temperature was recorded at the gaging station shelter by a thermograph attached to the water-stage recorder. The thermograph sensor was located on the north side of the access chimney about 5 m above the ground. Precipitation was recorded near the basin outlet by a water-stage recorder over a storage tank. A nitrogen gas bubbler was used to mix the antifreeze (ethylene glycol) and precipitation to keep it in a liquid state. Many problems were encountered in the first year's operation of the precipitation gage. These problems included recorder insensitivity, clock stoppage, snow blowing into the shelter, and the possibility of the collection orifice bridging over with snow. Because of the poor quality of the record only the total precipitation between visits was determined (table 1). The total precipitation was broken into daily values of rain and snow using the precipitation record from the weather station at Yosemite National Park Headquarters (1,210-m altitude) and the air temperature record at site 1 in Maclure Glacier basin (p. 1*A*) as guides (pl. 1*D*). Instrument locations are shown on plate 1*A*.

WEATHER

Most precipitation in this area comes in the form of snow during the winter and spring months (November–April). This precipitation results from the orographic and frontal lifting associated with storms that move in from the Pacific Ocean. The major storms are usually of short duration and of high intensity. A small quantity of precipitation comes from local thunderstorms in the summer months.

Major frontal storms in early December 1966 and late January 1967 were responsible for most of the early winter precipitation. Below normal temperatures in March and April in conjunction with above normal precipitation contributed to a near record snowpack in the central and southern Sierra Nevada. Thunderstorm activity was present in the Maclure Glacier area July, August, and September. The weather station at Yosemite National Park Headquarters (1,210-m altitude) recorded 1.44 m of precipitation during the 1967 hydrologic year. This was 155 percent of the 61-yr average of 0.93 m.

Although air temperatures varied markedly from normal in most winter and spring months, the average temperature for the 1967 balance year (hydrologic year) was near normal at most Sierra Nevada stations. The average air temperature for the station at Yosemite National Park Headquarters was about 1°C (Celsius) above the long-term (61-yr) normal of 12°C. The average temperature for the balance year at Maclure Glacier measured at 3,520-m altitude was approximately 0°C.

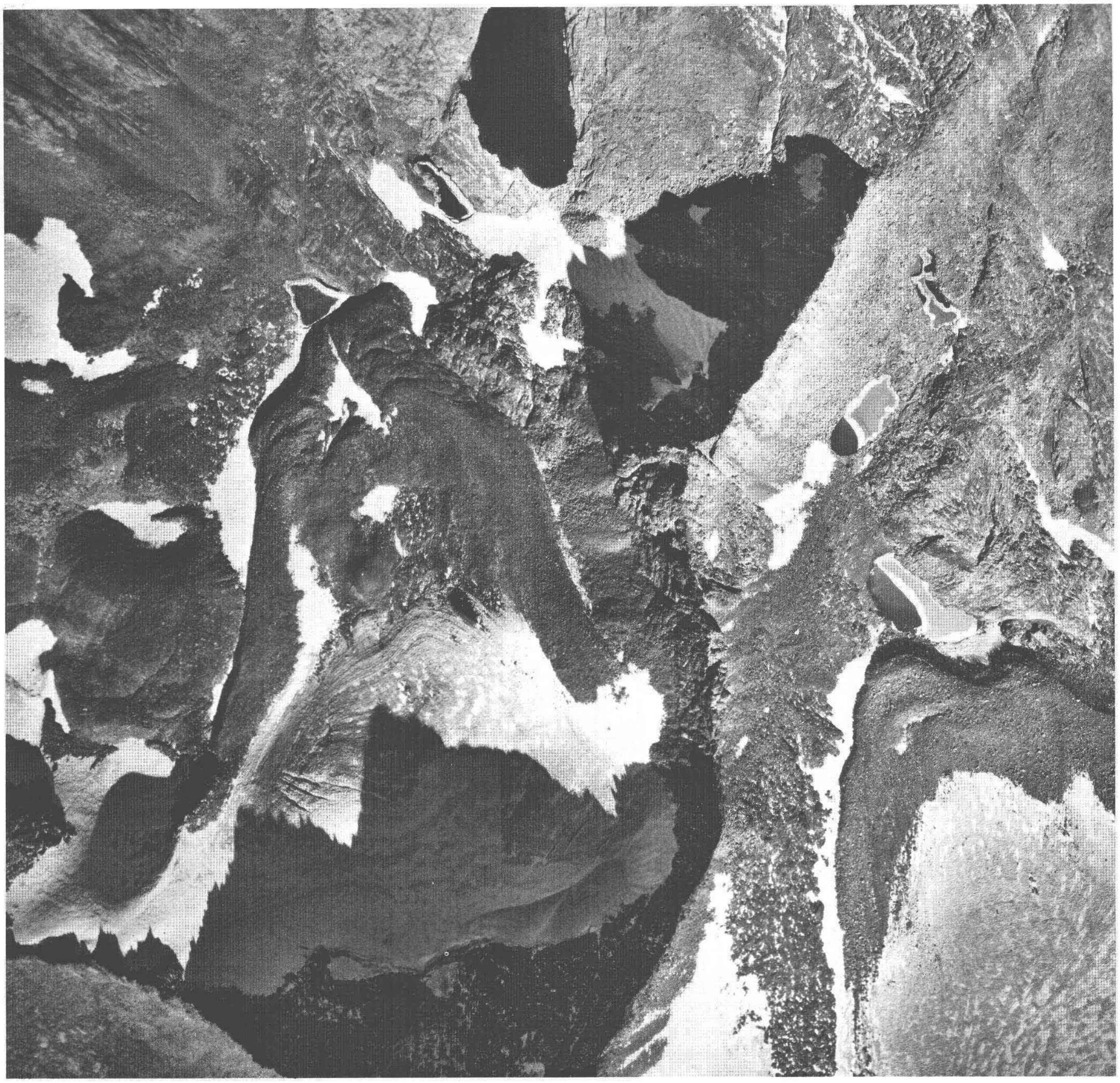

FIGURE 1.—Vertical aerial photograph of Maclure Glacier and most of the drainage basin, Sierra Nevada, California, October 25, 1966. (North, top of photograph.)

GLACIOLOGIC BALANCES

The measured winter snow balance, $\overline{b}_m(s)$, was determined by measuring the depth of snow and its density in the latter part of May 1967. The depth of the snow was measured at many locations over the entire basin; a snow pit was dug and samples taken to determine the density. These measurements, together with photographs, were used to draw a contour map (p. 1*B*) showing lines of equal water equivalent. The measured winter snow balance was 1.98 m averaged over the basin and 3.46 m on the glacier. The estimated error (table 2) in these values is high for several reasons. The extremely deep snowpack in 1967 made depth sounding difficult, some areas in the basin were inaccessible because of the steep slopes, and inconsistent depth soundings were obtained in some non-glacier covered areas because of the loose rock debris under the snow. The high values (greater than 5 m) for accumulation on the upper portion of the glacier are

TABLE 1.—*Instrumentation at Maclure Glacier during the 1967 hydrologic year*

[Continuous record ———, estimated record - - - -, occasional measurement •]

Station	Altitude (metres)	Measurement	1967 Hydrologic year												
			1966			1967									
			Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.
1	3510	Streamflow	-•-	- - -	- - -	- - -	- - -	- - -	- - -	- - ———	———	———	———	———	———
1	3510	Air temperature	- - ———	———	———	———	———	———	———	———	———	———	———	———	———
1	3510	Wind speed	———	———			—	———	———	———	———	———	———	———	———
2	3520	Precipitation	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - ———	———	———	———	———	———
S–28	3618	Balance								•		•	•		•
3	3680	Precipitation	•							•		•	•		
S–26	3683	Balance								•		•	•		•
Basin photographed			•				•			•		•	•		
Station occupied by personnel			—				—			—		—	—	—	—

believed to be caused in part by snow blowing into the basin from the south—a normal mode of accumulation on small cirque glaciers.

The annual balance, $\bar{b}_a$, was determined by combining measurements of the depth and density of the snow remaining at the end of the summer season, $\bar{b}_n(f)$, and by measurement of the amount of ice and firn ablation during the summer season, $\bar{b}_n(i)$, and using the adjustment terms $\bar{b}_0$ and $\bar{b}_1$ ($\bar{b}_a = \bar{b}_0 + \bar{b}_n(f) + \bar{b}_n(i) - \bar{b}_1$). A positive annual balance was found for both the basin (0.37 m) and the glacier (1.05 m). It is interesting to notice that for the 1967 hydrologic year almost one-half of the old firn and ice ablation occurred in the first 3 weeks of October 1966 (fig. 2). Due to the above normal winter and spring precipitation, 86 percent of the glacier was still covered by snow at the end of the summer season. These annual balance figures are considered to be more accurate than the winter balance figures (table 2) because the annual balance can be more easily measured. Photographs are helpful in determining the extent of residual snow in accessible areas.

Because of the small size of this glacier and cessation of melting soon after the end of the hydrologic year, the stratigraphic and annual balance changes are nearly synchronous. Values relating annual and net balances (table 2) were small, and only a few correction factors are necessary (table 2). The slight difference between the annual and net balance is due to the difference between $\bar{b}_0$ and $\bar{b}_1$, a reflection of the higher melt rates in October 1966 than in October 1967. Figure 2 illustrates the mass balance values that were measured and some important calculated values.

HYDROLOGIC BALANCE

Basin runoff during the hydrologic year totaled 1.60 m (1.51 m measured, plus 0.02 m estimated during the winter months, plus 0.07 m between Oct. 1 and Oct. 20, 1966). The source of this runoff was approximately 1 percent ice melt, 22 percent glacier snowmelt, 69 percent nonglacier snowmelt, and 8 percent rain. The sum of the components ($\bar{b}_0 + \bar{b}_x = \bar{b}_a + \bar{p}_a(r)$) serves as an independent check on runoff; they gave 1.75 m, or 0.15 m more runoff than indicated by streamflow. This difference is within the limits of estimated errors for all the parameters entering into the calculation.

The recording precipitation gage located near the mean altitude of the drainage basin gave a value of 2.03 m for the year. This is slightly larger than the calculated precipitation, $\bar{p}_a$*, as determined by runoff and ice storage changes.

SOUTH CASCADE GLACIER

DESCRIPTION

South Cascade Glacier (lat 48°22′ N., long 121°03′ W., fig. 3) is located in the North Cascades of Washington. This valley glacier occupies roughly one-half of a 6.11-km² basin. The mean ELA is 1,900 m. Water from the basin flows into the Cascade River then the Skagit River.

FIELD PROGRAM

The instrumentation and mass balance measuring program during 1967 was quite similar to that in 1966 (Meier and others, 1971). Most of the recording instruments operated throughout the year except for a short period in the late winter (table 3). Instrument locations together with snowline data during the ablation season are shown on plate 2.

WEATHER

The weather in the North Cascades during the balance year was characterized by a severe storm in October 1966, heavy midwinter precipitation, a cool, rather dry spring, and an unusually warm and dry summer season. The cloud cover in the North Cascades during the June–September ablation period averaged 15 percent below the long-term mean.

TABLE 2.—*Ice and water balances, Maclure Glacier basin, 1967 hydrologic and balance years*

[Values and errors in metres water equivalent expressed as averages over the glacier and basin except where indicated. Date: Hydrologic year, Oct. 1, 1966 (t_0) through Sept. 30, 1967 (t_1)]

	Glacier		Basin				
	Value	Error	Value	Error	Date	Term	Explanation
						Yearly mass balances	
$\bar{b}_a$	1.05	0.01	0.37	0.05	Hydrologic year	Annual balance	Total change in snow, firn, and ice storage during the 1967 hydrologic year, from t_0 to t_1; approximately equal to difference between precipitation as snow and meltwater runoff for the hydrologic year.
$\bar{b}_n$	1.10	.10	.39	.05	Oct. 20, 1966 to Oct. 15, 1967	Total mass net balance	Change in storage from the minimum balance in 1966 autumn (t_0') to the minimum in the 1967 autumn (t_1').
$\bar{b}_a(fi)$	1.10	.10	.39	.05	....do	Firn and ice net balance	Change in firn and ice storage between two consecutive summer surfaces.
						Accumulation and ablation	
$\bar{b}_m(s)$	3.46	0.20	1.98	0.20	May 24, 1967	Measured winter snow balance	Snowpack on the 1966 summer melt surface (ss_0); measured in late winter or spring in pits and by probing.
$\bar{b}_x$	3.35	.20	1.91	0.20	May 14, 1967	Maximum balance	Storage change from the beginning of the hydrologic year (t_0) to the maximum in the spring. Winter balance (b_w) equals maximum balance ($\bar{b}_x$) plus the absolute value of the initial balance increment ($\bar{b}_0$).
$\bar{b}_a(f)$	1.28	.10	.40	.05	Oct. 15, 1967	Net firnification	The increment of new firn in the accumulation area at t_1, measured after melting ceases in the autumn.
$\bar{b}_a(i)$	-.18	-.01	-.01	-.01	....do	Net ice balance	Ice and old firn melt in the ablation area during the 1967 melt season.
$\bar{c}_a$	3.46	.25	1.98	.20	Hydrologic year	Annual accumulation	Total accumulation of snow between t_0 and t_1.
$\bar{a}_a$	2.41	.25	1.61	.20	....do	Annual ablation	Total ablation of snow, ice, and old firn between t_0 and t_1. Approximately equal to the difference between annual rainfall and runoff.
						Values relating annual and net ice balances	
$\bar{b}_0$	-0.11	0.03	-0.07	0.01	Oct. 1-20, 1966	Initial balance increment	Storage change between time of minimum in 1966 autumn (t_0') and beginning of hydrologic year (t_0).
$\bar{b}_0(s)$	0	0	0	0	....	Initial snow balance	Snow accumulated on the 1966 summer surface (ss_0) at beginning of hydrologic year (t_0); measured in pits and by probing.
$\bar{b}_0(i)$	-.11	.03	.02	.01	Oct. 1-20, 1966	Initial ice balance	Ice and old firn melt after t_0 and before the winter snowpack covers the glacier; measured by ablation stakes.
$\bar{b}_1$	-.06	.02	-.05	.02	Oct. 1-15, 1967	Final balance increment	Storage change between time of minimum in 1967 autumn and the end of the hydrologic year.
$\bar{b}_1(ls)$	0	0	0	0	....	Final late snow balance	Snow accumulated on the 1967 summer surface (ss_1) at t_1.
$b_1(i)$	-.01	.01	0	0	Oct. 1-15, 1967	Final ice balance	Ice and old firn melt after t_1 and before the next year's snowpack covers the glacier.
						Glacier and basin dimensions	
S(fi)	[1]0.17	0.02	0.18	0.02	Oct. 15, 1967	Glacierized area	Glacier value includes firn and ice areas which normally are attached to the main trunk glacier. Basin value is the main glacier plus all other small glaciers and perennial snowfields in the drainage basin. Ice-cored moraine and other permafrost areas are not included as glacierized areas.
S	[1].17	.02	.97	.01	....do	Total area	Glacier and water drainage basin above the stream gaging station.
AAR	[2].86	.03	.39	.03	....do	Accumulation area ratio	Area of new firn, accumulation area, divided by the total area. An index of annual balance.
ELA	3,640	5	.....	.....	....do	Equilibrium line altitude	Average altitude where snow ablation equals snow accumulation. An index of annual balance.

[1]Square kilometres.
[2]Dimensionless.

TABLE 2.—*Ice and water balances, Maclure Glacier basin, 1967 hydrologic and balance years*—Continued

	Glacier Value	Glacier Error	Basin Value	Basin Error	Date	Term	Explanation
						Glacier and basin dimensions—Continued	
ΔL	5	3	.....	.....	Hydrologic year	Advance or retreat	Average horizontal distance change of terminus of the glacier in direction of flow.
						Precipitation and runoff	
p_a	.....	.....	2.03	0.50	Hydrologic year	Gaged annual precipitation	Total snow and rain caught during the hydrologic year by a shielded gage at 3,520-m altitude.
$p_a\ (r)$	.....	.....	.14	.05	....do	Gaged annual precipitation as rain	Precipitation occurring as rain caught during the hydrologic year by the same gage at 3,520-m altitude.
$\bar{p}_a$	3.60	0.21	2.12	.21	....do	Annual basin precipitation	Area averaged snow and rainfall measured during the hydrologic year by precipitation gages and snow balance measurements.
$\bar{p}_a\ (r)$	.14	.06	.14	.06	....do	Annual basin precipitation as rain	Area averaged rainfall measured by gages during the hydrologic year. Rain distinguished by air temperature records, visual observations, and photographic record.
p_a*	3.44	.28	1.97	.10	....do	Calculated annual precipitation	Area average annual snow and rain precipitation; the sum of annual stream runoff and annual storage change ($\bar{b}_a$).
$\bar{r}_a$	2.39	.15	1.60	.09	....do	Annual runoff	Stream discharge for the year divided by glacier or basin area, expressed as average depth of water over the area; measured by stream stage recorder and stream discharge measurements.

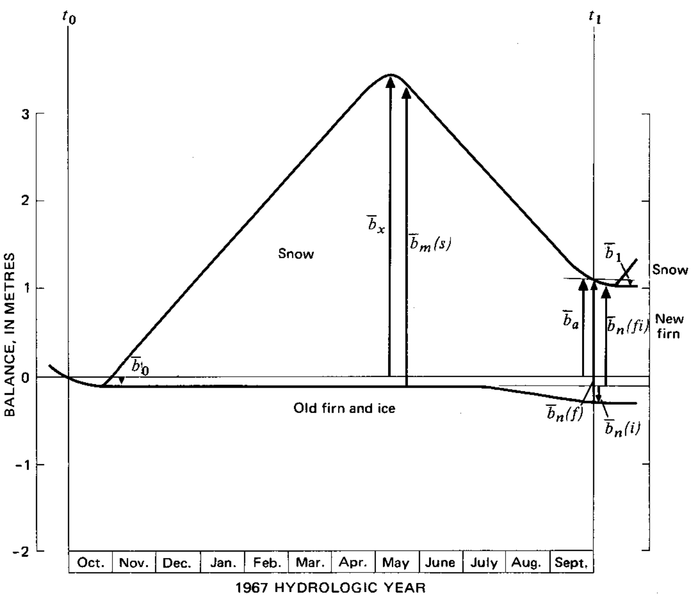

FIGURE 2.—The balance of Maclure Glacier, 1967 hydrologic year. (Refer to table 2 for additional values.)

GLACIOLOGIC BALANCES

The measured winter snow balance, $\bar{b}_m(s)$, was determined by field measurements on May 4-5, 1967. Snow pits and density cores were used to determine the snowpack water equivalent at index stations P-1, near the equilibrium line, and P-0, in the ablation area. More than 100 snow depth soundings were made on the glacier and in the nonglacierized area of the basin to expand the index station data to determine values for $\bar{b}_m(s)$. The maximum balance, $\bar{b}_x$, occurred on approximately May 17. The value of $\bar{b}_x$ is less than $\bar{b}_m(s)$ because it is measured from the beginning of the hydrologic year, t_0. Considerable storage change, $\bar{b}_0$, occurred in October 1966 and must be accounted for when determining $\bar{b}_x$:

$$\bar{b}_x=\bar{b}_m(s)+\bar{b}_0(i)+\Delta\bar{b}(s),$$

where $\Delta\bar{b}(s)$ equals the additional snow accumulation between May 5 and May 17. The value for $\Delta\bar{b}(s)$ for the glacier was estimated to be 0.05 m and 0.03 for the basin on the basis of precipitation and temperature records (pl. 2, table 4, fig. 4).

During the early ablation season, over 30 ablation stakes were installed on the glacier and other areas of snow in the basin. These stakes were periodically measured and serviced. The last readings of the season were made in late October by probing through 1-2 m of snow to the firn or ice for the minimum 1967 balance. The ablation stake data, periodic density cores and pits at index stations, and fall photography resulted in a map of net balance, $\bar{b}_n$. Because the station was not occupied October 1, 1967, estimates for values of $\bar{b}_i$, $\bar{b}_i\ (ls)$, and $\bar{b}_i\ (i)$ were made based on precipitation and temperature records.

Ablation during the summer was intense and resulted in a proportionally greater amount of mass loss from the higher levels of the glacier than in previous year. As a result, the equilibrium line altitude for 1967 was 1,870 m, slightly below the average equilibrium line altitude of 1,900 m. Despite the large spring snowpack the annual balance on September 30, 1966, was -0.58 m. The values for

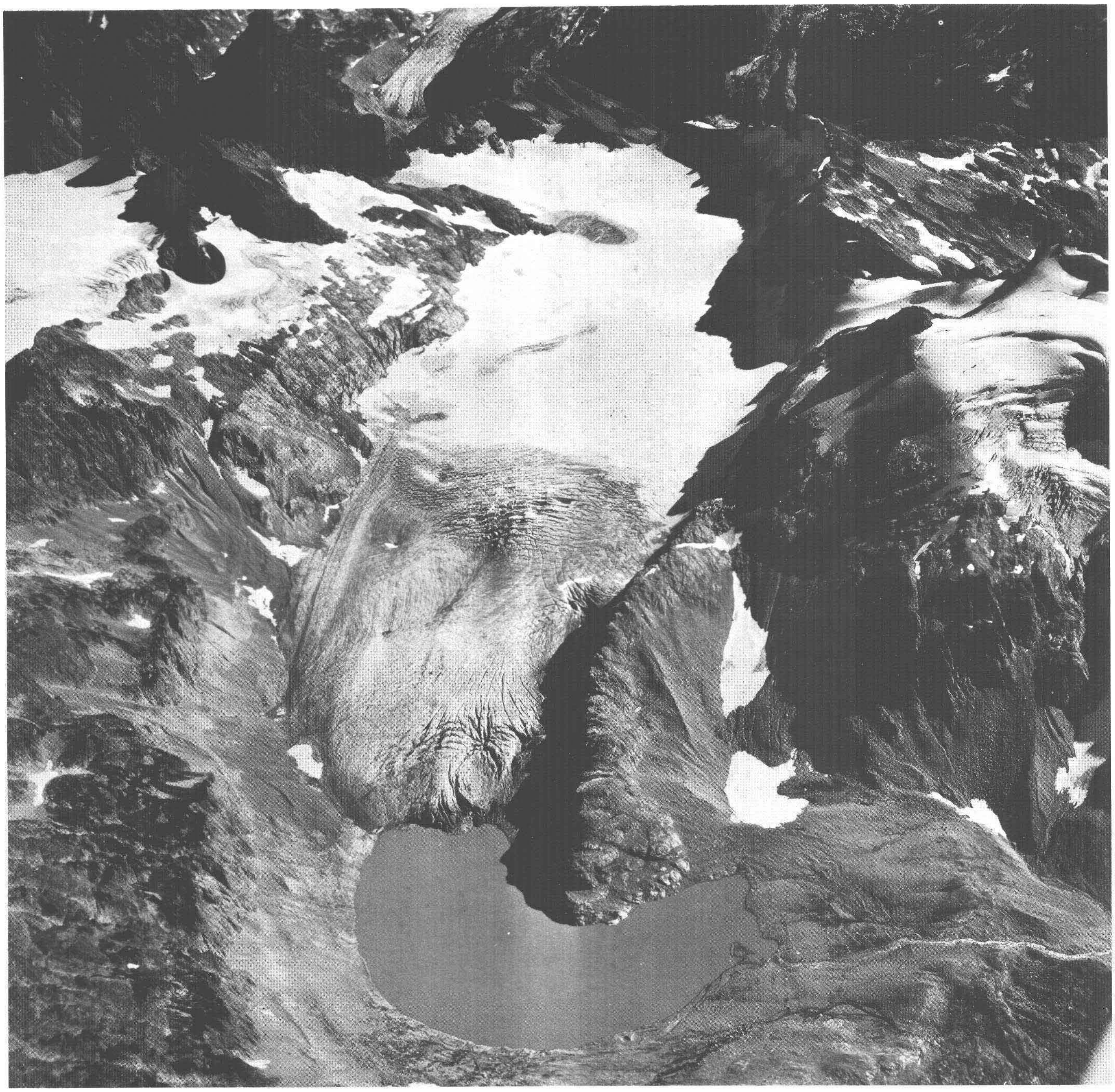

FIGURE 3.—Oblique aerial photograph of South Cascade Glacier and drainage basin, North Cascade Range, Washington, September 20, 1967. An unusual condition is shown here in that much firn and ice are exposed at higher altitudes around Sentinel Peak (upper left). Yet, at a lower altitude, the glacier still retains a considerable amount of surplus snow. The greater snow accumulation on the lower, more level glacier surface is probably due to a more than normal movement of snow by wind drifting and (or) avalanching from higher altitudes to the glacier. The partial nourishment of glaciers by this means is an important factor but has received little attention in mass balance studies. It has been calculated that 32 percent of the South Cascade Glacier snow accumulation was by redeposition this year.

glacier accumulation and ablation ($\underline{c}_a$ and $\bar{a}_a$) are somewhat higher than $\bar{b}_x$-$\bar{b}_a$ as they account for snow that fell and melted before May 17 and snow that fell and melted after May 17.

HYDROLOGIC BALANCE

The hydrologic balance throughout the year for the basin is shown on plate 2*D*. The hydrologic balance is the difference between precipitation and runoff. This may

TABLE 3.—*Instrumentation at South Cascade Glacier during the 1967 hydrologic year*

[Continuous record ———, estimated record – – – –, occasional measurement •]

Station	Altitude (metres)	Measurement	1967 Hydrologic year												
			1966			1967									
			Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.
1	1610	Streamflow	—	—	—	– – –	– – –	– – –	– – –	– – –	—	—	—	—	—
1	1610	Air temperature	—	—	—	—	—		—	—	—	—	—	—	—
1	1610	Precipitation	—	—	—	– – –	– ——	——	—	—	—	—	—	– –	– –
1	1610	Wind speed	—	– –	—	—	—	—	—		—	—			
1	1610	Balance					•	•			• • •	•			
2	1840	Air temperature	—	—	—	—	—	– –	– – –	—	—	—	—	—	—
2	1840	Precipitation	– •								—	—	—	— –	—
2	1840	Wind speed									—	—	—	—	
3	2250	Air temperature	—	—	—	—	—	—	—	—	—	—	—	—	
4	2530	Air temperature	—	—	—					—	—	—	—	—	
P-0	1730	Balance	•	•						•	•	• •	•	• •	•
P-1	1860	Balance	•	•			•			•	•			•	•
P-1	1860	Precipitation	•				•			•	• •	• •	• •	• •	
P-1	1860	Air temperature									—	—	—	—	
P-3	2045	Balance								•	•	• •			•
Basin photographed										•	•	• •	•	• •	•
Station occupied by personnel			—				•		•	—	—	—	—	—	—

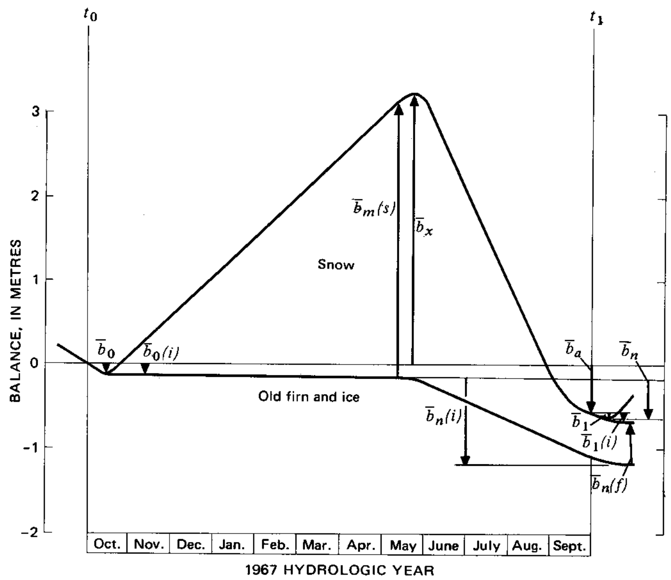

FIGURE 4.—The balance of South Cascade Glacier, 1967 hydrologic year. (Refer to table 4 for additional values.)

appear to be a simple calculation; however, there are several complications. Precipitation is difficult to measure directly and accurately. The recording gage catch of 2.17 m, p_a, is probably much below the actual precipitation. This is because most of the precipitation occurs as wind-driven snow, which the gage catches inefficiently, and because the gage is located at a nonrepresentative place in the basin—the lowest area. A better measurement is to determine a value for basin rainfall, by use of several simple gages scattered over the basin in the summer, and a value for basin snowfall, by determining the water equivalent of the maximum snow accumulation at many points in the basin. The sum of the two values for 1967 was 2.87 m, designated $\bar{p}_a$. This method does not account for snow that fell and ablated before the maximum snowpack was measured.

The second method, $\bar{p}_a$*, is the sum of the annual runoff and the measured storage change or basin balance. The main problem with this method is that liquid storage within the glacier is unaccounted for so that runoff does not equal input. The difference between $\bar{p}_a$ and $\bar{p}_a$* (0.69 m) can be due to either or both errors in measurements and (or) delayed runoff. In the cumulative precipitation curve (pl. 2*D*), $\bar{p}_a$* was used as basin precipitation and distributed according to the gage precipitation at site 1. Neither method accounts for evaporation, condensation or sublimation.

Total runoff for the year was 3.83 m—15 percent derived from glacier ice melt, 49 percent from glacier snow melt, 20 percent from nonglacier snow melt, and 16 percent precipitation as rain.

WOLVERINE GLACIER

DESCRIPTION

Wolverine Glacier (lat 60°24′ N., long 148°54′ W.) is a valley glacier on the Kenai Peninsula in south-central Alaska. The mean ELA is 1,200 m. Perennial snow and ice

TABLE 4.—*Ice and water balances, South Cascade Glacier basin, 1967 hydrologic and balance years*

[Values and errors in metres water equivalent expressed as averages over the glacier and basin except where indicated. Date: Hydrologic year, Oct. 1, 1966 (t_0) through Sept. 30, 1967 (t_1)]

	Glacier		Basin				
	Value	Error	Value	Error	Date	Term	Explanation
Yearly mass balances							
$\bar{b}_a$	-0.58	0.15	-0.27	0.08	Hydrologic year	Annual balance	Total change in snow, firn, and ice storage during the 1967 hydrologic year, from t_0 to t_1.
$\bar{b}_n$	-.63	.15	-.31	.08	Oct. 17, 1966 to Oct. 14, 1967	Total mass net balance	Change in storage from the minimum balance in 1966 autumn (t_0') to the minimum in the 1967 autumn (t_1').
$\bar{b}_a(fi)$	-.58	.15	-.27	.08	Hydrologic year	Annual firn and ice balance	Change in firn and ice storage during the 1967 hydrologic year; excludes late summer snow on the basin.
Accumulation and ablation							
$\bar{b}_m(s)$	3.28	0.12	2.22	0.23	May 4-5, 1967	Measured winter snow balance	Snowpack on the 1966 summer melt surface (ss_0); measured in late winter or spring in pits and by probing.
$\bar{b}_x$	3.18	.15	2.18	.25	May 17, 1967	Maximum balance	Storage change from the beginning of the hydrologic year (t_0) to the maximum in the spring. Winter balance (b_w) equals maximum balance ($\bar{b}_x$) plus the absolute value of the initial balance increment ($\bar{b}_0$).
$\bar{b}_a(f)$	.50	.10	.23	.05	Hydrologic year	Annual firnification	The increment of new firn in the accumulation area at t_1, measured after melting from this residual snowpack (firn) ceases in the autumn.
$\bar{b}_a(i)$	-1.08	.10	-.50	.05	....do	Annual ice balance	Ice and old firn melt in the ablation area during the hydrologic year.
$\bar{c}_a$	3.40	.20	2.27	.25	....do	Annual accumulation	Total accumulation of snow between t_0 and t_1.
$\bar{a}_a$	3.98	.20	2.54	.20	....do	Annual ablation	Total ablation of snow, ice, and old firn between t_0 and t_1.
Values relating annual and net ice balances							
$\bar{b}_0$	-0.10	0.05	-0.05	0.05	Oct. 1-17, 1966	Initial balance increment	Storage change between time of minimum in 1966 autumn (t_0') and beginning of hydrologic year (t_0).
$\bar{b}_0(s)$	0	0	0	0		Initial snow balance	Snow accumulated on the 1966 summer surface (ss_0) at beginning of hydrologic year (t_0); measured in pits and by probing.
$\bar{b}_0(i)$	-.15	.02	-.07	.02	Oct. 1 to Nov. 5, 1966	Initial ice balance	Ice and old firn melt after t_0 and before the winter snowpack covers the glacier; measured by ablation stakes.
$\bar{b}_1$	-.05	.02	-.02	.01	Oct. 1-14, 1967	Final balance increment	Storage change between time of minimum in 1967 autumn and the end of the hydrologic year.
$\bar{b}_1(ls)$	0	0	0	0		Final late snow balance	Snow accumulated on the 1967 summer surface (ss_1) at t_1.
$\bar{b}_1(i)$	-.10	.05	-.04	.02	....do	Final ice balance	Ice and old firn melt after t_1 and before the next year's snowpack covers the glacier.
Glacier and basin dimensions							
$S(fi)$	[1]2.80	0.04	3.15	0.05	Sept. 30, 1967	Glacierized area	Glacier value includes firn and ice areas which normally are attached to the main trunk glacier. Basin value is the main glacier plus all other small glaciers and perennial snowfields in the drainage basin. Ice-cored moraine and other permafrost areas are not included as glacierized areas.
S	[1]2.80	.04	6.11	.02	....do	Total area	Glacier and water drainage basin above the stream gaging station.
AAR	[2].58	.05	.29	.09	....do	Accumulation area ratio	Area of new firn, accumulation area, divided by the total area. An index of annual balance.
ELA	1,870	20	.....	.....	....do	Equilibrium line altitude	Average altitude where snow ablation equals snow accumulation. An index of annual balance.
ΔL	-17	3	.....	.....	Hydrologic year	Advance or retreat	Average horizontal distance change of terminus of the glacier in direction of flow.

[1]Square kilometres.
[2]Dimensionless.

TABLE 4.—*Ice and water balances, South Cascade Glacier basin, 1967 hydrologic and balance years*—Continued

	Glacier		Basin				
	Value	Error	Value	Error	Date	Term	Explanation
						Precipitation and runoff	
p_a	.....	.....	2.17	0.30	Hydrologic year	Gaged annual precipitation	Total snow and rain caught during the hydrologic year by a shielded gage at 1,610-m altitude.
$p_a(r)$	.....	.....	.42	.08	....do	Gaged annual precipitation as rain	Precipitation occurring as rain caught during the hydrologic year by the same gage at 1,610-m altitude.
$\bar{p}_a$	4.00	0.35	2.87	.20	....do	Annual basin precipitation	Area averaged snow and rainfall measured during the hydrologic year by precipitation gages and snow balance measurements.
$\bar{p}_a(r)$	.60	.05	.60	.05	....do	Annual basin precipitation as rain	Area averaged rainfall measured by gages during the hydrologic year. Rain distinguished by air temperature records, visual observations, and photographic record.
$\bar{p}_a{}^*$	.....	.....	3.56	.16	....do	Calculated annual precipitation	Area average annual snow and rain precipitation; the sum of annual stream runoff and annual storage change ($\bar{b}_a$).
$\bar{r}_a$	.....	.....	3.83	.15	....do	Annual runoff	Stream discharge for the year divided by glacier or basin area, expressed as average depth of water over the area; measured by stream stage recorder and stream discharge measurements.

covers 72 percent of the 24.6-km^2 drainage basin[1]. The stream from the glacier enters Nellie Juan River, which empties into Kings Bay, a fiord in Prince William Sound.

FIELD PROGRAM

The snow and ice balance measurements which began in the 1966 hydrologic year were expanded in 1967 to a more thorough program. The snow balance was measured on April 1, 14 days before the time of maximum balance. A stream stage recorder (site 1, table 5) was installed 0.1 km below the terminus of the glacier and began recording on May 28, 1967. A 0.2-m diameter (U.S. Weather Bureau 8-in.) storage precipitation gage was also installed at the stream gaging station.

A combination air temperature and precipitation recorder was installed at 1,000-m altitude (site 3) and began recording on May 27, 1967. The gage was designed specially for this project and consists of a 0.3-m diameter conical orifice, 3 m above the ground surface, shielded by freely swinging metal slats (fig. 5). The precipitation holding tank area is 5 times larger than the orifice area and accommodates a 0.3-m diameter float sensor. Rain and snow are dissolved in a methanol-glycol (60-40 percent by volume) antifreeze solution that is self-circulating during the addition of snow (Mayo, 1972). Air temperature is sensed by a finned, gas-filled bulb mounted 2 m above a level tundra area in a ventilated white screen. A south-facing sun slot provides noontime marks on the air temperature record. Both precipitation and the air temperature record on a Stevens A-35T spring-powered recorder which operates 4.5 months unattended.

A 0.2-m storage precipitation gage was operated only during the summer season at 940-m altitude (site 2). This gage was read daily during storms when personnel were in the basin.

[1]Drainage basin area for Wolverine Glacier has been revised from that reported in Meier and others (1971, p. A22).

A network of stakes was installed in the 1966 ablation area in June 1967. Unusually intense melting in 1967 caused many of the stakes to melt out of the ice. The remaining stakes were measured September 15–22 and these data were used to make a map of the ice balance. Continuing intense fall storms prevented all attempts to measure the firn balance.

Aerial photographs of Wolverine Glacier basin were taken at 2–8 week intervals during the ablation season (table 5). A map of the transient snowlines and exposed firn edges (pl. 3*A*) made from these photographs shows that nearly all snow was removed, leaving only 10 percent of the glacier covered with new firn at the end of the ablation season.

WEATHER

The weather in Alaska during the 1967 hydrologic year departed markedly from the normal as indicated by the departures from the 44-yr record at Seward, Alaska (U.S. Dept. of Commerce, 1967–68). Seward, 40 km southwest of Wolverine Glacier, is the closest long-record weather station to the glacier. October 1966 had above average (115 percent) precipitation and colder (by 2.4°C) temperatures than normal. Precipitation from November 1966 through May 1967 was very low; monthly totals ranged from only 101 mm in December (63 percent of average) to only 21 mm in May (20 percent of average). The dry trend reversed itself in June, became normal throughout July and August, then excessively wet by September, when Seward received 662 mm of rain (272 percent of average). The excessive rain caused flooding in the Kenai Mountains.

The meager winter snowpack was followed by an early

TABLE 5.—*Instrumentation at Wolverine Glacier during the 1967 hydrologic year*

[Continuous record ——, estimated record – – – –, occasional measurement •]

Station	Altitude (metres)	Measurement	1967 Hydrologic year												
			1966			1967									
			Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.
1	370	Streamflow	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	——	——	——	——	—
1	370	Precipitation													
A	650	Balance	•					•		•			•	•	
2	940	Precipitation								•	•		•	•	
3	1000	Air temperature								—	——	——	——	——	
3	1000	Precipitation									——	——	——	——	
B	1110	Balance	•						•		•			•	
C	1350	Balance	•						•						
Basin photographed								•		•		•	•	•	•
Station occupied by personnel			—					—	—	—	—		—	—	

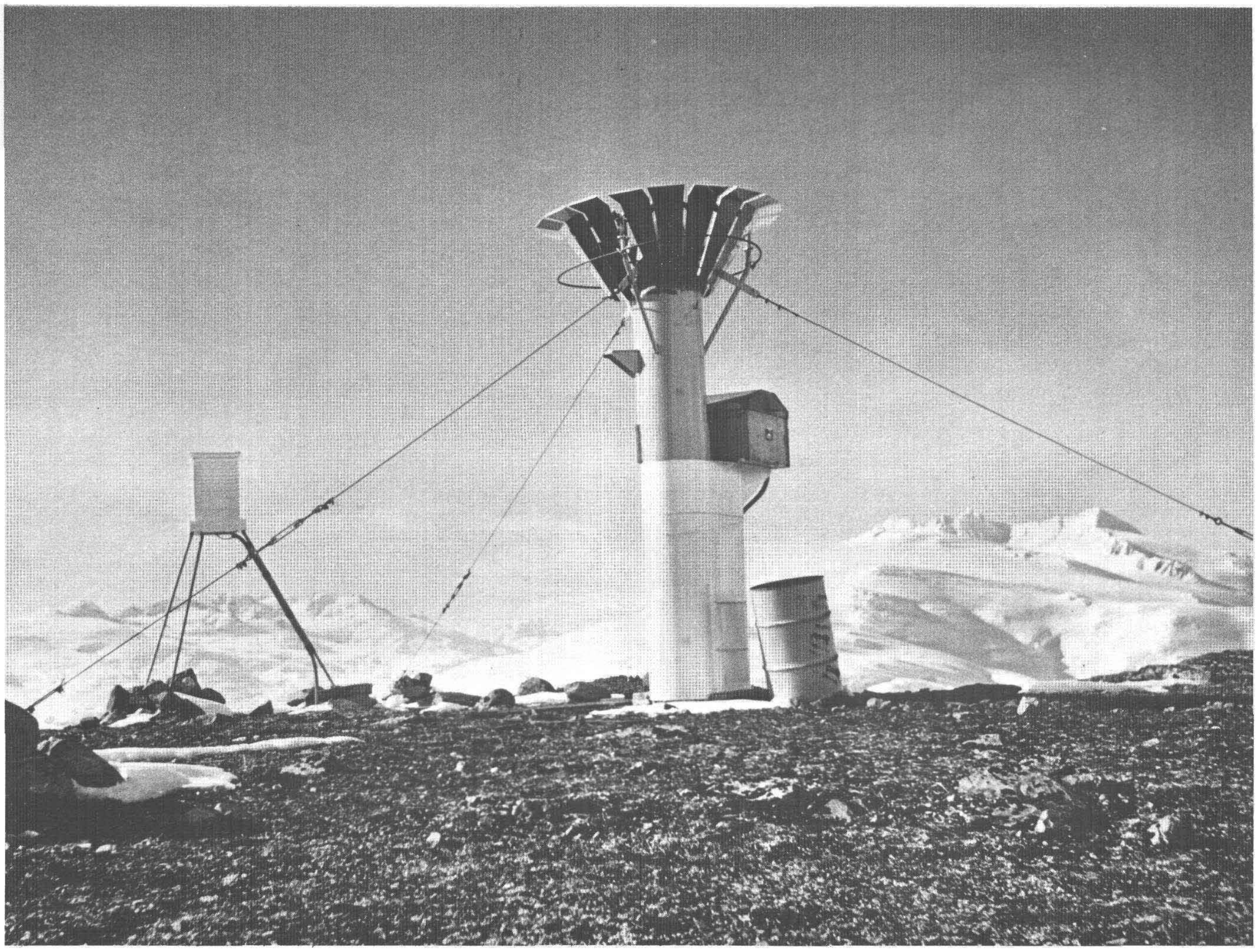

FIGURE 5.—Photograph of precipitation and air-temperature gage at Wolverine Glacier, Kenai Mountains, Alaska. This recording gage operates throughout the year at site 3, 1,000-m altitude (see pl. 3*A* for location). A specially designed antifreeze solution which is self-mixing enables precipitation occurring as snow to be recorded without the addition of heat. The wind screen on the left contains the air temperature sensing element.

spring and a warmer than normal summer. Temperatures at Seward were 0.3° to 1.8°C warmer than average from March through August. The relatively large departures from normal weather at Seward balanced, resulting in an annual average air temperature within 0.1°C of the 44-yr average. The annual precipitation was within 3 percent of the mean.

The results of these departures were very evident on Wolverine Glacier. October 1966 snowfall amounted to 3 m at 1,500-m altitude. The abnormally dry months which followed allowed 1-m tall runway markers, inserted in the snow near the middle of the glacier in October, to still protrude in April 1967. The abnormally warm spring resulted in continuous rapid melting.

The seasonal departures from the normal precipitation regime and the seemingly minor changes in the air temperature combined in this specific way to reproduce large magnitude changes on the glaciers and river flow in the Kenai Mountains during 1967. Therefore, the seasonal distribution of rain, snow, and temperature was, in this case, more important to the glacier regime than the annual total or mean value. This conclusion places large restraints on interpretations of glacier balance which are based on annual climatic data.

GLACIOLOGIC BALANCES

The initial snow balance, $\bar{b}_0(s)$ for the 1967 hydrologic year was estimated from measurements made in October 1966 to be 0.23-m water equivalent averaged over the basin. The measured snow balance, $\bar{b}_m(s)$ (table 6, fig. 6), increased from 0.23 m on October 1, 1966, to only 0.89 m by April 1, 1967. Strong winds during the winter eroded all the snow from rocky knolls and exposed parts of the glacier. Some of the snow was redeposited in valleys and part was lost by sublimation. The reversal of tracks made in the snow before one windstorm indicated wind erosion of 100–200 mm. Inspection of adjacent basins indicated a predominance of erosion over deposition. Thus, Wolverine Glacier basin served neither as the recipient of snow blown from upwind basins nor as the contributor to snow blown into downwind basins.

The maximum snow depth observed in April 1967 was 5.5 m and the average was about 2.5 m. The snow density ranged from 340 to 470 kg/m³ depending primarily on total snow depth. The average density was 410 kg/m³. The temperature in a 4.4-m snow pit at 1,350-m altitude ranged from a low of -9°C at 1 m depth to -4° at 4 m depth. The temperature at the base of 1-m snow on glacier ice at 1,020-m altitude was -6.5°C.

The initial ice balance, $\bar{b}_0(i)$, the amount of ice ablated from October 1 until winter, was small, -0.05 m averaged over the glacier. Part of the glacier remained bare of snow throughout the winter because of wind erosion. Measurement at one stake in bare ice indicated no winter ablation. Sun-cup type scalloping of the ice surface suggests that some sublimation had occurred but was judged to be less than 0.02 m.

Melting of snow and ice began in April. By July, much of the previous year's firn was exposed and melting. The annual old firn and ice balance, $\bar{b}_a(i)$, was -1.98 m averaged

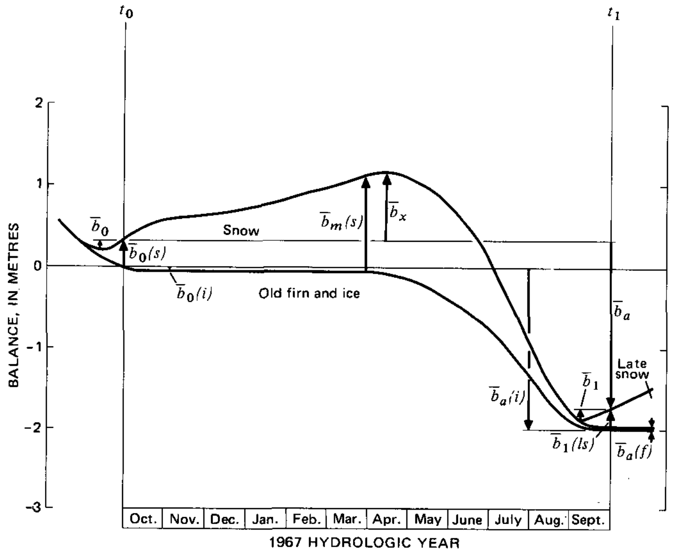

FIGURE 6.—The balance of Wolverine Glacier, 1967 hydrologic year. (Refer to table 6 for additional values.)

over the glacier. The small amount of residual snow which became firn, the annual firnification, $\bar{b}_a(f)$, was only 0.03 m, resulting in an annual firn and ice balance, $\bar{b}$ (fi), of -1.95 m for Wolverine Glacier in 1967. This is a relatively large change in glacier mass during one year, and was probably caused by the fact that ice and old firn have a lower albedo than snow.

The glacier plus perennial snowfield area was 18.2 km² at the beginning of the 1967 hydrologic year. The total area of ice and firn was 17.7 km² by the end of the year. The most pronounced losses in area were from melting of perennial snowfields adjacent to the glacier.

HYDROLOGIC BALANCE

The difference between input (mostly precipitation) and output (mostly runoff) is designated the hydrologic balance as distinguished from the glaciologic balance. No recording precipitation gage was operating in Wolverine Glacier basin until June 1, 1967, so the gage at Seward, Alaska, was used as an index to daily precipitation at Wolverine Glacier. From October 1, 1966, to March 31, 1967, the precipitation at Wolverine Glacier was estimated by:

$$\Sigma\,\bar{p}=\bar{b}_m(s)-\bar{b}_0(s)+\Sigma\,\bar{r}\text{ (Oct. 1, 1966, to Mar. 31, 1967) }+\bar{b}_0(i)$$
$$=0.89-0.23+0.09-0.04=0.71\text{ m}$$

During the same period, 0.65 m precipitation was recorded at Seward. The daily cumulative precipitation (pl. 3*D*) was computed by multiplying Seward precipitation by 71/65=1.09. For April and May, the ratio used was 1.6, the

TABLE 6.—*Ice and water balances, Wolverine Glacier basin, 1967 hydrologic and balance years*

[Values and errors in metres water equivalent expressed as averages over the glacier and basin except where indicated. Date: Hydrologic year, Oct. 1, 1966 (t_0) through Sept. 30, 1967 (t_1)]

	Glacier		Basin				
	Value	Error	Value	Error	Date	Term	Explanation
						Yearly mass balances	
$\bar{b}_a$	-2.04	0.52	-1.49	0.50	Hydrologic year	Annual balance	Total change in snow, firn, and ice storage during the 1967 hydrologic year, from t_0 to t_1; approximately equal to difference between precipitation as snow and meltwater runoff for the hydrologic year.
$\bar{b}_n$	-2.06	.52	-1.50	.52	Sept. 10, 1966 to Sept. 5, 1967	Total mass net balance	Change in storage from the minimum balance in 1966 autumn (t_0') to the minimum in the 1967 autumn (t_1').
$\bar{b}_a(fi)$	-1.95	.50	-1.42	.36	Hydrologic year	Annual firn and ice balance	Change in firn and ice storage during the 1967 hydrologic year; excludes initial and late snow on the basin.
						Accumulation and ablation	
$\bar{b}_m(s)$	1.17	0.10	0.89	0.10	Apr. 1, 1967	Measured winter snow balance	Snowpack on the 1966 melt surface (ss_0); measured in late winter or spring in pits and by probing.
$\bar{b}_x$	.86	.14	.68	.13	May 5, 1967	Maximum balance	Storage change from the beginning of the hydrologic year (t_0) to the maximum in the spring. Winter balance (b_w) equals maximum balance ($\bar{b}_x$) plus the absolute value of the initial balance increment ($\bar{b}_0$).
$\bar{b}_a(f)$	.03	.03	.02	.02	Hydrologic year	Annual firnification	The increment of new firn in the accumulation area at t_1, measured after melting from this residual snowpack (firn) ceases in the autumn.
$\bar{b}_a(i)$	-1.98	.50	-1.44	.36	...do	Annual ice balance	Ice and old firn melt in the ablation area during the hydrologic year.
$\bar{c}_a$	2.06	.25	1.55	.20	....do	Annual accumulation	Total accumulation of snow between t_0 and t_1.
$\bar{a}_a$	4.10	.50	3.04	.50	....do	Annual ablation	Total ablation of snow, ice, and old firn between t_0 and t_1. Approximately equal to the difference between annual rainfall and runoff.
						Values relating annual and net ice balances	
$\bar{b}_0$	0.10	0.10	0.09	0.09	Sept. 10-30, 1966	Initial balance increment	Storage change between time of minimum in 1966 autumn (t_0') and beginning of hydrologic year (t_0).
$\bar{b}_0(s)$	.30	.10	.23	.08	Oct. 1, 1966	Initial snow balance	Snow accumulated on the 1966 summer surface (ss_0) at beginning of hydrologic year (t_0); measured in pits and by probing.
$\bar{b}_0(i)$	-.05	.05	-.04	.04	Oct. 1-12, 1966	Initial ice balance	Ice and old firnmelt after t_0 and before the winter snowpack covers the glacier; measured by ablation stakes.
$\bar{b}_1$	.12	.10	.10	.10	Sept. 5-30, 1967	Final balance increment	Storage change between time of minimum in 1967 autumn and the end of the hydrologic year.
$\bar{b}_1(ls)$	.21	.10	.16	.10	Sept. 30, 1967	Final late snow balance	Snow accumulated on the 1967 summer surface (ss_1) at t_1.
$\bar{b}_1(i)$	-.02	.01	-.01	.01	Oct. 1-20, 1967	Final ice balance	Ice and old firnmelt after t_1 and before the next year's snowpack covers the glacier.
						Glacier and basin dimensions	
$S(fi)$	[1]17.7	0.2	18.2	0.2	Sept. 30, 1966	Glacierized area	Glacier value includes firn and ice areas which normally are attached to the main trunk glacier. Basin value is the main glacier plus all other small glaciers and perennial snowfields in the drainage basin. Ice-cored moraine and other permafrost areas are not included as glacierized areas.
			17.7	.2	Sept. 30, 1967		
S	[1]17.7	.2	24.6	.2	....do	Total area	Glacier and water drainage basin above the stream-gaging station.
AAR	[2].10	.02	.07	.02	....do	Accumulation area ratio	Area of new firn, accumulation area, divided by the total area. An index of annual balance.

[1]Square kilometres.
[2]Dimensionless.

TABLE 6.—*Ice and water balances, Wolverine Glacier basin, 1967 hydrologic and balance years*—Continued

	Glacier		Basin				
	Value	Error	Value	Error	Date	Term	Explanation
Glacier and basin dimensions—Continued							
ELA	1,700	.....	.....	.....	....do	Equilibrium line altitude	Average altitude where snow ablation equals snow accumulation. An index of annual balance.
ΔL	-5	3	.....	.....	Hydrologic year	Advance or retreat	Average horizontal distance change of terminus of the glacier in direction of flow.
Precipitation and runoff							
$\bar{p}_a$	2.90	0.30	2.44	0.30	Hydrologic year	Annual basin precipitation	Area averaged snow and rainfall measured during the hydrologic year by precipitation gages and snow-balance measurements.
$\bar{p}_a(r)$	.84	.20	.89	.20	....do	Annual basin precipitation as rain	Area averaged rainfall measured during the hydrologic year. Rain distinguished by air temperature records, visual observations, and photographic record.
$\bar{p}_a$*	3.58	.95	2.98	.70	....do	Calculated annual precipitation	Area average annual snow and rain precipitation; the sum of annual stream runoff and annual storage change ($\bar{b}_a$).
$\bar{r}_a$	5.62	.80	4.47	.50	....do	Annual runoff	Stream discharge for the year divided by glacier or basin area, expressed as average depth of water over the area; measured by stream-stage recorder and stream-discharge measurements.

same ratio determined for the later period June 1 to September 30 by gages in Wolverine Glacier basin. The inferred precipitation in April and May was 0.08 m or only 3 percent of the annual total.

The recording precipitation gage (site 3, data on pl. 3*D*) is located in one of the driest (as determined by gages in subsequent years) and possibly one of the windiest parts of the basin, so its catch is at best only an index of the total precipitation into the basin. The gage at 370-m altitude (site 1) received three times more than the recording gage because it is more protected from wind and because low clouds produce rain at site 1 while they do not cover site 3. This situation is persistent and common. The altitude distribution of the annual precipitation (pl. 3*E*) was determined using the distribution of the measured snow balance plus the catch of the three gages in the summer. The annual precipitation, $\bar{p}_a$, was computed using the snow balance measurements, a 2-month estimate based on the Seward gage, and the gages placed in the basin, and was 2.44 m for the 1967 hydrologic year.

An estimate of the total basin precipitation can also be made by treating the entire basin as a large gage where the annual runoff plus annual storage change (neglecting condensation and evaporation) equals precipitation. This calculated annual precipitation, $\bar{p}_a$*, for 1967 was 2.98-m water equivalent.

The daily runoff from Wolverine Glacier basin (pl. 3*D*) from May 28 through September 30, 1967, shows a close correlation between air temperature plus rain precipitation. The cumulative runoff (pl. 3*D*) includes 0.3 m (7 percent of the total) estimated runoff from October 1966 through May 27, 1967, plus the measured daily streamflow. The 1967 annual runoff, r_a, was 4.47 m averaged over the basin.

The recorded stream stage (height) shows a strong diurnal fluctuation with minimums at approximately 4 a.m. (local time) and peaks at about 2 p.m. Abrupt decreases in streamflow for 5 to 15 minutes occur randomly in the record, followed immediately by an unusual rise then a return to normal. None of these abrupt events are caused by weather changes, so must represent short-term plugging and release within the subglacial drainage system. Some rises are sufficiently abrupt to be a threat to persons wading the stream.

An estimate of the daily basin balance and annual balance (pl. 3*D*) can be calculated from the precipitation and runoff measurements (hydrologic balance.) This can be compared with the balance measured at points (such as index stations A, B, and C) or with the basin balance determined by glaciologic methods. The maximum basin balance occurred on April 14, 1967, the last date with winter temperatures. The cumulative runoff equaled the precipitation by June 21. By September 5, the amount of streamflow runoff exceeded the precipitation 2.8 times, which illustrates one way in which a glacier can have a large influence on a glacier-fed river. At the end of the 1967 hydrologic year, the hydrologic balance, $\bar{p}_a = \bar{r}_a$, was -2.03 m. The annual balance, $\bar{b}_a$, for the basin measured glaciologically was -1.49 m. These two values are independent measurements of the annual storage change. The difference between the two values is primarily due to the large uncertainties in the measurements for this year or to the possible release of liquid storage from within the glacier.

GULKANA GLACIER

DESCRIPTION

Gulkana Glacier (lat 63°15′ N., long 145°28′ W., fig 7) is a branched valley glacier on the south flank of the Alaska Range. The accumulation zone consists of four cirque glaciers which converge in a simple south-flowing ablation area. The mean ELA is about 1,700 m. The basin area is 31.6 km² and is 70 percent covered with perennial snow and ice. Drainage from the glacier flows into first the Delta, then the Tanana, and finally the Yukon Rivers north of the Alaska Range.

FIELD PROGRAM

Streamflow measurements from Gulkana Glacier basin began September 16, 1966, at a gage installed 1.3 km downstream from the terminus of the glacier (site 1, pl. 4*A*). The winter flow recession was defined by discharge measurements (table 7), the early spring rise by discharge measurements and weather data, and the summer open-water flow by discharge measurements and a continuous record of the stream stage in the natural channel. A U.S. Weather Bureau 8-inch storage precipitation gage was installed at site 1.

A large storage precipitation gage was installed on April 18, 1967, at 1,480-m altitude (site 2, pl. 4*A*) in the basin. Continuous recording of precipitation and air temperature began on September 3, 1967, and will appear in reports covering subsequent hydrologic years. Balance index station C (pl. 4*A*) was relocated at 2,020-m altitude in the eastern cirque of Gulkana Glacier.

Vertical photographs were taken on August 31, 1967, by Austin Post and were used to redefine the margin of Gulkana Glacier and other glaciers and perennial snowfields in the basin.

WEATHER

The weather recorded at a U.S. Weather Bureau station at Trims Camp (U.S. Dept. of Commerce, 1967–68), 23 km northwest of Gulkana Glacier, was near normal during the 1966–67 winter season but departed significantly from the previous 10 years of record during the summer of 1967. A series of strong storms in July and August 1967 produced heavy rainfall below 1,800-m altitude in mid-August culminating in widespread flooding in interior Alaska. At Trims Camp, the July precipitation was 161 percent of normal; August was 168 percent of normal. The July and August storms deposited heavy accumulations of wet snow above 1,800-m altitude on Gulkana Glacier (pl. 4*D*). Air temperatures measured at Trims Camp were near normal during the 1967 hydrologic year.

GLACIOLOGIC BALANCES

The 1967 hydrologic year at Gulkana Glacier began with an average of 0.27 m water equivalent of snow, $\bar{b}_0(s)$, already accumulated on the 1966 summer surface (table 8, fig. 8). By April 27, 1967, the measured winter snow balance, $b_m(s)$ (pl. 4*B*) averaged 1.05 m on the glacier. The

FIGURE 7.—Vertical aerial photomosaic of Gulkana Glacier, Alaska Range, Alaska, August 31, 1967. The higher altitudes of the glacier are covered with late snow which fell several weeks earlier. (See pl. 4*A*.)

TABLE 7.—*Instrumentation at Gulkana Glacier basin during the 1967 hydrologic year*

[Continuous record———, estimated record– – – –, occasional measurement •]

Station	Altitude (metres)	Measurement	1967 Hydrologic year												
			1966			1967									
			Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.
1	1140	Streamflow	– – –	– – •	– – –	• – –	– – –	– – –	– – –	– – –	– – •—	——	——	——	– – –
1	1140	Precipitation									•	•		• •	
2	1480	Air temperature												——	
2	1480	Precipitation							•		•			•——	
A	1380	Balance		•					•		•			•	
B	1650	Balance		•					•					•	
C	2020	Balance		•					•					•	
Basin photographed									•	•	•	•		•	
Station occupied by personnel				—		•			—		–	—	–	—	

snow densities varied from 330 to 370 kg/m^3 over most of the basin, which is approximately twice the snow density found in the lowlands of interior Alaska. Measurements at seven pits showed that at any given altitude the snow density increased as a result of depth or loading. At the same time, the snow density decreased with altitude when comparing equal depths of snow. Temperatures at the base of the snowpack ranged from -4° to -9°C and varied over the glacier in a similar manner as the snow density; the 330 to 340 kg/m^3 density snow was -8° to -9°C at its base whereas the 360 to 370 kg/m^3 density snow was -4° to -6°C. The temperature data were used to compute the amount of snow meltwater expected to refreeze during the spring in the underlying permeable firn by assuming that all heat required to warm the firn to 0°C was provided by refreezing water. The calculated internal accumulation ice averaged 0.02 m water equivalent over the glacier.

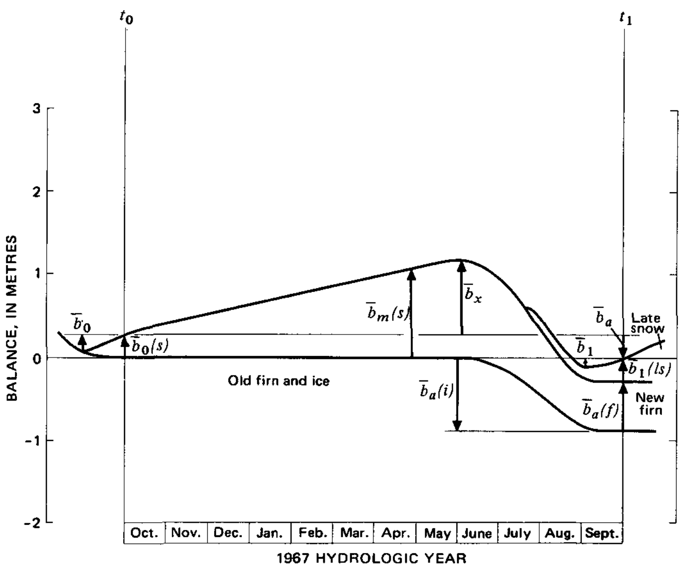

FIGURE 8.—The balance of Gulkana Glacier, 1967 hydrologic year. (Refer to table 8 for additional values.)

During the 1966–67 winter, an extensive stream icing (aufeis) formed from the glacier terminus to the stream gage covering an area of 0.4 km^2 with 1 to 4 m of ice. At least 0.03 km^2 of the icing, up to 1 m thick, remained at the end of the summer season (see fig. 7).

Snowmelt began in late May 1967 and the maximum glacier balance, $\bar{b}_x$ (0.90 m), occurred about June 4, 1967. Above 2,100-m altitude, the snowpack accumulated intermittently throughout the summer and a summer surface formed in July during short periods of melting. Near the glacier terminus, 5 to 6 m of combined snowmelt and icemelt was measured during the summer. Snowmelt equaled accumulation at 1,740-m altitude. The severe July and August storms brought hail and dense wet snow above 1,800-m altitude. Late snow covered the entire glacier briefly on September 1, 1967, then covered the basin completely on September 19, 1967, to end the melt season. The late snow balance, $\bar{b}_i(ls)$, averaged 0.25-m water equivalent by the end of the 1967 hydrologic year.

Approximately 60 percent of the snow measured on April 27, 1967, $\bar{b}_m(s)$, remained as new firn and internal accumulation, $\bar{b}_a(f)$, at the end of the melt season in September 1967. Small patches of firn remained at 1,500-m altitude, but the main accumulation area was above 1,700-m (pl. 4).

Ablation of glacier ice began in June 1967 near the terminus where 5.4-m water equivalent of melting occurred. Melting was continuous through the summer until September 1, 1967, and was then intermittent until September 19, 1967, when the glacier became snow covered. During August lateral erosion by Phelan Creek removed some additional ice by calving. Approximately 46 percent more ice and old firn melted in 1967 than new firn accumulated, so the annual firn and ice balance, $\bar{b}_a(fi)$, of Gulkana Glacier was -0.28 m.

HYDROLOGIC BALANCE

The basin winter precipitation from October 1, 1967, t_0, to April 27, 1967, was approximately the measured snow

TABLE 8.—*Ice and water balances, Gulkana Glacier basin, 1967 hydrologic and balance years*

[Values and errors in metres water equivalent expressed as averages over the glacier and basin except where indicated. Date: Hydrologic year, Oct. 1, 1966 (t_0) through Sept. 30, 1967 (t_1)]

	Glacier		Basin				
	Value	Error	Value	Error	Date	Term	Explanation
						Yearly mass balances	
$\bar{b}_a$	−0.30	0.14	−0.24	0.13	Hydrologic year	Annual balance	Total change in snow, firn, and ice storage during the 1967 hydrologic year, from t_0 to t_1; approximately equal to difference between precipitation as snow and meltwater runoff for the hydrologic year.
$\bar{b}_n$	−.20	.15	−.17	.15	Sept. 1, 1967	Total mass net balance	Change in storage from the minimum balance in 1966 autumn (t_0') to the minimum in the 1967 autumn (t_1').
$\bar{b}_a(fi)$	−.28	.14	−.23	.13	Hydrologic year	Annual firn and ice balance	Change in firn and ice storage during the 1967 hydrologic year; excludes late summer snow on the basin.
						Accumulation and ablation	
$\bar{b}_m(s)$	1.05	0.12	0.89	0.10	Apr. 27, 1967	Measured winter snow balance	Snowpack on the 1966 summer melt surface (ss_0); measured in late winter or spring in pits and by probing.
$\bar{b}_x$	.90	.10	.77	.10	June 4, 1967	Maximum balance	Storage change from the beginning of the hydrologic year (t_0) to the maximum in the spring. Winter balance (b_w) equals maximum balance ($\bar{b}_x$) plus the absolute value of the initial balance increment ($\bar{b}_0$).
$\bar{b}_a(f)$	.61	.10	.39	.08	Hydrologic year	Annual firnification	The increment of new firn in the accumulation area at t_1, measured after melting from this residual snowpack (firn) ceases in the autumn.
$\bar{b}_a(i)$	−.89	.11	−.62	.09	....do......................	Annual ice balance	Ice and old firn melt in the ablation area during the hydrologic year.
$\bar{c}_a$	1.80	.30	1.48	.20	....do......................	Annual accumulation	Total accumulation of snow between t_0 and t_1.
$\bar{a}_a$	2.10	.33	1.72	.25	....do......................	Annual ablation	Total ablation of snow, ice, and old firn between t_0 and t_1. Approximately equal to the difference between annual rainfall and runoff.
						Values relating annual and net ice balances	
$\bar{b}_0$	0.20	0.07	0.16	0.07	Sept. 1–30, 1966	Initial balance increment	Storage change between time of minimum in 1966 autumn (t_0') and beginning of hydrologic year (t_0).
$\bar{b}_0(s)$	.27	.10	.20	.10	Oct. 1, 1966	Initial snow balance	Snow accumulated on the 1966 summer surface (ss_0) at beginning of hydrologic year (t_0); measured in pits and by probing.
$\bar{b}_0(i)$	0	.01	0	.01	....do......................	Initial ice balance	Ice and old firn melt after t_0 and before the winter snowpack covers the glacier; measured by ablation stakes.
$\bar{b}_1$	.10	.05	.09	.05	Sept. 1–30, 1967	Final balance increment	Storage change between time of minimum in 1967 autumn and the end of the hydrologic year.
$\bar{b}_1(ls)$	.25	.05	.19	.05	Sept. 30, 1967	Final late snow balance	Snow accumulated on the 1967 summer surface (ss_1) at t_1.
$\bar{b}_1(i)$	0	.01	0	.01	....	Final ice balance	Ice and old firn melt after t_1 and before the next year's year's snowpack covers the glacier.
						Glacier and basin dimensions	
$S(fi)$	[1]19.3	0.2	22.2	0.3	Sept. 30, 1967	Glacierized area	Glacier value includes firn and ice areas which normally are attached to the main trunk glacier. Basin value is the main glacier plus all other small galciers and perennial snowfields in the drainage basin. Ice-cored moraine and other permafrost areas are not included as glacierized areas.
S	[1]19.3	0.2	31.6	0.3	....do......................	Total area	Glacier and water drainage basin above the stream gaging station.
AAR	[2].60	.03	.41	.03	....do......................	Accumulation area ratio	Area of new firn, accumulation area, divided by the total area. An index of annual balance.

[1]Square kilometres.
[2]Dimensionless.

TABLE 8.—*Ice and water balances, Gulkana Glacier basin, 1967 hydrologic and balance years*—Continued

	Glacier		Basin				
	Value	Error	Value	Error	Date	Term	Explanation
						Glacier and basin dimensions—Continued	
ELA	1740	20	.....	.....	....do	Equilibrium line altitude	Average altitude where snow ablation equals snow accumulation. An index of annual balance.
ΔL	-50	20	......	......	Hydrologic year	Advance or retreat	Average horizontal distance change of terminus of the glacier in direction of flow.
						Precipitation and runoff	
$\bar{p}_a$*	2.43	0.33	2.15	0.28	Hydrologic year	Calculated annual	Area average annual snow and rain precipitation; the sum of annual stream runoff and annual storage change ($\bar{b}_a$).
$\bar{r}_a$	2.73	.30	2.39	.25	....do	Annual runoff	Stream discharge for the year divided by glacier or basin area, expressed as average depth of water over the area; measured by stream stage recorder and stream discharge measurements.

balance, $\bar{b}_m(s)$ (0.89 m), minus the initial snow balance, $\bar{b}_0(s)$ (0.20 m), as no rain runoff or melting occurred during the period. The ratio of this calculated winter precipitation (0.69 m) to the precipitation (0.66 m) measured at Trims Camp weather station is 1.04:1. The annual precipitation for Gulkana Glacier basin, $\bar{p}_a$* (2.15 m), was estimated as the sum of the annual runoff, $\bar{r}_a$ (2.39 m), and the annual balance, $\bar{b}_a$ (-0.24 m). Thus, the precipitation from April 27, 1967, to September 30, 1967, t_1, can be calculated (2.15-0.69=1.46 m). The precipitation gage at 1,480-m altitude recorded 0.76 m of rain and snow, and Trims Camp received 0.70 m during the same period. The windshield on the precipitation gage in the glacier basin was damaged by high winds during the storms. The wind deflection slats proved to be too light, so the gage may have intercepted only part of the wind-driven snow and rain. The ratio of the calculated Gulkana Basin precipitation (1.47 m) to Trims Camp summer precipitation (0.70 m) is 2.1:1. The cumulative precipitation, $\bar{p}_a$* (pl. 4*D*) was derived by applying the above ratio to daily precipitation measurements made at Trims Camp. Because of large uncertainties in the correlation, the estimated standard error of this analysis is ±0.3 m.

Part of the winter streamflow from Gulkana Glacier refroze in the valley bottom to form a large aufeis sheet. The remainder, 0.03 m^3/s average over the winter, flowed past the stream-gaging station. The total winter runoff was surprisingly great considering the facts that no surface melting occurred in the winter, that no sedimentary rocks underlie the basin and that permafrost is present in part of the exposed bedrock. Only a thin veneer of ice contact deposits covers the valley floor. Even though very little ground water could be stored in the basin and part of the winter runoff refroze above the gage, there was 55 mm of runoff averaged over the basin from October 1, 1966 to May 20, 1967, the period of no surface melt runoff. It is estimated that only 1-5 mm of annual runoff could be caused by internal friction in the moving ice, and an additional 5 mm annual runoff due to geothermal heat flow melting the glacier sole. Approximately 50 mm of runoff during the winter must have come from ground water and water stored temporarily within the glacier, the major part of which is judged to be drainage of water from the glacier.

The August 8–17, flood-producing storm (Childers and others, 1972) brought approximately 315 mm of rain and wet snow averaged over Gulkana Glacier basin. This precipitation caused numerous mudflows on the ice-cored moraines adjacent to Gulkana Glacier and a peak streamflow discharge of 65 m^3/s. A means of comparing flood peaks is to calculate the peak discharge per unit area of several basins. Gulkana Glacier basin produced approximately 2.1 $m^3s^{-1}km^{-2}$. The four other basins with measured highest peak runoff during that storm include three in the Alaska Range; Birch Creek with 1.2 $m^3s^{-1}km^{-2}$, Slime Creek, 1.1 $m^3s^{-1}km^{-2}$, and McCallum Creek, 0.7 $m^3s^{-1}km^{-2}$; and one in the Yukon-Tanana upland, Idaho Creek with 1.3 $m^3s^{-1}km^{-2}$. Gulkana Glacier basin has the highest average altitude, greatest relief, and largest glacier coverage of the five basins. These combined factors at Gulkana Glacier produced the highest measured runoff rate in August 1967.

The annual runoff from the glacier basin, $\bar{r}_a$ (2.39 m), was the highest ever measured for interior Alaska. Snow melt contributed 1.10 m (46 percent) of the runoff, glacier ice melt, 0.62 m (26 percent), and rainfall, 0.67 m (28 percent). The ice loss from the basin, $\bar{b}_a$ (-0.24 m), was equal to 10 percent of the runoff.

RELATIONSHIPS BETWEEN HYDROLOGY OF THESE GLACIERS

Winter balance, $\bar{b}_w$, can be considered to be an index of annual accumulation, $\bar{c}_a$, and annual ablation, $\bar{a}_a$, can be considered an index of annual energy received. The winter balance at Maclure Glacier is almost equal to an annual accumulation. At progressively higher latitudes, however, the winter balance becomes a poorer index of annual accumulation. The northern glaciers receive much more snowfall during the summer season than the southern glaciers. In the same manner the annual ablation is a better indicator of energy received on the southern glaciers than on the northern glaciers. The annual ablation is greater at both Wolverine and South Cascade Glaciers than at Maclure Glacier, probably because Maclure is at a very much higher altitude than the other glaciers. The amount of summer rainfall, $\bar{p}_a$-$\bar{c}_a$, in 1967 was greatest at Wolverine Glacier, which is adjacent to the Gulf of Alaska. The large amount of rain combined with the very negative balance produced the greatest glacier runoff at Wolverine Glacier.

The dates and lengths of the summer and winter seasons followed an expectable pattern. The winter season is shortest and the summer season is longest at the southern glacier. The time of maximum balance was less variable than the time of minimum balances. The minimum balances occur considerably earlier in the north than the south. Since the summer season ended after the end of the 1967 hydrologic year at Maclure and South Cascade the annual accumulation of firn, $\bar{b}_a(f)$ could not be defined and neither glacier had an initial snow balance, $\bar{b}$ (*s*), nor a final late snow balance, $\bar{b}_1$ (*s*).

Long-term average balances, precipitation, and runoff cannot be calculated at these glacier basins by the usual means because the period of record is too short. However, by using the available balance measurements, the known long-term equilibrium altitude of the glacier, nearby precipitation records, and estimating the mass change $\Sigma \bar{b}_a$, for each glacier over the past half century, fairly reliable predictions for mean annual precipitation, $\bar{p}_a$, accumulation, $\bar{c}_a$, glacier balance, $\bar{b}_a$, ablation, $\bar{a}_a$, and runoff, $\bar{r}_a$, can be obtained.

All United States IHD glaciers have had a negative balance averaging 0.2 to 0.5 m per year during this century. Over the period South Cascade Glacier received the greatest mass and had the highest runoff. The greatest glacier activity along the North Pacific Coast can be inferred to be at approximately 54° N. latitude. Glaciers in the Brooks Range are the least active.

The rapid decrease in glacier activity from Wolverine Glacier to McCall Glacier is produced by the combined effects of latitude and remoteness from the primary precipitation source, the Pacific Ocean. (McCall Glacier information was provided by D. Trabant, oral commun., 1975.) A similar but less pronounced decrease in glacier activity occurs from west to east across the cordillera because precipitation is blocked by the coastal mountains. Therefore, local variations from the glacier hydrology shown here (fig. 9) are to be expected.

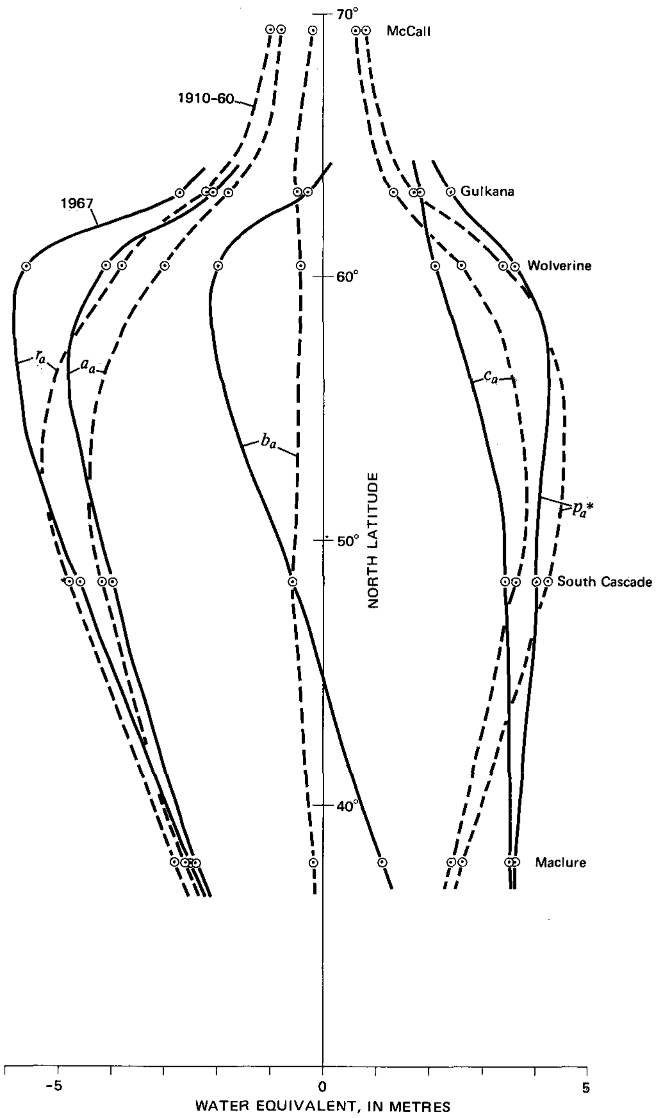

FIGURE 9.—Annual glacier hydrology as a function of latitude. Average calculated for 1910–60, dashed; measured values in 1967, solid. McCall Glacier information provided by D. Trabant (oral commun., 1975).

A comparison between the 1967 hydrologic year data and the 50-year means indicates that the 1967 annual ablation was close to that predicted for the mean at all glaciers. The annual accumulation of snow was, however, much more variable. The differences in 1967 accumulation from the average of each glacier correlated directly with the departures of the 1967 annual balance of each glacier from the long-term mean balance.

The 1967 precipitation total did not depart from the mean in a way that could be used to predict the balance. Maclure Glacier had a greater than normal precipitation and a higher than normal balance. On the other hand, both South Cascade and Wolverine received normal amounts of precipitation but only Wolverine had a strongly negative balance.

Annual precipitation in 1967 also could not be used as a predictor of runoff. Maclure Glacier received abnormally large amounts of precipitation yet had near normal runoff. Wolverine Glacier had a normal amount of precipitation and unusually high runoff.

In 1967 the variations from normal annual accumulation controlled the glacier balances. However, from these preliminary results it cannot be determined whether winter or summer seasons are, on the average, more important to variations in glacier health. Furthermore, simple reliance on values such as $\bar{b}_x$, $\bar{b}_m(s)$, and $\bar{b}_w$, as indicators of mass and energy exchange can be misleading.

Part of the snow accumulation at each glacier is by redeposition from areas surrounding the glacier. Assuming that $\bar{b}_m(s)$ (basin) represents the original deposition value of snow on both the glacier and nonglacier areas, the much larger value for $\bar{b}_m(s)$ (glacier) is then due to the transport of snow from the slopes. The original deposition value includes direct precipitation, rime icing plus snow blown into the basin, and minus snow blown out of the basin. Fraction, F, of glacier accumulation derived from slopes by drifting and avalanching is:

$$F=[\bar{b}_m(s)\text{glacier}-\bar{b}_m(s)\text{basin}]/\bar{b}_m(s)\text{glacier}.$$

The percent contribution by avalanching and wind drift to the measured snow balance on each glacier during 1967 was 43 percent of the total glacier snowpack for Maclure, 32 percent for South Cascade, 24 percent for Wolverine, and 15 percent for Gulkana. That a small cirque glacier like Maclure received nearly half of its nourishment by redeposition shows that redeposition on smaller glaciers is a significant factor.

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