A comparison of glacier mass balance by glaciological, hydrological and mapping methods, South Cascade Glacier, Washington

Wendell V. Tangborn, Robert M. Krimmel and Mark F. Meier

Abstract. Three different methods of determining glacier mass balance were compared on South Cascade Glacier during the period 20 June to 10 September 1970. The mass loss measured on the glacier by the glaciological and mapping methods agrees within 2%. The mass loss for the drainage basin calculated by the hydrological method is 38% greater than the loss for the same area measured by the glaciological method. This discrepancy is probably due to the release of liquid water storage from the glacier in summer. These liquid storage changes may account for errors in attempts to measure the annual balance of glaciers by hydrological means.

Résumé. Trois méthodes différentes pour déterminer le bilan de masse glaciaire ont été comparés sur le 'South Cascade Glacier' durant la période du 20 juin au 10 septembre 1970. La perte de masse mesurée sur le glacier par les méthodes glaciologique et cartographique est en accord à moins de 2%. La perte de masse pour le bassin versant calculée par la méthode hydrologique est 38% plus grande que la perte pour la même surface mesurée par la méthode glaciologique. Cette contradiction est probablement due à l'écoulement en été d'eau liquide stockée dans le glacier. Ces variations du stock liquide peuvent expliquer les erreurs commises en cherchant à évaluer le bilan annuel de glaciers par la méthode hydrologique.

The readjustment of the size or volume of a glacier (its net or annual balance) in response to external changes is an important indicator of the long-term relationship between glaciers and their environment. Often this annual change is quite small and only cumulative balances over many years cause pronounced geometric changes in the glacier. A problem arises when determining the annual change largely because the input (mostly precipitation) to glaciers and output (ablation) from glaciers are usually large numbers while the differences between them (net mass balance) are small, often an order of magnitude less. Therefore, the absolute value of net mass balance is easily masked by errors in the measured variables.

'Combined Heat, Ice and Water Balances at Selected Glaciers Basins' is a major snow and ice programme of the International Hydrological Decade (UNESCO/IASH, 1970). Some doubt has been expressed that sufficiently accurate mass and water balance measurements could be made in glacierized catchments on either yearly, seasonal, or short-term time intervals. Since this is a basic stipulation of the programme, a careful evaluation of relative accuracies by means of independent comparisons of different measurement methods is required.

The three methods most often used are the glaciological, hydrological, and mapping (geodetic). Kasser (1954, 1959, 1961) compared runoff, evaporation, and precipitation from the Aletsch Glacier with mass balance data and changes in volume measured from several topographic maps. This work is of major importance in defining the hydrological balance of a glacierized catchment, but for several reasons (including use of index techniques and nonsynchronous measurement periods) few results on relative balance accuracies were produced. Hoinkes (1970), in a long-term study of Hintereisferner and adjoining glaciers, compared mapping and glaciological methods for the period 1954-64 with excellent agreement. He also computed hydrological
balances for 1957-58 and 1958-59 using glaciological results for the ice balance term and attributed the residual left over to evaporation. He noted a tendency in dry summers for the hydrologically calculated mass balances to be too negative and vice versa, and attributed this to variations in evaporation on snow and ice-free slopes.

Schytt (1970) compared the hydrological and glaciological methods on the Storglacier in northern Sweden for three recent years. His preliminary results show considerably more runoff than can be expected from the precipitation and balance measurements. Stenborg (1970) also reported an apparent excess of runoff as compared with the remaining terms in a balance equation.

Meier and Tangborn (1965) made a comparison between the mapping changes on South Cascade Glacier over a three-year period with glaciologically computed balances corrected with use of hydrological data over the same period. These results showed very good agreement, with the differences between the two values (1.3%) being far less than the estimated standard error of either (7 and 10%). Tangborn (1966) compared the hydrological and glaciological methods for seven years on South Cascade Glacier with good results. However, basin precipitation was determined for the hydrological method by a simple method which assumed that precipitation at an index station located near the centre of the glacier was representative of the average basin precipitation. Results of basin-wide data collected since 1965 show that winter balance values at this index station average about 1 metre greater than the mean for the basin.

A comparison of these three methods was attempted over a summer period on South Cascade Glacier in 1970. The period chosen was 20 June to 10 September (82 days) because the greatest change in mass of this glacier occurs during this time, and because this circumvented the difficulty of measuring precipitation in winter. Thus, it was hoped that errors in each measurement could be evaluated more easily.

Because of the techniques employed, it was impossible to compare directly all three methods for the same area. The mapping and glaciological methods were compared for the trunk glacier (2.55 km$^2$) only. Glaciological and hydrological methods were compared for the whole drainage basin (6.11 km$^2$), including the slopes around the trunk glacier on which lay perennial ice, ephemeral snow, bare rock, and a lake. It was found that the variation of liquid water storage within the glacier had to be considered in comparing glaciological and hydrological methods, and liquid water balances were computed throughout the period from 1 May to 30 September. Finally, results of the glaciological/hydrological comparison on an annual basis were analysed in light of the liquid water storage results.

**MAPPING METHOD**

Between 20 and 23 June, 112 points were surveyed on the glacier. The points were triangulated and vertical angles measured simultaneously from bedrock stations with one-second theodolites using an existing precise triangulation network. A party on the glacier targeted the glacier surface and probed to ice or firn if the point was covered with snow. Between 10 and 12 September the same horizontal intersections were found by using the earlier survey notes. A computer reduction of the survey data gave the change in altitude of the surface at each point. Usually the horizontal locations were repeated to within 0.5 m. When distances were greater than this due to crevasses or other difficulties, a surface elevation at the spring position was calculated using local slopes if the area was relatively flat; about 10 points were rejected because of nonrepeated locations in steeper areas. The vertical coordinate values at points are considered to be accurate to ±0.1 m (standard error).

Surface altitude change was adjusted to water equivalent change by using a density of 0.9 when the point was over ice in both June and September; if the point was over snow at either time density from nearby pits was used in connection with the probing
depth at the point. The adjustment in the accumulation zone used the known density variation with depth. A further adjustment considering vertical strains due to horizontal extending or compressing flow would be necessary for accurate point values but was not required for this purpose since point values were integrated over the whole glacier. The computation of mass lost at a point is considered to be accurate to 5%, neglecting the effect of vertical strains.

Values of mass lost at each point ranged from 7.0 m at the terminus to 2.4 m near the head. The average in the ablation zone was about 3.5 m and in the accumulation zone about 2.8 m. The total mass lost was determined by first contouring a map of point values of mass loss, then averaging the values between contours, multiplying by the area included in that contour, and summing. The point-to-area integration accuracy is believed to have no effect on the error bound given above. The map area was that of the trunk glacier on 10 September, and the change in glacier area during the summer was not considered. The mass change was $-7.55 \times 10^6$ m$^3$ of water equivalent, an average vertical change of $-2.96$ m over the defined glacier area, with a standard error of $0.38 \times 10^6$ m$^3$.

**GLACIOLOGICAL METHOD**

The glaciological method is the most usual method for measuring mass balances on glaciers. The techniques used during this comparison were identical to those used in our annual balance measurements and very similar to those used in many other countries (for example, Østrem and Stanley, 1969). For the purposes of this comparison, two measurements (on 20 June and again on 10 September) would appear to suffice. However, continuous mass balance data were obtained from 1 May until 30 September for other purposes (Meier et al., 1971), and these data were found to be useful in calculating liquid water storage changes which were pertinent to the glaciological/hydrological method comparison.

In the 1970 summer, 28 aluminium stakes, set to either ice or firn and distributed over the glacier, were read every one to two weeks. Snowpack density was determined by snow pits dug to ice or firn every 10 days. Snow thickness was measured at a very large number of points by probing. Daily measurements were made of snow surface depression and surface snow density at an index station near the centre of the glacier. In addition, snowlines were mapped every 10 to 20 days from daily photographs taken by a time-lapse camera.

In the part of the basin not occupied by the trunk glacier (59% of the total area), much of which is very steep and nearly inaccessible, balances were calculated on the basis of four stakes and a probing network which covered about 50% of the nonglacier area. The remaining area, too steep to traverse and with a highly variable snowpack, was mapped for winter balance on the basis of the snowline recession (for area changes) and ablation at stakes near the same altitude but located in accessible areas. All the snow had melted from this area by 10 September so that only the 20 June balance was made in this way.

Errors resulting from this method can be classed as known and unknown. Known errors include those associated with probing snowpack thickness, determining density at a point, reading ablation stakes, sinking of stakes into firn or ice, and mapping snowlines. Fairly reliable standard errors can be assigned to each of these. The unknown errors arise from the lateral variation in density and depth of the snowpack, the possible refreezing of meltwater in firn (known to be small in this temperate glacier), the subjective drawing of balance contours, and other unknown unknowns. Errors due to glacier movement (stakes do not maintain the same position) and due to vertical extension or compression of ice adjacent to the stake are minor and are not included.
The mass balance of the glacier on 20 June (Fig. 1a) was $4.65 \times 10^6$ m$^3$ of water equivalent (1.85 m averaged over the glacier) with a standard error of $0.25 \times 10^6$ m$^3$. The glacier mass balance on 10 September (Fig. 1b) was $-2.65 \times 10^6$ m$^3$ ($-1.05$ m average) with a standard error of $0.13 \times 10^6$ m$^3$. Thus the surface mass change as determined by the glaciological method for the trunk glacier was $-7.30 \times 10^6$ m$^3$ ($-2.90$ m averaged over the glacier surface) of water equivalent, with a standard error estimated at $0.28 \times 10^6$ m$^3$. This result is for an integration of vertically measured values over the same area as used in the mapping method. To this surface mass change should be added a small amount of horizontal mass flux, due to flow out from the terminus ($-0.016 \times 10^6$ m$^3$), inflow from two areas of small, connected ice masses ($+0.006 \times 10^6$ m$^3$), and inflow from a triangular prism along the remainder of the rock border as the glacier thickness changed ($+0.004 \times 10^6$ m$^3$). Also, the internal melt due to ice deformation and the loss of potential energy of meltwater plus the basal melt is estimated at 1 cm ($0.03 \times 10^6$ m$^3$). The resulting mass balance change is $-7.39 \times 10^6$ m$^3$; a conservative standard error of $0.40 \times 10^6$ m$^3$ (5.4%) allows for a large uncertainty in the net flux along the margin and the englacial and subglacial melt. The difference between this result and the balance change measured by the mapping method ($-7.55 \times 10^6$ m$^3$) is far less than the assigned errors.

Considering the basin as a whole, the 20 June balance was $6.35 \times 10^6$ m$^3$ and the 10 September balance was $-3.04 \times 10^6$ m$^3$. Ice flow across the margins and ice loss below the surface are estimated at $-0.09 \times 10^6$ m$^3$. Thus the mass change as determined by the glaciological method for the whole drainage basin is $-9.48 \times 10^6$ m$^3$ of water equivalent ($-1.55$ m averaged over the basin area). The standard error is estimated at $0.50 \times 10^6$ m$^3$ (6.8%), larger than for the trunk glacier due to uncertainties in determining changes in snow depth and density on steep inaccessible slopes. This result cannot be compared with results of the mapping method since mapping was not extended to the bordering slopes, but it can be compared with the hydrological result.

### HYDROLOGICAL METHOD

This is the least direct of the three methods for determining balance (storage) changes, because the desired result is the residual after subtracting several large quantities in a balance equation. Not all of the necessary quantities can be measured directly.

A water balance equation (valid for any period of time in a drainage basin) can be written as

$$P(l) - E(l) - R(l) + F(i) = B(l)$$

where $P$ is precipitation, $E$ is net evaporation/condensation, $R$ is net runoff (outflow minus inflow), $F$ is the melting of ice and snow, $B$ is the liquid water balance, $(l)$ designates liquid water and $(i)$ designates change from ice to liquid water. Certain other terms (such as groundwater storage changes) which are unimportant at South Cascade Glacier are omitted. Similarly, an ice balance equation can be written as

$$P(i) - E(i) - F(i) = B(i)$$

where $(i)$ designates ice and snow. Again, certain unimportant minor terms (such as ice runoff) have been omitted.

Combining, and designating the summer period with the subscript $s$,

$$P_s(l) + P_s(i) - E_s(l) - E_s(i) - R_s(l) - B_s(l) = B_s(i)$$

(1)

If all the terms on the left-hand side were accurately measured, the result would be a hydrological computation of ice balance change which should compare closely with results of the glaciological method. Unfortunately, the evaporation terms can only be...
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FIGURE 1a. Ice balance map and photograph of South Cascade Glacier on 20 June 1970, the beginning of the comparison period. Ice balance values, shown as numbers, are the average for the area between contours and are in metres of water equivalent. Balances were measured to the 1969 summer surface. Areas of exposed rock and water are shown by stippled and striped pattern. The photographs are two of a series taken throughout the ablation season by a time-lapse camera.
FIGURE 1b. Ice balance map and photograph of South Cascade Glacier on 10 September 1970, the end of the comparison period. Ice balance values, shown as numbers, are the average for the area between contours and are in metres of water equivalent. Balances were measured to the 1969 summer surface. Areas of exposed rock and water are shown by stippled and striped pattern. The photographs are two of a series taken throughout the ablation season by a time-lapse camera.
A comparison of glacier mass balance estimated from scattered measurements, and the liquid water balance term cannot be measured directly.

For the period 20 June to 10 September 1970, $P_s(I) + P_s(z)$ was measured at a network of storage and recording precipitation gauges and equalled $1.25 \times 10^6$ m$^3$ (205 mm averaged over the basin) with an estimated standard error of $0.10 \times 10^6$ m$^3$. $E_s(I)$ was not measured directly but is estimated from the amount of liquid water exposed at the surface and reasonable evapotranspiration rates as $0.30 \times 10^6$ m$^3$ (50 mm average) with a standard error of about the same value. Occasional measurements of $E_s(I)$ in previous years showed an evaporation/condensation balance of approximately zero; LaChapelle (1959) working on a glacier in a similar environment measured a net $E(I)$ of 3.5 m for a 37-day period in midsummer. We therefore estimated $E_s(I)$ at $0.06 \times 10^6$ m$^3$ (10 mm average) with a standard error of about the same value. $R_s(I)$ was measured by digital and analogue stage recorders working above a covered weir (Tangborn, 1963), calibrated by many measurements of streamflow discharge through the use of a Price current meter according to standard US Geological Survey procedures (Carter and Davidian, 1968) and checked occasionally by salt dilution measurements; the value obtained is $14.31 \times 10^6$ m$^3$ (2.3 m averaged over the basin) with a standard error of $0.50 \times 10^6$ m$^3$. From this should be subtracted a small amount of surface water inflow from a glacier in a neighbouring basin, measured to be $0.30 \times 10^6$ m$^3$. Daily values of runoff and precipitation are shown in Fig. 2a.

The sum of the terms on the left-hand side of equation (1) except for $B(I)$ is $-13.12 \times 10^6$ m$^3$, with a standard error of $0.60 \times 10^6$ m$^3$. This differs from the glaciologically determined balance ($-9.48 \times 10^6$ m$^3$) by considerably more than assigned errors. Thus we conclude that unless there were gross mistakes in error estimation, the term $B(I)$ is not negligible.

Could gross mistakes in certain measurements cause this large discrepancy? Perhaps the glaciological balance was drastically undermeasured. If all the error were due to faulty measurements on the nonglacier part of the basin (because of the steep terrain this area is difficult to measure) this would require an error of $-1.1$ m averaged over this area; thus the nonglacier winter balance should have been 2.1 m instead of 1.0 m. An error this large is difficult to believe. As an independent check, the mass loss in snowmelt from an adjacent nonglacier basin (Salix Creek) for the 1 May to 30 June period was determined and used to calculate the mass loss for the unglacierized part of the glacier basin. (The areas are similar in altitude distribution.) These mass changes agree within 5% indicating that the mass balance measurements for the nonglacier areas are not faulty. Assuming all the discrepancy occurs on the trunk glacier balance measurement implies a measurement error of 1.55 m on the glacier. In view of the close agreement between the mapping and glaciological method losses, this is also difficult to believe.

Large errors in map scale or surface snow density could affect the glaciological and mapping methods equally and preserve the apparent internal consistency, but are ruled out because the mapping and surveying have been repeated many times with many methods without discrepancy and the density changes necessary for glaciological/hydrological method agreement are entirely unreasonable.

Precipitation during the comparison period may have been underestimated. An additional 0.64 m (in addition to the 0.20 m measured by gauges) would be necessary to account for the excessive runoff. The possibility of this large an error resulting from unmeasured precipitation is unlikely. Analysis of runoff of both the glacier basin and the adjacent Salix Creek basin during the few periods of rain during the summer shows no unusually large discharge to account for such a large error in precipitation measurement. A large value of condensation (negative evaporation) might be considered as a cause of the discrepancy, but a condensation excess over evaporation of 600 mm for this
FIGURE 2a. Daily values of runoff (solid line) and precipitation (bars) in the South Cascade Glacier drainage basin. Runoff was measured at a weir at the outlet of the lake; precipitation is an average of measured amounts at seven gauges located throughout the drainage basin. Solid bars indicate precipitation occurring as snow, dashed bars indicate rain.

FIGURE 2b. Daily liquid storage changes in the drainage basin calculated as the difference between the measured input (the daily balance change) and output from the drainage basin (runoff). Positive values indicate water going into storage, negative values show the release of stored water.

FIGURE 2c. Cumulative liquid storage changes in the drainage basin during the 1970 ablation season, an integration of the daily values in Fig. 2b. Maximum liquid storage occurred on 2 June; minimum storage is not shown but, based on the shape of the storage curve, probably occurred a few days after 1 October.

82 day period is meteorologically impossible. Groundwater inflow cannot be entirely discounted: the steep, well-defined basin is composed of relatively impermeable crystalline rocks, but one fault zone crosses the basin boundary at a point where water from an adjacent glacier could enter. The discrepancy would require groundwater inflow at a rate of 510 l/s; this seems highly unlikely.

Finally, the measurements of runoff might be faulty. However, an error of 26% seems most improbable in view of the stable control structure, a stable and well-defined river stage/discharge relationship, frequent calibration, and checks with different types of discharge measuring techniques.

Thus, we must conclude that the source of the discrepancy is a change during the 82 day period in liquid water storage, $B_s(t)$.

LIQUID WATER BALANCE

The changes in liquid water balance can be calculated from mass balance and hydrological data. Neglecting minor terms such as evaporation and assuming that mass
A comparison of glacier mass balance on day $j$ can be computed as follows:

$$B_j = -k_1 k_2 x_j S b_j(i) + S p_j(i + 1)/n - R_j$$

where $x_j$ is the percentage of total basin area which is snow-covered on day $j$, $S$ is the total basin area, $b_j(i)$ is the balance change on day $j$ at a midglacier index station, $p_j(i + 1)$ is the precipitation (liquid and solid) caught in $n$ gauges on day $j$; $R_j$ is the runoff volume on day $j$. The correction factor $k_1$ adjusts the sum of measured daily surface balances at the index station for each week to the changes in mass balance at the index station determined by pits through the snowpack each week. The factor $k_2$ adjusts the balance change at the index station to the average balance change over the whole basin whenever basin-wide mass balance surveys are made (about every two weeks). Daily values of $B(l)$ are shown in Fig. 2b.

The daily liquid water balance values can be summed over any time interval. For the 82 day summer period,

$$B_{10 \text{ Sept.}} = \sum_{j=20 \text{ Jun}}^{10 \text{ Sept.}} B_j(l) = -3.64 \times 10^6 \text{ m}^3$$

A curve of cumulative daily liquid water balance changes (Fig. 2c), beginning on 1 May when daily measurements began, shows that maximum liquid water storage occurred on 2 June. This should not be confused with the maximum water equivalent of snow and ice storage $[B(i)]$ which occurred on 16 May. During the period 1 May to 19 June, $0.49 \times 10^6 \text{ m}^3$ of liquid water was added to storage in the drainage basin. From 20 June to 30 September, $3.64 \times 10^6 \text{ m}^3$ of water was removed from storage. From 1 September to 30 September (the end of the hydrological year) an additional $0.45 \times 10^6 \text{ m}^3$ of water was removed from storage. The change during the season 1 May to 30 September was $-3.60 \times 10^6 \text{ m}^3$. These changes are shown in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Mapping method</th>
<th>Glaciological method</th>
<th>Hydrological method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trunk Glacier</td>
<td>Trunk Glacier</td>
<td>Drainage Basin</td>
</tr>
<tr>
<td>1 May to</td>
<td>$-1.40$</td>
<td>$-3.41$</td>
<td>$-2.92$</td>
</tr>
<tr>
<td>19 June</td>
<td></td>
<td></td>
<td>$+0.49$</td>
</tr>
<tr>
<td>20 June to</td>
<td>$-7.55$</td>
<td>$-7.39$</td>
<td>$-9.48$</td>
</tr>
<tr>
<td>10 Sept.</td>
<td></td>
<td></td>
<td>$-13.12$</td>
</tr>
<tr>
<td>11-30 Sept.</td>
<td>$-0.58$</td>
<td>$-0.61$</td>
<td>$-1.06$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$-0.45$</td>
</tr>
</tbody>
</table>

A physical mechanism for this storage and release of meltwater can be sketched briefly. A glacier differs from a normal porous-medium aquifer in that (1) the fluid is heavier than the solid and pressures in water-filled holes can exceed the pressure in the solid ice nearby, (2) ice is a weak solid and readily deforms by plastic flow resulting in continuous deformation as well as enlargement or reduction of passageways depending on pressure differences between ice and water or air, and (3) heat generated by viscous dissipation (loss of potential energy) or carried from the surface can enlarge passageways by melting.

During long periods of little ablation (late fall, winter, early spring), there is an increased tendency for meltwater passageways to close, causing meltwater and rain to
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go into storage, likely into small cavities and channels within and at the base of the
glacier. Movement of the glacier would tend further to seal off these drainage routes
during the fall and winter. After ablation begins in the spring, storage of water
continues to take place, but the hydrostatic head of the stored water is increasing
rapidly. This causes ice deformation around channels, reopening a three-dimensional
network of passageways, and water begins to drain from the glacier. Drainage
continues at a diminishing rate throughout the summer, and the passageways begin to
close up when the production of meltwater tapers off. Thus, much of the water
occurring as runoff during the summer was produced actually during the previous
spring and fall. Crucial to this argument is the assumption that there is a certain delay
between the advent of higher water pressure and the opening of passageways. If the
adjustment of passageway size to water pressure were primarily accomplished by
plastic flow of the ice, a delay of some months would be expected, because the
pressure differences would be relatively small – of the order of $10^{-1}$ to $10^{-3}$ bars.

IMPLICATIONS TO ANNUAL BALANCES

Several glaciologists have attempted to compare balances by hydrological and glacio-
logical techniques on an annual basis. This is generally done by assuming the following
($w$ denotes winter, and $a$ denotes annual):

\[ P_w(i) + P_w(i) = B_w(i) \]
\[ B_a(i) = 0 \]
\[ E_w(i + i) = 0 \]
\[ F_w(i + i) = 0 \]

Thus the balance equation for the year is assumed to be

\[ B_w(i) - R_w(l) - E_s(i + l) + P_s(i + l) - R_s(i + l) = 0 \] (3)

Equation (3) has usually failed to balance (more mass has appeared as runoff than
can be accounted for in the input terms) when applied to other glaciers. Our work
suggests that a large decrease in the liquid water storage occurs during the summer.
This should be balanced by an approximately equivalent increase in liquid water
storage in winter $B_w(l)$. Calculations based on equation (3) will tend to be unbalanced
by the amount of seasonal liquid water storage change: $B_s(l)$ will be calculated by the
summer balance terms, but $B_w(l)$ is ignored. Such a tendency is illustrated in annual
balance calculations for the last six years at South Cascade Glacier (Table 2). There-
fore, liquid water storage changes in glaciers should not be ignored, and use of
equation (3) to calculate glacier balances may be open to question.

CONCLUSIONS

The mapping and glaciological methods show a close agreement and both methods can
be considered reliable. The small discrepancy between them can be explained by small
errors in both methods. On an annual basis less relative accuracy should be expected in
either method because smaller changes occur then.

The hydrological method shows extreme unreliability in measuring mass balance
changes over short-time periods, due apparently to the storage and release of
meltwater, probably from within the glacier. This virtually eliminates using runoff
measurements from a glacier to examine daily or weekly heat balances for a glacier.
Over longer periods of time (annually or longer) the hydrological method may be
useful in determining mass balances if total precipitation can be measured, and annual
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TABLE 2. Annual balances South Cascade Glacier, 1965-70. (All values are in metres of water equivalent, averaged over the drainage basin, 6.11 km².)

<table>
<thead>
<tr>
<th>Hydrological year</th>
<th>Winter ice balance* $B_w(i)$ (+)</th>
<th>Winter runoff $R_w(i)$ (-)</th>
<th>Summer runoff $R_s(i)$ (-)</th>
<th>Summer precipitation $P_s(i + l)$ (+)</th>
<th>Annual ice balance† $B_a(i)$ (-)</th>
<th>Summer liquid water balance‡ $B_s(i)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1965</td>
<td>2.48</td>
<td>0.61</td>
<td>2.78</td>
<td>0.43</td>
<td>−0.04</td>
<td>−0.44</td>
</tr>
<tr>
<td>1966</td>
<td>1.82</td>
<td>0.64</td>
<td>2.61</td>
<td>0.48</td>
<td>−0.48</td>
<td>−0.47</td>
</tr>
<tr>
<td>1967</td>
<td>2.41</td>
<td>0.58</td>
<td>3.25</td>
<td>0.32</td>
<td>−0.28</td>
<td>−0.82</td>
</tr>
<tr>
<td>1968</td>
<td>1.89</td>
<td>0.82</td>
<td>2.94</td>
<td>0.80</td>
<td>0</td>
<td>−1.07</td>
</tr>
<tr>
<td>1969</td>
<td>2.09</td>
<td>0.61</td>
<td>3.32</td>
<td>0.55</td>
<td>−0.34</td>
<td>−0.95</td>
</tr>
<tr>
<td>1970</td>
<td>1.58</td>
<td>0.52</td>
<td>3.09</td>
<td>0.43</td>
<td>−0.59</td>
<td>−1.01</td>
</tr>
</tbody>
</table>

* Measured at about 1 May.
† Determined by surface glaciological methods.
‡ Algebraic sum of the other terms.

Changes in liquid water storage can be assumed to be negligible. To examine the water storage potential of a glacier and the consequences related to such a storage phenomenon requires that both precipitation and runoff data be obtained.

Comparisons between annual balances determined hydrologically and glaciologically have consistently shown an excess of runoff on this glacier and on other glaciers also. A possible explanation for these discrepancies is seasonal liquid water storage which is not included in the water balance calculations. More detailed measurements of late fall and early winter ablation, precipitation, and runoff on glaciers are necessary for proper annual hydrological balances.

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