SOUTH CASCADE GLACIER: THE MODERATING EFFECT OF GLACIERS ON RUNOFF 1/

By

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It is known that glaciers are natural moderators of streamflow and that runoff from glaciers can be greater during warm, dry years than during the cool, wet ones (1, 2, 3). However, the exact mechanisms that control this regulating process are incompletely understood. Investigations conducted on South Cascade Glacier in Washington give some insight into this increasingly important phenomenon.

The South Cascade Glacier is a small glacier (2.72 km^2) with a mean equilibrium line altitude of about 1,870 m. The drainage basin has an area of 6.25 km^2 with a relief of nearly 1,000 m. The U.S. Geological Survey has carried on research in the basin since 1957; since 1965 a program of mass, water and heat balance research has been in progress as part of the International Hydrological Decade.

The runoff from a glacier is a result of the ablation of snow that fell the previous and earlier winters including the melt of firn and ice, rain that fell on the glacier, and release of liquid water that had been stored temporarily in the internal drainage network of the glacier. The release of water stored within the glacier does not begin until well after ablation has begun. The input of this storage, on the order of 1 m averaged over South Cascade Glacier, occurs during the previous fall, winter, and spring (4, 5). The variability of glacier runoff is the result of the combined variance of these factors. Of the three, summer rainfall causes the least deviation in variance from nonglacier conditions; however, the other two factors significantly change the natural variance and cause glaciers to be important runoff moderators.

As shown in Figure 1, the presence of only a few small glaciers in a large drainage basin has a substantial effect on the variance of summer streamflow. This is an important factor when making streamflow forecasts, particularly during periods of low precipitation.

The mechanisms which cause glaciers to moderate streamflow are:

1. During years of greater than normal precipitation, when nonglacier areas have high runoff, the greater snowfall occurring on glaciers retards ablation. Because the albedo of snow is usually 0.6 to 0.85 and the albedo of ice is less than half of this, the ratio of exposed ice ablation to snow ablation will vary between 2 and 3 depending on the proportion of direct solar radiation to the total energy input on the glacier surface. The reverse is true during years of low precipitation and less snow accumulation. The earlier exposure of ice to radiation will cause greater glacier melt, thus compensating for the diminished streamflow from other sources.

2. Also, in years of high snow accumulation, a greater than average amount of avalanching and drifting occurs from the steeper slopes surrounding glaciers, producing an even greater protective blanket over the low albedo ice, and amplifying the effect given in (1).

3. The release of liquid storage from within the glacier aquifer each summer will also tend to moderate glacier runoff because this storage and release mechanism is nearly independent of any external climatic variations (similar amounts of storage and release appear to occur each year regardless of the amount of precipitation) (4, 5).

Results of the South Cascade Glacier IHD program from 1965-73 can be used to exemplify these effects. The winter of 1971-72 produced record high snowfall over most of the North Cascades of Washington while the winter of 1972-73 produced a nearly record low snowpack. The maximum water balance averaged over the South Cascade Glacier in May was 4.27 m in 1972 and 2.21 m in 1973. In 1971-72 the amount of snow deposited on the glacier by avalanching and drifting was about 57% of the total glacier accumulation, while in the low snowfall year of 1972-73 it was only 26%. These two contrasting years in addition to

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data for the 1965-71 period provide an excellent opportunity to demonstrate the moderating effect of glaciers on runoff.

Graphs of runoff (daily and cumulative), daily precipitation, daily average air temperature, and index station snow balance versus time for 1972 and 1973 for the South Cascade Glacier drainage basin are presented in Figures 2 and 3. Several facts are notable: Cumulative runoff (total runoff from the basin) was 4.07 m in 1972 and 3.70 m in 1973. Total May-September precipitation (rain plus snow) was 0.76 m in 1972 and 0.58 m in 1973. Air temperatures were roughly parallel throughout the period and the average of the daily means was 7.3°C in 1972 and 7.4°C in 1973. Cloud cover was similar during both years and averaged 40 to 50% over the summer. The one parameter that shows a large difference between the two years is the index station snow balance. The 1972 snow balance was generally equal to about twice the 1973 snow balance at any given time (Figure 2). This demonstrates that, even though the winter of 1971-72 had much greater snow accumulation than 1972-73 and that the summer climate of both years was similar, runoff for both years was approximately the same.

The retardation or acceleration of ablation rate can be seen by plotting total snow accumulation against (a) observed runoff from the glacier basin, and (b) calculated runoff from the same basin assuming no glacier to be present.

In Figure 3, observed annual runoff, Ry, is plotted as a function of total basin snow accumulation, A_t, for the 1965-73 period (triangles). A fitted regression line to these data gives a slope of nearly zero and an intercept of 3.6. The interpretation of this is clear--the presence of a glacier covering about half of this basin makes runoff nearly independent of input. The calculated (no glacier) runoff is that which would result if a glacier was not present in the basin and is equal to the total annual precipitation (evaporation-condensation is not considered in this simple approximation). The slope of the calculated runoff versus snow accumulation line is nearly equal to unity, in striking contrast with the observed. Furthermore, the standard deviation of the Ry values is 0.26 whereas that for the A_t values is 0.37, showing that Ry is much less variable from year to year than A_t. It should be noted that if A_t was abnormally high in a "no glacier" basin, the factors that regulate the streamflow in a glacier basin would begin to have an effect and if this continued for several seasons the "no glacier" basin would by definition become a glacier basin.

The fitted regression lines in Figure 3 of calculated and observed runoff require further explanation. During a several year period that a glacier neither loses nor gains mass the annual average glaciological balance will be zero and A_t + summer precipitation, Ps, should equal Ry. For the period 1965-73 the glaciological balance, averaged over South Cascade Basin is -0.10 m, yet the average Ry is 3.68 m and Ps + A_t is 2.69 m, a difference of 0.99 m. This discrepancy may be attributed to a measured value of A_t that is too low. At is determined by measurement of snow in the basin in the spring; A_t should also include liquid water storage within the glacier but this is impossible to measure. To account for this, we have added Ry - (Fs + - 0.10 = 0.89 to A_t. This simply displaces both the observed and calculated lines to the right but does not alter the conclusions.

The significance of Figure 3 is that the observed runoff from South Cascade Glacier basin for the past 10 years is remarkably independent of winter accumulation. The observed runoff as a function of measured winter accumulation increases linearly with a slope near unity. The intersection of these two lines at roughly A_t = 3.2 m could be defined as the "mean accumulation limit" for this drainage basin. This can be defined explicitly as the approximate value for basin snow accumulation which, if exceeded, will actually produce less runoff than would be expected if no glacier were present.

The significance of these results is that summer runoff from glacierized areas has considerably less variance of that from nonglacierized areas. This is an especially important consideration in many areas where streamflow is a critical factor in the low precipitation months of the growing season. For example, the farmers in eastern Washington depending on the Stehekin or Wenatchee Rivers for irrigation are far less prone to serious water shortages caused by unpredictable fluctuations in streamflow in August and September than are farmers who use water from drainages that do not have even the small fraction of the glaciers found in the Stehekin (3.4% glacierized) or the Wenatchee (0.5% glacierized) River drainages.

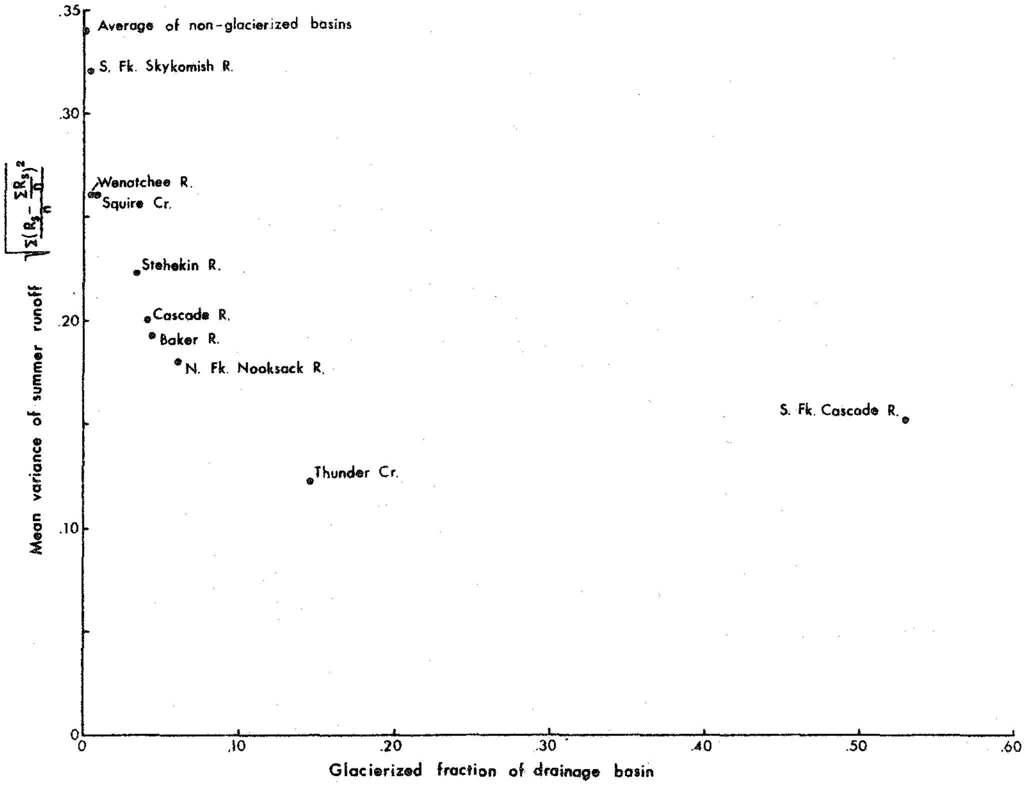
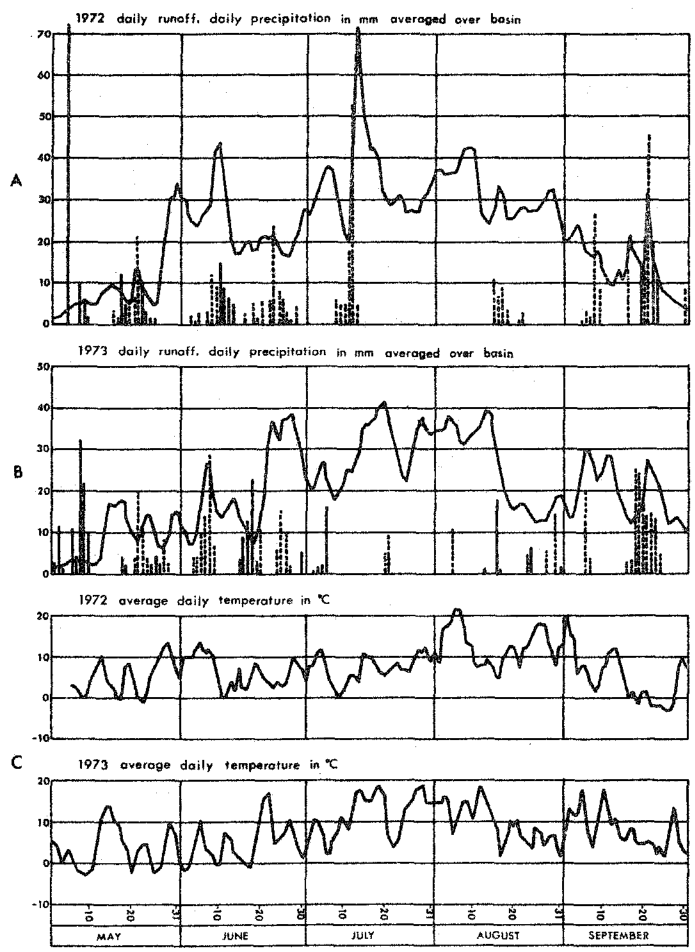


Figure 1.--Variance of summer runoff versus percent of glacierized areas for several drainage basins in the North Cascades.



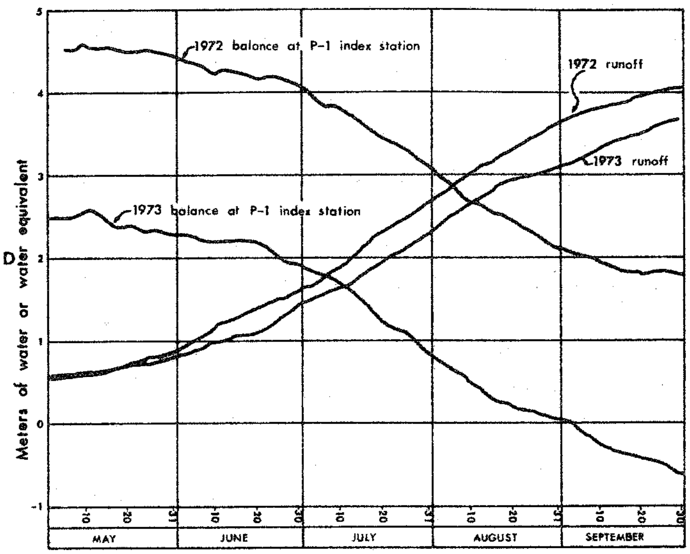


Figure 2.--South Cascade Glacier hydrological and meteorological data for 1972 and 1973. A. 1972 daily runoff and precipitation (continuous line is runoff, solid lines are snow, dashed lines are rain). B. 1973 daily runoff and precipitation (shown as in A). C. 1972 and 1973 average daily air temperatures. D. 1972 and 1973 index station snow balance and basin runoff.

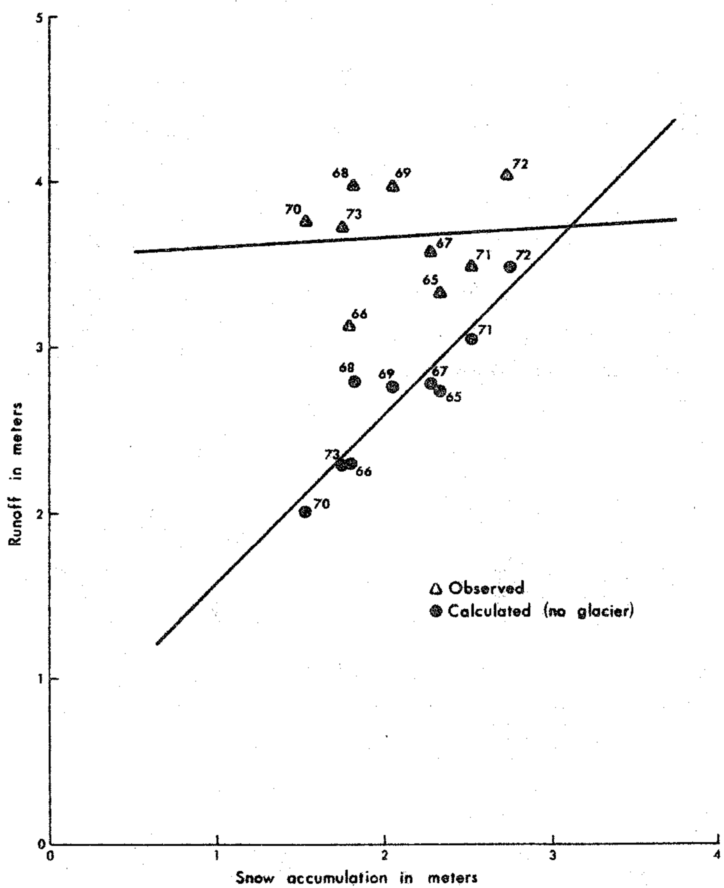


Figure 3.--Observed and calculated (no glacier) runoff versus snow accumulation, South Cascade Glacier, 1965-73).

In conclusion:

1. Glaciers are very efficient natural regulators of streamflow on both a seasonal and annual basis, and just a few small glaciers on a large drainage can be of significant economic importance.

2. More thorough investigations on the possibilities of predicting streamflow from glaciers are needed, particularly in areas where water supplies for irrigation and other uses are critical.

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