THE IMPACT OF MOUNT ST. HELENS ASH DEPOSITION ON SNOWMELT

By

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INTRODUCTION

The eruptions of Mount St. Helens during the spring and summer of 1980 deposited large quantities of volcanic ash over several thousand square miles of Washington and the adjacent states. Part of this area (primarily the Cascade Mountains) was snow covered during the main eruption on May 18 and depositions of ash from a trace to over 100 millimeters (4 inches) in thickness undoubtedly created a significant change in the melt rate of the snowpack. As it is likely that Mount St. Helens will continue to emit at least light dustings of ash for several years or for even decades, an understanding of the effect of ash deposition on snow hydrology and subsequent runoff would seem to be of value. The impact on hydrology is potentially important in the Pacific Northwest where forecasts of water supplies are critically needed for irrigation and hydroelectric power (e.g., the Yakima and Columbia basins).

With this motivation, we conducted an analysis of the effect of volcanic ash deposition on snowmelt runoff in several Cascade Mountain drainages. Although others (Driedger, 1981) have conducted controlled experiments to determine the effect of ash cover on snowpack ablation, our interest was focused on the integrated effect of such changes on runoff from moderate to large drainages (on the order of hundreds of square kilometers).

BACKGROUND

The effect of volcanic ashfall on snow has been observed in Alaska, Japan, New Zealand, Iceland, the USSR and many other areas of the world (Wilcox, 1959). In most instances, because of the remoteness of the volcanoes, there have not been serious economic consequences brought about by changes in the hydrology. Fortunately, the main eruption of Mt. St. Helens on May 18 occurred when the bulk of the mountain snowpack was not at its seasonal maximum in the Cascades. Also, the 1980 snowpack was below normal and flooding due to increased melt rates did not occur.

Several studies have previously been conducted of the effect on ablation of the deposition on snow of coal dust or other fine material (Bazhev, 1971). It has been shown that a thin layer of soot can change a new snow surface albedo from 0.75 to 0.10 and increase the melting by 220% on a clear day in July (Meier, 1969). The effect of solar radiation as a contributing factor in snowmelt variations due to albedo changes must, of course, be taken into account. Significant increases in melt will occur only when direct solar insolation (shortwave) is the principal energy component for snowmelt. During periods of cloudy weather, when other forms of melt energy (convection and long-wave radiation) predominate, the effect of decreased surface reflectivity will be negligible.

Insofar as cloudiness prevailed throughout the Pacific Northwest for several weeks following the May 18 eruption, gross changes in basin runoff were not observed. Any ashfall-induced changes in basin runoff, then, were apparently subtle. It is the purpose of this paper to identify the timing and magnitude of these changes.

ANALYTICAL METHODS

A major problem in estimating changes in natural systems is the confounding effect of variability resulting from natural variability in the systems themselves, errors in the models used to characterize them, and measurement error. In this work, the problem is to

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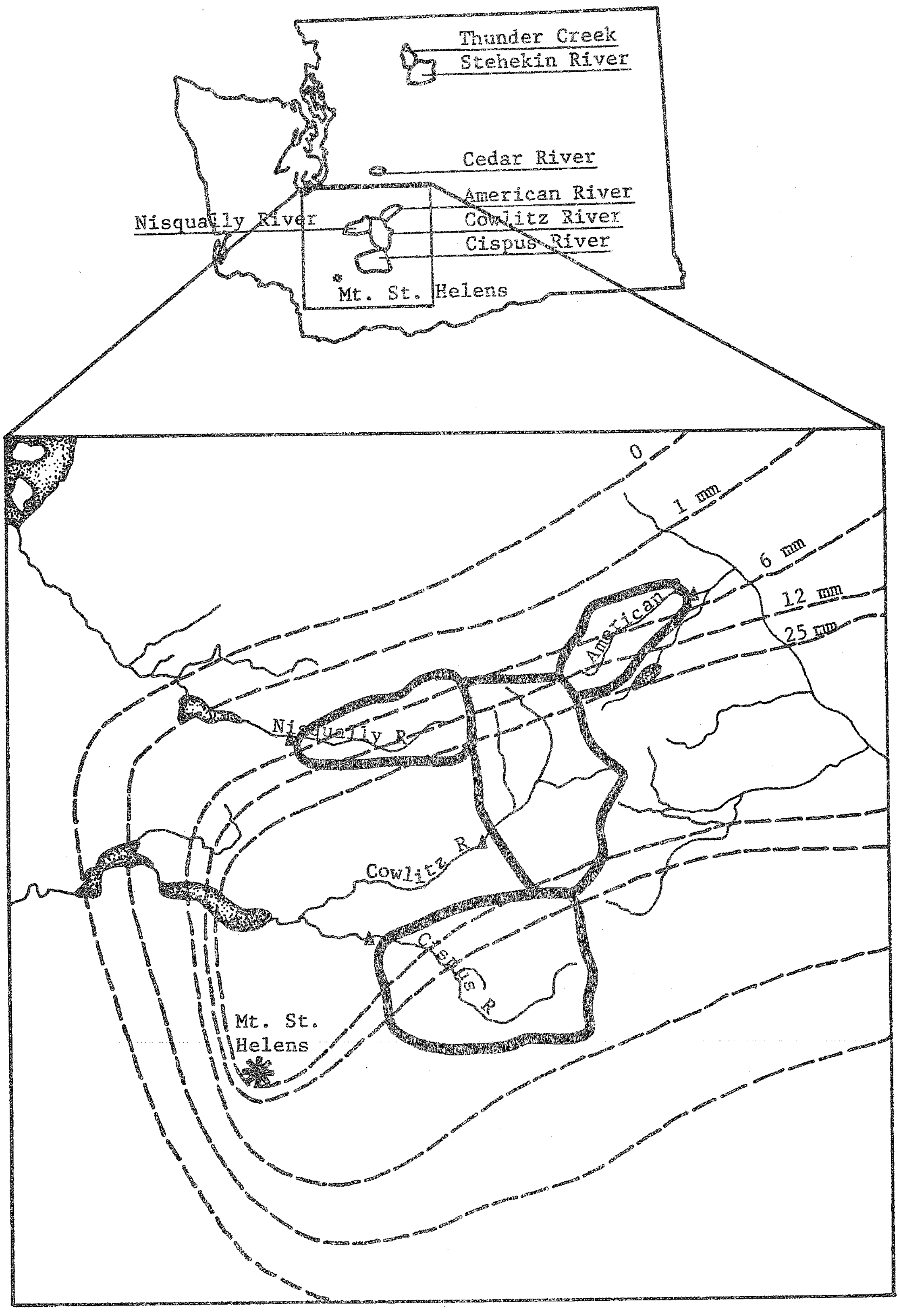

Figure 1. Target and Control Basin locations and ash deposition profiles for May 18 eruption.

distinguish between the aggregate effect of variability of estimates of seasonal runoff patterns for climatically and hydrologically similar basins, and the impacts of the Mt. St. Helens eruption. Alternately, the problem may be approached by attempting to distinguish between year to year variability of seasonal forecast errors, and forecast error related to the eruption.

One method of effecting the analysis which was originally considered was to make use of a rainfall/snowmelt runoff model applied to the basins of interest to facilitate comparison of expected runoff, given historic watershed conditions, with that actually obserbed. However, our experience with such models in basins affected by the eruption (Lettenmaier, et al., 1981) lead us to conclude that model errors, resulting primarily from data limitations, would be large enough to obscure any real changes which might have taken place. We have, therefore, made use of the two alternate approaches noted above:

(a) Paired comparisons of potentially affected basins with climatically and hydrologically similar basins which did not receive significant ash deposits.

(b) Year to year comparisons of seasonal runoff forecasting error for potentially affected basins.

Choice of basins was based on economic importance of the basins, availability of continuous streamflow records, and the amount of ash deposited by the eruptive activity of the mountain. The seven basins considered are shown in Figure 1, along with ash deposition contours estimated by the State of Washington Department of Natural Resources (1981). Although some ash was deposited by small eruptions beginning March 27, 1980 (Figure 2), most ashfall resulted from the major May 18 eruption, and the contours shown are the result of this event.

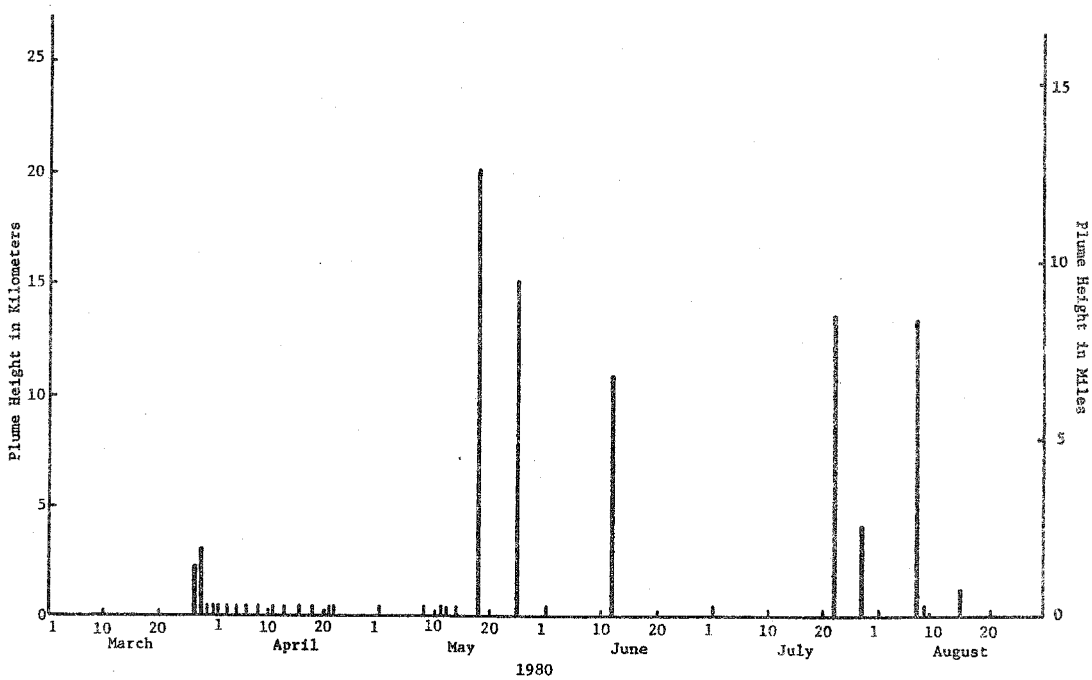

Figure 2. Mt. St. Helens Eruption History, March - August, 1980. (Plume heights not recorded for minor eruptions.)

Three of the basins considered - the Cedar, Thunder Creek, and the Stehekin - are outside the area in which substantial ash deposition occurred. These basins were used as controls, to represent "normal" runoff conditions during the 1980 water year. The remaining four basins (Nisqually, American, Cispus, and Cowlitz) received substantial ashfall and may have experienced altered runoff patterns.

Although the control basins lie 100-200 km from the potentially affected (target) basins, they are within the same climatological regime as the target basins. This is evidenced by the high correlation coefficients between stations for the April 1 - August 31 snowmelt period (Table 1). Also, as shown by the basin characteristics (Table 2) the basins are hydrologically similar as well. Two of the control basins (Thunder Creek and the Stehekin) are high elevation drainages with some glacierized area, while the third (Cedar) is an intermediate elevation basin which receives large amounts of precipitation, much of it as snowfall, but has no glacierized area. Of the target basins, all but one (the American) have some glacierized area, but this area is very small for the Cispus and Cowlitz. Thus, the control stations represent the same range of hydrologies as the test basins.

Table 1. Correlation Matrix for April 1 - August 31 runoff for control and target stations, 1951-79.

		Control Stations			Target Stations			
		Cedar	Thunder Cr.	Stehekin	Nisqually	American	Cowlitz	Cispus
Control Stations	Cedar	1.00						
	Thunder Cr.	.57	1.00					
	Stehekin	.73	.89	1.00				
Target Stations	Nisqually	.90	.72	.76	1.00			
	American	.80	.83	.92	.80	1.00		
	Cowlitz	.91	.78	.88	.93	.91	1.00	
	Cispus	.90	.71	.84	.94	.90	.95	1.00

Table 2. Basin Characteristics[a]

Basin Identifier	Type[b]	U.S.G.S. Gage No.	Drainage Area $Km^2(mi^2)$	Mean Annual Runoff $mm(cfs/mi^2)$	Mean Ann. Precip. mm(inches)	Mean Ann. Snowfall cm(inches)	Average Elev. m(ft)	Avg. Main Channel Slope m/km(ft/mi)	Forested Area %
Cedar R.	C	12-1150	106(41)	2340(6.8)	3050(120)	1120(440)	984(3230)	22(116)	77
Thunder Cr.	C	12-1755	272(105)	2030(5.9)	3280(129)	860(340)	1770(5800)	49(257)	61
Stehekin R.	C	12-4510	871(344)	1410(4.1)	2510(99)	740(290)	1560(5130)	26(137)	83
Nisqually R.	T	12-0825	344(133)	2030(5.9)	2390(94)	850(335)	1220(4020)	36(192)	82
American R.	T	12-4885	205(79)	1070(3.1)	1880(74)	890(350)	1480(4860)	12(64)	91
Cowlitz R.	T	14-2265	743(287)	2000(5.8)	2410(95)	1140(450)	1290(4230)	21(111)	85
Cispus R.	T	14-2325	831(321)	1450(4.2)	2130(84)	760(300)	1260(4130)	16(84)	76

[a] from U.S. Geological Survey Basin Characteristics File

[b] C = Control, T = Target

MULTIPLE BASIN COMPARISONS

The method selected to make the multiple basin comparisons was to compute the long-term mean runoff for a monthly data window for each day within the period March 1 - August 31, 1980 as

$$C_{i\ell} = \frac{1}{N_y \tau} \sum_{j=1}^{N_y} \sum_{k=1-\tau/2}^{i+\tau/2} X_{jk}^{C_\ell} \qquad \ell = 1, \ldots, 3$$

$$T_{im} = \frac{1}{N_y \tau} \sum_{j=1}^{N_y} \sum_{k=i-\tau/2}^{i+\tau/2} X_{jk}^{T_m} \qquad m = 1, \ldots, 4$$

$X_{jk}^{C_\ell}$ and $X_{jk}^{T_m}$ are the raw daily control station (ℓ) and target station (m) runoff for day k in year j; N_y is the number of years (29) in the base period 1951-79, and τ = 30 days.

To investigate short-term runoff differences between stations, we computed five day weighted average flows at both target and control stations for the period March 1 - August 31, 1980 as

$$C_i^* = \sum_{\tau^*=1}^{5} \alpha_{\tau^*} X_{30,\ i+\tau^*-3}^{C_\ell}$$

$$T_i^* = \sum_{\tau^*=1}^{5} \alpha_{\tau^*} X_{30,\ i+\tau^*-3}^{T_m}$$

where $(\alpha_{\tau^*}, \tau^* = 1, \ldots, 5) = (0.10\ 0.23\ 0.34\ 0.23\ 0.10)$. This symmetric weighting scheme yields a five day weighted average flow for March-August 1980 with the largest weight on day i, and lesser weights on the previous and succeeding two days. This is intended to damp out variations in flow which might be attributable to the time of passage of storms between basins and other short term effects not related to ashfall-induced runoff changes.

The normalized flow ratio sequences

$$Q_{i\ell m} = \frac{T_{im}^*/T_{im}}{C_{i\ell}^*/C_{i\ell}}$$

were then computed for $\ell = 1, \ldots, 3$; $m = 1, \ldots, 4$. These sequences represent the ratios of the 1980 5-day weighted average flow to the long-term 30 day average for the target station ℓ normalized by the equivalent ratio for the control station m. For comparison purposes, the mean $\overline{Q_{i\ell m}}$ and standard deviation $S_{i\ell m} = \{\mathrm{Var}(Q_{i\ell m})\}^{1/2}$ were also computed for the 29 year base period 1951-1979. Thus, approximate confidence bounds can be obtained by forming n-standard deviation envelopes about $\overline{Q_{i\ell m}}$; assuming a normal distribution and for n = 1, approximately 68% of all realizations of $Q_{i\ell m}$ should be within this envelope. Thus, it is possible to judge whether excursions of the 1980 values of $Q_{i\ell m}$ are likely to be random or whether they can be attributed to abnormalities in runoff patterns related to ashfall.

Also of interest in comparison of 1980 runoff is the effect of cloud cover on runoff variations. As noted above, altered albedo due to ash cover will have an appreciable effect on melt only on clear days. It has been shown that the monthly average temperature range at selected stations is a good index to cloud cover in the Northwest (Tangborn, 1980). Thus, we computed the weighted average daily temperature range,

$$D_i = \sum_{\tau^*=1}^{5} \alpha_{\tau^*} (T_{max_{i+\tau^*-3}} - T_{min_{i+\tau^*-3}})$$

where T_{max_i} and T_{min_i} are the day i maximum and minimum temperatures at Stampede Pass (NWS 45-8009), a manned National Weather Service observation station at elevation 1130 meters (3700 ft) on the Cascade Crest, in the vicinity of the Cedar River watershed. The normalized temperature ratio was then computed as

$$D_i^* = D_i/\overline{D}_i + 3.0$$

where $\overline{D}_i$ is the mean of D_i over the 29 year period 1951-1979.

Figures 3-6 show $Q_{i\ell m}$ (solid line) as well as $\overline{Q}_{i\ell m}$ (dashed) and the envelope $\overline{Q_{i\ell m} \pm S_{i\ell m}}$ (dotted). Also shown is D_i^* (upper dashed). It should be noted that the numerical range of D_i^* is arbitrary, its significance lies wholly in that high values represent clear conditions while low values represent cloudy conditions, hence minimal incident short wave radiation.

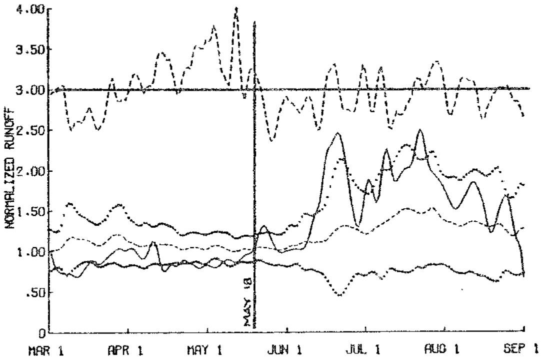

Figure 3(a). Nisqually vs. Cedar

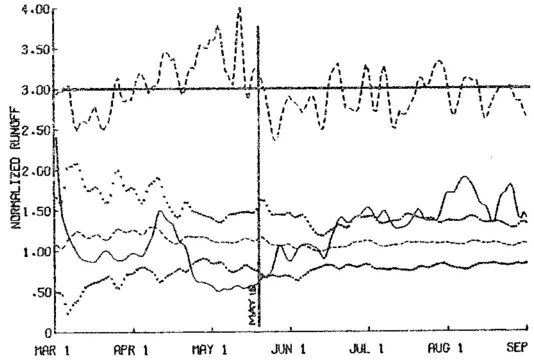

Figure 3(b). Nisqually vs. Stehekin

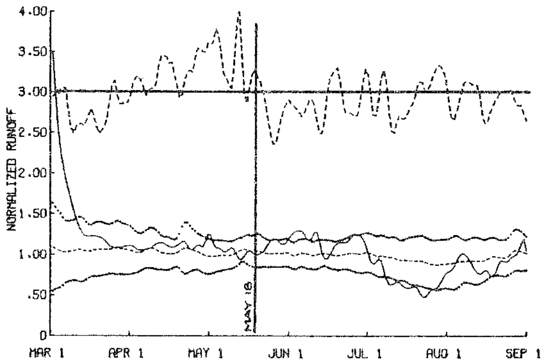

Figure 4(a). American vs. Stehekin

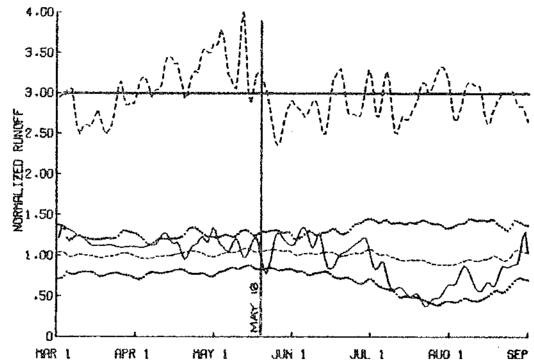

Figure 4(b). American vs. Thunder Cr.

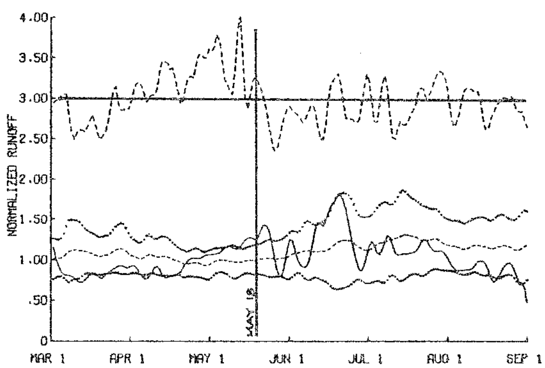

Figure 5(a). Cowlitz vs. Cedar

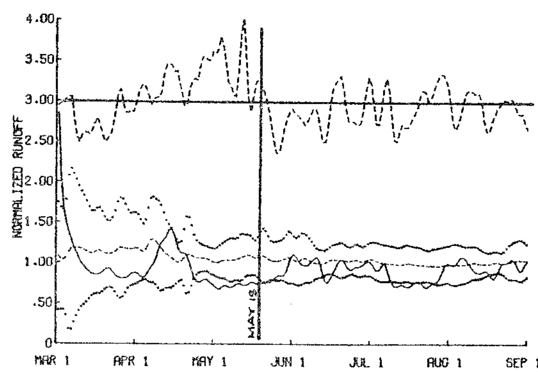

Figure 5(b). Cowlitz vs. Stehekin

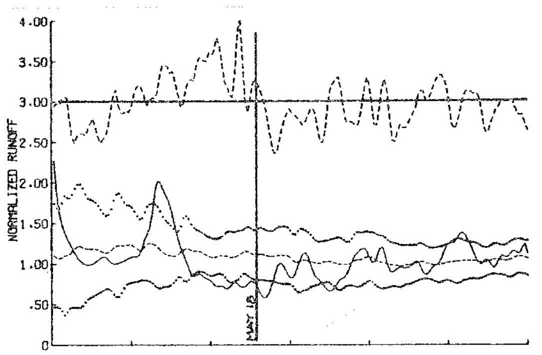

Figure 6(a). Cispus vs. Cedar

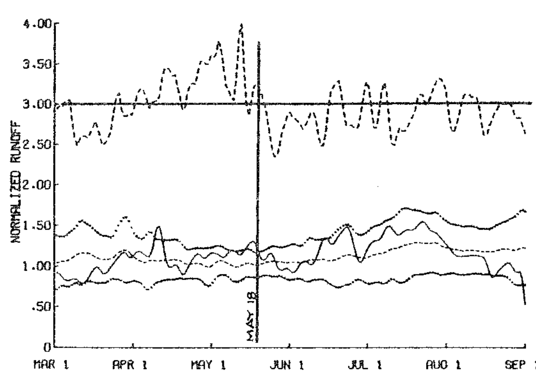

Figure 6(b). Cispus vs. Stehekin

Figures 3-6. Target vs. Control Normalized flow Sequences and Temperature Range, March-August, 1980. Solid line is $Q_{i\ell m}$, dashed line is $\overline{Q}_{i\ell m}$, dotted line is $\overline{Q}_{i\ell m}$ $S_{i\ell m}$. Upper dashed line is normalized five day weighted average temperatur range at Stampede Pass.

Figures 3a-b, which show runoff comparisons for the Nisqually River, give the clearest indication of ash-induced runoff changes. The effect appears primarily as increased runoff during the period June 15-August 15. Runoff peaks are seen to correspond in most cases with temperature range peaks (clear skies) with a lag of several days between the temperature range and runoff peak. This is apparently the result mostly of increased snowmelt. Since the Nisqually is hydrologically similar to the Stehekin River, the indication in Figure 3 of a runoff peak in early April, followed by a period of abnormally low flow from early April through late May appear to be significant. The early April runoff peak appears for the Cowlitz and Cispus Rivers as well in Figures 5 and 6 and may have been the result of ash cover from the March 27 and 28 eruptions which spread a thin ash layer over the area north and east of the mountain. The early April-late May low flow period is, however, somewhat puzzling.

Snowfall records for April and May, 1980 at Stampede Pass indicate a total snow accumulation of about 400 millimeters (16 inches) during the period April 4-10, with additional amounts of 75 millimeters (3 inches) April 14-15, and 75-100 millimeters (3-4 inches) April 19-20, and essentially no snowfall thereafter. The runoff peak in early April may have resulted from accelerated melt of the early April snowfall, and may have been terminated by covering of the ash by the mid month snow. Records of volcanic activity of the mountain indicate that the episodes of small eruptions ended April 22, and that the mountain was relatively quiet through mid-May, which would support this explanation. However, there is no apparent reason why the melt rate should have been abnormally low prior to the May 18 eruption.

Figure 4 indicates some evidence of changed runoff patterns in the American River, taking the form of higher than normal runoff early in the melt season, and lower than normal runoff later. This may have been the result of accelerated melt due to ash effects in May, and lesser runoff later in the spring and early summer as a result of early removal of the snowpack. Runoff changes in this basin are less apparent than for the Nisqually River, possibly due to the lesser importance of high elevation snowfields in this basin.

Figures 5 and 6 indicate no conclusive evidence for runoff changes in the Cowlitz and Cispus Rivers, with the exception of the early April runoff peak noted above. This is somewhat curious, since these two basins are the closest of those investigated to the mountain, and are known to have received large amounts of ashfall (Figure 1). However, much of the snow accumulation in these basins had melted by the time of the first clear weather following the May 18 eruption (mid-June) so snowmelt effects may have been minimal. Some modest indication of altered melt effects may, however, be indicated by correspondence between periods of low cloud cover and small runoff peaks. These results appear to agree with the Geological Survey study (Driedger, 1981) which demonstrate maximum melt rate at an ash depth of about 5 mm and a below normal rate when ash deposition exceeds 25 mm. Therefore, snowmelt in these two drainages may have been reduced following the May 18 eruption due to the insulating effect of the several inches of volcanic ash deposited during this major eruption.

STREAMFLOW FORECASTING TESTS

One of the consequences of abnormal snowmelt due to lower surface albedo would be greater difficulty in forecasting streamflow from those watersheds affected by ash deposition. Greater than expected snowmelt due to increased absorption of solar radiation would tend to produce more water than a model calibrated using historic data would predict, resulting in more positive forecast errors. Therefore, June 1 forecasts for the June-July season were made for the Nisqually, Cispus, Cedar and Thunder basins for the 1960-80 period to test whether the target watersheds (Nisqually and Cispus River basins) would display an unusual forecast error in 1980 relative to the control basins (Cedar River and Thunder Creek). A hydrometeorological forecasting model (HM model) was employed to make this evaluation (Tangborn, 1977). This model is based on an estimate of the basin's total water storage, calculated by the difference between basin precipitation and observed runoff. Basin precipitation is approximated by precipitation observed at National Weather Service Cooperative weather stations. An average of three precipitation stations (Mayfield Dam, Longmire and Snoqualmie Falls) were used for all three basins so that forecast errors caused by the precipitation estimate would be common to all forecasts. A split-sample technique was utilized so that the forecasts were calculated from coefficients developed the previous year. Therefore, the full sample was not influenced by the unusual 1980 conditions.

RESULTS OF FORECASTING TESTS

Figures 7-10 show the results of the forecast analysis presented as plots of forecasted versus observed runoff. ρ and C_v are the correlation coefficient and coefficient of variation, respectively for a linear relationship between forecast and observed runoff. The results show that while there does not appear to be a statistically significant difference in the 1980 forecasts between the affected and unaffected basins, the Nisqually runoff for the June-July season was greater than predicted by the model where the unaffected basins were both less than predicted. The error difference between the average of the two unaffected basins and that of the Nisqually for the June-July season was 144 mm (7.6 inches), averaged over the respective drainages, equal to a mean daily flow of 12.8 m/s (450 cfs) for the Nisqually River. This amount would be equivalent to an increase in ablation of 40%,

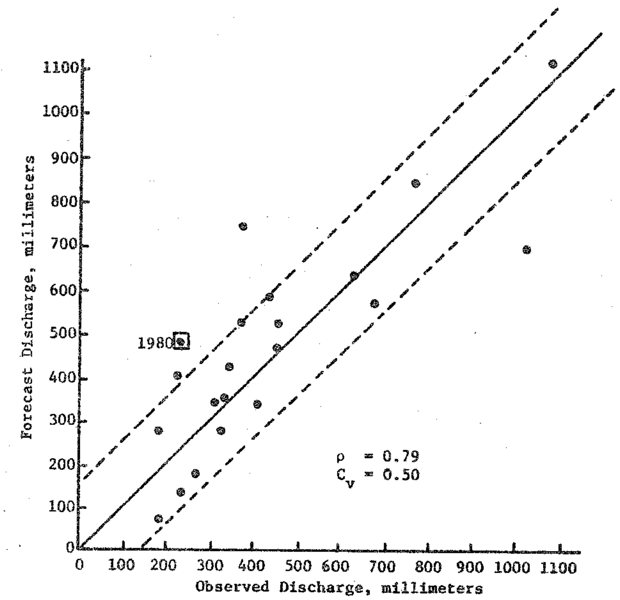

Figure 7. June-July HM model split sample forecast errors 1960-80 for Cedar River.

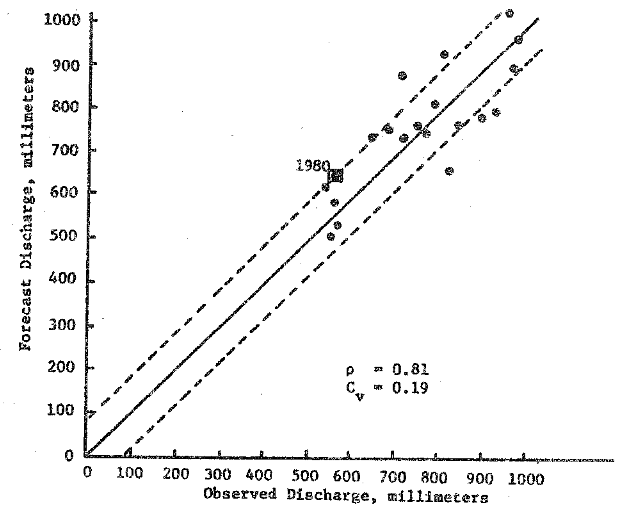

Figure 8. June-July HM model split sample forecast errors 1960-80 for Thunder Creek.

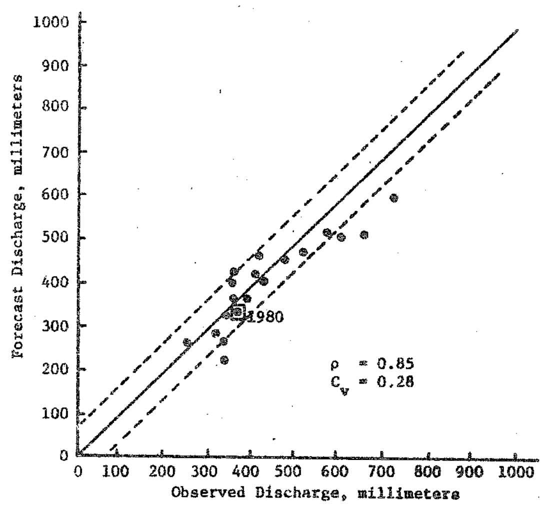

Figure 9. June-July HM model split sample forecast errors 1960-80 for Nisqually River.

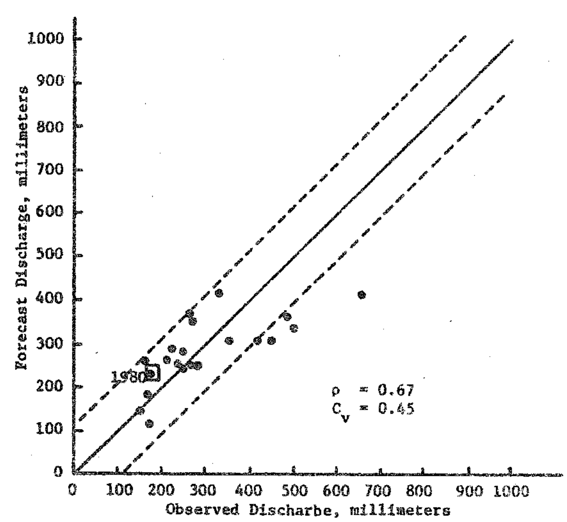

Figure 10. June-July HM model split sample forecast errors 1960-80 for Cispus River.

averaged over the total drainage area, which was estimated to have an approximate snowcover of 25 percent on May 18. The Cispus River 1980 forecast does not show an unexpected increase in observed runoff, possibly due to the insulating effect of the heavy ashfall this drainage received on May 18.

CONCLUSIONS

The eruptions of Mount St. Helens during the spring and early summer of 1980 measurably affected snowmelt in nearby watersheds. Of those tested, the Nisqually River basin demonstrated the greatest hydrologic influence of ash deposition on snow. The effects are less apparent for the American, Cowlitz, and Cispus River basins, most likely because these lower altitude watersheds contained less snow. However, there is also some evidence that the larger deposition of ash in these basins had an insulating effect which retarded melt in the months following the May 18 eruption. Incoming solar radiation strongly influences the effect that a decreased albedo will have on melt rates, and the above average cloudiness in the Pacific Northwest following the May 18 eruption caused the hydrologic effect of ash deposition to be less severe than if clear skies had predominated in the post-eruption period. This is also demonstrated by the apparent increase in runoff for the Nisqually, Cispus, and Cowlitz basins in mid April resulting from modest ashfall associated with early eruptive activity.

Runoff forecasts for the two months following the main eruption did not appear to be strongly influenced by ash deposits in the affected basins, although differences in forecast errors between control and target basins were consistent with the results obtained from the multiple basin comparisons.

Generally, runoff changes were subtle, however this appears to be the result of cloudy conditions following the eruption, and a below average snowpack. Had more normal climatic conditions prevailed, it is likely that much larger changes would have been observed.

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