A Reanalysis of the Skagit Cloud Seeding Project[1]

PETER V. HOBBS AND ARTHUR L. RANGNO

Atmospheric Sciences Department, University of Washington, Seattle 98195

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ABSTRACT

In a previous analysis by Hastay and Gladwell (1969) of the Skagit Cloud Seeding Project, the actual runoffs of the Skagit River during the two seeded years were compared to the runoffs predicted by a principal component (or covariate) analysis technique. It was concluded that seeding from ground generators with silver iodide increased the annual runoff of the Skagit River by at least 15% in the second year of the Skagit Project (the 1964 water year) and that this result was significant at the 0.005 (or higher) level. In this paper it is shown that this conclusion cannot be substantiated due to the inclusion in their analysis of a control river which behaved anomalously during the 1964 water year and on which the statistical significance of Hastay and Gladwell's result rests. Comparisons of the runoff of the Skagit river during the 1964 water year with the runoffs of two similarly situated rivers, with which the Skagit is well correlated historically, show no significant effects due to seeding.

1. Introduction

In the 1960's a two-season, non-randomized, cloud seeding experiment was undertaken in the Skagit River Basin of northwestern Washington under the auspices of the State of Washington's Department of Conservation. The objective of the experiment was to see if the runoff from the Skagit River could be increased by ground-based seeding with silver iodide. In the 1963 water year (October 1962 through September 1963) seeding was carried out during storm conditions with a westerly flow component for approximately ten weeks (31 January 1963 through 10 April 1963). In the 1964 water year (October 1963 through September 1964) the seeding in westerly flows was increased fivefold and began in November 1963 and continued through April 1964. Fig. 1 shows the locations of the Skagit River Basin and the silver iodide generator sites which were operated during the second year of the experiment. The rivers examined in this study are identified in Table 1.

Hastay and Gladwell (1969) analyzed the effects of the seeding in the Skagit River Basin by comparing the annual (water year) runoffs of the Skagit River (gauged at Newhalem) with the runoffs predicted by a principal component (or covariate) regression technique. The covariates were the runoffs of three (control) rivers, two series of July and August precipitation data, and a summer (June through August) temperature index. They concluded that cloud seeding produced no statistically significant effect on the runoff from the Skagit River during the 1963 water year but that in the 1964 water year it increased the runoff of the Skagit River by 15%, which was significant at the 0.005 level.

This paper is concerned with a reanalysis of the Skagit Cloud Seeding Project. It will be shown that the apparent increase in runoff of the Skagit River during the 1964 water year, compared to the control variables used by Hastay and Gladwell, was due to a natural decrease in runoffs in a northwest to southeast direction across western Washington. The apparent anomaly in the runoff of the Skagit River disappears when compared to similarly situated rivers.

Runoff data for this study were compiled from the U. S. Geological Survey publication. *Surface Water Supply of the United States*, Part 12, volume numbers 1316, 1317, 1736, 1932, 1933, 2132, 2133; and U. S.

TABLE 1. Rivers examined in this study.

River	Gauging station	Watershed area (km^2)	USGS gauge number
Skagit	Newhalem	3043	1780
Skagit	Near Concrete	7089	1940
Cascade	Marblemount	435	1825
Sauk	Near Sauk	1849	1895
Baker	Concrete	769	1935
Hoh	Near Forks	655	0412
Elwa	McDonald Bridge	697	0455
North Fork of the Nooksak	Near Glacier	272	2050
South Fork of the Nooksak	Near Wickersham	267	2090
Skykomish	Near Gold Bar	1386	1345
Stehekin	Stehekin	891	4510

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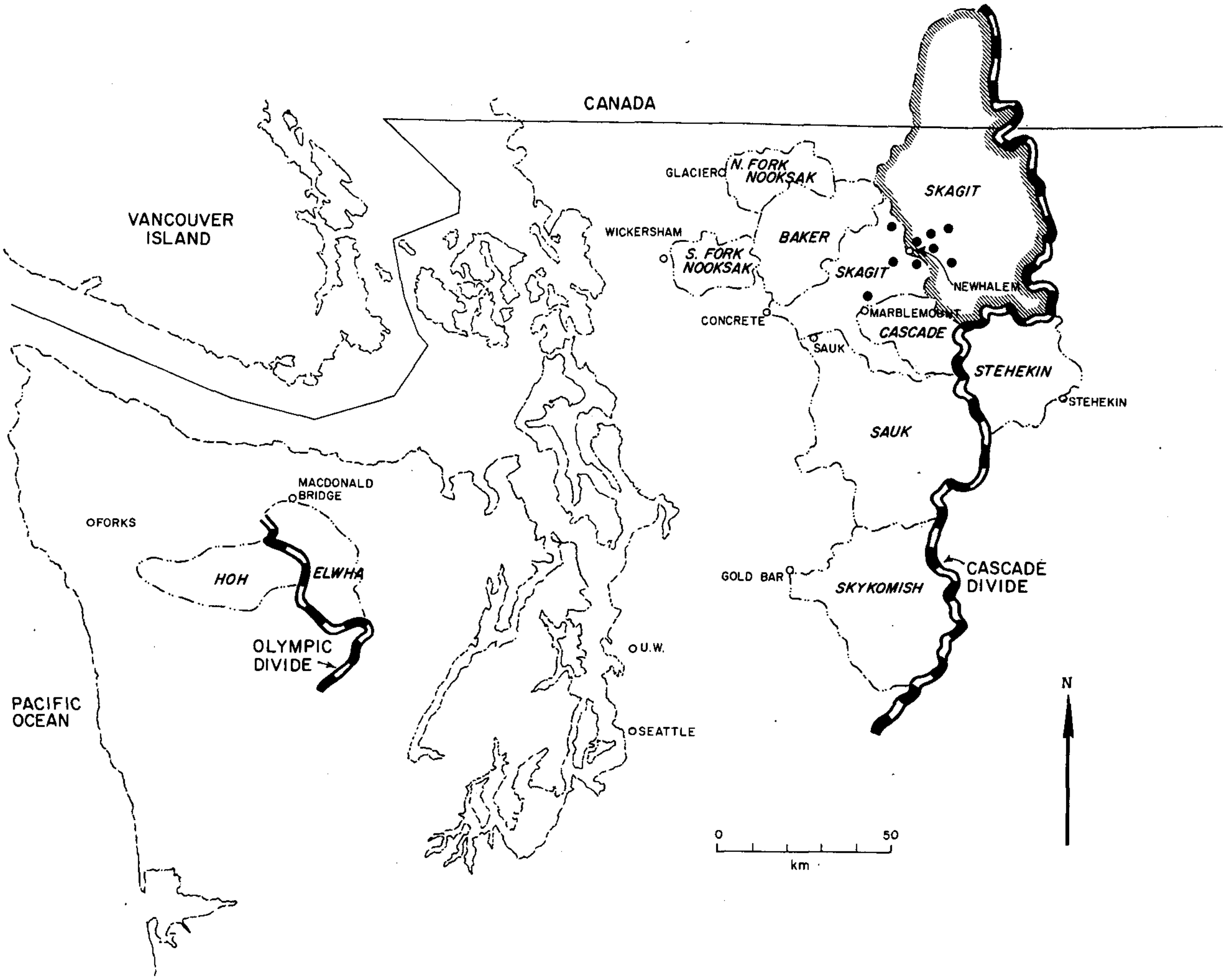

FIG. 1. The location of the target watershed (the Skagit River above Newhalem) for the Skagit Cloud Seeding Project (within hatched area). The silver iodide ground generator sites for the Project are indicated by the closed circles. River basins (large lettering) and gauging stations (small lettering and open circles) referred to in this paper are also shown.

Geological Survey *Water Resources Data Reports* WA71-1 through WA76-1.

2. Reanalysis of the Skagit cloud seeding project

Shown in Fig. 2 is the principal component regression diagram on which Hastay and Gladwell based their conclusions. It can be seen that the runoff of the Skagit River at Newhalem in the 1964 water year was unprecedentedly higher than that predicted by the principal component regression technique.

The possibility that this could have been due to natural causes rather than seeding was suggested by the fact that Hastay and Gladwell reported that the statistical significance of the difference between the actual runoff from the Skagit in 1964 and the runoff predicted by the principal component technique increased from 0.01 to 0.001 if the streamflow measurements at Concrete were used rather than those at Newhalem. The Skagit streamflow measurement at Concrete includes flows from two of the control rivers (the Sauk River gauged near Sauk and the Cascade River gauged at Marblemount) plus a third non-seeded river (the Baker gauged near Concrete). Since only one of the silver iodide generators could have affected the Skagit watershed between Concrete and Newhalem, a reasonable expectation would have been that if the runoff anomaly were due to seeding its statistical significance would have been less at the Concrete gauge than at the Newhalem gauge. Furthermore, Hastay and Gladwell reported that the removal of the three non-seeded rivers which contributed to the runoff of the Skagit River between Concrete and Newhalem did not produce an increase in the statistical significance of the anomaly. In other words, the runoffs from the non-seeded rivers at Concrete contributed as much to increase the statistical significance of the runoff anomaly as did the flow of the Skagit River between Concrete and Newhalem.

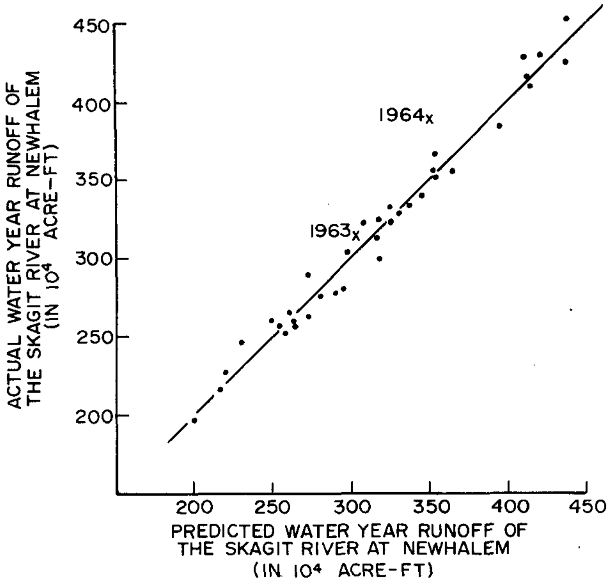

FIG. 2. The actual runoff of the Skagit River at Newhalem compared to the runoff predicted by Hastay and Gladwell's principal component regression technique. Each point represents a water year. The two water years (1963 and 1964) of the Skagit Cloud Seeding Experiment are shown by crosses. The period of evaluation is 1929–66, the same as that used by Hastay and Gladwell.

To understand the origin of the 1964 runoff anomaly shown in Fig. 2, we first compare the runoff of the Skagit River at Newhalem with the runoffs of the three control rivers used as explanatory variables in the principal component regression analysis, namely, the Sauk River (gauged near Sauk), the Cascade River (gauged at Marblemount) and the Stehekin River (gauged at Stehekin). The locations of these watersheds, and others to be discussed in this paper, are shown in Fig. 1. The annual runoffs of the Sauk, Cascade and Stehekin Rivers are highly correlated with the runoff of the Skagit River at Newhalem (Figs. 3–5) with correlation coefficients of 0.97, 0.96 and 0.98, respectively, during the 1929–62 period.

It can be seen from Figs. 3–5 that the runoff of the Skagit River at Newhalem was anomalous only with respect to the runoff of the Stehekin River at Stehekin (more than two standard deviations above the historical

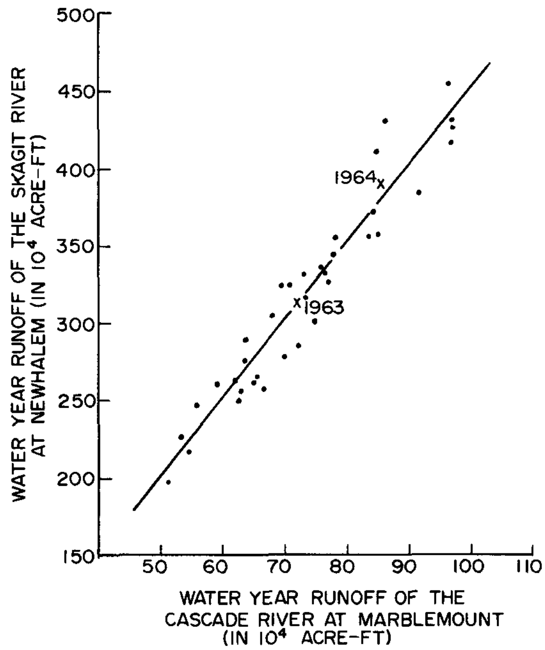

FIG. 4. Regression diagram of the Skagit and Cascade Rivers. The two years in which the Skagit was seeded are indicated by crosses.

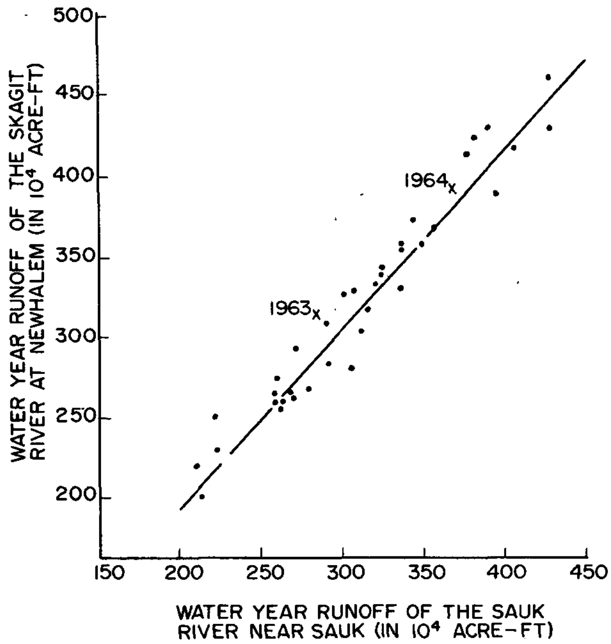

FIG. 3. Regression diagram for the runoffs by water year of the Skagit and Sauk Rivers. The two years in which the Skagit was seeded are indicated by crosses.

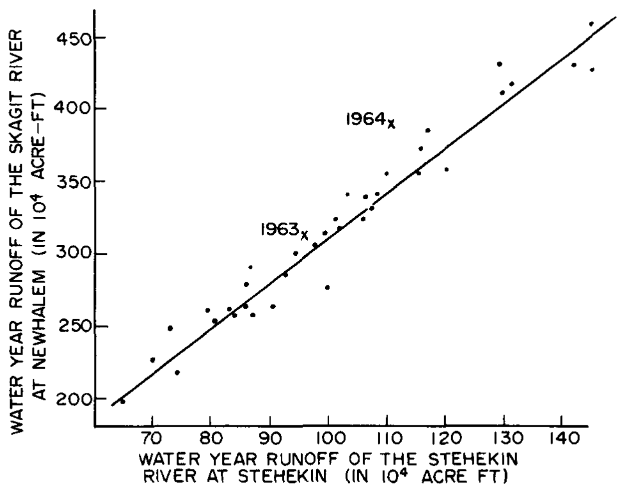

FIG. 5. Regression diagram of the Skagit and Stehekin Rivers. The two years in which the Skagit was seeded are indicated by crosses.

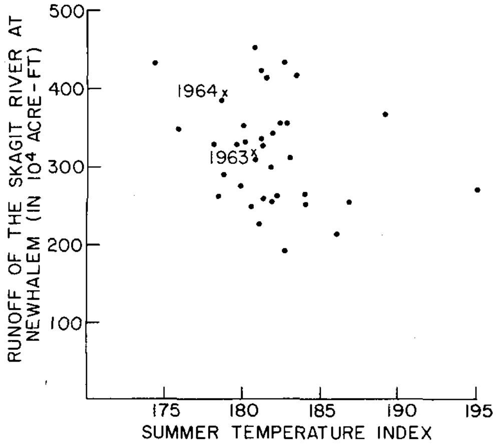

FIG. 6. Regression diagram of one of the six explanatory variables (summer temperature index) used in Hastay and Gladwell's principal component analysis.

regression line). In fact, closer scrutiny of the discrepancies between 1964 runoff of the Skagit River at Newhalem and that predicted by the principal component regression technique (Fig. 2), on the one hand, and that which would have been predicted from the runoff of the Stehekin River at Stehekin (Fig. 5), on the other hand, shows that the two discrepancies are virtually identical. (The correlation between runoff of the Skagit River and that predicted by the principal component analysis technique is 0.99). How is it that a principal component regression technique incorporating numerous explanatory variables had a predictive power almost the same as that based on just one of the variables?

The answer to this question is to be found in the transformation to orthogonal components which is required in principal component analysis in order to eliminate redundant variables. As we have seen in Figs. 3 and 4, the runoffs of the Skagit River at Newhalem in 1963 and 1964 show no appreciable departure from the historical regression with the runoffs of the Sauk and Cascade Rivers. However, this information was subjugated in Hastay and Gladwell's analysis because the runoffs of the Sauk and Cascade Rivers (being historically highly correlated with the runoff of the Stehekin River) were screened out in the transformation to orthogonal components. Thus, virtually all of the predictive power of the principal component analysis technique resided in the historical correlation between the runoff of the Skagit River at Newhalem and the Stehekin River at Stehekin. The introduction of the summer temperature index, for example, provided no useful predictive power for the runoff of the Skagit River (Fig. 6). It should be emphasized that this failing is not peculiar to the principal component regression technique used by Hastay and Gladwell. Any multiple regression technique which incorporated the Stehekin River as a predictor would no doubt have yielded similar results to those obtained by Hastay and Gladwell.

Since Hastay and Gladwell's conclusion concerning the effects of seeding is, in effect, based on the 1964 anomaly between the runoffs of the Skagit and Stehekin rivers (the Stehekin being the control), we will now consider this anomaly in more detail to see if it might have been due to natural causes.

Shown in Fig. 7 is a regression diagram for the total runoff from five non-seeded rivers (the North Fork of the Nooksak below Glacier, the South Fork of the Nooksak near Wickersham, the Baker River at Concrete, the Sauk River near Sauk, and the Cascade River at Marblemount), which drain to the west of the Cascade crest (as does the Skagit River) and the runoff from the non-seeded Stehekin River which drains to the east of the Cascade crest (see Fig. 1 for locations and Table 1 for details on the rivers). It can be seen that, compared to the westerly flowing rivers, the easterly flowing Stehekin River had a relatively low runoff in 1964. A similar effect is seen in Fig. 8 which shows the runoff of the Hoh River, which drains down the western slopes of the Olympic Mountains, against the runoff from the Elwha River which drains down the eastern slopes of the Olympics (Fig. 1); again it can be seen that in 1964 the runoff from the easterly flowing river was relatively low compared to the westerly flowing river. Clearly in the 1964 water year there was an anomalous gradient in the runoffs of the rivers in western Washington, with rivers, such as the

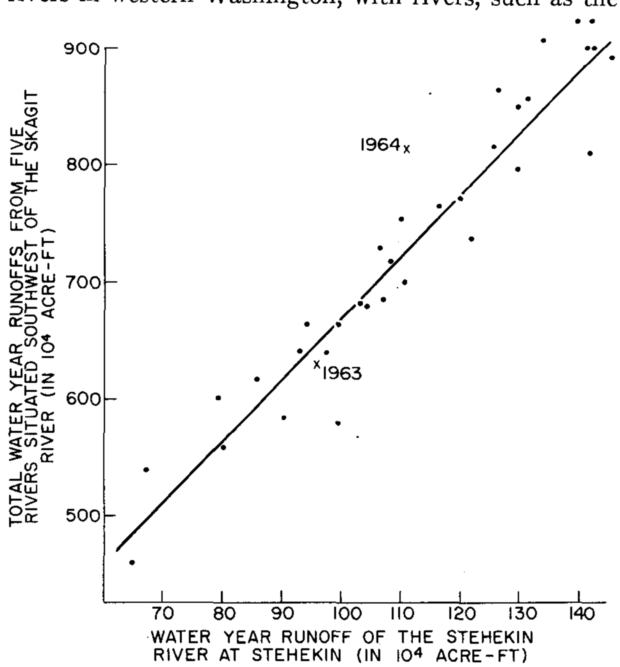

FIG. 7. Regression diagram for the total runoff by water year from five non-seeded rivers which drain down the western slopes of the Cascade Mountains and the runoff of the Stehekin River which drains down the eastern slope of the Cascades. The data period begins with 1944 (the earliest year available) and extends through 1976.

Stehekin, which drain to the east of the large mountain ranges carrying less water than would have been predicted from their historical correlations with rivers, such as the Skagit, which drain to the west of the mountain ranges.

Since the Stehekin watershed lies considerably south as well as east (relative to the crest of the Cascades) of the Skagit, the possibility of an anomalous north-to-south gradient in runoffs in 1964 was also investigated. That this was indeed the case can be seen from Fig. 9, which shows the runoffs from two westerly flowing rivers in the Cascades, namely, the Skykomish River gauged at Gold Bar and the total runoff from the North and South Forks of the Nooksak River [which lie 130 km to the north of the Skykomish (see Fig. 1)]. Again it can be seen that the 1964 water year was anomalous, in that the runoff from the Skykomish (the more southerly river) was less than that which would have been predicted from its historical correlation with the more northerly Nooksak Rivers.

We conclude from these observations that the 1964 water year was quite anomalous with respect to the runoffs of rivers in western Washington in that there was an unusually large gradient in runoffs from the northwest to the southeast, with rivers to the northwest having relatively higher runoffs than usual. This gradient caused the runoff from the Skagit River in 1964 to be greater than that which would have been predicted based on its historical correlation with the runoff from the more southeasterly Stehekin River. In the principal component regression analysis used by Hastay and Gladwell this anomaly was inadvertently interpreted as an increase in the runoff of the Skagit due to cloud seeding. The fact that the runoff of the Skagit was not appreciably affected by the cloud seeding can be seen by comparing its runoff with the Nooksak Rivers, the Baker, the Cascade and the Sauk Rivers which are all situated to the west of the Cascade Divide (Figs. 3, 4 and 7). As mentioned previously, a quirk of the principal component analysis technique resulted in the effective elimination of the runoffs of the Sauk and the Cascade Rivers in evaluating the runoff from the Skagit River.

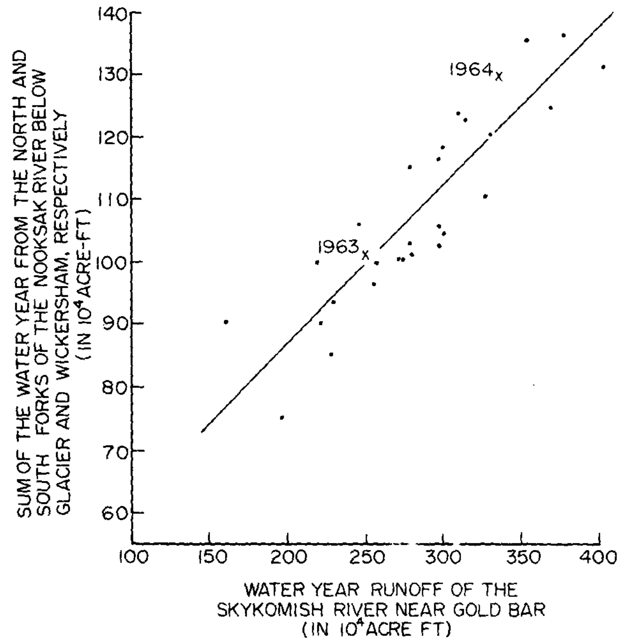

FIG. 9. Regression diagram for the runoff of the Skykomish River and the total runoff from the North and South Forks of the Nooksak River. The data base is 1938 through 1966.

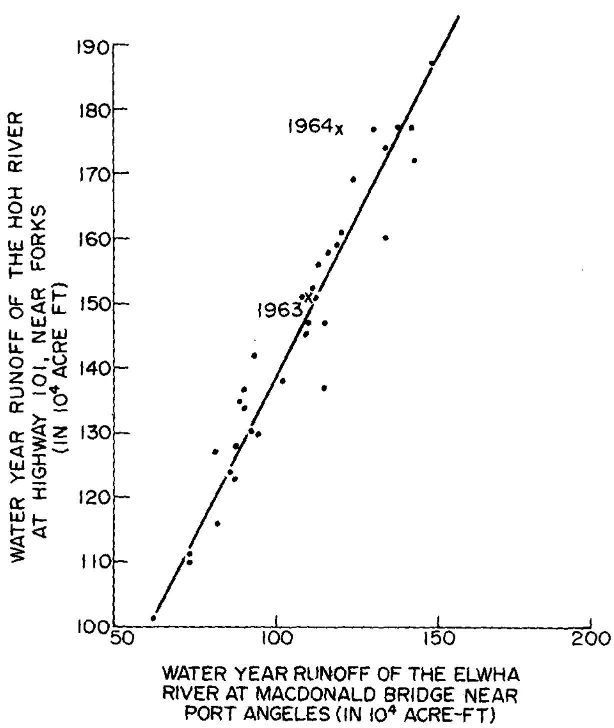

FIG. 8. Regression diagram for the runoff from the Hoh River (which drains down the western slopes of the Olympic Mountains) and the runoff of the Elwha River (which drains down the eastern slopes of the Olympics). The data base is 1929 through 1964. In 1965 the gauge on the Hoh River was discontinued.

3. Summary and conclusions

This study [and a companion one of the Wolf Creek Pass Cloud Seeding Experiment by Rangno (1978)] has revealed the dangers of accepting the results of analyses of cloud seeding experiments in which anomalous effects are automatically attributed to cloud seeding. In the case of the Skagit Cloud Seeding Project, we have shown that Hastay and Gladwell's conclusion that cloud seeding produced at least a 15% increase in the runoff of the Skagit River in the 1964 water year was due almost entirely to the anomalously high runoff of the Skagit River relative to the Stehekin River. However, we have shown that this anomaly was due to a widespread (natural) anomaly in the 1964 water year in which there was an unusually steep northwest to southeast gradient in the runoffs from all rivers in western Washington.

Despite the earlier erroneous conclusions arrived at the Skagit Cloud Seeding Project, the technique of comparing the annual runoff from a target watershed in a cloud seeding experiment with the runoffs from control watersheds with which the target is historically highly correlated is a potentially powerful and efficient means of evaluating cloud seeding effects. The lesson to be learned from the present study is that great care must be taken to allow for any natural anomalies in the meteorology and/or hydrology which might be present during the period of the experiment.

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REFERENCES

Hastay, M., and J. S. Gladwell, 1969: Statistical evaluations of a cloud-seeding program at the streamflow control level. *J. Hydrol.*, **9**, 117–135.

Rangno, A., 1978: A reanalysis of the Wolf Creek Pass cloud seeding experiment. (Submitted for publication to *J. Appl. Meteor.*)