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Cloud Seeding Operations in the Bishop Creek, California Watershed

by
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CALIFORNIA ELECTRIC POWER COMPANY

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CLOUD SEEDING OPERATIONS IN THE BISHOP CREEK, CALIF., WATERSHED

FERGUSON HALL, T. J. HENDERSON, AND STUART A. CUNDIFF

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ABSTRACT

Cloud seeding operations using dry ice dispensed from aircraft have been carried out by the California Electric Power Co. in the High Sierra near Bishop, Calif., since February 1948. Limited visual observations suggest that snow showers can be produced from non-precipitating orographic clouds by seeding, the snow reaching the ground at the higher elevations. Comparison of the annual runoff from the seeded watershed with that from adjacent areas for the 3 years 1948, 1949, and 1950 showed a positive departure in the 1948–49 season significant at the 1 percent level. Significant departures did not appear during the other two years, but the average for the 3 years was significant at the 5 percent level. From the same analysis it might be estimated that the average annual flow during the 3-year period was augmented by 9 percent, with 90 percent confidence limits being zero and 18 percent. On the other hand the unusual circulation prevailing during the 1948–49 winter may have been responsible, at least in part, for the departure in flow during this season. Snow pack comparison did not indicate a significant increase in the Bishop area, but it is shown that such a result is not incompatible with the possiblity that additional precipitation was produced which was not reflected in the snow surveys.

I. INTRODUCTION

In February of 1948 the California Electric Power Co. began a series of tests to determine the extent to which the snow pack over its Bishop Creek, Calif., watershed could be increased by cloud seeding techniques. Operations have continued, and an estimate can be made of the results obtained during 1948, 1949, and 1950.

At the invitation of the power company a representative of the U. S. Weather Bureau visited the site of the operations in the spring of 1950, and began an independent analysis of results. The company had previously made a preliminary estimate that the runoff from Bishop Creek had been increased from 10 to 14 percent during the first 2 years of the operation. This report summarizes the methods of operation and analysis of the results, and combines the findings of both the company and the Weather Bureau.

The power company owns and operates four hydroelectric systems on the eastern slopes of the Sierra Nevada along the upper Owens Valley and Mono Basin in California. These systems draw their water supply from four different watersheds along the slope, with Bishop Creek to the south, and Rush, Leevining, and Mill Creeks to the north. Several other watersheds are located between Bishop and Rush Creeks, the most important being Rock Creek, immediately to the north of Bishop, and Owens River, which derives its initial flow from an area between Rock and Rush Creeks. To the south, Big Pine Creek and its watershed immediately adjoin Bishop, but there are no other important streams in this direction.

The eastern face of the Sierra Nevada is very precipitous, falling from the ridge line of around 12,000 feet to the valley floor at 4,000 feet in a distance of 5 to 15 miles. The flow of the streams is quite light on the average, and the hydro plants are designed to operate on a high head and small volume, some of the plants having a head in excess of 1,600 feet. On Bishop Creek there are 5 plants operating between 8,200 feet and 4,500 feet.

A map of the area is shown in figure 1. It will be observed that the Bishop watershed (outlined)

FIGURE 1.—Map of Bishop Creek, Calif., and surrounding area. The heavy dots outline the Bishop watershed.

is approximately 15 miles long, north and south, and 5 to 10 miles wide. Most of the area is above 8,000 feet, with the major boundaries at around 12,000 feet. Figure 2 shows an aerial view of the watershed.

During most of the year (autumn, winter, and spring) this portion of the Sierra is subject to the passage of frontal systems associated with middle-latitude cyclones which move in over the west coast from the ocean. With the approach of these storms the increased circulation produces over the mountains orographic clouds which,

PHOTOGRAPH BY ROBERT SYMONS

FIGURE 2.—Aerial photograph of Bishop Creek watershed. View is to the southwest. South Lake is visible to the left of center, and Lake Sabrina to the right.

when the wind has a westerly component (the usual case), build up on the western slopes, reach maximum development at the crest, and rapidly dissipate over the eastern slopes. As the storms move closer upper and middle clouds appear in the usual sequence and usually merge with the orographic clouds. Following the storm passage the upper clouds soon disappear, but the orographic clouds may persist for a day or so. Before and after the main storm passage the bases of the clouds lie close to the mountain tops (12,000 to 14,000 ft.) and cloud tops range from 17,000 to 30,000 feet. Often during these periods the tops present a quite regular appearance and little turbulence is normally encountered. As the storms grow to maximum intensity the clouds usually lose this regular appearance and give evidence of considerable convective activity.

Although considerable precipitation falls from the cloud systems during actual storm passages, little or none may fall from the orographic clouds preceding and following the main storm passage. If precipitation does occur it is often limited to the highest elevations, is quite light, and consists of fine crystals. Such clouds are observed to contain considerable supercooled water and often give no evidence of the presence of ice crystals in the upper portions.

The purpose of the operations described here was to test the hypothesis that the amount of precipitation from these orographic clouds could be increased by providing additional ice particles

artifically through cloud seeding. No attempt was made to seed the clouds during the height of storm passages, under the assumption that natural nucleation was sufficient, and to avoid possible reduction in snow due to overseeding.

Dry ice (solid carbon dioxide) was used almost exclusively in the tests, although on a few occasions silver iodide smoke was dispensed from an aircraft generator. The dry ice was ground into pieces ranging in size from rice grains for clouds 4,000 feet thick to the size of a man's thumb for the thickest clouds. It was dispensed manually from a hole in the floor of a P–38 aircraft at a rate of about 1 or 1.5 pounds per mile. This rate was chosen after earlier tests indicated that greater amounts produced rapid dissipation of the clouds.

On each seeding occasion thickness and temperature distribution of the clouds were determined during climb to altitude. Short flights through the clouds permitted a rough observation of icing intensity, from which the presence of supercooled droplets could be ascertained and a general idea of the moisture content of the clouds obtained. Next a small seeding run was made on the edge of the cloud to determine the reaction of the cloud, and estimates of wind direction and speed were obtained. The seeding runs were usually made at right angles to the wind and at a sufficient distance upwind to allow 5 to 10 minutes for the seeded clouds to drift over the watershed. The seeding was done just above the cloud tops, and the scattering of the dry ice behind the plane produced a seeded path about 600 feet wide on the cloud tops. A radio station was installed in the Weather Bureau Office at the Bishop Airport, and the official in charge maintained communication with the pilot during flights. A magnetic recording was made of radio and intercom communications.

Localization of the seeding was attempted throughout the experiments, in order that the adjacent streams and areas could be used as statistical controls on the tests. In approximately 6 cases during the project, however, seeding was probably inadvertently carried out over the adjacent areas to the north. Since this number is relatively small compared to the total number of seedings during the 3 years, it is not thought that the effects would seriously affect the evaluation.

Operations were conducted only during the autumn, winter, and spring, except for some silver iodide seeding in July and August 1950. The dates on which seeding flights were made are as follows:

1948

February 2, 3, 4, 5, 10, 17, 28
March 27
April 2, 6, 9, 13, 15, 21, 28, 29
May 9, 11, 12, 13, 14, 15, 18, 19, 29
June 5, 7
October 11, 13
November (none)
December 3, 5, 7, 16

1949

January (none)
February 3, 6, 9, 10, 11, 20, 24, 25
March 1, 2, 3, 22, 28, 30
April 7, 15, 18
May 9, 14, 15 16, 18, 19
November 9
December 7, 8, 15, 17, 18

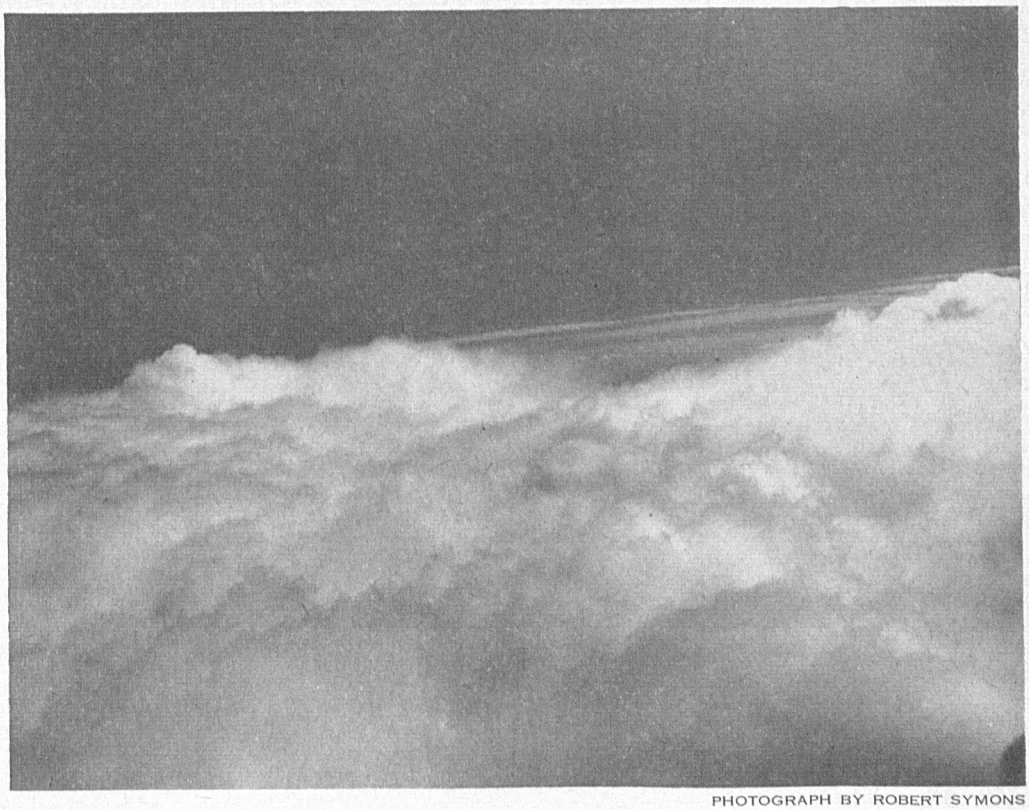
1950

January 2, 11, 16, 24, 28
February 10
March 5, 8, 17, 22, 23
April 7
May 2, 27
June (none)
July 24*, 25*, 26*, 27*
August 2*

* Silver iodide seeding.

II. VISUAL EFFECTS OF SEEDING

When dry ice is dropped from an airplane onto the tops of stable supercooled clouds, the transition of the seeded portion of the cloud from one of water drops to one of ice crystals can usually be observed visually. Subsequently, the seeded portion of the cloud may bulge upward slightly, and in other cases dissipation occurs, sometimes leaving a hole through which the ground is visible. The effect spreads laterally to some extent in the course of time. Under the conditions of the present experiments the seeded portions of the clouds quickly took on a fuzzy appearance, and bulging of the tops often occurred very soon after the seeding. In some cases the bulging was quite



PHOTOGRAPH BY ROBERT SYMONS

FIGURE 3.—View of cloud tops following seeding run. Fuzziness in texture and build-up of tops can be observed.

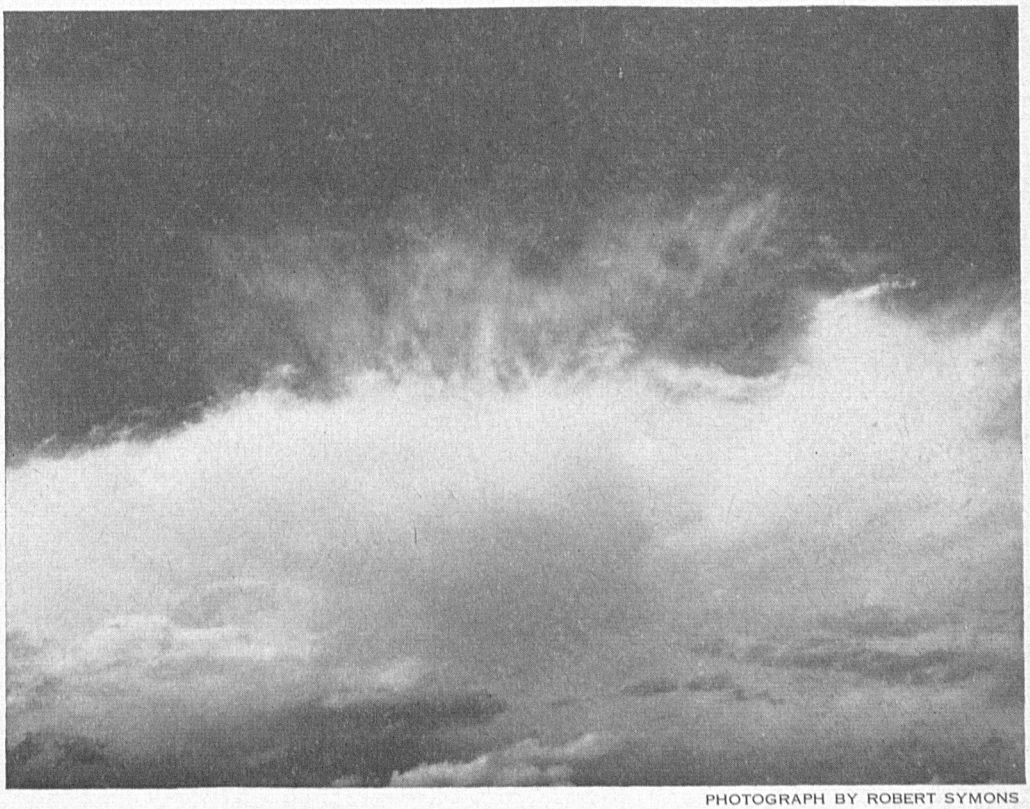


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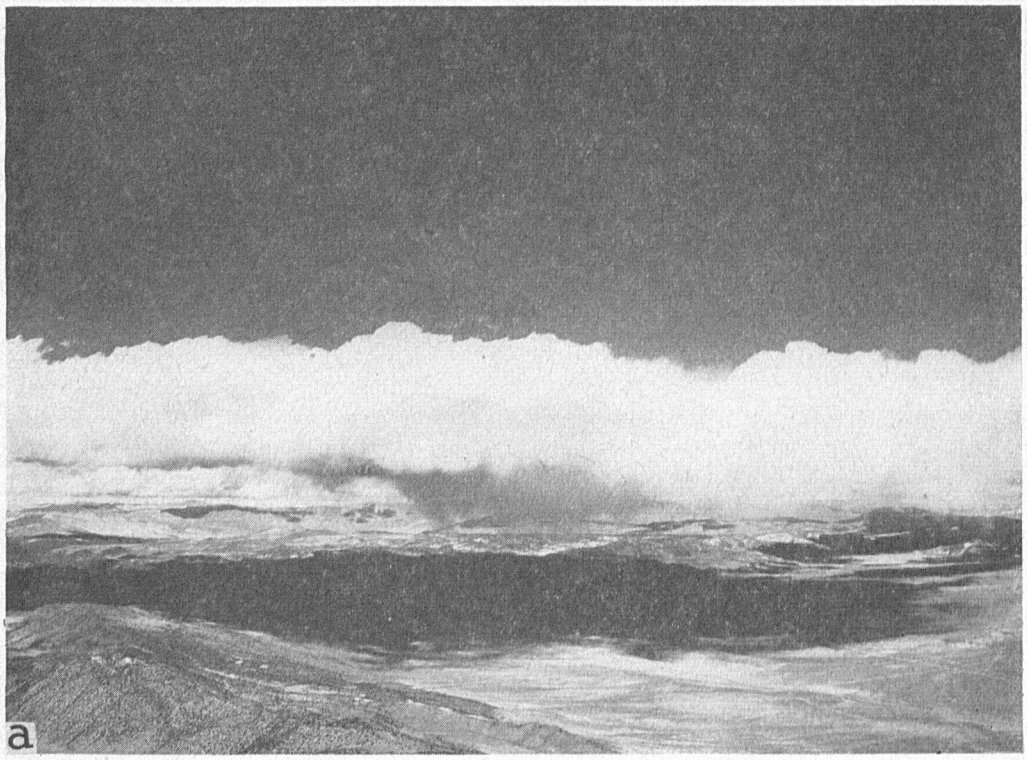
FIGURE 4.—Intense build-up of cloud top following seeding. Appearance indicates considerable instability believed caused by release of latent heat of fusion by seeding.



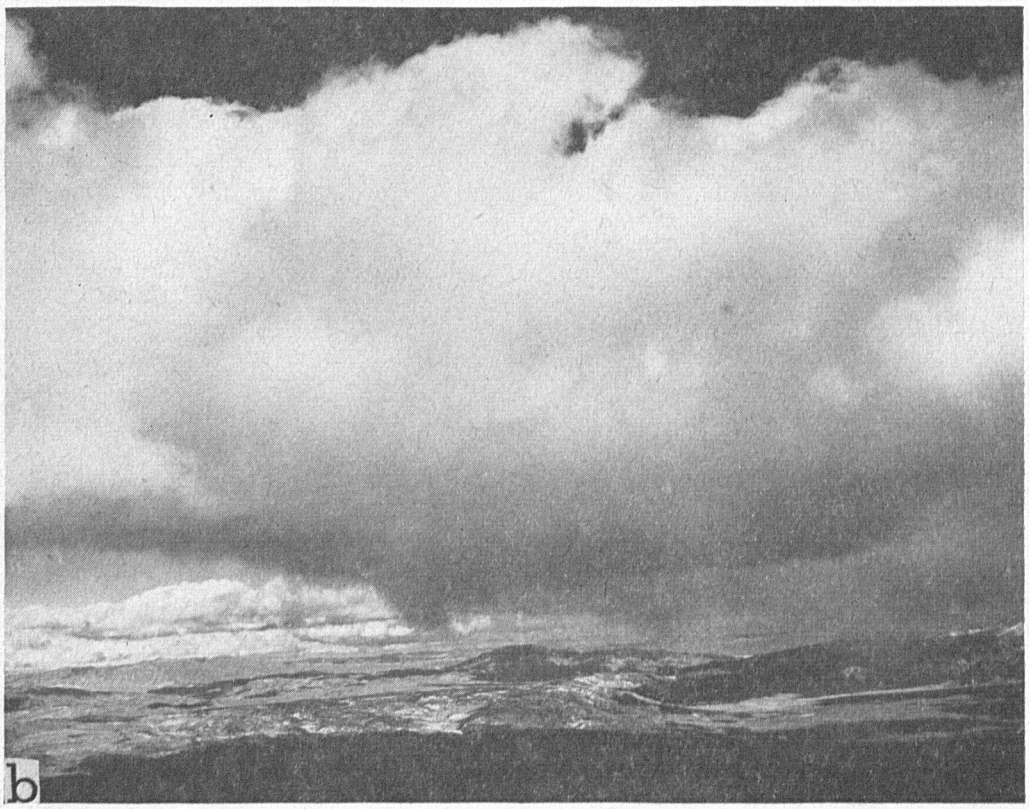


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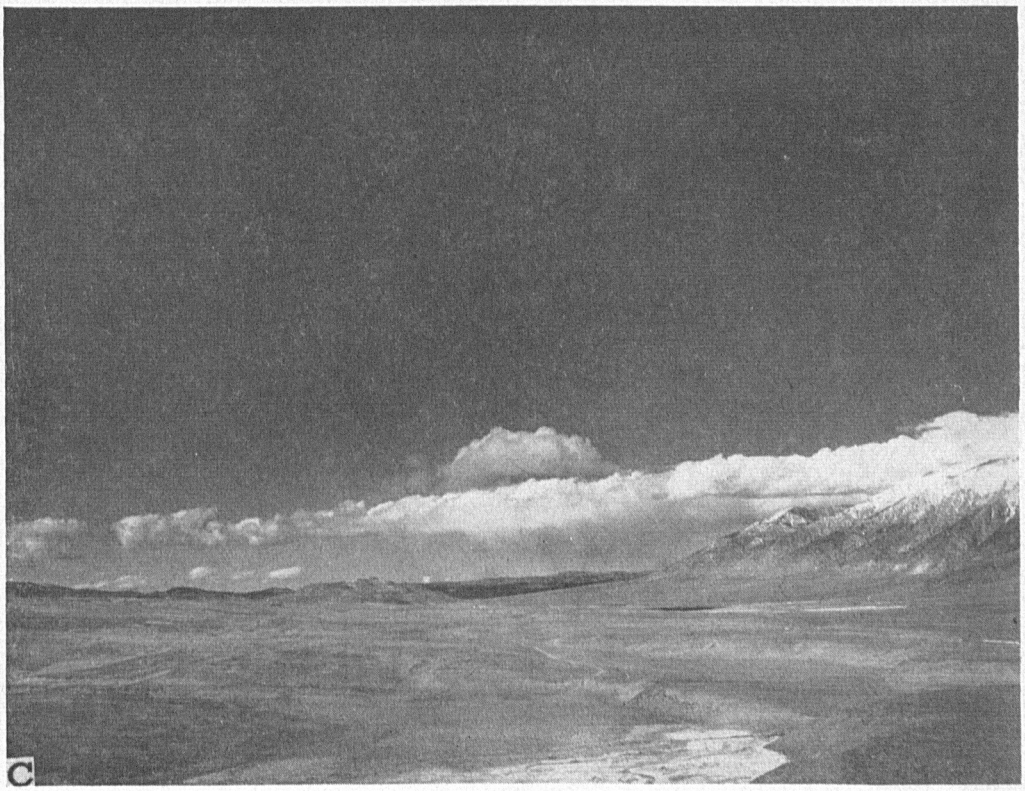
FIGURE 5.—Effect of seeding clouds over the lower Mono Basin (about 40 miles northwest of Bishop). Three examples are shown.



PHOTOGRAPH BY ROBERT SYMONS

FIGURE 5.—Continued

limited, but in others the cloud became somewhat unstable, and expanded vertically for thousands of feet. An example of fuzziness and light bulging is shown in figure 3. Figure 4 illustrates a rather large-scale release of instability. Partial dissipation of the clouds in the immediate vicinity of the seeding is also noted at a later stage in many cases.

The changes occurring in the cloud tops are not sufficient to establish that precipitation falls from the seeded cloud or reaches the ground, or is in excess of that which would have fallen naturally. Numerous tests by the Weather Bureau and Air Force [1, 2, 3] disclosed that changes in the appearance of the tops or upper portions of clouds were often not associated with precipitation from the bases. This was found to be true in various parts of the country including the Donner Pass area of the Sierra, where 15 tests were made in 1949. Consequently, little weight can be attached to observations of cloud tops as a measure of additional precipitation reaching the ground.

Observations of the bases of seeded clouds are difficult in the Bishop watershed, because of the hazard of flying near the mountains in cloudy and precipitating conditions and because the view from the valley floor is usually obscured by intervening hills and clouds. In a few cases, however, such observations have seemed to indicate an increase in precipitation or a shower apparently falling from the seeded portions of the clouds. On a few occasions the superintendent of the company has observed the seeding operations from high elevations in the watershed. Shortly after the seeding he has observed that the precipitation changed from fine ice crystals to thick wet flakes which fell for a half hour or so and produced an inch or more of snow. Subsequently the precipitation stopped, and there appeared to be a pronounced depression in the clouds over the area which seemed to persist for some time.

In a few cases cloud seeding tests have been made over the valley where the view is unobstructed. Figure 5 shows examples of the effects of such operations. In other cases, however, no effects were observable. It appears from the photographs that most if not all of the precipitation was evaporating before reaching the surface (here about 8,000 to 9,000 ft.), and would thus

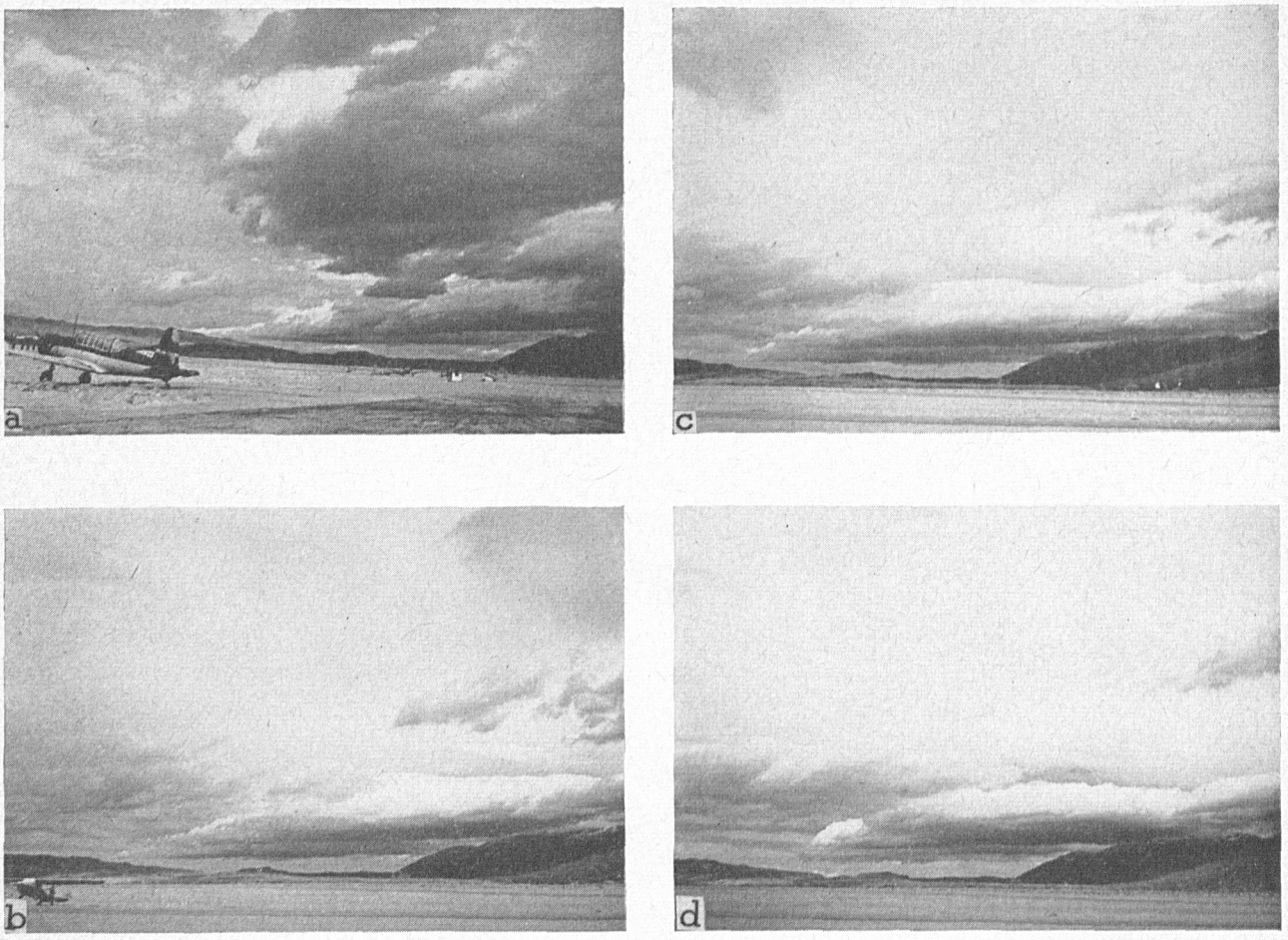


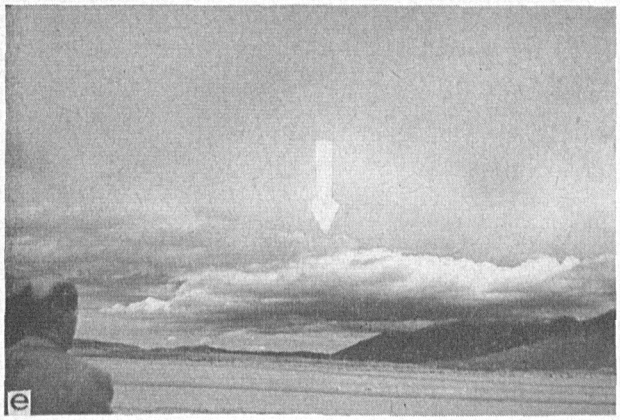
FIGURE 6.—Series of photographs of cloud seeding operation on March 17, 1950. View is to the north and cloud mass has formed over the White Mountains.

(*a*) Forty minutes prior to seeding.
(*b*) Thirty minutes prior to seeding.
(*c*) Twenty minutes prior to seeding.
(*d*) Ten minutes prior to seeding.

be classed as "virga." If such precipitation fell on the higher elevations, however, a substantial portion would have reached the surface before evaporating.

Figure 6 shows a series of photographs of a seeding operation conducted as a visual test on March 17, 1950. The view is to the north from Bishop Airport, and the clouds have built up against the White Mountains on the eastern side of Owens Valley. The valley floor is at 4,000 feet and the mountains average 12,000 feet. A storm had passed earlier in the day, and the clouds are typical of post-frontal conditions. Cloud bases were at 12,000 feet with a temperature of 0° C., and tops at 16,500 feet with a temperature of −9° C. It will be noted that prior to and at the time of seeding (figs. 6 (*a*) to 6 (*e*)) there appeared to be no appreciable precipitation falling from the cloud system, while in figure 6 (*f*), 10 minutes after seeding, a rather heavy snow shower can be observed. Winds at cloud level were from the west at approximately 30 m. p. h., and taking into account the drift of the cloud in 10 minutes, it would appear that the snow is falling from the seeded portion of the cloud. Figure 6 (*g*) shows considerable dissipation of the cloud and a reduction in intensity of the shower.

A similar series of photographs is shown in figure 7. The occasion was March 22, 1950, and weather conditions were comparable with those of the preceding example, a cold front having passed about an hour earlier. As indicated, seeding occurred between the times of figures 7 (*a*) and 7 (*b*) in a run from east to west, but little if any effect that could be ascribed solely to the seeding was apparent, although the appearance of a new



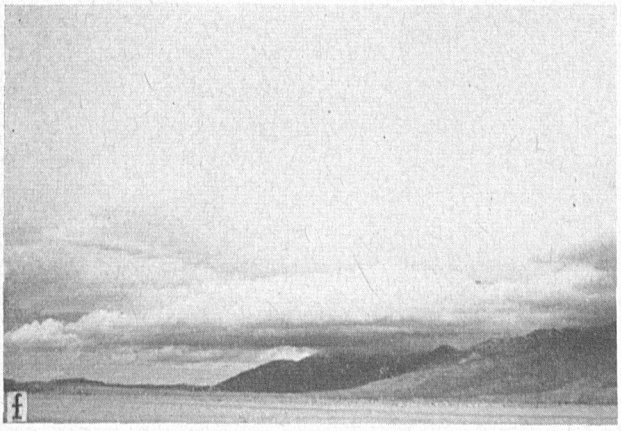


FIGURE 6.—Continued

(*e*) *Time of seeding operation.* Dry ice was dropped into cloud top approximately as indicated by arrow.
(*f*) Ten minutes after seeding. Snow shower from seeded portion of cloud is visible on mountains.
(*g*) *Twenty minutes after seeding.* Seeded portion of cloud is drifting across White Mountains. Snow is still falling but seeded portion appears to be dissipating.
(*h*) Thirty minutes after seeding. Entire cloud system is breaking up due to movement of frontal system to the east.

cloud buildup in figure 7 (*c*) might be attributed to the operation.

Figure 8 shows a series of photographs of a seeding operation over the crest of the Sierra on March 17, 1950, the same day as the test of figure 6, and about a half hour later. Conditions over the mountains an hour before seeding are illustrated in figure 8 (*a*), and indicate the difficulty of observations directly into the mountains. The view is toward the west with Mount Tom to the right. Seeding was carried out at the time of figure 8 (*b*) over Piute Pass, indicated by the arrow. In figures 8 (*c*) and 8 (*d*) a darker cloud mass appears in the vicinity of the seeding operation, but it is difficult to ascribe it to the seeding.

A similar operation on March 22, 1950, the same day as the tests of figure 7, is illustrated in figure 9. Again low clouds obscure conditions within the watershed. Considerable instability is apparent on this occasion, making cloud characteristics irregular, and preventing the detection of any singular effects from the seeding.

In summary, visual observations of the effects of seeding on the tops and upper portions of the clouds, although of interest, do not afford a satisfactory means of estimating artificially produced precipitation reaching the ground, because of the imperfect correlation between cloud top effects and precipitation effects. Observations of seeded clouds from below or at the side indicate, from the few observations available, that showers can often be produced by cloud seeding, and it is probable that at the higher elevations much of such precipitation reaches the ground before evaporating. In many cases, however, it is

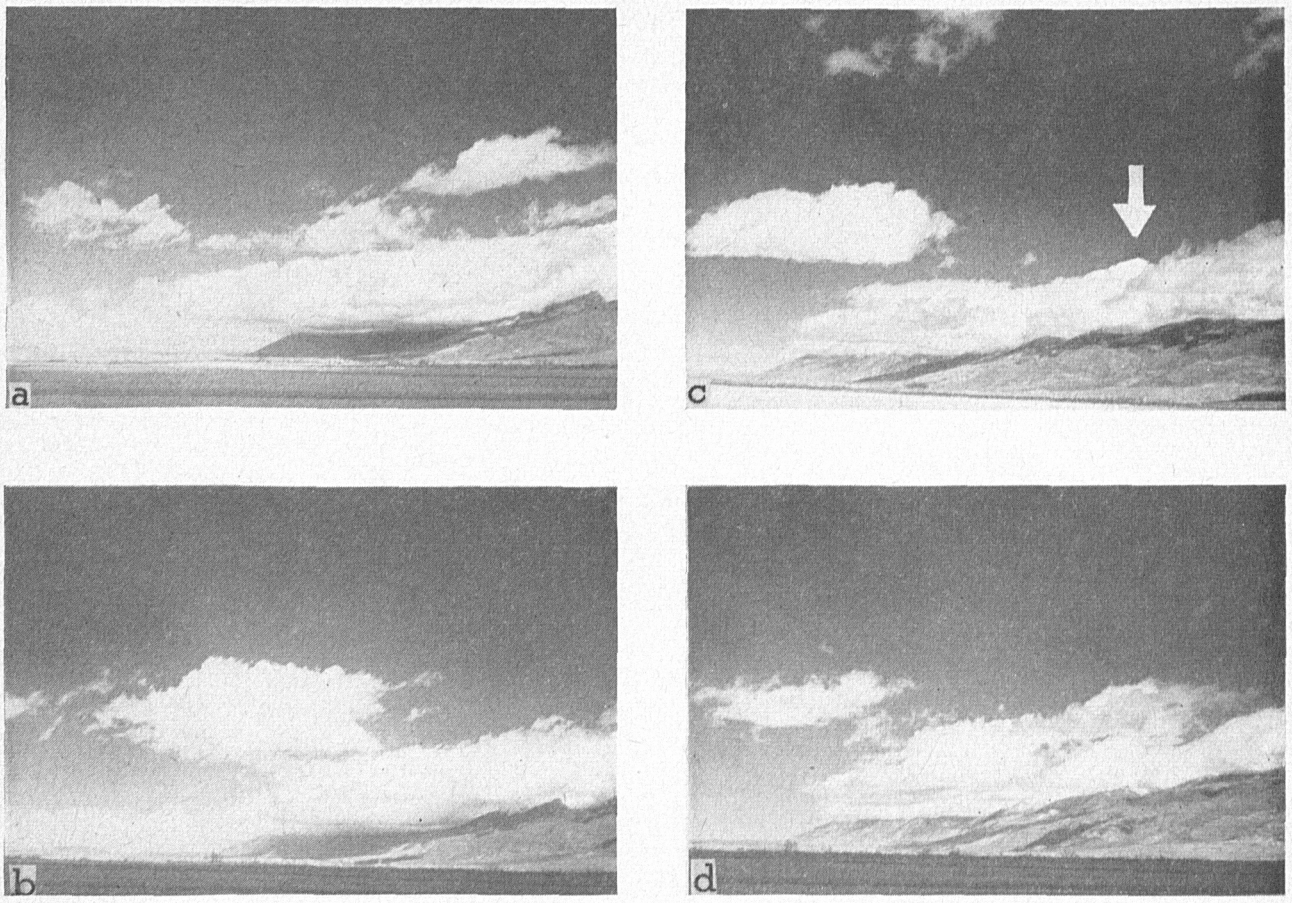


FIGURE 7.—Series of photographs of cloud seeding operation on March 22, 1950. View is the same as in figure 6.

(*a*) Seeding is about to begin. Runs were made to and from crest of White Mountains in an east-west direction.

(*b*) Five minutes later. Seeding runs completed.

(*c*) Nine minutes after seeding. New cloud buildup is visible (indicated by arrow).

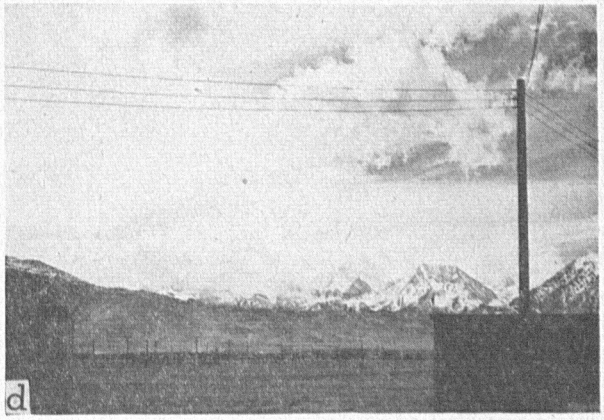
(*d*) Seventeen minutes after seeding. Entire cloud system is moving off.

impossible to clearly differentiate between natural effects and those which may be due to seeding. Direct observations from the ground at the higher elevations were few in number, but did seem to indicate a change in the character of the snowfall followed by dissipation of the clouds.

III. EFFECT ON FLOW OF BISHOP CREEK

The purpose of the experiments was to determine the possibility of increasing the flow of Bishop Creek, and it will be desirable to attempt a determination of whether a significant increase in the flow occurred over what might otherwise have been expected. Such a study is desirable not only because the flow is the ultimate result of interest, but also because it provides the most sensitive index of evaluation available under the circumstances of the tests. This is due to the high correlation between the natural flow of Bishop Creek and that of adjacent streams not subject to the seeding effect.

Natural flow is defined as the total water entering a stream above the point of measurement during a particular period. On Bishop Creek the *actual* flow is obtained by Venturi measurements on the flow line leading to the final plant in the system located in the valley at an elevation of 4,500 feet. This flow includes water from the storage reservoirs at the higher elevations (Lake Sabrina, South Lake, North Lake) as well as



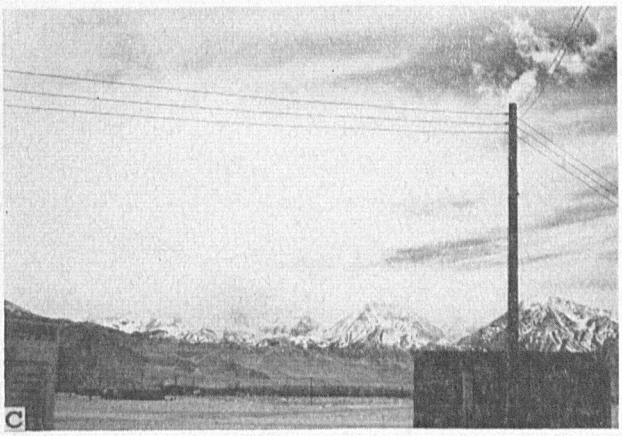


FIGURE 8.—Series of photographs of cloud seeding operation over Sierra Nevada on March 17, 1950. View is toward the west from Bishop Airport.

(*a*) One hour prior to seeding. Clouds obscure all but the lower elevations.

(*b*) Time of seeding operation. Approximate location of seeding is indicated by arrow.

(*c*) Five minutes after seeding.

(*d*) Ten minutes after seeding.

(*e*) Two hours after seeding.

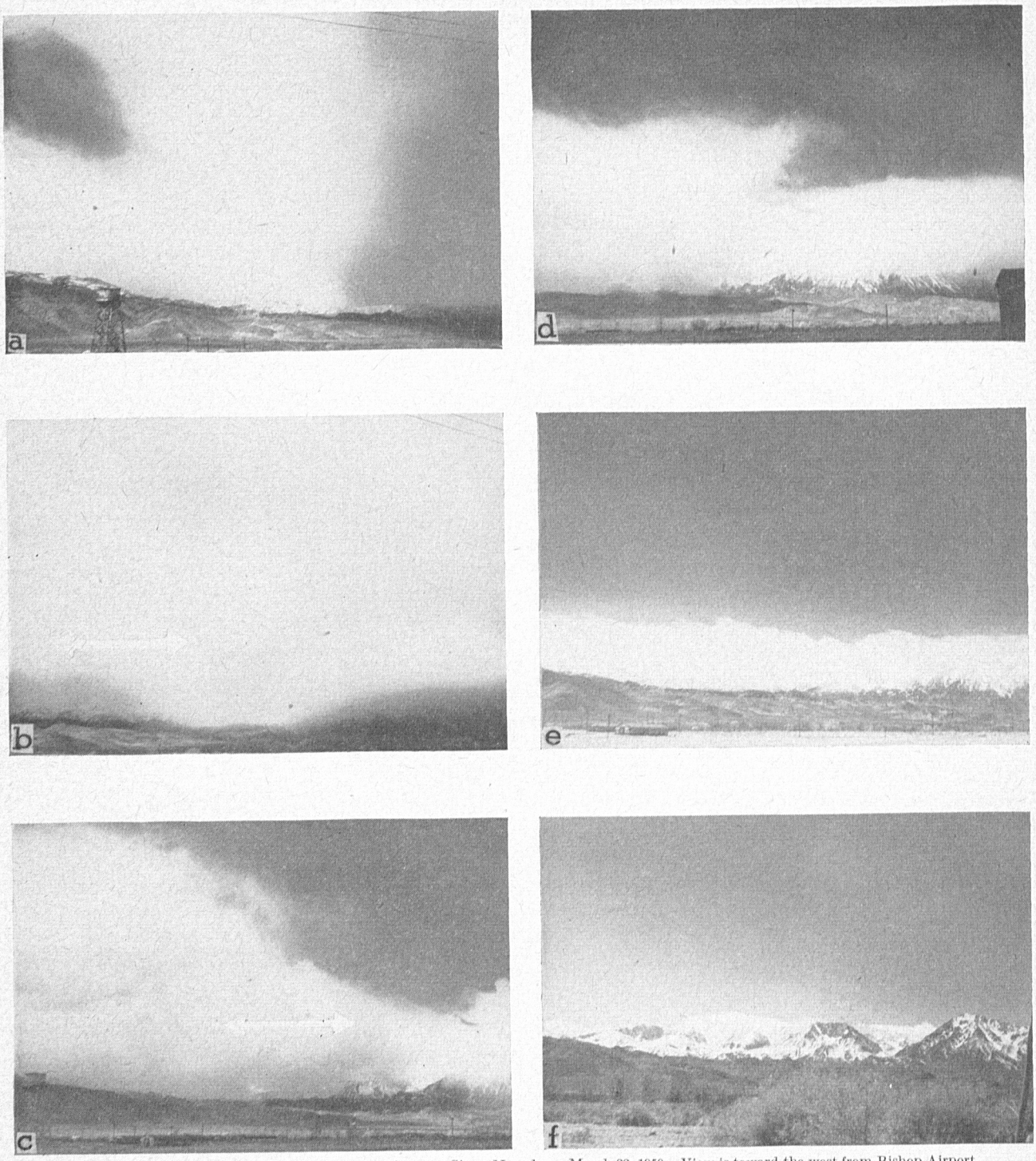


FIGURE 9.—Series of photographs of seeding operation over Sierra Nevada on March 22, 1950. View is toward the west from Bishop Airport.

(*a*) One hour before seeding.

(*b*) Beginning of seeding runs (lasting 6 minutes). Approximate location of seeding is shown by double arrow.

(*c*) Fifteen minutes after seeding. Approximate location of seeding runs again indicated. Pilot reported visible effect on cloud top.

(*d*) Twenty-five minutes after seeding.

(*e*) One and one-half hours after seeding.

(*f*) Four hours after seeding.

accretions at lower levels added to the flow lines through small catchment dams located just below each plant. *Natural* flow is determined from the *actual* flow combined with storage or draft in the reservoirs. Examination of the Venturi records over the past several years gave no evidence of irregularity, and since there has been no silting behind the storage dams there is no reason to believe that the topography of the reservoirs has changed since the original survey.

Flow of Rush Creek, another in the company's system, is determined in the same manner as that of Bishop Creek. Again Venturi records have been examined for consistency, and silting in the reservoirs has been negligible.

Rock Creek is under the control of the city of Los Angeles, and measurements of flow are made at the base of the mountains with propeller type gages.

Owens River is also in the Los Angeles system. Prior to 1936 the flow was measured directly at the Gorge station (Owens River at Long Valley near the site of the dam indicated in fig. 1). From April 1936 through April 1937 the flow at this station was computed from its relationship to a lower station (Owens River at Little Round Valley). This was necessary because of diversions and excavations for the dam which was installed at the head of the gorge and which created the Long Valley Reservoir. From May 1937 through April 1941 the record was again obtained at the regular station. From May 1941 to date the flow has been computed from storage and draft measurements. The water from Rush and Mill Creeks, to the north, is now added to Owens River, but is not included in the flow values here used. Irrigation diversions are normally made above the reservoir. These are not included directly in the flow values, but since some return occurs above the point of measurement, some of this water is included.

To detect any systematic changes that might have occurred in the flow characteristics of these streams or in the systems of measurement, double-mass curves of the comparative cumulated flow of the various streams were prepared both for annual

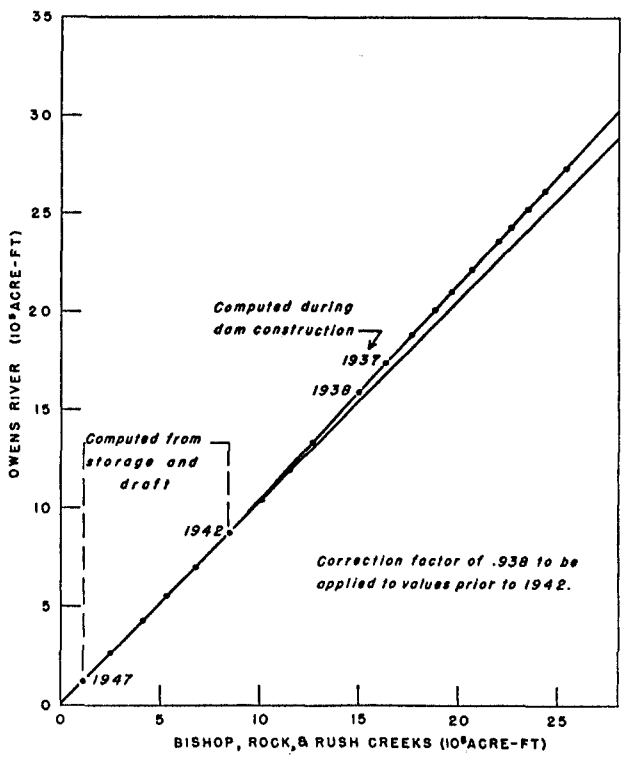


FIGURE 10.—Double-mass curve showing comparison of cumulative annual natural flow of Owens River and the combined flows of Bishop, Rock, and Rush Creeks.

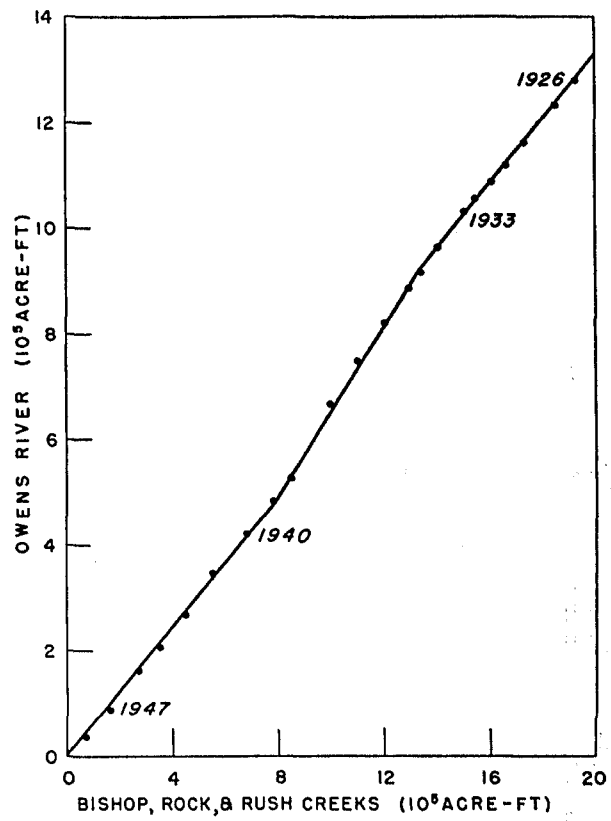


FIGURE 11.—Double-mass curve showing comparison of cumulative April-July natural flow of Owens River and the combined flows of Bishop, Rock, and Rush Creeks.

and April-July flow. No changes were detected in the flows of Bishop, Rock, or Rush Creeks. The annual flow of Owens River, when compared with the individual and combined flows of Bishop, Rock, and Rush Creeks, does show evidence of systematic change around 1941 or 1942. This is illustrated in figure 10. Straight lines have been fitted to the points before and after this change, and an adjustment factor, based on the difference in slope of the two lines, has been obtained by which values prior to 1942 can be multiplied to bring the points into the line fitting the 1942–47 points. Such adjustment does not affect the random fluctuations in the relationship, and thus will not affect regressions using the adjusted values. Neither is it felt that any freedom has been lost in the process, in view of the separate knowledge of the change in measurement occurring at the time. A similar double-mass curve for the April-July flow is shown in figure 11. It will be seen that three distinct regimes can be identified. In view of the limited number of observations in each regime no adjustment has been attempted and the April-July flow of Owens River has not been used in the analysis.

The year used in reporting flowage is the *water year* beginning October 1 and ending September 30, and the term "annual flow" will refer to the flow during the water year. The April-July flow is also used extensively in the area, since it represents quite well the melt of the snow at the higher elevations where precipitation is greatest, and since it usually constitutes a large fraction of the annual flow.

Annual and April-July natural flow of the various streams for the period of record are listed in table 1. Data for Rock Creek and Owens River were kindly furnished by the city of Los Angeles. Both original and adjusted values are given for the Owens River annual flow.

Considering first the natural flow of Bishop Creek alone, a frequency distribution of the annual values is shown in figure 12. The values for the three seeding years are shown by the arrows, and the mean and the values for one and two standard

TABLE 1.—*Natural flow of streams in the Bishop area*

Water year	Annual natural flow (10^3 acre-feet)					April-July natural flow (10^3 acre-feet)			
	Owens River		Rock Creek	Rush Creek	Bishop Creek	Owens River	Rock Creek	Rush Creek	Bishop Creek
	Actual	Adjusted							
1913–14					1,004				603
1914–15					867				517
1915–16					999				647
1916–17	2,083	1,955			848	1,097			518
1917–18	1,713	1,607			670	782			441
1918–19	1,695	1,591			695	738			428
1919–20	1,479	1,388			646	620			405
1920–21	1,495	1,403	242		688	658	142		434
1921–22	2,000	1,877	316		970	1,078	194		650
1922–23	1,691	1,587	203		651	629	112		372
1923–24	1,095	1,028	113		405	316	55		211
1924–25	1,169	1,097	142		564	473	70		353
1925–26	1,236	1,159	167	337	575	491	104	311	384
1926–27	1,520	1,426	308	463	791	719	211	410	532
1927–28	1,117	1,048	217	313	540	416	122	267	324
1928–29	990	929	167	239	434	332	89	215	247
1929–30	1,009	947	146	263	401	333	81	243	256
1930–31	730	685	106	179	345	196	47	147	173
1931–32	1,375	1,290	242	427	748	701	162	379	514
1932–33	1,163	1,092	166	267	518	475	97	239	315
1933–34	933	876	130	221	439	307	62	175	234
1934–35	1,296	1,216	187	446	583	650	118	383	386
1935–36	1,404	1,318	242	402	682	706	158	360	459
1936–37	1,607	1,508	262	397	778	843	172	365	525
1937–38	2,470	2,318	458	648	1,103	1,387	301	533	707
1938–39	1,481	1,390	230	256	626	437	106	201	337
1939–40	1,524	1,430	254	403	654	634	161	350	429
1940–41	1,682	1,578	334	539	959	774	208	477	636
1941–42	1,689	1,689	271	495	837	742	148	410	505
1942–43	1,498 (1,552)	1,498	268	453	759	631	158	384	473
1943–44	1,255 (1,244)	1,255	210	349	615	400	112	296	357
1944–45	1,623 (1,617)	1,623	292	482	856	750	182	400	560
1945–46	1,434 (1,489)	1,434	316	340	787	499 (554)	182	238	467
1946–47	1,190 (1,197)	1,190	215	333	616	383 (393)	117	250	361
1947–48	1,068 (1,061)	1,068	138	346	493	445 (438)	76	303	285
1948–49	962	962	155	324	585	362	100	301	336
1949–50	1,046 (1,049)	1,046	176	319	560	384	118	294	300

Numbers in parentheses are values supplied by the city of Los Angeles after the evaluation had been completed. Tests indicate that use of the new values would have no effect on the results obtained.

deviations [1] are indicated. Although the values during seeding all fall below the mean, this does not establish that seeding had no effect, since in the absence of seeding the points might have been even lower. The chart does serve to illustrate the lack of sensitivity of analysis using only data from the seeded area, since large increases in flow would be required for detection. A similar analysis using overlapping 3-year means showed that the mean for the seeding years was exceeded in 25 out of the 32 three-year means of the pre-seeding period. Again, however, the dispersion of the previous values was so great that such a comparison would be quite insensitive. These tests do, however, suggest that no large increases in the flow were produced.

Consideration of the Bishop flow alone fails to take into account the general wetness or dryness of the years which in the past produced the wide variations in the flow values. To provide a more sensitive means for predicting what the flow of Bishop Creek would have been without seeding, the flow of Bishop has been compared with that of adjacent streams which were unaffected by the seeding. The results are shown in figures 13 to 17. In figure 13 (Bishop annual *vs.* Rock annual) three regression lines have been drawn, one for the period of record (1921–47) prior to seeding, one for the same period but omitting the 1938 value, and one for the period 1926–47, omitting 1938. The 1938 value was omitted in the two cases since it is felt locally that the flow was so heavy as to be non-representative of more normal relationships. The

[1] In a normal distribution 67 percent of the values would be expected to fall between a value one standard deviation (σ) above and below the mean value and 95 percent between values of 2σ above and below.

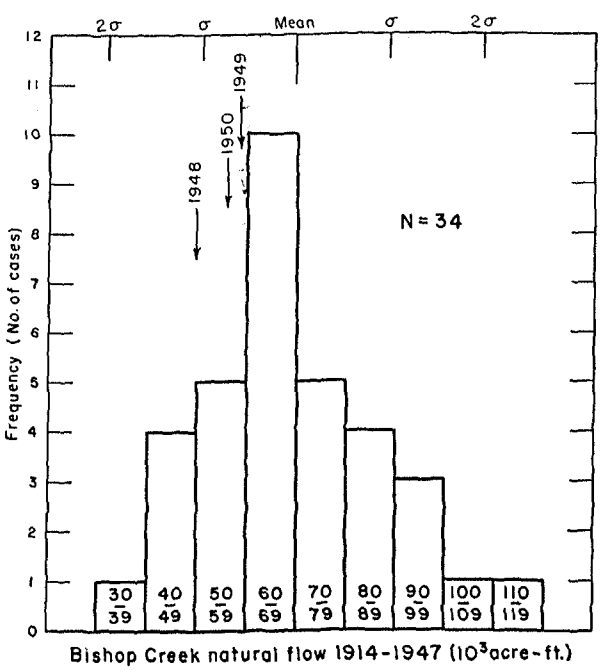


FIGURE 12.—Histogram of annual natural flows of Bishop Creek, 1914–47. Flow during seeding years is shown by arrows.

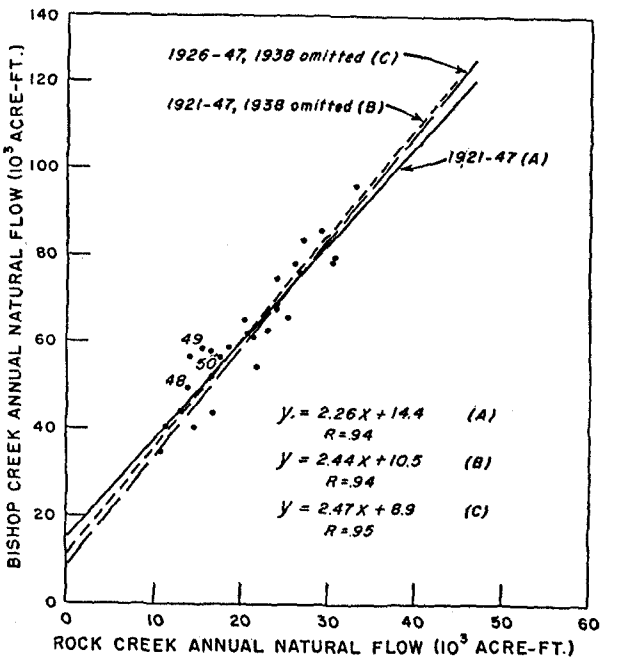


FIGURE 13.—Comparison between annual natural flows of Bishop and Rock Creeks. Regression lines are shown for three different groupings of past data.

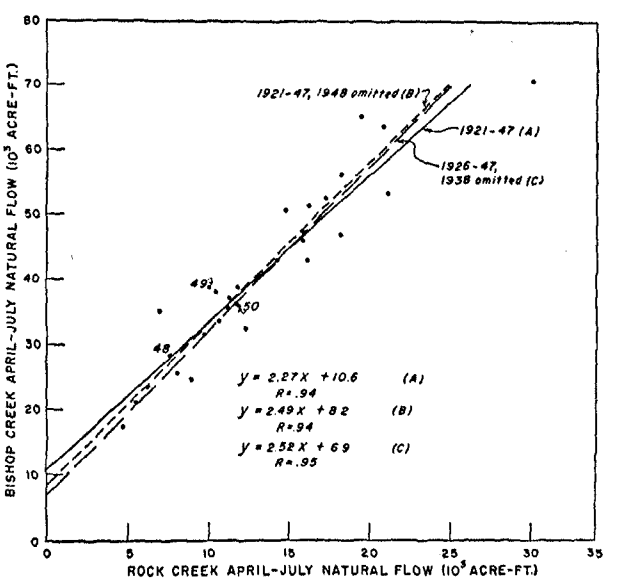


FIGURE 14.—Comparison between April-July natural flows of Bishop and Rock Creeks. Regression lines are shown for three different groupings of past data.

use of the 1926–47 data will be discussed later. It will be noted that the 1948 value falls above the regression lines, although not by a significant amount. The 1949 point is well above the line, although exceeded or equalled in 1925, and, if the line for the entire period is used, exceeded in 1922. The 1950 value lies close to the three lines. A similar diagram for the April-July flow is shown in figure 14, in which the 1948 and 1949 points are relatively closer to the lines and less significant than before, and 1950 is below the line, although not by a significant amount.

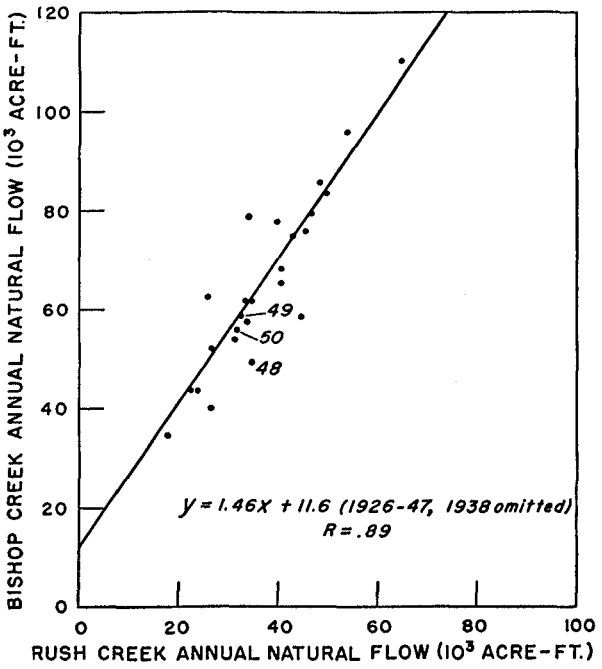


FIGURE 15.—Comparison between annual natural flows of Bishop and Rush Creeks.

Corresponding diagrams relating Bishop with Rush Creek are shown in figures 15 and 16. The correlation is less, since Rush Creek is much farther to the north. In both diagrams the 1948, 1949, and 1950 points lie below the line, with the 1948 April-July point being rather significantly low. It will be noted that inclusion of 1938 would make little difference in the location of the regression line. Comparison of Bishop with the adjusted annual flow of Owens River is presented in figure 17. The 1938 value does not appear unrepresentative when the entire record is considered, but might appear so in relation only to the 1926–47 values. The 1948 and 1950 points do not appear unusual, but the 1949 value is well above the line. Its significance depends greatly upon which regression line is used. If the longer record is considered most reliable, 1949 was equalled in 1932 and exceeded in 1941. If the shorter period is used, 1949 was about equalled in 1941.

Several points are evident from these comparisons:

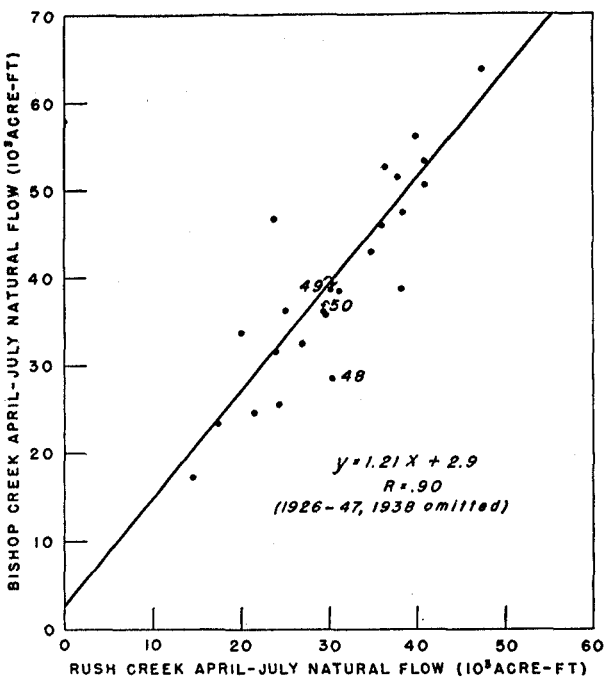


FIGURE 16.—Comparison between April-July natural flows of Bishop and Rush Creeks.

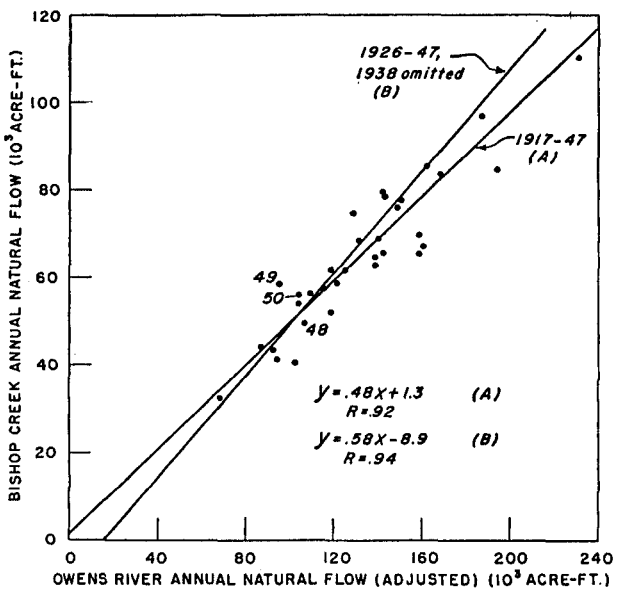


FIGURE 17.—Comparison between annual natural flows of Bishop Creek and Owens River (adjusted).

(1) The variance about the regression lines is much less than that around the mean of Bishop Creek, when the flow of that stream alone is considered.

(2) The variance about the regression lines in the different diagrams, and for different periods of data, is different.

(3) The flow of Bishop Creek for the year 1949 appears to stand out on a number of the charts but not on others.

(4) The Bishop flows for 1948 and 1950 do not depart materially from expectation on most of the charts, but 1948 is quite low in figure 16.

(5) Different estimates of the seeding effect could be made by using each of the different diagrams.

(6) Different estimates could be made by using different periods of data.

In order to make the best possible use of the flow data in evaluating the effects of seeding, the relationship between the flow of Bishop Creek and that of the other streams prior to seeding was established by multiple regression. This technique makes it possible to utilize all available information, and objectively weights the flows of the adjacent streams in such a way as to furnish the best possible estimate of the Bishop flow with the available flow data.

Of the four streams involved, Rush Creek has the shortest record, the data being available only since 1926. Rock Creek data are available since 1921, and Owens River since 1917. A standard regression using all of the streams is therefore limited to data for the period 1926–47. It is for this reason that regression lines in figures 13, 14, and 17 were drawn for this period. In order to avoid possible nonlinearity arising from the 1938 flow and to make the analysis as sensitive as possible, the data for 1938 have been omitted in this instance.

Limitation of past data to 1926 results in the discarding of the information contained in the flow records of Rock and Owens prior to that time. In order to include these data in the over-all analysis, a second multiple regression has been established for the entire period 1917–47. This has been done by estimating the flow of Rush prior to 1926 by separate regression with Owens and Rock for 1921–25 and with Owens alone for 1917–20. The flow of Rock has been similarly estimated from Owens for the period 1917–20. Using values thus obtained for the earlier years and the actual data where available, the second regression has been established. In this case the 1938 values have been included. In both cases the regressions have been assumed linear, since it was found that this assumption explained a greater proportion of the comparability than any other plausible hypothesis.

The 1926–47 regressions were computed for both annual and April-July flow. As mentioned previously, it was not feasible to adjust Owens April-July values, so this stream was used only in the annual case. The 1917–47 regression was computed only for annual flow.

Considering first the data for the period 1926–47 (omitting 1938), the regression equations were found to be, for the annual flow, in thousands of acre feet:

$$\text{Bishop} = -1.788 + 1.235(\text{Rock}) + .394(\text{Rush}) + .191\ (\text{Owens})$$

and for the April-July flow, again in thousands of acre feet:

$$\text{Bishop} = 2.231 + 1.737(\text{Rock}) + .484(\text{Rush})$$

The squared multiple correlation coefficients were .9584 for the annual case and .9479 for the April-July case.

The actual flows of Bishop Creek as compared with the flows computed from these relationships are shown in figure 18 for the annual case and in figure 19 for the April-July case. It will be ob-

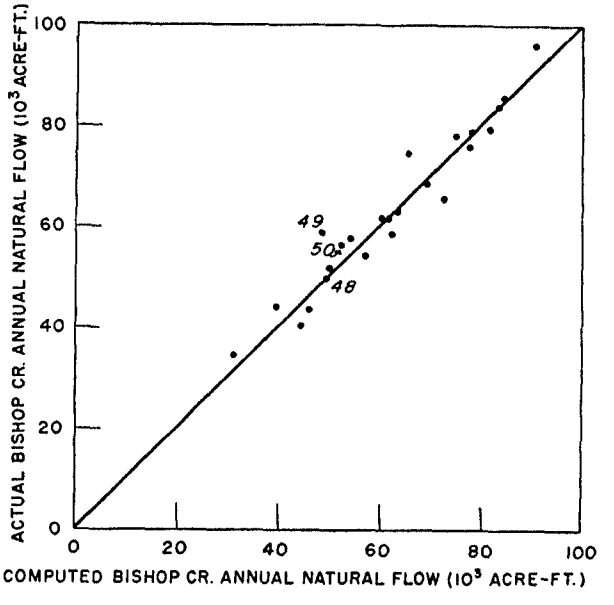


FIGURE 18.—Comparison between actual and computed annual natural flows of Bishop Creek (based on 1926–47 data).

served that the relationship is not perfect, the computed and actual values differing somewhat each year. The extent to which the points for the seeding years deviate from the computed values determines the statistical significance of such points, and also permits rather crude estimates of the magnitude of any seeding effect. A measure of the residual variability around the computed values was obtained in each case by methods outlined in Ezekial [4]. The two seeding years 1949–50 were then combined, as were all three seeding years, and the significance of the means established both by a method devised by Thom [5] and by one given by Fisher [6]. The results are presented in table 2.

In this table deviation from computed flow is in thousands of acre-feet, S is the standard deviation, t is the ratio of the deviation to the standard deviation, and P is the probability of finding a departure of that magnitude and sign due to the normal variation in flow between the streams.

TABLE 2.—*Annual and April-July stream flow (1926–1947 data)*

Water Year	Deviation from computed flow	Percent deviation	S	t	P
ANNUAL FLOW					
1948	0	0	4.12	0	0.50
1949	10.0	20.6	3.96	2.53	.01
1950	3.5	6.7	3.80	.92	.18
1949–50	[1] 6.8	[1] 7.5	2.89	2.34	.014
1948–49–50	[1] 4.5	[1] 9.0	2.54	1.77	.05
APRIL-JULY FLOW					
1948	−1.7	−5.6	3.39	−0.50	>0.70
1949	4.4	12.8	3.18	1.38	.10
1950	−1.0	−2.7	3.10	−.32	>.50
1949–50	1.7	5.1	2.29	.74	>.20
1948–49–50	−.8	−2.6	2.01	−.42	>.60

[1] Mean.

When the annual flow is considered, and values showing probabilities of natural occurrence of 0.05 or less as significant, are used, 1949 shows a flow which is significantly greater than normal expectation. Neither 1948 nor 1950 show unusual flows. When 1949 is averaged with 1950 and with 1948 and 1950, the mean results are also significantly greater than expectation, due primarily to the rather wide departure in 1949.

As regards the April-July flow, there appear to be no significant departures for any of the 3 years. Neither is the 3-year average significant. This seems to indicate that if seeding was effective

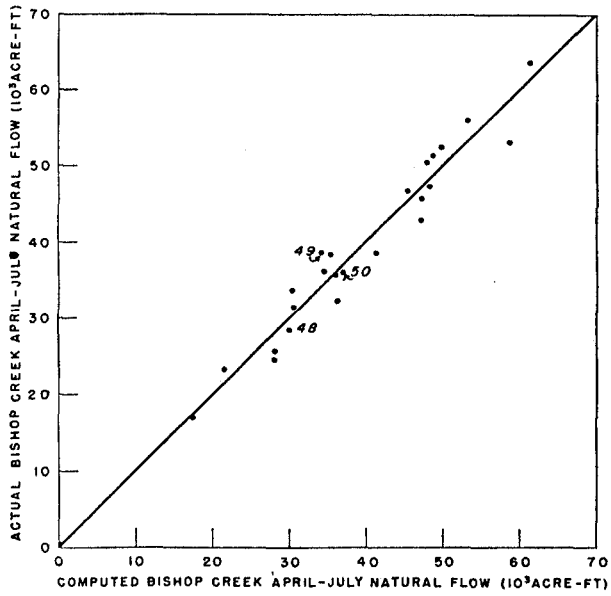


FIGURE 19.—Comparison between actual and computed April-July natural flows of Bishop Creek.

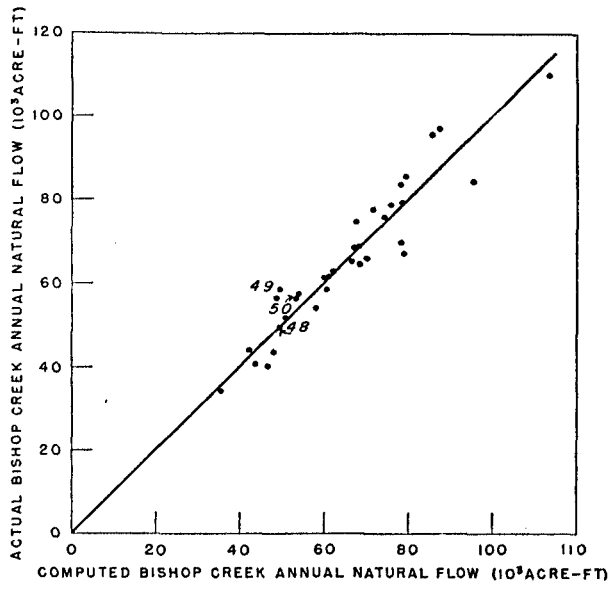


FIGURE 20.—Comparison between actual and computed annual natural flows of Bishop Creek (based on 1917–47 data).

annually, its contribution did not affect the flow during April-July significantly. The question of whether seeding, at least in 1949, may have produced any additional precipitation at the lower elevations where the bulk of the snow would have melted prior to April, is discussed later.

Considering now the second type of regression, using all of the available data back to 1917, and supplying the earlier values for Rock and Rush by

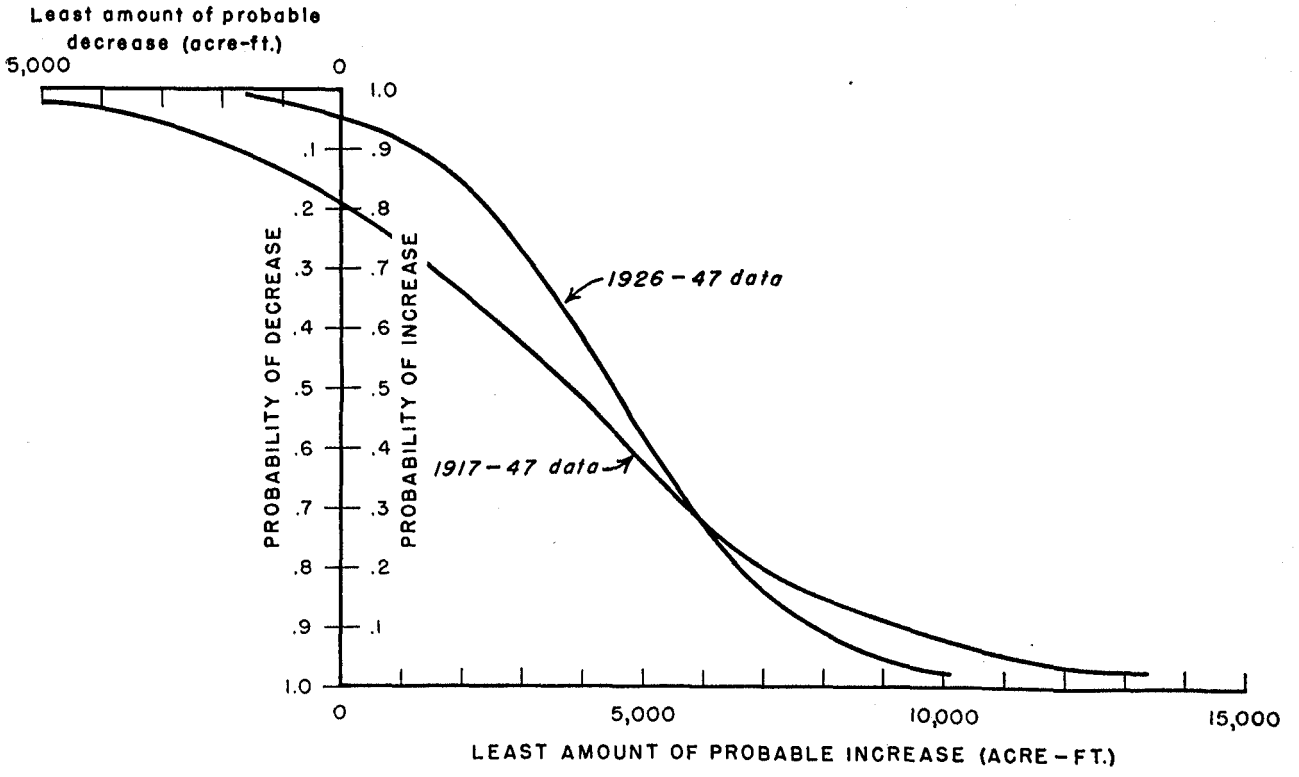


FIGURE 21.—Chart showing probability of increase or decrease of average annual natural flow of Bishop Creek from seeding. Probabilities are that amount of increase or decrease was equal to or greater than amounts shown. Curves based on 1926–47 and 1917–47 data are shown.

estimation, the following relationship for the annual flow in thousands of acre-feet is obtained:

$$\text{Bishop}=8.636+1.224\ (\text{Rock})+.312\ (\text{Rush})+.124\ (\text{Owens})$$

with a squared multiple correlation coefficient of 0.9026. Actual flows are plotted against computed values in figure 20. The results of the analysis are summarized in table 3.

TABLE 3.—*Annual flow (1917–47 data)*

Water Year	Deviation from computed flow	Percent deviation	S	t	P
1948	−3.0	−0.06	6.79	−0.04	>0.50
1949	8.8	17.8	6.59	1.34	.085
1950	2.9	5.4	6.10	.47	>.30
1949-50	5.8	11.4	Fisher's method		.12
1948-49-50	3.8	7.5	Fisher's method		.20

According to this analysis none of the seeding years shows departures significant at the 5 percent level, although again 1949 shows the greatest deviation. The earlier regression, using only the more recent data, might be thought of as furnishing a more accurate estimate of possible effects since the correlation is greater. On the other hand it did not make use of all available data. The above analysis used the additional flow data for Rock Creek and Owens River, but in such a way that makes it more difficult to estimate the significance, since the true variability between Rock, Rush, and Owens during the early years was not known and was assumed zero.

Since the 3-year average deviation in annual flow was barely significant at the 5 percent level in the first analysis and was less significant in the second, estimates of the quantitative effects of seeding can be stated only rather broadly. It will be recalled that in the first analysis the average 3-year increase was 4,500 acre-feet, and in the second 3,800 acre-feet. These figures were obtained by crediting all the flow above the regression line to seeding. Since, as will be observed in previous years, the points normally vary around the regression line in a random fashion, it cannot be stated with certainty just where the natural points would have fallen during the seeding years in the absence of the seeding. This residual uncertainty as to the magnitude of the seeding

effects can be expressed in terms of probability using the theory of confidence limits. This is illustrated graphically in figure 21, which shows the probability of obtaining the observed 9 percent 3-year average increase for different (minimum) values of the true seeding effect. Thus, for example, the chart could be used to say (using the 1926–47 curve) that the true increase was 2,000 acre-feet or more with 84 percent confidence, 4,500 acre-feet (the 9 percent average increase) or more with 50 percent confidence, and 9,000 acre-feet or more with 5 percent confidence. Similarly one could say that seeding produced a decrease in flow with 5 percent confidence.

Further uncertainty would arise in attempting to use these results as an indication of effects which might occur in the future. The results are based on only three seasons of operation, and are the result of seeding under the particular weather conditions then prevailing. The apparently greater effect in 1949 suggests, though it does not establish, that conditions may have been more favorable during that season. In order to establish a basis for prediction of future seeding results, continuation of the tests for a sufficient number of years to establish variability of results would be necessary. It would also be of interest to determine whether any seeding effects varied with the general wetness of the season or whether they were independent of natural precipitation.

Notwithstanding the uncertainties remaining, the results thus far obtained might be of some use to the company in deciding whether to continue operations on a routine basis. Knowing the cost of the seeding operations, and the value of different amounts of additional water, the company could make use of the probabilities in figure 21 to decide whether it wished to risk further outlays. If, for a modest increase with a fairly high probability, the cost is low compared with the value of the increase, the company might consider it desirable to engage in seeding operations on a regular basis.

Returning to the analysis of seeding effects, it appeared desirable to compare the flows of the various streams, taking into account their geographical location, in order to see if any noticeable pattern could be detected. Since the seeding had been almost entirely concentrated over the Bishop watershed, the effects should have been greatest in this area and should have decreased with increasing distance to the north. Such analysis should also suggest whether seeding effects overflowed

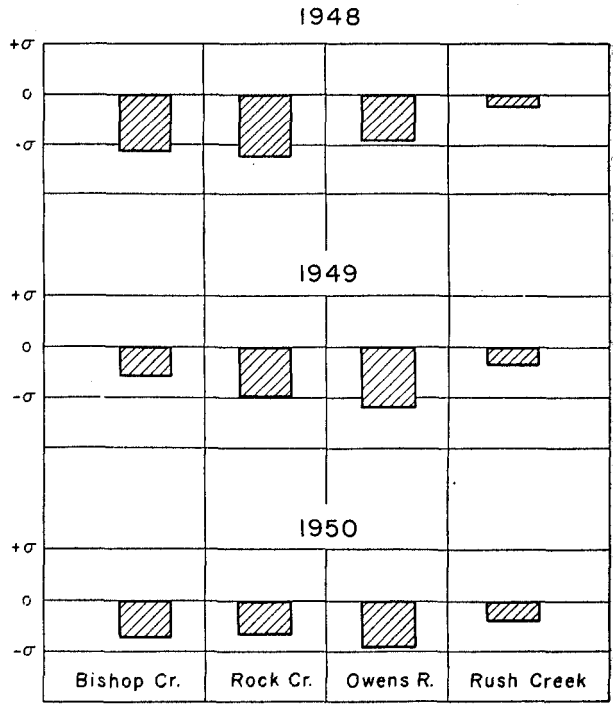


FIGURE 22.—Deviations of Bishop, Rock, Owens, and Rush from their historical means in terms of standard deviation during the seeding years.

onto the adjacent areas to such an extent that it would not be proper to consider them as controls. The annual flows of the several streams, in terms of standard deviations, are shown in figure 22. All flows were below normal for each of the 3 years. In 1948 the variations are in the opposite direction from what would be expected from a significant seeding effect. Owens and Rush have lower negative departures than Bishop and Rock. In 1949 Bishop shows up favorably as compared to Rock and Owens, and a carry-over of seeding to Rock might be suggested, but again Rush shows the least negative departure. In 1950 there appears little significant difference between Bishop,

TABLE 4.—Departure of three-year Bishop flow from those predicted by 1926–47 regression

3-year period	Departure (10^2 acre-ft.)	3-year period	Departure (10^2 acre-ft.)
1926–28	−27	1935–37	−19
1927–29	−86	1939–41	−29
1928–30	−106	1940–42	−20
1929–31	−41	1941–43	+35
1930–32	+37	1942–44	−20
1931–33	+100	1943–45	−10
1932–34	+111	1944–46	+16
1933–35	+21	1945–47	+30
1934–36	−5	1948–50	+135

Rock, and Owens, but for the third time Rush has a small negative deviation. In general there seems to be little information to be gained from considering the geographical position of the several streams over that furnished on the basis of the regressions.

Another way in which to examine the significance of the departure of the Bishop flow as compared to the adjacent streams over the 3-year seeding period is to examine the departure of the actual 3-year flows of Bishop Creek from those predicted from the 1926–47 regression. The results are presented in table 4, and indicate that the departure during 1948–50 of 13,500 acre-feet exceeded all of the preceding values, the greatest covered by the period of record being the 11,100 acre-foot value during 1932–34.

IV. SNOWPACK COMPARISONS

Depth and water content of snow are measured periodically at established locations (courses) throughout the Sierra during the winter. The survey made around the first of April is considered most representative of the winter's snow catch, at least for higher elevations. There are seven courses in the Bishop area, three in the Rock Creek watershed, and others to the north. Those referred to herein are shown in figure 1. The April survey data for the various courses are given in table 5.

Numerous comparisons of the Bishop snowpack with that in the adjacent areas have been made. Only a few representative illustrations will be presented here. Figure 23 compares the average of the three high Bishop courses with the high Rock Creek course. As will be noted, all the points for the seeding years fall below the regression line,

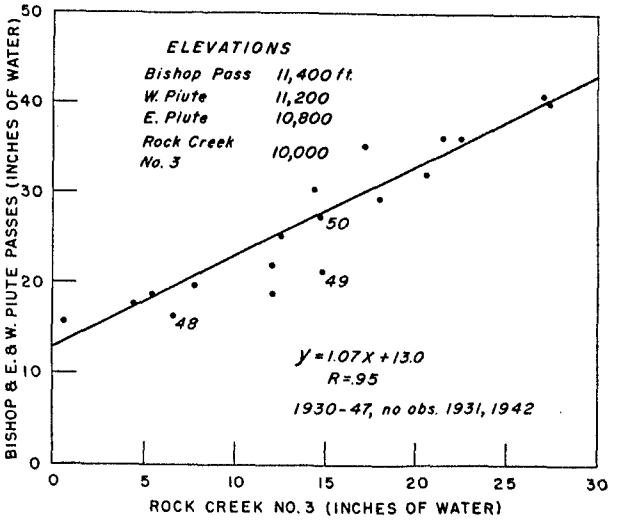


FIGURE 23.—Comparison of snowpack on three highest Bishop courses with that on highest Rock Creek course.

TABLE 5.—*April snowpack (inches of water)*

Year	Bishop Pass	West Piute Pass	East Piute Pass	Saw-mill	North Lake	South Fork Meadows	Bishop Park	Rock Creek No. 1	Rock Creek No. 2	Rock Creek No. 3	Mammoth No. 1	Mammoth No. 2	Minarettes No. 1	Minarettes No. 2	Agnew Pass	Tioga Pass	Dana Meadows
1926	-------	-------	-------	-------	-------	-------	-------	1.8	3.3	6.8	24.2	11.6	[1] 11.1	[1] 16.6	-------	-------	-------
1927	-------	-------	-------	-------	-------	-------	-------	[1] 13.3	[1] 13.9	[1] 17.6	[2] 46.2	[2] 8.5	[2] 8.5	[2] 31.4	-------	[4] 33.6	[4] 40.0
1928	-------	-------	-------	-------	-------	-------	-------	0.0	0.8	5.6	[3] 19.0	[3] 4.9	4.0	17.7	-------	[4] 16.4	[4] 20.8
1929	-------	-------	-------	-------	-------	-------	-------	4.3	5.8	7.8	20.1	8.9	8.2	18.2	-------	[4] 16.8	[4] 17.0
1930	15.3	21.4	10.6	-------	4.9	-------	-------	0.0	0.0	0.6	24.1	5.5	4.5	16.6	21.5	22.1	19.5
1931	8.8	12.4	5.5	3.7	([5])	-------	-------	[1] 0.0	[1] 0.0	[1] 2.3	[1] 15.5	6.3	[1] 5.4	[1] 11.0	10.6	9.9	13.0
1932	40.2	44.0	21.7	28.2	15.0	11.9	9.7	10.9	11.1	17.2	57.4	25.8	26.4	40.6	41.6	35.0	39.8
1933	24.9	19.2	14.6	13.3	5.1	4.9	-------	5.2	4.9	7.8	31.6	14.5	14.2	23.2	24 3	17.2	22.4
1934	21.0	21.0	11.2	14.6	([5])	([6])	([6])	T	T	4.4	21.7	6.1	4.0	16.3	16.6	16.9	18.0
1935	22.8	24.0	9.4	13.3	6.1	4.1	([6])	9.0	8.7	12.1	40.6	17.4	18.3	27.7	30.2	24.9	29.6
1936	-------	-------	-------	22.1	16.7	9.0	8.0	14.7	15.1	17.6	49.1	24.3	27.8	39.1	34.6	34.9	35.5
1937	46.6	43.1	19.2	-------	-------	-------	-------	17.9	16.7	22.5	58.1	33.5	33.2	42.8	40.9	-------	43.0
1938	46.8	45.0	31.3	35.5	19.8	15.3	18.6	19.1	19.1	27.1	74.4	38.4	41.2	55.6	60.2	-------	43.5
1939	23.5	22.4	10.1	12.2	5.1	([6])	([6])	0.0	1.1	5.5	21.2	5.0	4.9	13.6	17.0	12.4	18.0
1940	31.6	37.9	18.9	13.8	9.4	2.3	([6])	10.4	11.6	18.0	52.3	24.0	24.3	36.7	([7])	34.9	35.1
1941	46.3	44.4	29.6	24.5	17.5	14.0	11.5	16.2	19.3	27.4	64.4	33.9	32.2	43.2	41.5	38.4	38.5
1942	38.3	42.8	22.0	22.7	11.2	9.0	8.3	[1] 9.6	[1] 10.6	[1] 14.2	[1] 49.4	[1] 26.6	[1] 24.6	[1] 38.2	37.7	35.4	36.5
1943	34.6	40.3	21.4	21.2	13.7	7.2	6.7	10.1	12.8	20.6	54.9	22.8	22.1	39.5	35.7	34.9	37.7
1944	27.5	[8] 32.0	16.2	17.5	12.6	6.5	10.1	7.2	8.4	12.6	34.9	16.3	17.3	25.5	29.9	21.6	27.1
1945	41.1	40.8	26.7	26.6	18.1	13.3	11.5	17.3	16.8	21.5	56.8	28.3	27.6	43.4	40.3	34.6	39.5
1946	39.3	34.6	17.2	19.3	6.1	3.7	([6])	6.5	9.4	14.5	48.5	21.2	23.5	34.0	30.9	32.1	29.8
1947	27.3	28.4	10.2	14.1	5.3	([6])	([6])	4.2	5.1	12.1	35.1	15.5	13.2	24.9	23.4	19.6	23.9
1948	17.5	23.9	7.4	9.1	3.9	([6])	([6])	0.7	2.1	6.7	27.9	10.9	11.2	20.5	18.2	15.7	21.1
1949	28.0	22.4	13.2	16.2	10.3	3.6	7.1	9.8	11.8	14.9	43.1	22.1	23.8	31.6	34.1	15.3	26.9
1950	35.3	34.0	12.5	16.7	7.0	([6])	([6])	10.0	12.8	14.5	38.9	18.3	20.0	30.2	25.3	22.5	29.5

[1] March Survey.
[2] May Survey.
[3] February Survey.
[4] One Point Method.
[5] Patches.
[6] No snow.
[7] No measure.
[8] Approximate.

with 1949 showing the greatest departure. The correlation is comparable to that obtained between the flows of Bishop and Rock Creeks. Proceeding farther north, figure 24 shows a comparison of Bishop with the two courses in the Mammoth (Owens River source region) area. The 1949 point again is low, and 1950 is above the line although not by a significant amount. Figure 25 shows a comparison of the five highest Bishop courses with the Agnew (Rush Creek area) and Tioga Pass and Dana Meadows (Leevining area) courses. Here 1948 and 1949 are still below the line (although 1949 is much closer), and 1950 is well above, but one is impressed with the "normality" of the points for the 3 years.

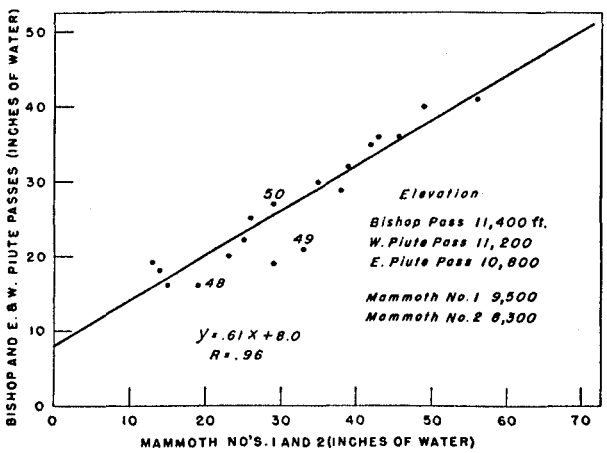


FIGURE 24.—Comparison of snowpack on three highest Bishop courses with that in Mammoth area.

Comparison of two of the low Bishop courses with the lowest Rock Creek course is shown in figure 26, and again fails to show significant increases in the Bishop area.

These comparisons would seem to indicate somewhat negative seeding effects, and thus would appear to contradict the results obtained in comparing flows of the streams. It would appear, however, quite possible that seeding increased the total precipitation over the watershed without this being clearly reflected in the snow surveys. To investigate to what extent snowpack comparisons might be expected to depart from flow comparisons of two streams, the joint distribution of differences between actual flows and those computed from snow surveys for Bishop (Bishop and East and West Piute Passes) and Rock Creeks (courses 1, 2, and 3) is presented in figure 27. Because of the homogeneity of the region it might be expected that the two streams would behave somewhat similarly, and the diagram does indicate a tendency for the points to lie in the upper right and lower left quadrants. The points for seeding years 1948 and 1950 follow this trend and thus fall within normal expectation. The rather wide displacement of the 1949 point in the upper left quadrant might be attributed to the seeding (as, for example, increased snow laid down during wind and other conditions not usually prevailing during

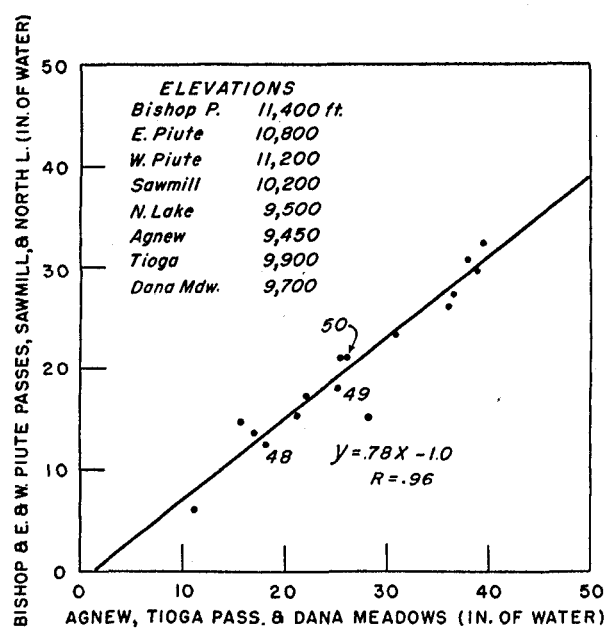


FIGURE 25.—Comparison of snowpack on five Bishop courses with that in Rush Creek area and to the north.

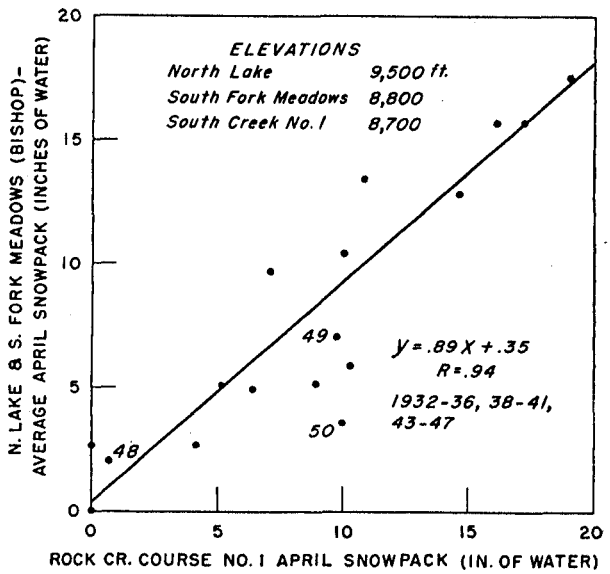


FIGURE 26.—Comparison of snowpack on low Bishop courses with that on lowest Rock Creek course.

snowfall and not therefore falling proportionately on the snow courses), but probably more important is the fact that such a deviation would appear possible naturally in view of the scatter of the points for other years, thus affording a means of resolving the conflict between the estimates of seeding results from the flows and from the snow surveys. A similar diagram comparing Bishop with Owens River gave substantially the same results.

Furthermore the purpose of the seeding was not to increase snowpack on the snow courses necessarily, but rather to increase the flow of the stream, and since it further might appear that the flow was a better measure of the precipitation over the entire watershed than were the surveys, it seems justifiable to accept the results based on the flow as furnishing the better measure of the results of the seeding operations.

The wide displacement of the 1950 point in the lower left quadrant was apparently not connected with seeding since it indicates that both the Bishop and Rock area suffered departures in the same direction. A similar departure was observed in the flow of Owens River.

Snow survey data can also be used to study any possible redistribution of snowpack within the Bishop watershed which might have resulted from seeding operations. A comparison between the three highest and two lower courses is shown in figure 28. The 1948 and 1949 values fall below the regression line, meaning that the lower courses fared better than the higher ones, with the 1949 point being the more significant. Neither point falls beyond the range of experience, however, and neither appears particularly significant in view of the relatively low correlation. The 1950 point, on the other hand, falls well above the line, although probably not by a significant amount. A similar analysis using the two lowest Bishop courses (South Fork Meadows and Bishop Park) was quite comparable, except that the 1949 point appeared relatively even lower.

If, for the moment, the 1948 and 1949 points were considered as indicating real effects, it would suggest that any additional precipitation had been produced mainly at lower elevations. Since seeding in 1948 did not begin until February and was on a rather experimental basis, it would not be expected that any results would substantially affect the annual or summer flow. At the same time a few induced showers might augment the lower courses sufficiently to account for the observed

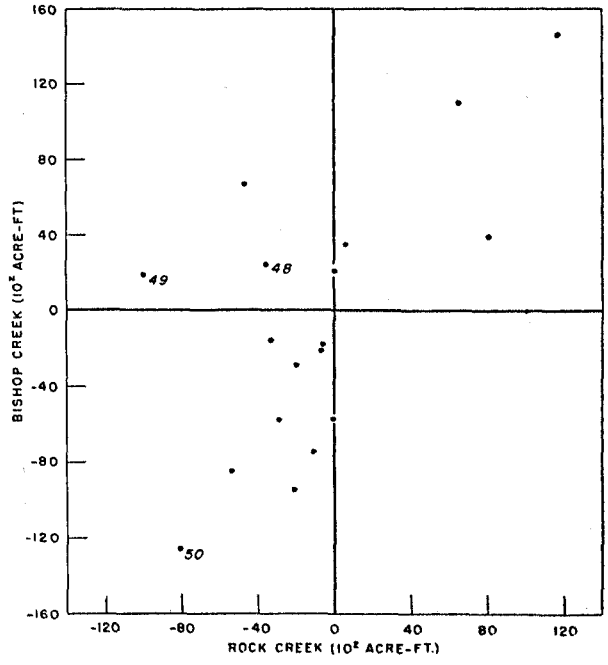


FIGURE 27.—Departures of Bishop annual flow from that expected from snowpack compared with similar departures of Rock Creek.

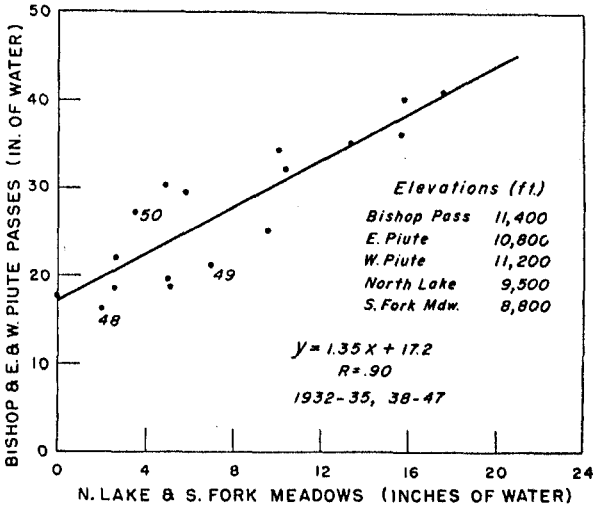


FIGURE 28.—Comparison of snowpack on high and low courses in Bishop watershed.

relationship. In 1949 additional snow at the lower elevations might not only account for the relationship, but explain the fact that the flow analysis suggested more of an increase in the annual than in the April-July runoff, since most of the snow at and below the lower courses melts before April. This reasoning cannot, however, be followed in the case of 1950. In view of the shortness of the experiment and the inconsistencies between the years, it is not felt that much significance can be attached to variations between the Bishop courses.

There are three precipitation gages in the Bishop watershed. One is located at each of the main storage reserviors, Lake Sabrina and South Lake, as shown in figure 1, and the third is located at a lower elevation. To the north the nearest gage with a long record is located at Gem Lake in the Rush Creek watershed. Data are given in table 6. A comparison of the Bishop annual precipitation (mean of South Lake and Sabrina) with that of Gem Lake is shown in figure 29. The relationship is rather poor, and in view of the low correlation little significance can be attached to the position of the points for the seeding years.

TABLE 6.—*Precipitation (inches)*

Year	Bishop annual	Gem Lake annual	Bishop Oct.-Mar.	Bishop Oct.-May
1924-25	15.9	24.6	8.5	10.6
1925-26	14.3	28.4	7.5	10.8
1926-27	26.4	31.3	19.8	22.9
1927-28	14.6	25.8	9.8	14.2
1928-29	12.2	20.6	7.6	9.4
1929-30	12.3	22.9	7.4	10.6
1930-31	12.6	19.4	5.1	7.3
1931-32	24.1	27.2	20.9	21.8
1932-33	13.3	16.7	9.0	10.7
1933-34	13.7	17.0	10.5	11.0
1934-35	17.8	28.2	10.4	15.5
1935-36	22.8	25.1	18.3	19.4
1936-37	21.1	24.7	19.1	19.9
1937-38	33.6	34.2	24.8	27.3
1938-39	13.2	17.4	9.1	10.5
1939-40	13.6	29.1	12.0	13.0
1940-41	23.5	37.7	17.5	21.5
1941-42	17.6	29.8	14.9	16.6
1942-43	16.5	28.7	12.6	15.5
1943-44	12.9	23.5	11.0	12.8
1944-45	22.6	28.0	17.9	20.0
1945-46	20.6	20.6	17.0	17.8
1946-47	16.5	16.1	13.7	15.6
1947-48	10.0	13.0	6.4	9.4
1948-49	16.0	13.6	11.0	13.5
1949-50	15.2	13.7	11.5	12.9

Values for Bishop are averages of Sabrina and South Lake gages. Annual values are for the period October 1 through September 30.

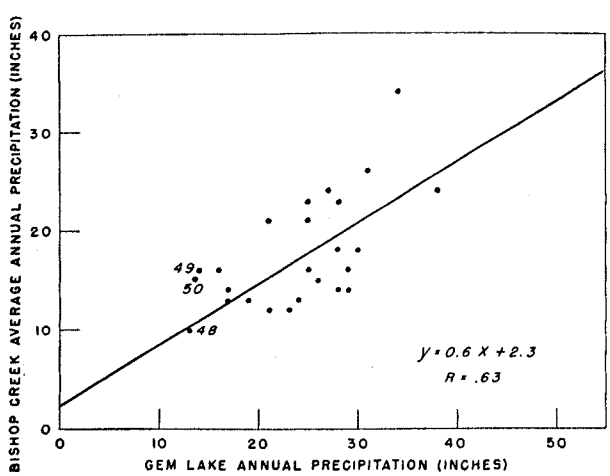


FIGURE 29.—Comparison of precipitation in Bishop and Gem Lake (Rush Creek) watersheds.

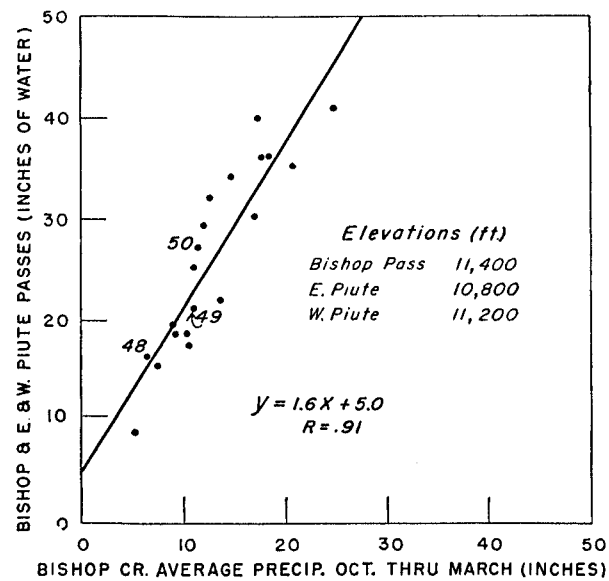


FIGURE 30.—Comparison of Bishop snowpack (high courses) with precipitation gage catch.

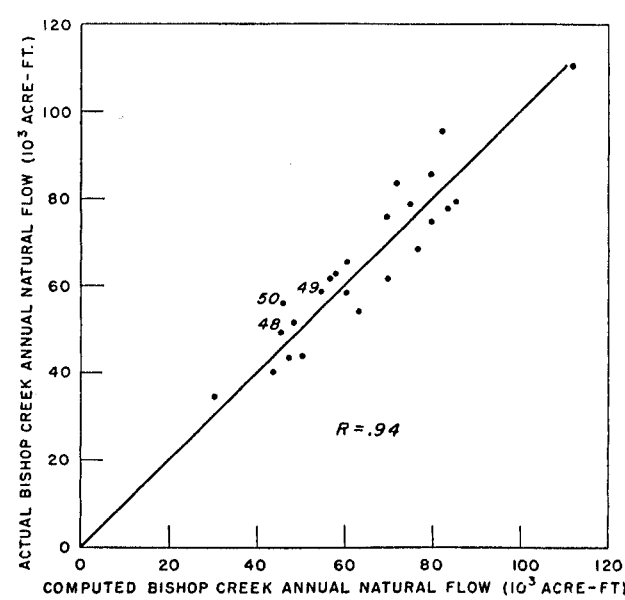


FIGURE 31.—Comparison of actual Bishop annual natural flow with that computed from precipitation data.

Figure 30 shows a comparison of the snow pack at the three highest Bishop courses with the October-March precipitation. No significant departures are noted for the seeding years, although the distribution of points is quite similar to those in the comparisons between the high and low snow surveys.

Figure 31 presents a comparison between true annual natural flow of Bishop Creek and that computed on the basis of precipitation according to the formula

Annual flow (10^3 acre-ft.) =

$$-.72+(3.5X_0+.64X_1+.56X_2)$$

where X_0, X_1, and X_2 are the Bishop Oct.–May precipitation (inches) for the current, previous, and 2d previous years, respectively. None of the individual seeding years appears significant, although the fact that all three points fall above the line might suggest that any additional precipitation may have fallen elsewhere than in the vicinity of the gages.

VI. THE UNUSUAL WEATHER OF THE 1948–49 WINTER

The foregoing analysis indicates that rather pronounced departures occurred in the 1948–49 season in the relationships between the flows of Bishop and certain of the adjacent creeks. Whether these unusual features were the result of seeding or were due to natural causes cannot be answered by purely statistical methods which merely furnish an estimate of the probabilities of natural cause. The rather low probability of purely natural causation in the 1948–49 season suggests that further investigation of this period be made. One of the possibilities is to examine the general weather conditions during this year.

It will be recalled that the 1948–49 winter season was characterized by marked extremes of weather in different parts of the world. A study of the weather and circulation during this season has been made by Klein [7]. Examination of his various charts reveals that during January 1949 a center of pronounced negative height departure from normal at the 700-mb. level was located almost over the Bishop area. Similar departures in the general vicinity of California were also present in February and March.

Whether the wind flow and other factors associated with these height anomalies could have produced the unusual distribution of realizable water as between the various adjacent watersheds is not determined, and much more knowledge of the local conditions as affected by circulation patterns would be necessary before an answer to this question could be attempted. The possibility that such effects contributed at least in part to the results of the flow and snow survey comparisons must, of course, be recognized.

VII. SUMMARY OF 1948, 1949, 1950 OPERATIONS

1. *Visual observations.*—Conversion of supercooled cloud tops to ice crystals was generally produced by the seeding. In most cases a noticeable bulging of the cloud tops was produced initially, with occasional pronounced release of instability, although subsequent dissipation of the seeded clouds was often noticed. Limited observations of cloud bases from the valley floor suggest that snow showers can be produced from nonprecipitating clouds by seeding. Such precipitation is usually in the form of virga over the valley, but will reach the ground at higher elevations. A few observations from the ground at high elevations suggest that seeding can have the effect of changing the character, rate, and duration of snowfall.

2. *Stream flow.*—Individual comparisons of the flow of Bishop Creek with that of adjacent streams led to conflicting conclusions. Multiple regressions between the flow of Bishop and that of adjacent streams indicated that the 1949 annual flow deviated rather widely from expectation in one of the two analysis procedures used. Neither the 1948 nor 1950 annual flows showed significant departures, nor did the April-July flows during any of the 3 seeding years. Because of the deviation in the 1949 annual flow, the 3-year average annual

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flow showed a similar deviation which, using the more favorable procedure, was just significant at the 5 percent level. Considerable uncertainty exists regarding the probable amount of increase over the 3-year period, but the value probably lies between 0 percent and 18 percent, with 1 chance in 20 that the value was negative and an equal chance that it was above 18 percent. Comparison of departures of Bishop and the adjacent streams from their historical means did not reveal any consistent increases in Bishop flow or definite indications of the carryover of seeding effects onto adjacent areas.

3. *Snow surveys.*—Comparison of snowpack in the Bishop watershed with that in adjacent areas failed to demonstrate any significant increase in the Bishop area. The data rather tended to suggest an opposite effect, but it was shown that this result was not incompatible with the possibility that additional precipitation was produced which did not appear in the snow surveys. Comparison of high and low level courses within the Bishop watershed gave little suggestion of any consistent effect, although in two of the years (1948 and 1949) the lower courses had a greater proportion than normal.

4. *Precipitation.*—Comparison of precipitation gage catch in the Bishop area with that in an adjacent area showed a low correlation, and little significance could be attached to the relation during the seeding years. Significant departures from the normal relationship between the snowpack at the higher elevations and the catch in the gages were not observed. The data suggested that any additional precipitation did not fall primarily in the vicinity of the gages.

5. *Conditions of the test.*—The seeding operations were conductd in an area where orography greatly influences cloud formation and precipitation. Operations were in general limited to occasions where orographic clouds alone were present. Such clouds are supercooled over a large portion of the year and often give little or no natural precipitation. The high elevation of the watershed was favorable for the production of precipitation reaching the ground rather than merely virga, because of the limited opportunity for evaporation. Seeding was primarily accomplished by dropping dry ice from an airplane and had to be timed so that any induced precipitation would strike a relatively small target area. Seeding opportunities were limited. No attempt was made to influence the precipitation during the summer months. Seeding was begun late in the 1947–48 season and most of the earlier operations involved experimentation with different seeding techniques.

It was also pointed out that an unusual circulation pattern prevailed over the experimental area during the winter season 1948–49, particularly in January, and may have contributed in whole or in part to the departures in the relationships between the flows of the several streams.

The results of these tests should be considered in the light of the special conditions prevailing and of the particular procedures adopted. Translation of the results to other regions or climatic regimes or to other seeding techniques should be done only with extreme caution.

VIII. FURTHER EVALUATION

Analysis of individual days of seeding and individual storms has been considered, and it is felt that further evaluation might profitably proceed along this line. Additional precipitation records are available in the control areas which have limited records in terms of years but which would be suitable for such a study. More refined analysis might also be concerned with explaining the apparently more successful results suggested for the year 1948–49.

IX. THE 1951 SEASON

The seeding operations continued during the 1950–51 season. However an extensive seeding project using ground silver iodide generators was conducted during this period on the headwaters of the San Joaquin River just to the west of the Bishop-Rock Creek area. The existence of such operations will have to be taken into consideration in the evaluation of the 1950–51 Bishop project. Such evaluation can only be made under at least one of two assumptions:

1. That the silver iodide seeding has such a small effect compared to dry ice that it can be

TABLE 7.—*1951 data*

Annual natural flow (10^2 acre-ft.)		April-July natural flow (10^2 acre-ft.)		Snowpack (April snow survey) (inches of water)		Precipitation (inches)	
Bishop Creek	605	Bishop Creek	376	Bishop Pass	31.9 } mean=26.7	Bishop ave. annual	15.48
Rock Creek	213	Rock Creek	128	E. Piute Pass	11.1	Bishop ave. Oct.-May	13.91
Owens River	1,171	Owens River	472	W. Piute Pass	37.2	Bishop ave. Oct.-Mar	11.28
Rush Creek	398	Rush Creek	313	Sawmill	13.5	Gem Lake annual	20.5
				North Lake	none		
				S. Fork Meadow	none		
				Rock Creek No. 1	none		
				Rock Creek No. 2	0.7		
				Rock Creek No. 3	8.5		
				Mammoth No. 1	33.8 } mean=18.6		
				Mammoth No. 2	3.4		
				Agnew	20.9 } mean=25.1		
				Tioga Pass	24.0		
				Dana Meadows	30.6		

Predicted flows [1] of Bishop Creek (10^2 acre-ft.)		Predicted flow [1] of Rock Creek (10^2 acre-ft.)	
Annual from 1926–47 regression (fig. 18)	626	Annual from snowpack (fig. 27)	172
Annual from 1921–47 regression (fig. 20)	616		
April-July from 1926–47 regression (fig. 19)	396		
Annual from snowpack (fig. 27)	674		
Annual from precipitation (fig. 31)	639		

[1] Calculated by the same methods used to obtain the computed flows that are plotted in the reference figures.

neglected. Although it is currently felt that dry ice is a much more effective agent than silver iodide because of its ability to work at higher temperatures, and although many of the orographic clouds do not extend to low enough temperatures for silver iodide to become effective, there nevertheless remains the possibility that under the circumstances the silver iodide might have had some effect.

2. That the area affected by the silver iodide can be determined and can be disregarded in studies relating to Bishop. It is almost impossible to specify the drift of silver iodide at present, so that attempts to plot its coverage would be hardly practical.

It is not justifiable to assume that the silver iodide spread sufficiently to cover both Bishop and the adjacent areas equally during occasions of dry ice seeding, and then to assume that the same type comparisons as before can be made between Bishop and the adjacent streams. This is because no past data are available as to the normal relationship between the streams in the presence of the silver iodide project, thus seeming to prohibit the use of control streams as a basis for analysis.

It is possible, however, to examine the data for 1950–51 under assumption (1) above, that is, that the silver iodide had a small and negligible effect compared to the dry ice, and then consider the results tentative until the effect of silver iodide seeding has become more clearly defined.

The pertinent data for 1950–51 are given in table 7.

Seeding operations were carried out on the following dates:

1950	*1951*
October (none)	January (none)
November 16, 20	February 3, 4
December 2, 7	March 29
	April 4, 5, 6, 16, 17, 19, 28
	May 19*
	June 1, 2

It will be observed from the data that the actual flow of Bishop Creek fell below that predicted on the basis of the regressions, as well as that predicted from the snowpack and precipitation. On the other hand, the three highest Bishop snow courses (Bishop, and East and West Piute Passes) received an unusually high snowpack as compared with the Rock Creek Course No. 3 (fig. 23), the Mammoth courses (fig. 24), and Agnew, Tioga, and Dana Meadows (fig. 25). The lower Bishop courses received less snow than normal, as did the low courses in the adjacent Rock Creek watershed (fig. 26). Comparison of the high with the low Bishop courses (fig. 28) shows, of course, a high displacement of the 1951 point toward the high courses. The data suggest that the seeding may have had the effect of increasing the Bishop April 1 snowpack at the higher elevations only, but not furnishing sufficient additional water to show up in the flow of Bishop Creek. Plotting the 1951 point on figure 27 gives some suggestion that the seeding may have decreased the snowpack at the lower elevations.

*Silver iodide seeding.

X. THE 1952 SEASON

Because there was adequate natural precipitation, no cloud seeding operations were carried out over the Bishop Creek watershed during the 1951–52 season.

ACKNOWLEDGMENTS

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Many discussions with Mr. Robert F. Symons, pilot of the seeding plane, provided an excellent picture of the seeding operations and the conditions under which they were carried out, and in addition furnished many interesting sidelights on the variations in cloud and precipitation conditions within the Bishop area. Several of the photographs were taken by Mr. Symons who kindly permitted us to reproduce them here.

The authors are also grateful to Mr. Ernest I. Bulpitt, superintendent of hydro generation, for the benefit of his careful observations of the seeding operations and his suggestions regarding analysis, both furnished against a background of lifelong experience in the area.

And finally the authors express their greatest thanks to Mr. Albert Cage, president of the company, whose unflagging interest made both the project and this report possible.

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APPENDIX

The formula for the variance as given by Ezekial [4, p. 344] is

$$V_{y_c}=(1-R^2)V_y\left(1+\frac{1}{n'}+C_{11}x_1^2+C_{22}x_2^2+C_{33}x_3^2+2C_{12}x_1x_2+2C_{13}x_1x_3+2C_{23}x_2x_3\right)$$

where V_{y_c} is the variance about the regression surface, R is the multiple correlation coefficient, V_y is the variance of Y, n' is the number of degrees of freedom, C_{ij} are the Gaussian coefficients, and the x's are deviations from the means of the independent variables (in our case of the flows of the adjacent streams).

Thom has extended this formula to cover the mean of several independent tests (years) by writing

$$V_{y_c}=(1-R^2)V_y\left(\frac{1}{k}+\frac{1}{n'}+C_{11}\bar{x}_1^2+C_{22}\bar{x}_2^2+C_{33}\bar{x}_3^2+2C_{12}\bar{x}_1\bar{x}_2+2C_{13}\bar{x}_1\bar{x}_3+2C_{23}\bar{x}_2\bar{x}_3\right)$$

where k is the number of years to be averaged, and the $\bar{x}$'s are averages of the departures in the k years.

For the annual case, using the 1926–47 data, the formula is

$$V_{y_c}=13.1949\left(\frac{1}{k}+\frac{1}{17}+.006943\bar{x}_1^2+.001900\bar{x}_2^2+.000501\bar{x}_3^2-.001219\bar{x}_1\bar{x}_2-.002580\bar{x}_1\bar{x}_3-.000960\bar{x}_2\bar{x}_3\right)$$

and for the April-July case is

$$V_{y_c}=9.6138\left(\frac{1}{k}+\frac{1}{18}+.007310\bar{x}_1^2+.001869\bar{x}_2^2-.006074\bar{x}_1\bar{x}_2\right)$$

where x_1 is the deviation of Rock Creek in 10^3 acre-feet
x_2 is the deviation of Rush Creek in 10^3 acre-feet
x_3 is the deviation of Owens River in 10^3 acre-feet

Fisher [6] shows that if $P_1, P_2, \ldots P_n$, are the probabilities of occurrence of n independent events, twice the sum of their logarithms is distributed as χ^2 with $2n$ degrees of freedom.

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