# ROLE OF SNOWMELT AND SNOWPACK STORAGE IN PRODUCTION OF RUNOFF ON FEATHER RIVER BASIN DURING DECEMBER 1955 FLOOD

By

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Seven years ago a lawsuit was brought against the Pacific Gas and Electric Company for its cloud seeding activities on the Feather River watershed. The charges stated that cloud seeding caused additional rain and snow to fall on the watershed prior to the December 1955 flood. As a result the plaintiffs claimed the Company's weather modification program had made a substantial contribution to the runoff which broke the levee and flooded Yuba City on December 24, 1955.

In preparing a defense for this lawsuit, we felt it was necessary to be ready to discuss individually and collectively all of the major factors which contributed to runoff from the Feather River Basin. The authors of this paper intend to evaluate only one of these factors; namely, the role of the snowpack in the production of runoff on the front face of the Feather River Basin during the December 1955 flood. See Figure 1 for a description of the front face of the Feather River watershed.

An objective analysis of the role of snowmelt and snowpack storage in the production of runoff requires that an estimate be made of the drainage from the snow country. Drainage estimates were based upon theoretical calculations of potential snowmelt and snowpack compaction over short intervals of time during the storm. The following basic data, which describe the weather, snowpack, and watershed, were needed before calculations of potential snowmelt and snowpack compaction could be made.*

1. Daily snow depths over watershed during the storm.
2. Hourly precipitation over snow-covered area of watershed.
3. Basin configuration and forest cover.
4. Mean hourly air temperature and dewpoint temperature for various watershed elevations.
5. Mean hourly wind speed for various watershed elevations.
6. Density of snowpack at beginning of storm.
7. Distribution of area by elevation bands for the watershed.

First, we constructed daily snow depth versus elevation profiles. Due to the shortage of snow measurements in the Feather River Basin, we decided to make use of the more plentiful data available on the adjoining Yuba River watershed. Snow depths taken by the California State Highway Department along U. S. Route 40, which passes through the southern edge of the Yuba watershed, were utilized along with regular U. S. Weather Bureau observations. Linear adjustments were made in recorded snow depths where differences in observation time occurred.

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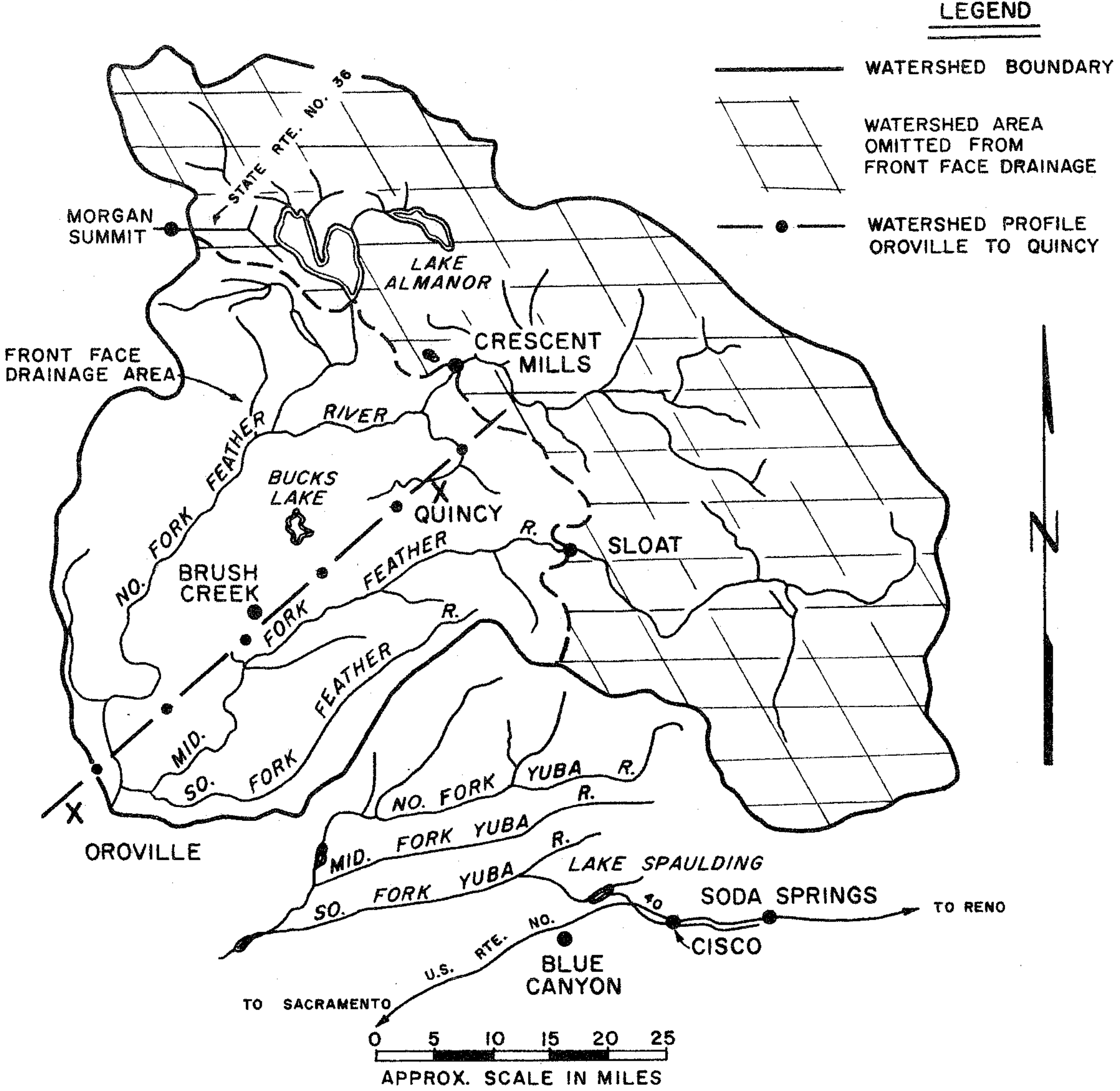
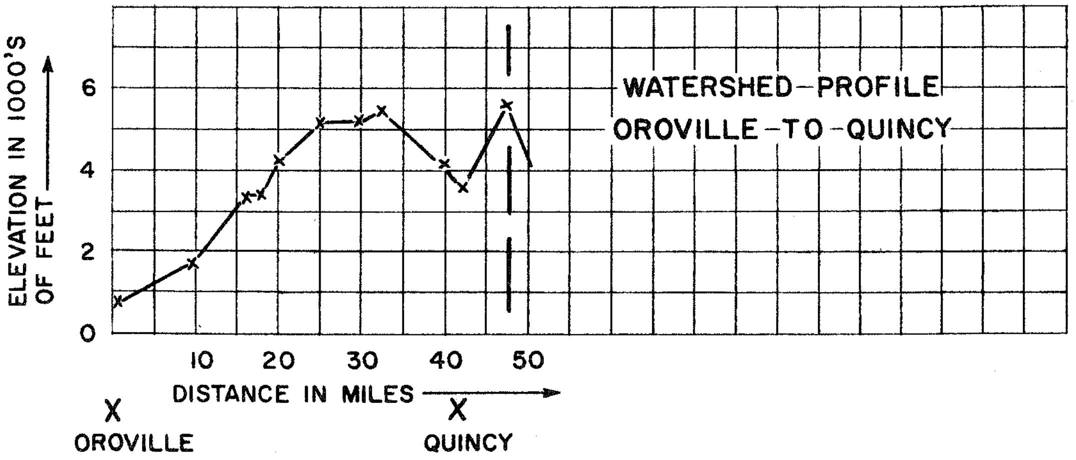
*FIG. 1 FEATHER RIVER BASIN*





Once the daily snow profiles for the Yuba watershed were completed, they were translated northward and keyed to Bucks Lake in the Feather River Basin. The measurement at Bucks Lake (5,300' elevation) is the only medium-to-high elevation station on the front face of the Feather River Basin for which daily snow depth measurements were available.

Hourly precipitation figures for the storm were developed for the watershed using the recording gage at Bucks Lake. During periods when the hourly observations were missing, daily measurements made by Pacific Gas and Electric Company at Bucks Lake were keyed to the Brush Creek hourly observations. With only the Bucks Lake measurement available, we did not have enough data to apply either the Thiessen or Isohyetal method of precipitation analysis to the front face. However, unpublished work by Hünsaker shows that during moderate to heavy warm storms, mountain precipitation gages with similar exposures in the same general area often record comparable rainfall amounts. Taking into account the heavy widespread nature of the December 1955 storm, the authors believe that the Bucks Lake measurement gives a reasonable estimate of the precipitation which fell in the snow-covered area of the Feather River watershed.

Potential snowmelt was calculated using the snowmelt equation developed, by the U. S. Army Corps of Engineers, at the Central Sierra Snow Laboratory (1). This equation is written as follows:

$$M = (0.029 + 0.0084\,KV + 0.007P_r)(T_a - 32) + 0.09$$

$M$ = Total daily snowmelt in inches per day.

$T_a$ = Mean temperature of saturated air at 10 foot level in degrees Fahrenheit.

$V$ = Mean wind speed 50 feet above surface (in miles per hour).

$P_r$ = Precipitation in inches per day.

$K$ = Basin constant.

Forest cover and basin configuration determine the value of the Basin Constant "K". A heavily forested basin calls for a 0.3 value of "K", while 1.0 is used for an unforested plain. After reviewing the forest cover and watershed configuration data compiled by Lucille Richards, of the United States Forest Service in Berkeley, California (2), (3), the following assumed values of "K" were used to compute the snowmelt on the Feather River Basin:

5,000' elevation - .4

6,000' elevation - .5

7,000' elevation - .7

Additional data necessary for the melt computations such as dewpoint temperatures and wind speeds were translated northward from the U. S. Weather Bureau Station at Blue Canyon (5,280' elevation). The wind data were adjusted for elevation using a procedure developed by S. Schamach of the U. S. Bureau of Reclamation. Temperature data were adjusted for elevation by using the U. S. Bureau's Technical Paper No. 14 (4). Blue Canyon's dewpoint temperatures were adjusted downward one degree in accordance with Figure 4-5A, Page No. 145, of the U. S. Weather Bureau's Hydrometeorological Report No. 36 (5).

Variable storm conditions can cause the rate of melt to change considerably during a 24-hour period. Therefore, the daily snowmelt equation was divided by eight so that melt computations could be made in three hourly increments.

$$M_3 = (0.00362 + 0.00105\,KV + 0.007P_{r3})(T_a - 32) + 0.0112$$

The characteristic of the precipitation determines whether or not new snow is being added to the pack during the course of the storm. For the purposes of this study, it was assumed that the precipitation fell as snow when the dry bulb temperature was equal to or less than 34 degrees Fahrenheit.

The snowpack compaction formula used to compute the depth of the snow in three hourly increments is the same one developed by Bertle in his paper. Therefore, we will avoid any detailed discussion and merely state it for the sake of completeness.

$$Y = -0.47X + 147.4$$

$X$ = Initial water content of snow plus added water in percent of initial water content.

$Y$ = Snowpack depth in percent of initial depth.

.474 and 147.4 = are emperical constants.

Before the compaction of the snowpack during the storm could be computed for three hourly increments, initial snow depth and density estimates were made. The initial snow depth measurements were taken from the constructed snow depth versus elevation profile for December 15, 1955. An initial density of 31% was estimated for the existing snowpack for all elevations at the beginning of the storm. This estimate was based upon seasonal computations made by the U. S. Bureau of Reclamation using data from Soda Springs in the neighboring Yuba Basin.

New snow which fell during the storm was assumed to have a density of 31% at 5,000, 23% at 6,000, and 15% at 7,000 feet. These estimates of snow density are supported to some degree by observed 24-hour densities of new snowfall at Twin Lakes (8,000 foot elevation) under conditions similar to December 1955; i.e., alternating periods of rain and snow at the 5,000 foot elevation mark. Twin Lakes is located approximately 10 miles south of Lake Tahoe. The calculated snow depths based upon these estimated densities give good consistency with observed snow depths (See Figure 2).

Drainage from the snowpack is the amount of water which reaches the ground during the course of a storm. Snowpack drainage for any given period of time is a function of the initial pack density, initial pack depth, and the amount of liquid water added to the pack by snowmelt and/or rainfall. In order to assess the role of snowmelt and snowpack storage in the daily production of runoff, three hourly drainage figures were derived for the 5,000, 6,000, and 7,000 foot elevation levels. The 5,000 foot drainage covers the area from the lip of the snowpack to the 5,500 foot elevation mark. The 6,000 foot drainage extends from 5,500 feet to 6,500 feet, and the 7,000 foot drainage takes in the rest of the watershed above 6,500 feet. Calculations were made for different watershed elevations to account for variations in pack depth, pack densities, and snowmelt rates.

Drainage begins when the snowpack reaches a density of about 40 to 45%. This is the threshold density of snow and has been established by observation and laboratory experiments. The procedure followed in calculating the compaction of the snow gives the latest pack density. In our computations, once the compaction procedure indicates the snow has reached a density of 45%, drainage was assumed to begin. Algebraically speaking, the three-hourly drainage for any given elevation in a watershed can be stated as follows:

$D_{3\ hr.} = (W + R) - .45\ (DS - DSM)$ = Amount of snowpack drainage for three-hour period.

$W$ = Initial water content of snowpack at beginning of three-hour period.

$R$ = Amount of rainfall during three-hour period.

$DS$ = Initial depth of snowpack at beginning of three-hour period.

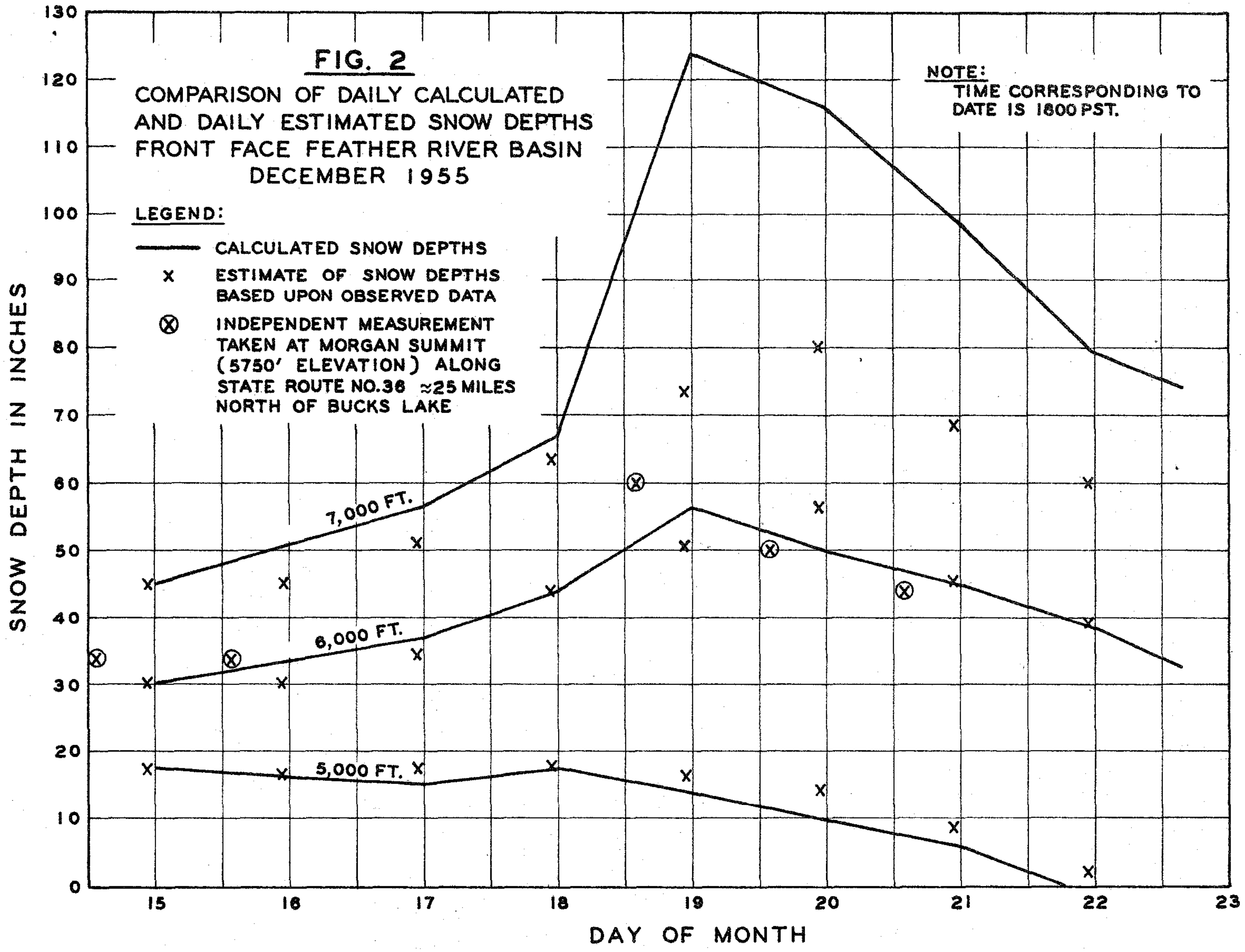


FIG. 2

COMPARISON OF DAILY CALCULATED AND DAILY ESTIMATED SNOW DEPTHS FRONT FACE FEATHER RIVER BASIN DECEMBER 1955

LEGEND:

| | |
|---|---|
| — | CALCULATED SNOW DEPTHS |
| x | ESTIMATE OF SNOW DEPTHS BASED UPON OBSERVED DATA |
| ⊗ | INDEPENDENT MEASUREMENT TAKEN AT MORGAN SUMMIT (5750′ ELEVATION) ALONG STATE ROUTE NO.36 ≈25 MILES NORTH OF BUCKS LAKE |

NOTE:
TIME CORRESPONDING TO DATE IS 1800 PST.

DSM = Amount snowpack depth was reduced by *dry snowmelt during three-hour period.

.45 = Threshold density of snow. The above equation is invalid for snow densities less than 45% because by definition the density of the pack must be 45% before drainage can occur.

Daily snowpack drainage computations include drainage from both the main snowpack and the lip area of the snowpack. The lip area is defined by the daily recession of the snowline. Due to the changing lip area caused by the recession of the snowline, the lip drainage was calculated separately from the main snowpack. This was necessary because of insufficient data to define accurately the recession of the snowline in three hourly increments (Figure 3). The lip area contribution of the snowpack to runoff production is computed as follows:

$D_L = .45 \left(\frac{AL}{2}\right) + \left(\frac{RA}{2}\right)$ = Drainage from daily lip section of snowpack. (Second term divided by 2 to eliminate rain on bare ground)

A = Area covered by daily recession of snowline.

L = Initial depth of snow at upper edge of daily lip section. See Figure 3.

R = Daily rainfall over lip section.

.45 = Threshold density of snow. The above equation is invalid for snow densities less than 45% because by definition the density of the pack must be 45% before drainage can occur.

The total daily water yield from the area covered by the snowpack is the sum of the drainages from the lip and the main snowpack. Drainage from the main snowpack was obtained by multiplying the daily drainage estimates for each elevation band by their respective areas. Figure 4 is an area versus elevation curve for the front face of the Feather River Basin. This curve was used to estimate the drainage area in each elevation increment or band.

Daily estimates of water yield from snowpack drainage do not describe the role of the snowpack in runoff production. Comparative information is needed which will give an estimate of what would have happened if rain had fallen on bare ground. Therefore, a daily estimate of the water yield from snowpack drainage is compared with the estimated yield from rainfall (assuming bare ground) over the same area covered by the snowpack. These estimates are of water reaching the ground before retention losses take effect. This comparison is illustrated by making a daily plot in acre-feet of the two sets of accumulated drainage figures beginning with December 15, 1955. The difference in the two curves gives a quantitative day-to-day estimate of the combined role of snowmelt and snowpack storage in the production of runoff (Figure 5).

The detention storage effect of the snowpack is apparent in Figure 5 for the period December 15 through December 20. Although rain on the snowpack began at 1800 on December 15, drainage did not begin until 1200 December 17 and then only at the lower elevations. At the time drainage began, about 40,000 acre-feet of rain water was stored in the snowpack. By 1800 December 17, 46,000 acre-feet of rain had fallen on the snowpack but only 11,000 acre-feet of drainage had been released. By 1800 on December 20 the accumulated drainage from the pack was equal to the rain that had fallen on it, but

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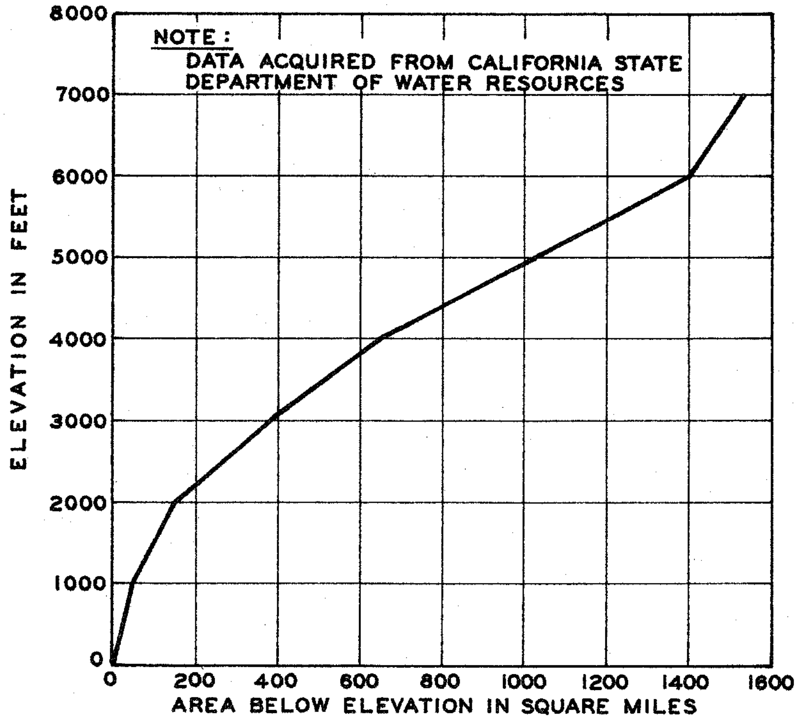
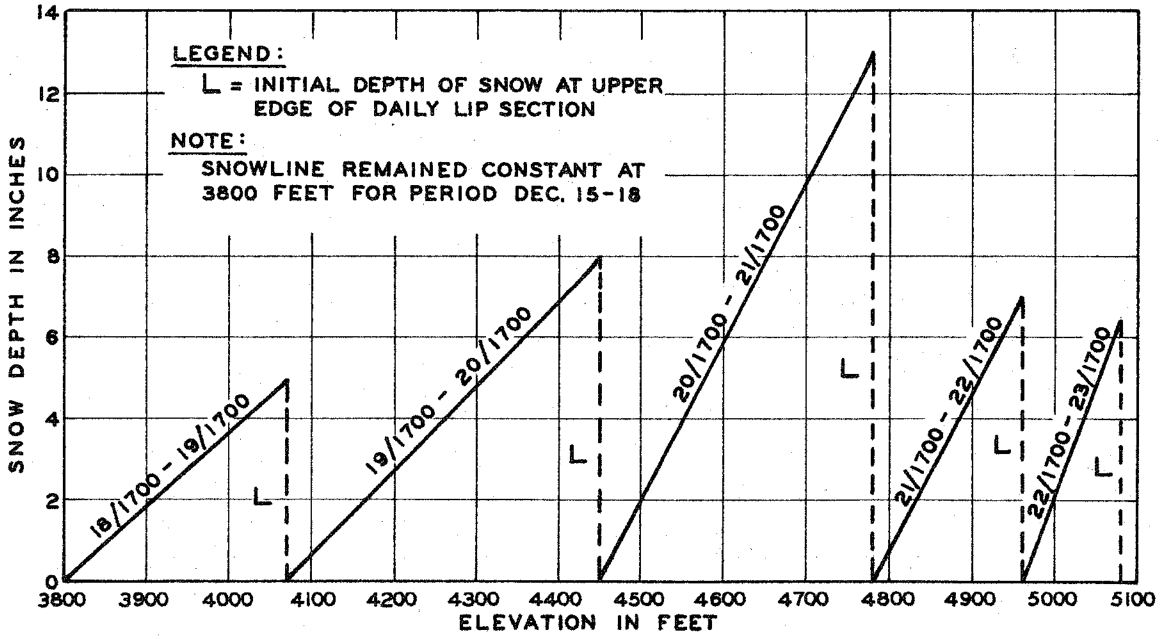
* Dry Snowmelt - The dry snow density is the density of the crystalline snow. It is a function of the original density of the snowfall and the amount of compaction which has taken place. The difference between the dry snow density and the pack density is due to the water held suspended or stored in the snow. Therefore, the water equivalent of the potential snowmelt is converted to snow depth using dry snow density.



NOTE:
DATA ACQUIRED FROM CALIFORNIA STATE DEPARTMENT OF WATER RESOURCES

AREA VS. ELEVATION CURVE
FRONT FACE FEATHER RIVER BASIN

FIG. 4



LEGEND:
L = INITIAL DEPTH OF SNOW AT UPPER EDGE OF DAILY LIP SECTION

NOTE:
SNOWLINE REMAINED CONSTANT AT 3800 FEET FOR PERIOD DEC. 15-18

DAILY RECESSION OF SNOWLINE - FEATHER RIVER BASIN
DEC. 18-23, 1955

FIG. 3

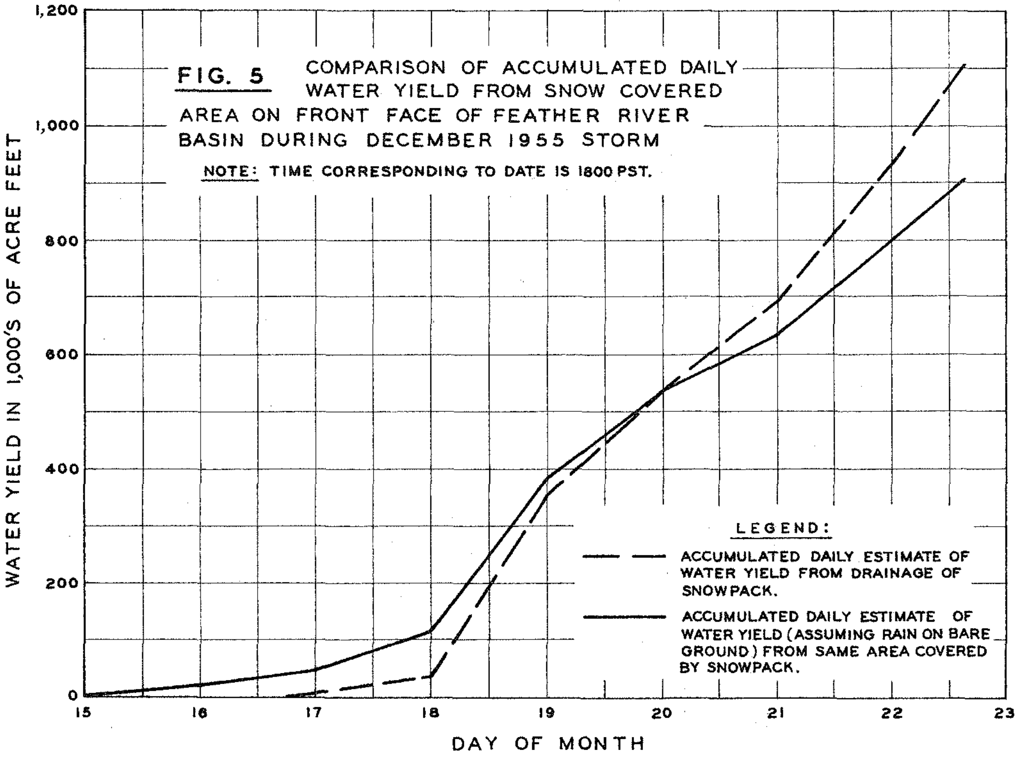


**FIG. 5** COMPARISON OF ACCUMULATED DAILY WATER YIELD FROM SNOW COVERED AREA ON FRONT FACE OF FEATHER RIVER BASIN DURING DECEMBER 1955 STORM

NOTE: TIME CORRESPONDING TO DATE IS 1800 PST.

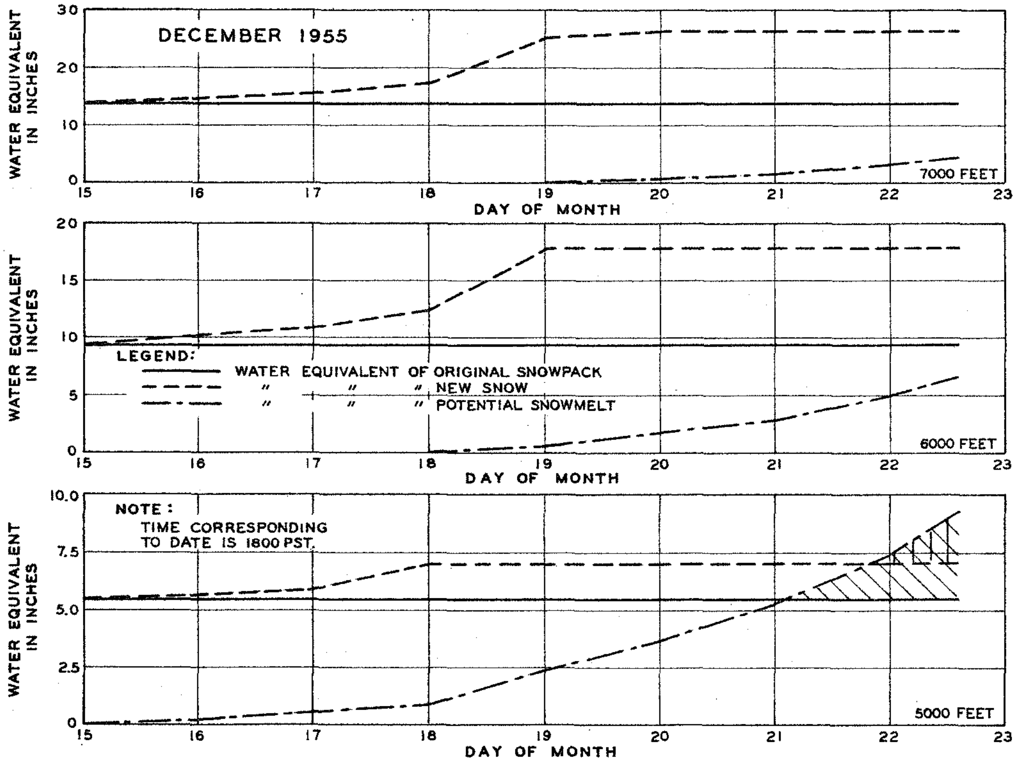


**FIG. 6** WATER EQUIVALENT OF ORIGINAL SNOWPACK PLUS NEW SNOW ADDED DURING STORM, AND THE ACCUMULATED DAILY POTENTIAL SNOWMELT

the equivalent of all the water accumulated from snowmelt was still in the pack. At the end of the storm (0900 on December 23) the total drainage from the pack had exceeded the accumulated rainfall by augmentation from snowmelt by approximately 196,000 acre-feet. In other words, the snowpack increased the water yield from the snow-covered area approximately 20%.

The above analysis shows the overall contribution of the snowpack to the production of runoff. However, two questions are raised: (1) Was the drainage supplied from snowmelt less than, equal to, or more than the water equivalent of the original snowpack at the beginning of the storm? and (2) How much water in both liquid and crystalline state was stored in the pack at the end of the storm?

Comparison of the water equivalent of the original snowpack, of the snow added during the storm, and of the accumulated daily snowmelt potential (see Figure 6) at the 5,000 foot level shows that the original pack was gone by 2100 on December 21 and the entire pack was gone and all storage released by 1200 on December 22.

At the 6,000 and 7,000 foot levels the situation was quite different. Melt began at about 1800 December 18 at the 6,000 foot level and at 1800 December 19 at the 7,000 foot level. At neither level was there sufficient melt to remove the original snowpack.

The situation at 0900 December 23, when rain and melt had practically ceased, is summarized in the following table:

TABLE 1

Snowpack Summary @ 0900 December 23, 1955

| Elevation Band (Feet) | Original Snowpack | Added Snow | Total Snow-pack | Potential Snowmelt | Original Pack Remaining | Total Snow Remaining | Rain & Melt Water Stored | Total Water In The Pack |
|---|---|---|---|---|---|---|---|---|
| | Water Equivalent in Inches Depth | | | | | | | |
| 5,000 | 5.5 | 1.62 | 7.12 | 9.31 | 0 | 0 | 0 | 0 |
| 6,000 | 9.3 | 8.63 | 17.93 | 6.77 | 2.53 | 11.16 | 3.43 | 14.59 |
| 7,000 | 13.95 | 12.88 | 26.83 | 4.25 | 9.70 | 22.58 | 10.98 | 33.56 |

From the above analyses the authors draw the following conclusions:

1. The small or "optimum" snowpack, which existed in December 1955 at the 5,000 foot level, was melted by the melt potential of the storm. In cases of this type, temporary detention of rain and melt water may actually augment the rainfall contribution to surface runoff during critical time periods.

2. The snowpack was greater than the melt potential of the storm at the 6,000 and 7,000 foot levels. Under these conditions large amounts of water may be stored in the remaining snowpack, thereby reducing the rainfall and snowmelt contribution to surface runoff during the critical time periods. Our calculations, summarized in Table 1, show that the snowpack at the end of the storm was storing approximately 24% and 33% liquid water by weight at the 6,000 and 7,000 foot levels respectively. This amount of storage is 5 to 10 times greater than previous studies indicate.

# REFERENCES

(1) Corps of Engineers, U. S. Army, North Pacific Division: Snow Hydrology. Paragraph 6-04.13, Portland, Oregon, 30 June 1956.

(2) Richards, Lucille G.: Forest Densities, Ground Cover, and Slopes -- In the Snow Zone of the Sierra Nevada West-side. Technical Paper No. 40, U. S. Department of Agriculture - Forest Service, Berkeley, California, October 1959.

(3) Richards, Lucille G.: Terrain Features of Drainage Basins in the Sierra Nevada West-side Snow Zone. Technical Paper No. 58, U. S. Department of Agriculture - Forest Service, Berkeley, California, May 1961.

(4) U. S. Department of Commerce - Weather Bureau: Tables of Precipitable Water and Other Factors for a Saturated Pseudo-Adiabatic Atmosphere. Technical Paper No. 14, Washington, D. C., 1951.

(5) U. S. Department of Commerce - Weather Bureau: Interim Report Probable Maximum Precipitation in California. Hydrometeorological Report No. 36, Washington, D. C., October 1961.

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