# an empirical method of estimating daily average basinwide snowmelt

## U. S. Geological Survey

Water-Resources Investigations

14-73

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PREPARED IN COOPERATION WITH THE
CALIFORNIA DEPARTMENT OF WATER RESOURCES

| BIBLIOGRAPHIC DATA SHEET | 1. Report No. | 2. | 3. Recipient's Accession No. |
|---|---|---|---|

4. Title and Subtitle

AN EMPIRICAL METHOD OF ESTIMATING DAILY AVERAGE BASINWIDE SNOWMELT

5. Report Date
June 1973

6.

7. Author(s)


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8. Performing Organization No. WRI 14-73

9. Performing Organization Name and Address


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10. Project/Task/Work Unit

11. Contract/Grant No.

12. Sponsoring Organization Name and Address

Same as 9 above.

13. Type of Report & Period Covered

Final report

14.

15. Supplementary Notes

Prepared in cooperation with the California Department of Water Resources

16. Abstracts


In this study the traditional, but relatively unreliable, degree-day method computing daily snowmelt has been modified by the addition of a daily index of th areal extent of the snowpack. The index used is actually a computed index of dai water equivalent of the pack. However, because a fairly close relation often exi between water equivalent and areal extent of the snowpack at the start of the mel season, a relation, albeit a weaker one, also often exists during the melt season between the decreasing water-equivalent index and the shrinking snowpack area. T proposed method can be readily modified to make advantageous use of any available data from a pressure-pillow snow gage in the basin.


17. Key Words and Document Analysis. 17a. Descriptors

*Air temperature, *snowmelt, *snowpack, *water equivalent, rain, routing, snow surveys, California

17b. Identifiers/Open-Ended Terms

*Degree-day method, North Yuba River, pressure-pillow snow gage

17c. COSATI Field/Group Ø2C

8043-02

| 18. Availability Statement | 19. Security Class (This Report) UNCLASSIFIED | 21. No. of Pages 27 |
|---|---|---|
| No restriction on distribution. | 20. Security Class (This Page) UNCLASSIFIED | 22. Price |

# AN EMPIRICAL METHOD OF ESTIMATING

# DAILY AVERAGE BASINWIDE SNOWMELT

By S. E. Rantz

U.S. GEOLOGICAL SURVEY Water Resources Division.

Water-Resources Investigations 14-73

Prepared in cooperation with the

California Department of Water Resources



June 1973

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June 1973

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## AN EMPIRICAL METHOD OF ESTIMATING DAILY AVERAGE BASINWIDE SNOWMELT

By S. E. Rantz

## ABSTRACT

This report presents an empirical method of computing daily average basinwide melt from a mountain snowpack. The term "average basinwide melt" refers to the depth at which the melted snow would stand if distributed evenly over the entire basin, rather than over the snow-covered area alone. Once obtained, the daily basinwide snowmelt values are used as input to a hydrologic routing model to compute daily values of snowmelt runoff.

The independent variables used in the empirical relation are (1) daily values of mean air temperature observed in or near the basin being studied and (2) an index of the daily water equivalent of the snowpack, based originally on snow-course data observed in or near the basin April 1 of each year. (April 1 is the approximate date when snow surveys are routinely made.) The dependent variable is daily average basinwide snowmelt, or more properly, an index of that melt. The daily index values of snowmelt needed to develop the relation are obtained by applying the hydrologic routing model, in reverse, to the streamflow records for a few snowmelt seasons, thereby computing the values of daily basinwide snowmelt required to generate the observed daily stream discharges.

The method developed here is intended for use with basins that lack either (1) the specialized meteorological data needed for applying the more sophisticated snowmelt equations that are based on rigorous physical laws of heat transfer or (2) data from a recording pressure-pillow snow gage, which gives a continuous record of water equivalent of the snowpack at a point and thereby provides an index of daily average basinwide snowmelt. Where such data deficiencies exist, daily snowmelt runoff has been commonly estimated by use of the degree-day method, in which air temperature and time-of-year (month) act as indexes of (1) the meteorological conditions that affect snowmelt and (2) the change in areal extent of the snowpack as the melt season progresses. The proposed empirical method does not provide an improved index of meteorological conditions, but, by use of a daily index of water equivalent of the snowpack, it does provide a far superior index of areal extent of the snowpack in the course of its ablation during the melt season. The proposed method can be readily modified to make advantageous use of any available data from a pressure-pillow snow gage in the basin.

The primary uses of the method would be in computing daily records of snowmelt runoff for years prior to the establishment of a stream-gaging station, and in short-term forecasting of snowmelt runoff based on temperature predictions made while the melt season is in progress. The reliability of such forecasts would be enhanced by using current streamflow records to adjust current values of the water-equivalent index of the snowpack.

## INTRODUCTION

The principles of heat transfer involved in the melting of a mountain snowpack are well understood, and an operational method, in the form of equations, is available for applying those principles to determine or predict daily snowmelt (U.S. Army Corps of Engineers, 1960). The computed snowmelt can then be routed to a stream channel. Intensive instrumentation of the watershed is required, however, to provide the meteorological data required for application of the snowmelt equations. Rarely will the hydrologist have all the necessary data, but quite often, by some improvising, he can make satisfactory estimates of the data that are lacking (Rantz, 1964). Many watersheds are equipped with one or more recording pressure-pillow snow gages, each of which gives a continuous record of water equivalent of the snowpack, thereby providing an index of daily average basinwide snowmelt. At least as often, however, the data deficiencies for a watershed are practically insurmountable, and the only information available consists of daily streamflow hydrographs for several years, a record of daily precipitation and air temperature at a climatological station in or near the basin being studied, and snow-course data for April 1 observed in or near the basin. (Snow surveys are routinely made on or about April 1 of each year, at which time the water equivalent of the snowpack is usually at its annual maximum.)

When faced with such data deficiencies, how does one study the snowmelt hydrology of a basin? In the years prior to 1955, before the development of the snowmelt equations cited above, the standard approach, and one still used by many hydrologists, was the empirical degree-day method (Wisler and Brater, 1959, p. 313-314). In that method the daily mean air temperature during a period of melt is used as an index of the integrated effect of radiation and sensible heat exchange. The degree-day method further assumes that negligible melting will occur when the air temperature is below some base value, usually 32°F. The difference, therefore, between the mean air temperature for any given date and the base temperature is the degree-days for that date. For example, if a base of 32°F is used, a day whose mean temperature is 49°F has 17 degree-days. Degree-days are then correlated with observed snowmelt runoff to provide a temperature index of melt runoff, using a separate correlation for each month of the season.

A weakness of the method lies in the fact that temperature is generally unsatisfactory as a basin index of the effect of such pertinent meteorological elements as wind, humidity, and radiation. Also, the method gives no consideration to the albedo of the snow surface, which may vary considerably with time, particularly as a result of early spring snowfalls. Because the degree-day index is correlated with basin runoff, its evaluation becomes complicated by such hydrologic factors as basin storage and lag, evapotranspiration losses, and particularly by the varying areal extent of the snowpack, which shrinks as the melt season progresses. It is not surprising, therefore, that the degree-day index for a given basin invariably shows wide variation with time, both within the snowmelt season and between snowmelt seasons, and the use of an average monthly degree-day index commonly gives highly erroneous estimates of daily snowmelt runoff.

*Purpose and scope.*--Nothing can be done about the shortcomings of the degree-day itself as an index of meteorological conditions, but the degree-day method would be improved tremendously if a satisfactory index of the areal extent of the snowpack on any given date could be improvised. The purpose of this study, therefore, was to modify the degree-day method by providing such an index.

For convenience, the basin used to test the proposed method was that of the North Yuba River (fig. 1) upstream from the U.S. Geological Survey gaging station below Goodyears Bar, Calif. In an earlier study of that basin by Rantz (1964), snowmelt had been computed, using complete meteorological data, for the melt seasons of 1956 and 1958 when the snowpack was extremely heavy, and for the melt season of 1959 when the snowpack was extremely light. Available, therefore, for those years were daily values of rainfall, air temperature, and average basinwide snowmelt, as well as the water equivalent of the snowpack on April 1. (The term "average basinwide snowmelt" refers to the depth at which the melted snow would stand if distributed evenly over the entire basin, rather than over the snow-covered area alone.) Accordingly, this study was restricted to the years 1956, 1958, and 1959. Not only were the basic data readily available for those years, but a wide range of total annual snowmelt runoff is represented by those years. Only a minimal amount of the climatological data available for the basin was utilized because the aim of the study was to demonstrate the applicability of the proposed method to meager data, and not to obtain the best possible reproduction of the North Yuba River runoff record by using all pertinent basic information.

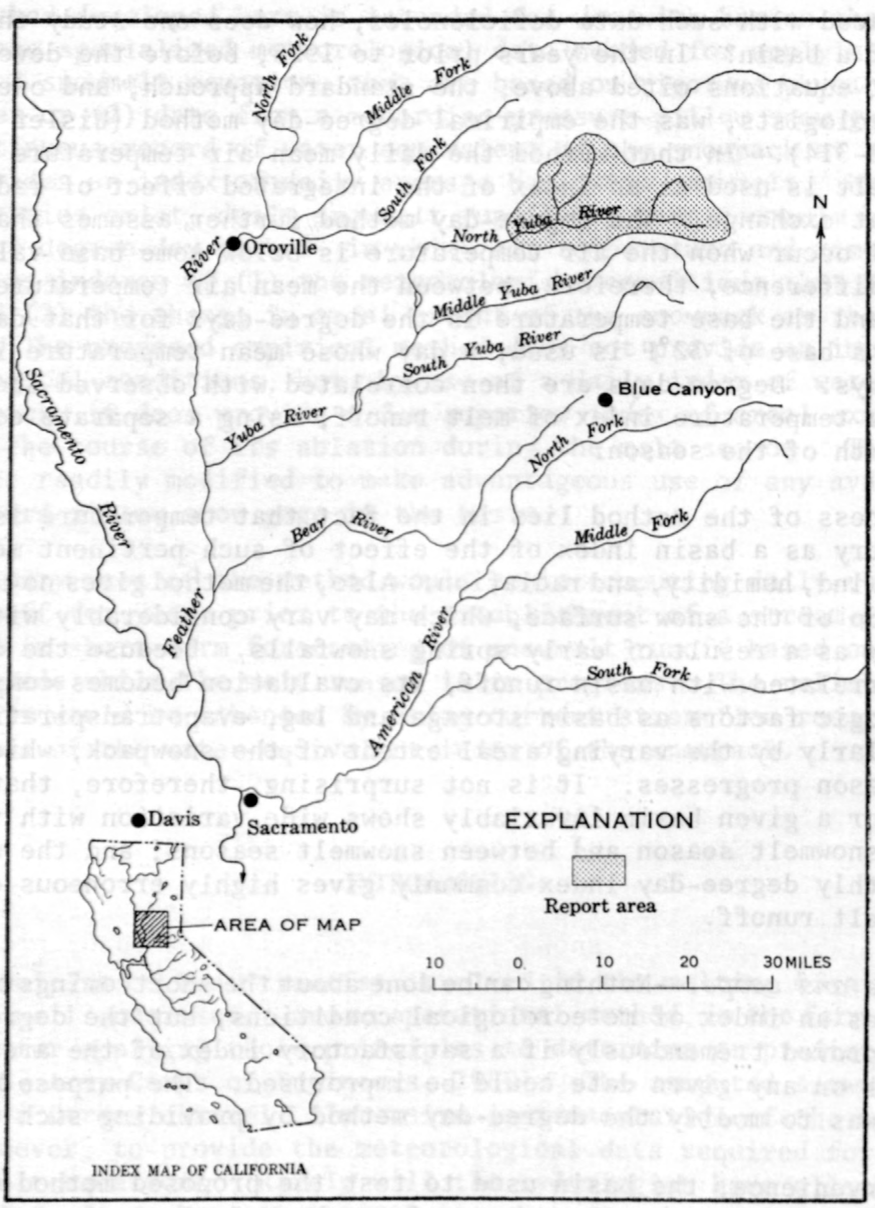


FIGURE 1.--Report area.

## DAILY AVERAGE BASINWIDE SNOWMELT

As a preliminary step in relating daily average basinwide snowmelt to air temperature and water equivalent of the snowpack, it is necessary to obtain values of daily snowmelt for use in defining the relation. In explaining how those snowmelt values are obtained, it is helpful to first discuss the procedure that would be followed for a basin having the specialized meteorological data needed to reliably compute daily snowmelt.

Where such meteorological data are available, they are used by the hydrologist in equations of heat transfer to compute the melt from each of several altitude zones in the basin. He then routes the melt, through basin storage, to the stream-gaging station he is considering. The daily melt from the various zones may be routed individually, or they may be combined before routing to provide a basinwide value of daily snowmelt. In either case, a lag factor must be introduced in recognition of the facts that (1) generally very little of the day's snowmelt reaches the ground-snow interface before noon and (2) there is generally appreciable distance between the melting snowpack and the stream-gaging station. For reasons that will become evident shortly, we assume here that the hydrologist combines the daily zonal snowmelt values for each day to obtain an average basinwide snowmelt value for that day. Rainfall that occurs on days of snowmelt augments the daily supply of water to be routed. A part of the supply infiltrates into the ground, some to be used to satisfy soil-moisture deficiencies caused by evapotranspiration, and some to reach the underlying ground-water body. The remainder of the total daily supply is assumed to be direct runoff and may be routed to the stream-gaging station by some device, such as the unit hydrograph. Ground-water outflow is likewise routed to the gaging station.

After following the above procedure to compute daily streamflow for a few years of historic record, the hydrologist compares computed discharges with those recorded. If necessary, he adjusts his basin parameters and routing coefficients to obtain closer agreement between computed and recorded discharge. He then has a satisfactory model for predicting daily streamflow from short-term predictions of meteorological conditions.

Let us assume now that the hydrologist lacks the necessary meteorological data for reliably computing snowmelt, but desires a method of predicting daily snowmelt runoff. One course of action that he might take would be as follows. He would first confine himself to the analysis of rainfall that occurred before or after the annual snowmelt period. For those rain periods that are free of snowmelt, he would compute daily basinwide precipitation from the record obtained at a precipitation gage or gages in or near the basin. In making that computation he would use an isohyetal map of mean annual precipitation to obtain the ratio of gaged precipitation to basinwide precipitation. He would next devise a routing procedure--for example, unit hydrograph--for converting basinwide precipitation to streamflow. Then, on the assumption that his routing procedure, adjusted for lag, is applicable to snowmelt routing, he would use the routing procedure in reverse. He would apply the adjusted routing procedure to observed streamflow data for several snowmelt seasons, to compute daily values of average basinwide water supply. The values obtained for rainless days would represent average basinwide snowmelt. For those days that had rain, average basinwide rainfall would be subtracted from the computed supply to obtain daily snowmelt values.

At this point the hydrologist would have no way of appraising the adequacy of his basin parameters and routing constants, because he has no idea of the true value of the daily increments of snowmelt. The daily values of snowmelt he obtained are in fact indexes of daily average basinwide snowmelt, but at this point even their adequacy as indexes, for use in an empirical snowmelt equation, cannot be evaluated. The next step to be taken is to relate the computed daily indexes of average basinwide snowmelt to air temperature and to daily indexes of water equivalent of the snowpack as determined originally from the April snow survey of each year. If that relation is satisfactory, a means becomes available for predicting daily basinwide indexes of snowmelt from air-temperature observations, after which the daily snowmelt indexes can be converted to daily runoff by use of the selected routing procedure. If the relation for predicting basinwide snowmelt indexes is unsatisfactory, basin parameters and routing constants must be adjusted by a trial-and-error procedure to produce index values of daily average basinwide snowmelt that can be related satisfactorily to air temperature and water-equivalent index.

It is with that latter relation that this paper is concerned. The inadequacy of the time-honored degree-day method has already been discussed, and the purpose of this study is to modify the method by providing an additional parameter for use--namely, daily indexes of the water equivalent of the snowpack. To test the practicality of the proposed modification, use will be made of the readily available hydrologic data from the previously mentioned study of the North Yuba River basin (Rantz, 1964). It will be assumed that the daily values of average basinwide snowmelt were obtained from a routing study such as that described above, although they were actually computed from detailed meteorological data.

## RELATION OF BASINWIDE SNOWMELT TO AIR TEMPERATURE AND WATER EQUIVALENT OF SNOWPACK

### Discussion of Parameters

The average basinwide depth of snowmelt on a given day is equal to the average melt, in inches per unit area of snow cover, multiplied by the areal extent of the snowpack on that day and divided by the total area of the basin (a constant). With the limited data to be used we have no way of determining absolute values of either daily melt or daily area of the snowpack, nor is it necessary that we have absolute values of those elements. The only absolute values we are concerned with are the final values of daily streamflow, and they will be estimated by applying index values of daily basinwide snowmelt to an appropriate routing model. The empiricism involved in that procedure differs only in degree from that used in routing precipitation on a mountain basin to a stream-gaging station. The precipitation values used as input to the precipitation routing model are usually indexes of the true basinwide precipitation, albeit much more reliable indexes than the snowmelt indexes we will be using in this study.

The use of daily mean air temperature in a relation involving snowmelt is obvious. Though imperfect as an index of climatological conditions, air temperature does reflect the integrated effect of radiation and sensible heat exchange. There is nothing to be gained by using degree-days rather than mean air temperature, because if it is desirable to subtract some constant value from mean air temperature, the correlation will so indicate and will also indicate the "best" value of that constant. To more sharply define the joint effect of progressively increasing radiation and sensible heat exchange during the snowmelt season, a separate relation is used for each half of each month of the season--April through June in westside drainage basins of the Sierra Nevada, such as that of the North Yuba River.

To obtain true daily values of the areal extent of the snowpack, it would be necessary to observe the recession of the snowline as the melt season progresses. That is rarely practical, however, and daily indexes are used in this study. The procedure used for obtaining indexes of snowpack area is based on the fact that on about April 1 of each year, when the annual snow accumulation is usually at its maximum, a fairly close relation often exists between water equivalent of the snowpack and altitude of the snowline (Potts, 1944). It was reasoned that the April water equivalent at some high altitude--one sufficiently high to remain snow-covered at the time direct snowmelt runoff ceases at the gaging station--could be used as an index of basinwide water equivalent, and, therefore, as an index of snowpack area. On the first day of direct snowmelt runoff, usually about April 1, the water equivalent at the selected altitude, as obtained from the April snow survey, would be used directly. The snowmelt, or index of snowmelt, computed for the first day, would be subtracted from the water equivalent of the first day to give the water-equivalent index to be used on the second day. The procedure would be continued throughout the season until direct snowmelt runoff ceased. The water-equivalent index used for any day would be that of the preceding day minus the computed snowmelt for that preceding day. It was obvious that the water-equivalent index, computed in the manner described above, would have to be combined with date, or at least with month, to have any meaning as an index of areal extent of the snowpack. That fact further dictated the use of separate snowmelt relations for each half-month of the season.

Direct surface runoff was assumed to start on the first day, after the snow survey of late March or early April, when the recorded hydrograph at the stream-gaging station showed the easily identifiable diurnal fluctuation that is characteristic of snowmelt runoff. Direct surface runoff was assumed to cease on the day when streamflow receded to the discharge recorded on the starting date of direct runoff, and entered the base-flow recession phase of the runoff cycle.

## Data Used in the Study

As mentioned earlier, the data used in this report were obtained from a study by Rantz (1964) of the snowmelt hydrology of the North Yuba River basin (fig. 1) upstream from the stream-gaging station below Goodyears Bar, Calif. The basin ranges in altitude from 2,450 feet to 8,590 feet, and has a drainage area of 245 square miles. Figure 2 shows the relation of water equivalent of the snowpack to altitude at the start of the snowmelt seasons of 1956, 1958, and 1959. The snowpack was extremely heavy in 1956 and 1958, and extremely light in 1959. For the purpose of this study, the water equivalent at an altitude of 7,000 feet was used as the index of areal extent of the snowpack--18 percent of the area of the total basin lies above that altitude. Table 1 shows the water equivalent of the snowpack in early April at the 7,000-foot level, as obtained from figure 2, and the duration of the period of direct snowmelt runoff, for the 3 years that are being studied.

TABLE 1.--*Period of direct snowmelt runoff and water equivalent of the snowpack at altitude of 7,000 feet in 1956, 1958, and 1959*

| Year | Period of direct snowmelt runoff | | Water equivalent, in inches, of snowpack at 7,000-foot altitude at start of melt season |
|---|---|---|---|
| | Start | End | |
| 1956 | April 6 | June 30 | 49.1 |
| 1958 | April 8 | June 30 | 60.9 |
| 1959 | April 1 | May 16 | 20.0 |

All other data used are given in tables 2-4. Column 2 of the tables lists values of daily mean air temperature at Downieville Ranger Station during the periods of direct snowmelt runoff in 1956, 1958, and 1959. Downieville Ranger Station, at an altitude of 2,895 feet, is used as the index station for air temperature over the snowpack. In column 3 of the tables are values of daily average basinwide snowmelt as computed for the report by Rantz (1964). Those values are identical with the values of supply given in column 2 of table 3 of the previously cited report by Rantz, except for those days on which rain occurred. Rainfall has been subtracted from the published figures to provide values of snowmelt. Column 4 of tables 2-4 of the present report gives the accumulated values of daily snowmelt.

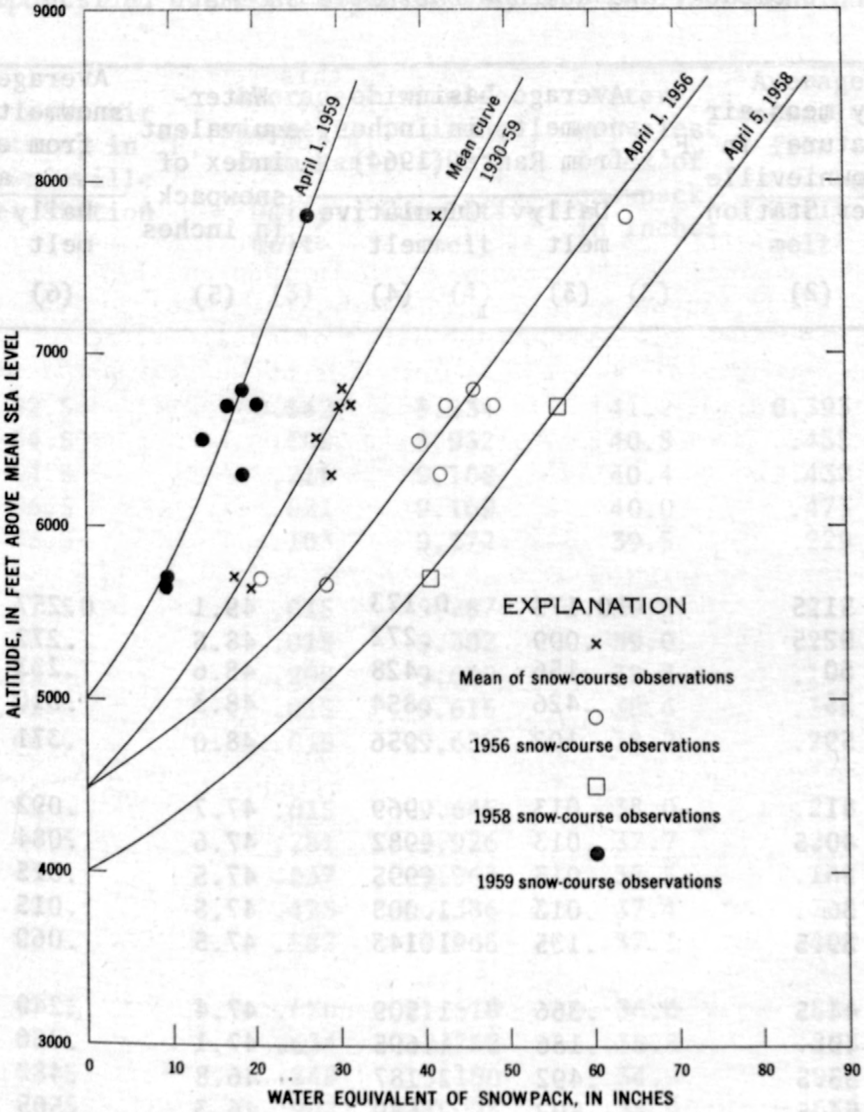


FIGURE 2.--Relation of water equivalent of snowpack to altitude, at start of melt season.

TABLE 2.--*Daily values of mean air temperature, water-equivalent index of the snowpack, and average basinwide snowmelt in 1956*

| Day | Daily mean air temperature, in °F, at Downieville Ranger Station | Average basinwide snowmelt, in inches, from Rantz (1964) | | Water-equivalent index of snowpack, in inches | Average basinwide snowmelt, in inches, from equations 2 and 3 | |
|---|---|---|---|---|---|---|
| | | Daily melt | Cumulative melt | | Daily melt | Cumulative melt |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| *April* | | | | | | |
| 1 | | | | | | |
| 2 | | | | | | |
| 3 | | | | | | |
| 4 | | | | | | |
| 5 | | | | | | |
| 6 | 51.5 | 0.173 | 0.173 | 49.1 | 0.257 | 0.257 |
| 7 | 52.5 | .099 | .272 | 48.8 | .272 | .529 |
| 8 | 50 | .156 | .428 | 48.6 | .233 | .762 |
| 9 | 55 | .426 | .854 | 48.3 | .310 | 1.072 |
| 10 | 59 | .102 | .956 | 48.0 | .371 | 1.443 |
| 11 | 41 | .013 | .969 | 47.7 | .092 | 1.535 |
| 12 | 40.5 | .013 | .982 | 47.6 | .084 | 1.619 |
| 13 | 36 | .013 | .995 | 47.5 | .015 | 1.634 |
| 14 | 36 | .013 | 1.008 | 47.5 | .015 | 1.649 |
| 15 | 39.5 | .135 | 1.143 | 47.5 | .069 | 1.718 |
| 16 | 44.5 | .366 | 1.509 | 47.4 | .249 | 1.967 |
| 17 | 49 | .186 | 1.695 | 47.1 | .366 | 2.333 |
| 18 | 53.5 | .492 | 2.187 | 46.8 | .482 | 2.815 |
| 19 | 54.5 | .502 | 2.689 | 46.3 | .505 | 3.320 |
| 20 | 58 | .825 | 3.514 | 45.8 | .592 | 3.912 |
| 21 | 58 | .649 | 4.163 | 45.2 | .588 | 4.500 |
| 22 | 56.5 | .711 | 4.874 | 44.6 | .546 | 5.046 |
| 23 | 57.5 | .711 | 5.585 | 44.1 | .568 | 5.614 |
| 24 | 59 | .643 | 6.228 | 43.5 | .601 | 6.215 |
| 25 | 50 | .042 | 6.270 | 42.9 | .373 | 6.588 |
| 26 | 42.5 | .023 | 6.293 | 42.5 | .186 | 6.774 |
| 27 | 42.5 | .230 | 6.523 | 42.3 | .185 | 6.959 |
| 28 | 45 | .353 | 6.876 | 42.1 | .246 | 7.205 |
| 29 | 46.5 | .463 | 7.339 | 41.9 | .283 | 7.488 |
| 30 | 51 | .653 | 7.992 | 41.6 | .392 | 7.880 |

TABLE 2.--*Daily values of mean air temperature, water-equivalent index of the snowpack, and average basinwide snowmelt in 1956*--Continued

| Day | Daily mean air temperature, in °F, at Downieville Ranger Station | Average basinwide snowmelt, in inches, from Rantz (1964) | | Water-equivalent index of snowpack, in inches | Average basinwide snowmelt, in inches, from equations 4 and 5 | |
|---|---|---|---|---|---|---|
| | | Daily melt | Cumulative melt | | Daily melt | Cumulative melt |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| *May* | | | | | | |
| 1 | 52.5 | 0.542 | 8.534 | 41.2 | 0.393 | 8.273 |
| 2 | 54.5 | .398 | 8.932 | 40.8 | .435 | 8.708 |
| 3 | 54.5 | .216 | 9.148 | 40.4 | .432 | 9.140 |
| 4 | 56.5 | .021 | 9.169 | 40.0 | .473 | 9.613 |
| 5 | 45.5 | .103 | 9.272 | 39.5 | .229 | 9.842 |
| 6 | 47.5 | .015 | 9.287 | 39.3 | .272 | 10.114 |
| 7 | 47 | .015 | 9.302 | 39.0 | .259 | 10.373 |
| 8 | 42 | .298 | 9.600 | 38.7 | .150 | 10.523 |
| 9 | 51 | .015 | 9.615 | 38.6 | .343 | 10.866 |
| 10 | 48 | .015 | 9.630 | 38.2 | .277 | 11.143 |
| 11 | 45 | .015 | 9.645 | 38.0 | .212 | 11.355 |
| 12 | 44.5 | .281 | 9.926 | 37.7 | .200 | 11.555 |
| 13 | 43 | .037 | 9.963 | 37.5 | .168 | 11.723 |
| 14 | 49 | .423 | 10.386 | 37.4 | .293 | 12.016 |
| 15 | 57 | .582 | 10.968 | 37.1 | .458 | 12.474 |
| 16 | 61.5 | .650 | 11.618 | 36.6 | .824 | 13.298 |
| 17 | 63 | .634 | 12.252 | 35.8 | .852 | 14.150 |
| 18 | 65.5 | .848 | 13.100 | 34.9 | .905 | 15.055 |
| 19 | 58.5 | .908 | 14.008 | 34.0 | .679 | 15.734 |
| 20 | 63 | .990 | 14.998 | 33.4 | .795 | 16.529 |
| 21 | 64 | .969 | 15.967 | 32.6 | .804 | 17.333 |
| 22 | 66.5 | 1.063 | 17.030 | 31.8 | .851 | 18.184 |
| 23 | 65 | .984 | 18.014 | 30.9 | .788 | 18.972 |
| 24 | 60.5 | .708 | 18.722 | 30.1 | .652 | 19.624 |
| 25 | 61.5 | .780 | 19.502 | 29.5 | .664 | 20.288 |
| 26 | 63.5 | .980 | 20.482 | 28.8 | .698 | 20.986 |
| 27 | 58.5 | .647 | 21.129 | 28.1 | .561 | 21.547 |
| 28 | 55.5 | .613 | 21.742 | 27.6 | .481 | 22.028 |
| 29 | 61 | .596 | 22.338 | 27.1 | .599 | 22.627 |
| 30 | 62.5 | .767 | 23.105 | 26.5 | .619 | 23.246 |
| 31 | 58.5 | .623 | 23.728 | 25.9 | .517 | 23.763 |

TABLE 2.--*Daily values of mean air temperature, water-equivalent index of the snowpack, and average basinwide snowmelt in 1956*--Continued

| Day | Daily mean air temperature, in °F, at Downieville Ranger Station | Average basinwide snowmelt, in inches, from Rantz (1964) Daily melt | Average basinwide snowmelt, in inches, from Rantz (1964) Cumulative melt | Water-equivalent index of snowpack, in inches | Average basinwide snowmelt, in inches, from equations 6 and 7 Daily melt | Average basinwide snowmelt, in inches, from equations 6 and 7 Cumulative melt |
|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| *June* | | | | | | |
| 1 | 55.5 | 0.527 | 24.255 | 25.3 | 0.259 | 24.022 |
| 2 | 57.5 | .493 | 24.748 | 25.1 | .282 | 24.304 |
| 3 | 66 | .714 | 25.462 | 24.8 | .384 | 24.688 |
| 4 | 57 | .304 | 25.766 | 24.4 | .268 | 24.956 |
| 5 | 49 | .249 | 26.015 | 24.1 | .169 | 25.125 |
| 6 | 51.5 | .298 | 26.313 | 24.0 | .198 | 25.323 |
| 7 | 57 | .331 | 26.644 | 23.8 | .262 | 25.585 |
| 8 | 59.5 | .312 | 26.956 | 23.5 | .288 | 25.873 |
| 9 | 63 | .368 | 27.324 | 23.2 | .325 | 26.198 |
| 10 | 62 | .377 | 27.701 | 22.9 | .309 | 26.507 |
| 11 | 59 | .254 | 27.955 | 22.6 | .271 | 26.778 |
| 12 | 61.5 | .245 | 28.200 | 22.3 | .295 | 27.073 |
| 13 | 62 | .220 | 28.420 | 22.0 | .297 | 27.370 |
| 14 | 63.5 | .091 | 28.511 | 21.7 | .309 | 27.679 |
| 15 | 53 | .154 | 28.665 | 21.4 | .193 | 27.872 |
| 16 | 54.5 | .180 | 28.845 | 21.2 | .149 | 28.021 |
| 17 | 56.5 | .191 | 29.036 | 21.1 | .163 | 28.184 |
| 18 | 65.5 | .281 | 29.317 | 20.9 | .229 | 28.413 |
| 19 | 68 | .272 | 29.589 | 20.7 | .246 | 28.659 |
| 20 | 55.5 | .190 | 29.779 | 20.4 | .151 | 28.810 |
| 21 | 58 | .204 | 29.983 | 20.3 | .168 | 28.978 |
| 22 | 65 | .238 | 30.221 | 20.1 | .217 | 29.195 |
| 23 | 67 | .304 | 30.525 | 19.9 | .229 | 29.424 |
| 24 | 62.5 | .206 | 30.731 | 19.7 | .195 | 29.619 |
| 25 | 62.5 | .228 | 30.959 | 19.5 | .193 | 29.812 |
| 26 | 69 | .234 | 31.193 | 19.3 | .236 | 30.048 |
| 27 | 75 | .294 | 31.487 | 19.1 | .275 | 30.323 |
| 28 | 76.5 | .297 | 31.784 | 18.8 | .281 | 30.604 |
| 29 | 76 | .258 | 32.042 | 18.5 | .273 | 30.877 |
| 30 | 70 | .205 | 32.247 | 18.2 | .229 | 31.106 |

TABLE 3.--*Daily values of mean air temperature, water-equivalent index of the snowpack, and average basinwide snowmelt in 1958*

| Day | Daily mean air temperature, in °F, at Downieville Ranger Station | Average basinwide snowmelt, in inches, from Rantz (1964) | | Water-equivalent index of snowpack, in inches | Average basinwide snowmelt, in inches, from equations 2 and 3 | |
|---|---|---|---|---|---|---|
| | | Daily melt | Cumulative melt | | Daily melt | Cumulative melt |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| *April* | | | | | | |
| 1 | | | | | | |
| 2 | | | | | | |
| 3 | | | | | | |
| 4 | | | | | | |
| 5 | | | | | | |
| 6 | | | | | | |
| 7 | | | | | | |
| 8 | 42 | 0.098 | 0.098 | 60.9 | 0.122 | 0.122 |
| 9 | 44.5 | .161 | .259 | 60.8 | .164 | .286 |
| 10 | 48.5 | .186 | .445 | 60.6 | .234 | .520 |
| 11 | 51 | .128 | .573 | 60.4 | .277 | .797 |
| 12 | 49.5 | .168 | .741 | 60.1 | .250 | 1.047 |
| 13 | 53.5 | .419 | 1.160 | 59.9 | .318 | 1.365 |
| 14 | 52 | .438 | 1.598 | 59.5 | .292 | 1.657 |
| 15 | 51 | .328 | 1.926 | 59.2 | .274 | 1.931 |
| 16 | 53 | .356 | 2.282 | 59.0 | .535 | 2.466 |
| 17 | 53.5 | .324 | 2.606 | 58.4 | .546 | 3.012 |
| 18 | 51 | .489 | 3.095 | 57.9 | .470 | 3.482 |
| 19 | 50.5 | .301 | 3.396 | 57.4 | .453 | 3.935 |
| 20 | 53.5 | .413 | 3.809 | 57.0 | .538 | 4.473 |
| 21 | 56 | .749 | 4.558 | 56.4 | .607 | 5.080 |
| 22 | 56 | .203 | 4.761 | 55.8 | .604 | 5.684 |
| 23 | 40 | .071 | 4.832 | 55.2 | .143 | 5.827 |
| 24 | 40.5 | .034 | 4.866 | 55.1 | .157 | 5.984 |
| 25 | 44.5 | .262 | 5.128 | 54.9 | .270 | 6.254 |
| 26 | 47.5 | .524 | 5.652 | 54.6 | .355 | 6.609 |
| 27 | 46 | .122 | 5.774 | 54.3 | .311 | 6.920 |
| 28 | 50.5 | .138 | 5.912 | 54.0 | .437 | 7.357 |
| 29 | 51.5 | .655 | 6.567 | 53.5 | .463 | 7.820 |
| 30 | 49.5 | .361 | 6.928 | 53.1 | .405 | 8.225 |

TABLE 3.--*Daily values of mean air temperature, water-equivalent index of the snowpack, and average basinwide snowmelt in 1958*--Continued

| Day | Daily mean air temperature, in °F, at Downieville Ranger Station | Average basinwide snowmelt, in inches, from Rantz (1964) | | Water-equivalent index of snowpack, in inches | Average basinwide snowmelt, in inches, from equations 4 and 5 | |
|---|---|---|---|---|---|---|
| | | Daily melt | Cumulative melt | | Daily melt | Cumulative melt |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| *May* | | | | | | |
| 1 | 54.5 | 0.641 | 7.569 | 52.7 | 0.528 | 8.753 |
| 2 | 56 | .724 | 8.293 | 52.1 | .564 | 9.317 |
| 3 | 54 | .746 | 9.039 | 51.6 | .506 | 9.823 |
| 4 | 57.5 | .915 | 9.954 | 51.1 | .595 | 10.418 |
| 5 | 60 | 1.021 | 10.975 | 50.5 | .655 | 11.073 |
| 6 | 55.5 | .663 | 11.638 | 49.8 | .531 | 11.604 |
| 7 | 53.5 | .636 | 12.274 | 49.3 | .476 | 12.080 |
| 8 | 60 | .826 | 13.100 | 48.8 | .638 | 12.718 |
| 9 | 62 | .964 | 14.064 | 48.2 | .683 | 13.401 |
| 10 | 64 | .365 | 14.429 | 47.5 | .725 | 14.126 |
| 11 | 52 | .268 | 14.697 | 46.8 | .420 | 14.546 |
| 12 | 46.5 | .206 | 14.903 | 46.4 | .282 | 14.828 |
| 13 | 44 | .508 | 15.411 | 46.1 | .220 | 15.048 |
| 14 | 53 | .705 | 16.116 | 45.9 | .438 | 15.486 |
| 15 | 57.5 | .723 | 16.839 | 45.4 | .544 | 16.030 |
| 16 | 64 | .995 | 17.834 | 44.9 | 1.107 | 17.137 |
| 17 | 66 | 1.053 | 18.887 | 43.8 | 1.154 | 18.291 |
| 18 | 65.5 | 1.091 | 19.978 | 42.6 | 1.104 | 19.395 |
| 19 | 60 | .960 | 20.938 | 41.5 | .882 | 20.277 |
| 20 | 63.5 | .798 | 21.736 | 40.6 | .983 | 21.260 |
| 21 | 63 | .700 | 22.436 | 39.6 | .942 | 22.202 |
| 22 | 65 | .609 | 23.045 | 38.7 | .987 | 23.189 |
| 23 | 54.5 | .595 | 23.640 | 37.7 | .625 | 23.814 |
| 24 | 54 | .427 | 24.067 | 37.1 | .599 | 24.413 |
| 25 | 60 | .923 | 24.990 | 36.5 | .776 | 25.189 |
| 26 | 59 | .832 | 25.822 | 35.7 | .728 | 25.917 |
| 27 | 58 | .757 | 26.579 | 35.0 | .684 | 26.601 |
| 28 | 55 | .648 | 27.227 | 34.3 | .583 | 27.184 |
| 29 | 57 | .520 | 27.747 | 33.7 | .630 | 27.814 |
| 30 | 58.5 | .656 | 28.403 | 33.1 | .661 | 28.475 |
| 31 | 59.5 | .578 | 28.981 | 32.4 | .675 | 29.150 |

TABLE 3.--*Daily values of mean air temperature, water-equivalent index of the snowpack, and average basinwide snowmelt in 1958*--Continued

| Day | Daily mean air temperature, in °F, at Downieville Ranger Station | Average basinwide snowmelt, in inches, from Rantz (1964) | | Water-equivalent index of snowpack, in inches | Average basinwide snowmelt, in inches, from equations 6 and 7 | |
|---|---|---|---|---|---|---|
| | | Daily melt | Cumulative melt | | Daily melt | Cumulative melt |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| *June* | | | | | | |
| 1 | 55.5 | 0.483 | 29.464 | 31.7 | 0.325 | 29.475 |
| 2 | 59 | .201 | 29.665 | 31.4 | .377 | 29.852 |
| 3 | 52.5 | .115 | 29.780 | 31.0 | .271 | 30.123 |
| 4 | 51 | .410 | 30.190 | 30.8 | .246 | 30.369 |
| 5 | 61 | .416 | 30.606 | 30.5 | .396 | 30.765 |
| 6 | 59.5 | .434 | 31.040 | 30.1 | .369 | 31.134 |
| 7 | 54.5 | .193 | 31.233 | 29.8 | .291 | 31.425 |
| 8 | 56 | .153 | 31.386 | 29.5 | .310 | 31.735 |
| 9 | 52.5 | .140 | 31.526 | 29.2 | .256 | 31.991 |
| 10 | 49.5 | .294 | 31.820 | 28.9 | .210 | 32.201 |
| 11 | 56.5 | .187 | 32.007 | 28.7 | .309 | 32.510 |
| 12 | 56.5 | .168 | 32.175 | 28.4 | .305 | 32.815 |
| 13 | 50 | .135 | 32.310 | 28.1 | .211 | 33.026 |
| 14 | 61 | .399 | 32.709 | 27.9 | .363 | 33.389 |
| 15 | 65.5 | .383 | 33.092 | 27.5 | .419 | 33.808 |
| 16 | 68.5 | .298 | 33.390 | 27.1 | .327 | 34.135 |
| 17 | 69 | .327 | 33.717 | 26.8 | .328 | 34.463 |
| 18 | 72 | .290 | 34.007 | 26.4 | .352 | 34.815 |
| 19 | 66 | .264 | 34.271 | 26.1 | .291 | 35.106 |
| 20 | 63 | .221 | 34.492 | 25.8 | .260 | 35.366 |
| 21 | 68 | .273 | 34.765 | 25.5 | .303 | 35.669 |
| 22 | 67.5 | .250 | 35.015 | 25.2 | .295 | 35.964 |
| 23 | 73 | .307 | 35.322 | 24.9 | .341 | 36.305 |
| 24 | 68 | .249 | 35.571 | 24.6 | .292 | 36.597 |
| 25 | 65 | .261 | 35.832 | 24.3 | .262 | 36.859 |
| 26 | 70 | .307 | 36.139 | 24.0 | .302 | 37.161 |
| 27 | 65.5 | .162 | 36.301 | 23.7 | .260 | 37.421 |
| 28 | 61.5 | .200 | 36.501 | 23.5 | .224 | 37.645 |
| 29 | 62 | .200 | 36.701 | 23.3 | .226 | 37.871 |
| 30 | 59 | .187 | 36.888 | 23.0 | .199 | 38.070 |

TABLE 4.--*Daily values of mean air temperature, water-equivalent index of the snowpack, and average basinwide snowmelt in 1959*

| Day | Daily mean air temperature, in °F, at Downieville Ranger Station | Average basinwide snowmelt, in inches, from Rantz (1964): Daily melt | Average basinwide snowmelt, in inches, from Rantz (1964): Cumulative melt | Water-equivalent index of snowpack, in inches | Average basinwide snowmelt, in inches, from equations 2 and 3: Daily melt | Average basinwide snowmelt, in inches, from equations 2 and 3: Cumulative melt |
|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| *April* | | | | | | |
| 1 | 55 | 0.193 | 0.193 | 20.0 | 0.225 | 0.225 |
| 2 | 58.5 | .340 | .533 | 19.8 | .263 | .488 |
| 3 | 55 | .373 | .906 | 19.5 | .224 | .712 |
| 4 | 57 | .647 | 1.553 | 19.3 | .245 | .957 |
| 5 | 57 | .481 | 2.034 | 19.0 | .244 | 1.201 |
| 6 | 56 | .399 | 2.433 | 18.8 | .232 | 1.433 |
| 7 | 57 | .013 | 2.446 | 18.6 | .243 | 1.676 |
| 8 | 53.5 | .013 | 2.459 | 18.3 | .203 | 1.879 |
| 9 | 51.5 | .162 | 2.621 | 18.1 | .181 | 2.060 |
| 10 | 54 | .260 | 2.881 | 17.9 | .208 | 2.268 |
| 11 | 54 | .462 | 3.343 | 17.7 | .207 | 2.475 |
| 12 | 53.5 | .401 | 3.744 | 17.5 | .201 | 2.676 |
| 13 | 53 | .139 | 3.883 | 17.3 | .195 | 2.871 |
| 14 | 50.5 | .215 | 4.098 | 17.1 | .167 | 3.038 |
| 15 | 49.5 | .359 | 4.457 | 17.0 | .156 | 3.194 |
| 16 | 49 | .306 | 4.763 | 16.8 | .239 | 3.433 |
| 17 | 52 | .200 | 4.963 | 16.6 | .289 | 3.722 |
| 18 | 46.5 | .137 | 5.100 | 16.3 | .194 | 3.916 |
| 19 | 48.5 | .266 | 5.366 | 16.1 | .227 | 4.143 |
| 20 | 51.5 | .279 | 5.645 | 15.9 | .277 | 4.420 |
| 21 | 54 | .360 | 6.005 | 15.6 | .317 | 4.737 |
| 22 | 54.5 | .435 | 6.440 | 15.3 | .324 | 5.061 |
| 23 | 58.5 | .274 | 6.714 | 14.9 | .387 | 5.448 |
| 24 | 60.5 | .591 | 7.305 | 14.6 | .418 | 5.866 |
| 25 | 58.5 | .010 | 7.315 | 14.1 | .381 | 6.247 |
| 26 | 48 | .010 | 7.325 | 13.8 | .210 | 6.457 |
| 27 | 43 | .165 | 7.490 | 13.5 | .128 | 6.585 |
| 28 | 48.5 | .251 | 7.741 | 13.4 | .216 | 6.801 |
| 29 | 59 | .345 | 8.086 | 13.2 | .383 | 7.184 |
| 30 | 62 | .376 | 8.462 | 12.8 | .428 | 7.612 |

TABLE 4.--*Daily values of mean air temperature, water-equivalent index of the snowpack, and average basinwide snowmelt in 1959*--Continued

| Day | Daily mean air temperature, in °F, at Downieville Ranger Station | Average basinwide snowmelt, in inches, from Rantz (1964) | | Water-equivalent index of snowpack, in inches | Average basinwide snowmelt, in inches, from equations 4 and 5 | |
|---|---|---|---|---|---|---|
| | | Daily melt | Cumulative melt | | Daily melt | Cumulative melt |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| *May* | | | | | | |
| 1 | 53.5 | 0.013 | 8.475 | 12.4 | 0.203 | 7.815 |
| 2 | 39 | .013 | 8.488 | 12.2 | .044 | 7.859 |
| 3 | 40 | .056 | 8.544 | 12.1 | .054 | 7.913 |
| 4 | 41.5 | .090 | 8.634 | 12.1 | .070 | 7.983 |
| 5 | 47 | .067 | 8.701 | 12.0 | .130 | 8.113 |
| 6 | 48 | .148 | 8.849 | 11.9 | .140 | 8.253 |
| 7 | 54 | .199 | 9.048 | 11.7 | .203 | 8.456 |
| 8 | 59.5 | .255 | 9.303 | 11.5 | .260 | 8.716 |
| 9 | 55.5 | .234 | 9.537 | 11.3 | .216 | 8.932 |
| 10 | 55.5 | .192 | 9.729 | 11.1 | .214 | 9.146 |
| 11 | 64 | .243 | 9.972 | 10.9 | .300 | 9.446 |
| 12 | 64 | .220 | 10.192 | 10.6 | .297 | 9.743 |
| 13 | 68.5 | .305 | 10.497 | 10.3 | .339 | 10.082 |
| 14 | 57.5 | .150 | 10.647 | 9.9 | .224 | 10.306 |
| 15 | 44 | .043 | 10.690 | 9.7 | .089 | 10.395 |
| 16 | 44 | .041 | 10.731 | 9.6 | .073 | 10.468 |

## Derivation of the Relations

The earlier discussion of parameters (p. 6-7) indicates the rationale used in the derivation of the snowmelt relations. Date within the melt season is a factor in the effectiveness of: (1) Air temperature as an index of the heat transfer to the snowpack, which in turn is an index of average snowmelt; and (2) water-equivalent index at a single altitude level as an index of basinwide water equivalent, which in turn is an index of areal extent of the snowpack. Consequently, the snowmelt season was divided into six periods and a separate relation was used for each. Those periods were April 1-15 and 16-30, May 1-15 and 16-31, and June 1-15 and 16-30. Because daily average basinwide snowmelt is the daily product of average melt and areal extent of the snowpack, divided by total basin area (a constant), we expect the form of the daily equation for each of the six periods to be:

$$Sm = a(WE + b)\ (T + c), \tag{1}$$

where $Sm$ = average basinwide snowmelt, in inches,
$WE$ = water-equivalent index of the snowpack, in inches, at 7,000 feet,
$T$ = mean air temperature, in degrees Fahrenheit, at Downieville Ranger Station,
and $a$, $b$, and $c$ are constants. Furthermore, we expect $a$ to be positive, $b$ to be either positive or negative, and $c$ to be negative.

The data from tables 2-4 were plotted with $Sm$ (col. 3) as ordinate, $T$ (col. 2) as abscissa, and $WE$ as the parameter for a family of curves. The value of $WE$ used for any day was equal to the difference between accumulated snowmelt (col. 4) on the preceding day and the value of $WE$ on the first day of snowmelt. The general position of the plotted points verified the predicted model, as expressed by equation 1. The scatter of those points, however, was quite chaotic; the scatter diagrams are not shown here. A fact immediately apparent was that minus 35 was a suitable value of $c$, because all trial curves tended to converge to a snowmelt value of zero when $T$ = 35°F. That simplified the ensuing trial-and-error procedure to obtain values of $a$ and $b$ that would not only fit the plotted points as satisfactorily as possible, but would also provide a fairly uniform transition between relations for each of the six 2-week periods. The equations of daily snowmelt that were finally derived follow.

| | | | |
|---|---|---|---|
| April | 1-15 | $Sm = 0.00015\ (WE + 55)\ (T - 35)$ | (2) |
| April | 16-30 | $Sm = 0.00030\ (WE + 40)\ (T - 35)$ | (3) |
| May | 1-15 | $Sm = 0.00040\ (WE + 15)\ (T - 35)$ | (4) |
| May | 16-31 | $Sm = 0.00085\ (WE)\ (T - 35)$ | (5) |
| June | 1-15 | $Sm = 0.00050\ (WE)\ (T - 35)$ | (6) |
| June | 16-30 | $Sm = 0.00036\ (WE)\ (T - 35)$ | (7) |

## DISCUSSION OF RESULTS

Tables 2-4 show the melt computed by applying equations 2-7 to the index values listed in column 2 (air temperature) and column 5 (water equivalent) of the tables. In column 5, the water-equivalent index at the 7,000-foot altitude is reduced on each successive day by the computed snowmelt for the previous day. For example, on the first page of table 2, the melt season starts April 6, 1956, with a water equivalent of 49.1 inches, obtained from the snow surveys of early April of 1956. The computed melt April 6, shown in column 6, is 0.26 inch. The water equivalent, therefore, April 7 is 48.8 inches (49.1 minus 0.26). The computed snowmelt values in column 6, when compared with those in column 3, show only fair agreement. That degree of agreement is probably as high as can be expected, because the index values used as independent variables in equations 2-7 are not completely satisfactory. They are, however, the only ones available for use in most basins. Incidentally, it should not be inferred that the values of daily average basinwide snowmelt in column 3, which are used as a standard of comparison, are without error. The values in column 3 were obtained from the 1964 study of the North Yuba River basin. In that study the computed daily values of point snowmelt are considered to be satisfactory, but the daily values of areal extent of the snowpack were derived from a continuous inventory of snowmelt and are subject to considerable error.

Column 7 of tables 2-4 gives accumulated values of computed daily snowmelt. Those values are plotted as dotted-line curves in figures 3-5. For visual comparison, the accumulated values of melt in column 4 of tables 2-4, obtained from the 1964 study of the North Yuba River basin, are plotted as solid-line curves in figures 3-5. The two curves have fair agreement in 1956 and 1958, and what seems to be poor agreement in 1959 (fig. 5). However, most of the discrepancy in 1959 is attributable to the poor agreement in the first 5 days in April, during which equation 2 underestimated the total 5-day melt by 0.8 inch. That error is carried through the entire 1959 snowmelt period in the dotted-line curve of cumulative daily snowmelt.

Where the snowpack covers a large range of altitude, it is not unusual for large errors in computed daily snowmelt to occur during the first few days of the melt season. At that time of the year a "heat deficit" of varying magnitude often exists in the high-altitude part of the snowpack, and the heat received there during those days is not available to cause melt, but instead primes the snowpack, or readies it, for later melt (Rantz, 1964, p. 20). Furthermore, the albedo of the snowpack at that time tends to vary from year to year because the occurrence of snowfall is highly variable in early spring. Referring again to figure 5, if, during April 1959, the hydrologist had kept an additional cumulative record of daily average basinwide snowmelt, computed by applying his routing model in reverse to currently observed streamflow, he would have noticed April 5 that equation 2 had badly underestimated the melt for the first 5 days of the month. He could then have adjusted his values of accumulated snowmelt and water equivalent for use in equation 2 for the days following April 5. On resuming his computations, using equations 2-5, he would have obtained daily values of average basinwide snowmelt, which when accumulated would give the dashed-line curve in figure 5. That curve agrees satisfactorily with the solid-line curve in figure 5.

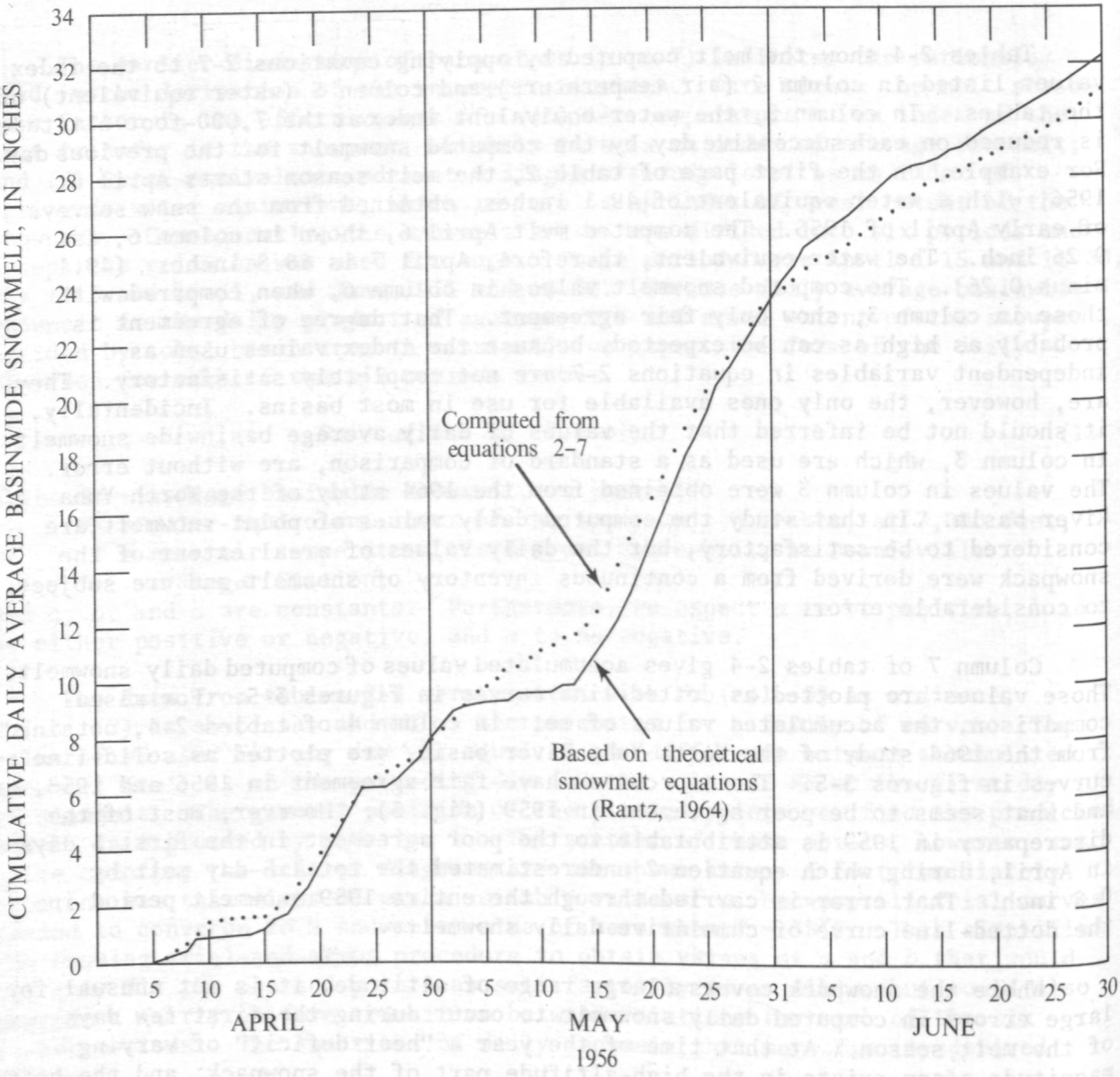


FIGURE 3.--Comparison of graphs of cumulative daily average basinwide snowmelt for 1956, based on theoretical and empirical snowmelt equations.

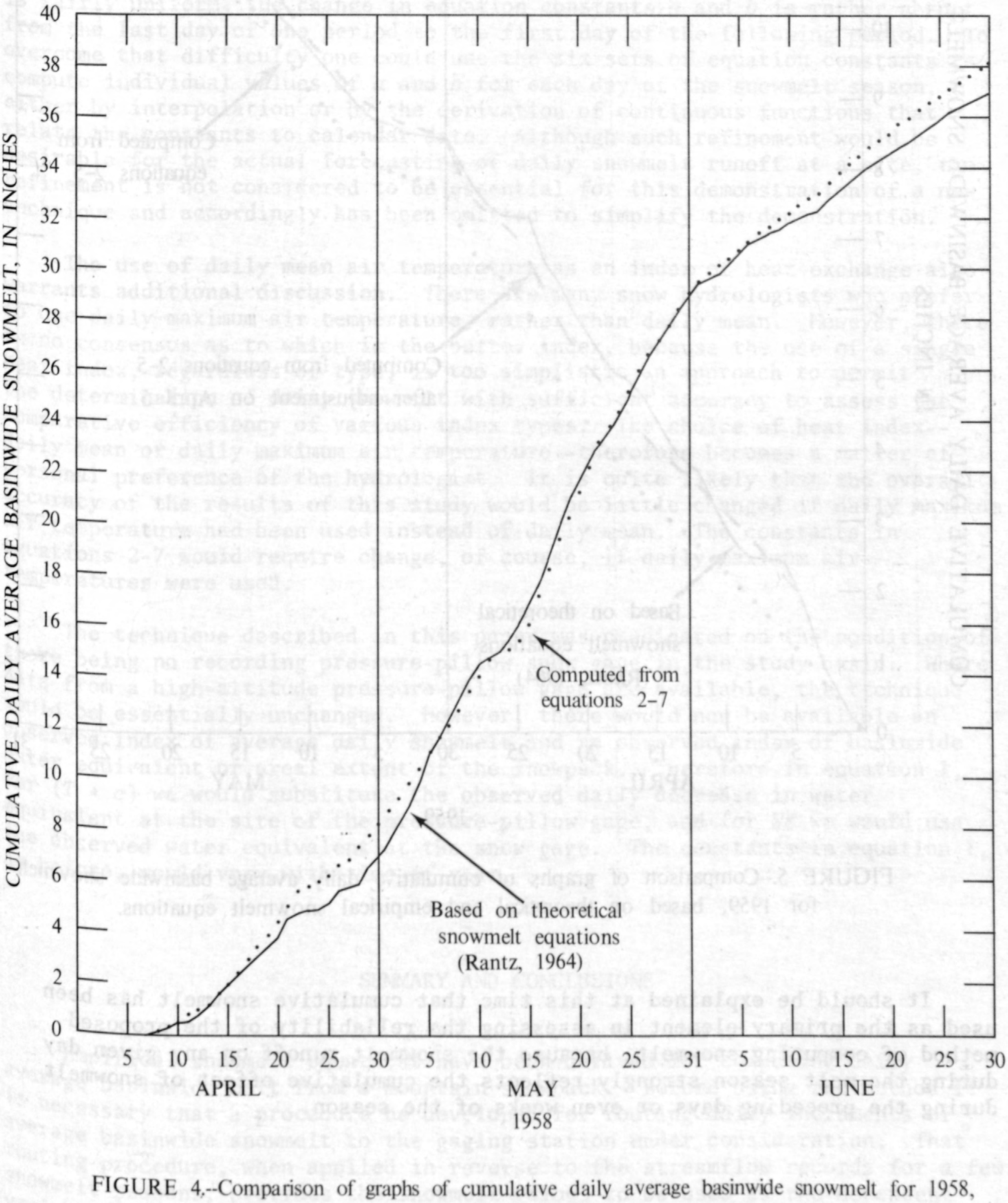


FIGURE 4.--Comparison of graphs of cumulative daily average basinwide snowmelt for 1958, based on theoretical and empirical snowmelt equations.

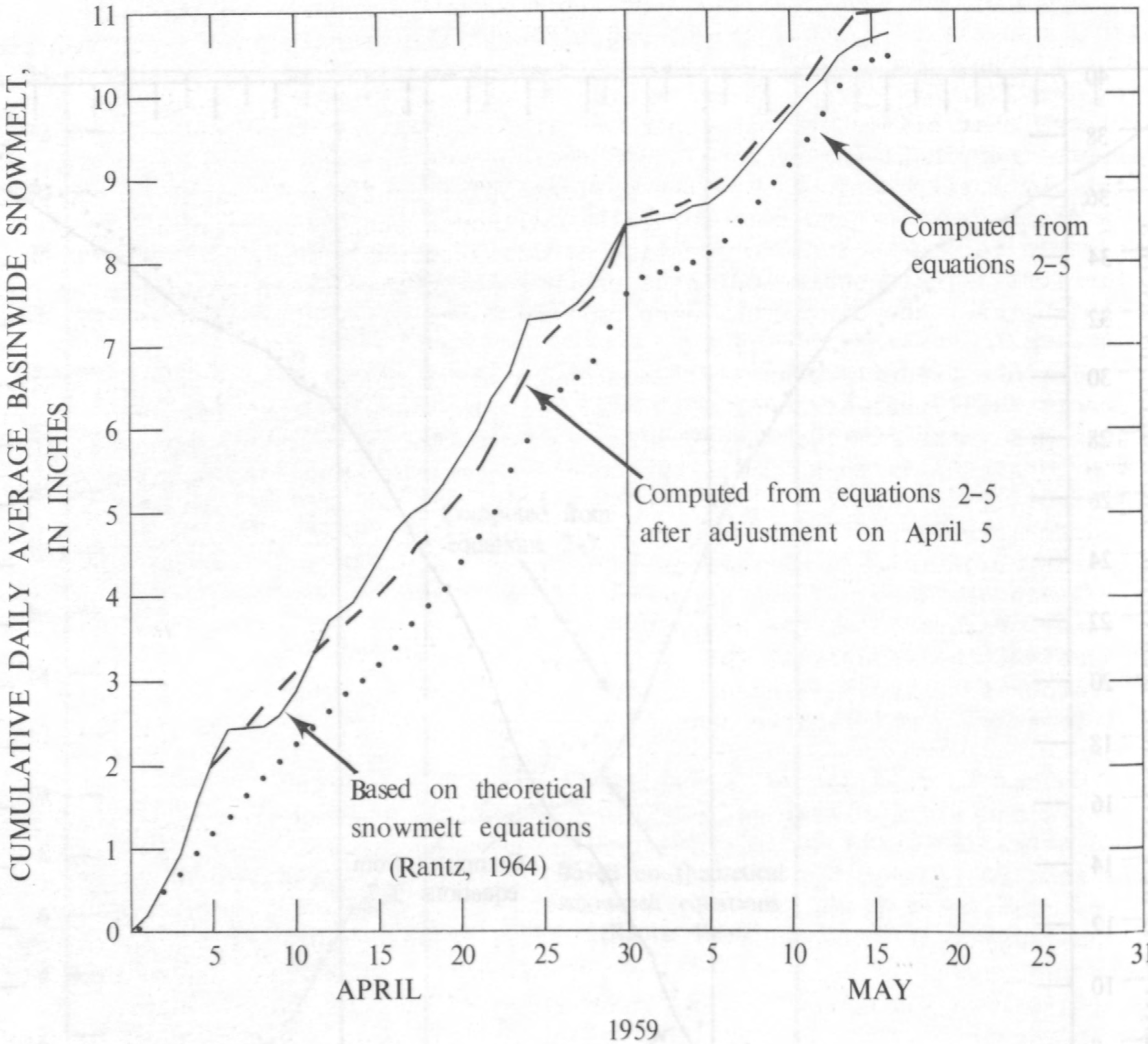


FIGURE 5.--Comparison of graphs of cumulative daily average basinwide snowmelt for 1959, based on theoretical and empirical snowmelt equations.

It should be explained at this time that cumulative snowmelt has been used as the primary element in assessing the reliability of the proposed method of computing snowmelt, because the snowmelt runoff on any given day during the melt season strongly reflects the cumulative effect of snowmelt during the preceding days or even weeks of the season.

Each of the equations 2-7 represents an average daily relation for use within a specified 2-week period, and although the transition between relations is fairly uniform, the change in equation constants $a$ and $b$ is rather abrupt from the last day of one period to the first day of the following period. To overcome that difficulty one could use the six sets of equation constants to compute individual values of $a$ and $b$ for each day of the snowmelt season, either by interpolation or by the derivation of continuous functions that relate the constants to calendar date. Although such refinement would be desirable for the actual forecasting of daily snowmelt runoff at a site, the refinement is not considered to be essential for this demonstration of a new technique and accordingly has been omitted to simplify the demonstration.

The use of daily mean air temperature as an index of heat exchange also warrants additional discussion. There are many snow hydrologists who prefer to use daily maximum air temperature, rather than daily mean. However, there is no consensus as to which is the better index, because the use of a single heat index, regardless of type, is too simplistic an approach to permit the determination of daily snowmelt with sufficient accuracy to assess the comparative efficiency of various index types. The choice of heat index--daily mean or daily maximum air temperature--therefore becomes a matter of personal preference of the hydrologist. It is quite likely that the overall accuracy of the results of this study would be little changed if daily maximum air temperature had been used instead of daily mean. The constants in equations 2-7 would require change, of course, if daily maximum air temperatures were used.

The technique described in this paper was predicated on the condition of there being no recording pressure-pillow snow gage in the study basin. Where data from a high-altitude pressure-pillow gage are available, the technique would be essentially unchanged. However, there would now be available an observed index of average daily snowmelt and an observed index of basinwide water equivalent or areal extent of the snowpack. Therefore in equation 1, for $(T + c)$ we would substitute the observed daily decrease in water equivalent at the site of the pressure-pillow gage, and for $WE$ we would use the observed water equivalent at the snow gage. The constants in equation 1, as before, would vary with time of year.

## SUMMARY AND CONCLUSIONS

Empirical snowmelt equations have been derived for computing daily average basinwide melt from a mountain snowpack. Before using the method it is necessary that a procedure be developed for routing daily increments of average basinwide snowmelt to the gaging station under consideration. That routing procedure, when applied in reverse to the streamflow records for a few snowmelt seasons, provides the snowmelt values to be used as the dependent variable in evaluating the constants in the proposed empirical snowmelt equations. Individual values of the constants are derived for each 2-week period of the snowmelt season.

The daily snowmelt equations that were derived are of the form

$$Sm = a(WE + b)\ (T + c),$$

where $Sm$ = average basinwide snowmelt, in inches,
$WE$ = water-equivalent index of the snowpack, in inches, at some selected high altitude,
$T$ = mean air temperature, in degrees Fahrenheit, at a climatological station in or near the study basin,
and $a$, $b$, and $c$ are constants.

The water-equivalent index at the start of the melt season is determined from the routine snow surveys made in or near the basin on or about April 1. The index for each subsequent day is obtained by subtracting the computed snowmelt for the preceding day from the water-equivalent index of the preceding day. The water-equivalent index is, in effect, an index of the areal extent of the snowpack on each day.

The proposed snowmelt equations seem to be a great improvement over those used in the traditional degree-day method. It is intended that the method described above be used only in the absence of the specialized meteorological data needed for applying the more sophisticated snowmelt equations that are based on rigorous physical laws of heat transfer and in the absence of data from a high-altitude pressure-pillow snow gage in the study basin. However, it would seem that the snowmelt equations can be readily modified to make advantageous use of any available data from a pressure-pillow gage in the basin, as explained on page 23.

## REFERENCES CITED

Potts, H. L., 1944, A photographic snow-survey method of forecasting runoff: Am. Geophys. Union Trans., pt. 1, p. 149-152.

Rantz, S. E., 1964, Snowmelt hydrology of a Sierra Nevada stream: U.S. Geol. Survey Water-Supply Paper 1779-R, 36 p.

U.S. Army Corps of Engineers, 1960, Runoff from snowmelt: Eng. Manual 1110-2-1406, 59 p.

Wisler, C. O., and Brater, E. F., 1959, Hydrology: New York, John Wiley and Sons, Inc., 408 p.

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