Dr. Church used the record of the Klamath Basin at Spencer Bridge in his tabulation. Due to the fact that the Klamath Project diverts through their "A" canal, around 200,000 acre-feet during the period April to September above the Spencer Bridge Station and since there may be either inflow into or diversion from Klamath River through the Lost River Diversion (also in connection with the Project) which is also above the Spencer Bridge Station, a truer picture would be obtained by using the "net inflow" into Upper Klamath Lake. This "net inflow" is the amount of water available at the outlet of the lake after the variables such as evaporation and unknown irrigation-use from streams and springs flowing into the lake have had their effect.

To Dr. Church's table has been added the percentage-figures based upon the net-inflow records of Upper Klamath Lake, using the 38-year mean (1904-42). It will be noted that his findings and conclusions relative to soil-effect are still further verified by using the above, there being a still greater spread during March to July and April to July. The fact that July shows the minimum flow instead of September is probably due to irrigation up-country above the Lake outlet.

To Table 1 also has been added the figures based upon the record of Station 722, North Fork of Rogue River, the source of which adjoins the Klamath Basin on the west in the Crater Lake Region and which is also in a volcanic formation watershed. By coincidence the results rather closely follow Dr. Church's percentages using the Klamath River, Spencer Bridge Station.

A SIMPLE PROCEDURE FOR THE DAY-TO-DAY FORECASTING OF RUNOFF FROM SNOW-MELT

Ray K. Linsley, Jr.

Synopsis--During recent years numerous methods for the prediction of rate of snow-melt and resultant runoff have been presented [see 1, 2, 3, 4 of "References" at end of paper]. Some solutions were based on thermodynamic principles. Others made use of simple empiricisms. As yet, however, no procedure has completely supplanted the use of the degree-day factor [4, 5]. The outstanding virtue of the degree-day method is its extreme simplicity. Only records of dry-bulb temperature are necessary to compute degree-days and a simple multiplication by a degree-day "factor" completes the computation of the volume of snow-melt. The great disadvantage of the procedure is that it neglects humidity, radiation, and other factors known to influence the melting-rates of snow. It is the purpose of this paper to outline the methods developed by the office of the Weather Bureau at Sacramento, California, for applying the degree-day procedure to river-forecasting in the Sacramento and San Joaquin river-basins.

Introduction--In the development of river-forecasting schemes for the Sacramento River District it was necessary to include a procedure which would enable the forecaster to anticipate the probable contribution of melting snow to stream-flow, especially during flood-periods. Since melting snow is not ordinarily a large contributor to floods in this region [6] and since the forecast for the entire district, comprising some 45,000 square miles, must be completed in a very short time, the procedure for predicting snow-melt runoff had to be as simple and as mechanical as was consistent with the necessary accuracy. Few records of meteorological elements other than temperature and precipitation are available from the remote areas of the Sierra Nevada where the heavy snowpack accumulates. These facts all indicated that the degree-day procedure would probably be the only satisfactory approach.

There are two difficulties which must be overcome before such a procedure can be considered adequate for purposes of forecasting. The first of these arises from the extreme range in elevation between the lower limit of the snow and the upper elevation of the basins. Because of this difference in elevation melting may often take place over only the lower portion of the snow-field. The second difficulty develops because the degree-day number is only an approximate index of many melting-factors. It therefore is quite likely to be a variable, and the laws governing this variation must be understood before the procedure can be applied.

The solution finally adopted is based on the use of two curves. The first has been named the "unit-melt diagram" (Fig. 1) while the second is the degree-day-number curve (Fig. 2).

The unit-melt diagram--Depending upon antecedent conditions, the lower limit of the snowpack in the Sierra Nevada may range from about the 3,000-foot level upwards. Melting of snow can take place only in the zone from the snow-line up to approximately the elevation of the 32° isotherm. Runoff from the melting snow will probably only occur in the lower portion of this melting-zone, since in the upper reaches most of the available heat will serve only to ripen the snow to the point where subsequent melting can result in runoff.

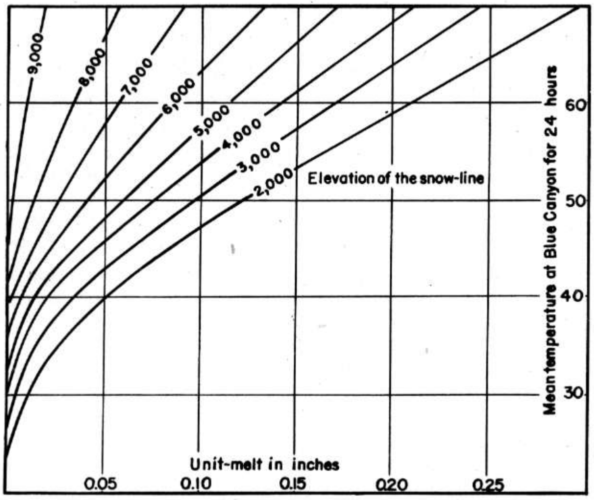

Fig. 1--Unit-melt curves, Tuolumne River above Don Pedro Dam

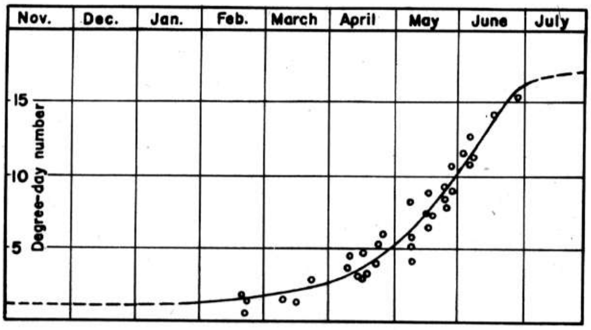

Fig. 2--Degree-day-number curve, Lower San Joaquin Basin

In applying the degree-day method to estimate the snow-melt or runoff from this zone it is first necessary to determine the average number of degree-days above 32° F which occurred over this melting-zone during a given period. The computation involves the steps of:

(1) Dividing the basin into intervals of elevation
(2) Determining the mean temperature in each elevation interval and converting this temperature to degree-days above 32° F
(3) Weighting the degree-days in each zone in proportion to the drainage-area within each zone
(4) Dividing the sum of the weighted degree-days by the total basin-area to get average degree-days for the basin

The unit-melt diagram of Figure 1 was computed in just this manner and thus permits the forecaster to determine the average number of degree-days effective for snow-melt at a single entry. The controlling elements are the temperature at an index-station and the elevation of the snow-line. The final result is given in terms of "unit-melt" rather than degree-days. The term unit-melt as used in this paper may be defined as the depth of runoff in inches over the entire drainage-basin if 0.01 inch of runoff occurs in the melting-zone for each degree-day above 32° F. It is determined simply by dividing average degree-days over the basin by 100.

Figure 1 makes use of only one temperature index-station. Temperatures at other elevations were determined by assuming a lapse-rate of temperature of 3° F per 1000-foot change in elevation. This approach was necessitated by the lack of available stations. More stations would have been used had they been available. The assumption of the lapse-rate of 3° F per 1000 feet is justified by the fact that this diagram is designed for use primarily during flood-periods when heavy rain would make the moist adiabatic lapse-rate applicable. If desired, similar curves could be developed assuming other values of lapse-rate. A lapse-rate of 3°.5 F per thousand feet proved more satisfactory in the Upper San Joaquin Basin. In any case if the index-station is selected near the average elevation of the snowpack, errors in the assumed lapse-rate will be at least partially self-compensating.

Since degree-days are a function of both time and temperature, the unit-melt diagram must be developed for a specified time-unit. Figure 1 applies for 24-hour periods. A similar diagram could be developed for use with six-hour periods or values from Figure 1 could be divided by four.

The relative positions of the curves of the unit-melt diagram are dependent on the percentage of basin-area within each interval of elevation. Basins of similar topographic characteristics, therefore, will have, regardless of size, nearly similar unit-melt diagrams. It has been found possible to use the same unit-melt diagram for several basins without serious error. A comparison of curves of percentage-area against elevation will indicate the feasibility of this step.

The degree-day number--The unit-melt diagram gives values of snow-melt runoff only if one degree-day results in 0.01 inch of runoff. It is usually necessary to determine a factor by which the unit-melt may be multiplied to give actual volumes of snow-melt or runoff. Since relations of this sort are used primarily for stream-flow forecasting and since it is quite difficult to determine actual volumes of snow-melt, the degree-day number will usually express the runoff per degree-day.

The degree-day number may be determined by dividing the total runoff from the basin for a short period by the concurrent unit-melt. The observed runoff should be corrected for runoff from rainfall. This may be done by means of a rainfall-runoff relation for the basin, but because of the possible error in such a procedure it is usually best to determine the degree-day number from periods when little or no rain occurred. Correction of the observed runoff for base-flow will undoubtedly improve the results. However, the separation of base-flow from surface-runoff during periods of snow-melt is a rather difficult process and little error will result if the base-flow is included.

Runoff from snow-melt probably reaches the stream mostly through sub-surface and ground-water channels with relatively small amounts of true surface-runoff. If we consider three successive weekly periods, some of the accretion to base-flow during the first week will appear as stream-flow during the second week, making the apparent degree-day number computed for the second week too high. However, some of the accretion to base-flow during the second week will appear in the streams at a later time, thus compensating for the first error. If the degree-day number is computed for successive periods during the melting-season, it is probable that if one computation gives a figure that is too high the following period may give a result that is too low. Thus the average throughout the season should be approximately correct.

If the degree-day number determined in the manner just discussed appears to be a constant or reasonably constant value, the solution is complete. In fact, the abscissas of the unit-melt diagram may then be multiplied by this constant and the use of a separate degree-day factor eliminated.

It is characteristic of basins tributary to the Central Valley of California that the degree-day number increases as the season progresses. Figure 2 is a curve showing the variation of the degree-day number with calendar date as determined for the Stanislaus and Tuolumne rivers. Almost identical curves were developed for the Mokelumne, American, Kings, Kaweah, Merced, and Upper San Joaquin rivers, but the variation becomes less pronounced in the northern basins.

It is believed that the principal cause of this variation is the gradual ripening of the snow as the season advances, allowing greater amounts of runoff for the same amount of melt or same number of degree-days. The curve also reflects a normal seasonal variation in humidity, solar radiation, and other melting factors for which the dry-bulb temperature alone is not a completely adequate index. It is possible, since the elevation of the melting-zone increases as the season progresses, that the curve also reflects some errors in the area-elevation relationship used to develop the unit-melt curves. The temperature index-station, Blue Canyon, is situated well to the north of the Stanislaus and Tuolumne rivers. The seasonal range in temperature is greater in the southern portion of the valley. Thus during May and June the temperatures at Blue Canyon may be lower than the temperatures at the same elevation in the basins. This is substantiated by the fact that the curves for the northern basins for which Blue Canyon is used as an index are lower during May to July.

The points plotted on Figure 2 represent data taken from the Tuolumne River above Hetch Hetchy, Don Pedro, and the Stanislaus River above Melones. The scatter of points about the average curve undoubtedly results from short-term variations in meteorological conditions, errors in separating runoff from base-flow, errors in estimating elevation of the snow-line, and errors in basic data. When the curve is applied to actual forecasting, much of this deviation can be eliminated. It has, for example, been the writer's experience that it is much simpler to estimate the current elevation of the snow-line than it is to estimate its position on a given date several years past. Moreover, the forecaster can superimpose on the average degree-day-number curve, a secondary variation to allow for known variations in humidity, radiation, and other elements from the average conditions.

Snow-melt by rainfall--The water-content of snow melted by rainfall on the snow-surface is readily susceptible to computation by the procedures just outlined. The heat of fusion of ice is 144 British thermal units per pound while the specific heat of water is one British thermal unit per pound. If the snow is initially at 32° F, then the depth of water melted from the snow by heat from rain is [2]

$$D = (1/144)\ P(T - 32) = 0.007\ P(T - 32) \qquad (1)$$

where P is the depth of rainfall in inches and T is the temperature of the rain. T is best expressed by the wet-bulb temperature during the rain. During periods of rainfall the wet-bulb and dry-bulb temperatures are very nearly equal. The value of unit-melt taken from a diagram similar to Figure 1 therefore gives the term 0.01 (T - 32). Then

$$D = 0.7\ P\ M_u \qquad (2)$$

where M_u is the unit-melt.

It has been noted by many writers [2, 6, 8] that the quantity of water melted from snow by rainfall is small in comparison with other factors. This is quite true but in flood-forecasting it may not be negligible. For example, assuming a snow-line of 5,000 feet and mean temperature of 45°, the unit-melt from Figure 1 is about 0.04 inch. Assuming six inches of rain in 24 hours (not an infrequent occurrence), the resulting snow-melt from equation (2) would equal 0.17 inch on the entire basin. For the American River at Folsom, California, this might increase the crest from 0.5 to 1.0 foot.

Distribution of runoff--The distribution of the predicted runoff from snow-melt with respect to time may be accomplished in various ways. In the Sacramento River District, snow-melt occurring without appreciable rainfall is distributed by means of distribution-graphs. These graphs were developed by trial from records of stream-flow for periods of snow-melt without concurrent rainfall. They are much less sharply peaked than are the distribution-graphs for rainfall-runoff.

When runoff is primarily from rainfall, the estimated snow-melt runoff is added to the predicted rainfall-runoff and the total used in predicting stream-flow by the usual forecast-methods, unit-graphs, or rainfall-runoff-crest-stage relations. In some basins within the district no records of stream-flow are available for Weather Bureau river-gages. In such cases the flood-crest is usually predicted directly from rainfall without recourse to runoff. The degree-day-number curves for these basins are derived from records for adjacent basins and the values of degree-day number are doubled. The predicted snow-melt by this means is added to the rainfall. This is equivalent to assuming a rainfall-runoff percentage of 50.

In the upper San Joaquin Basin where prolonged heavy snow-melt runoff occurs the distribution-graph procedure does not prove satisfactory for predicting the outflow-hydrograph, and a routing procedure was developed.

A recession-curve for periods of snow-melt runoff was developed by plotting flow on one day against flow 24 hours later [9] (Fig. 3). This recession is quite similar to the ground-water recession but does not adhere to the equation $Q = Q_0 k^t$ developed by Barnes [8], probably because of the inclusion of small amounts of surface-runoff at high flows. From this recession a curve of storage versus flow was developed. The storage equation is

$$(\bar{I} - \bar{0}) = \text{change in storage} \qquad (3)$$

where $\bar{I}$ and $\bar{0}$ equal average inflow and outflow, respectively, for the routing period. This can be altered to read

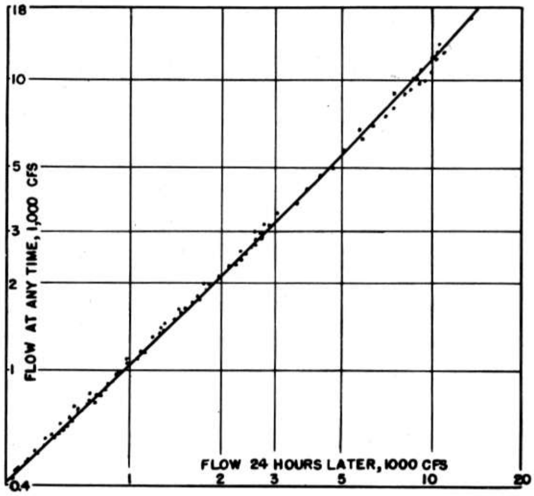

Fig. 3--Recession, Kings River at Piedra

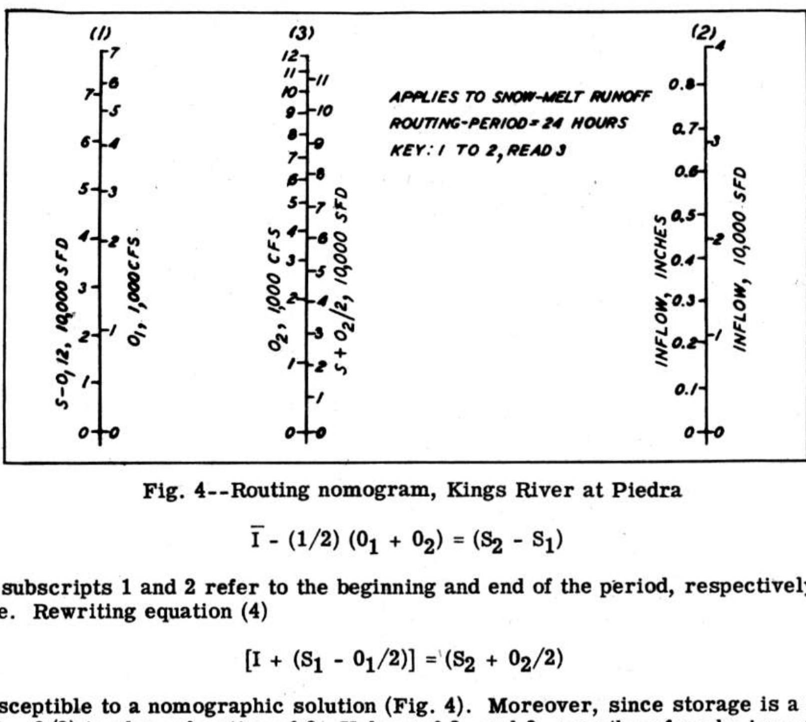

Fig. 4--Routing nomogram, Kings River at Piedra

$$\bar{I} - (1/2)\,(0_1 + 0_2) = (S_2 - S_1) \tag{4}$$

where the subscripts 1 and 2 refer to the beginning and end of the period, respectively, and S is the storage. Rewriting equation (4)

$$[I + (S_1 - 0_1/2)] = (S_2 + 0_2/2) \tag{5}$$

This is susceptible to a nomographic solution (Fig. 4). Moreover, since storage is a function of outflow, $(S + 0/2)$ is also a function of 0. Values of 0_1 and 0_2 may therefore be inserted in place of $(S_1 - 0_1/2)$ and $(S_2 + 0_2/2)$ on the nomogram. Since the inflow from melting snow is computed in inches, values of $\bar{I}$ in inches can be inserted in place of the values in second-foot-days on scale (3). A straight-edge held from the proper flow-value for the beginning of the routing period to the estimated value of I for the period permits reading 0_2 from the central scale.

This provides a very rapid forecasting-procedure and by reversing the process can be used to compute daily values of inflow for the development of the degree-day-number curve.

Conclusion--A method has been presented for the day-to-day prediction of runoff from melting snow with a minimum of labor. The usefulness of the method is increased by the fact that the working curves used in the method may often serve more than one basin. The procedure is applicable in those regions where a semi-permanent snowpack develops during the winter and is particularly adaptable to the basins in which an extreme range in elevation restricts melting at any instant to limited portion of the snow-cover. No new theoretical approach to the problem of melting snow has been introduced, but it is believed that the method should provide a simple and practical tool for hydrologists.

A more complete system of observations of snow-line elevation is essential before the full value of this procedure can be realized in many basins. It is believed also that systematic observations of quality of snow will provide valuable information on the degree-day number. It seems probable that this number may actually prove nearly constant when adjustment for snow-quality is included.

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DISCUSSION

R. A. WORK (Irrigation Engineer, United States Division of Irrigation and Oregon Experiment Station, Medford, Oregon)--I was interested in Mr. LINSLEY'S hope that the day-degree snow-melt would be a constant. CLYDE appeared to find that snow-melt was a constant. In fact, in Clyde's bulletin "Snow melt characteristics," he gives the value. But Messrs. CHILDRETH and FROST and I, working at Crater Lake, found that snow-melt there was not a constant.

The questions of snow-quality, snow-texture, and day-degree versus hour-degree entered into the picture. Our observations of snow-melt were refined to the point of calculation of hour-degrees, and there seems quite a difference in behavior of snow under varying conditions of hour-degrees above 32 compared to day-degrees above 32.

THREE UNUSUAL RUNOFF-YEARS IN THE HUMBOLDT BASIN, NEVADA, 1940-41, 1941-42, AND 1942-43

J. E. Church and H. P. Boardman

The presentation of the paper "The Humboldt Basin, Nevada: Two unusual years, 1940-41 and 1941-42" at the Pasadena Regional Meeting [Trans. Amer. Geophys. Union, pp. 156-159, 1942] and "Forecasting runoff for power and irrigation from relatively low-level areas" by HARRY OLSEN and E. B. PRICE at the Corvallis Regional Meeting (pp. 55-62) makes the present paper desirable as emphasizing the factors of soil-moisture and ground-water level that have previously seemed quite subordinate to those of snow-cover and precipitation.

Unusual opportunity for observing the effect of high water-table on increasing the flow of the Humboldt has been afforded for a second year, while abnormal snow-melt, winter rains, and