survey program in California. Major emphasis should continue to be placed on April 1 surveys. I would certainly not recommend that all early-season snow surveys be discontinued. The value of basic data on early season snow cannot be entirely based upon results of water supply forecasts. However, expansion of the snow survey network for February and March measurements is definitely of secondary importance. The necessity of maintaining some of the more expensive and difficult courses for early season measurements is not as great as we may have previously thought. Study should continue into the feasibility of substituting more readily available information, such as aerial marker data or snow cover photographs, into our early-season forecasts in the interest of accuracy and economy.

The author would like to express his appreciation to Burton Hewett and Edward Hills of the Cooperative Snow Survey office who helped with much of the laborious computation required for this paper, and to Frank Jones of the Machine Computing Section of the Department of Water Resources, who reviewed the statistical approach used.

AERIAL RECONNAISSANCE OF MOUNTAIN SNOW FIELDS FOR MAINTAINING
UP-TO-DATE FORECASTS OF SNOWMELT RUNOFF DURING THE MELT PERIOD

by

Walter J. Parsons and Glenn H. Castle [1]

1. The rapid increase in the need for water in the western states and the construction of numerous multipurpose storage reservoirs to control and reregulate the snowmelt runoff from high mountain basins has increased the need for more accurate forecasting of the snowmelt runoff and particularly for means of progressively adjusting the forecasts as the runoff season advances so that these reservoirs can be operated more efficiently. A promising method of making such progressive adjustments is based on the use of frequent aerial reconnaissance surveys of the mountain snow fields as they melt away.

2. The widespread snowfields on high mountain basins, although actually complex in shape and depth, can be considered for forecast purpose to be simple snow wedges on the mountain slope with their feather edge at the snowline and their greatest depth near the crestline. The total volume of such a snow wedge, which can be correlated with subsequent snowmelt runoff, can be represented as the product of the snow covered area and the average snow depth in inches of water. The snow covered area can be measured at frequent intervals by aerial reconnaissance methods. The average snow depth can be measured initially by regular snow course survey methods and subsequently adjusted for any changes which may have occurred after the date of those surveys by use of regularly available precipitation data. By means of the methods described in this paper, the remaining volume of runoff to be expected after any date in the melt season can be determined with reasonable accuracy solely by occasional measurement of the snow covered area.

3. Forecasting of the remaining runoff during the snowmelt season by this method was first attempted on the Kings River watershed, a 1,500 square mile mountain watershed on the western slope of the Sierra Nevada, east of Fresno, California. A major portion of the runoff of this river occurs between 1 April and 31 July and results from melting of high elevation winter snows. Six years of aerial snow cover data are now available for this watershed. Preliminary forecast curves have also been developed for the adjacent 2,100 square mile Kern River basin where five years of aerial snow cover data are now available. In both cases the snow cover data was obtained by direct sketching of the boundary of the snow covered area on 1 to 500,000 scale aeronautic charts during reconnaissance flights made at altitudes of 10,000 to 15,000 feet in a small high wing plane that provided excellent visibility of the ground. This method of measurement was found to be rapid, accurate, and capable of giving consistent results on Sierra Nevada basins. Direct visual identification of the edge of the snowfields as it wandered in and out of canyons, across polished granite pavements and through masking timber was more positive for an observer flying 2,000 to 5,000 feet above the terrain than could be done from subsequent office study of black-and-white aerial photographs. On-the-spot selection of a generalized line that would average the irregular edge of the

KINGS RIVER BASIN
REMAINING RUNOFF
60 DAYS

Prepared by B. D. M.   January 1959   CHART 2

KINGS RIVER BASIN
SNOW COVER

Prepared by B.D.M.   January 1959   CHART 1

1952
1954
1955
1956
1957
1958
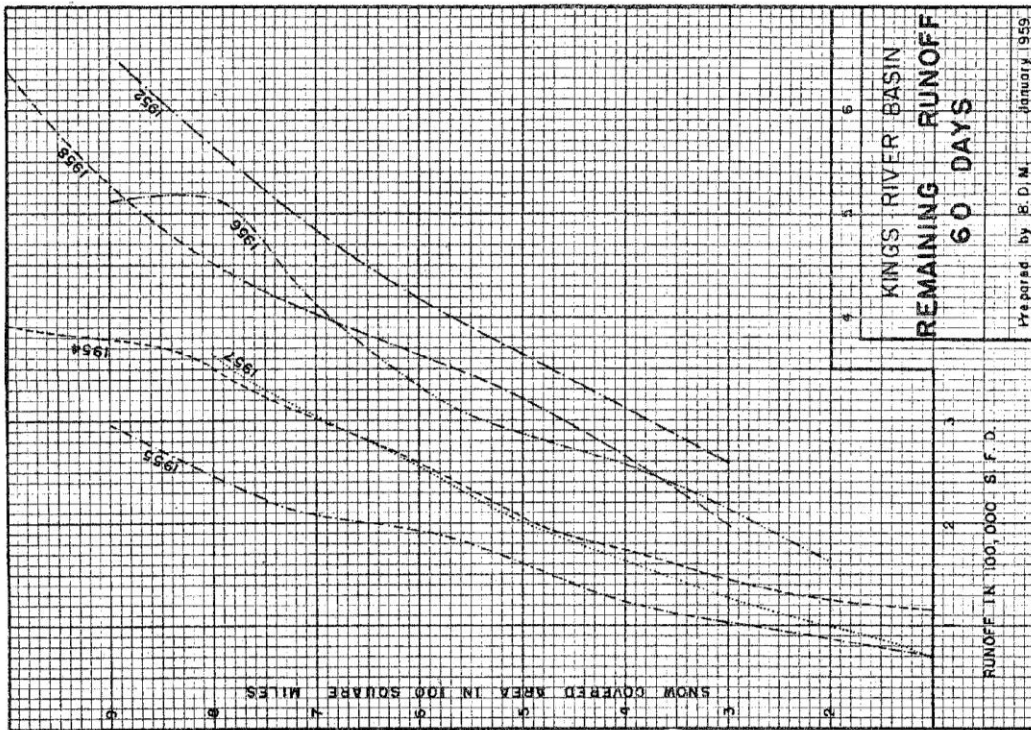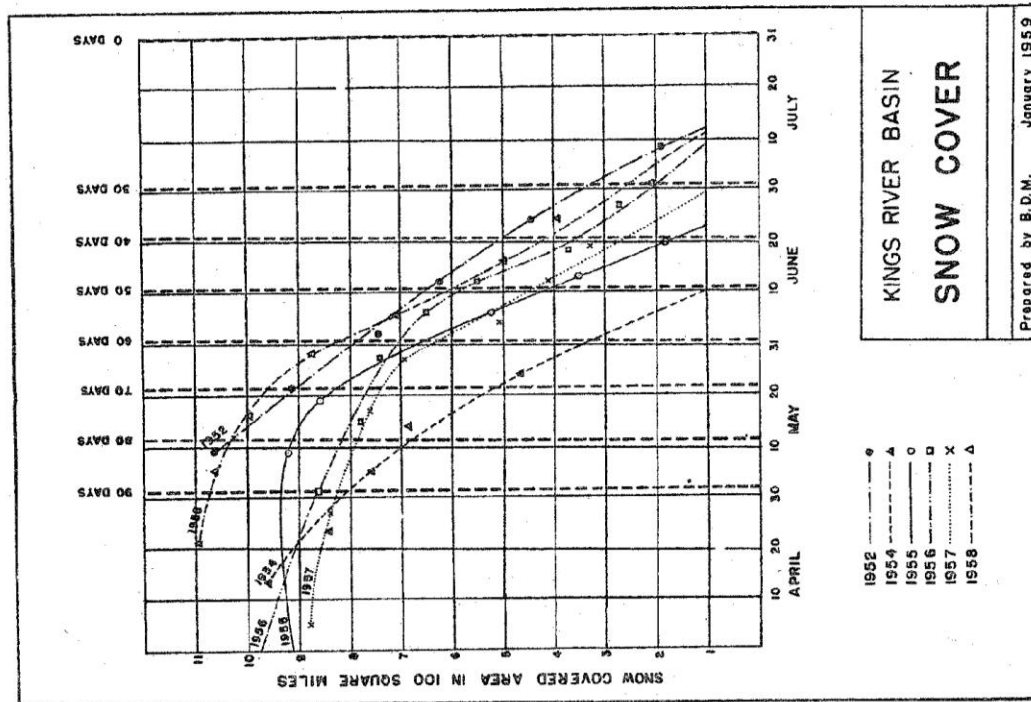
snow fields, and the location of this line in relation to landmarks shown on the aeronautic chart was technically difficult but within the ability of engineer observers. Each successive snowline survey was sketched on a blank transparent sheet overlaying the aeronautic chart in order to assure a current map uninfluenced by previous determinations.

4. The first step in developing a set of current forecast curves for the Kings River watershed was to plot the successive measured areas of snow cover against the dates of each reconnaissance flight, as shown on chart 1. It will be seen that the rate of decrease in snow-covered areas in different years is quite similar but that the dates for any given area differ considerably. The next step was to replot this area data against the runoff observed to occur during various periods of from 30 to 90 days after the date of observation. Chart 2 is the resultant diagram for a 60-day period. This diagram shows that the runoff which actually occurred after the snow covered area had receded to 700 square miles varied from as little as 210,000 second-foot-days in 1955 to as much as 480,000 second-foot-days in 1952, or a difference of 270,000. For a 300 square mile snow area, the observed runoff varied from 105,000 in 1955 to 260,000 in 1952 or a difference of 155,000 second-foot days.

5. These differences in volume of runoff in different years can be largely accounted for by a second factor, the depth of the snow wedge. Examination of the 1 April snow course data for the various years shows that the average water depth varied from 69 percent of normal in 1955 to 199 percent in 1952. The difference in total runoff volume from the last 700 square miles of snow area in these two years could be considered as the difference in volume between two 700 square mile snow wedges, one with an altitude of 69 units (1955) and the other with an altitude of 199 units (1952), as illustrated on chart 3. This average percent of normal water content at various key snow courses in the watershed is hereafter called the snow index.

6. Since abnormal precipitation after the 1 April snow survey can cause considerable change in the snow index, it is desirable to correct the initial index value to reflect any such change. It is not practical to obtain new snow surveys each time a new forecast is desired, due to the high cost of such surveys in both time and money. It has also been found that snow survey data taken after a considerable amount of the pack has melted away is not as reliable as earlier data because of the extreme difference in rate of depletion at the various courses that can result from their different exposure to the sun. Precipitation at a nearby rainfall station was therefore selected as a better factor for adjustment of the snow index.

7. For the Kings River basin, the selected rainfall station is Giant Forest (elevation 6,360 ft) which has a normal annual precipitation of 42.5 inches, of which 35.5 inches normally falls prior to 1 April, about 5 inches during April, 2 inches in May, and 1 inch in June. For the purpose of these snowmelt runoff forecasts, the assumption was made that after 1 April, the departure from normal of the average precipitation over the snow fields will be the same in inches as the departure from normal of the recorded precipitation at Giant Forest. The snow index derived from the 1 April snow survey data is therefore adjusted for later dates in the melt season by algebraically adding the departure in inches from normal precipitation at Giant Forest between 1 April and the selected date, to the initial water content of the snow shown by the 1 April snow surveys. For example, if the average 1 April water content at the key snow courses is 40 inches compared with a normal of 30 inches, the 1 April snow index would be 40/30 or 133 percent. On 1 June, if the Giant Forest precipitation since 1 April has been only 4 inches, the departure from normal would be 5 (April normal) plus 2 (May normal) less 4 or minus 3 inches. The adjusted snow index for 1 June would then be (40 - 3)/30 or 123 percent.

8. The 1 April snow indices for successive dates in each of the six years of record were adjusted in this manner so as to give corrected indices up to 31 July, the terminal date used in these forecasts. This date was selected because it was both the terminal date of other forecast systems in this area and near the end of major snow runoff season.

9. One additional factor was known to have some effect on the magnitude of the snow index and was used in this study. This was the departure from normal of the antecedent October-March run-off. This antecedent runoff roughly measured the portion of the subsequent snowmelt season runoff that will come from ground storage and which will be independent of the snow volume above the ground. Departures from normal of this antecedent runoff during the six years for which snow cover data is available ranged from minus 38 percent in 1954 to plus 150 percent in 1956. Study indicated that this factor should have a weight of about one-eighth. For example if there had been an antecedent runoff departure of plus 40 percent, an increment of 40/8 or 5 percent should be added to the snow

index for 1 April. This weight is poorly defined and may be modified in subsequent years. The snow indices for the six years used in development of this forecast are shown on table 1. It was found that use of these adjustments to the snow index brought the scattered curves of chart 2 into a much tighter group.

10. After consideration of all the foregoing, a simple graphical method was developed to forecast the remaining runoff that should occur after any date in the snowmelt season, based primarily on current snow covered area data supplied by aerial reconnaissance. This graphical method is illustrated by the following example selected at random from the period of experience on Kings River. See chart 4. The trial date is 1 June 1956, (60 days after the primary snow survey on 1 April and 60 days before the end of the snowmelt season on 31 July. On this date the measured snow area was 695 square miles. The observed runoff for each other year of record for the 60 day period following the date upon which the snow area was 695 square miles was plotted against the adjusted snow index for that year. A smooth curve was drawn through these points. The intersection of this curve with the adjusted snow index for 1 June 1956 (143) gives a forecast of 400,000 second-foot-days remaining runoff between this date and July 31. The actual runoff during this period was 405,000 second-foot-days or minus 1 percent error in the forecast.

11. A similar procedure was used when the date of desired forecast falls on an odd date between the even 10-day dates for which runoff-area date has been tabulated. As an example it was assumed that an area measurement was made on 6 June 1956, 55 days before the terminal date of 31 July. The snow covered area was 645 square miles. Working curves were drawn for 60 and 50 day periods and a curve for the desired 55 days interpolated between these curves. See chart 5. The intersection of this interpolated curve with the adjusted index value of 143 for 6 June 1956 gave a forecast of 363,000 second-foot-days for the remaining runoff to 31 July. The actual runoff for this period was 390,000 second-foot-days. The forecast error would be 27,000 second-foot-days or minus 7 percent.

12. In order to test the overall accuracy of this forecast method, trial forecasts were made at 10 days intervals for each of the six years for which snow covered area data is available. The resultant forecast errors in second-foot-days versus days before 31 July and versus snow covered area are shown on charts 6 and 7. Looking at chart 6, it will be seen that the forecast error are large for periods longer than 70 days but that they generally decrease to less than 50,000 second-foot-days (about 6 percent of the total snowmelt runoff) for all periods less than 60 days. The average error from 70 to 30 days ranges from 35,000 second-foot-days at 70 days to 15,000 second-foot-days at 30 days. The one exception occurred in 1958 when the weather was unusually stormy and cold until the latter half of the snowmelt season. Looking at chart 7 which shows the same forecast errors against snow covered area, it will be seen that the errors are large for areas greater than 700 square miles but are acceptably small for all smaller areas. Similar comparisons in terms of percent of remaining runoff indicate that the forecast errors average less than 10 percent during the period from 75 days to 30 days and from 700 to 300 square miles of snow covered area.

13. Considering all these tests, the method was found to give acceptable results from 15 May to 1 July whenever the measured area during this period ranged between 700 and 300 square miles. The physical reasons for these limits are probably as follows. Prior to 15 May and 700 square miles, the detailed slope of the snow wedge may be irregular due to late storms which lay down shallow downhill extensions of the snowfields. After this date and area, these shallow extensions have melted away and the main snow wedge tends to have a uniform consistent slope. After 1 July and 300 square miles, the snowfields usually break up into many small detached areas. The total area of these snow patches is difficult to measure by the aerial reconnaissance method with satisfactory accuracy. In addition, during this final period, an increasingly large portion of the runoff comes from underground storage distributed over the entire mountain slope rather than directly from the melting snowfields. This portion of the runoff does not have a consistent relationship to the remaining snowfield area and can be better forecast by other methods.

14. Operation experience at multipurpose reservoirs along the Sierra Nevada in California indicate that current forecasts of the remaining runoff are a very valuable tool during the period from mid-May to early July. During this period the rate of inflow is high, the reservoirs are filling rapidly, and day-by-day decisions must be made as to just how much water should be wasted in order to reliably retain control of the inflow during the remainder of the snow runoff season. Extensions of the original 1 April total runoff forecast, based on complete snow course data, becomes progressively less reliable. An original error of only 10 percent for such forecasts may
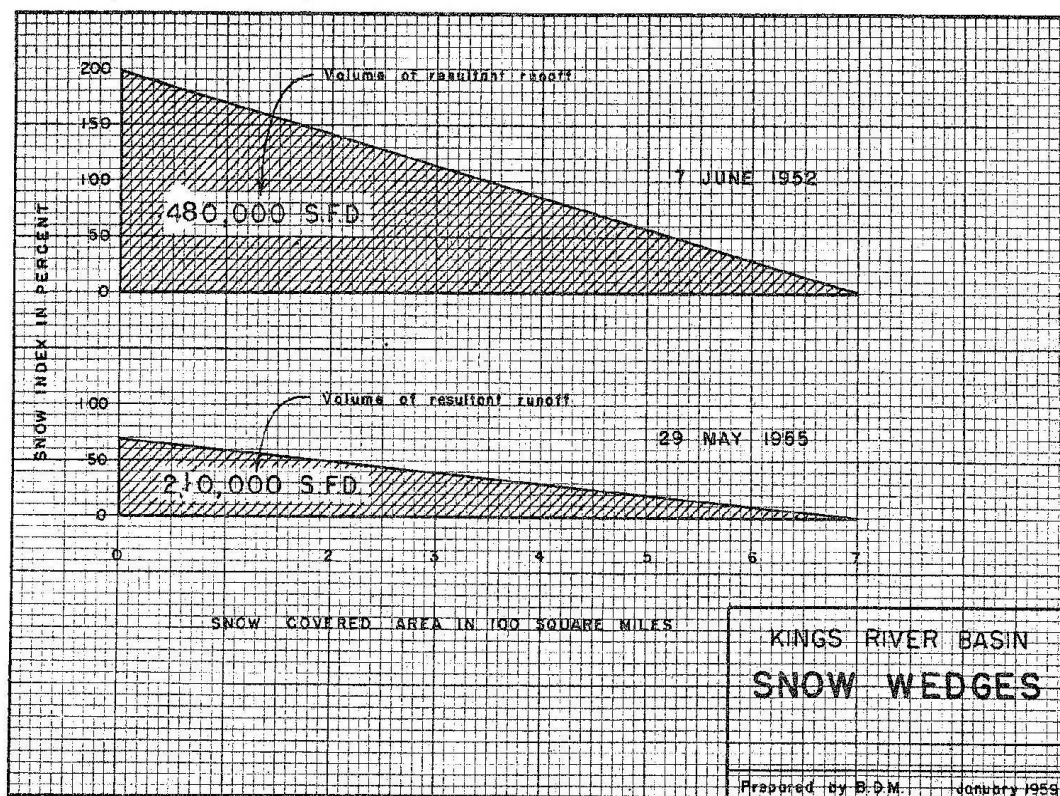
KINGS RIVER BASIN
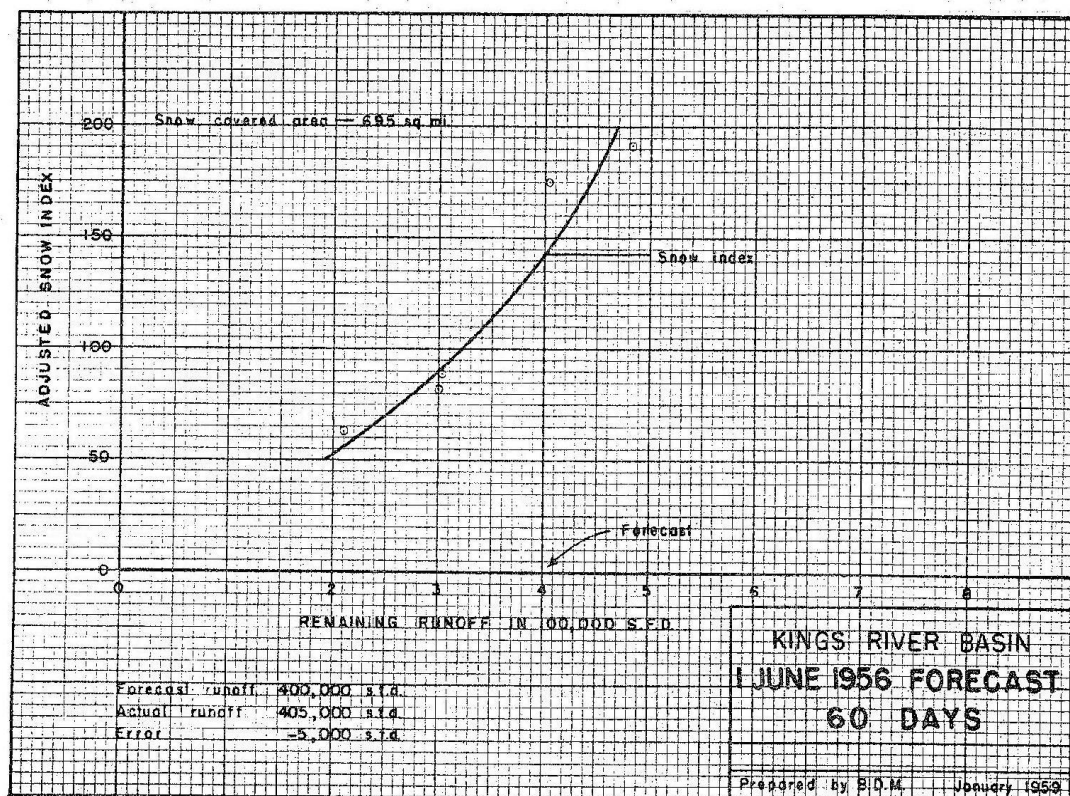SNOW WEDGES

Prepared by B.D.M.   January 1959

CHART 3

KINGS RIVER BASIN
1 JUNE 1956 FORECAST
60 DAYS

Forecast runoff 400,000 s.f.d.
Actual runoff   405,000 s.f.d.
Error   -5,000 s.f.d.

Prepared by B.D.M.   January 1959

CHART 4

Snow covered area — 645 sq.mi.

ADJUSTED SNOW INDEX

50 DAYS
55 DAYS
60 DAYS

Snow index 6 June 1956

Forecast

REMAINING RUNOFF IN 100,000 S.F.D.

Forecast runoff   363,000 s.f.d.
Actual runoff   390,000 s.f.d.
Error   −27,000 s.f.d.

KINGS RIVER BASIN
6 JUNE 1956 FORECAST
55 DAYS

Prepared by B.O.M.   January 1959

CHART 5

ERROR IN FORECAST OF REMAINING RUNOFF—1,000 S.F.D.

1956
1955
1953
1954
1956
1957

DAYS BEFORE 31 JULY

KINGS RIVER BASIN
FORECAST ERRORS
VOLUME VS LENGTH OF PERIOD

Prepared by B.O.M.   January 1958

CHART 6

KINGS RIVER BASIN
FORECAST ERRORS
VOLUME VS. SNOW COVER

Prepared by B.D.M.   January 1959
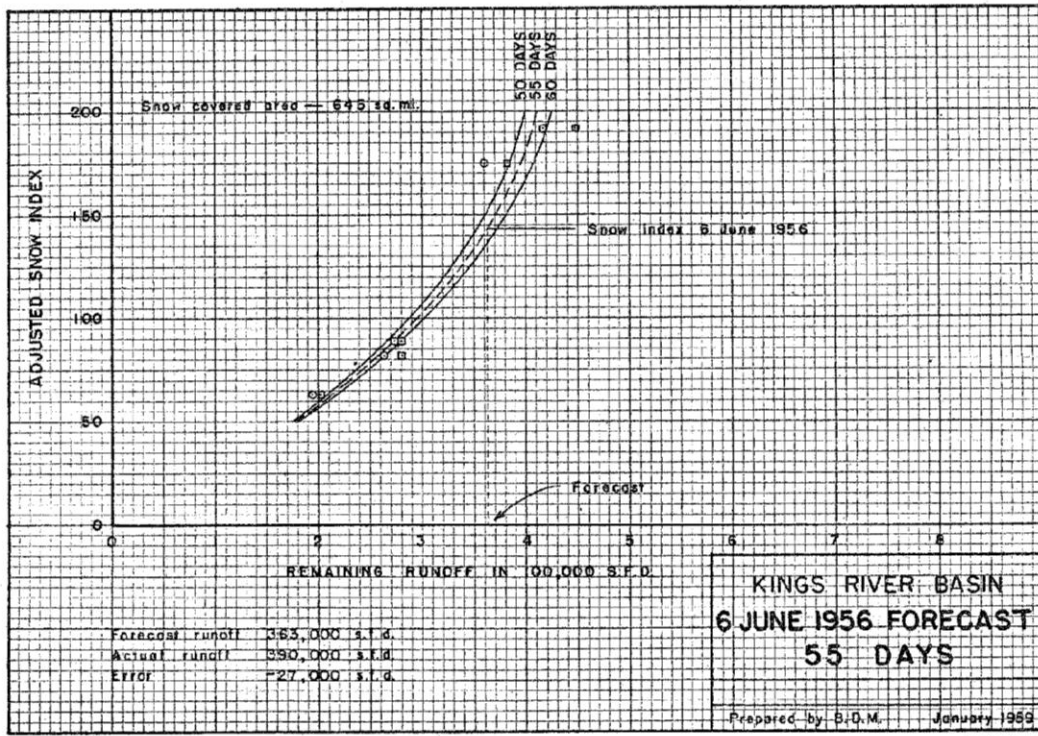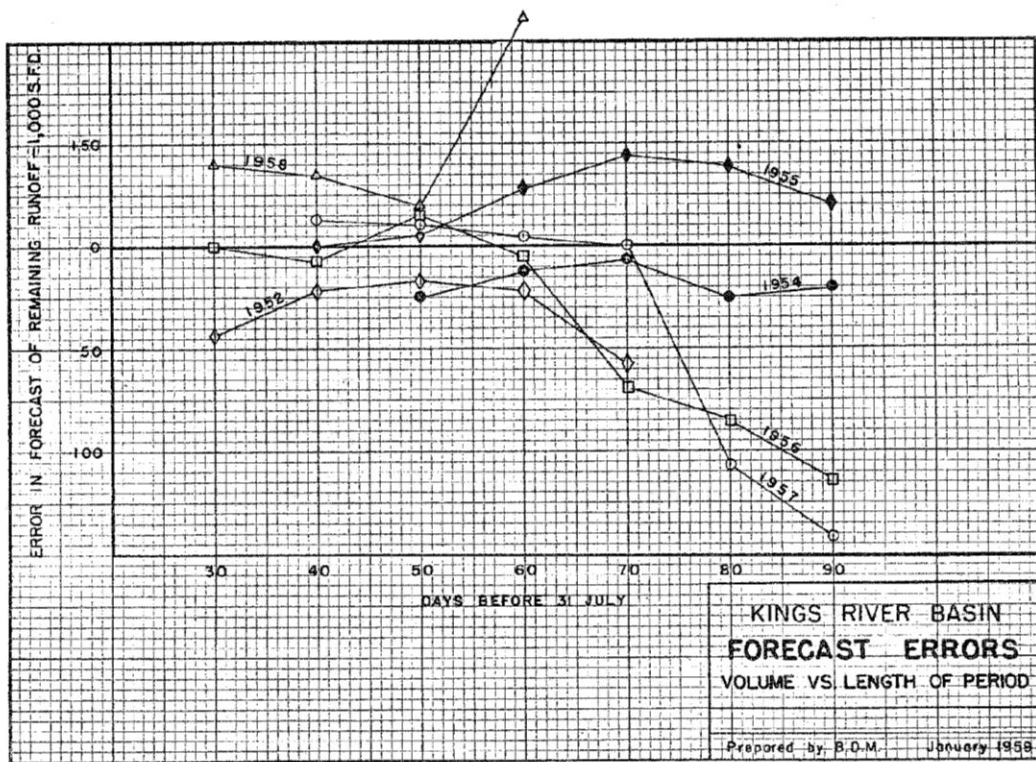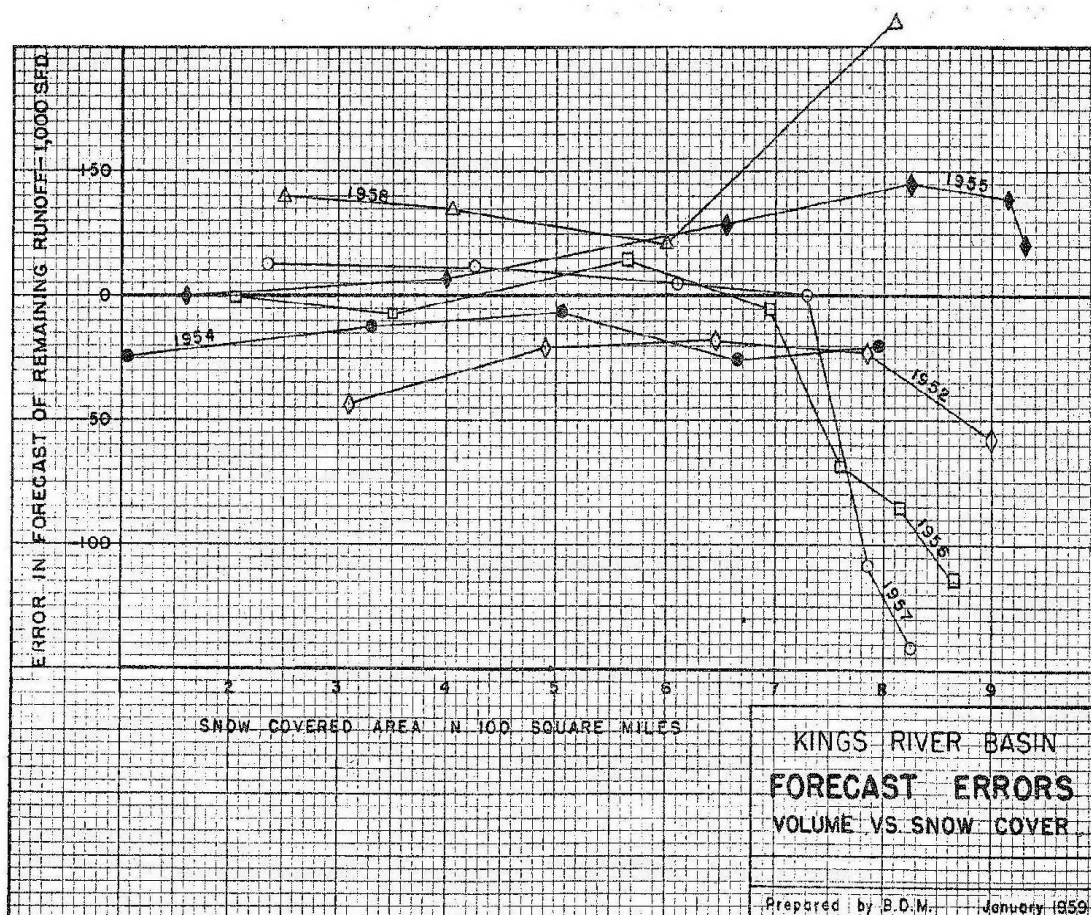
CHART 7

56

have swollen to over 20 percent, in terms of the remaining runoff. At such times, the ability to make current forecasts with an average error that remains below 10 percent of the remaining runoff, by means of this snow covered area method, becomes attractive.

15. The simple graphical method presented in this paper has demonstrated that reasonably accurate forecasts of remaining runoff can be made on the basis of a comparatively short period of snow data. As more data becomes available, it is probable that the series of individual forecast curves now being used can be combined into a single reliable nomograph chart that will shorten the time required to make each forecast without causing a significant loss of accuracy. Preparation of such a nomograph, solely on the basis of the six years of experience on the Kings River Basin, appears to be premature at this time.

16. In summary, on the basis of six years of snow reconnaissance data on Kings and Kern River Basins in California, a simple graphical method has been developed for making current forecasts of the remaining snowmelt runoff volume on the basis of frequent measurements of the remaining snow covered area and a snow index derived from 1 April snow course survey data adjusted for antecedent runoff and subsequent precipitation. The resultant current forecasts have average errors of less than 10 percent during the critical period from 75 to 30 days before the end of the snowmelt season. This accuracy is much better than could be obtained by extension of an original 1 April total volume forecast. The resultant current forecasts for the latter half of the snow runoff season are a valuable supplement to the commonly used 1 April total volume forecasts.

Table 1
Kings River Basin

Snow Indices

Year	Unadjusted Snow Index 1 April	Adjusted Snow Index 1 April (a)	31 July (b)
1952	199	204	192
1954	98	93	82
1955	69	64	63
1956	112	131	141
1957	65	60	89
1958	146	147	175

(a) Adjusted for antecedent runoff
(b) Adjusted for subsequent precipitation