X-913-77-48
PREPRINT

TM 78083

THE USE OF SNOWCOVERED AREA IN RUNOFF FORECASTS

(NASA-TM-78083) THE USE OF SNOWCOVERED AREA IN RUNOFF FORECASTS (NASA) 33 p N78-16410
HC A03/MF A01 CSCL 08L
Unclas
G3/43 02501

ALBERT RANGO
JACK F. HANNAFORD
RODERICK L. HALL
MICHAEL ROSENZWEIG
A. JEAN BROWN

MARCH 1977

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

X-913-77-48
Preprint

THE USE OF SNOWCOVERED AREA IN RUNOFF FORECASTS

Albert Rango
Jack F. Hannaford
Roderick L. Hall
Michael Rosenzweig
A. Jean Brown

March 1977

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

CONTENTS

Page

ABSTRACT 1

INTRODUCTION 2

  Study Area Description 3
  Historical Water Supply Forecast 4
  Data Sources 5

ANALYSES 8

  Investigation 1 8
  Investigation 2 12

DISCUSSION 18

CONCLUSIONS 21

ACKNOWLEDGEMENTS 22

REFERENCES 21

TABLES

Table — Page

1 Seasonal Streamflow for the Kings and Kern River Watersheds 23

2 Comparison Statistics for Regression Equations 23

3 Comparison of "Modified" Conventional and Snowcover Model Average Forecast Errors (1000 acre feet) for the Kings River (n = 20) 24

4 Comparison of "Modified" Conventional and Snowcover Model Average Forecast Errors (1000 acre feet) for the Kern River (n = 18) 24

ILLUSTRATIONS

Figure		Page
1	Location map showing the Kings and Kern River watersheds in California as seen in the 0.6-0.7 μm channel of Landsat on April 30 and May 1, 1976	25
2	Area-elevation statistics on the Kings and Kern River watersheds and location of the average April 1 snowline elevation	26
3	Areal extent of snowcover from satellite and aircraft observations for the Kings River watershed, 1973	27
4	Standard error of forecast procedure (with and without snowcovered area) vs date during snowmelt	28
5	Standard error of various forecast procedures vs date during snowmelt	29

THE USE OF SNOWCOVERED AREA IN RUNOFF FORECASTS

By Albert Rango, Jack F. Hannaford, M. ASCE, Roderick L. Hall, M. ASCE,

Michael Rosenzweig, and A. Jean Brown, M. ASCE

ABSTRACT

Long-term snowcovered area data from aircraft and satellite observations have been investigated for application to water supply forecasting in California's southern Sierra Nevada Mountains. These observations have proven useful in reducing seasonal runoff forecast error on the Kern River watershed when incorporated into procedures to update water supply forecasts as the melt season progresses. Similar use of snowcovered area on the Kings River watershed produced results that were about equivalent to methods based solely on conventional data. Snowcovered area will be most effective in reducing forecast procedural error on watersheds with: (1) a substantial amount of area within a limited elevation range; (2) an erratic precipitation and/or snowpack accumulation pattern not strongly related to elevation; and (3) poor coverage by precipitation stations or snow courses restricting adequate indexing of water supply conditions. When satellite data acquisition and delivery problems are resolved, the derived snowcover information should provide a means for enhancing operational streamflow forecasts for areas that depend primarily on snowmelt for their water supply.

(KEY WORDS: aircraft; forecasting; <u>remote sensing</u>; <u>runoff</u>; satellites; <u>snow</u>; water resources.)

THE USE OF SNOWCOVERED AREA IN RUNOFF FORECASTS

By Albert Rango,[1] Jack F. Hannaford,[2] M. ASCE,
Roderick L. Hall,[2] M. ASCE, Michael Rosenzweig,[3]
and A. Jean Brown,[4] M. ASCE

INTRODUCTION

Since 1972 several earth resources and environmental satellites, such as Landsat and NOAA, have been launched which have direct application to snowcover mapping. The characteristics of these satellites and their potentials for snowcover monitoring and subsequent runoff prediction have been discussed by Rango and Itten (1976). Although the utilization of snowcovered area (SCA) as an additional parameter in seasonal runoff predictions seems logical and has been shown to be useful (Leaf, 1971), the duration of satellite data is too short for conclusive testing of SCA in conventional approaches. In order to expeditiously estimate the potential value of satellite SCA data in runoff predictions, simplified linear multiple regression analyses of longer term aircraft visual observations of SCA for two watersheds in the southern Sierra Nevada in California were conducted.

---

[1] Research Hydrologist, Goddard Space Flight Center, Greenbelt, MD.
[2] Principal, Sierra Hydrotech, Placerville, CA.
[3] Formerly Operations Research Analyst, Goddard Space Flight Center; presently Acting Chief, Electric Power Analysis Division, Energy Information Administration, Department of Energy, Washington, D.C.
[4] Chief, Snow Surveys Branch, California Department of Water Resources, Sacramento, CA.

Study Area Description

The Kings and Kern Rivers are adjacent watersheds (Figure 1) that discharge into the Central Valley near Fresno and Bakersfield, California, respectively. Each basin ranges in elevation from below 1000 feet (300 m) in the foothill areas to over 14,000 feet (4300 m) along the Sierra Nevada crest which is the eastern boundary for both watersheds. The Kings River has an east-west orientation with high sub-basin divides and sub-basin drainage in deep canyons. The Kern River, on the other hand, has a north-south orientation with the Sierra crest along the eastern drainage boundary and the similarily high Great Western Divide along the western boundary of the basin. The Kern River is characterized by plateau areas with broad meadows and timbered slopes, although the North Fork heads in steep rocky areas near the Kings-Kern divide and flows in a deep canyon through most of its length to Lake Isabella. Area-elevation graphs in Figure 2 illustrate the relatively uniform distribution of area with elevation on the Kings River as contrasted with the concentration of area between 6000 (1830 m) and 9000 feet (2750 m) on the Kern River. The average elevation of the April 1 snowline as taken from California Department of Water Resources (CDWR) records is also shown in Figure 2 for both watersheds.

The 1,545 mi^2 (4002 km^2) Kings River has an average annual runoff of 1,567,600 af (1,934.0 million m^3) which represents 19 inches (48 cm) of runoff, 74 percent of which occurs during the April-July snowmelt period. Snowpack accumulation increases with elevation to about 9500 feet (2900 m) and is fairly consistent at about 30 inches (75 cm) of water above that elevation, although local topography may affect accumulation to some extent. Average annual precipitation at the 9000 foot (2750 m) elevation is about 35 inches (90 cm). Precipitation measurements made along the frontal slope at the western side of the basin appear to be representative of or at least proportional to precipitation at the higher elevations, although some minor variations may occur.

The 2,074 mi^2 (5372 km^2) Kern River watershed (above Lake Isabella) has an average annual runoff of 626,600 af (773.2 million m^3) which represents 5.7 inches (14.5 cm) of runoff, about 67 percent of which occurs during the April-July snowmelt. Precipitation varies both with elevation and location in the basin. At 9000 feet (2750 m) average annual precipitation along the Great Western Divide exceeds 35 inches (90 cm), while at the same elevation along the Sierra crest precipitation may be as low as 16 inches (40 cm). Precipitation, snowpack accumulation, and snowcover appear much more variable over the Kern basin than over the Kings basin.

Precipitation and resulting runoff are extremely variable from season to season in the southern Sierra, emphasizing the importance and need for an adequate water supply forecasting program. Table 1 illustrates the wide range of runoff experienced within the recent past.

Historical Water Supply Forecast

The CDWR makes water supply forecasts of April-July (snowmelt period) runoff for all major snowmelt streams in California, including the Kings and Kern Rivers. The California Cooperative Snow Survey Program was initiated in 1929 and the first forecasts using snow survey data were issued in 1930. Forecasts are issued by CDWR as Bulletin 120, "Water Conditions in California," in four reports stating conditions as of February 1, March 1, April 1, and May 1. The Kings and Kern Rivers, as well as other selected Sierra streams, have weekly updates of water supply forecasts from February 1 through July 1. Present methods for updating as the snowmelt season progresses are limited by the quality and type of real-time data available during the melt period. Forecast error tends to be concentrated in the remaining runoff volume. Current forecast procedures are based upon about 45 years of data to reflect the extreme variability which has been noted from season to season in these basins.

Data Sources

One of the primary reasons that the Kings and Kern Rivers in the southern Sierra were selected as watersheds for investigation of SCA as a water supply forecast parameter was availability of historic data on snowcovered area. Since 1952, the U.S. Army Corps of Engineers (USACE) has collected and assembled information on SCA from the Kings, Kern and several other watersheds. SCA has been mapped from a low flying light aircraft by an observer using topographic maps with suitable landmark identification. Aircraft observations generally started before May 1 and continued periodically until the SCA of the Kings River was depleted to less than 100 mi^2 (250 km^2). Most years had only three or four observations, but heavy snow years sometimes had as many as eight observations.

Data on SCA from aircraft observations and satellite imagery were plotted against time to provide estimates of SCA on specific dates for use in analysis. Only during 1973 were there adequate data from both aircraft and satellite for comparison. During 1974 only one aircraft observation was made and the USACE program was subsequently discontinued. Figure 3 is a plot of snowcovered area for the Kings River for 1973 showing both aircraft and Landsat data. Unfortunately, aircraft observations for 1973 were not made by the same personnel who had compiled the earlier data. After discussions with past and present USACE personnel, minor adjustments (using highway and weather station snow depth information plus snow survey water equivalent data) were made in the historic aircraft snowcover observations to make them more comparable to the satellite observations. There is still a consistently greater snowcovered area observed by Landsat than observed by the aerial surveys. This difference was first noted by Barnes and Bowley (1974) and attributed to the fact that aerial surveys excluded lower elevation transient snowcover from their measurements.

The conventional water equivalent (also referred to as water content) data applicable to the Kings and Kern Rivers were obtained by cooperators in the California Snow Survey Program and sent to CDWR. Other pertinent hydrometeorological information such as precipitation and runoff records were obtained by CDWR on an operational basis for water supply forecasting and other purposes. The data are developed by CDWR into basin indices for application to regression equations or multiple-graphical solutions for predicting April-July runoff. Forecast procedures after April 1 are currently based on the April 1 forecast updated using observed precipitation and limited telemetered automatic snow sensor data. The indices used for development of the April 1 forecast procedures are as follows:

1. Snowpack Index - This index is based upon the observed water equivalent at approximately 20 snow courses in each basin as of April 1. On some basins, including the Kings and Kern, two separate indices are developed for the high and low elevation snow zones, respectively. This index is expressed in terms of percent of average, as are most indices in the forecast procedures, and represents the relative quantity of water stored as snowpack on the date of forecast. Adjustment may be made for precipitation occurring between the actual date of measurement and April 1.
2. October-March Precipitation Index - This index, developed from approximately six lower elevation mountain stations, provides an indication of basinwide seasonal wetness.
3. April-June Precipitation Index - This index is a measure of precipitation occurring during the snowmelt season at about six stations and permits a level of updating as the season progresses after April 1. Observed precipitation data are used to replace average precipitation figures as the snowmelt season progresses.
4. October-March Runoff Index - This index relates both to basin wetness and volume of water not stored in the basin as a result of early season runoff.
5. Previous Year Runoff Index - This index is expressed as a volume for the previous April-July and may be related to the carryover from the previous runoff season.

For use in this study, these indices were developed according to the CDWR procedures with data supplied by CDWR. Analysis was performed for the period of record represented by the combined aircraft and satellite observations of snowcover data, which was 25 years on the Kings River and 23 years on the Kern.

ANALYSES

Independent analyses were undertaken almost simultaneously by NASA and Sierra Hydrotech - CDWR teams utilizing similar basic data to demonstrate the potential effect of SCA in water supply forecasting on the Kings and Kern Rivers. Although the objectives of the two investigations were somewhat different, similar results were obtained in both investigations. The NASA study (Investigation 1) was intended to demonstrate that SCA on a given date is applicable to forecasting seasonal runoff. The Sierra Hydrotech-CDWR study (Investigation 2) was intended to go one step further and to develop and demonstrate a procedure for updating water supply forecasts during the period of snowmelt utilizing SCA as a parameter. Both investigations were exploratory in nature and not intended to represent the most advanced techniques in statistical methods or water supply forecasting.

Investigation 1

Approach. An evaluation of conventional - and SCA-based seasonal runoff predictions on May 1 was made. In this approach only the low altitude estimate of SCA was used in analysis. Although aircraft observations began in 1952 and ended in 1973, observations were not readily available for each watershed in every intervening year. As a result, at the time Investigation 1 was conducted, only 20 and 18 years of aircraft SCA data were initially available for the Kings and Kern River watersheds, respectively. Conventional data were developed into forecast indices only for the years with existing SCA data. The existing forecast procedure used by CDWR was employed as the model for developing the "modified" (reduced data base) conventional regression equation.

In deriving a regression model using SCA for predicting seasonal flow, standard step-wise techniques were first utilized to determine the order of entry of the predictors. Several alternative orders and combinations were then considered to investigate potential reductions in the number of variables required while achieving an acceptable significance level (≤ 0.05). The "modified" conventional model was run against all the statistically acceptable SCA models in a prediction mode, and the various runoff forecast values were compared to the actual runoff figures.

On the May 1 forecast date all data were available except the April-June precipitation index. To simulate a real forecasting situation on May 1, the actual April precipitation was combined with the expected (average) May and June precipitation to obtain the best estimate of the April-June precipitation index.

Both the "modified" conventional and the set of "snowcover" models were exercised to determine which would provide the better forecast for each watershed. Since the number of available data points was limited and several variables were being considered, a series of regressions was used to make the forecasts. This technique consisted of deleting the forecast year from the data base, deriving the regression equation coefficients from the remaining data, and then making a forecast for that deleted year. The absolute value of the difference between the forecast and the actual runoff represented the error of the forecast. The forecast and forecast error were computed for each year. The average and the standard deviation of the errors were calculated and tabulated for each watershed and the best "snowcover" model selected based on the minimizing of these values.

Results. The regression model used by the CDWR on the Kings River is of the form:

$$Y = A_1X_1 + B_1X_2 + C_1X_3 + D_1X_4 + E_1$$

where

Y = April-July runoff
X_1 = April 1 snowpack index
X_2 = October-March precipitation index
X_3 = previous year April-July runoff
X_4 = April-June precipitation index

In this "modified" conventional equation the regression coefficients, A_1, B_1, C_1, and D_1, and the regression constant, E_1, are slightly different than their counterparts in the CDWR model because of the reduced data base resulting from the testing of SCA.

The regression model used by the CDWR on the Kern River is of the form:

$$Y = A_2X_1X_2 + B_2X_3 + C_2X_4 + D_2X_5 + E_2X_6 + F_2$$

where

X_1 = April 1 high elevation snowpack index

X_5 = April 1 low elevation snowpack index

X_6 = May 1 snowpack index

The regression coefficients and constant in the "modified" conventional equation are again slightly different than those in the current CDWR equation.

On the Kings River the resulting "snowcover" model for all years of record had the following form:

$$Y = A_3X_4 + B_3X_2X_7 + C_3$$

where

X_7 = May 1 SCA in percent of basin

A_3 = 1.18869

B_3 = 0.17573

C_3 = 45.58954

On the Kern River the best alternative model had the following form:

$$Y = A_4X_2X_7 + B_4X_1 + C_4X_6 + D_4$$

where

A_4 = 0.04332

B_4 = 2.54

$$C_4 = 2.02$$

$$D_4 = -135.022$$

Both final Kings and Kern "snowcover" models resulted from the step-wise regression analysis.

The statistics for the models on the Kings and Kern Rivers are shown in Table 2. These models were then compared on each watershed by evaluating the difference between actual and forecast runoff (which was assumed to be the forecast error) for each year in the data base. The average yearly forecast errors and the standard deviations of the errors are tabulated in Tables 3 and 4 along with the change in forecast parameter resulting from the incorporation of SCA. Although slight increases in forecast error occur when SCA is included in the prediction procedures on the Kings River, major reductions in forecast error using SCA are realized on the Kern River.

Investigation 2

Approach. Investigation of the application of SCA as a parameter in CDWR water supply forecasting has been limited to the April-July snowmelt period because most watersheds are 100 percent snowcovered before April 1. On the average, only about 10 to 15 percent of the annual precipitation falls after April 1. Prior to April 1, most of the total error in water supply forecasts is attributed to the uncertainty of the amount of precipitation occurring after the date of forecast. As the snowmelt season progresses, however, procedural error contributes an increasing portion of total forecast error, justifying additional analytical work to improve techniques for correcting or updating the forecast during the snowmelt period.

This approach was predicated on the operational requirement for accurate updating of water supply forecasts throughout the period of snowmelt runoff. Forecasts prepared by CDWR have historically been for the April-July snowmelt period. Updating has been primarily on the basis of precipitation observed subsequent to the April 1 forecast. Any procedural error in the April 1 forecast would be forced into the forecast of remaining runoff during the melt season. A forecast made on June 1 might contain the same procedural error as the forecast made on April 1, even though half of the snowmelt runoff for the season may have already occurred. The desirability of providing a forecast technique which would reduce the magnitude of procedural error as the season progresses is obvious.

Only a limited amount of data is available from these high mountain watersheds during the period of snowmelt. Precipitation from manned stations and some telemetered stations is available on a daily basis. Snowpack water equivalent measurements on a few snow courses are made about May 1, and some continuous snow sensor records are available, but data are limited. Additionally, the melt process during April introduces uncertainty into the meaning of observed water equivalent at specific locations. May 1 measurements have been used with some success in the Kern basin to reflect precipitation and melt occurring during April.

Observed runoff and depletion of SCA as the melt season progresses provide additional parameters on a near real-time basis to reflect the progress of melt in the watershed. This investigation developed and demonstrated techniques for updating conventional CDWR forecast procedures during the progress of melt. Forecast procedures were developed for April 1, May 1, May 15, June 1 and June 15 for the Kings and Kern River basins. The use of Landsat SCA data for 1973-76 and previous aircraft observations available for Investigation 2 provided 25 years of record on the Kings and 23 years of record on the Kern for analysis. Procedure stability was an important factor to assure a logical sequence of operational forecasts during the progress of the season.

Basic data utilized in the conventional CDWR procedure were used to prepare the April 1 procedure. Two procedures were then developed for May 1 and each subsequent date, one with and one without SCA to observe the effect of SCA in improving forecast reliability. In both procedures, runoff between April 1 and date of forecast was used as an additional parameter. Since existing CDWR procedures have techniques for handling precipitation during the snowmelt season, precipitation subsequent to date of forecast was assumed known and does not contribute to "procedural error" described in the analysis.

The general form of the forecast procedure equation is

$$Y = ax_1 + bx_2 + cx_3 + dx_4 + ex_5 + fx_6 + gx_7 + hx_1 x_8 + k$$

where

Y = runoff in acre-feet from date of forecast through July 31

x_1 = high snow index

x_2 = low snow index

x_3 = October-March precipitation index

x_4 = April-June precipitation index

x_5 = October-March runoff

x_6 = previous year April-July runoff

x_7 = runoff April 1 through date of forecast

x_8 = snow covered area in square miles

Regression coefficients are represented by a-h and k represents the regression constant. The conventional April 1 procedures use x_1 through x_6. Procedures for other times use x_7 or x_7 and x_8, depending upon whether SCA is to be included or not. SCA times April 1 snowpack index (adjusted for precipitation between April 1 and date of forecast) was used as an index of the volume of water available for snowmelt runoff during the melt period. Constraints on time and period of record did not permit investigation of more complex, non-linear analysis techniques, and exploration of hydrologic models used in water supply forecasting was not justified at this time.

Employing techniques presently utilized by CDWR, "forecasts" were made for each year of record and compared to observed runoff. Because of the limited data set, independent test data were not available and forecasts were made using data employed in derivation of the regressions. Although not statistically acceptable, the intention here was only to see if the SCA was a predictor worth pursuing for runoff prediction techniques. If the answer to this question is positive, more rigorous techniques would be used to incorporate SCA into operational procedures. Standard errors and other pertinent statistical measures were calculated for each date of forecast and results with and without SCA as a parameter were then compared, recognizing the limitations of these simple regression techniques.

Results. Figure 4 illustrates the variation in standard error, expressed as a percentage of April-July runoff, for forecast updates, depicting the effective reduction in forecast error as snowpack is depleted. Updating procedures without SCA are shown as a dashed line while updating procedures utilizing SCA are shown as a solid line. Figure 5 illustrates the same variation in standard error, expressed as a percentage of remaining snowmelt runoff for forecast updates. The dashed and solid lines represent standard error of procedures without SCA and with SCA respectively. The dotted lines represent error remaining if the procedure were used according to standard CDWR practice at the current time. In interpretation of Figures 4 and 5, it should be noted that although procedural error (in acre-feet) remains constant throughout the period, it will increase in terms of percent of remaining runoff as the melt season progresses.

On the Kings River (Figure 4), standard error increases slightly between April 1 and May 1, probably as a result of additional forecast parameters used on May 1 which increase degrees of freedom lost. After May 1, standard error declines appreciably until on June 15 it is approximately 70 percent of the error on April 1. This reduction in error is expressed in terms of percent of remaining runoff in Figure 5. The improvement over the existing procedure is apparent. The addition of SCA as a parameter, however, seems to offer little or no significant improvement in procedural error during the melt season.

On the Kern River (Figure 4), standard error for the procedure without SCA follows approximately the same pattern as on the Kings. If SCA is included, however, substantial reduction in standard error is apparent as the season progresses. By including SCA as a parameter, May 1 error is reduced approximately 45 percent and May 15 error about 40 percent, representing a corresponding decrease in the volumetric error of remaining runoff. The late season values of standard error on the Kern and the Kings are now relatively close. It is suggested that the use of SCA as a forecast parameter during the snowpack depletion period has allowed forecast accuracy on the two watersheds to be brought more into line with each other than possible with conventional parameters alone. The reduction in terms of percent of remaining runoff is depicted in Figure 5. Further inspection of changes of regression coefficients from date to date suggests that the Kern River equations are relatively stable — more so than those on the Kings River. Even though the precise numerical value of decrease in procedural error to be obtained by using these methods can not be generalized for all watersheds, it is apparent that SCA provides information pertinent to updating forecasts which is not readily available from other sources investigated here.

DISCUSSION

Use of SCA as a parameter in forecasting snowmelt runoff may result in significant improvement of forecasting procedures under certain circumstances. SCA in Investigation 1 reduced the average May 1 forecast error by 29 percent and the standard deviation of forecast error by 8 percent on the Kern River, but appeared to have no substantial or significant effect on the Kings River. Similarily, under Investigation 2, there appeared to be considerable improvement for each update on the Kern River using SCA, but no significant changes on the adjacent Kings River. It may be hypothesized that watershed characteristics, as well as availability of data representative of the watershed, may be related to the response of forecast procedures to SCA. Following is a discussion of factors which may influence the effectiveness of SCA as a parameter in water supply forecasting.

The conventional April 1 forecast procedure for the Kings River is relatively more accurate (when expressed in terms of percent of April-July runoff) than is that for the Kern River. April 1 procedural standard error represents about 7.5 percent of average April-July runoff on the Kings River and about 11.5 percent on the Kern, assuming that precipitation after April 1 is known. The higher degree of accuracy for the Kings River procedure may result partially from greater unit runoff and data which are more representative of conditions within the watershed. In any event, the higher initial degree of accuracy on the Kings River may make it considerably more difficult to obtain a marked improvement as a result of SCA or other update parameters as the season progresses.

The relatively inconsistent relationship between precipitation, snowpack accumulation, elevation, and location within the Kern River watershed described previously may be one of the more important reasons why SCA represents an effective parameter in updating Kern forecasts. The Kings River has a much more uniform area-elevation distribution than the Kern River (Figure 2). The relatively large area between 6000 and 9000 feet (1830-2750 m) on the Kern River is subject to extreme variability in snowpack accumulation and depletion, perhaps enhancing the value of SCA as a prediction parameter. It might be visualized that the Kings River consists of a number of smaller basins somewhat similar in character and can be predicted well with a forecast procedure representing basins of that character. The Kern River, on the other hand, consists of a number of smaller basins of diverse character. It might be possible to break the Kern area into a number of sub-basins and forecast each sub-basin independently. SCA may provide an attractive intermediate solution to water supply forecasts in areas with inhomogeneous characteristics and limited hydrologic data.

Most watersheds in the central and southern Sierra appear to be quite homogeneous from a hydrologic standpoint, more so than perhaps most other western U.S. watersheds. Northern Sierra, eastern Sierra, and other watersheds in California, however, appear much more diverse than the Kings River and those watersheds immediately to the north of the Kings, suggesting that SCA might prove to be an effective parameter for water supply forecasting in California.

Watersheds with (1) a substantial degree of area within a limited elevation range, (2) an erratic precipitation and snow accumulation pattern not strongly related to elevation, and (3) poor coverage with precipitation data or stations which do not give a reliable index to the water producing areas of the basin may show the greatest response to use of SCA as a parameter in volumetric forecasting.

Even though the Kings River did not appear to respond significantly to use of SCA in water supply forecasting in this preliminary investigation, one should not discount possible applications on streams typical of the Kings River. SCA on the Kings River has been found useful in hydrologic modeling of daily snowmelt and runoff (Hannaford, 1977). Hydrologic modeling procedures are used in some operational forecasting, and it is hoped that near real-time satellite imagery may prove to be useful for these types of predictions.

Procedures for updating the remaining volume of snowmelt runoff using SCA will be used operationally on the Kings and Kern Rivers during 1978. In order to assure widespread use of SCA-derived operational forecasts, however, it will be necessary to receive SCA information on a regular, near real-time basis (≤ 72 hours). The possibility of cloud cover during a Landsat overflight may at times result in an 18-day or greater interval between observations. Some type of alternative observational capability, such as NOAA or aircraft SCA estimates, during such periods may be required.

CONCLUSIONS

1. Long-term SCA data from aircraft and satellite observations have been shown to be useful in reducing seasonal runoff forecast error on the Kern River watershed when incorporated into water supply forecast procedures. Both one-time and regular updates of forecasts were improved using SCA. Similar analysis on the Kings River indicated that SCA produced forecasts were generally as good as conventional forecasts but no significant improvement was noted.

2. Comparison of the Kings and Kern River watersheds indicates that certain watershed conditions may enhance the usefulness of remotely sensed SCA data. SCA will most likely reduce forecast procedural error on watersheds with: (a) a substantial degree of area within a limited elevation range; (b) an erratic precipitation and/or snowpack accumulation pattern not strongly related to elevation; and (c) poor coverage by precipitation stations or snow courses restricting adequate indexing of water supply conditions.

3. Assuming that operational acquisition and delivery problems associated with space information will be resolved, satellite data as it is accumulated should provide a means for enhancing operational seasonal streamflow forecasts for areas that depend on snowmelt-derived water supplies. In many cases, satellite-acquired SCA data can provide for much more objective, uniform, and controlled information than that possible from aircraft platforms.

ACKNOWLEDGEMENTS

This study was partially funded by NASA under contract No. NAS5-22957. Valuable data for the study was kindly furnished by the U. S. Army Corps of Engineers, Sacramento District, Sacramento, California, and the California Department of Water Resources, Snow Surveys Branch, Sacramento, California. Susan Howard, formerly at Goddard Space Flight Center (GSFC), Greenbelt, Maryland, and Betsy O'Brien of GSFC provided important data analysis support for Investigation 1.

APPENDIX. —REFERENCES

1. Barnes, J. C., and Bowley, C. J., "Handbook of Techniques for Satellite Snow Mapping," Final Report, NAS5-21803, NASA Goddard Space Flight Center, Greenbelt, Maryland, 1974, 95 pp.
2. Hannaford, J. F., "Application of Satellite Imagery to Hydrologic Modeling Snowmelt Runoff in the Southern Sierra Nevada," Final Report, NAS5-22957, NASA Goddard Space Flight Center, Greenbelt, Maryland, 1977, 48 pp.
3. Leaf, C. F., "Areal Snow Cover and Disposition of Snowmelt Runoff in Central Colorado, "Research Paper RM-66, USDA Forest Service, Fort Collins, Colorado, 1971, 19 pp.
4. Rango, A., and Itten, K. I., "Satellite Potentials in Snowcover Monitoring and Runoff Prediction," Nordic Hydrology, Vol. 7, 1976, pp. 209-230.

Table 1

Seasonal Streamflow for the Kings and Kern River Watersheds

Season	April-July Runoff					
	Kings			Kern		
	1000 AF	(million m^3)	% Average	1000 AF	(million m^3)	% Average
1976	301.8	(372.4)	26%	103.9	(128.2)	25%
1969	2,631.8	(3247.6)	227%	1,349.5	(1665.3)	321%
Average	1,157.0	(1428.0)		420.0	(518.0)	

Table 2

Comparison Statistics for Regression Equations

Statistics	Kings River "Modified" Conventional Model	Kings River SCA Model	Kern River "Modified" Conventional Model	Kern River SCA Model
Degrees of freedom	4, 15	2, 17	5, 12	3, 14
F-test value	161.3*	218.4*	156.0*	355.3*
R^2 value	97.1	95.9	97.9	98.4
Standard error of estimate	120.9	145.7	35.6	30.5
Standard deviation of the seasonal yield (y)	712.5	712.5	243.2	243.2

*Significant at the .005 level

Table 3

Comparison of "Modified" Conventional and Snowcover Model Average Forecast Errors (1000 acre feet) for the Kings River (n = 20)

	Conventional Model	Snowcover Model	Change
Average Forecast Error	114.9	120.9	+ 5%
Standard Deviation of Forecast Errors	106.4	107.7	+1%

Table 4

Comparison of "Modified" Conventional and Snowcover Model Average Forecast Errors (1000 acre feet) for the Kern River (n = 18)

	Conventional Model	Snowcover Model	Change
Average Forecast Error	40.11	28.67	-29%
Standard Deviation of Forecast Errors	25.28	23.31	- 8%

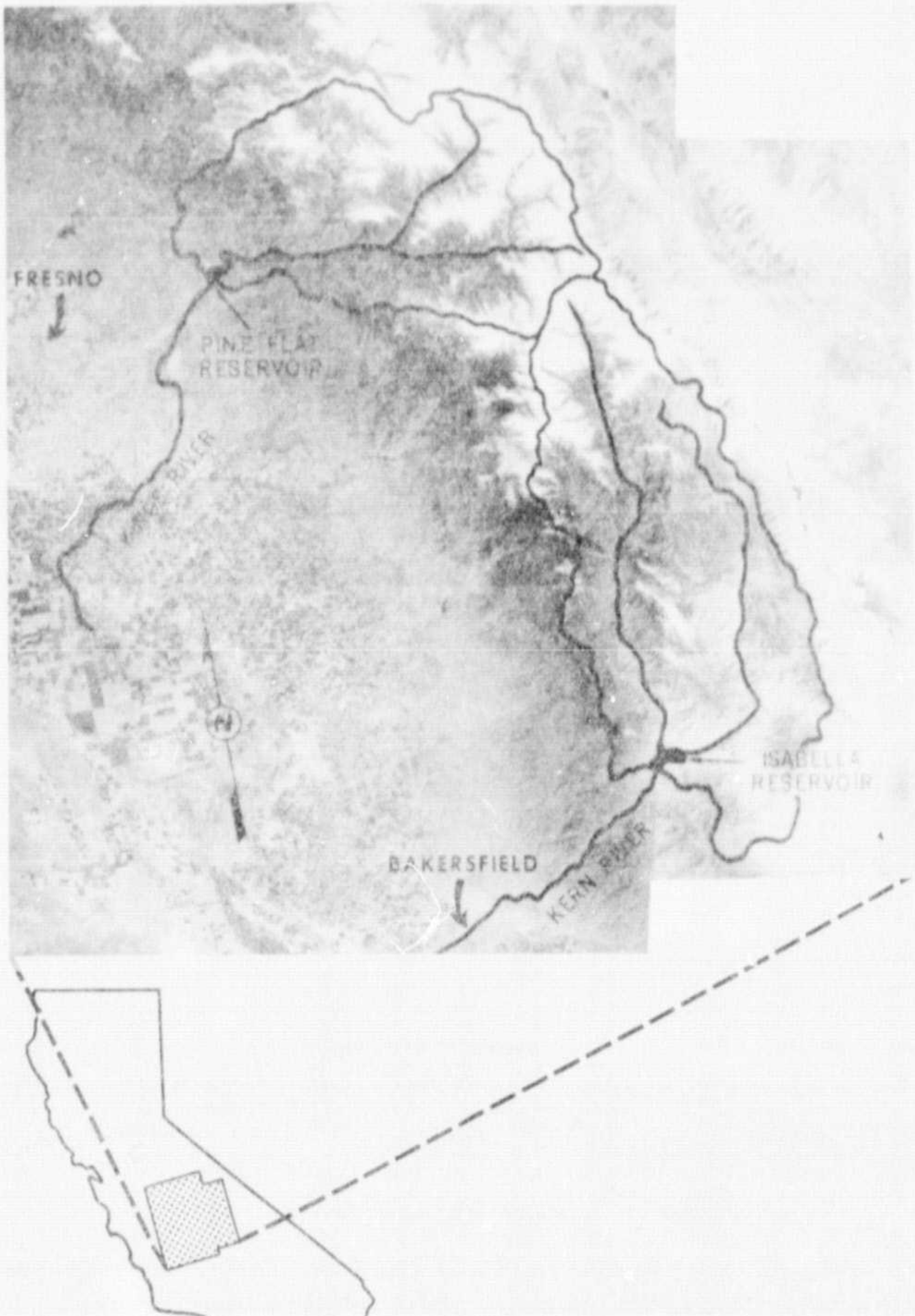

Figure 1. Location map showing the Kings and Kern River watersheds in California as seen in the 0.6-0.7μm channel of Landsat on April 30 and May 1, 1976.

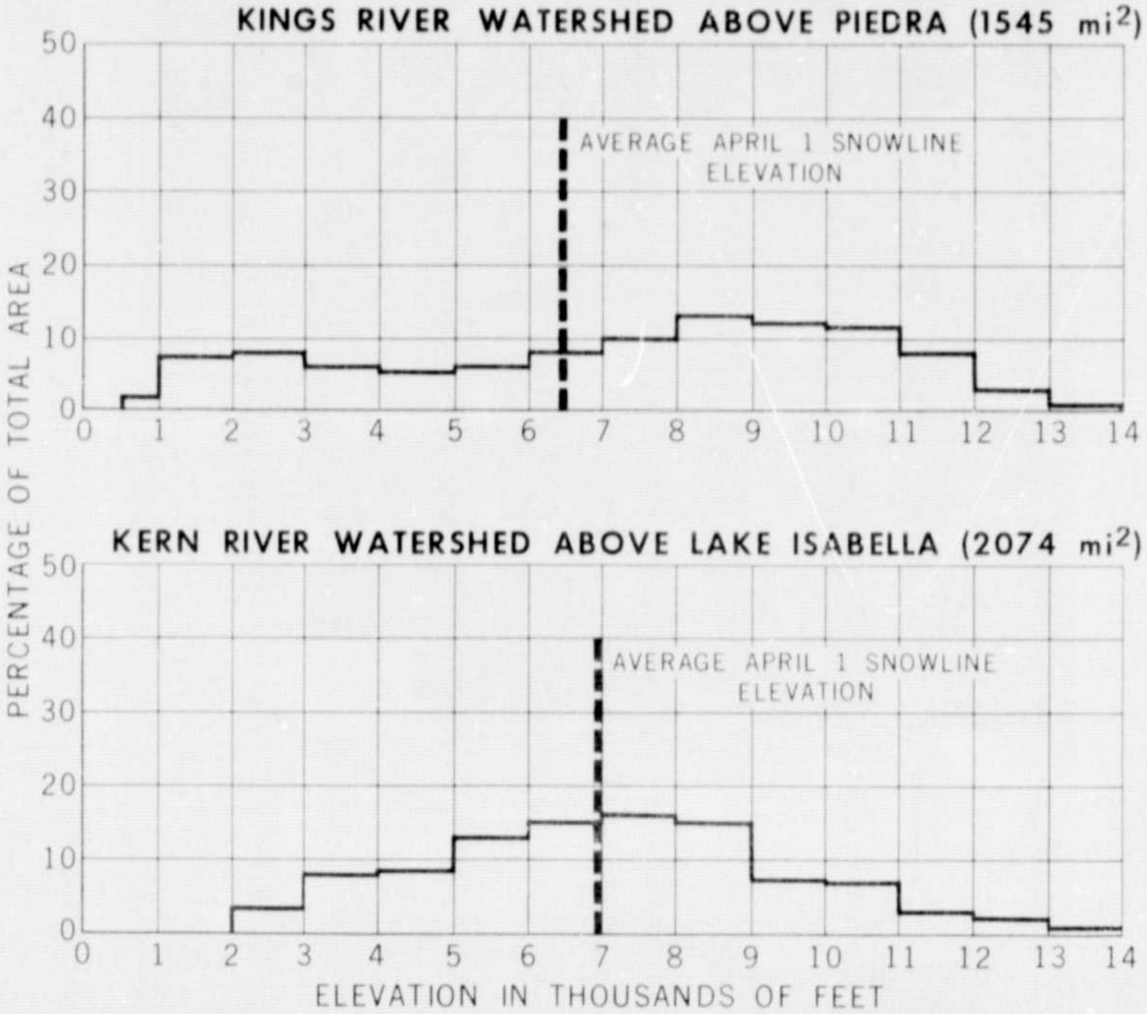

Figure 2. Area-elevation statistics on the Kings and Kern River watersheds and location of the average April 1 snowline elevation.

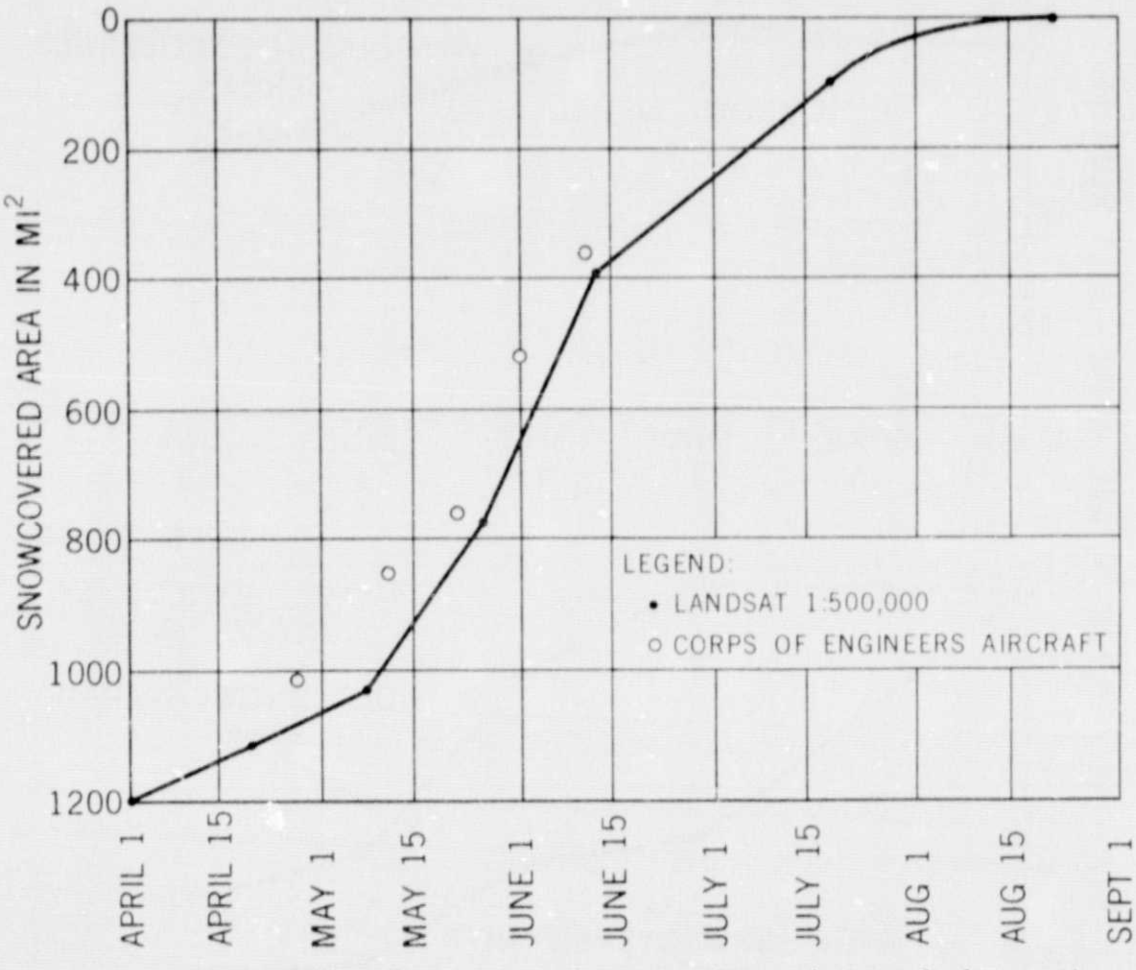

Figure 3. Areal extent of snowcover from satellite and aircraft observations for the Kings River watershed, 1973.

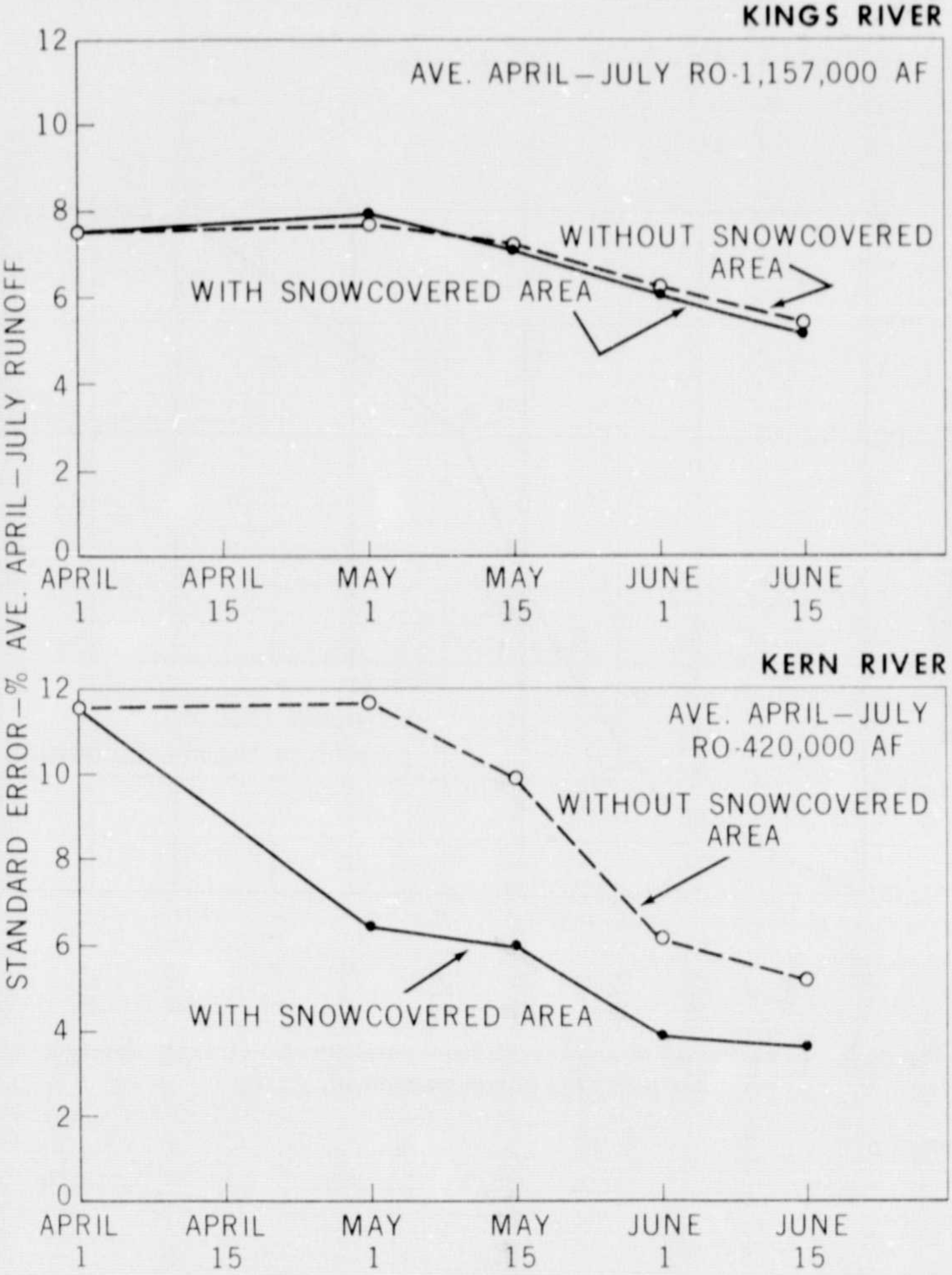

Figure 4. Standard error of forecast procedure (with and without snowcovered area) vs date during snowmelt.

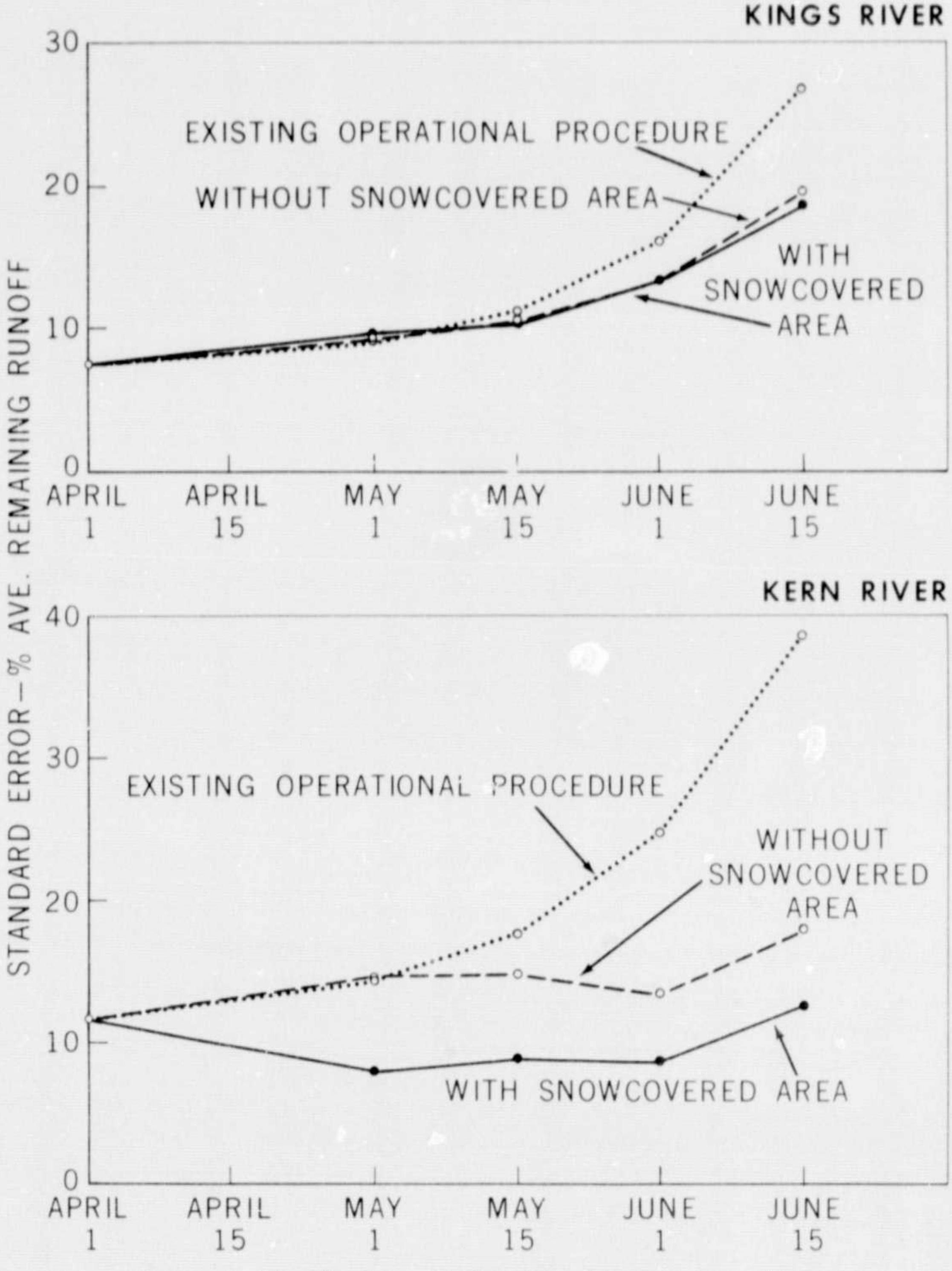

Figure 5. Standard error of various forecast procedures vs date during snowmelt.