APPLICATION OF SNOWCOVERED AREA TO RUNOFF FORECASTING IN SELECTED BASINS OF THE SIERRA NEVADA, CALIFORNIA

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ABSTRACT

The California Applications Systems Verification and Transfer (ASVT) project, one of four ASVT's sponsored by NASA in the western United States, established two study areas covering the range of conditions found in California. These study areas were used to map SCA in near real-time mode; to compare satellite derived SCA with conventional snow data; and to operationally test the effects of incorporating SCA into the state's forecasts of snowmelt runoff. Results obtained during the four years of the ASVT indicate a potential improvement in the forecast accuracy by introducing SCA for those watersheds having a limited amount of representative real-time data during the period of snowmelt. Cloud cover and timely receipt of imagery were the major limitations to the usefulness of SCA.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) has been sponsoring research and investigation into utility of satellite imagery in water supply and other hydrologic forecasting in the western United States in the form of Applications Systems Verification and Transfer (ASVT) projects. NASA has contracted with the California Department of Water Resources (DWR) to investigate the operational application of snowcovered area from satellite imagery to DWR's hydrologic forecasting responsibilities, primarily in water supply forecasting in the Sierra Nevada. DWR subcontracted with Sierra Hydrotech, a consulting firm in Placerville, California, for technical assistance in determining snowcovered area (SCA) from satellite imagery, and in investigating applications of SCA to hydrology.

The objective of this paper is to report on the results and conclusions arrived at during the four years of the California ASVT project.

Background

The Sierra Nevada and the southern portion of the Cascade Range supply California's fertile San Joaquin and Sacramento Valleys with water for agricultural, municipal, and industrial use. The average water-year runoff of Sierra streams tributary to the San Joaquin Valley and Tulare Lake Basin is approximately 11 million cubic dekametres (9 million acre-feet), while the average water-year runoff of Sierra and Southern Cascade streams tributary to the Sacramento Valley is approximately 19 million dam^3 (15 million ac-ft). In southern Sierra streams where elevations range up to about 4 300 metres (14,000 feet), as much as 75 percent of the average annual runoff occurs during the April-July snowmelt season. In the northern Sierra streams where elevations are much lower, only about 40 to 50 percent of the average annual runoff occurs during the snowmelt season.

The high degree of development and use of water in California's Central Valley has required development of forecast techniques for predicting volume and time-distribution of snowmelt runoff for water management purposes. Water management problems in certain areas require continual surveillance of streamflow and updating of forecasts during the runoff season to provide for management decisions as the season progresses. Forecast technology has advanced to the degree that application of new data types may possibly generate only limited improvement in forecast accuracy, particularly early in the season when forecast error is highly dependent upon the precipitation which occurs after the date of forecast. Development of new data types, such as snowcover from satellite imagery, will not eliminate the necessity or advisability of collecting data on precipitation, snowpack water content, and rates of snowpack accumulation and melt in the foreseeable future.

Objectives

The basic objective of the California ASVT was to explore within an operational time frame the application of SCA obtained from satellite imagery in the State's snowmelt runoff forecasting procedures. Three specific tasks or areas of investigation were defined.

1. Data Interpretation. This task involved mapping SCA and equivalent snow lines from historic satellite and aircraft observations; and in a near real-time operational mode when the satellite imagery was available within 72 hours of satellite passage.

2. Data Analysis. This task involved developing and applying techniques to estimate SCA and to check the data. It further involved comparing imagery from various conventional and satellite sources to refine interpretative

techniques and to determine compatibility to SCA derived from satellite imagery with aircraft observations and other pertinent snowcover information.

3. Data Application. This task involved incorporating SCA operationally into volumetric projections of water year and snowmelt season (April-July) runoff, and investigating the use of SCA to refine and update a continuing analysis of the rates and remaining volume of snowmelt runoff during the progress of snowmelt.

Area of Investigation

The geographical area of this investigation is California's Sierra Nevada. The study area selected by DWR was composed of a northern and a southern project area. The northern project area included 24 watersheds and subwatersheds in or adjacent to the Sacramento River above Shasta Dam and the Feather River above Oroville Dam. The southern project area included 14 watersheds and subwatersheds in or adjacent to the San Joaquin, Kings, Kaweah, Tule, and Kern River Basins. The southern project area represented the relatively high elevation "high Sierra" region and the northern project area was characterized by lower elevations and more transient areas of snowcover. (Note that the Sacramento River Basin technically lies to the north of the Sierra in the Cascade Range.) Figure 1 shows the locations of these basins.

INTERPRETATION OF HISTORIC SCA DATA

Techniques described by Barnes and Bowley, 1974, were adapted to interpretative problems encountered in the Sierra project areas. Problems related to reflectivity of the bare, light colored granite rocks were critical in the southern Sierra, while problems related to timber cover, extensive cloud cover, and long shadows were most critical in the north. During the initial phases of the project, historical imagery obtained from NASA was interpreted for the 38 watersheds and subwatersheds within and adjacent to the Sierra project areas. Watersheds vary in size from 100 square kilometres (40 square miles) to 16 600 km^2 (6,400 mi^2). Determining SCA simultaneously from a relatively large number of basins and subbasins in each study area permitted crosschecking between adjacent and nearby basins, thus providing a means of estimating snowcover conditions even when portions of a given project area were obscured by clouds.

By 1978, preanalysis and editing of interpreted data indicated that sufficient historic information has been obtained from most of the subwatersheds for investigative purposes. As a consequence, analysis of many subbasins was discontinued and the program for acquisition, reduction and interpretation of satellite imagery was expanded to meet the future operational needs of DWR. NASA provided historic Landsat data so that 22 major watersheds in

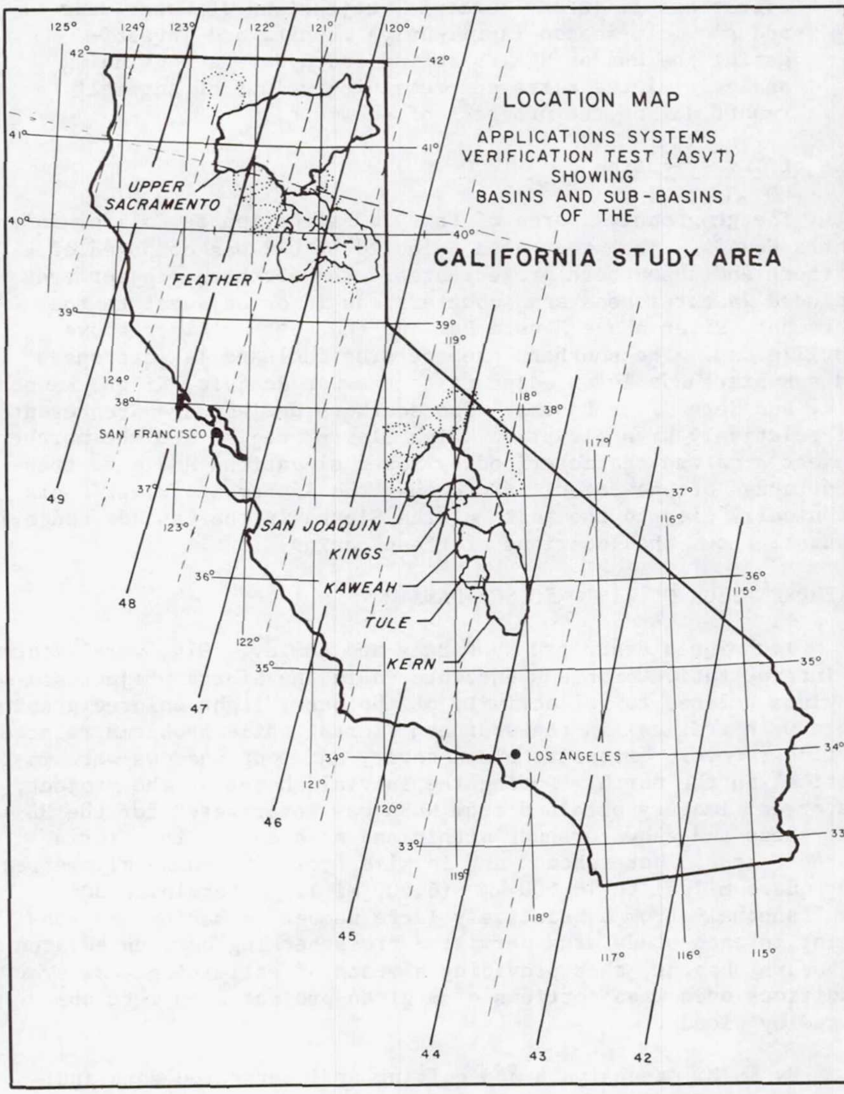


Figure 1. California Study Area

the Sierra Nevada, Cascade Range, and Coast Range could be interpreted to provide a data base for development of forecasting procedures in all the major snowmelt runoff areas of California. See Figure 2.

Historic data were initially reduced from Landsat images by both overlay and Zoom Transfer Scope (ZTS). Comparison of results indicated that reduction of Landsat images at a scale of 1:500,000 using the ZTS gives more consistent results, but takes considerably more time than a 1:1,000,000 direct overlay. NOAA images were also reduced by ZTS to fill the period between Landsat images.

In the reduction of Landsat imagery, the following items have been noted:

1. Transparencies of the Landsat imagery appear to be more consistent and more easily interpreted on the ZTS than the prints.

2. Direct overlay onto 1:1,000,000 prints takes about one-third the time of 1:500,000 ZTS analysis using transparencies, but the consistency of results observed using the transparencies has reduced the time required for data analysis.

3. Landsat imagery received well after the fact on transparencies is decidedly better and more easily interpreted than the near real-time data from Quick Look, or imagery from other sources such as NOAA.

For purposes of this investigation, an image set was defined as an image or group of images representing a nominal time of observation. NOAA images which cover much of the western United States in a single image have only one image per image set. A single NOAA image set includes all of California, but data were interpreted from two enlarged prints, each covering a portion of the Sierra. Landsat image sets may have included up to eleven images taken over a period of six days to cover the snowmelt streams of the State. The image set for a given basin or area represents all images required to describe that area on a given nominal date of observation.

Interpreted data representing a basin day includes the snow-covered area and effective snow line of a given basin or subbasin for a given image set. The overlap of images on succeeding passes provides an opportunity to obtain observational data when storm activity and clouds may obscure a single pass. Some data sets have been reinterpreted as techniques were improved. A significant portion of the imagery received but not interpreted was either obscured by cloud cover, had no remaining snow, or was outside the time period of investigation.

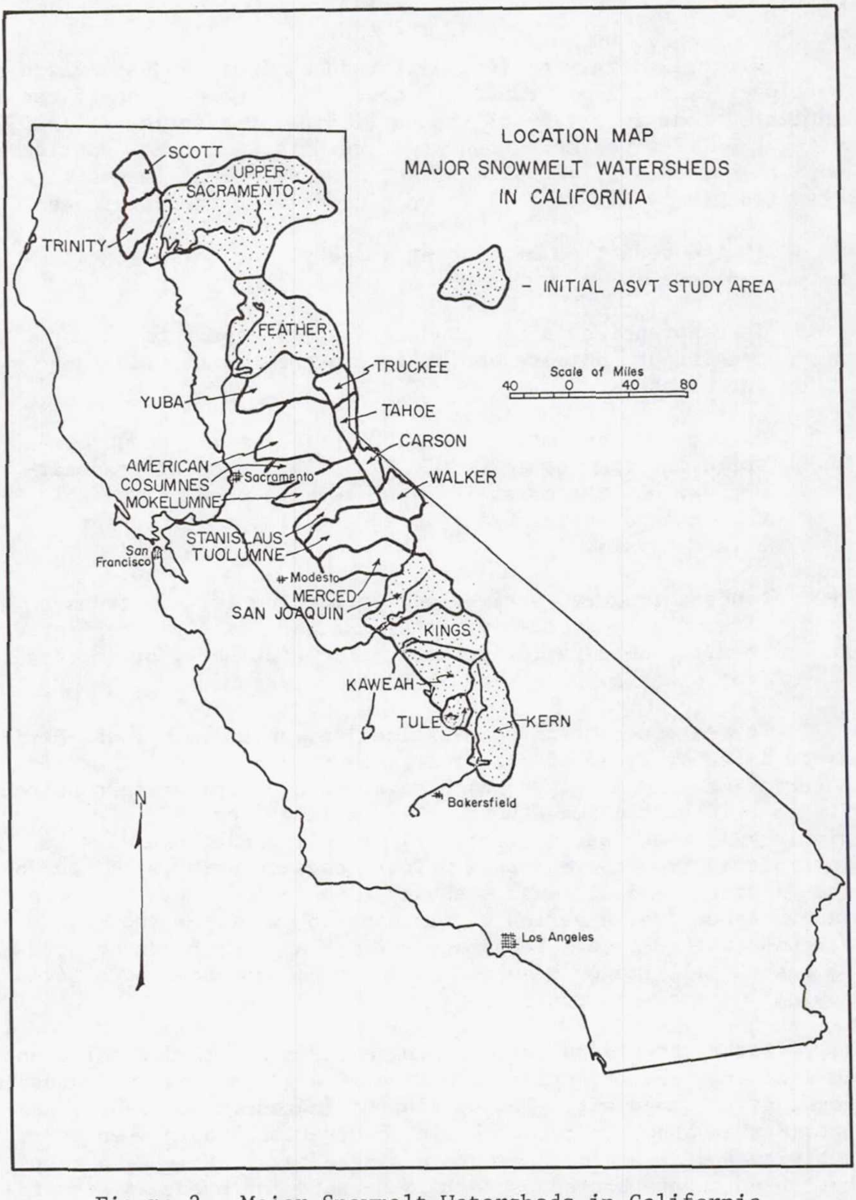


Figure 2. Major Snowmelt Watersheds in California

INTERPRETATION OF OPERATIONAL SCA DATA

Canadian Quick Look imagery from Landsat was obtained directly from Integrated Satellite Information Services (ISIS), a Canadian readout station and service, during the snowpack accumulation and melt periods of 1976 through 1979 for use in operational forecasting. Additionally, Quick Look Landsat imagery was obtained from NASA.

One of the major operational problems during the 1978 and 1979 snowmelt seasons was securing timely imagery when runoff forecasts were required. Perhaps the greatest delay during 1978 was caused by the mail service. Canadian Quick Look imagery was postmarked in a timely fashion after observation, but mail delivery was much slower than in past seasons. Quick Look from NASA usually, but not always, arrived after the Canadian Quick Look. The average time was about five to six days as compared to the 72 hours originally hoped for. During 1979, data handling problems early in the season made it impossible to obtain near real-time data. NOAA and GOES imagery were used for supplemental data or when real-time data from Landsat was not available. Timeliness of data delivery cannot be overstressed with regard to operational forecasts.

DATA ANALYSIS

Evaluation of results indicated that SCA can be practically determined from Landsat using the Zoom Transfer Scope for watersheds as small as 100 km^2 (40 mi^2), and snowpack depletion may be determined within reasonable limits of accuracy even as the area of snowpack becomes fragmented. Cross-basin plots were developed for the various major basins and subbasins, making it possible to estimate SCA on watersheds that were partly or completely cloud covered from data available on adjacent basins or subbasins.

Interpretative techniques improved with the increase in experience of the interpreter. A considerable amount of time was spent in checking and reanalyzing early (1973-1976) data sets to provide a data base for all watersheds that was homogeneous throughout the entire six-year period of available satellite imagery. This process included the important step of editing and preanalysis of the data, which involved deciding whether the data being obtained represented the data needed.

Comparison of Satellite and Aircraft Observations

During the heavy snow season of 1952, the U. S. Army Corps of Engineers (Sacramento) initiated observations of snowcovered area from low flying aircraft in the southern Sierra Nevada in connection with the operation of reservoirs during the period of snowmelt. Initial work was done in the Kings River Basin for operation of Pine Flat Reservoir. Observations extended to the

Kern River in 1954, and eventually included the Kaweah and Tule River Basins. Observations were taken more or less routinely during the period of major snowmelt. The program continued for about 20 years until 1973.

During 1978, the Corps resumed aircraft observations in the southern Sierra as the result of the unusually heavy snowpack conditions and potential for spill of snowmelt runoff from reservoirs. Although the Corps was furnished data from the satellite observations throughout the ASVT program, the data generally arrived in Sacramento too late to meet the Corps' requirements for forecasting, necessitating resumption of the aircraft observations for that heavy runoff year. Information on SCA for estimation of both rate and volume of snowmelt runoff was obtained from aircraft and satellite. In many cases, aircraft observations varied considerably from the satellite observations. Figure 3(a) delineates the snowcovered area in the Kings River Basin during the 1973 season as derived from Landsat imagery, NOAA imagery, and aircraft observations. Figure 3(b) delineates snowcovered area during 1978 season, including the Canadian Quick Look imagery. Data in 1973 and 1978 for the Kern River Basin appears in Figures 4(a) and 4(b), and similar results were noted on other watersheds.

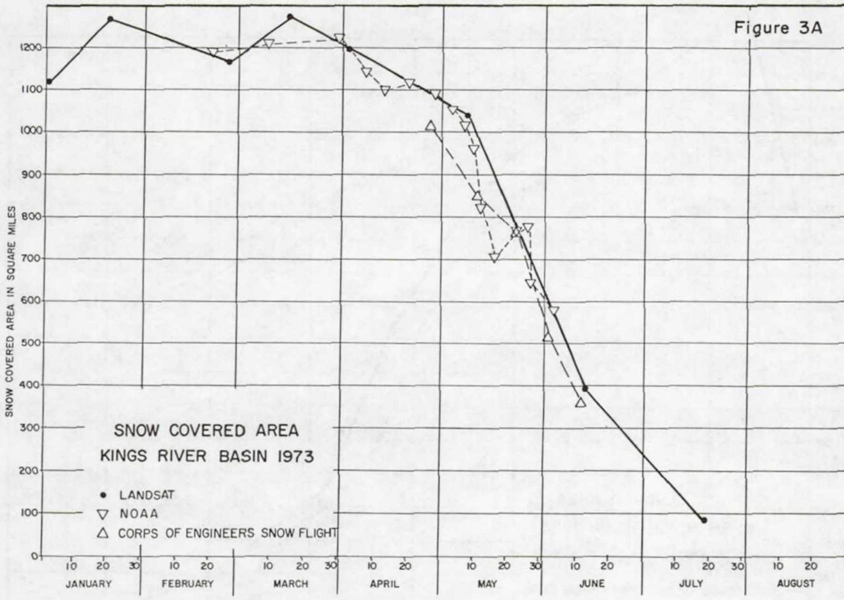
It will be noted that in general, the aircraft observations in 1978 appeared to show less snowcover than satellite observations as of a given date. Some precipitation occurred about mid-June 1978 which included light snowfall at higher elevations, and was probably very apparent to observers at that time. The Corps of Engineers attributes the difference between aircraft observations and Satellite SCA to the following possible causes:

1. Aircraft observers deleted patches of snow that were below the major unbroken snowpack. Historical aircraft observations, however, may not be entirely consistent in this respect.

2. Aircraft observers tried to delete areas with fresh light snowpack which did not represent the major winter accumulation. These areas might show up as snowcovered area on the satellite imagery, but an observer close to the ground could identify the freshly fallen snow on bare ground and eliminate it from the observation.

3. Aircraft observers and methods changed at various times.

During analysis, it was arbitrarily decided to make a correction to all aircraft observed data by increasing the aircraft observations by eight percent on the Kings River and 14 percent on the Kern River. Obviously, there is no means for otherwise testing or adjusting aircraft observations prior to the availability of satellite imagery.



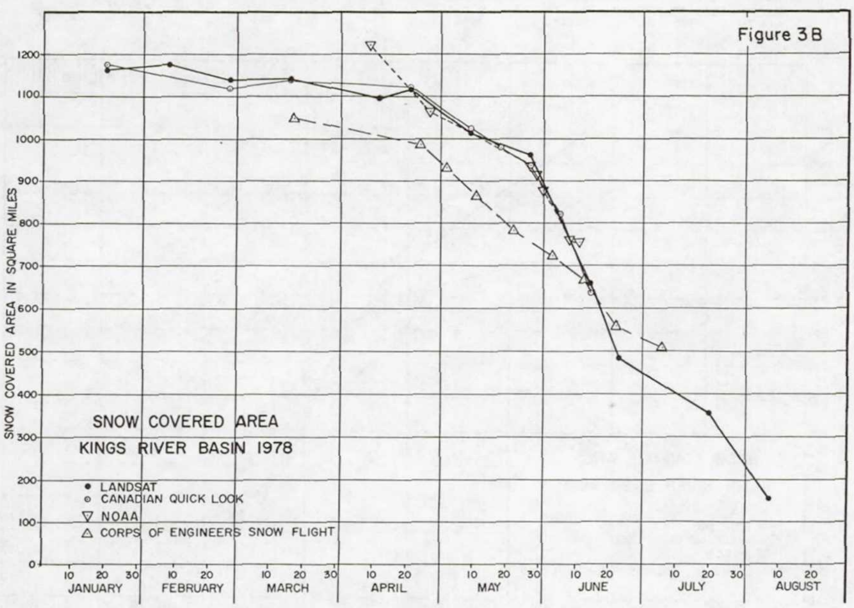


Figure 3. Snowcovered Areas

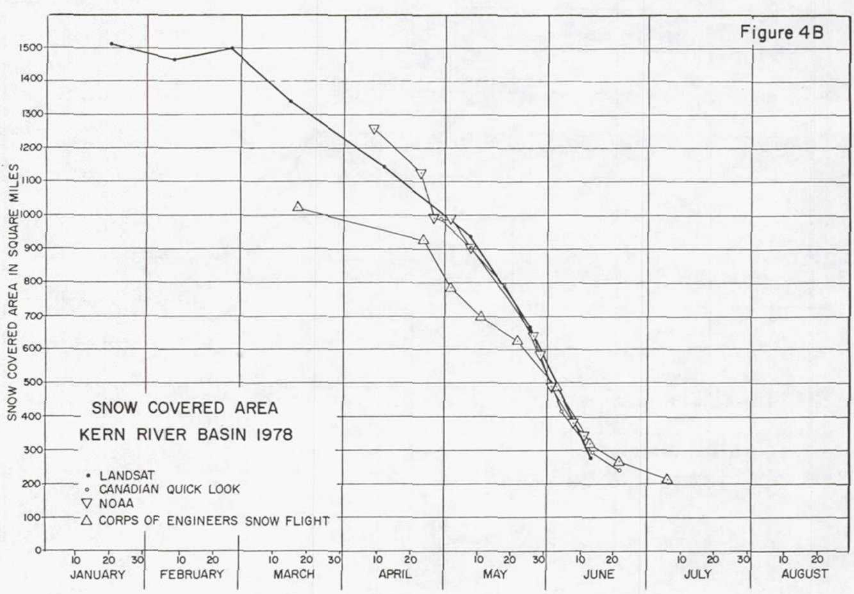


Figure 4. Snowcovered Areas

DATA APPLICATION

Although utilization of snowcovered area as a supplemental parameter in seasonal runoff predictions seems logical and has been shown by various investigators to be useful (Rango, et al, 1979), the duration of satellite data is too short for conclusive testing of SCA in most conventional approaches to water supply forecasting. In order to expeditiously investigate the potential value of satellite SCA data in runoff prediction, long-term aircraft observations of SCA were used as a parameter in testing operational forecasting procedures for the Kings and Kern River watersheds in the southern Sierra Nevada.

Test Basins

The Kings and Kern Rivers are adjacent watersheds (Figure 2) in the southern Sierra, ranging in elevation from about 300 metres (1,000 feet) in the foothill areas to over 4 300 metres (14,000 feet) along the Sierra crest, which is the eastern boundary for both watersheds. The Kings River has an east-west orientation with high subbasin divides and subbasin drainage in deep canyons. The Kern River has a north-south orientation with the Sierra crest along the eastern drainage boundary and the similarly high Great Western Divide along the western boundary of the basin. The Kern River is characterized by plateau areas with broad meadow areas and timbered slopes, although the North Fork heads in the steep rocky areas near the Kings-Kern divide and flows in the deep canyons for most of its length to Lake Isabella. About 74 percent of the Kings River annual runoff of about 2 million dam^3 (1.6 million ac-ft) occurs during the April-July snowmelt period. About 67 percent of the average Kern River annual runoff of 773,000 dam^3 (627,000 ac-ft) occurs during the April-July snowmelt.

Test Procedures

In a preliminary analysis, a multiple regression technique was utilized to relate runoff subsequent to the date of forecast to causitive parameters. The analysis was intended to develop and demonstrate a procedure for updating water supply forecasts during the period of snowmelt to reflect observed conditions of precipitation, runoff, and change in SCA with the intention of reducing the residual error in the remaining flow subsequent to date of forecast.

The analysis was predicated on the operational requirement for accurate updating of water supply forecasts throughout the period of snowmelt runoff. Forecasts prepared by DWR have historically been for April-July snowmelt period. Updating has been primarily on the basis of precipitation observed subsequent to the April 1 forecast. Only a limited amount of data is available from the high mountain watersheds on a continuing basis during the period of snowmelt. Observed precipitation, runoff, and depletion of SCA as the melt season progresses provide parameters on a near real-time basis to reflect the progress of melt in the watersheds. This investigation developed and demonstrated usable techniques for updating the conventional DWR forecast procedures during the progress of snowmelt.

The updating procedures used the same data as the conventional DWR procedures, which includes high and low elevation snow indexes (based on snow water content measurements), October-March precipitation index, precipitation during the period of snowmelt, and previous year's April-July runoff. In addition, the updating procedures included the runoff from April 1 through date of forecast, and SCA as of the date of forecast.

Figure 5 illustrates the variation in standard error, expressed as a percentage of April-July runoff, for forecast updates, and depicts the effective reduction in forecast error as the melt season progresses. Updating procedures without SCA are shown as a dashed line, while updating procedures utilizing SCA are shown as a solid line. On the Kings River, standard error increased slightly between April 1 and May 1, probably as a result of additional forecast parameters (observed runoff and SCA) used subsequent to April 1 which increased the degrees of freedom lost. After May 1, standard error declined appreciably until on June 15 it was approximately 70 percent of the error on April. The addition of SCA as a parameter on the Kings River appeared to offer little significant improvement in procedural error during the melt season. On the Kern River, standard error declined as the season progressed, but inclusion of SCA as a parameter appeared to make a substantial decrease in volumetric error of remaining runoff as the season progressed.

The analysis indicated that use of SCA as a parameter in forecasting snowmelt runoff may result in significant improvement of forecasting procedures under certain circumstances. It may be hypothesized that watershed characteristics, as well as availability of data representative of the watershed, may be factors related to response of forecast procedures to SCA. Historically, forecast errors on the Kern River have been substantially larger (percentage-wise) than those on the Kings River. Inclusion of SCA during the period of snowpack depletion allowed forecast accuracy on the two watersheds to be brought more in line with each other than was possible with conventional parameters alone. This suggests that SCA provides information pertinent to updating forecasts under some circumstances which may not be readily available from other basic data investigated here.

During the 1978 season, a forecast procedure using SCA was developed for the Kaweah River Basin which is adjacent to both the Kings and Kern River Basins. This procedure was developed specifically for operational use during the unusual 1978 snowmelt season.

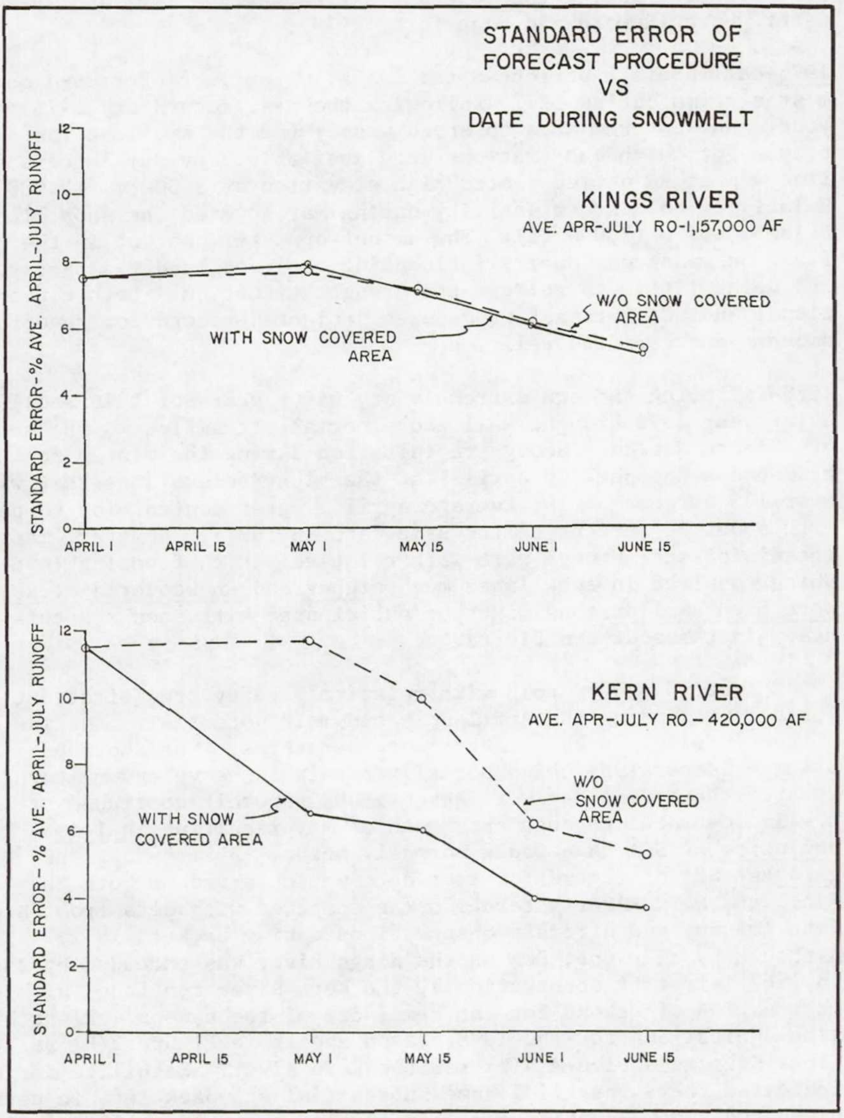


Figure 5. Standard Error of Forecast Procedure vs. Date During Snowmelt

Operational Forecasting

Water supply forecasts utilizing SCA as a forecast parameter were prepared during the snowmelt period for the 1977 and 1978 water years (Howard and Hannaford, 1979).

1977-California experienced the driest water year of record on most streams during 1977, following the near record dry 1976 water year. Snowcovered area observed was by far the smallest for any season for which observations were available. By May 1 the snow line was at an unprecedented high elevation of 3 000 m (10,000 ft). Relatively cold storm activity during May lowered the snow line to below 2 100 m (7,000 ft). The amount of water content in the fresh snowpack was small, influencing observed runoff slightly, and doing little to relieve the drought situation. Both conventional and SCA forecast procedures projected record low runoff amounts and verified well.

1978-Following the two extremely dry water years of 1976 and 1977, water year 1978 brought well above normal streamflow to the southern Sierra Nevada. Heavy precipitation during the winter months produced a snowpack by April 1 at the higher elevations that was over 175 percent of the average April 1 water content (as compared with about 20 percent of the same date in 1977). However, many of the winter storms were warm with relatively high freezing levels which resulted in snow lines much higher and snowcovered areas were much smaller than might be anticipated with snowpack this heavy in the southern Sierra.

April was very cold with relatively heavy precipitation, further increasing the April-July snowmelt potential. May was dry with only slightly below average temperatures. The short periods of high temperature which normally result in heavy snowmelt runoff towards the end of May were absent, and snowmelt continued at relatively low rates through the month of May resulting in less depletion of SCA than would normally occur. By mid-May, the greatest SCA of record for that date was observed on both the Kings and Kern River watersheds (as compared with data from satellite imagery and aircraft observations dating back to 1952). Although by mid-June, SCA on the Kings River was exceeded by that in 1967 (aircraft observations), the Kern River continued with the maximum SCA of record for the remainder of the season. Plots of time against SCA for the 1978 season appear in Figure 3(b) for the Kings River and Figure 4(b) for the Kern River. Satellite imagery indicated there was still some substantial snowpack left in certain protected high elevation portions of the watersheds well into August and some isolated snowfields persisted throughout the summer.

Because SCA on April 1 was well below that which might normally be anticipated with the relatively large snowpack water content at the higher elevations, water supply forecasts for the Kings and Kern Rivers using SCA as a parameter were substantially lower than those from other sources. By May 1, forecasts were raised as a result of heavy precipitation during April, but forecasts utilizing SCA were still substantially below the forecasts utilizing the conventional procedure. Subsequent updates gave similar results.

Forecasts utilizing SCA verified well, while conventional procedures tended to overforecast. The record large SCA after May 1 gave some assurance that flow which had not materialized prior to that date was still available in the form of snowpack within the watersheds. The forecasts utilizing SCA were conveyed to operating agencies in the southern Sierra as part of the NASA program. The major operational problem during the 1978 snowmelt season, as discussed under SCA Data Interpretation, was in securing imagery at the time forecasts were required.

CONCLUSIONS

The areal extent of snowcover as derived from satellite imagery does appear to have some potential for improving the timeliness and frequency of hydrologic forecasts in California's ASVT test areas. The greatest potential for water supply forecasting is probably in improving forecast accuracy and in expanding forecast services during the period of snowmelt. Problems of transient snow line and uncertainties in future weather are the main reasons that SCA appears to offer little in water supply forecast accuracy improvement during the period of snowpack accumulation.

During snowmelt, both rate and volume of snowmelt runoff can be related to receding SCA as well as other parameters. Based on the period of analysis of approximately 25 years, including both aircraft and satellite observations, SCA appears to offer considerable improvement in accuracy of forecast updates under certain conditions. The improvement in accuracy appears to be greatest from watersheds with a limited amount of representative data available from the watershed on a real-time basis during the period of melt. Also, SCA may have some potential in making forecast procedures more responsive to conditions involving unusual distribution of snowpack throughout the watershed.

Use of SCA, from an operational standpoint, can become restricted when there is considerable cloud cover over the mountainous region for extended periods of time. At these times, neither the Landsat nor the daily NOAA imagery may be available. The experience of the interpreter is extremely valuable in estimating SCA during partial cloud cover from observed SCA on portions of the observed basins and adjacent basins. This skill may be critical to the operational use of SCA. Delivery of imagery from the source to the interpreter also may pose a critical problem. Operational experience during the past two seasons suggests that much more rapid dissemination of observed satellite imagery will be required before completely effective use can be made of SCA in DWR forecast responsibilities.

SCA as a forecast parameter does not obviate the need for other accurate data from conventional sources to define water supply and anticipated runoff. SCA does, however, provide one more piece of supplemental information needed to increase the reliability of forecast updates during the period of snowmelt runoff. DWR plans to continue the interpretation of satellite imagery associated with water supply forecasting on California's snowmelt streams.

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