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INTERPRETATION OF SNOWCOVER FROM SATELLITE IMAGERY FOR USE IN WATER SUPPLY FORECASTS IN THE SIERRA NEVADA

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ABSTRACT

The California ASVT test area is composed of two study areas; one in Northern California covering the Upper Sacramento and Feather River Basins, and the other covering the Southern Sierra Basins of the San Joaquin, Kings, Kaweah, Tule, and Kern Rivers. The paper describes the experiences of reducing snowcover from satellite imagery; the accuracy of present water supply forecast schemes; and the potential operational advantages of introducing snowcover into the forecast procedures.

INTRODUCTION

The National Aeronautics and Space Administration is investigating application of satellite imagery to interpretation of snowcover in the western United States, including California's Sierra Nevada. The objective of the overall investigation is application of data on areal extent of snowcover to operational water supply forecasts. NASA has contracted with the California Department of Water Resources to explore potential application of snowcover data from satellite imagery to the Department's hydrologic forecasting responsibilities. The Department of Water Resources has contracted with Sierra Hydrotech, a consulting firm in Placerville, California, for technical assistance in developing procedures for data reduction and in investigating applications of satellite data on snowcover to hydrology.

The objective of this paper is to outline plans and goals of the California investigation and to report upon progress made in achieving these goals over the past year.

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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. Portions of this water supply are exported via the California State Water Project for use in Southern California. The average water-year runoff of Sierra streams tributary to the San Joaquin Valley and Tulare Lake Basin is approximately 9 million acre-feet, while the average water-year runoff of Sierra and Southern Cascade streams tributary to the Sacramento Valley is approximately 15 million acre-feet. In southern Sierra streams where elevations range up to 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.

It is interesting to note that the first program of formalized snow water content measurements was initiated here in the Lake Tahoe Basin by Dr. James E. Church, University of Nevada. As early as 1910 Dr. Church made measurements of snowpack water content with a snow sampling tube, similar to that used today, with the objective of predicting the annual rise of Lake Tahoe as a means of resolving certain water rights problems in the Truckee River Basin.

The importance of water in the Central Valley of California has long generated a keen interest by water managers in methods of predicting the volume of the seasonal water crop and the time-distribution of runoff for operational planning. Although water supply forecasts have been utilized since well before the turn of the century, the State of California coordinated the early diverse interests through initiation of the California Cooperative Snow Survey Program in 1929. The legislature mandated in that year than an annual and seasonal projection of the State's snowmelt water crop be made. The program of snow measurement and water supply forecasting has been conducted continuously by the State and its cooperators for 45 years.

The high degree of development and use of water in California's Central Valley has required development of sophisticated techniques for predicting volume and time-distribution of 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.

INVESTIGATION

The objectives of the California ASVT investigation and the location of the study areas are described in the next two sections.

Objectives

The technical objectives of the California ASVT may be grouped as (1) reduction and interpretation of basic snowcover data, and (2) operational application of snowcover to water supply forecasting. It should be pointed out that development of sophisticated techniques for snowcover reduction is not part of the first objective. The purpose of the snowcover reduction phase is merely to quickly learn how to obtain data required later during the operational applications phase of the study. Once the applicability of snow covered area from satellite imagery to the State's hydrologic responsibilities has been determined, then techniques for reduction and interpretation of imagery for operational purposes can be finalized.

The most important objective of the investigation is the determination of the applicability of snow covered area from satellite imagery to water supply forecasting in general, but more specifically the updating of forecasts as the melt season progresses and the estimation of potential rates of melt and corresponding stream discharge. Initial investigation suggests that adequate data on snow covered area may prove of more value in estimating melt rate and updating forecasts than in preparation of early season water supply forecasts.

Study Area

The study area, comprising 38 major basins and sub-basins is actually two study areas covering a wide variety of topographic, climatologic, and hydrologic conditions. The first study area covers the Sacramento River above Shasta Dam and the Feather River above Oroville Dam and includes 24 major basins and sub-basins within and adjacent to these two watersheds. The other area is composed of five southern Sierra streams, the San Joaquin, Kings, Kaweah, Tule and Kern River Basins, and includes 14 major basins and sub-basins for which data is being reduced. Plate 1 shows the location of these study areas.

DATA REDUCTION AND INTERPRETATION

Techniques for reduction and interpretation of snow covered area from satellite imagery were reviewed (ref. "Handbook of Techniques for Satellite Snow Mapping", December 1974 by James C. Barnes and Clinton J. Bowley) and adapted to conditions found in the northern and southern project areas. Different techniques and the work of different technicians have been compared to investigate reproducibility of results. Most of the actual data reduction has been restricted to the 1:1 million LANDSAT imagery to develop the necessary technical skills required for interpretation of the lower resolution, smaller scale (1:3.5 million and 1:10 million) NOAA imagery. The more detailed LANDSAT imagery is available only on an 18 or nine-day cycle, while the lower resolution NOAA imagery is potentially available daily. It is hoped that the more detailed LANDSAT data may be used as a neans of checking and calibrating the lower resolution NOAA data to permit more detailed investigation of change in snowpack area with time.

LANDSAT Imagery

LANDSAT imagery for 1972-73 and 1973-74 for 38 basins and sub-basins within and adjacent to the areas of investigation has been reduced to (a) maps of snow covered area, (b) area of snowcover in square miles, and (c) equivalent snow line elevation. LANDSAT images have been interpreted at the 1:1 million scale by direct overlay and, for investigation of reliability of results, they have also been interpreted at a scale of 1:500,000 using the Zoom Transfer Scope. Comparative results have not been examined at this time.

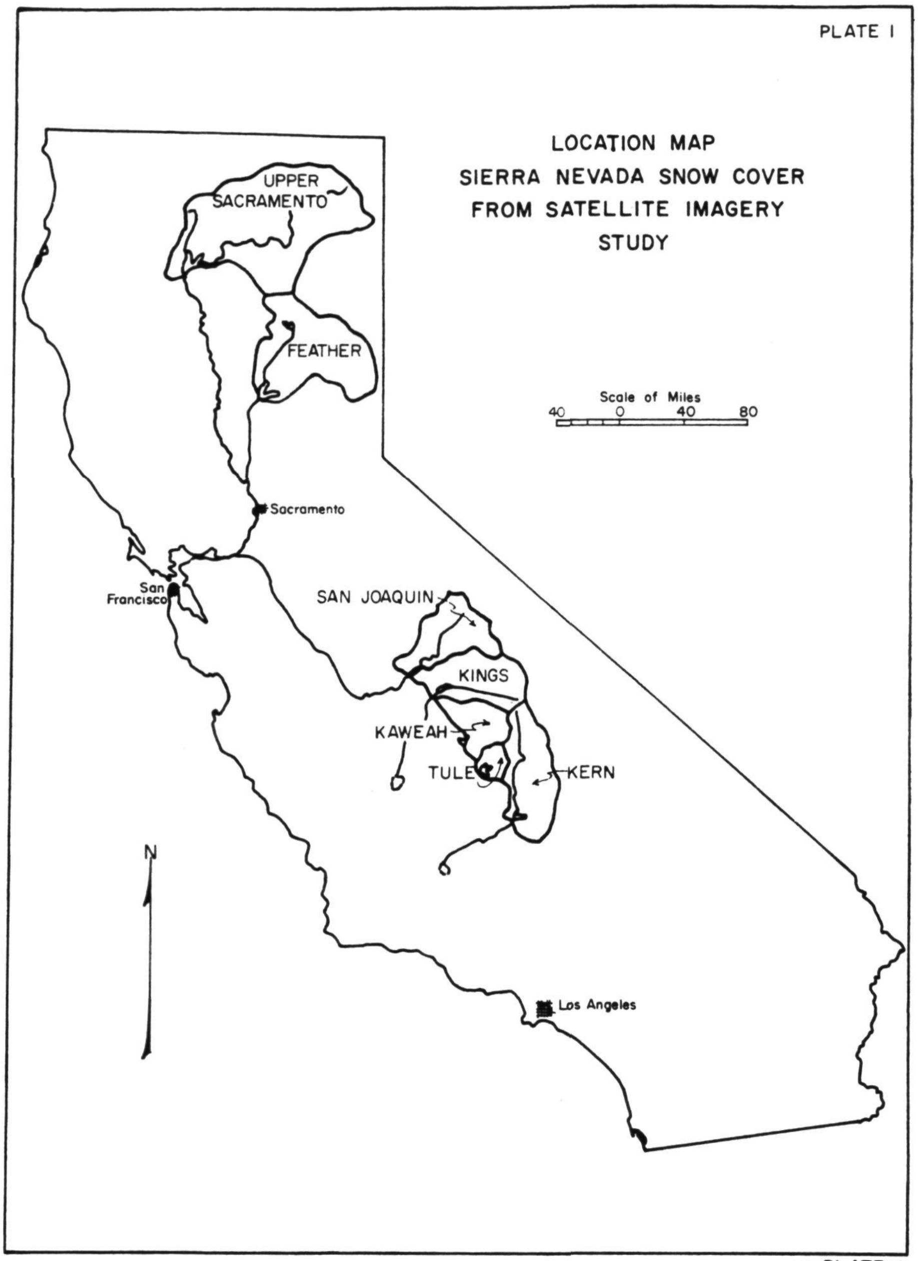
LOCATION MAP
SIERRA NEVADA SNOW COVER
FROM SATELLITE IMAGERY
STUDY
Scale of Miles
40 0 40 80
UPPER SACRAMENTO
FEATHER
Sacramento
San Francisco
SAN JOAQUIN
KINGS
KAWEAH
TULE
KERN
N
Los Angeles

PLATE I

Estimates of snow covered area from a relatively large number of basins and sub-basins in each study area are being made simultaneously. In some cases, cloud cover, missing imagery, or other factors may contribute to loss of data from a specific basin or portion of the study area on any given day. Basins vary in size from 38 square miles to 6,400 square miles. The approach permits crosschecking between adjacent and nearby basins which will provide for a means of estimating snowcover conditions even when portions of a given project area may be obscured by clouds.

The following table summarizes LANDSAT imagery which has been reduced at this time.

Project Area	No. of Basins and Sub-Basins	No. of Days of Record Reduced
Northern	24	29
Southern	14	39

At the present time, it is impossible to reduce "current" data within a strictly operational time frame. LANDSAT imagery is being received about three weeks to a month after it is originally taken. Although it is recognized that the program is not intended to provide operational data at this time, it should be pointed out that satellite imagery should be received in Sacramento within three days of the satellite pass to be of optimum operational value in projecting melt rates and updating water supply forecasts. Time required for reduction and interpretation of satellite imagery, even utilizing the hand techniques currently employed, should not pose an operational problem in reducing data from the 20 major snowmelt watersheds in California.

NOAA Imagery

Additional work has been done in study of techniques for reducing the lower resolution NOAA imagery. Difficulty has been encountered in obtaining consistent results, a problem which was somewhat anticipated due to the small size of many sub-basins. Although snow lines are very apparent in certain exposed areas, particularly where great elevation changes exist, it is often difficult to interpret area of snowcover in heavy timber. Enhancement and enlargement techniques currently being investigated offer encouragement that the NOAA imagery may become more helpful.

WATER SUPPLY FORECASTING

Water supply forecasts prepared by the California Cooperative Snow Surveys Program relate snowmelt season runoff to indexes of basin wetness and water stored as snowpack within the basin as reflected by measurements of precipitation, snowpack water content, and other hydrologic parameters. Since the days of Dr. Church, water supply forecasts have been based upon indexes of snow water volumes in basins. No operational water supply forecast has ever successfully attempted to measure the snow water volume. Thus errors (and consequently an opportunity for improvement) in water supply forecasts are related to indexing capability and not necessarily to accuracy of volumetric measurement. It is hoped that satellite imagery can provide supplemental data on snowcover which will result in improved indexing of the snowpack contribution to runoff.

Forecast Errors

Most April-July water supply forecasts procedures currently in use by DWR have been developed to the point that procedural error, or error in the snowpack-precipitation-runoff relationships, should give calculated April-July runoff values having standard errors smaller than 10 to 15 percent of observed runoff values. However, precipitation subsequent to the date of forecast is a major factor in forecast error. To illustrate the magnitude of this factor, April-July runoff forecast error funnel diagrams for the Feather River inflow to Lake Oroville and the San Joaquin River inflow to Millerton Lake (Friant) are presented on Plate 2. The June 1 error represents the basic forecast scheme error or that error which remains after all forecast parameters have been identified. The increases in error ranges that occur with earlier forecast dates are due only to uncertainty in future weather conditions.

To summarize the existing forecast error situation for each basin in the study area, the following tabulation of April 1 forecast and procedural error is presented.

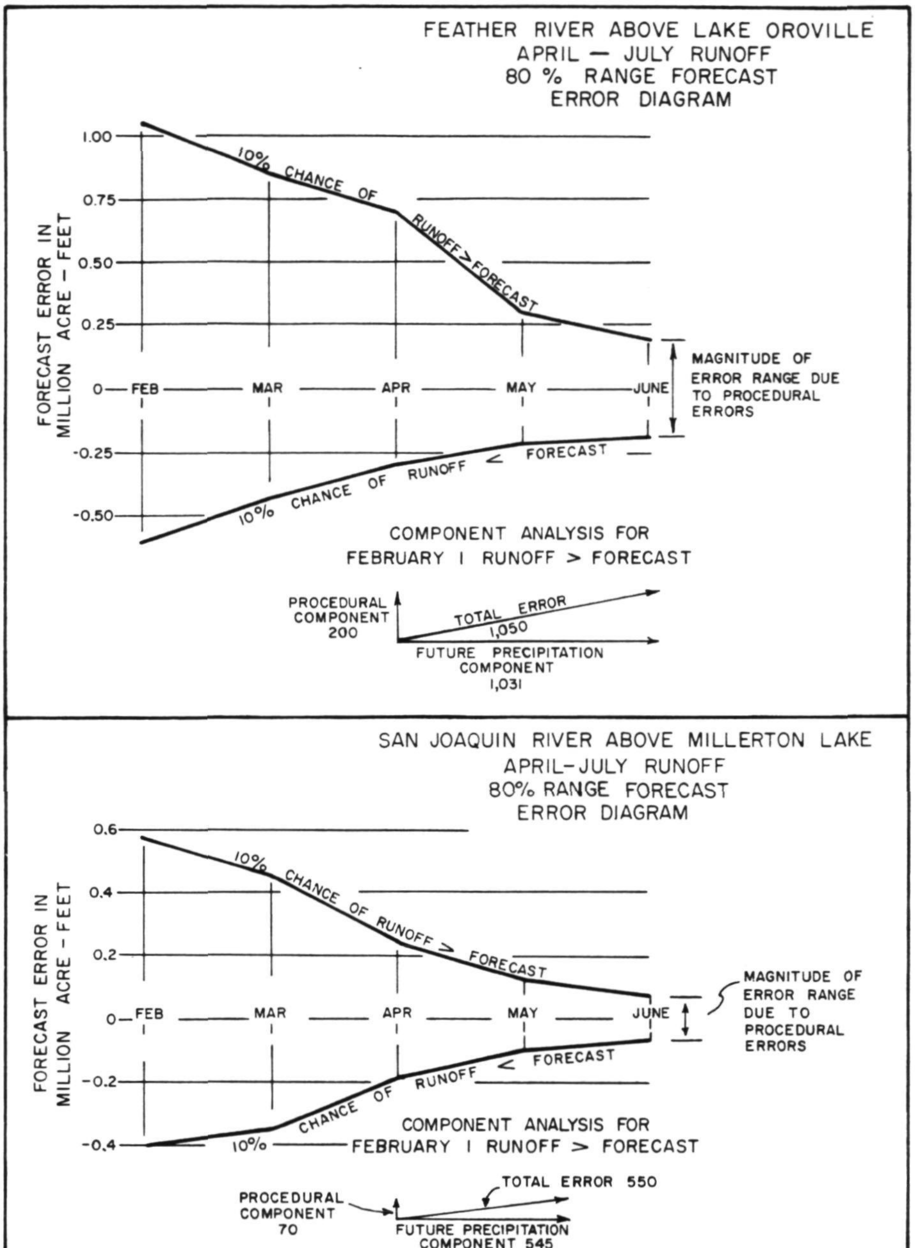
FEATHER RIVER ABOVE LAKE OROVILLE
APRIL — JULY RUNOFF
80 % RANGE FORECAST
ERROR DIAGRAM
FORECAST ERROR IN MILLION ACRE - FEET
1.00
0.75
0.50
0.25
0
-0.25
-0.50
FEB
MAR
APR
MAY
JUNE
10% CHANCE OF RUNOFF > FORECAST
10% CHANCE OF RUNOFF < FORECAST
MAGNITUDE OF ERROR RANGE DUE TO PROCEDURAL ERRORS
COMPONENT ANALYSIS FOR
FEBRUARY 1 RUNOFF > FORECAST
PROCEDURAL COMPONENT 200
TOTAL ERROR 1,050
FUTURE PRECIPITATION COMPONENT 1,031
SAN JOAQUIN RIVER ABOVE MILLERTON LAKE
APRIL-JULY RUNOFF
80% RANGE FORECAST
ERROR DIAGRAM
FORECAST ERROR IN MILLION ACRE - FEET
0.6
0.4
0.2
0
-0.2
-0.4
FEB
MAR
APR
MAY
JUNE
10% CHANCE OF RUNOFF > FORECAST
10% CHANCE OF RUNOFF < FORECAST
MAGNITUDE OF ERROR RANGE DUE TO PROCEDURAL ERRORS
COMPONENT ANALYSIS FOR
FEBRUARY 1 RUNOFF > FORECAST
PROCEDURAL COMPONENT 70
TOTAL ERROR 550
FUTURE PRECIPITATION COMPONENT 545

PLATE 2

Forecast Point	80 Percent Error Range[1/] in Percent of Average April-July Runoff April Forecast	Forecast Procedure
Sacramento inflow to Shasta	56.4	24.8
Feather inflow to Oroville	53.7	20.4
San Joaquin inflow to Friant	31.9	12.0
Kings inflow to Pine Flat	34.4	12.0
Kaweah inflow to Terminus	33.2	15.5
Tule inflow to Success	42.4	34.0
Kern inflow to Isabella	52.5	28.6

1/ This range is the sum of positive and negative errors. For example, the April 1 San Joaquin 80 percent error range shown on Plate 2 is from -180,000 acre-feet to +240,000 acre-feet for a total error range of 430,000 acre-feet. 430,000 acre-feet ÷ 1,193,000 acre-feet = 31.9%. (1,193,000 acre-feet is the average April-July flow of the San Joaquin.)

The above tabulation indicates that the greatest forecast procedural or scheme error exists in the Sacramento, Feather, Tule and Kern forecasts. Thus, it is expected that these basins are the ones which could benefit most from incorporation of snow line location data into a forecast. Such a conclusion is logical because these basins are the ones which have the greatest variability in snow line location.

Operational Applications

Preliminary work has been undertaken to investigate the potential benefits obtainable through observation of areal snowcover and hydrologic modeling as related to updating of late season runoff projections. The Corps of Engineers has obtained estimates of the extent of areal snowcover in the Kings River Basin by aircraft observation and mapping for over twenty years. Records consist of periodic observations and estimates of the area of snowpack cover during the period of spring snowmelt, generally from early May until the remaining area of snowcover becomes less than 100 square miles in this 1,500 square mile watershed. These observations of snowpack areal extent have been plotted against time to obtain a recession of the snow covered area on a year-by-year basis.

Preliminary analysis indicates that a correlation exists between observed melt rate, remaining area of snowcover, the April 1 measurement of snowpack water content adjusted for subsequent precipitation, and the remaining volume of snowmelt runoff after the date of observation. The characteristics of this relationship are delineated in Plate 3. Even though techniques in current use appear quite effective in relating observed melt rate to remaining volume of runoff for southern Sierra watersheds, refinement of the technique through detailed daily or periodic observation of snow covered area could provide additional reliability and confidence.

Watersheds in the southern Sierra are characterized by a high correlation between snow line elevation and area of snowcover, at least through a major part of the snowmelt season. However, in the northern Sierra, topography and precipitation characteristics of the watersheds lead to a situation in which the area of snowcover may be more variable, both from season to season and from date to date within a given snowmelt season. Although no investigation has yet been made of relationships which may exist between melt rate, snowcover, and remaining runoff in northern Sierra basins, if such relationships can be established they would be effective tools in updating runoff projections as the snowmelt season progresses. Further investigation of the relationship between snow covered area and other factors, such as rate of change of water content at snow sensor sites, could provide effective parameters for updating water supply forecasts and estimating future runoff rates.

Updating Forecasts--The degree of forecast accuracy in many cases is not so critical early in the snowmelt season when precipitation after the date of forecast represents the major portion of forecast error and there is still ample time for adjustment of water management plans. However, as the snowmelt season progresses from mid-May through early July, procedural error remains the same in terms of acre-feet and the amount of water represented by this error may become critical in the operation of a water project. In the southern Sierra, the critical period is generally from mid-May through mid-June when snowmelt runoff rates are highest and reservoirs are nearing capacity. In the northern Sierra, these critical dates normally occur earlier in the snowmelt season. Procedures for updating forecasts as the snowmelt season progresses are of great value to water managers who must make important decisions regarding reservoir filling, reduction of spills, flood releases and the requirements of water users.

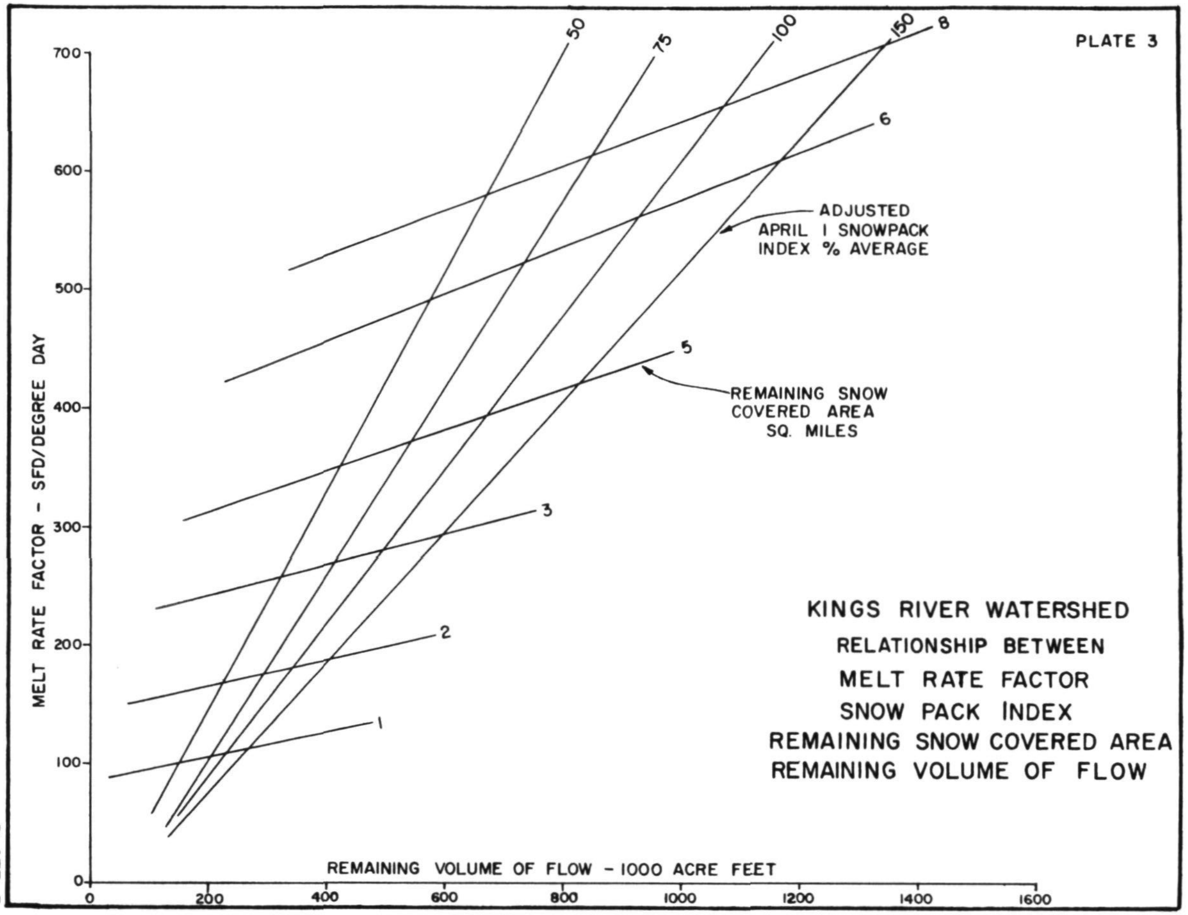
PLATE 3
MELT RATE FACTOR - SFD/DEGREE DAY
REMAINING VOLUME OF FLOW - 1000 ACRE FEET
50
75
100
150
8
6
5
3
2
1
ADJUSTED APRIL 1 SNOWPACK INDEX % AVERAGE
REMAINING SNOW COVERED AREA SQ. MILES
KINGS RIVER WATERSHED
RELATIONSHIP BETWEEN
MELT RATE FACTOR
SNOW PACK INDEX
REMAINING SNOW COVERED AREA
REMAINING VOLUME OF FLOW

PLATE 3

Hydrologic Models--The Department of Water Resources operates hydrologic models on the Kings and San Joaquin Rivers which simulate daily snowmelt runoff through evaluation of snowpack quantity, temperature, and other factors relating to runoff. An important feature of these models is that the quantity of runoff remaining as snowpack can be assessed and predictions of remaining flow revised as the snowmelt season progresses. Hydrologic modeling techniques permit updating forecasts of remaining flow with a much higher degree of accuracy than would be possible utilizing only conventional water supply forecasting techniques.

FUTURE PLANS

Work will continue on reduction of LANDSAT imagery to expand the file of historic data. Additional investigation and reduction of the lower resolution NOAA imagery will be pursued, with particular emphasis on the period of snowmelt (April through July). It is anticipated that sufficient data will soon be available to permit more detailed investigation of application of snow covered area to projections of water supply and melt rate.

The capability of reducing snowcover for satellite imagery is being developed now within the staff of the Snow Surveys Branch, which will establish the necessary skill at the operational level. The Department's water supply forecasters will become involved in testing the extent to which the addition of snowcover to the procedures improves the water supply forecast. They will be aided in this effort by assistance and advice from Sierra Hydrotech.

CONCLUSIONS

The following conclusions have been reached with regard to data reduction and interpretation, although they must be considered preliminary at this time due to the limited amount of work which has been accomplished.

1. When working with 1:1 million scale imagery a reasonably accurate snow line can be drawn for the southern Sierra Nevada basins by using a direct overlay.

2. The Sacramento and Feather basins have been more difficult to analyze using direct overlays because
   - imagery has given poorer coverage,
   - cloud cover is more frequent,

- vegetation hides more snow,
- geologic conditions (lava flows) cause confusion in interpretation,
- sun angle is lower,
- topography is more erratic and does not provide an easily identified elevation change, and
- the relationship between elevation and snowcover is less consistent than in the southern Sierra Nevada.

3. The promise of snow covered area definition providing improvement in water supply forecasts is greater for the Feather and Sacramento basins because the snowcover area differs greatly from year to year.

4. Use of NOAA 1:10 million imagery has presented many problems, particularly in the northern Sierra. Image quality does not allow large magnification using a Zoom Transfer Scope and distortion is very bad.

5. Use of NOAA 1:3.5 million imagery may be practical once more experience has been obtained.