APPLICATION OF SATELLITE IMAGERY TO HYDROLOGIC MODELING SNOWMELT RUNOFF IN THE SOUTHERN SIERRA NEVADA

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ABSTRACT

Snowcovered area was examined as a parameter for estimating rate of snowmelt runoff as input to an operational hydrologic model. SCA and surface air temperature provided a very effective means for simulating daily snowmelt runoff for the Kings River.

INTRODUCTION

General

The purpose of this investigation has been to explore the application of satellite imagery to hydrologic modeling of snowmelt runoff in the southern Sierra Nevada. The investigation has been conducted under the sponsorship of the National Aeronautics and Space Administration in conjunction with the California Applications Systems Verification and Transfer Project.

Objectives

The major objective of this investigation has been to develop and test application of areal extent of snowcover to hydrologic simulation of daily snowmelt runoff on the Kings River basin in California's southern Sierra Nevada. The California Department of Water Resources (CDWR) currently operates a hydrologic model to simulate daily runoff on the Kings River basin for operational purposes. Although previous investigation leading to the Kings River model suggested that areal extent of snowcover influences rate as well as remaining volume of snowmelt, techniques had not been developed to incorporate this parameter in the operational model, since at that time, only intermittent observations of snowcovered area by low flying aircraft were available.

This investigation was intended to (1) explore techniques for application of snowcovered area (SCA) to the existing Kings

River hydrologic model, (2) develop and describe SCA-snowmelt relationships in a manner to make the technique readily transferable to other similar watersheds, and (3) develop techniques for interpolating and extrapolating SCA for operational use on a daily basis from satellite observations as well as precipitation and temperature data. This investigation by Sierra Hydrotech has been considered complimentary to "Operational Applications of Satellite Snowcover Observations in California" currently being conducted by the California Cooperative Snow Survey Branch, (CDWR) and sponsored by NASA.

BACKGROUND

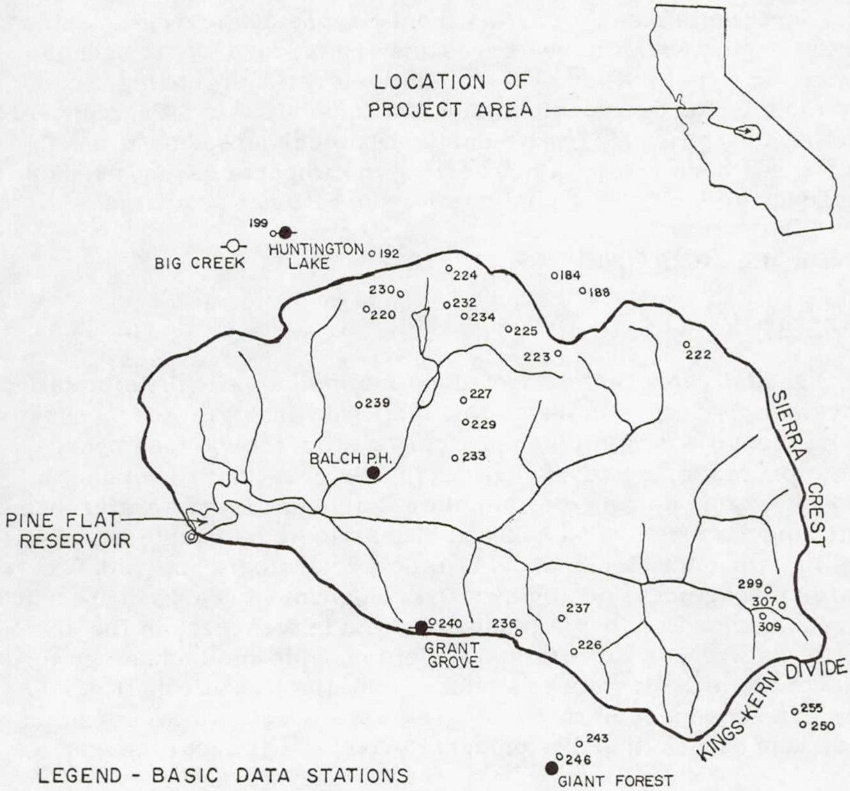
General

Water originating from snowmelt in California's southern Sierra Nevada has high value for municipal and agricultural application. Detailed information on the volume and rate of snowmelt runoff through operational hydrologic forecasts is important in water management decision making. For half a century, measurements of snowpack water content have been made on a monthly basis in these watersheds for the purpose of estimating volume of runoff, and for over 20 years, aircraft observations of the areal extent of snowpack were made. Satellite observation of areal extent of snowcover have been interpreted for each snowmelt season since 1973.

Study Area Description

The Kings River is a southern Sierra Nevada watershed (Figure 1) that discharges into the Central Valley near Fresno, California. The basin ranges in elevation from below 300 m in the foothill areas to over 4300 m along the Sierra Nevada crest, which is the eastern boundary ot the watershed. The Kings River has an east-west orientation with high subbasin divides and subbasin drainage in deep canyons. The average elevation of the April 1 snow line is about 1900 m, although late winter and early spring storms may cause a temporary drop, or "transient" snow line, lasting sometimes only a few days. The distribution of area with elevation is relatively uniform within the area of major melt contribution between 1900 m and 3600 m elevation.

The 4000 km^2 Kings River basin has an average annual runoff of 1,568,000 acre-feet ($1934x10^6m^2$) which represents 480 mm of runoff, 75 percent of which occurs during the April-July snowmelt period. Snowpack accumulation increases with



LEGEND - BASIC DATA STATIONS

◎ MODELING POINT

○ SNOW COURSE, CALIF. NO.

● PRECIPITATION STATION

-○- TEMPERATURE STATION

-●- PRECIP. & TEMP. STATION

FIGURE 1

PROJECT AREA

KINGS RIVER HYDROLOGIC MODEL

elevation to about 2800 m and is fairly consistent at about 800 mm of water above that elevation, although local topography may affect accumulation to some extent. Average annual precipitation at the 2800 m elevation is about 900 mm. Winter 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, making these data useful for hydrologic analysis within the basin. Precipitation and resulting runoff are extremely variable from season to season in the southern Sierra, emphasizing the importance and need for an adequate hydrologic analysis for operational requirements.

HYDROLOGIC MODELING

General

A model represents a technique for mathematically simulating physical processes or relationships. A hydrologic model consists of mathematical relationships representing the various hydrologic processes occurring within the watershed. A hydrologic model may be designed to simulate daily flow from a watershed utilizing various hydrologic and climatologic parameters, resulting in output which can provide timely hydrologic analysis for water management decisions. Hydrologic models are not specific forecasts nor are they intended to provide forecasts in the same sense as weather forecasts. Models provide the technology to enable the hydrologists to evaluate the effect upon runoff of various sequences of climatologic or meteorologic events which may represent either historical or hypothetical occurrences.

Description of Existing Model

Digital hydrologic models have been developed and used as water management tools in the southern Sierra Nevada since the snowmelt season of 1969, when a hydrologic model was developed for simulation of daily runoff during the snowmelt season for the Kings River basin.[1/2/] The Kings River hydrologic model, and a similar model for the San Joaquin River, are operated weekly during each snowmelt season by CDWR.

The existing Kings River hydrologic model[1/] evolved through development of several submodels representing various runoff processes as illustrated in Figure 2. The general mathematical characteristics of each submodel were developed and fit to approximately 25 years of observed data. The Kings River hydrologic model consists of five basic submodels of varying

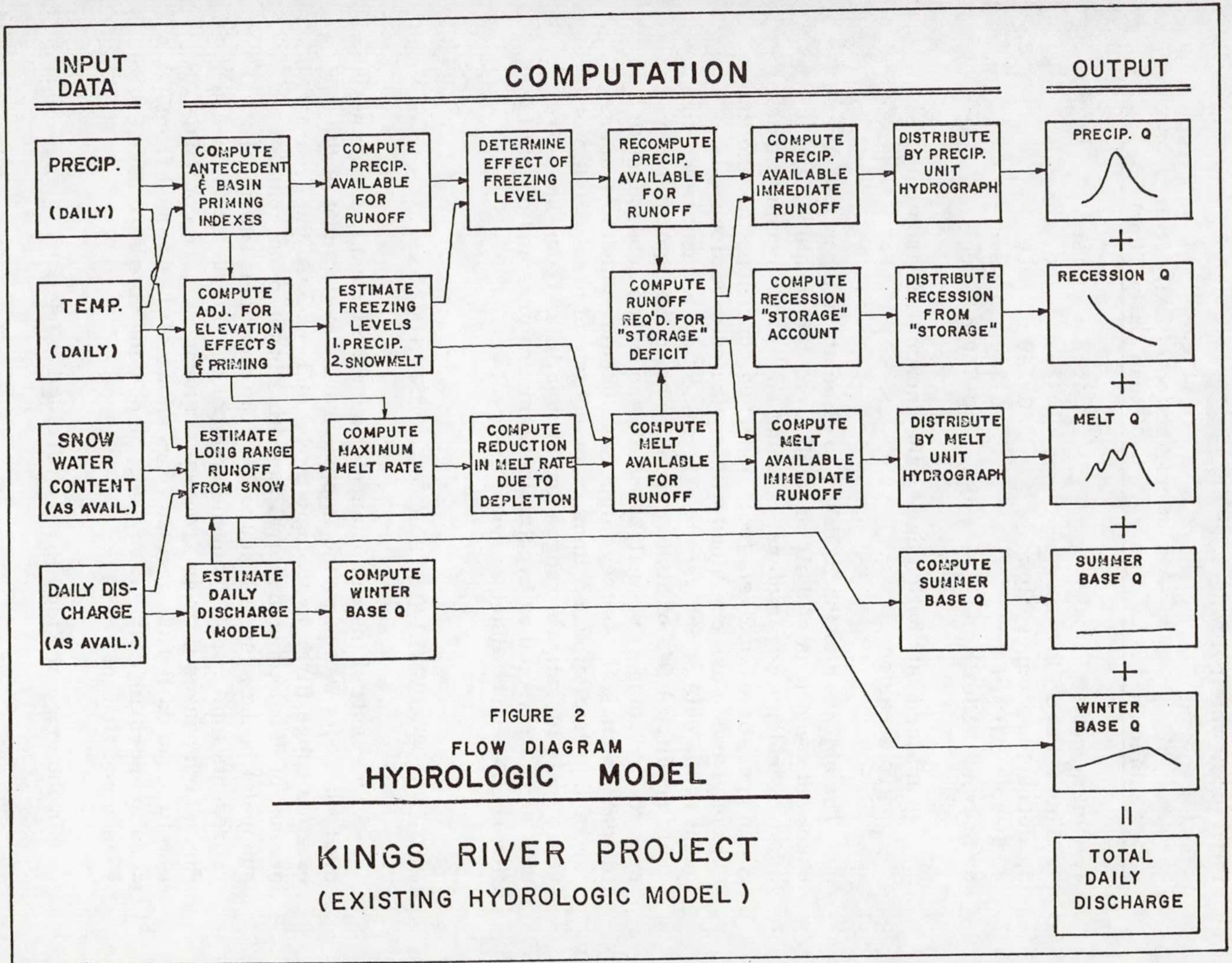


FIGURE 2

FLOW DIAGRAM

HYDROLOGIC MODEL

KINGS RIVER PROJECT

(EXISTING HYDROLOGIC MODEL)

complexity and influence on the overall hydrograph. The submodel of primary concern in the present investigation is that related to snowmelt flow.

Submodel	Magnitude of Contribution of Daily Hydrograph (Mean Daily Flow)
1. Summer Base Flow	2.8-8.5 m^3/sec
2. Winter Base Flow	0-25 m^3/sec
3. Recession Storage Flow	0-140 m^3/sec
4. Precipitation Flow*	0-1400 m^3/sec
5. Snowmelt Flow	0-750 m^3/sec

*A major contribution during the snowmelt season only on rare occasions

The objective of the model is to simulate daily runoff given observed conditions of daily precipitation, temperature, and other hydrologic parameters including snowpack accumulation. As an operational analysis tool, observed conditions through the date of analysis are combined with projected conditions subsequent to the date of analysis to determine flow sequences which could result. A file of historic conditions in the computer permits the hydrologist to analyze runoff sequences subsequent to the date of analysis as they might have occurred under temperature and precipitation regimes from any one of nearly 30 historic years or to investigate ranges and probabilities from the entire data set. Projected or hypothetical temperatures and precipitation regimes may also be used if desired.

ORIGINAL SNOWMELT SUBMODEL DESCRIPTION

As a result of the importance of snowmelt runoff, the snowmelt submodel was of prime importance in development of the original Kings River hydrologic model and received the greatest amount of developmental work, resulting in the most complex submodel in the system (Figure 2). The snowmelt submodel represents total runoff from the snowpack, both surface flow and flow which passes through "recession storage". The contribution to mean daily flow derived from snowmelt has varied from zero to approximately 750 m^3/sec, depending upon size of season and time of year.

In the original Kings River hydrologic model, daily snowmelt volume was based upon total quantity of snowpack, degree of snowpack priming, volume of remaining snowmelt runoff, and mean daily air temperature as an index to the effect of available energy on snowpack. A portion of the daily melt was passed through recession storage and the remainder was distributed by a four-day unit hydrograph. The original snowmelt model proved to be very effective under most conditions, in spite of its very empirical nature.

The final report on the original model stated that both snowpack volume and SCA are related to melt rate. However, the SCA relationship was not defined in that investigation. It should be pointed out that relationships between the remaining volume and rate of snowmelt runoff may still prove useful in operational analysis of runoff subsequent to the last date of satellite observation.

SCA SNOWMELT SUBMODEL - DEVELOPMENT AND DESCRIPTION

General Approach

The objective of this investigation was to develop techniques using SCA as a parameter to estimate the rate of snowmelt contribution as input to the Kings River hydrologic model. Although previous investigation leading to the Kings River model suggested that areal extent of snowcover influenced rate of snowmelt runoff, the technique had not been developed to incorporate this parameter in the operational model. Utilization of SCA required a relationship between the rate of snowmelt contribution to the runoff hydrograph and temperature, SCA, and related parameters which would permit simulation of daily snowmelt runoff from the hydrologic model. The original snowmelt submodel was completely removed from the hydrologic model and replaced by the SCA submodel, since the basic techniques used in the two submodels differed conceptually.

The SCA snowmelt submodel is based upon the following premises:

. . . The technique was to be capable of transference to other similar watersheds given the comparable characteristics of those watersheds. It was hypothesized that the greatest degree of transference could be achieved through development of the snowmelt submodel by elevation bands or zones within the watershed, basing the melt procedures upon similar and differing characteristics of the zones as well as relative levels of energy input.

. . . Melt in any elevation zone in the basin can be related to air temperature within that zone.

. . . Melt of snowpack may occur at any point or elevation zone in the watershed (assuming air temperatures are above freezing in that zone), but runoff will occur from the snowpack in a given elevation zone only after the snowpack in that zone becomes fully "primed". For purposes of the snowmelt submodel, the effective "elevation of prime" represents that elevation above which no snowmelt is available to the snowmelt hydrograph.

. . . The rate at which snowmelt is made available to the snowmelt hydrograph is proportional to the area of fully primed snowpack within each elevation zone below the "elevation of prime" as well as the temperature within each zone.

Basic Data - Elevation Zones and Temperatures

Figures 3 and 4 show various types of basic data used as input to the SCA snowmelt submodel and the Kings River hydrologic model. The following comments refer specifically to basic data as related to the SCA snowmelt submodel.

In the development phase, SCA was interpreted from satellite imagery by 150 m (500 foot) elevation bands or zones. It should be pointed out that the developmental model using elevation zones of snowpack is not particularly well suited to operational forecasting as the reduction of satellite imagery by 150 m elevation zones is a time consuming process. This approach is better left to the research and developmental stages of analysis, while a more simplified approach to data reduction is more applicable to operational analysis during the forecast season. Fortunately, in the Kings River watershed, the basinwide SCA seems to provide an adequate index to be used in future operational work, while analysis by zones provides for a means of transference of techniques to other areas and watersheds.

Temperature used in analysis is mean daily surface air temperature derived from three stations in or adjacent to the watershed and adjusted to an approximate elevation of 2100 m for

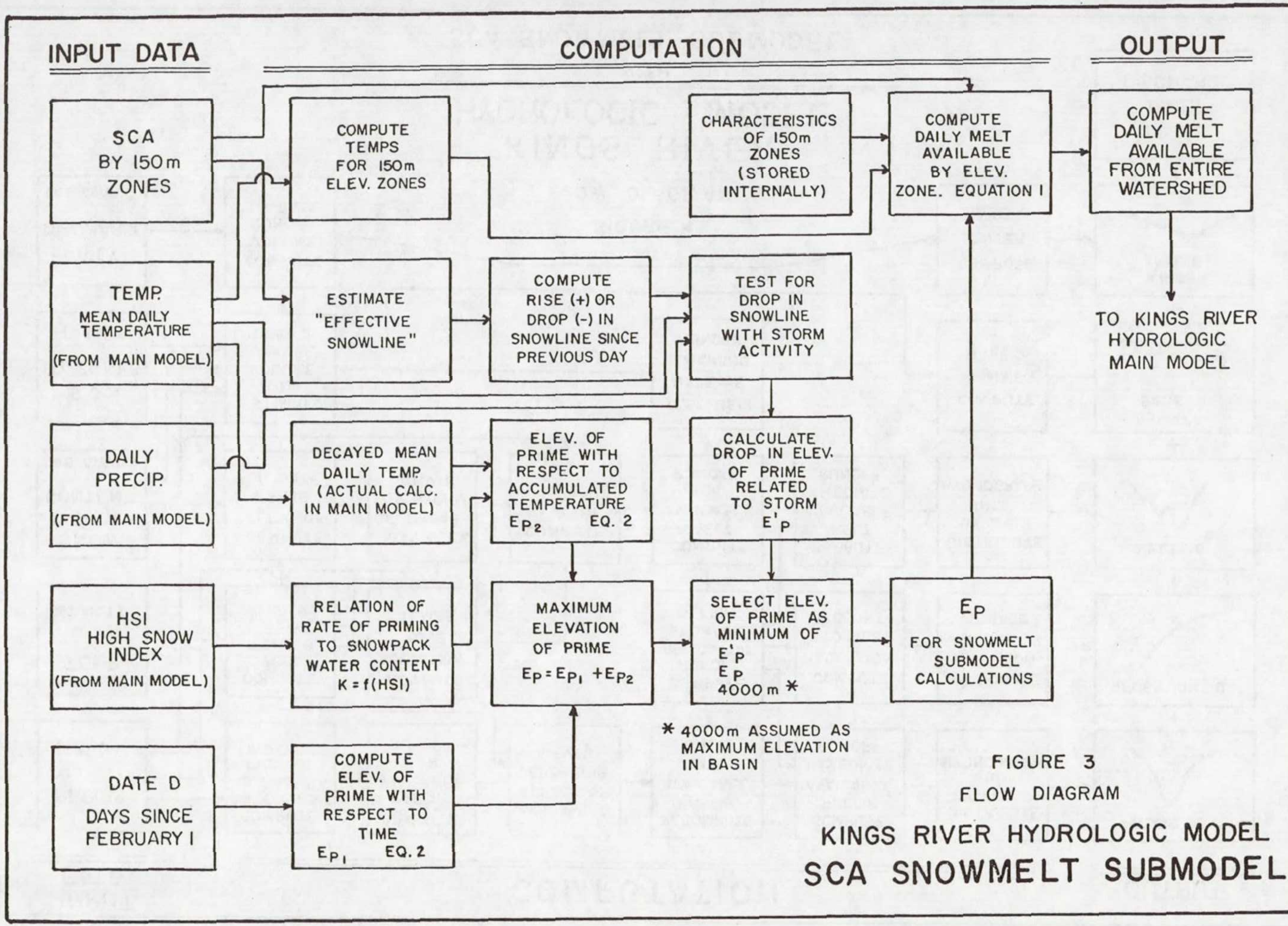


FIGURE 3
FLOW DIAGRAM
KINGS RIVER HYDROLOGIC MODEL
SCA SNOWMELT SUBMODEL

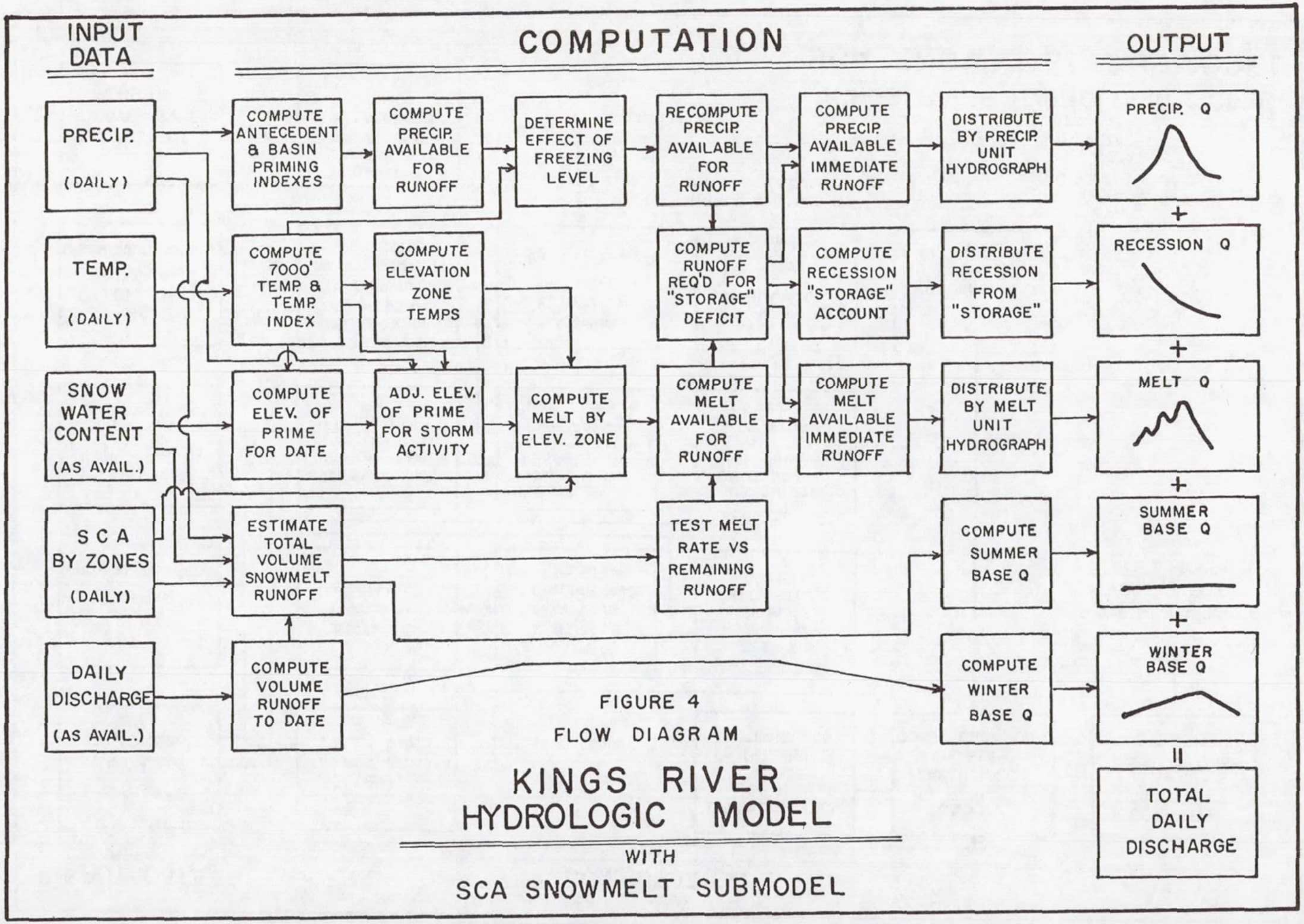


FIGURE 4
FLOW DIAGRAM

KINGS RIVER
HYDROLOGIC MODEL

WITH

SCA SNOWMELT SUBMODEL

analysis purposes. Air temperature is one of the few measurements related to the input of energy to the watershed which has been recorded systematically over the years. Fortunately, temperature appears to provide a good integration of the effect of available energy upon the snowpack under most conditions, both during accumulation and melt of the snowpack. Temperature within each elevation zone was based on the mean daily model temperature computed with a lapse rate of 6.4°C/km. Analysis indicated that a base temperature of -1°C appeared to give the most satisfactory results. Melt was computed on the basis of the difference between the mean daily temperature (adjusted by lapse rate) and -1°C.

Melt by Zones

The snowmelt submodel was first developed for that portion of the season after which the entire watershed was considered to be primed and producing melt. This simplified the process of developing and calibrating techniques to calculate melt by elevation zones. The same basic technique is utilized throughout the entire snowmelt season, but during the period of priming, only a portion of the SCA in the watershed has the ability to produce water contributing to the runoff hydrograph.

Operation of the existing model uses input data in conventional units and output for operational analysis is also in similar units. The SCA snowmelt submodel was similarly developed in the conventional system. However, the following equations are shown in SI units. Melt volume for each elevation zone is computed by the following equation according to the flow chart in Figure 3.

Equation 1 $$QMELT_z = C_q C_z A_z P_z T_z$$

Where: $QMELT_z$ = daily melt volume from given elevation zone "z" expressed as a mean daily flow rate, m^3/sec

C_q = coefficient to describe relationship between area, temperature and melt. The value of C_q was about 0.024

C_z = coefficient to adjust for the efficiency within the elevation zone. Values were near 1.0, probably dependent upon loss characteristics of the zone

A_z = area within elevation zone in square kilometers

P_z = percentage of the zone subject to melt on a given day limited by SCA in zone and "elevation of prime" as described in the following section

T_z = effective temperature above base within elevation zone "z", ^{o}C.

The summation of QMELT from all zones is the output from the SCA snowmelt submodel and the required input for the Kings River hydrologic model. A value of QMELT for any elevation zone was calculated as zero (1) if there was no SCA within the zone, and (2) if the temperature for the zone was less than -1^{o}C, or (3) if the effective elevation of prime was lower limit of the zone. Although analysis suggests that the relationship between temperature and melt is not linear, it appears to be sufficiently linear throughout the range of temperature where significant melt occurs that the assumption of the linear relationship is not detrimental. One degree C change in temperature with this relationship represents about 2 mm of QMELT as input to the basic hydrologic model. This figure does not appear at all inconsistent with observed depletion of snowpack of 50 mm per day with observed mean daily air temperature (corrected for elevation) in the order of 20^{o}C.

Melt During Prime

Analysis of melt volume and melt rate during the period of snowpack priming is complicated by the fact that the snowpack is not fully primed throughout the watershed, and therefore the watershed is not capable of producing runoff from the entire SCA, no matter what the temperature. It has been assumed for purposes of the model that the watershed produces no snowmelt runoff above the "elevation of prime" and all of the runoff required to meet the observed hydrograph of snowmelt runoff comes from the area of the watershed which is snowcovered below the effective "elevation of prime". It was assumed that a given set of temperature and SCA conditions would produce snowmelt volume equivalent to that derived from the relationship in section "Melt by Zones", and that any reduction or difference between the calculated and observed melt was attributable to the fact that no runoff occurred above an "elevation of prime", regardless of temperature.

To systematically develop relationships to describe the "elevation of prime", the basinwide melt was calculated from the relationship in section "Melt by Zones". Next, the volume of daily melt required to reproduce the observed hydrograph was estimated. The difference between the calculated and "observed" melt volumes was then used to determine the elevation above which no snowmelt could occur if the "observed" runoff hydrograph were to be realized from "calculated" melt. This elevation was defined for purposes of the SCA snowmelt model as the effective "elevation of prime". The elevation of prime was then defined in terms of other measured or calculated parameters considered related to the priming process. Many combinations of parameters were tested to establish a relationship between "elevation of prime" and the following factors.

. . . Temperature -- A decayed accumulative temperature (0.96 daily decay factor) was based upon the accumulation of degree days above freezing at 2100 m from January 1. This factor represented a measure of the accumulation of energy to which the snowpack might be subjected as reflected by air temperature.

. . . Date -- The date of the season also appears to reflect some measure of energy introduced to the snowpack that would be somewhat independent of temperature.

. . . Snowpack Water Content -- April 1 snow pack water content (expressed in percentage of average April 1 water content), updated for subsequent precipitation, was used to describe the amount of snowpack which must be primed before runoff would occur. The greater the water content of the snowpack, the slower the elevation of prime would rise.

The basic equation for computation of elevation of prime for the Kings River SCA snowmelt submodel took the following form:

Equation 2 $$E_p = 945K\left((1.009)^D + .00987\frac{(T1-55.5)}{K}\right)$$

Where: E_p = the elevation of prime in metres

D = number of days since February 1

T1 = decayed accumulated temperature (^{o}C days at 2100 m) since January 1 with a decay factor of 0.96

K = a variable affecting the elevation of prime as related to snowpack water content (HSI). K decreases with increasing HSI

HSI = high snow index expressed as a percentage of average April 1 water content, adjusted for subsequent precipitation.

The resulting elevation of prime represents the maximum elevation to which the watershed is fully primed and capable of producing snowmelt (for purposes of model computation) as of the given date. A flow diagram for calculation of the elevation of prime appears in Figure 3.

Generally during the spring snowmelt period, the elevation of prime will continue to increase as the season progresses. However, spring storms may deposit new snowpack at lower elevations. Usually this pack is transient and may melt in a few days with little increase in rate or volume of runoff. Snowmelt is often retarded below what might be expected with the increased area of snowpack until the freshly fallen snow has become primed. Occasionally, heavy precipitation may occur and some substantial increase in water supply and rate of runoff may be noted from the new snowpack. This hydrologic process has been modeled to force the elevation of prime to drop when the snow line drops, and then increase at a rate dependent upon temperature until it equals the calculated elevation of prime in the basic equation. If the snow line drops, the elevation of prime is required to drop a like amount. On each subsequent day, the elevation of prime rises at a rate equal to the rise in snow line plus an additional rise related to the 2100 m temperature.

Compute Snowmelt and Runoff Hydrograph

A flow diagram for the Kings River hydrologic model with the SCA snowmelt submodel is shown in Figure 4. Daily calculation of melt to eventually appear as surface runoff from calculation of individual elevation zone melt volumes (figure 3) results in the volume of daily snowmelt available for distribution as runoff in the main model. A portion of the volume of melt is directed through "recession storage", dependent upon the current level in storage which, from a hydrologic standpoint, would represent how wet the basin had been. After addition of a portion of the daily volume of melt to recession storage, recession storage is depleted at approximately six percent of total volume per day to form the recession flow. Recession storage has the capability of smoothing a portion of the snowmelt by distributing it over many days as it is released from this temporary model storage. The remaining volume of snowmelt is distributed by a four-day unit hydrograph to produce the temperature related fluctuations noted in the observed runoff hydrograph.

Daily computed volumes of runoff distributed from recession storage and direct snowmelt runoff distributed by unit hydrograph are added to winter base flow, summer base flow, and precipitation flow derived from other submodels in the Kings River hydrologic model. The net result is a simulation of total mean daily discharge. During the period of maximum snowmelt runoff in seasons with average snowpack water content, the snowmelt submodel (including water distributed through recession storage) may account for 95 percent or more of the total mean daily flow. Winter base, summer base, and precipitation flow submodels account for the remainder.

Results

As of the present time, testing of the SCA snowmelt submodel for the Kings River hydrologic model has not been completed. The results of preliminary testing and analysis have, however, been encouraging. Simulated mean daily runoff for the Kings River computed as output from the model has been plotted for 1973, 1974, 1975 and 1976, in Figures 5 through 8. Plots are in conventional units representing actual input and output from the model. Plots represent mean daily discharge in cubic feet per second against time, April 1 through the end of snowmelt. Shown for comparison are the discharges calculated from the model, unimpaired discharges observed, observed air temperature corrected to 2100 m, observed effective snowline, and calculated elevation of prime.

Calculation of daily discharges using the SCA snowmelt submodel appears to give results which are entirely acceptable in analysis. In addition, the conceptual model appears to be more consistent with known hydrologic relationships than the formerly used snowmelt submodel. This fact may give assurance in extrapolating the techniques into extreme conditions as well as representing an academically esthetic improvement over the original model. At this time, no testing has been done on other watersheds, but it is believed that the conceptual model will have a high degree of transferability.

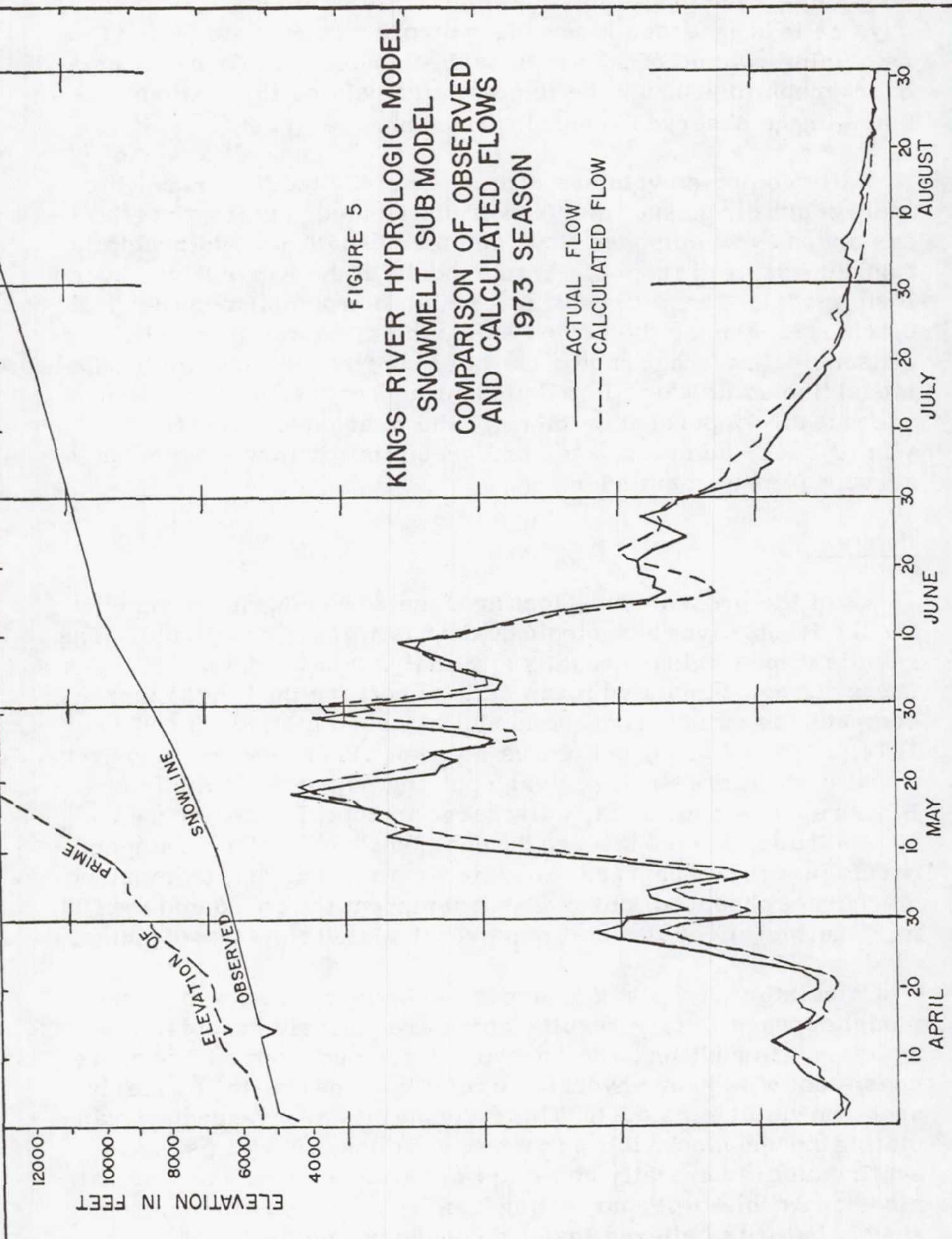


FIGURE 5
KINGS RIVER HYDROLOGIC MODEL
SNOWMELT SUB MODEL
COMPARISON OF OBSERVED AND CALCULATED FLOWS
1973 SEASON

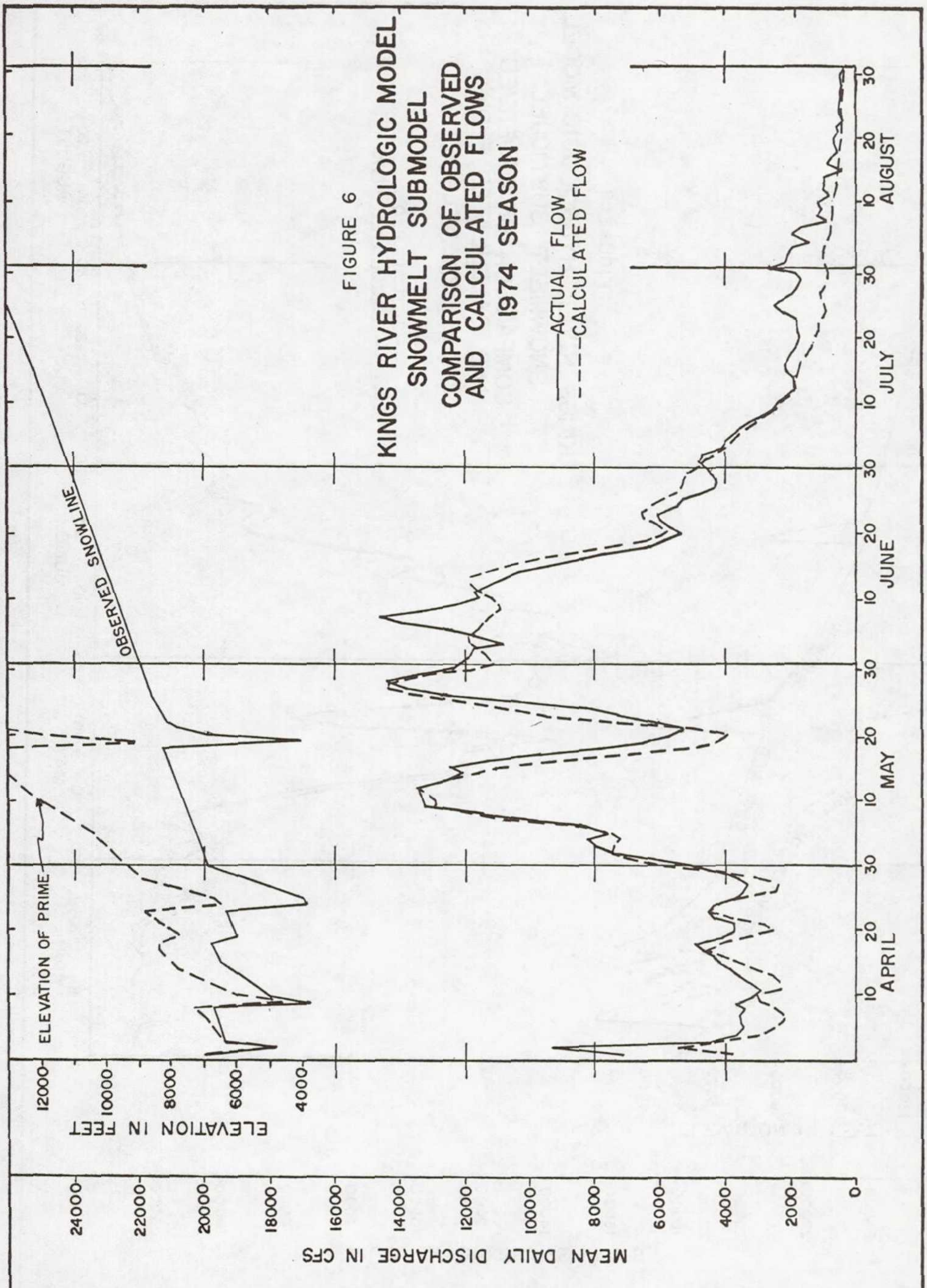


FIGURE 6
KINGS RIVER HYDROLOGIC MODEL
SNOWMELT SUBMODEL
COMPARISON OF OBSERVED
AND CALCULATED FLOWS
1974 SEASON
ACTUAL FLOW
CALCULATED FLOW
ELEVATION OF PRIME
OBSERVED SNOWLINE
ELEVATION IN FEET
12000
10000
8000
6000
4000
MEAN DAILY DISCHARGE IN CFS
24000
22000
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
10
20
30
APRIL
MAY
JUNE
JULY
AUGUST

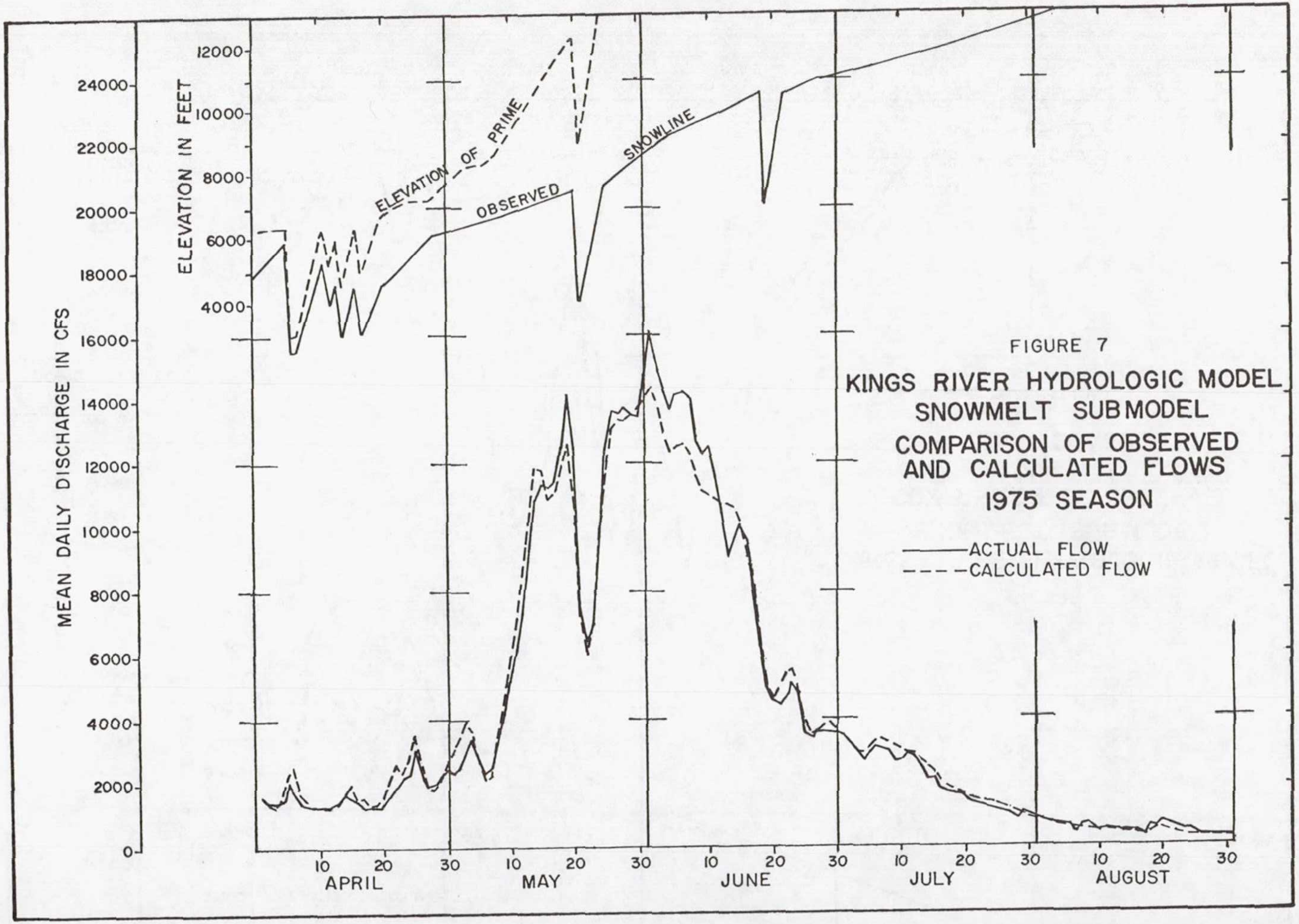


FIGURE 7

KINGS RIVER HYDROLOGIC MODEL
SNOWMELT SUBMODEL
COMPARISON OF OBSERVED AND CALCULATED FLOWS
1975 SEASON

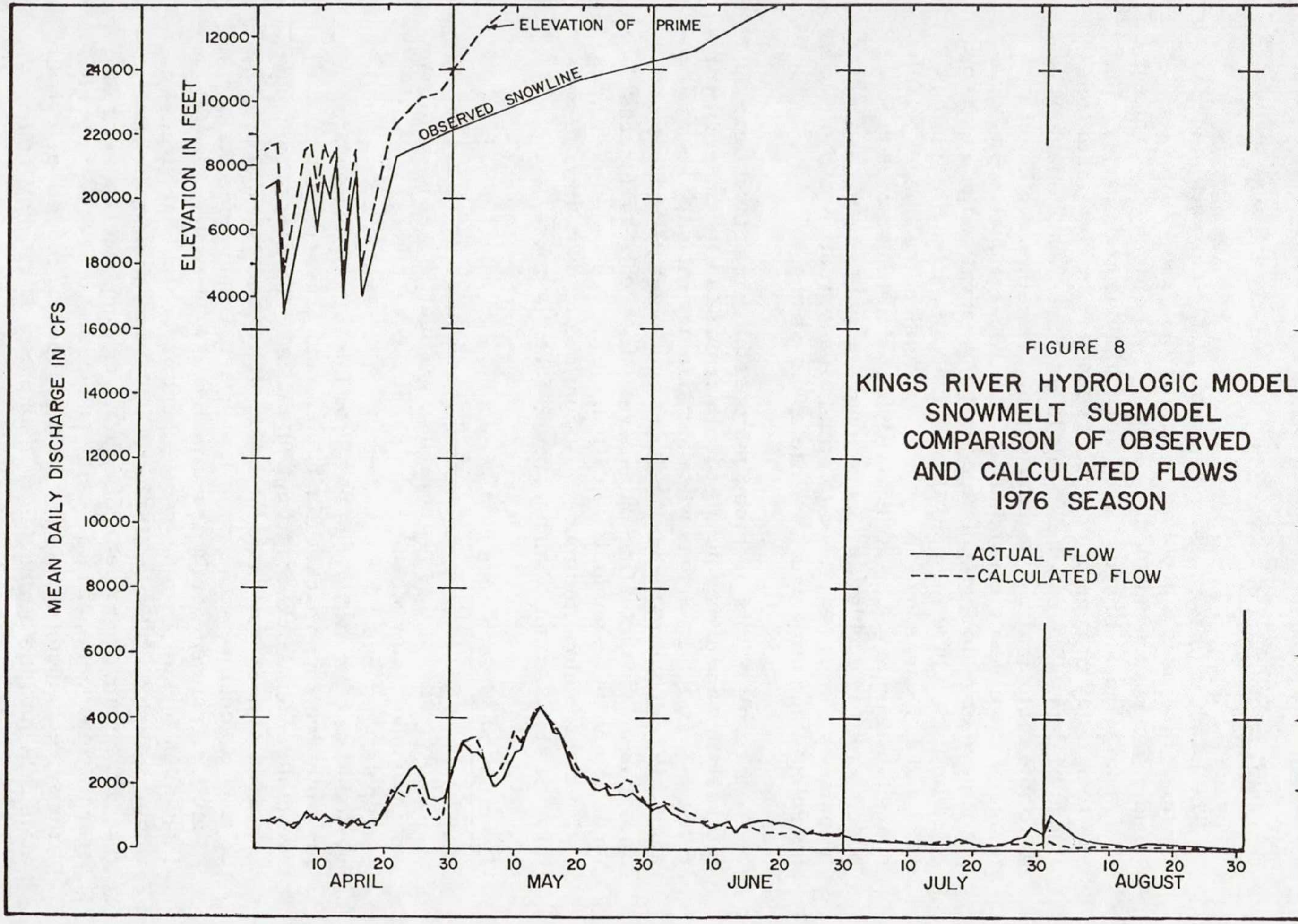


FIGURE 8

KINGS RIVER HYDROLOGIC MODEL
SNOWMELT SUBMODEL
COMPARISON OF OBSERVED
AND CALCULATED FLOWS
1976 SEASON

INTERPOLATION AND EXTRAPOLATION OF SCA

Availability of Imagery

The Landsat imagery is currently available only on a nine-day cycle. This poses a problem, since one image set obliterated by cloud cover may result in an 18-day period between observations that make Landsat imagery very difficult to use effectively. In addition, delay in receipt of imagery also adversely affects timeliness of data. The more difficult to interpret NOAA imagery is available historically on a daily cycle. Timeliness of satellite imagery has already caused difficulty in operational work, making it necessary to interpolate between observations and extrapolate into the future for operational analysis. Results for the 1977 and 1978 seasons have shown how misleading images widely spaced in time may be. Availability and timeliness of data may pose a critical problem in operational analysis, even though techniques can be developed to simulate snowmelt runoff through hydrologic modeling with satellite observations.

As a result of this problem, the possibility was investigated of interpolating and extrapolating results from satellite imagery with respect to time for periods when satisfactory imagery is not available. Modeling techniques are very sensitive to SCA, and an error in extrapolating data beyond the "date of forecast" tends to create an unstable situation. If the recession of SCA is estimated too slow, the model will continue to overestimate runoff until areal extent of snowcover is forcibly corrected.

Description of Technique

The objective of this phase of the investigation was to (1) allow for interpolation of SCA between observations and (2) permit extrapolation beyond the last date of satellite observation for the period of at least two weeks based on intervening temperature, precipitation, snowpack water content and characteristics, and available satellite observations. Results in the Kings River basin appeared entirely adequate for interpolation and extrapolation for up to two weeks beyond date of last observation during the period of melt. Tests suggest that estimates of SCA could be extrapolated even further than two weeks, but undoubtedly accuracy would decline with time. It should be borne in mind, however, that if the primary value of SCA in water supply forecasting or hydrologic modeling is to describe unusual or unprecedented conditions, techniques which may be developed to "model" or extrapolate SCA into the future using other parameters may not adequately reflect those unusual conditions.

Data have been collected for the Wind River Range in Wyoming to further test methods for extrapolating SCA. This testing is incomplete at the present time, but to date, many similarities have been noted between conditions in the Wind River and in the southern Sierra Nevada, in spite of the completely different climatologic and hydrologic regimes noted in the two areas.

SUMMARY AND CONCLUSION

From a technical standpoint, results of the investigation were entirely acceptable in terms of simulating mean daily discharge and reproducing the snowmelt hydrograph. The ability to simulate rate of snowmelt runoff utilizing areal extent of snowcover from satellite imagery as a parameter in hydrologic modeling was demonstrated. The presence of cloud cover, missing data, delayed data or other problems have made information on snowcover unavailable for operational forecasting for considerable periods of time even in the southern Sierra which is normally reasonably clear during the period of snowmelt. This problem appears to be one of the major operational problems in the use of SCA. Areal extent of snowcover or elevation of snow line may be extrapolated with adequate accuracy for water supply forecasting and some hydrologic modeling for extended periods of time.

Applicability of information on SCA from satellite imagery to hydrologic modeling in the Kings River basin was demonstrated, and additional work should be done in this area, not only on the Kings River, but on other watersheds. It is hoped that there is enough local interest in this work to sponsor operational use of SCA in hydrologic modeling in the southern Sierra Nevada within the next few years.

References

1. "Hydrologic Model Research and Application -- Kings and San Joaquin River Basins", Final Report, December 1971, Sierra Hydrotech.

2. Hannaford, J.F., Bush, R.H., Barsch, R.E. "The Development and Application of a Hydrologic Model as an Operational Tool", Proceedings 38th Annual Meeting, Western Snow Conference, April 21-23, 1970.

3. Linsley, R.K. "A Simple Procedure for the Day to Day Forecasting of Runoff from Snowmelt", Transaction American Geophysical Union, Vol. 24, Part 3, pps. 62-67, 1943.

4. Hannaford, J.F., Howard, C.H. "Upper Air Data as a Parameter in Estimating Snowmelt Runoff", Proceedings 43rd Annual Meeting, Western Snow Conference, April 23-25, 1975.