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NASA
National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

ABSTRACT

The study objective was to develop or modify methods in an operational framework that would allow incorporation of satellite derived snow cover observations for prediction of snowmelt derived runoff.

Data are reviewed and verified for five basins in the Pacific Northwest. The data are analyzed for up to a 6-year period ending July 1978, and in all cases cover a low, average, and high snow cover/runoff year.

Cloud cover is a major problem in these springtime runoff analyses and have hampered data collection for periods of up to 52 days. Tree cover and terrain are sufficiently dense and rugged to have caused problems.

The interpretation of snowlines from satellite data has been compared with coventional ground truth data and tested in operational streamflow forecasting models. When the satellite snow-covered area (SCA) data are incorporated in the SSARR (Streamflow Synthesis and Reservoir Regulation) model, there is a definite but minor improvement. Satellite SCA data are being used operationally for daily streamflow forecasting here in the Pacific Northwest via the SSARR model.

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INTRODUCTION

This final report of Contract S-53877 covers the analysis of snow cover data during calendar years 1973 through 1978 and is intended to fully comply with the report requirements of the contract. The objectives of this contractual study were to map snowlines, compare satellite products, and then incorporate these satellite products in forecasting models. In order to accomplish these study objectives, the following steps were taken: study basins were selected; local proficiency in reducing raw data was acquired; data timeliness was evaluated; both ground truth and satellite data were verified; the sensitivity of the forecasting model was tested; and the satellite data were operationally incorporated in a forecasting model. This study was a joint program of the Bonneville Power Administration, the North Pacific Division of the U.S. Army Corps of Engineers, and the National Weather Service.

Rationale

Snowmelt provides a large portion of the spring runoff in the Pacific Northwest, and accurate forecasts of this sring runoff are essential to optimum operation of the multi-purpose reservoir system. Therefore, any forecasting method that is faster, cheaper, or more accurate is desirable.

It had been demonstrated by 1972 that satellite imagery could be used to assess the aerial extent of snow cover in a basin, and by comparing imagery from different dates, to determine changes in the snow-covered area (SCA) over time. The next logical step was to see if this data could be related to and confirmed by available ground truth, to determine the time requirement for such data acquisition to be useful, and to develop or modify methods in an operational framework that could allow incorporation of satellite derived snow cover observations for prediction of snowmelt derived runoff.

To this end the National Aeronautics and Space Administration at Goddard Space Flight Center (NASA/GSFC or NASA) contracted for an Applications System Verification and Transfer (ASVT) for four areas in the United States. One of these four areas, the Pacific Northwest, was chosen to test the method's effectiveness in the face of persistent cloud cover, heavy forestation/tree canopy, and steeply sloping terrain.

Application

Streamflow in the Pacific Northwest has a high seasonal variability. In the portion of the Pacific Northwest lying between the Continental Divide and the Cascade Range, precipitation is mainly in the form of snowfall and accumulates in the late fall, winter, and early spring. Maximum runoff occurs in the late spring and early summer from melting snow and can produce devastating floods if the snowpack is widespread and heavy, if there is a sequence of exceptionally hot days and rapid melting, or if snowmelt occurs by a sequence of rain-on-snow. In the late summer and early fall, streamflows recede to a base flow condition, and some small streams dry up completely due either to natural conditions or to diversion of water for irrigation. Multi-purpose reservoirs were built to alleviate the problem of the temporal distribution of the annual runoff and the reservoir system cannot operate to best advantage without good forecasts.

Because of the potential for flooding, reservoirs in the Pacific Northwest have 49.7 million dam^3 (40.3 million acre-feet) of space that can be called upon for flood control. In the early spring, reservoirs east of the Cascades are drawn down to provide flood control storage at the various flood control projects. The amount of this evacuation is governed by forecasts of the total seasonal volumetric runoff. Palisades, Lucky Peak, Dworshak, Libby, and Hungry Horse are five such reservoirs with flood control storage.

More than 3 million hectares (7-1/2 million acres) of cropland in the Pacific Northwest are irrigated. Irrigation begins annually in March and continues into October, with the peak irrigation demand for water occurring in July and August. Because of the seasonal variability of streamflow, the springtime runoff is stored for release and use later in the irrigation season. Palisades and Lucky Peak Reservoirs are typical of such irrigation storage projects.

Over 80 percent of the electric energy produced in the Pacific Northwest comes from hydroelectric power generation. The majority of the installed hydroelectric capability in the area is located east of the Cascade Range, where streamflows are at a minimum in the winter and peak in the late spring. Conversely, the electric loads peak in the winter and are at a minimum in the late spring. Storage projects in the upper portions of the Columbia River Basin capture spring runoff to be released for power generation during the following winter. There are 53.6 million dam^3 (43-1/2 million acre-feet) of power storage in the Pacific Northwest, and Dworshak, Libby, and Hungry Horse Dams are typical of such storage projects. Water released from these dams generates power both at-site and at dams located downstream.

Proper operation of the reservoir for multiple purpose is heavily dependent on accurate forecasting and close monitoring of water levels. Water stored for hydroelectric generation is drafted in the winter season, with the amount dependent on the forecast of the ability of the spring snowmelt to refill the storage. However, additional water may be evacuated to create storage space for flood control in response to forecasts of the volumetric spring runoff. It is refilled based upon short-term forecasts of daily inflow, wherein storage space is always maintained to eliminate the peaks from the inflows and reduce flooding. Irrigation reservoirs, on the other hand, are refilled each winter and spring although some space for spring flood control is maintained - the amount based upon seasonal volumetric forecasts of runoff. Accurate volumetric and short-term forecasts are essential for proper reservoir operation. Libby Reservoir failed to refill in 1975 by about 250,000 dam^3 (200,000 acre-feet) when operated on a volumetric forecast that was 2,604,000 dam^3 (2,112,000 acre-feet) too high.

The Pacific Northwest experienced a drought in 1977, and many reservoirs failed to refill because of an inadequate snowpack. The volumetric runoff in many basins was the lowest in 50 years. Libby Reservoir failed to fill by 2,240,000 dam^3 (1,820,000 acre-feet), or 30 percent of its active storage capacity, Hungry Horse by 566,000 dam^3 (459,000 acre-feet) or 15 percent, and Dworshak by 612,000 dam^3 (496,000 acre-feet), or 25 percent. Anderson Ranch, Arrowrock, and Lucky Peak Reservoirs, on the Boise River, are operated as a system. Their combined storage deficit was 782,700 dam^3 (634,800 acre-feet), or 64 percent. The power system reservoirs, normally full on July 31, were deficit in 1977 by a total of 15.7 million dam^3 (12.7 million acre-feet) which is roughly equivalent to 14.1 billion kilowatthours. This deficiency represents 30 percent of the energy that can be generated by drafting all reservoirs from full to empty. Thus, forecasting procedures are subject to revision if any method can be found to improve the ability to predict rain or snowmelt derived runoff.

OBJECTIVES

The objectives of this contractual study were to map snowlines, compare satellite products, and then incorporate these satellite products in forecasting models.

Map Snowlines

The first objective was to map snowlines in several basins for at least 5 years. By choosing different basins through a time period of at least 5 years it was possible to observe the effects of cloud cover in obtaining data, examine the effects of slope and forest canopy in accurately reducing data, and to observe the variability of the snowpack from year to year.

Compare Satellite Products

The next objective was to compare satellite products with ground truth SCA data. The ground truth consisted of aerial snowcover as observed from low-altitude aircraft flights, and the hypothetical daily values of SCA generated by the computer streamflow forecasting model.

Incorporate Satellite Products

The final objective was to incorporate these satellite products in forecasting models. This objective was to develop or modify methods in an operational framework that would allow incorporation of satellite derived snowcover observations for prediction of snowmelt derived runoff.

STUDY APPROACH

A systematic approach was taken in this study to answer the question, "Can satellite derived snowcover observations be incorporated in forecasting models in an operational mode?" The following six steps were taken: (1) study basins were selected; (2) local proficiency in reducing raw data was acquired; (3) data timeliness was evaluated; (4) both ground truth and satellite data were verified; (5) the sensitivity of the forecasting model was tested; and (6) the satellite data were operationally incorporated in a forecasting model.

Select Study Basins

Basins were selected that would give a diversity of location, elevation, forest canopy cover, slope, and shadow parameters over the time frame 1973 through 1978. The availability of low level aerial snow flights was also considered.

Gain Local Proficiency

All 1973 and 1974 satellite data were from Landsat, and the raw data were reduced by Stanford Research Institute (SRI) operating under a subcontract. Stanford Research Institute also analyzed the 1975 Landsat data for all five basins, but beginning in 1975, the National Oceanic and Atmospheric Administration, National Environmental Satellite Service (NOAA/NESS) began collecting and analyzing satellite data for basins in the Pacific Northwest. In 1975, NOAA/NESS collected and analyzed satellite data from the NOAA series of polar orbiting satellites for the Boise and North Fork Clearwater Basins.

By 1976, Landsat data was essentially dropped in favor of that produced by the NOAA satellites. The NOAA satellite data were available on a daily basis, whereas the Landsat orbits over a given area were only every 9 days. To be fully usable (as explained later), the satellite SCA data would have to be no more than 48 hours old and yet the Landsat data could not be processed that rapidly.

Landsat quick-look imagery was purchased for the 1976 spring snowmelt season from the Canadian down-link in Prince Albert, Saskatchewan. Although several times the imagery was mailed the same day as the satellite pass, the median overall delay, including mail transit, was five days.[1]

Because of these factors and the high cost of having Landsat imagery analyzed by a subcontractor, it was decided, beginning with the 1976 data, to utilize primarily NOAA data for the balance of the study. It was later determined that the subcontractor's unfamiliarity with the basins had produced erroneous results for 1975, which then had to be reanalyzed.

When the change was made to the use primarily of NOAA data, it became necessary to develop a local or in-house proficiency for reducing and analyzing this data. To this end, Stan Schneider of NOAA/NESS visited the Pacific Northwest study center in January 1977 to instruct local personnel in the use of an optical zoom transfer scope (ZTS) to determine snowline from satellite imagery. After the instruction, both Landsat and NOAA data were analyzed on a ZTS by the local study team, and the results were compared and cross-checked for validity of measurement. Thus the data used for 1976-1978 were primarily from NOAA satellites and were analyzed either by NOAA/NESS or by the local study team.

Data Timeliness

The allowable time delay to receive satellite determined SCA data is either 24 or 48 hours. The computer model used for daily operational streamflow forecasting is the Streamflow Synthesis and Reservoir Regulation (SSARR) model[2] developed by the Corps of Engineers. The SSARR model had been developed as a streamflow forecasting tool and was fully operational. This model is one of the few that has snow data as input, and has had excellent success in forecasting streamflow in the Pacific Northwest. In using the SSARR model for streamflow forecasting, data for the 48-hour period preceding the start of the run is fed into the program, and the model is allowed to "tune-up" itself. The model uses the 48-hour antecedent single value of SCA, and the actual values of temperature and precipitation for the 48-hour period, to develop a best match for the streamflow value at the end of the 48-hour period, i.e., the start of the forecasting period. All forecasted values of streamflow are then adjusted by the proportional multiplier necessary to have the best-fit start-of-forecast streamflow equal to the observed start-of-forecast streamflow.

A 48-hour period is used for springtime snowmelt forecasting because a heavy snowpack can be greatly influenced by the temperature that occurred 48 hours before. In the wintertime, the initializing period for the forecasting runs is reduced to 24 hours.

NOAA/NESS has consistently analyzed the NOAA satellite data in its national office and sent facsimile pictures via land wires to the Columbia River Forecast Service (CRFS) in Portland well within a 24-hour period. The NOAA satellite down-link nearest to Portland is located at Redwood City, California. Because mail service between Portland and Redwood City can exceed 24 hours and facsimile quality is not good enough for direct analysis, local interpretation of NOAA data cannot be used for our operational forecasts.

Landsat quick-look imagery cannot be used for operational streamflow forecasting because the average 5-day delay in receiving imagery exceeds the 48-hour requirement of the SSARR model.

Data Verification

Both ground truth and satellite SCA data had to be verified before they could be used. A comparison of the two ground truth data and the satellite data, one with each other, provided a three-way verification of the data.

Ground Truth Data

The ground truth data consisted of forecasting model generated values of SCA, and of SCA data gathered by low altitude aerial flights.

At the end of each flood season, a streamflow reconstruction or "reconstitution run" is made for each basin with the SSARR model. As noted, these reconstitution runs are made only once, and are done at the end of the flood season to test the goodness of fit of the model to the actual basin runoff. In these reconstitutions, the model generates daily values of snow-covered area and of streamflow. When the computed hydrograph is compared with the observed hydrograph, a reconstitution run provides a visual check on the accuracy of the basin characteristics utilized in the model, and gives credence to the daily values of SCA which the model generates.

Two to four aerial snow flights are generally made over a basin during the melt season. The snow flight data determines the average elevation of the basin's snowline, and an area elevation table for the basin is used to determine the snow covered area. The snow flight data are checked by comparing the results to the SCA data generated in the SSARR reconstitution runs. Thus the ground truth data are cross-checked against each other, and the SSARR streamflows generated in the reconstitutions are compared with the observed hydrograph.

Satellite Data

Satellite derived SCA data were verified by comparison with snow flight data and with the SSARR generated SCA data. In addition, in some years both Landsat and NOAA satellite data were obtained which were compared with each other. In 1976, locally analyzed Landsat and locally analyzed NOAA data compared favorably. Some NOAA satellite data were analyzed both by NOAA/NESS personnel at their national headquarters and locally by the study team. The results of the analysis by two different people were variable.

Test the Model Sensitivity

The agreement between the SCA data obtained from satellite, snow flights, and that generated by the SSARR model was variable. This raised the question of the sensitivity of the SSARR model to snow cover data. If the model is insensitive to it, does it matter which SCA data is used, or its accuracy? The results proved the sensitivity of the model to SCA data, and thus showed that accurate data is essential.

Incorporate in Operational Mode

The last step in the study approach was to incorporate satellite data in the forecasting model in an operational mode. The SSARR model utilized snow-covered area data as an input variable, and was sensitive to this data. The CRFS was receiving satellite derived SCA data in a timely manner from NOAA/NESS. Based upon test experience, the CRFS is now subjectively using satellite snow-cover data in its operational streamflow forecasts.

STUDY AREAS

A total of six basins were studied in this ASVT. They were chosen to provide diversity in location, elevation, forest canopy cover, slope, and shadow areas.

The North Santiam Basin is in Oregon, at low elevation, and was primarily chosen for the work done by Dr. Mark Meier[3] to test snow cover area measurement methods, and because the entire basin could be viewed on one Landsat frame.

The Upper Snake Basin is primarily in Wyoming, has a medium-to-open tree cover, and is high elevation.

The Boise Basin is mid-elevation and is in southeastern Idaho. Forest cover is medium, and the slopes are not exceptionally steep.

The Dworshak Basin in central Idaho is low elevation and has a dense tree cover. It has steeply sloping ranges.

The Libby Basin is primarily in Canada, is high elevation, and has a dense tree canopy. The rugged terrain slopes steeply and is often cloud covered.

The Hungry Horse is a mid-elevation basin in Montana that has slopes steep enough to cause shadow problems. Tree cover varies from clear-cut to dense.

Satellite imagery showing the extent of snow cover was collected for the 1973 and 1974 snowmelt seasons for the following Columbia River Basins:

North Santiam River Basin (above Detroit Dam), Oregon

Upper Snake River Basin (above Palisades Dam), Idaho

Boise River Basin (above Lucky Peak Dam), Idaho

Runoff in the North Santiam occurs primarily in the winter and very early spring, and this basin was dropped from further study because no aerial snow flights are made for it.

The data collection from 1973 and 1974 was extended forward in time through 1978 for the Upper Snake and Boise Basins. In addition, data were also collected from 1975 through 1978 for:

North Fork Clearwater Basin (above Dworshak Dam), Idaho

Kootenai River Basin (above Libby Dam), Montana

South Fork Flathead River Basin (above Hungry Horse Dam), Montana

These areas were not studied for 1973 or 1974 because of the persistent problem of cloud cover. These basins were added to the study because in these basins snowmelt is the main contributor to runoff. The final five basins that were studied are shown in Figure 1 on the next page.

<u>North Santiam</u>

The North Santiam River above Detroit Dam drains an area of about 1,146km^2 (442 mi^2). The basin has a mean elevation of approximately 1,178 meters

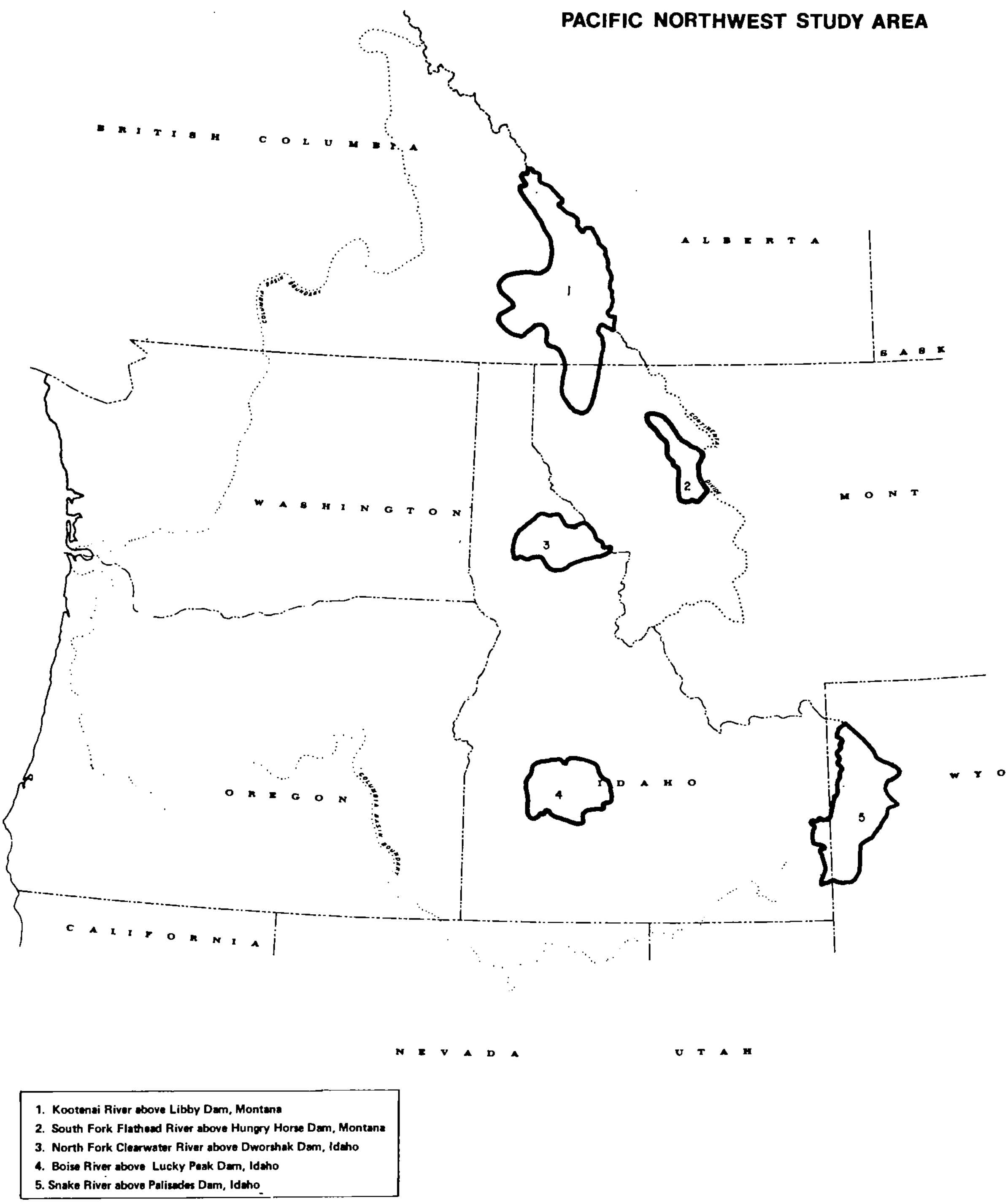

PACIFIC NORTHWEST STUDY AREA
BRITISH COLUMBIA
ALBERTA
SASK
WASHINGTON
MONT
OREGON
IDAHO
WYO
CALIFORNIA
NEVADA
UTAH
1
2
3
4
5
1. Kootenai River above Libby Dam, Montana
2. South Fork Flathead River above Hungry Horse Dam, Montana
3. North Fork Clearwater River above Dworshak Dam, Idaho
4. Boise River above Lucky Peak Dam, Idaho
5. Snake River above Palisades Dam, Idaho

Figure 1

(3,865 feet) and rises from 475.6 meters (1,560 feet) at the dam's normal water surface to 3,200 meters (10,497 feet) atop Mt. Jefferson. Essentially all of the basin is above 610 meters (2,000 feet), but only about 5 percent of it is above 1,830 meters (6,000 feet) elevation.

The North Santiam Basin is located on the west side of the Cascade Range. Because of the basin's location and exposure, the Coast Range does little to stop winter rainstorms which sweep in from the Pacific. The basin has a relatively low mean elevation, and thus snow may melt soon after falling.

Upper Snake

This basin includes approximately 13,340 km^2 (5,150 mi^2) above Palisades Reservoir. The basin rises from 1,713 meters (5,620 feet) at the reservoir to 4,197 meters (13,766 feet) on Grand Teton. The mean elevation is 2,810 meters (7,900 feet), and virtually all of the basin lies above 1,830 meters (6,000 feet). The entire basin lies high enough that snow is present year-round on a significant portion of the basin lying above the 2,740 meter (9,000 foot) elevation. Tree cover, slope, and aspect in this basin do not appear to have caused any problems interpreting the snowline from the satellite data.

Boise

The Boise River Basin drains approximately 7,254 km^2 (2,800 mi^2) above Lucky Peak Dam. Basin elevations vary from 3,247 meters (10,651 feet) atop Snowyside Peak to 933 meters (3,060 feet) at the dam's normal water surface. Virtually all of the basin is above elevation 1,220 meters (4,000 feet) with a mean elevation of 1,890 meters (6,200 feet). The entire basin is sufficiently high that large areas of snow are deposited and stay through the winter and spring. In the upper ridges surrounding the basin, there are a few permanent snowpacks. Tree cover, slope, and aspect in the Boise Basin do not appear to have caused any problems in interpreting the snowline from satellite data.

Dworshak

The North Fork of the Clearwater River Basin drains an area of 6,320 km^2 (2,440 mi^2) above Dworshak Dam. Elevations range from 488 meters (1,600 feet) at the dam's water surface to 2,450 meters (8,036 feet) atop Democrat Mountain. The basin has an average elevation of about 1,220 meters (4,000 feet) and is a topographically rugged, densely timbered, largely undeveloped area. The tree cover and terrain in the Dworshak Basin do not appear to have caused any major problems in interpreting the snowline from satellite data.

Libby

The Kootenai River Basin drains an area of 23,277 km^2 (8,985 mi^2) in the United States and Canada above Libby Dam in Montana. This basin rises from 750 meters (2,459 feet) at the dam's normal water surface to 3,619 meters (11,870 feet) at the summit of Mount Assiniboine in British Columbia. The mean elevation of the basin is about 1,980 meters (6,500 feet), and numerous mountain peaks are above 2,340 meters (8,000 feet) with six peaks exceeding 3,050 meters (10,000 feet). The Libby Basin has a dense tree canopy and steeply sloping terrain that hinders the determination of the snowline. Limestone or "white" rock outcroppings above the timberline can easily be mistaken for snow cover late in the snowmelt season.

Hungry Horse

The South Fork of the Flathead River Basin drains an area of 4,285 km^2 (1,654 mi^2) above Hungry Horse Dam. Elevations in the basin range from 1,085 meters (3,560 feet) at the dam's normal water surface to 2,852 meters (9,356 feet) atop Holland Peak. The basin has an average elevation of approximately 1,830 meters (6,000 feet). Tree cover in the basin varies from clearcut areas near the reservoir to dense evergreen stands in the headwaters. The tree canopy and steeply sloping terrain in the Hungry Horse Basin hinders the determination of the snowline. The rock outcroppings that crest the ridges above the timberline can easily be mistaken for snow cover late in the snowmelt season.

DATA REDUCTION

Analysis of information was dependent upon the source of the raw data, equipment available, and method of obtaining data.

Satellite Snow Cover Data

Raw data was obtained from Landsat and NOAA imagery. Percent of snow-covered area was determined by SRI, NESS, or BPA.

Landsat Imagery

Landsat imagery was collected and analyzed during the spring snowmelt seasons as follows:

BASIN/YEAR	1973	1974	1975	1976	1977	1978
North Santiam	SRI	SRI				
Upper Snake	SRI	SRI	SRI	SRI		
Boise	SRI	SRI	SRI	SRI		
N. F. Clearwater			SRI	SRI		
Kootenai			SRI			
S. F. Flathead			SRI	BPA		

Stanford Research Institute (SRI), under contract to Bonneville Power Administration (BPA), analyzed Landsat imagery in 1973 and 1974[4], and in 1975[5], using an electronic interactive analyzer. The 1973 and 1974 data were analyzed by single-band (MSS-5) radiance thresholding. Editing was done in conjunction with basin outline masks, contour elevation masks, and drainage pattern maps. A binary thematic map was created from the satellite imagery and stored in 2.5 x 2.5 km grid increments in a "scratch-pad" computer memory. Because of this storage feature, the radiance threshold level could, by subjective editing aided by the various masks, be altered for different portions of a basin and the "scratch-pad" memory be so revised. These grid increments held values of snow cover, varying by 1/10's, from no snow (0/10's), to fully (10/10's) snow covered. The snow covered area for the basin was then determined by summing, and the percent of basin that was snow covered was calculated.

SRI also analyzed the 1975 data for BPA by the same procedure except that each satellite image was entered from both bands 5 and 7, and displayed in color to assist in the subjective editing. The thematic snow map was again created in the scratch-pad memory by amplitude thresholding from band 5.

Stanford Research Institute did its analysis of 1976 Landsat imagery[2] for the Walla Walla District of the Corps of Engineers following the same procedures that they had used for the 1975 data.

Bonneville Power Administration analyzed 1976 Landsat data for the South Fork Flathead (Hungry Horse) Basin. Snowlines were traced onto a basin overlay map using an optical zoom transfer scope. Basin drainage maps were utilized to superimpose the snow image from band 5 onto the basin mask. The resulting snowline was then traced with a planimeter to determine the snow covered area.

NOAA Imagery

NOAA imagery was collected and analyzed during the spring snowmelt seasons by either Bonneville Power Administration (BPA) personnel or by National Oceanic and Atmospheric Administration/National Environmental Satellite Service (NESS) personnel as follows:

BASIN/YEAR	1973	1974	1975	1976	1977	1978
North Santiam						
Upper Snake				BPA	NESS	NESS
Boise			NESS	NESS	NESS	NESS
N. F. Clearwater			NESS	NESS	NESS	NESS
Kootenai			BPA	BPA	NESS	NESS
S. F. Flathead			BPA	BPA	BPA	BPA

Visible energy sent back from the NOAA satellite is received here on Earth as variable voltages which are in turn converted to one of 256 counts. Through a table look-up, these counts are converted to any one of 256 grey-scale or grey-level intensities. By expanding or compressing counts, different portions of the grey-scale can be expanded or elimated to accentuate different geologic, hydrologic, or meteorologic features on a satellite "photo" or image.

Visible imagery from the Very High Resolution Radiometer (VHRR) was collected from the NOAA series of polar orbiting satellites, and snowlines were traced as noted above by either BPA or NESS personnel onto a basin overlay using an optical zoom transfer scope. A zoom transfer scope was required to stretch the image and remove the lateral distortion, and to enlarge the image to a traceable size. The snow-covered areas, as outlined by the snowline traced onto the overlay, were then planimetered to determine percent of basin area that was snow covered. NESS used an electronic densitometer/planimeter, and BPA used either a digitizer or a hand planimeter.

Oversnow Aircraft Flights

Snow cover observations are made in the United States portion of the Columbia River Basin by the Corps of Engineers personnel in small aircraft flying at low altitude. Similar flights are made in the Canadian portion of the Basin by personnel from the British Columbia Hydro and Power Authority. In these snow flights, an experienced observer riding with the pilot looks out the window at the snowline, determines its elevation, and then plots the snowline on a map as the flight is made. At the end of the flight, this information is reduced to percent of basin which is snow-covered. Although the observers on these snow flights are experienced, the data gathered are entirely subjective, and the snowline which is traced excludes the lower lying patchy snow which is not considered to contribute to runoff. Two to four flights are generally made each season for each area depending upon the flood potential for that season, flying conditions, and the cloud cover over a basin. In the United States portion of the Basin, flights are generally made in April, May, and June; and in the Canadian portion in May and June.

Snowpack Depletion by Computer

The National Weather Service, the Bonneville Power Administration, and the Corps of Engineers, North Pacific Division are cooperators in the Columbia River Forecasting Service. Certain resources of the agencies are pooled in the interest of improving streamflow forecasting methods, to provide uniform forecasts, and to increase the efficiency of operation. Whereas, the reconstitution runs are made only once at the end of the flood season to test the model's fit, the operational runoff forecasts for streams in the Pacific Northwest are made daily using the Streamflow Synthesis and Reservoir Regulation (SSARR) computer model.

Snowmelt calculation in the SSARR model is made either by the temperature index method or by the use of the generalized snowmelt equation for a partially forested area. In general, the snowmelt equation is not used for daily operational forecasts because of the lack of real time energy budget data. At the present time, the temperature index method is used for operational forecasts.

The temperature index method determines snowmelt runoff as follows:

$$m = (T_A - T_b)\ R\ \frac{PH}{24}$$

where

m = Snowmelt runoff in inches of water over the snow cover area.

T_A = Period temperature (F) at the median elevation of the melting snowpack.

T_b = Base temperature (F), specified as a constant for a watershed.

R = Melt rate, specified to the computer, or given as a function of accumulated runoff, in inches of water per degree day.

PH = Period length in hours.

Values used for the base temperature and the melt rates can be adjusted in the daily runs. The base temperature can be adjusted to the minimum, mean, or maximum daily value; and the melt rate can be adjusted to conform to the natural variability encountered during the melt season.

Snowmelt determination in the SSARR requires that the snow-covered area be updated daily. The SSARR model has the ability to update the SCA value it carries when aerial flight or satellite data are unavailable. In mountainous areas of the western United States, snow-covered area depletion during the active snowmelt season can be expressed as a function of accumulated generated runoff as a percent of seasonal total. Figure 2 on the next page illustrates a typical curve relating snow cover to generated runoff. Such curves are generally considered uniform for specific watersheds from year to year. The general equation for such a curve is:

$$\frac{SCA}{100} = 1.0 - \frac{(\Sigma Q_g)^n}{100}$$

where

SCA = Snow-covered area as a percent of total watershed area.

Q_g = Accumulated generated runoff from snowmelt, in percent of seasonal total.

n = Parameter expressing characteristic of snowcover depletion for a watershed.

At the beginning of each computer run the initial snow-covered area, a total seasonal generated runoff, and an initial accumulated runoff must be input. The model then computes the initial percent of accumulated generated runoff. From this the program determines the ratio of the actual initial snow-covered area to the theoretical snow-covered area determined from the curve.

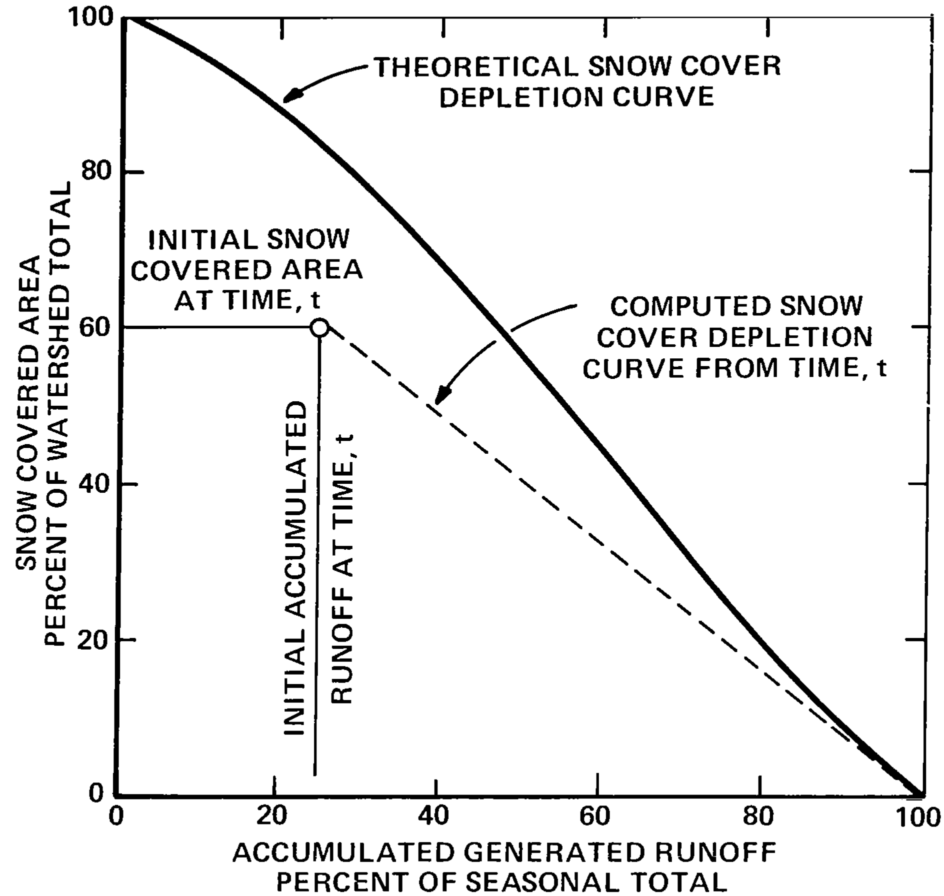


Figure 2. Snow covered area vs. generated runoff

The daily increment of computed snowmelt calculated by the temperature index method is added to the initial generated runoff. The incremented generated runoff is then used to determine the next day's snow cover by applying the value of the ratio of actual initial snow-covered area to the theoretical snow-covered area. This process is continued by daily increments throughout the computation period, and results in a computed snow cover depletion curve which is proportional to the theoretically shaped curve.

The streamflow forecasts are made daily during the spring freshet season and are made for small watersheds. The primary inputs to the SSARR model are indexed values of temperature and precipitation. Snow water equivalent data from snow courses are used in a volume forecast model which forecasts April-September runoff. Forecasts of this nature are generally made once per month, after snow data are collected, in January, February, March, and April. These forecasts of April through September volumetric runoff are in turn used as input to the SSARR model to forecast streamflows utilizing daily indexed values of temperature and precipitation. The model depletes the snowpack and snow-covered area and in turn develops forecasted streamflows at key points on the river. As the melt season progresses and additional aerial snow flights are made, the new snow flight data are used to update the snow cover data within the model, thus improving the accuracy of the daily streamflow forecasts.

For the purposes of this study, at the end of each flood season, a streamflow reconstruction or "reconstitution run" was made for each basin with the SSARR model. In these reconstitutions, daily indexed values of temperature and precipitation and also the total actual seasonal runoff are supplied to the model. The streamflows are initialized at target points in the basin with actual values, and the initial basin snow-covered area is supplied the model. Thereafter, throughout the time frame of the flood season study, actual observed daily values of temperature and precipitation (but not streamflow) are given to the program; and the SSARR model melts the snowpack, handles the overland and subsurface portions of runoff, and provides a channel routing to generate the daily streamflows at target locations. No intermediate adjustments for snow-covered area are made to these reconstitution runs. When compared with the observed hydrograph, a reconstitution run provides a visual check on the model's performance, and therefore, gives credence to the SCA curve generated by the model.

Data Reduction Problems

The major data reduction problems were physical features that hindered determining the snow line, and cloud cover that obliterated all or portions of a basin. Forest cover, shadow, and bare rock were physical features that imposed problems in determining the snow line. Cloud cover obscuring the ground was the greatest problem.

Forest Cover and Shadow

In the Dworshak, Libby, and Hungry Horse Basins tree cover, steep slopes, and sun angle/shadow caused problems in determining the snowline from the satellite imagery. In these three basins the mountain crests are above the timberline and are bare rock, making it easy to spot snow. Moving down the slopes into the timber it is increasingly difficult to determine the snowline, especially if the forest cover is dense. This caused only sporadic problems in the Dworshak Basin, but was a major problem in the Libby and Hungry Horse Basins. On the following five pages is a series of Landsat images for the Hungry Horse Basin illustrating the forest canopy, slope, and shadow problems. To the left of the Basin is Flathead Lake. Immediately to the right is the Middle Fork of the Flathead River, and beyond that the Continental Divide. The South Fork of the Flathead flows northwest out of the Basin, and Hungry Horse Reservoir is at the top of the picture just before the river leaves the Basin.

For clarity, these Landsat images (and the appropriate discussion for each figure) are shown separately on the next five pages.

In this picture (7 Mar 76) the little clearcut areas surrounding Hungry Horse Reservoir are snow covered, portions of the reservoir are snow covered, and the area east of the Rockies is snow covered. Note that the north-facing slopes show as black and appear to be snow free even though several small valleys in these areas have snow. Lakes and valleys in the headwaters are snow covered. The SCA is 95 percent.

Figure 3. Hungry Horse Basin, 7 Mar 76, Landsat Imagery, MSS 5

In this picture (3 Apr 76) the situation is much the same on north-facing slopes. Outside the basin, the valley around Flathead Lake has opened up. Within the basin, some additional areas have melted in the lower (northern) portion of the main valley. SCA is 87 percent.

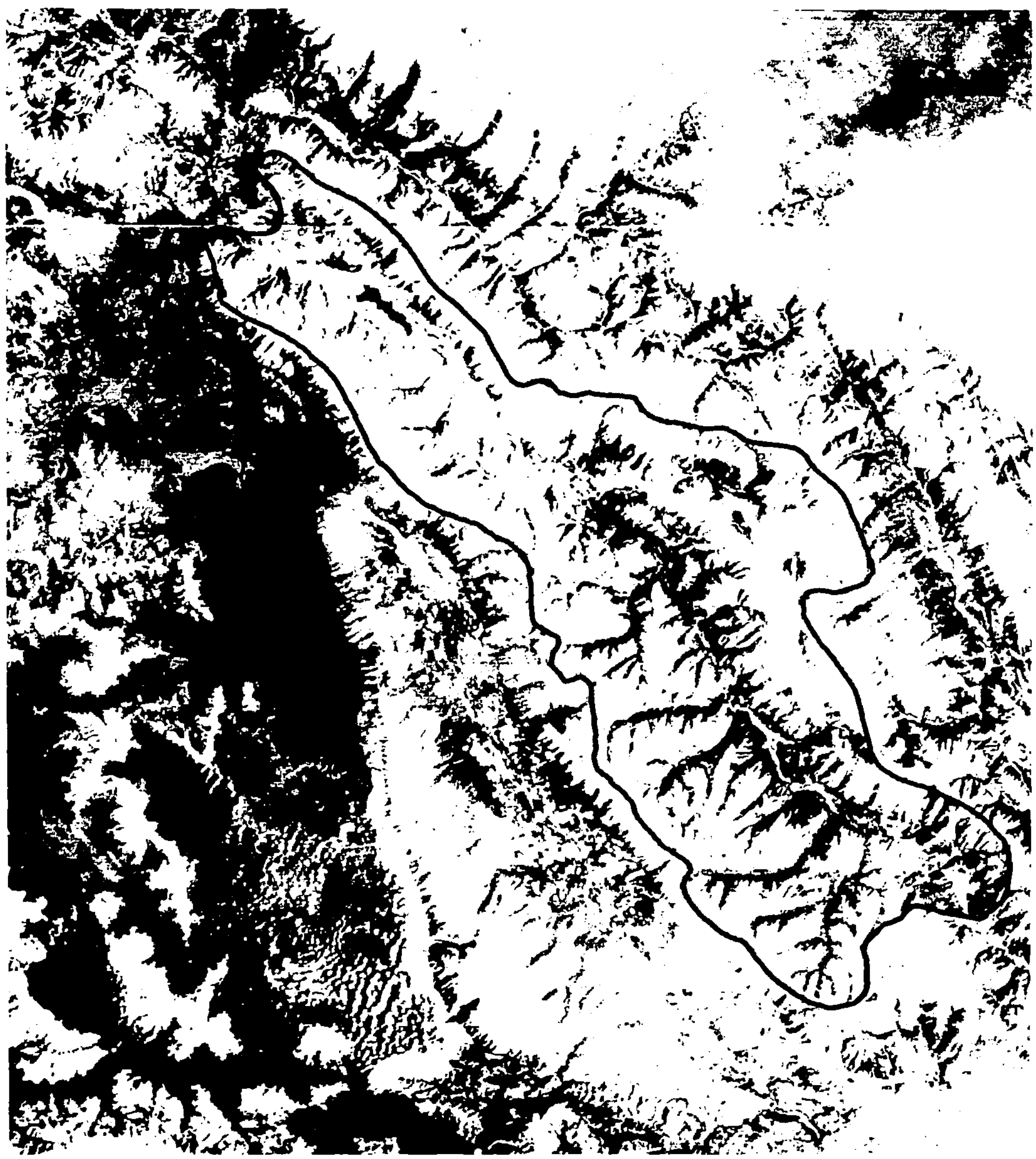


Figure 4. Hungry Horse Basin, 3 Apr 76, Landsat Imagery, MSS 5

In this picture (12 Apr 76) areas outside the basin east of the Rockies and in the Flathead Lake area are completely snow free. Within the basin, melting has continued up the main valley, and some melting has started on the south slopes of the side creeks. Within the side branches or small valleys, the low-lying snow intermittently visible on 7 March 76 has disappeared. Snow still shows in the clearcut areas. SCA is 74 percent.

Figure 5. Hungry Horse Basin, 12 Apr 76, Landsat Imagery, MSS 5

In this picture (30 Apr 76) melting has continued on the south-facing slopes and in some clearcut areas near Hungry Horse Reservoir. New snow has fallen at the higher elevations and also east of the Rockies. SCA is 70 percent.

Figure 6. Hungry Horse Basin, 30 April 76, Landsat Imagery, MSS 5

In this picture (18 May 76) melting has been rapid. The clearcuts are snow free, the main valley is completely barren, north and south slopes show equal in the photo. Note the rivers. All the rivers within and outside the basin that flow into Flathead Lake appear white from the muddy silt load. The Flathead River flowing south out of Flathead Lake is flowing clear and appears as gray. SCA in the Hungry Horse Basin is 48 percent.

Figure 7. Hungry Horse Basin, 18 May 76, Landsat Imagery, MSS 5

The Libby Basin is steeper, more densely forested, and is more difficult to snow map than Hungry Horse. NOAA/NESS personnel do not feel confident mapping the Libby Basin until the snow-covered area has dropped to below 50 percent.

Bare Rock

In both Libby and Hungry Horse Basins the crests of the mountain ranges are bare rock. This rock is a light or whitish grey that can be confused with snow late in the season. For this reason, snow mapping is discontinued when the SCA drops to 10 or 15 percent.

Cloud Cover

An ever present problem is that of cloud cover. Portions of the Columbia River Basin are often obscured by clouds during the spring season. Utilizing Landsat data, the best possible coverage would be every 9 days. Because the snowline changes rapidly during the spring snowmelt season, a 9-day spacing between satellite images is less than ideal. In actuality, cloud cover reduced this coverage by Landsat to as infrequent as 88 days, and in 1974 in the Upper Snake Basin only one usable Landsat image was obtained. This was unfortunate because 1974 in the Upper Snake Basin was a near-maximum snow cover year.

With NOAA data there were extended periods each year when one or more of the basins were obscured by clouds. These periods could be 30 to 40 days, and in 1978 for the Dworshak Basin was 52 days. Although these periods could be extensive, there has never been a case of only one image per melt season as with the Landsat data. Data on the persistence of cloud cover in the various basins are given on Table 1 on the following page.

It should be noted that this cloud cover would also, in some cases, preclude the collection of aerial snow flight data. Because cloud cover makes the collection of satellite data unreliable, the satellite-gathered SCA data cannot be used exclusively for operational purposes at this time. Nonetheless, NOAA satellite estimates of snow-covered area will be available more frequently than aerial flights and will have direct usefulness in the forecast model.

DATA VERIFICATION

The ground truth and satellite data which had been previously reduced had to be verified prior to use.

Ground Truth Data

The ground truth data consisted of SCA values generated by the streamflow forecasting model, and of SCA data gathered from low altitude aerial flights.

As noted previously, the SSARR reconstitution runs generate a hydrograph which when compared with the observed hydrograph provides a visual check on the model's performance, and therefore, gives credence to the SCA curve generated by the model.

TABLE 1
PACIFIC NORTHWEST MAXIMUM SEASONAL CLOUD PERSISTENCE

Basin	Landsat Imagery Cloud-Period	Landsat Imagery No. of Days	NOAA Imagery Cloud-Period	NOAA Imagery No. of Days
	1973			
Upper Snake	30 Mar-21 May	53		
Boise	8 May-11 Jun	35		
	1974			
Upper Snake	Only one Cloud-free image			
Boise	3 May-24 Jun	53		
	1975			
Upper Snake	31 May-25 Jun	26		
Boise	15 Mar-14 May	61	13 Apr- 7 May	25
Dworshak			7 Mar- 9 Apr	34
Libby			7 Mar- 9 Apr	34
Hungry Horse			7 Mar-11 Apr	36
	1976			
Upper Snake	14 Mar- 9 Jun	88	27 May-25 Jun	30
Boise	4 Apr-17 May	44	22 Mar- 3 Apr	13
Dworshak	5 Apr-18 May	44	13 Mar- 3 Apr	22
Libby			10 May-17 Jun	39
Hungry Horse	8 Mar- 2 Apr	26	22 May-17 Jun	27
	1977			
Upper Snake			20 Apr-31 May	42
Boise			21 Apr-30 May	40
Dworshak			28 Apr- 4 Jun	38
Libby			26 Apr- 4 Jun	40
Hungry Horse			1 May- 4 Jun	35
	1978			
Upper Snake			8 Mar- 8 Apr	32
Boise			9 May-30 May	22
Dworshak			10 Apr-31 May	52
Libby			29 Jun-13 Jul	15
Hungry Horse			20 Apr- 7 May	18

Other checks are also employed in verifying the SCA curve generated by the SSARR model, again through visual inspection of the closeness of fit between the observed and generated hydrograph. One of the basic inputs to the model is the total volume of runoff from rain and snowmelt that occurred for a particular period (i.e., April-July for many of the reconstitution runs) for a particular basin. Two main aspects of the model's validity for a watershed can be checked in this manner. First, the ability of a watershed to generate the total volumetric runoff in the proper period can be ascertained. Given actual daily values of temperature and precipitation, the two primary parameters that can be adjusted to improve the volume fit are initial soil moisture and initial snow-covered area. Secondly, the ability of a watershed model to match the peaks on the observed hydrograph can be verified. Again given actual daily values of temperature and precipitation in the reconstitution runs, the model parameters which are most effective in adjusting the peak flow for a basin are snow-covered area and melt rate, and the melt rate is temperature dependent. Thus it can be seen that the SCA parameter is highly important in assessing the proper performance of the SSARR model, and conversely, the SSARR reconstitution runs critically and closely assess a basin's snow-covered area during a given melt season.

In the aerial flights the average elevation of the basin's snowline is determined and an area elevation table for the basin is used to determine the snow-covered area. The SCA data determined from the aerial flights are checked by comparing the results to the SCA data generated in the SSARR reconstitution runs. These two ground truths provide a good cross-check to each other.

As well as being cross-checked to the SSARR ground truth data, the aerial flight data also cross-check to the satellite data. When flights are made, only the continuous snowline is plotted. Discontinuous patches are thin, contribute little to runoff, and are, therefore, not included. Conversely, the satellite imagery integrates patches into the overall snowline. Thus, the satellite SCA data are generally higher than the aerial flight data. When the 50 percent snowline (50 percent of patchy snow) is plotted, there is perfect agreement between the aerial flight and satellite data.

Satellite Data

Satellite derived SCA data were verified by comparing it with the SCA data from both the snow flights and the modeling reconstitution runs. In addition, cross-checks were made on the satellite data itself.

Retracing and measuring the same day's satellite scene on three separate occasions resulted in the SCA measurements ranging from 56 percent to 58 percent. In comparing snow cover from a given day's scene, with that of another satellite pass made one or two days later, the variation in snow-covered area was only a few percent.

Cross-checks were made by NOAA/NESS personnel in Silver Spring, Maryland, and BPA personnel in Portland, Oregon, by mailing the same NOAA image back and forth. In the Upper Snake basin for May 26, 1976, BPA measured 50 percent SCA, and NOAA/NESS measured 46 percent. BPA personnel tried to measure SCA on a NOAA photograph of the Upper Snake with a poor grey-scale definition for April 29, 1976, and were able to find only 75 percent snow cover. NOAA/NESS personnel analyzed a photograph with a much better grey-scale for April 30 (1 day later) and found 99 percent SCA. April 29, 1976, data for the Libby Basin were derived by both NOAA/NESS and BPA. The SCA was measured as 57 percent and 58 percent respectively by the two agencies.

The 1976 satellite data for the Hungry Horse Basin were analyzed by BPA personnel from both Landsat and NOAA imagery. The SCA values determined from the two different sets of imagery compared very favorably. Operator familiarity with the basin is essential for proper reduction of the data. Due to unfamiliarity with the basin, the 1975 satellite data for the Dworshak, Libby, and Hungry Horse Basins had to be completely reanalyzed.

SUMMARY AND COMPARISON OF SATELLITE DATA

The satellite data was compared with ground truth data for all the available years in each of the five basins. In the Upper Snake, Boise, and Dworshak Basins the satellite estimates of SCA are usable and useful forecasting tools. In the Libby Basin cloud cover and inaccurate determination of the snowline due to forest canopy make the use of satellite data marginal. Satellite estimates of SCA in the Hungry Horse Basin have generally been acceptable although forest canopy and bare rock make determination of the snowline difficult.

In general, 1975 had a maximum SCA, 1977 had a minimum SCA, and 1973, 1974, 1976, and 1978 had average SCA. This generalized relationship is shown on Figures 8 through 12 (pages 24 through 26).

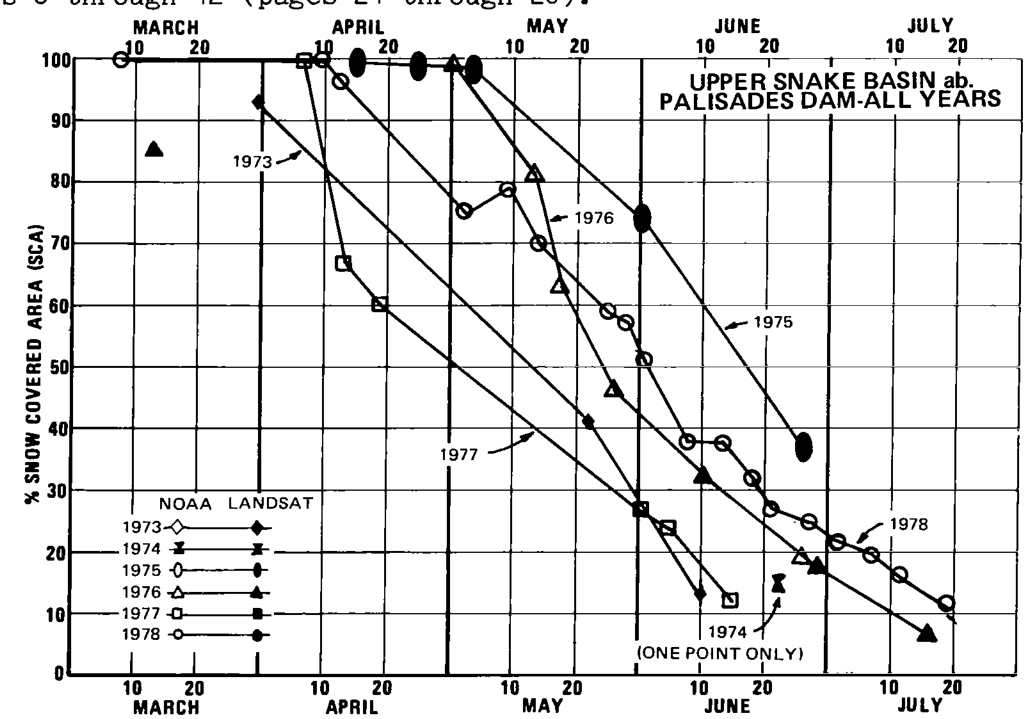


Figure 8

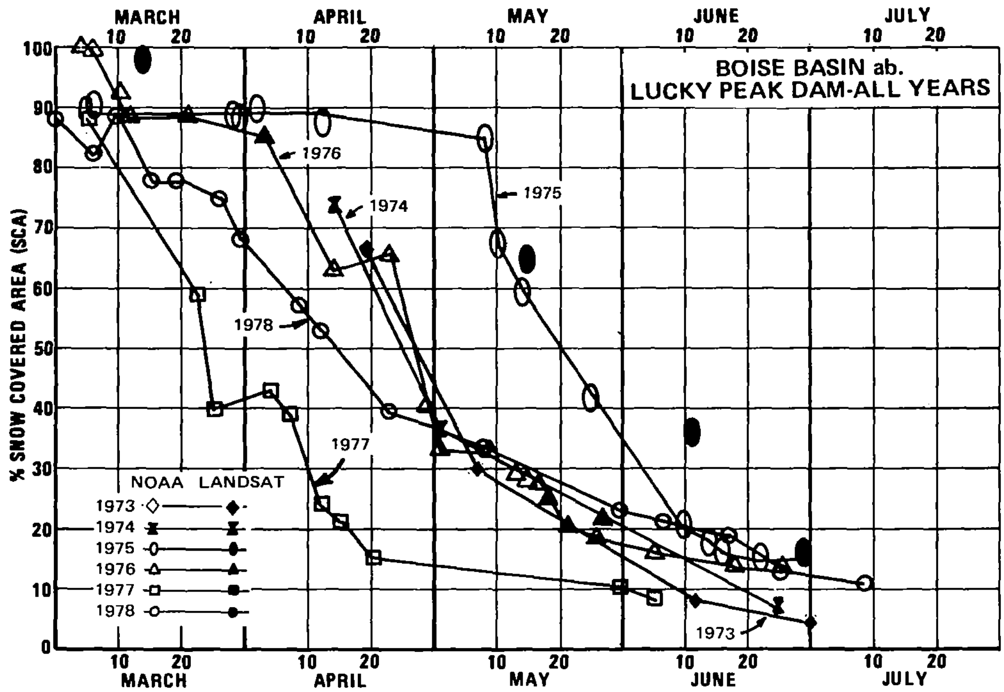


Figure 9

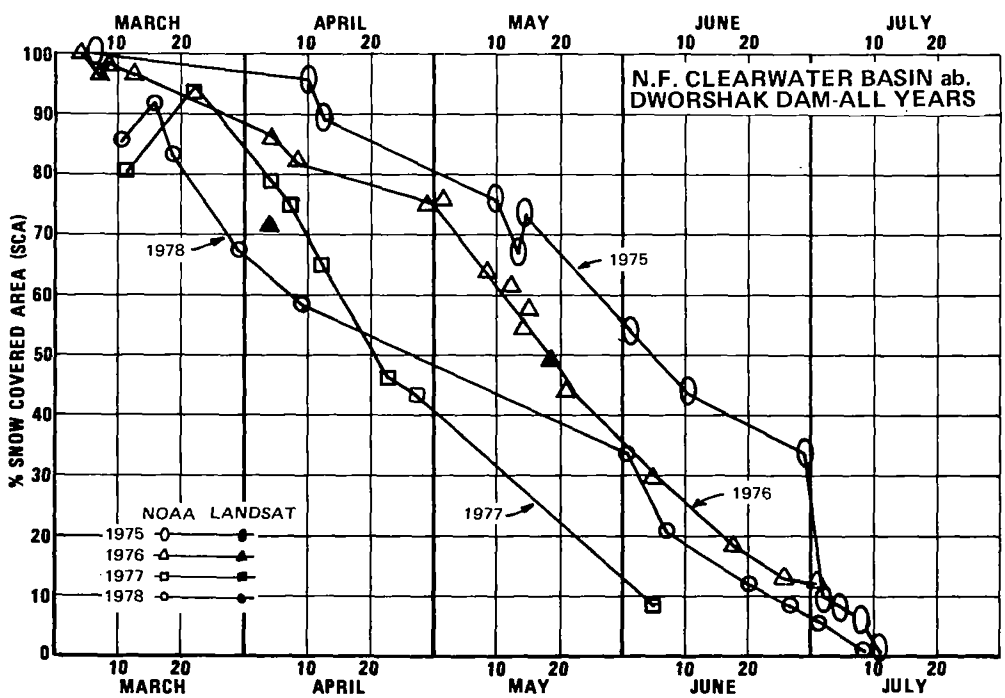


Figure 10

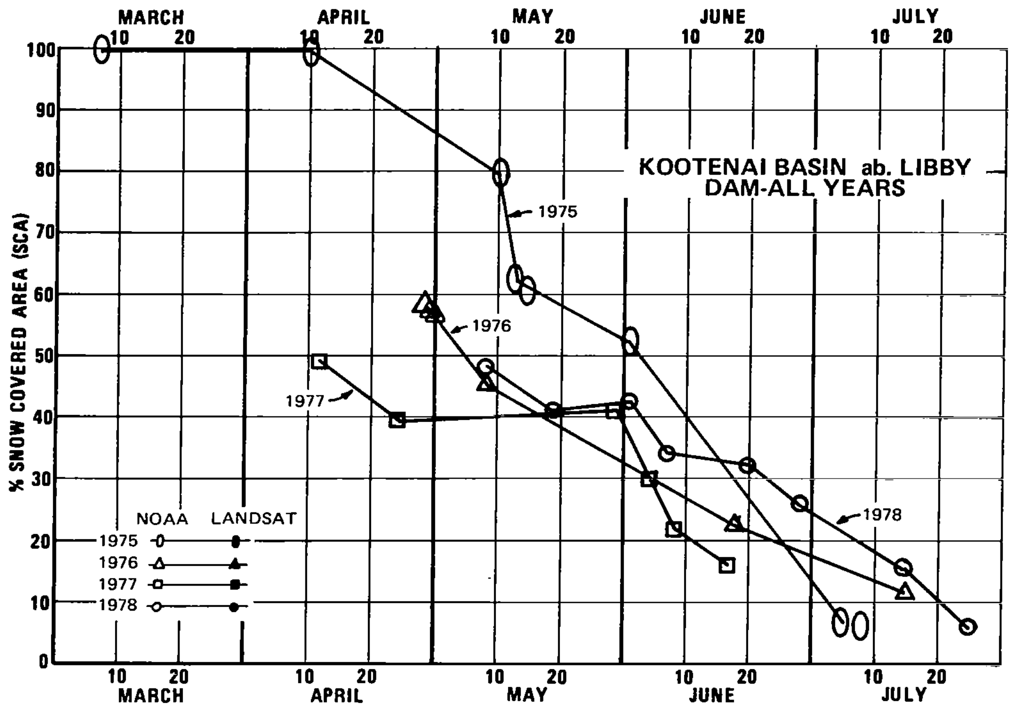


Figure 11

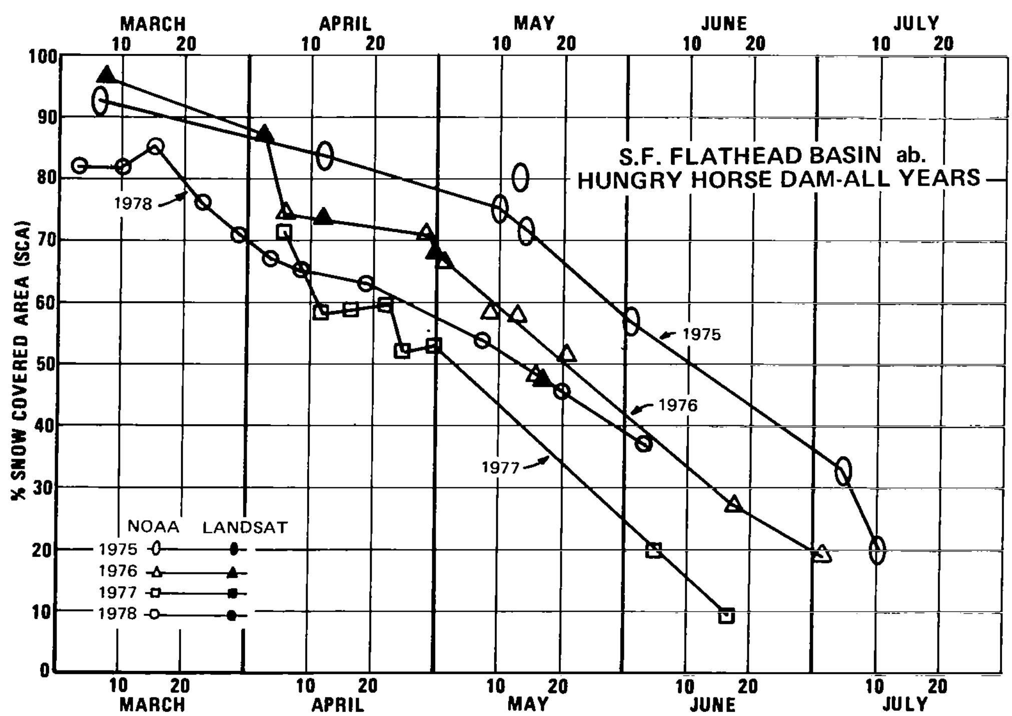


Figure 12

Figures 13 through 18 (pages 27 through 30) present satellite derived percent SCA vs. time, wherein SCA data for all five basins are shown on the same graph, one figure per year. The intent here was to see if there was a generalized relationship of relative SCA between the various basins. These graphs presuppose that temperature rises and snow melting occurred generally to the same degree over all five of the basins. While this is not absolutely true, in the spring during the snowmelt season the trend is for general warming basin-wide. In these general relationships, the Upper Snake had the greatest percent SCA at each point in time, and the Boise Basin had the least, with the Dworshak, Libby, and Hungry Horse Basins holding intermediate points. The high elevation Upper Snake Basin always started at or near 100 percent SCA and retained its relative snow cover longer than the other basins. The low-lying Boise Basin rarely started with 100 percent snow cover, and lost its snow earlier in the season. The Libby, Hungry Horse, and Dworshak Basins have SCA values in time that were intermediate between the Upper Snake and Boise Basin values, and the snow cover depletion of these three basins all trended along a common recession line. The recession lines were generally smooth and orderly, and did not erratically jump up and down. Thus in actual daily operational uses, when an operator/decisionmaker does not have a complete season's snow cover recession curve in front of him, he still knows that the percent SCA for the Boise Basin should generally be less than that of the Hungry Horse, Libby or Dworshak Basins, and that these basins in turn are lower than the Upper Snake Basin. He also knows that the continuously plotted percent SCA values for a given basin recede in an orderly manner, have only minor short-term accretions after April 1, and that the later it is in the melt season, the less these accretions will be.

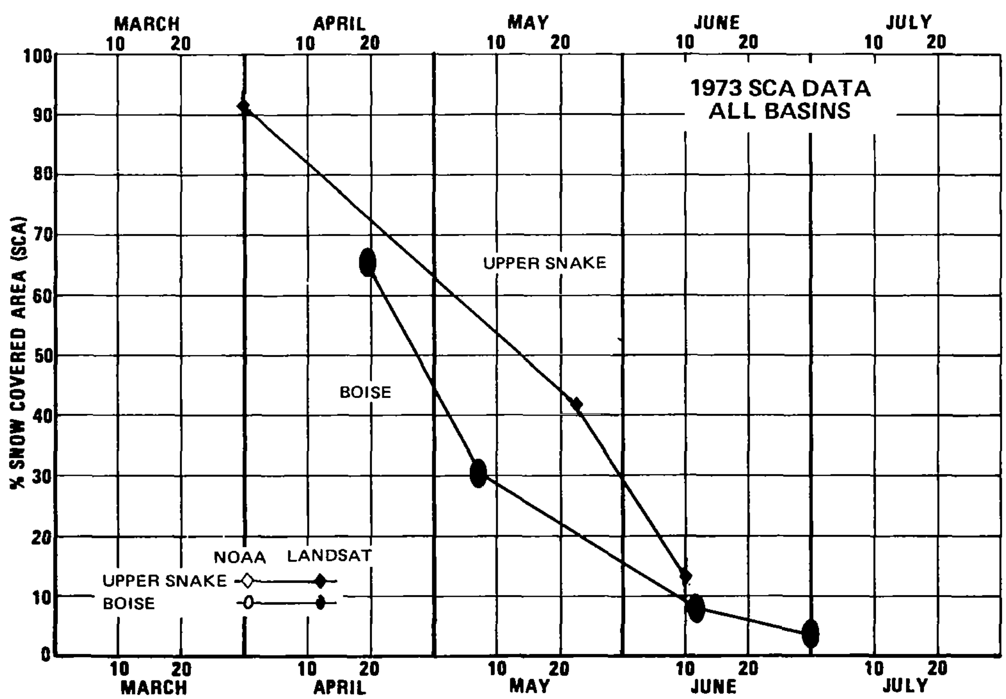


Figure 13

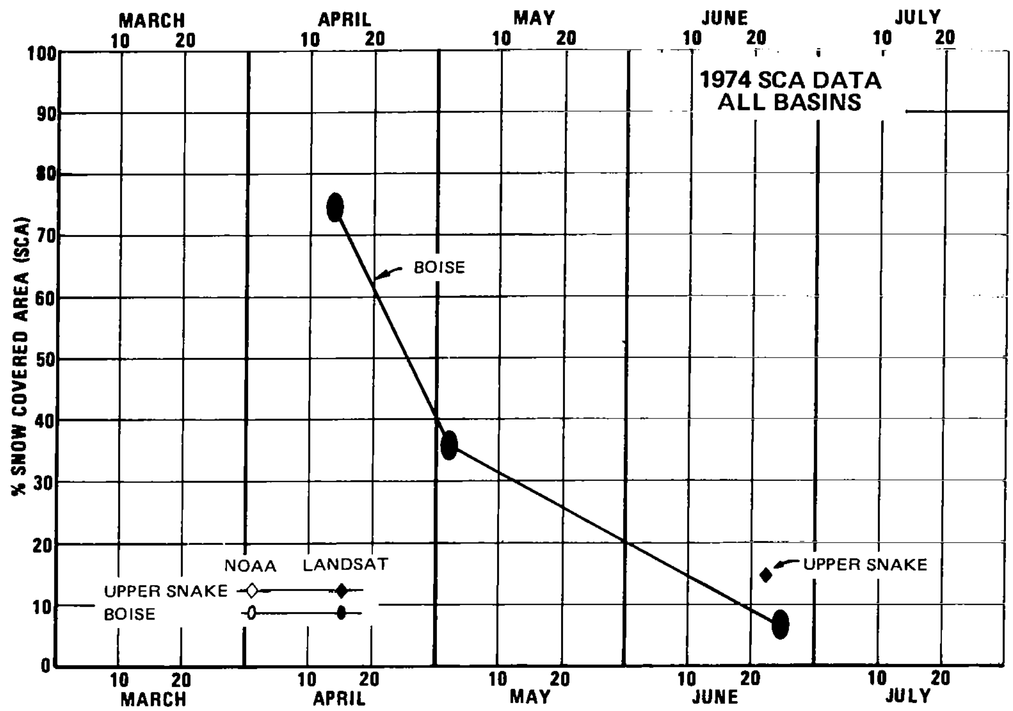


Figure 14

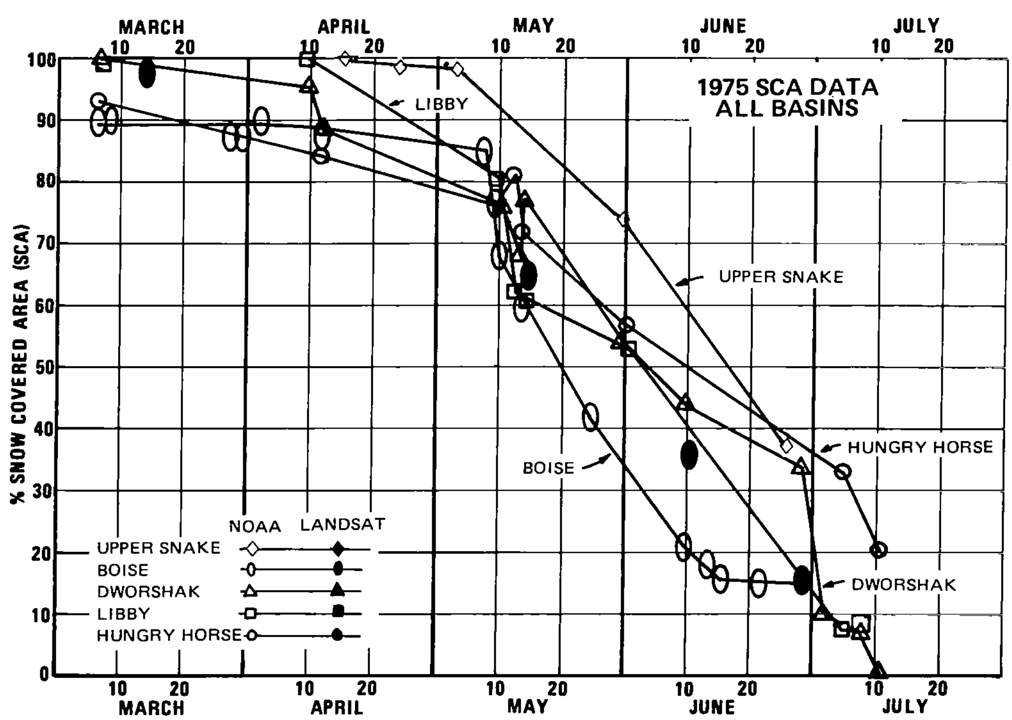


Figure 15

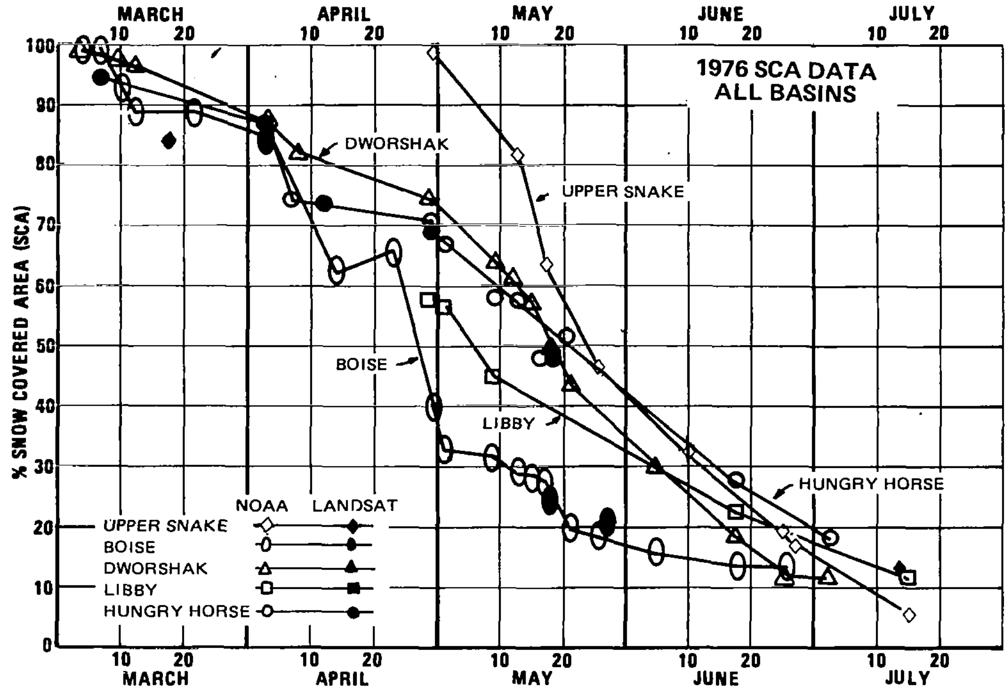


Figure 16

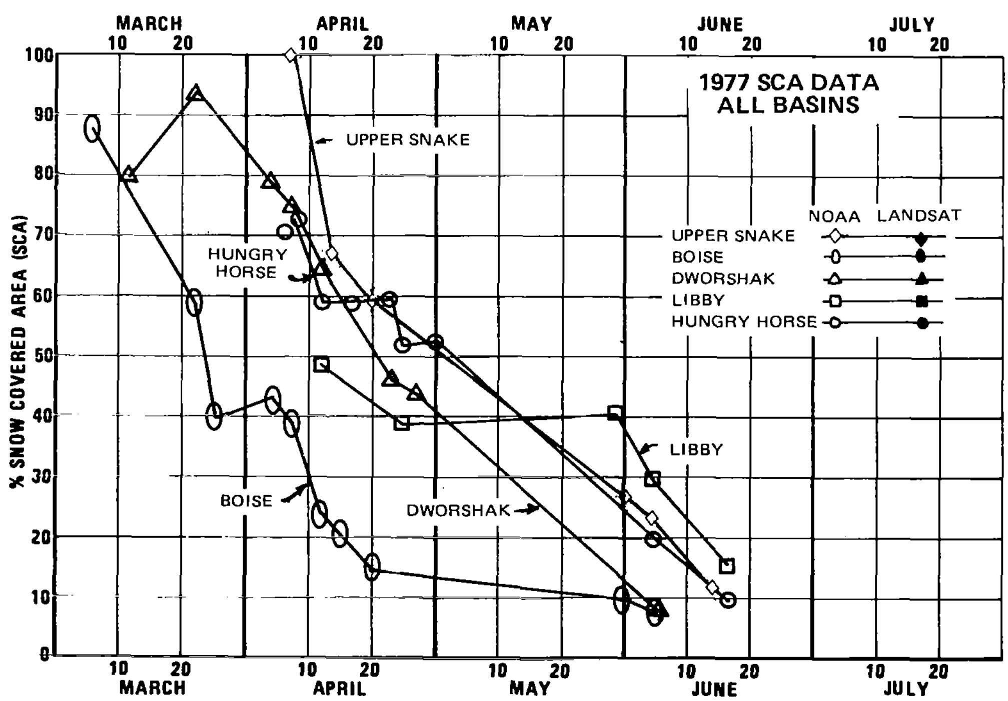


Figure 17

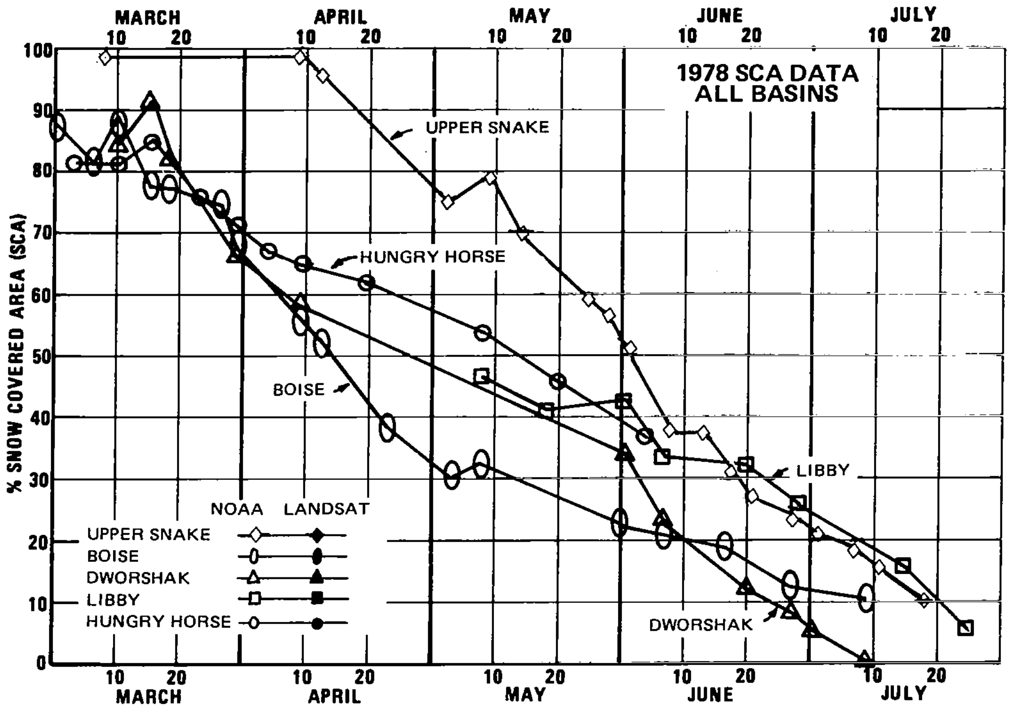


Figure 18

The satellite photos integrate the snowline and thus include areas of low-lying patchy discontinuous snow which contribute little to snowmelt runoff. This introduces a bias between the satellite data, snow flight data, and the SSARR generated data, wherein the satellite data shows a greater SCA for a given point in time. This is shown in Figures 19 through 21, and 23 through 31 (pages 33 through 35, pages 40 through 44, and pages 47 through 50).

In the following five subsections, the agreement between the various SCA data is extensively discussed year-by-year, and basin-by-basin. The generalized results for each basin are given in the last paragraph for each basin's discussion.

Upper Snake

Snow-covered area data for the Upper Snake Basin are presented on Table 2. These data for the Upper Snake are shown on Figures 8 and 19 through 22 (page 24, and pages 33 through 36). In 1975 (Figure 19), a high snowpack year, there is great agreement between the observed and computed hydrographs, and also good agreement between the SSARR and flight SCA data. The satellite data are slightly high because of the integrated snowline. In 1976 (Figure 20), an average snowpack year, there is excellent agreement between the two hydrographs, and between the SSARR and flight SCA data. The satellite SCA data are initially high because of the inclusion of patchy snow. After May 18, there is excellent agreement of SCA by all data means. The Landsat measured value of SCA for March 31 appears to be in error. The snowpack in 1977 (Figure 21) was extremely low. The satellite SCA data are high throughout the season because of the inclusion of patchy snow. The overestimation of SCA by satellite was 55 percent on April 8, decreasing to 10 percent on May 20 as the patchy snow melted. Notice that cloud cover obscured the basin from April 20 to June 1. The snowpack in 1978 (Figure 22) was average. There is excellent agreement between the satellite and flight SCA data for this year. Although there is good agreement between the observed and computed hydrographs, the causative SSARR estimate of SCA does not agree with either the flight or satellite SCA estimates.

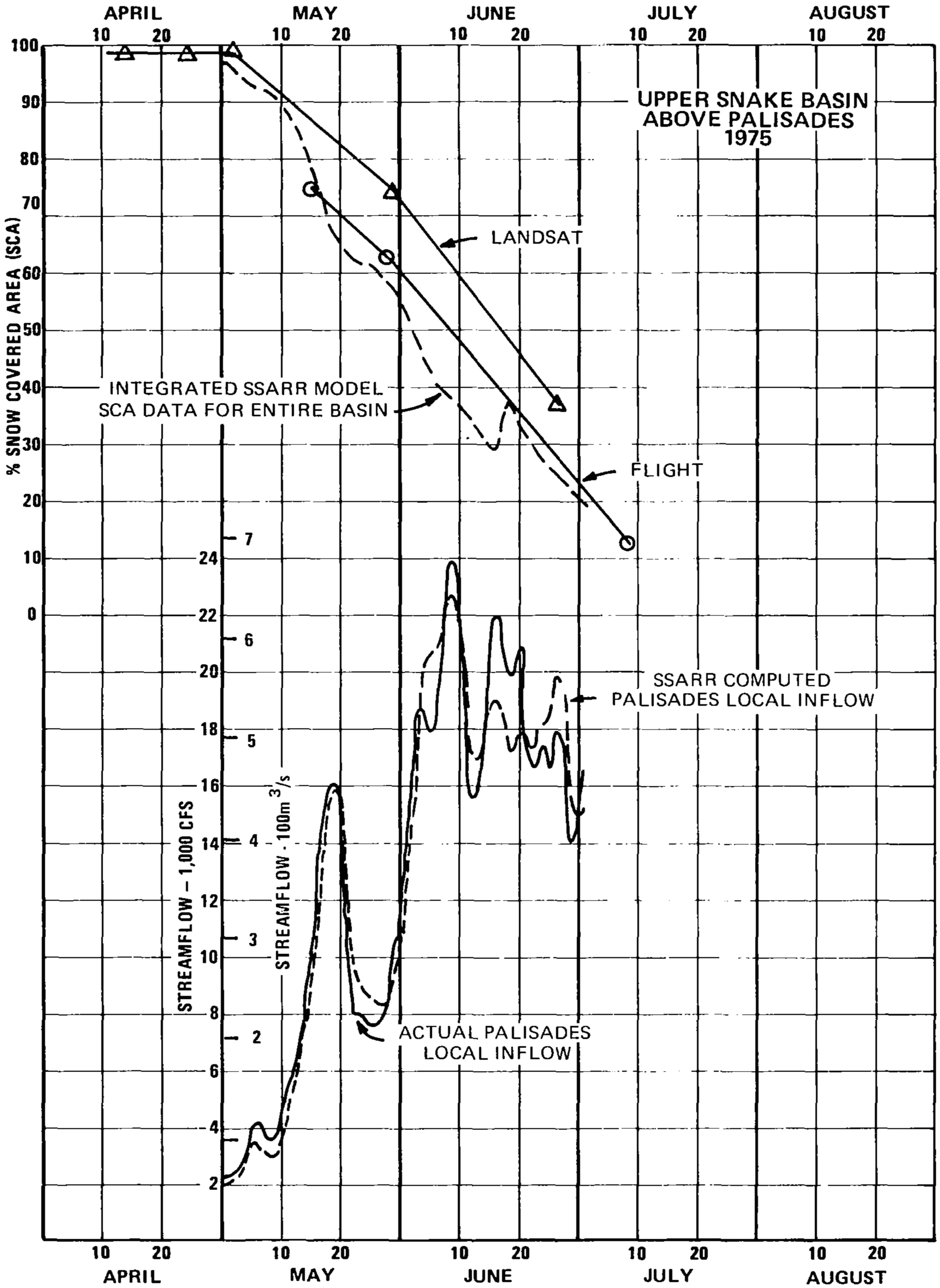
Results in the Upper Snake Basin have been excellent, although cloud cover obscuring the ground has been a problem. The agreement between satellite derived SCA estimates and ground truth data has been very promising.

TABLE 2
UPPER SNAKE BASIN ABOVE PALISADES DAM

	Percent of Basin Snow Covered			
Date	Aerial Flight	SSARR	NOAA	Landsat
29 Mar 73		100		92
22 May 73		33		41
9 Jun 73		19		14
22 Jun 74				15
15 Apr 75				100
24 Apr 75				99
3 May 75		95		99
15 May 75	75	77		
28 May 75	63	57		
30 May 75		54		74
26 Jun 75		26		37
9 Jul 75	12			

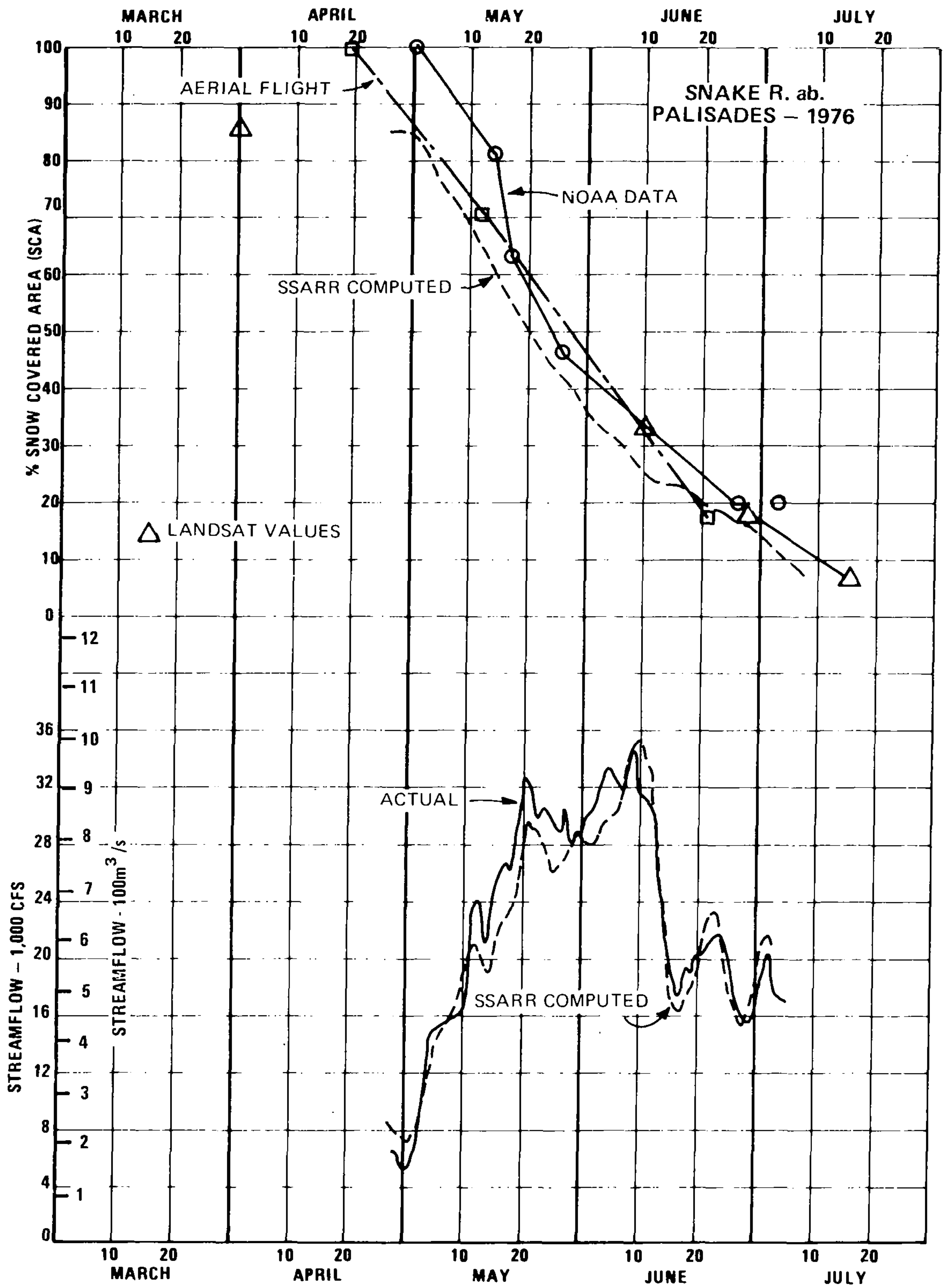
TABLE 2
(continued)

Date	Percent of Basin Snow Covered			
	Aerial Flight	SSARR	NOAA	Landsat
13 Mar 76				85
19 Apr 76	100			
30 Apr 76		85	99	
12 May 76	70	64		
13 May 76		63	81	
17 May 76		55	63	
26 May 76		42	46	
10 Jun 76		25		32
21 Jun 76	17	19		
26 Jun 76		16	19	
28 Jun 76		16		17
3 Jul 76		11	20	
16 Jul 76				6
7 Apr 77		44	100	
13 Apr 77		42	67	
19 Apr 77		41	60	
1 Jun 77		21	27	
3 Jun 77	20	20		
5 Jun 77		18	24	
15 Jun 77		11	12	
7 Mar 78			99	
9 Apr 78		94	99	
12 Apr 78		94	96	
2 May 78		88	75	
9 May 78		86	79	
10 May 78	80	85		
14 May 78		83	70	
25 May 78		73	59	
28 May 78		67	57	
1 Jun 78	46	66	51	
8 Jun 78		57	38	
13 Jun 78		52	38	
18 Jun 78		46	32	
21 Jun 78		43	27	
27 Jun 78	25	34	25	
1 Jul 78			22	
7 Jul 78			20	
11 Jul 78			16	
19 Jul 78			11	



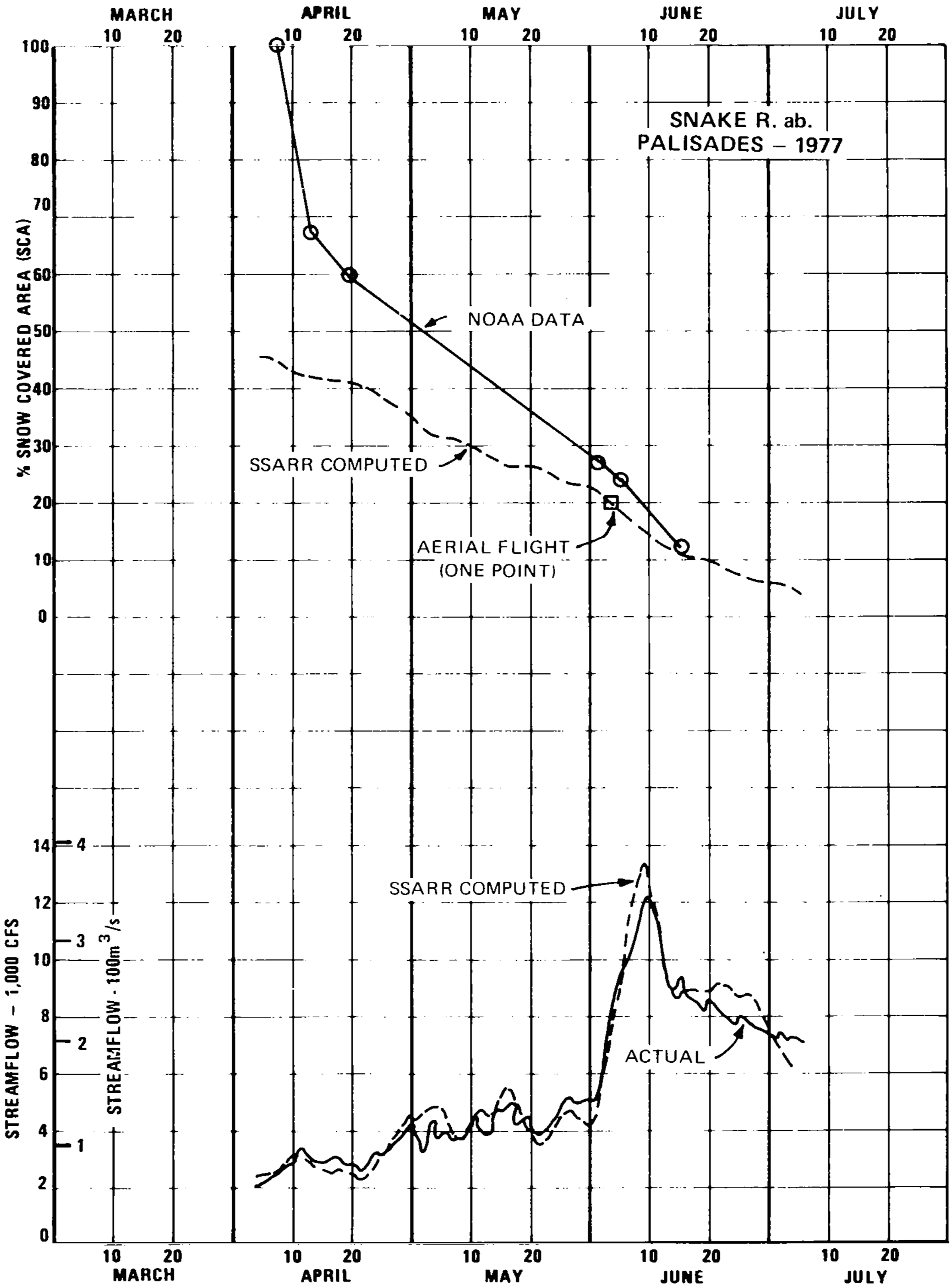
APRIL
MAY
JUNE
JULY
AUGUST
10
20
100
90
80
70
60
50
40
30
20
10
0
% SNOW COVERED AREA (SCA)
UPPER SNAKE BASIN
ABOVE PALISADES
1975
LANDSAT
INTEGRATED SSARR MODEL
SCA DATA FOR ENTIRE BASIN
FLIGHT
24
22
20
18
16
14
12
10
8
6
4
2
7
6
5
4
3
2
STREAMFLOW – 1,000 CFS
STREAMFLOW · 100m 3/s
SSARR COMPUTED
PALISADES LOCAL INFLOW
ACTUAL PALISADES
LOCAL INFLOW

Figure 19



MARCH
APRIL
MAY
JUNE
JULY
SNAKE R. ab.
PALISADES – 1976
AERIAL FLIGHT
NOAA DATA
SSARR COMPUTED
LANDSAT VALUES
% SNOW COVERED AREA (SCA)
ACTUAL
SSARR COMPUTED
STREAMFLOW – 1,000 CFS
STREAMFLOW - 100m³/s

Figure 20



SNAKE R. ab. PALISADES – 1977
MARCH
APRIL
MAY
JUNE
JULY
% SNOW COVERED AREA (SCA)
NOAA DATA
SSARR COMPUTED
AERIAL FLIGHT (ONE POINT)
STREAMFLOW – 1,000 CFS
STREAMFLOW - 100m³/s
SSARR COMPUTED
ACTUAL

Figure 21

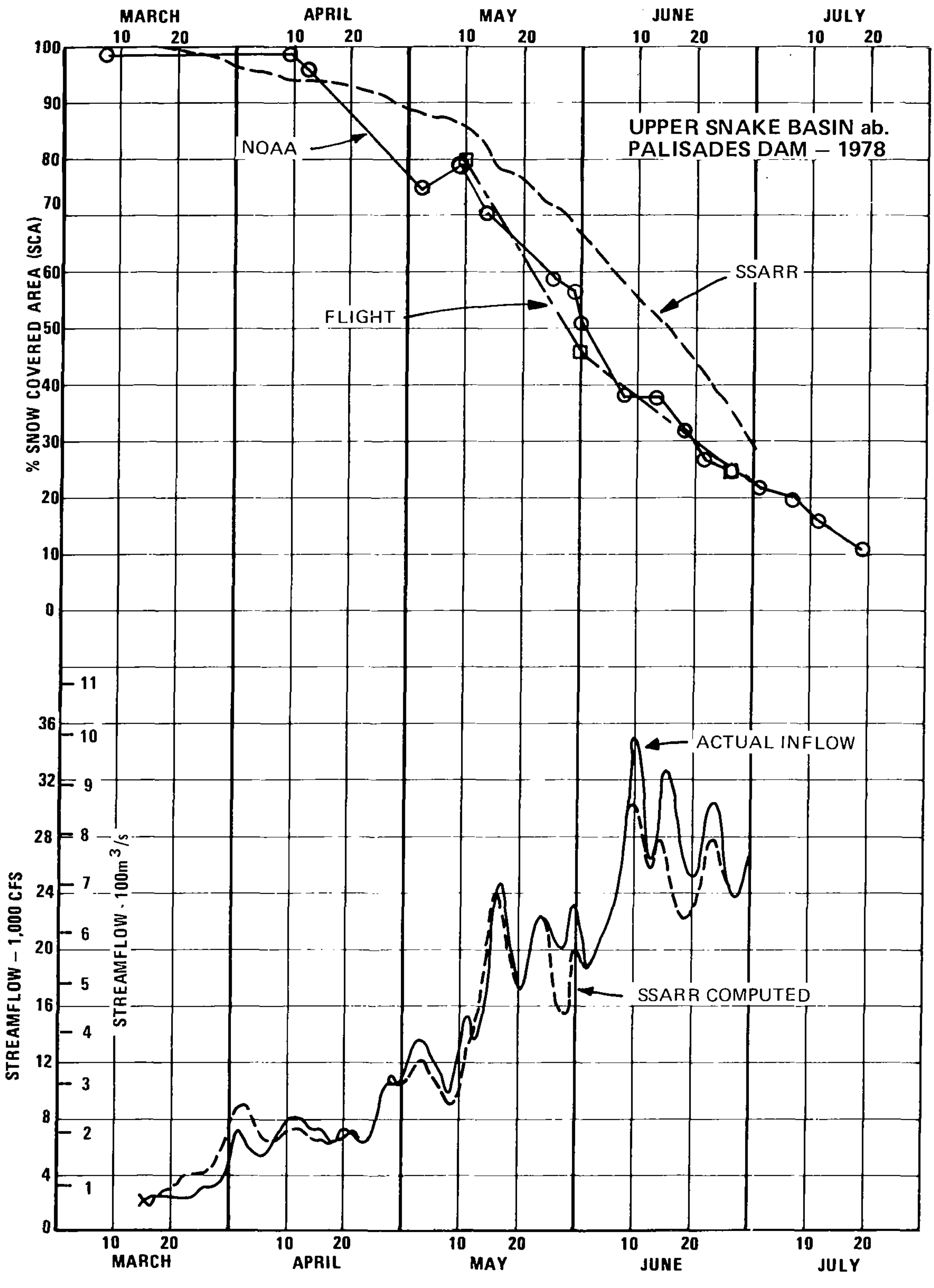

MARCH
APRIL
MAY
JUNE
JULY
UPPER SNAKE BASIN ab. PALISADES DAM – 1978
NOAA
SSARR
FLIGHT
% SNOW COVERED AREA (SCA)
ACTUAL INFLOW
SSARR COMPUTED
STREAMFLOW – 1,000 CFS
STREAMFLOW · 100m³/s

Figure 22

Boise

Snow-covered area data for the Boise Basin are given on Table 3. Data for the Boise Basin are shown on Figures 9 and 23 through 27 (page 25, and pages 40 through 44). In 1974 (Figure 23), an average snowpack year, there is fair agreement between the computed and observed hydrographs. The agreement between the three methods of measuring SCA is excellent after May 1. Prior to May 1 the satellite imagery saw too much patchy snow, and the April 21 snow flight data and/or SSARR data looks questionable in light of the general fit between the two hydrographs. The snowpack in 1975 (Figure 24) was high. The agreement between the two hydrographs was fair, and the agreement between SSARR and flight SCA data was good. The Landsat data interpretation appears to be a little high, but the NOAA satellite SCA data agrees excellently with the ground truth SCA data after the initial melt-down period of patchy snow.

There is good agreement in 1976 (Figure 25), an average snowpack year, between the observed and computed hydrographs. There is good agreement between the two ground truth SCA data (aerial snow flights and SSARR data), and there is also good agreement between the satellite data as measured from both Landsat and NOAA data. Because of the integration of the snowline, the satellite data were high throughout the 1976 spring melt season.

In 1977 (Figure 26) the snowpack was a record low. Note that on the hydrograph plot, one square represents only 11.3 m^3/s (400 cfs) and not 56.7 m^3/s (2,000 cfs) as on the other graphs for this basin. In light of this, the hydrograph agreement is good, and the aerial estimates of SCA agree well with those by the SSARR. The NOAA estimates of SCA are too high in the early part of the season, but are acceptable after April 20. Note that cloud cover obscured the basin from April 20 to May 31. In 1978 (Figure 27), snow cover was average. NOAA, SSARR, and aerial flight estimates of SCA all agree well. The fit between the observed and computed hydrographs is good.

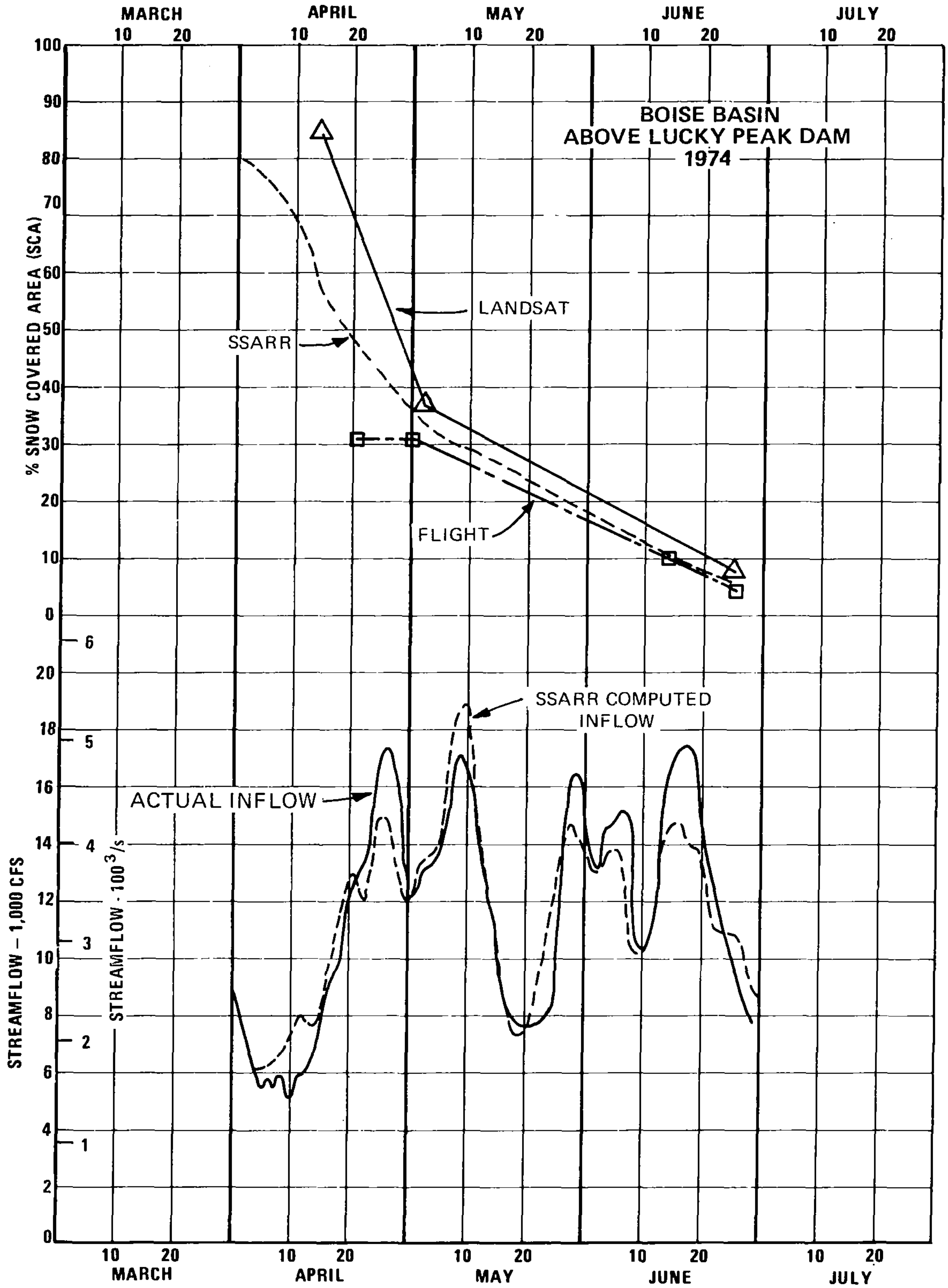
Results in the Boise Basin have been excellent. Cloud cover has been a problem in some years. The agreement between satellite and ground truth estimates of the SCA has been acceptably close.

TABLE 3
BOISE RIVER BASIN ABOVE LUCKY PEAK DAM

Date	Percent of Basin Snow Covered: Aerial Flight	SSARR	NOAA	Landsat
19 Apr 73		54		66
7 May 73		32		31
12 Jun 73		6		8
30 Jun 73		2		4
14 Apr 74		57		74
20 Apr 74	30	47		
29 Apr 74	30	36		
2 May 74		34		36
14 Jun 74	10	9		
25 Jun 74	4	6		7
5 Mar 75			88	
6 Mar 75			90	
14 Mar 75				98
28 Mar 75			88	
29 Mar 75			88	
2 Apr 75			90	
12 Apr 75			88	
2 May 75	67	67		
8 May 75		58	85	
10 May 75		50	68	
14 May 75		40	60	
15 May 75	50	39		65
25 May 75		25	42	
3 Jun 75	22	16		
10 Jun 75		10	21	
11 Jun 75		9		36
14 Jun 75		8	18	
16 Jun 75		7	16	
22 Jun 75		5	15	
29 Jun 75		4		16
9 Jul 75	3			
4 Mar 76			100	
6 Mar 76			100	
10 Mar 76			93	
12 Mar 76			88	
21 Mar 76			89	
3 Apr 76				85
4 Apr 76			85	
14 Apr 76			63	
19 Apr 76	33			
23 Apr 76			66	
29 Apr 76		31	40	

TABLE 3
(continued)

Date	Aerial Flight	SSARR	NOAA	Landsat
	Percent of Basin Snow Covered			
1 May 76		29	33	
9 May 76		21	32	
12 May 76	20	18		
13 May 76		17	29	
15 May 76		15	29	
17 May 76		13	28	
18 May 76		13		25
21 May 76		11	20	
26 May 76		8	19	
27 May 76		8		21
5 Jun 76		5	16	
18 Jun 76		3	14	
26 Jun 76		3	14	
5 Mar 77			88	
22 Mar 77			59	
25 Mar 77			40	
4 Apr 77		15	43	
5 Apr 77	25	15		
7 Apr 77		15	39	
12 Apr 77		14	24	
15 Apr 77		14	21	
20 Apr 77		13	15	
29 Apr 77	2	10		
31 May 77		5	10	
5 Jun 77		3	8	
28 Feb 78			88	
6 Mar 78			82	
10 Mar 78			89	
15 Mar 78		80	78	
18 Mar 78		77	78	
26 Mar 78		69	75	
29 Mar 78		60	68	
9 Apr 78		51	57	
12 Apr 78		48	53	
23 Apr 78		40	39	
3 May 78		36	31	
8 May 78		34	33	
9 May 78	35	33		
31 May 78	27	19	23	
7 Jun 78		13	21	
17 Jun 78		9	19	
27 Jun 78	5	6	13	
9 Jul 78		3	11	



MARCH
APRIL
MAY
JUNE
JULY
10
20
BOISE BASIN
ABOVE LUCKY PEAK DAM
1974
% SNOW COVERED AREA (SCA)
LANDSAT
SSARR
FLIGHT
SSARR COMPUTED
INFLOW
ACTUAL INFLOW
STREAMFLOW – 1,000 CFS
STREAMFLOW · 100^3/s

Figure 23

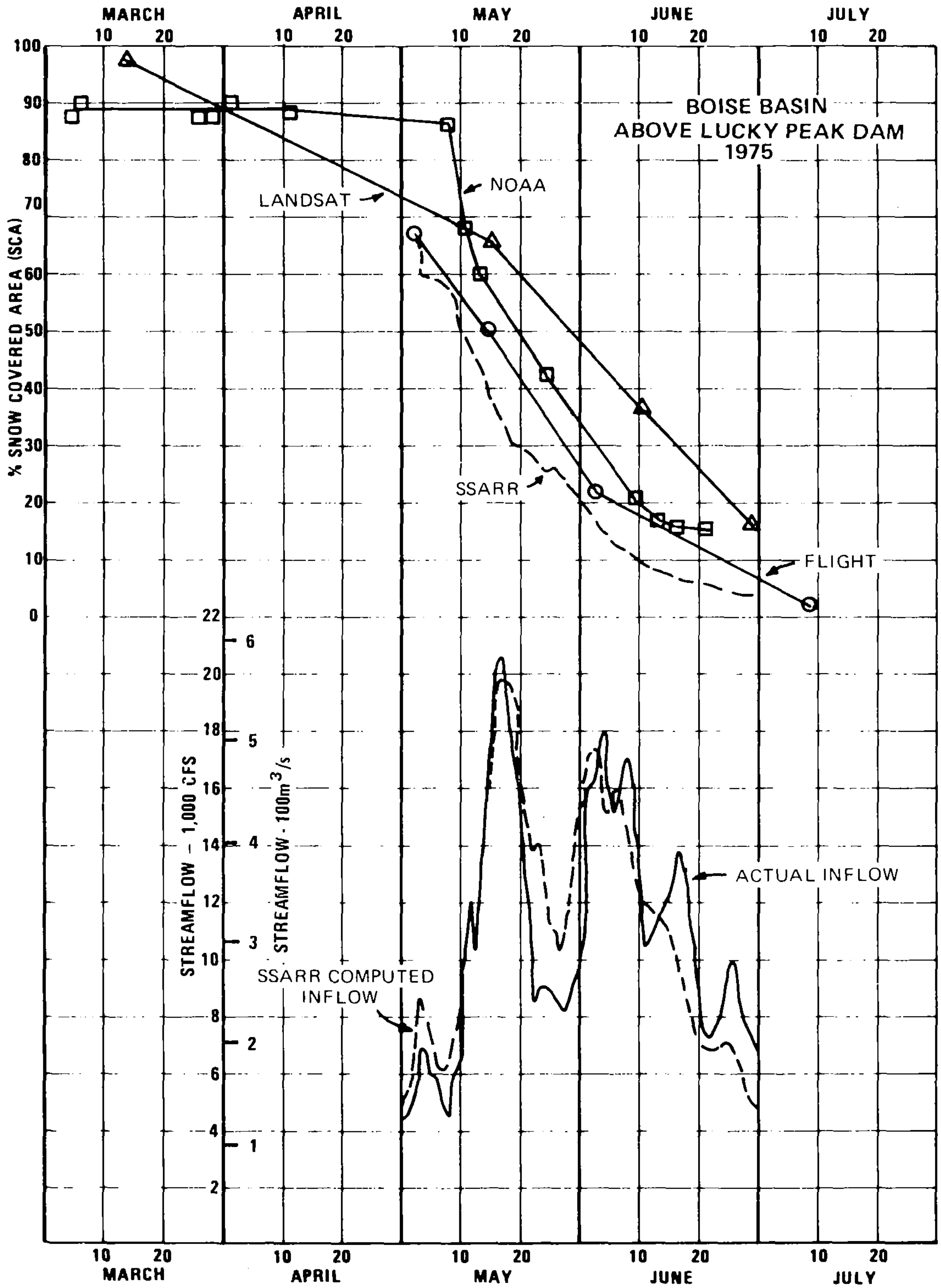

MARCH
APRIL
MAY
JUNE
JULY
10
20
100
90
80
70
60
50
40
30
20
10
0
% SNOW COVERED AREA (SCA)
BOISE BASIN
ABOVE LUCKY PEAK DAM
1975
LANDSAT
NOAA
SSARR
FLIGHT
22
20
18
16
14
12
10
8
6
4
2
6
5
4
3
2
1
STREAMFLOW – 1,000 CFS
STREAMFLOW · 100m^3/s
ACTUAL INFLOW
SSARR COMPUTED
INFLOW

Figure 24

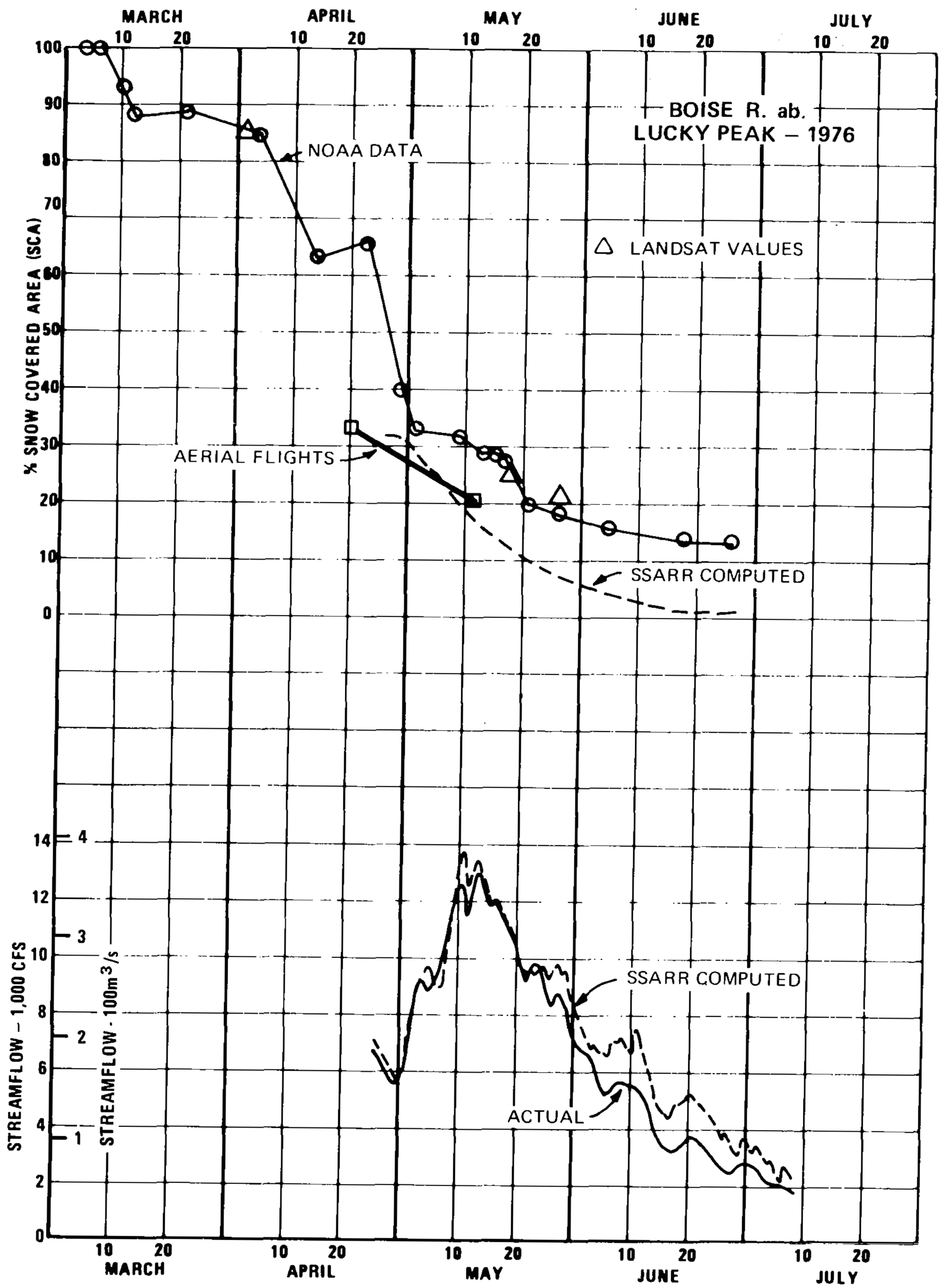
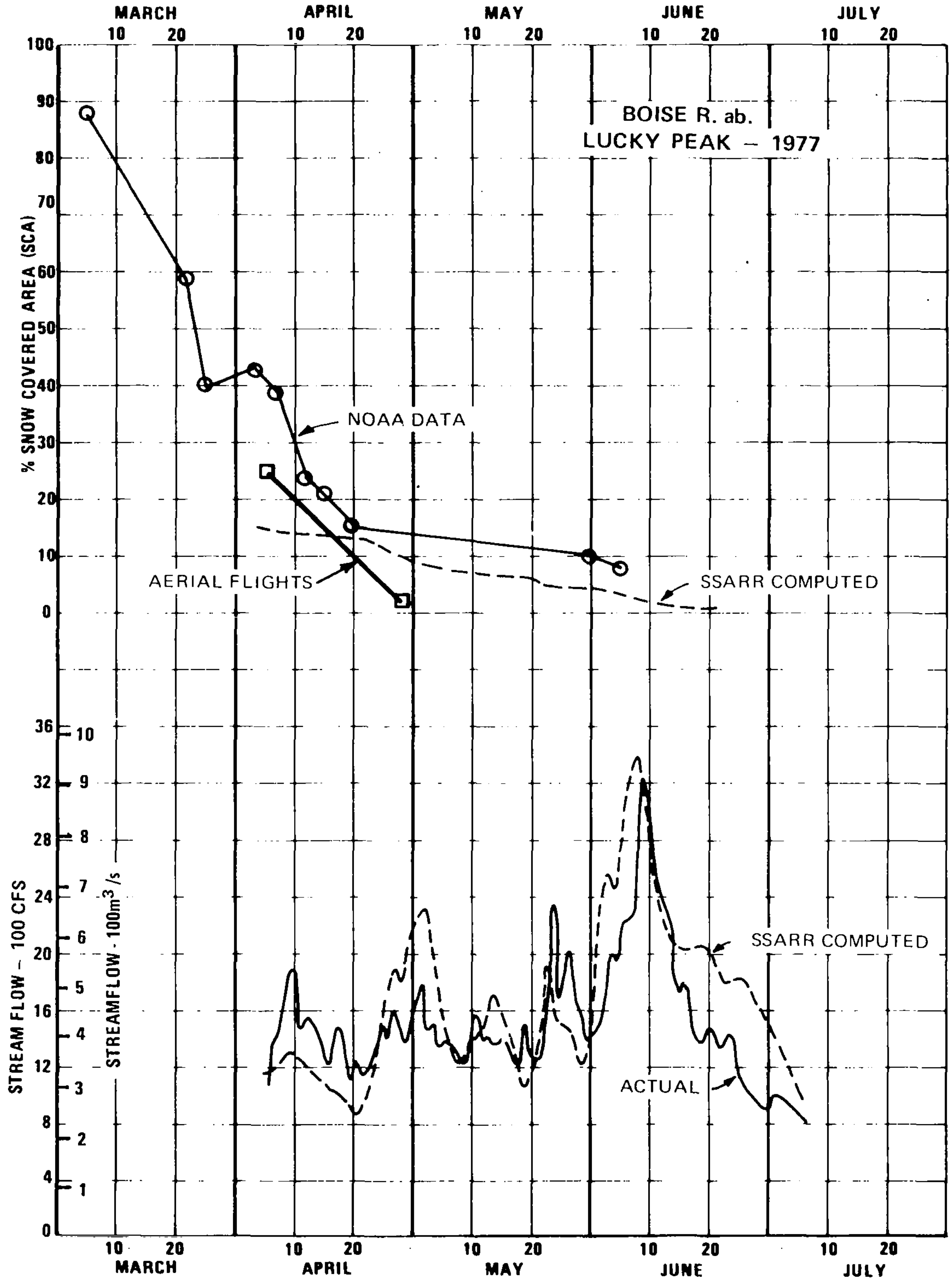
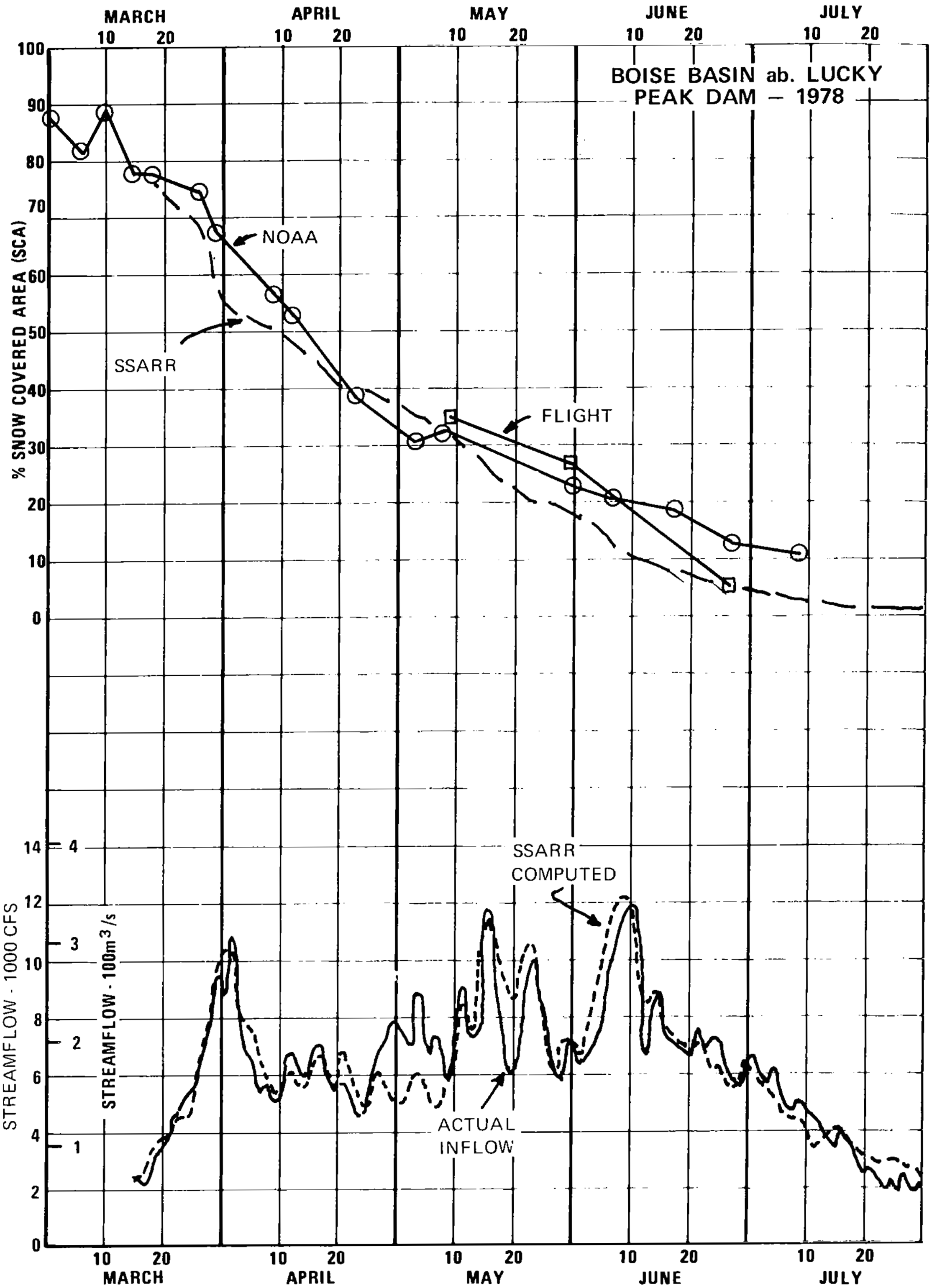

MARCH
APRIL
MAY
JUNE
JULY
BOISE R. ab.
LUCKY PEAK – 1976
NOAA DATA
LANDSAT VALUES
AERIAL FLIGHTS
SSARR COMPUTED
% SNOW COVERED AREA (SCA)
SSARR COMPUTED
ACTUAL
STREAMFLOW – 1,000 CFS
STREAMFLOW · 100m^3/s

Figure 25



MARCH
APRIL
MAY
JUNE
JULY
BOISE R. ab.
LUCKY PEAK – 1977
% SNOW COVERED AREA (SCA)
NOAA DATA
AERIAL FLIGHTS
SSARR COMPUTED
STREAM FLOW – 100 CFS
STREAMFLOW · 100m³/s
SSARR COMPUTED
ACTUAL

Figure 26



MARCH
APRIL
MAY
JUNE
JULY
10
20
BOISE BASIN ab. LUCKY PEAK DAM – 1978
% SNOW COVERED AREA (SCA)
NOAA
SSARR
FLIGHT
SSARR COMPUTED
ACTUAL INFLOW
STREAMFLOW - 1000 CFS
STREAMFLOW - 100m³/s

Figure 27

Dworshak

Snow-covered area data for the Dworshak Basin are given on Table 4. These data are shown on Figures 10 and 28 through 31 (page 25, and pages 47 through 50). In 1975 (Figure 28), the snowpack was high. The agreement between the NOAA and the flight estimates of SCA is generally good, although the satellite estimate, as usual, measures more snow than the aerial flight.

The snowpack in 1976 (Figure 29), was average. The hydrograph agreement was good, and the SSARR and flight estimates of SCA agreed well. The estimates of SCA using NOAA data were higher than those using SSARR, but were generally acceptable. The integration of patchy snow by NOAA overestimated throughout the season, with the difference decreasing as the melt season progressed.

The snowpack in 1977 (Figure 30) was extremely low. The observed and computed hydrographs match relatively well. Aerial flights were made in 1977, not to access flood potential, but to appraise the ability to refill reservoirs. Since discontinuous snow was not included, the spreads between the flight and SSARR estimates of SCA were wide. Because the NOAA data integrated the patchy snow, it well overestimated the SCA--particularly in the early part of the season.

In 1978 (Figure 31) the snowpack was average. The fit of the two hydrographs was acceptable thereby giving credence to the SSARR generated estimate of SCA. The fit between the estimates of SCA by SSARR, flight, and NOAA is exceptionally good.

Estimates of SCA from satellite data for the Dworshak Basin have been good and, like those for the Upper Snake and the Boise Basins, are usable.

TABLE 4
NORTH FORK CLEARWATER BASIN ABOVE DWORSHAK DAM

	Percent of Basin Snow Covered			
Date	Aerial Flight	SSARR	NOAA	Landsat
6 Mar 75			100	
10 Apr 75			96	
12 Apr 75			89	
3 May 75	87			
10 May 75			76	N
13 May 75			67	O
14 May 75			73	T
15 May 75	60			
1 Jun 75			54	
10 Jun 75			44	U
29 Jun 75			34	S
2 Jul 75			10	E
5 Jul 75			9	D
8 Jul 75			7	

TABLE 4
(continued)

Date	Percent of Basin Snow Covered			
	Aerial Flight	SSARR	NOAA	Landsat
9 Jul 75	0			
11 Jul 75			1	
4 Mar 76			100	
8 Mar 76			98	
12 Mar 76			97	
4 Apr 76			86	71
8 Apr 76			82	
19 Apr 76	70			
29 Apr 76		65	75	
9 May 76		51	64	
12 May 76	40	45	62	
15 May 76		41	58	
19 May 76		37	49	49
21 May 76		34	44	
5 Jun 76		22	30	
18 Jun 76		15	19	
26 Jun 76		12	13	
2 Jul 76		9	13	
11 Mar 77			80	
22 Mar 77			94	
4 Apr 77		42	79	
5 Apr 77	30	42		
7 Apr 77		40	75	
12 Apr 77		37	65	
23 Apr 77		34	46	
27 Apr 77		30	44	
29 Apr 77	10	29		
5 Jun 77		10	8	
10 Mar 78			85	
15 Mar 78		80	92	
18 Mar 78		78	83	
29 Mar 78		72	67	
9 Apr 78		64	58	
11 Apr 78	55	63		
9 May 78	50	46		
31 May 78	19	30		
1 Jun 78		29	34	
7 Jun 78		22	23	
20 Jun 78		14	12	
27 Jun 78		12	9	
1 Jul 78		10	6	
9 Jul 78			1	

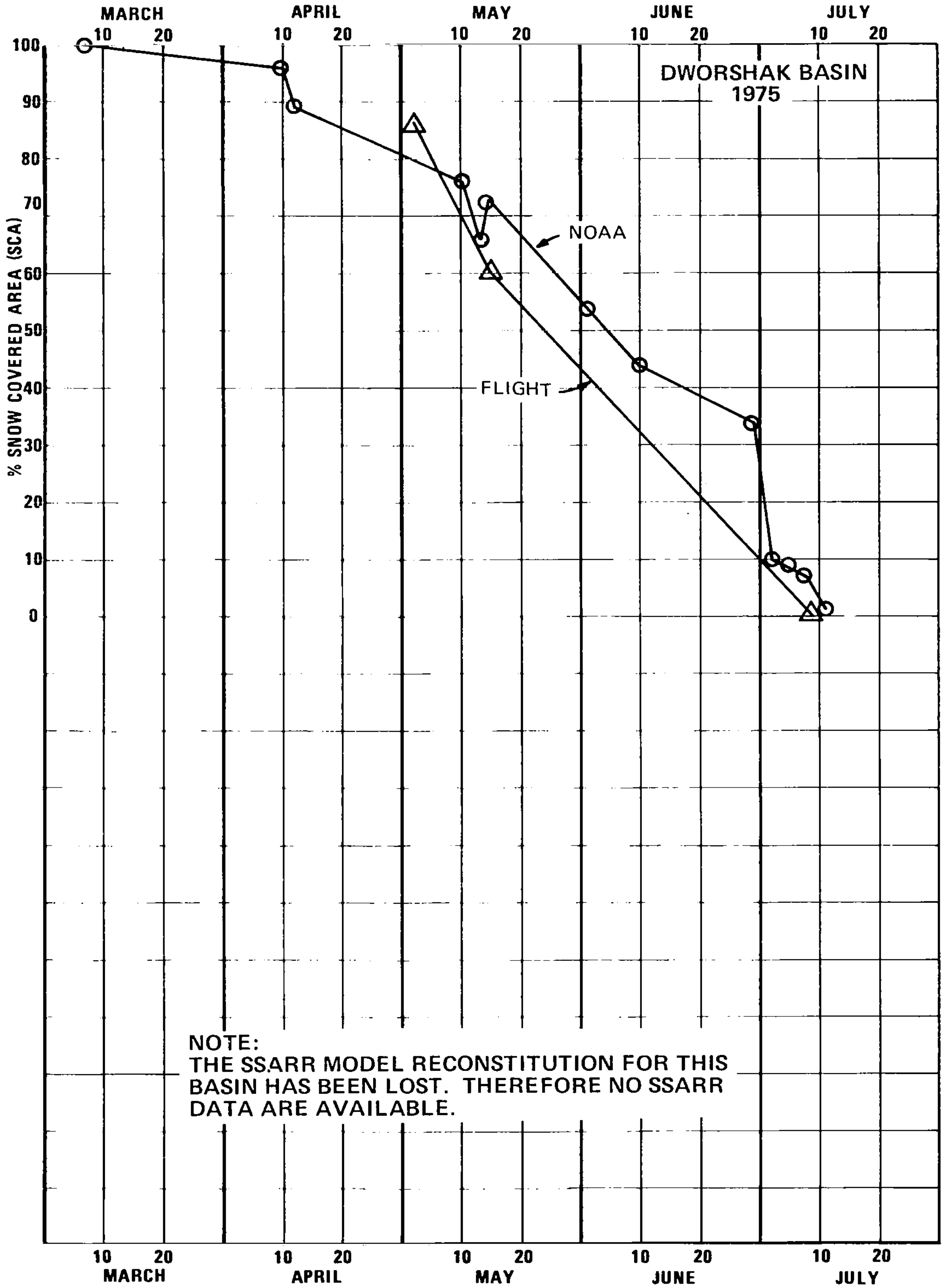
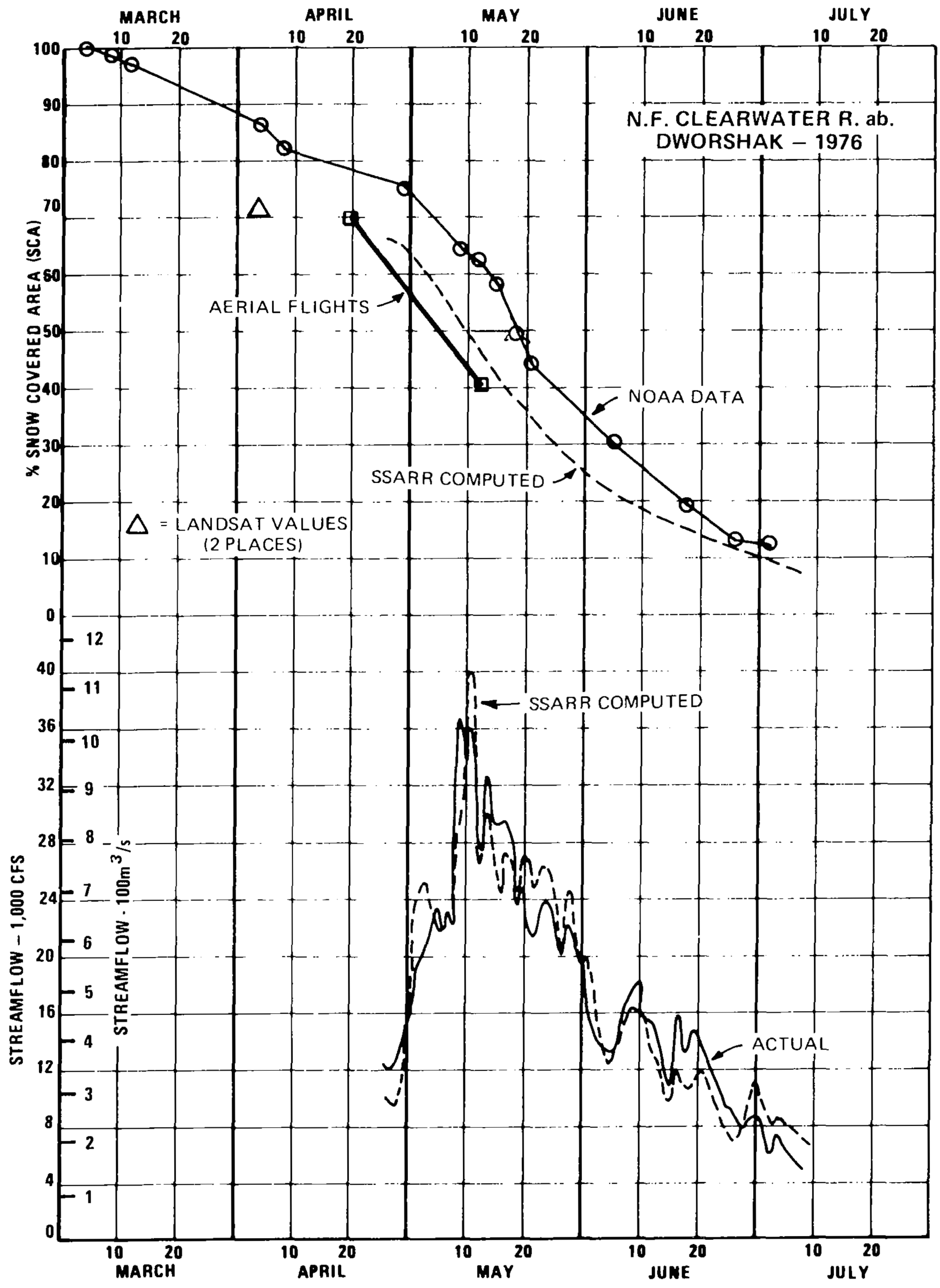

MARCH
APRIL
MAY
JUNE
JULY
10
20
100
90
80
70
60
50
40
30
20
10
0
% SNOW COVERED AREA (SCA)
DWORSHAK BASIN
1975
NOAA
FLIGHT
NOTE:
THE SSARR MODEL RECONSTITUTION FOR THIS BASIN HAS BEEN LOST. THEREFORE NO SSARR DATA ARE AVAILABLE.

Figure 28



MARCH
APRIL
MAY
JUNE
JULY
N.F. CLEARWATER R. ab. DWORSHAK – 1976
% SNOW COVERED AREA (SCA)
AERIAL FLIGHTS
NOAA DATA
SSARR COMPUTED
△ = LANDSAT VALUES (2 PLACES)
SSARR COMPUTED
ACTUAL
STREAMFLOW – 1,000 CFS
STREAMFLOW · 100m^3/s

Figure 29

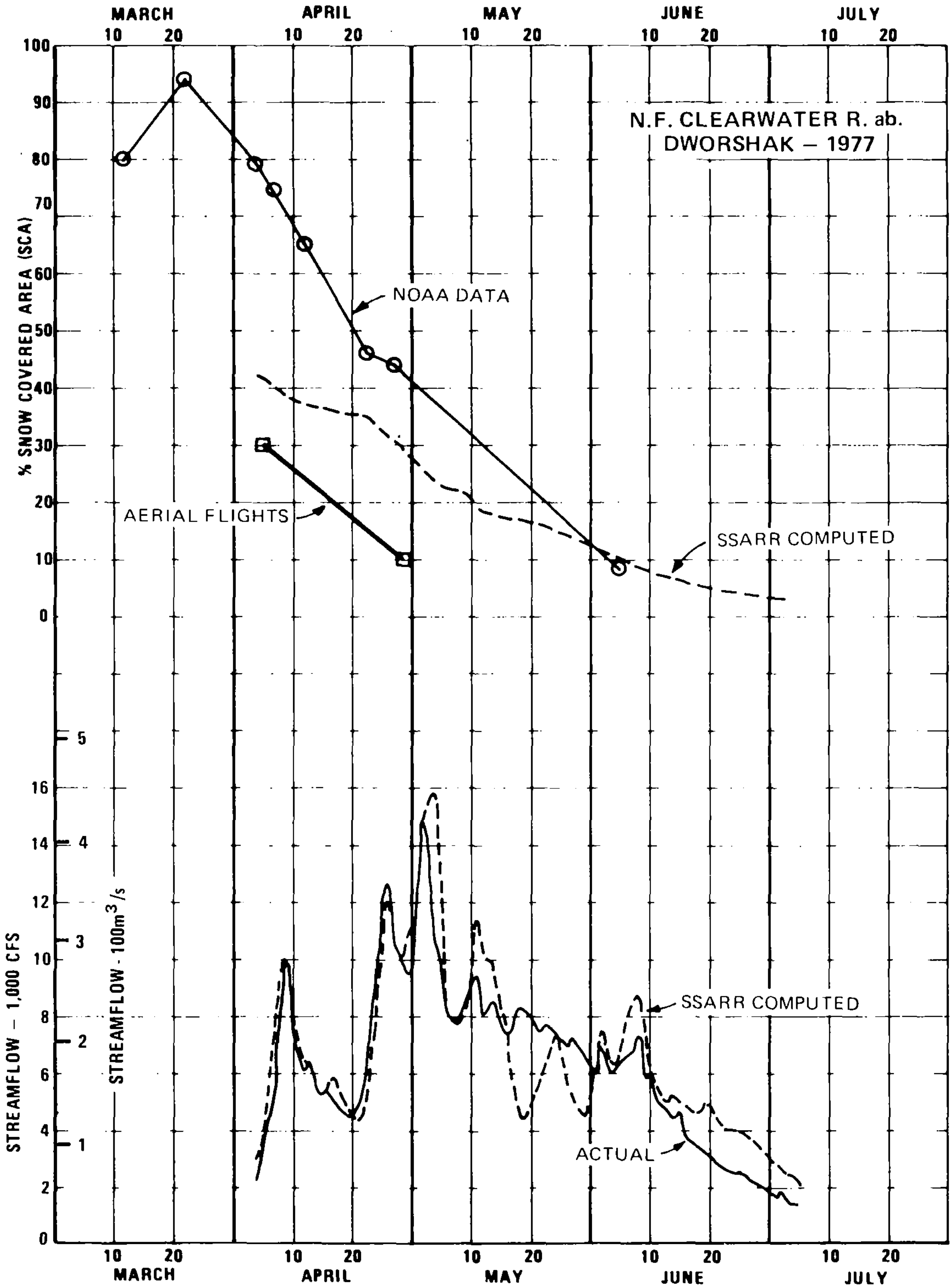

MARCH
APRIL
MAY
JUNE
JULY
N.F. CLEARWATER R. ab.
DWORSHAK – 1977
% SNOW COVERED AREA (SCA)
NOAA DATA
AERIAL FLIGHTS
SSARR COMPUTED
STREAMFLOW – 1,000 CFS
STREAMFLOW · 100m³/s
SSARR COMPUTED
ACTUAL

Figure 30

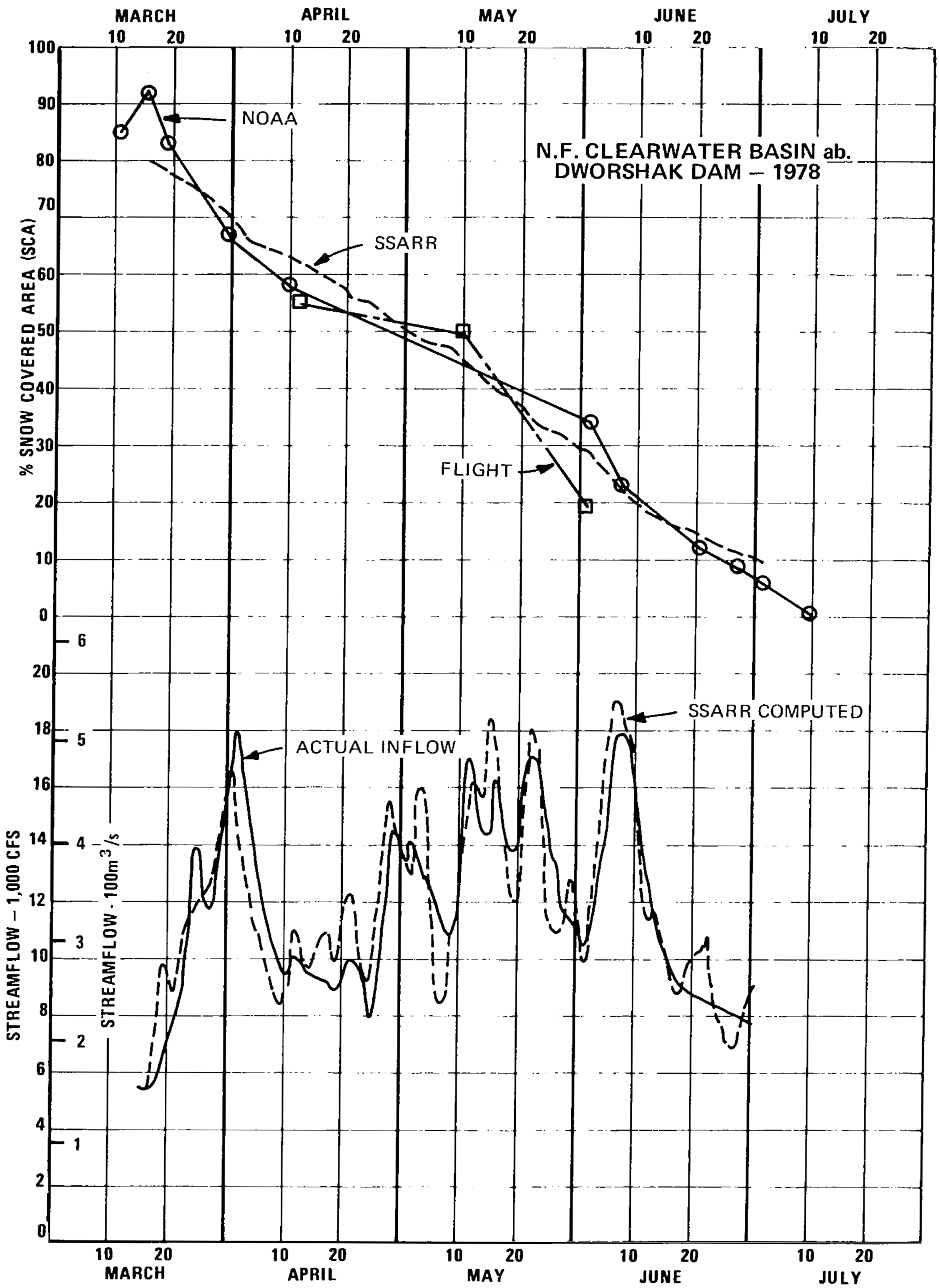

MARCH
APRIL
MAY
JUNE
JULY
NOAA
N.F. CLEARWATER BASIN ab.
DWORSHAK DAM – 1978
SSARR
FLIGHT
% SNOW COVERED AREA (SCA)
SSARR COMPUTED
ACTUAL INFLOW
STREAMFLOW – 1,000 CFS
STREAMFLOW · 100m³/s

Figure 31

Libby

Snow-covered area data for the Libby Basin are given on Table 5. Data for the basin are displayed graphically on Figures 11 and 32 through 35 (page 26, and pages 53 through 56). In the Upper Snake, Boise, and Dworshak Basins, the integration of patchy snow into the snowline causes the estimates of SCA from satellite data to exceed aerial flight data, particularly so at the start of the melt season. In the Libby Basin, the tree canopy is sufficiently dense such that the satellite estimates of SCA typically are lower than those of the aerial flights, particularly so at the start of the melt season.

In 1975 (Figure 32), snowpack was high. The agreement between the observed and computed hydrographs is acceptable as is the agreement between the SSARR and flight estimates of SCA. The satellite estimate of SCA, even though incorporating patchy snow, is below the flight data.

Snowpack in 1976 (Figure 33) was average. The two hydrographs fit well. The agreement between the SSARR and aerial flight estimates of SCA is poor. The NOAA satellite estimates are again low, accurately approaching probable values only after June 10.

The 1977 (Figure 34) snowpack was a record low, and no aerial flights were made that year. Although the hydrographs fit well, and the satellite data had much patchy snow integrated into the snowline that year, the SCA estimate from satellite data was low because of tree cover until after May 20.

The 1978 (Figure 35) snowpack was average. The hydrographs agreed nicely, as did flight to SSARR estimates of SCA. The NOAA data again were too low until about June 1 because of the tree canopy.

Results in the Libby Basin have been discouraging both because of long periods of cloud cover obscuring the ground, and because of the dense forest cover hiding the snowline. It appears that satellite data cannot accurately be used to estimate SCA in the Libby Basin until the basin's SCA has fallen to under 50, or even 40 percent. Because of this known fact, NOAA/NESS in recent years has not even started to measure the Libby Basin until SCA has diminished to about 50 percent.

TABLE 5
KOOTENAI RIVER BASIN ABOVE LIBBY DAM

Date	Percent of Basin Snow Covered					
	Aerial Flight			SSARR	NOAA	Landsat
	U.S.	Canada	Total			
6 Mar 75					100	
10 Apr 75					100	
10 May 75				83	80	N
13 May 75				79	62	O
14 May 75				77	61	T
15 May 75	73			73		
22 May 75		75		66		
30 May 75	61			59		U
1 Jun 75				57	53	S
11 Jun 75	41			38		E
2 Jul 75		36		16		D
5 Jul 75				9	7	
8 Jul 75				7	7	
29 Apr 76				86	58	
1 May 76				83	57	
9 May 76				68	45	
26 May 76			60	45		
18 Jun 76				24	23	
15 Jul 76				12	12	
12 Apr 77				78	49	
25 Apr 77				72	39	
30 May 77				37	41	
5 Jun 77				31	30	
17 Jun 77				15	16	
8 May 78				64	48	
16 May 78			59	59		
19 May 78				56	41	
31 May 78			48	48		
1 Jun 78				47	43	
7 Jun 78				37	34	
14 Jun 78			32	30		
20 Jun 78				25	32	
28 Jun 78				18	26	
14 Jul 78				7	16	
25 Jul 78				4	6	

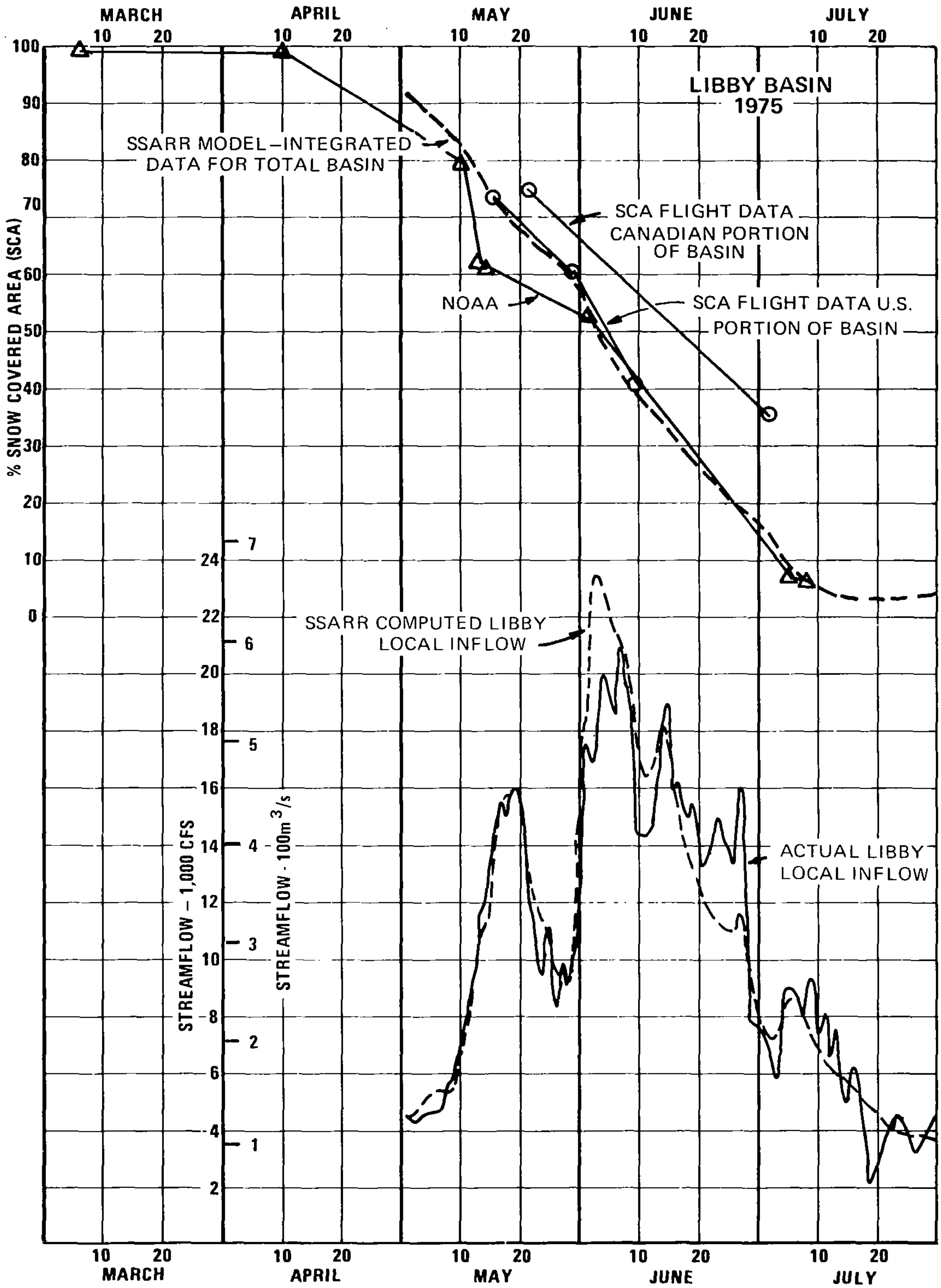

MARCH
APRIL
MAY
JUNE
JULY
10
20
100
90
80
70
60
50
40
30
20
10
0
% SNOW COVERED AREA (SCA)
LIBBY BASIN
1975
SSARR MODEL–INTEGRATED
DATA FOR TOTAL BASIN
SCA FLIGHT DATA
CANADIAN PORTION
OF BASIN
NOAA
SCA FLIGHT DATA U.S.
PORTION OF BASIN
SSARR COMPUTED LIBBY
LOCAL INFLOW
ACTUAL LIBBY
LOCAL INFLOW
STREAMFLOW – 1,000 CFS
STREAMFLOW · 100m3/s
24
22
20
18
16
14
12
10
8
6
4
2
7
6
5
4
3
2
1

Figure 32

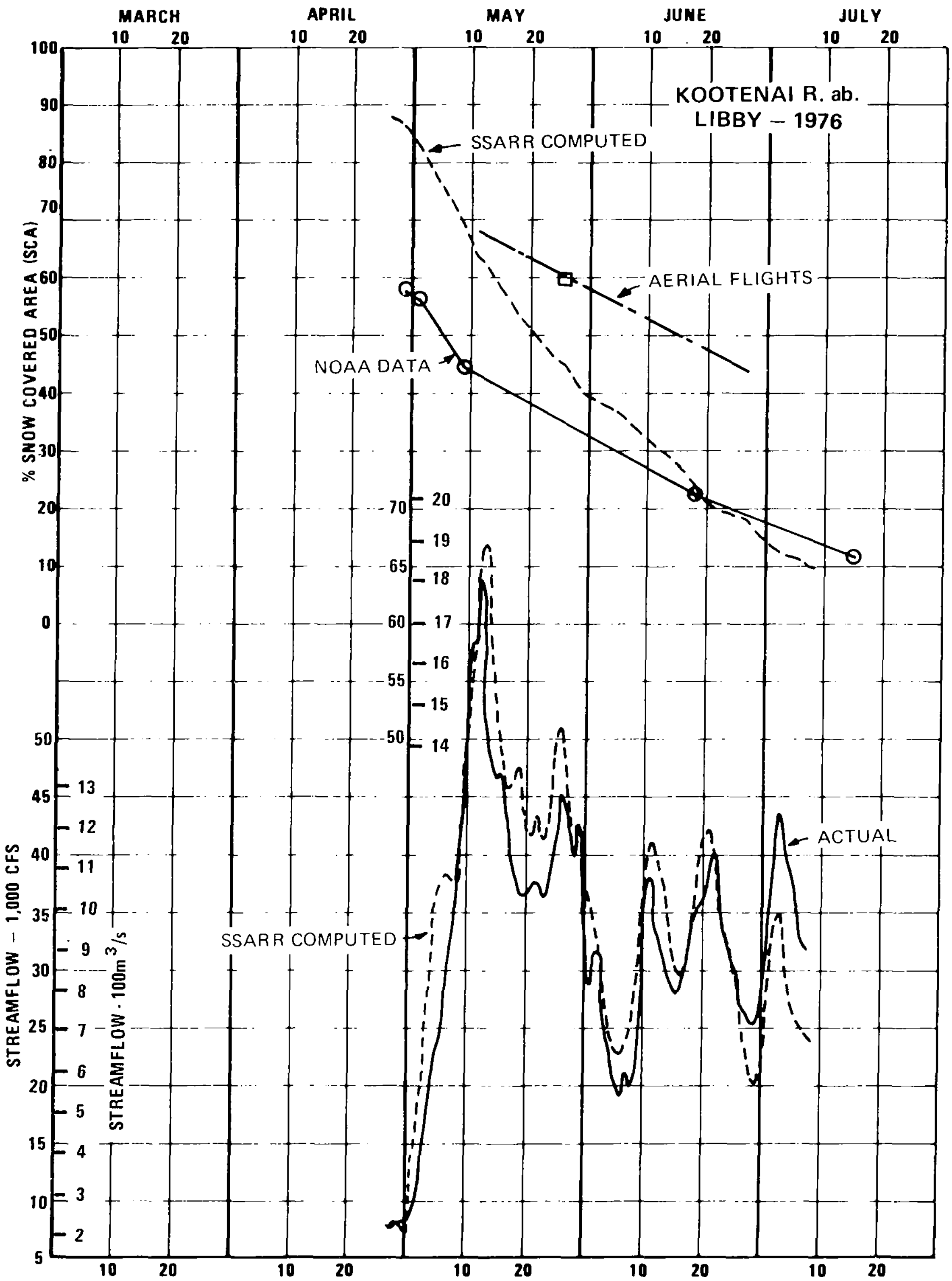

KOOTENAI R. ab. LIBBY – 1976
MARCH
APRIL
MAY
JUNE
JULY
SSARR COMPUTED
AERIAL FLIGHTS
NOAA DATA
ACTUAL
% SNOW COVERED AREA (SCA)
STREAMFLOW - 1,000 CFS
STREAMFLOW · 100m³/s

Figure 33

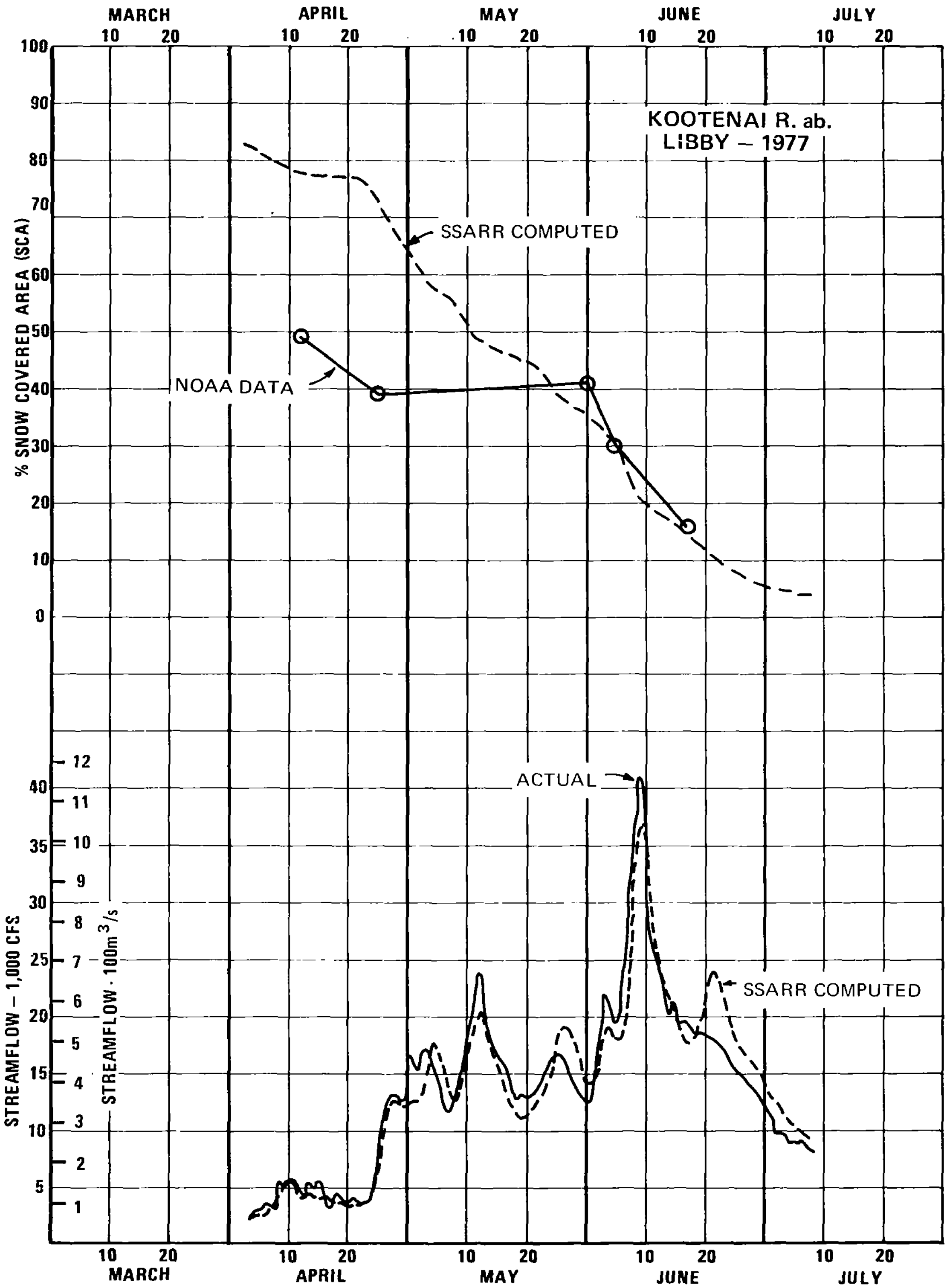
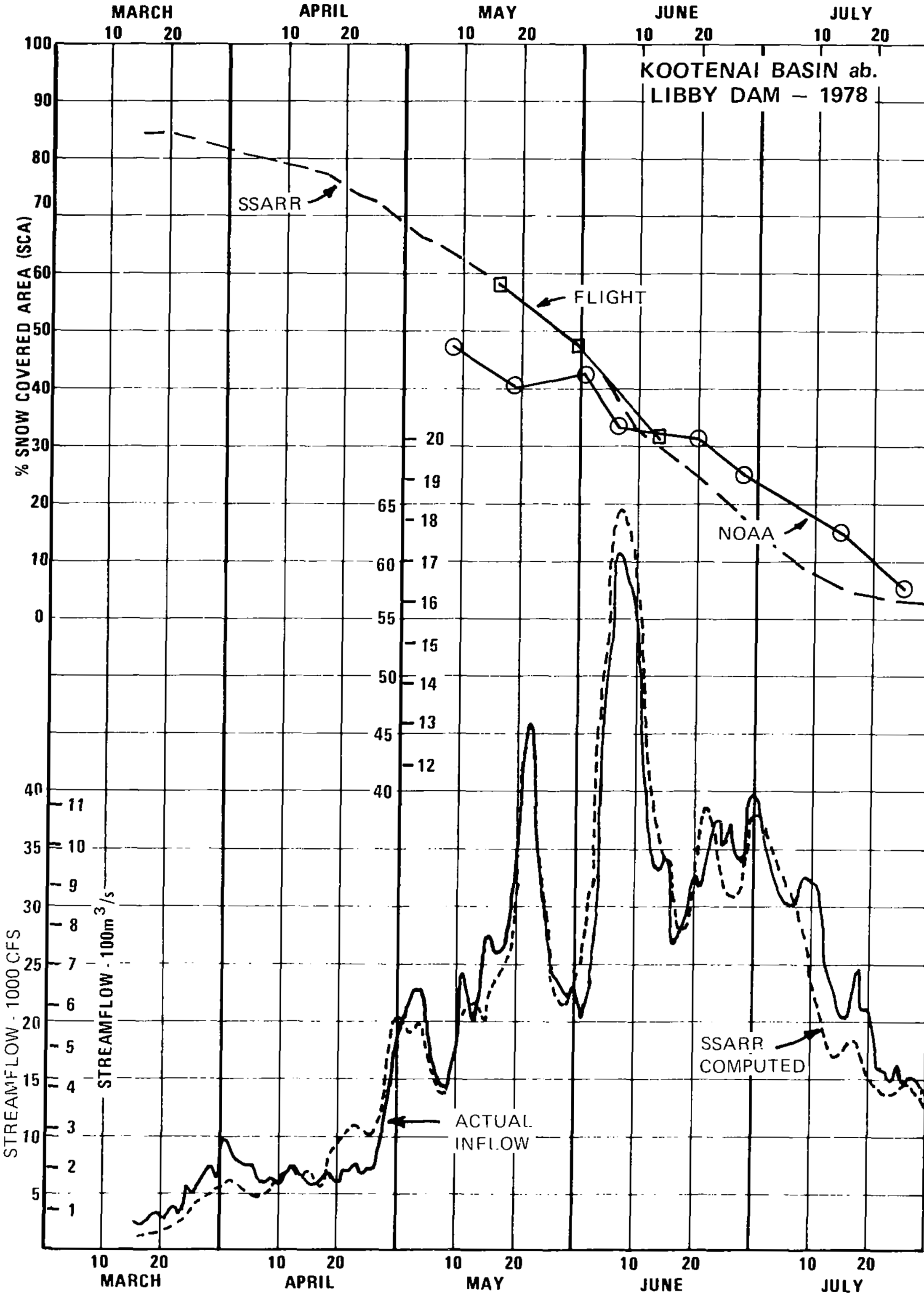

KOOTENAI R. ab. LIBBY – 1977
MARCH
APRIL
MAY
JUNE
JULY
% SNOW COVERED AREA (SCA)
SSARR COMPUTED
NOAA DATA
ACTUAL
SSARR COMPUTED
STREAMFLOW – 1,000 CFS
STREAMFLOW · 100m³/s

Figure 34



KOOTENAI BASIN ab.
LIBBY DAM – 1978
MARCH
APRIL
MAY
JUNE
JULY
% SNOW COVERED AREA (SCA)
SSARR
FLIGHT
NOAA
SSARR
COMPUTED
ACTUAL
INFLOW
STREAMFLOW - 1000 CFS
STREAMFLOW - 100m³/s

Figure 35

Hungry Horse

Snow-covered area data for the Hungry Horse Basin are given on Table 6. These data are shown graphically on Figures 12 and 36 through 39 (page 26, and pages 60 through 63). The Hungry Horse Basin, like the Libby, has a dense forest canopy that hides the snowcover on the ground. Satellite estimates of SCA in the Hungry Horse Basin are typically lower than aerial flight estimates. They also are less than SSARR estimates until the SCA diminishes to about 80 percent. When the SCA further depletes to about 50 percent, the satellite estimates of SCA cross over the SSARR estimates and remain above the SSARR estimates for the balance of the season.

In 1975 (Figure 36), a high snowcover year, the agreement between the observed and computed hydrographs is generally acceptable. Agreement between the flight and SSARR estimates of SCA is acceptable. The NOAA data estimates of SCA appear to be too low early in the season. This well could be caused by the forest canopy. Later in the season the satellite estimated SCA values appear to be a little too high. This could be caused by inclusion of patchy snow, inclusion of bare rock as snow, the SSARR estimate being too low, or some combination of these factors.

The 1976 (Figure 37) snowpack in the Hungry Horse Basin was average. The agreement between the two hydrographs is good, and the fit between the three estimates of SCA is quite good. Note that again the satellite estimated SCA is less than the SSARR in the early season and greater than the SSARR in the later season.

Hungry Horse snowpack in 1977 (Figure 38) was extremely low. The fit between the computed and observed hydrograph was quite good. No aerial flights were made in the Hungry Horse Basin in 1977. The fit between the SCA estimates made from SSARR and from satellite data is very good. Note that again the estimates cross in midmelt season.

The 1978 (Figure 39) snowpack in the Hungry Horse Basin was about average. The fit between the computed and observed hydrograph is acceptable in shape, but less than desirable for matching peaks. The satellite estimates of SCA generally agree with the flight data, but should be above the flight values because of the integration of patchy discontinuous snow into the SCA. The SSARR estimates of SCA generally agree with the flight data, but are known to be in error at several points because of the hydrograph match.

Satellite derived SCA estimates in the Hungry Horse Basin have generally been acceptable. In the early portion of the season, well before peak flows occur, the forest canopy hides a portion of the snow-covered ground, causing underestimation of the SCA. Toward the end of the melt season, care must be exercised in interpreting satellite imagery for SCA, not to include bare rock in the SCA estimates.

TABLE 6
SOUTH FORK FLATHEAD RIVER BASIN ABOVE HUNGRY HORSE DAM

Date	Percent of Basin Snow Covered			
	Aerial Flight	SSARR	NOAA	Landsat
6 Mar 75			93	
12 Apr 75			84	N
10 May 75		87	76	O
13 May 75		84	81	T
14 May 75		83	72	
15 May 75	89	82		
29 May 75	74	60		U
1 Jun 75		58	57	S
10 Jun 75	51	45		E
5 Jul 75			33	D
11 Jul 75			20	
7 Mar 76				95
3 Apr 76				87
7 Apr 76			74	
12 Apr 76				74
29 Apr 76		81	71	70
1 May 76		78	67	
9 May 76		66	58	
12 May 76	59	60		
13 May 76		59	58	
17 May 76		54	48	
18 May 76		53		48
21 May 76		50	52	
26 May 76	53	45		
18 Jun 76		23	28	
3 Jul 76		11	19	
6 Apr 77		73	71	
8 Apr 77		71	73	
12 Apr 77		69	58	
17 Apr 77		66	59	
23 Apr 77		63	60	
25 Apr 77		58	52	
30 Apr 77		49	53	
5 Jun 77		16	20	
17 Jun 77		5	10	
3 Mar 78			82	
10 Mar 78			82	
15 Mar 78		85	85	
23 Mar 78		83	76	
29 Mar 78		79	71	
4 Apr 78		77	67	
9 Apr 78		76	65	

TABLE 6
(continued)

Date	Percent of Basin Snow Covered Aerial Flight	SSARR	NOAA	Landsat
19 Apr 78		72	63	
2 May 78	63	67		
8 May 78		64	54	
16 May 78	61	61		
20 May 78		57	46	
3 Jun 78	45	51		
4 Jun 78		50	37	
14 Jun 78	31	42		

MODEL VERIFICATION

As a test of the sensitivity of the SSARR model, the snow-covered area data for 1975 in the Hungry Horse Basin was developed from Landsat imagery and used to prepare January through July volume runoff forecasts for this basin. These forecasts along with the May 1 snow-covered area as determined from the Landsat data plot were input to the SSARR basin model. The snow-covered area (Figure 40, page 64) developed from the 1975 Landsat data for Hungry Horse was in error and was subsequently reanalyzed from NOAA data (Figure 36, page 60), but for this purpose--to test the sensitivity of the SSARR model to SCA data--the nonagreement of the Landsat SCA to the aerial flight data would definitively show if the SSARR model was sensitive to SCA.

The dashed hydrograph (Figure 40, page 64) was computed by initializing the SSARR model with a snow-covered area of 97 percent. As seen on Figure 40, the dashed hydrograph closely approximated the actual hydrograph, and the SCA values generated by the SSARR model, and shown on the upper half of the figure closely approximate the aerial flight data. The model was next run with the Landsat values of SCA. The model was initialized on May 1 with 61 percent SCA, and the SCA values were updated to 56 percent on May 14, 56 percent on June 1, and 40 percent on June 11. The hydrograph generated on Figure 40 using these Landsat values is shown dotted. As can be seen, this hydrograph never could match any of the peaks because of insufficient initial snowpack, but does definitely portray the sensitivity of the SSARR model.

SSARR DAILY OPERATIONAL FORECAST MODEL APPLICATION

It is appropriate at this point to discuss some of the operational procedures used in the SSARR model during the spring snowmelt season. At the beginning of each season, usually late March or early April, the model is initialized. Values for the model parameters such as snow-covered areas, seasonal volume, soil moisture, initial melt rate, and baseflow infiltration are estimated from all available information. The model is run daily, and model parameters are adjusted until the forecast and observed hydrographs match within a

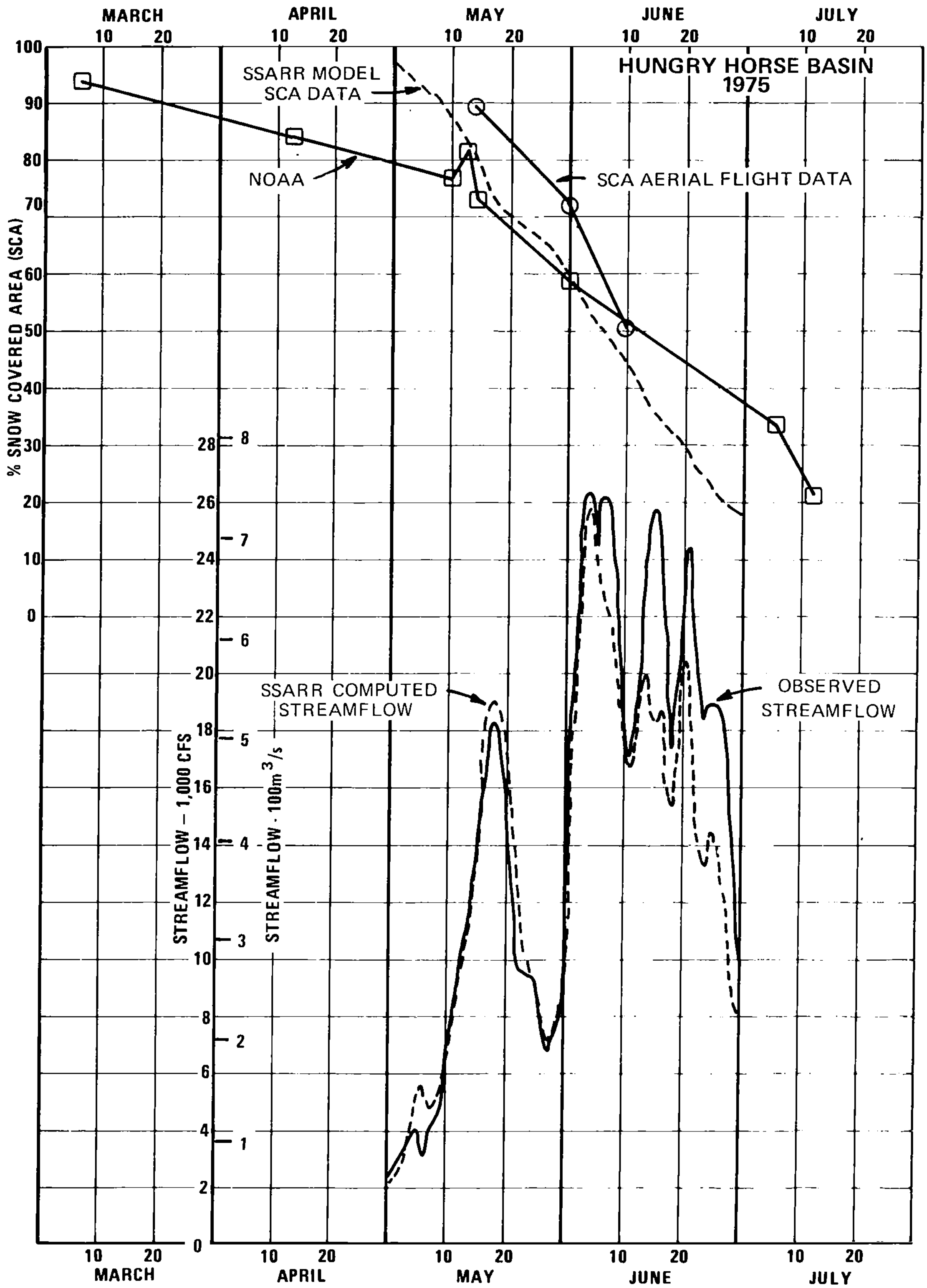

HUNGRY HORSE BASIN
1975
SSARR MODEL
SCA DATA
NOAA
SCA AERIAL FLIGHT DATA
SSARR COMPUTED
STREAMFLOW
OBSERVED
STREAMFLOW
% SNOW COVERED AREA (SCA)
STREAMFLOW – 1,000 CFS
STREAMFLOW · 100m³/s
MARCH
APRIL
MAY
JUNE
JULY

Figure 36

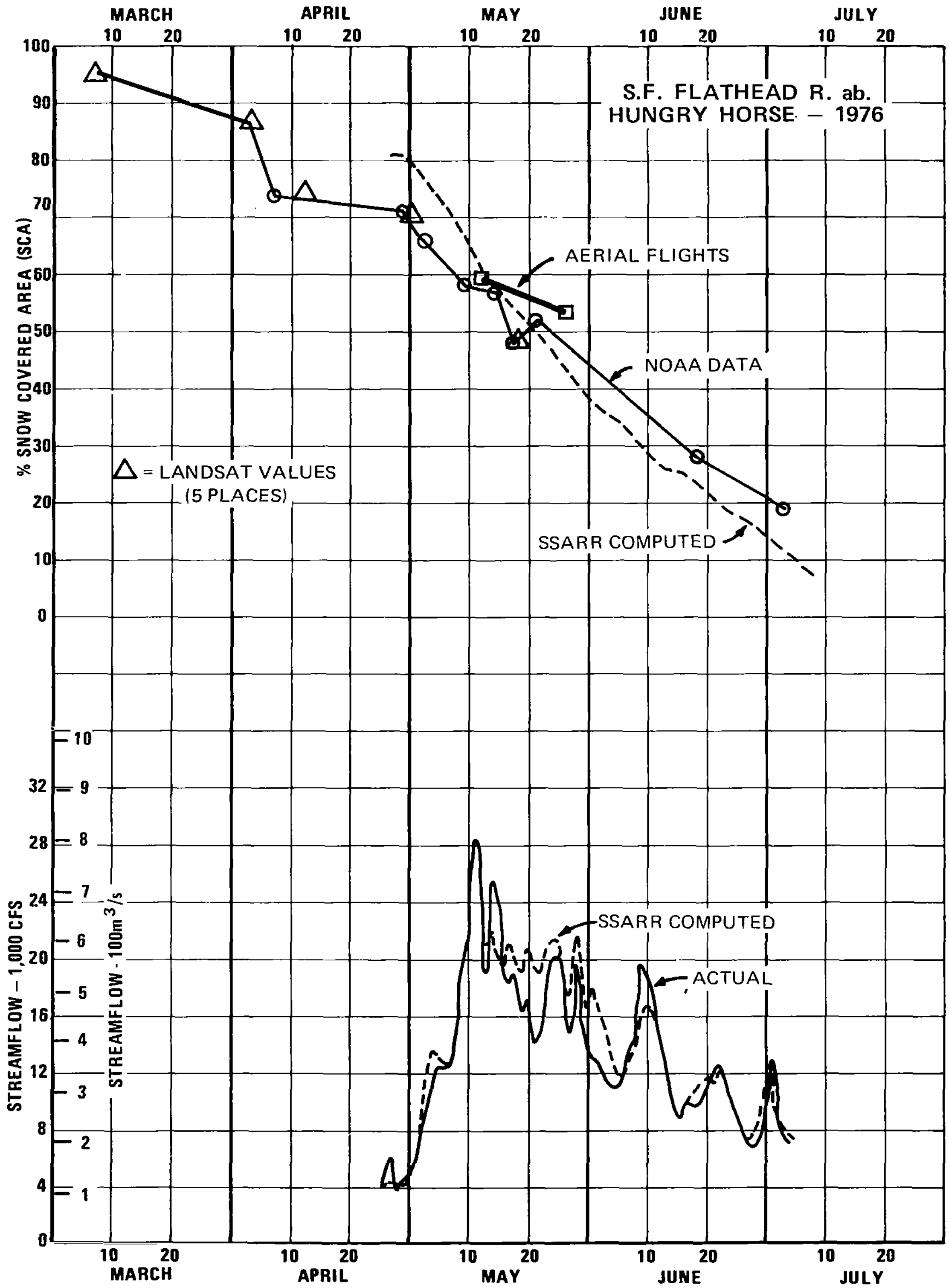

MARCH
APRIL
MAY
JUNE
JULY
S.F. FLATHEAD R. ab.
HUNGRY HORSE – 1976
% SNOW COVERED AREA (SCA)
AERIAL FLIGHTS
NOAA DATA
= LANDSAT VALUES
(5 PLACES)
SSARR COMPUTED
STREAMFLOW – 1,000 CFS
STREAMFLOW - 100m^3/s
SSARR COMPUTED
ACTUAL

Figure 37

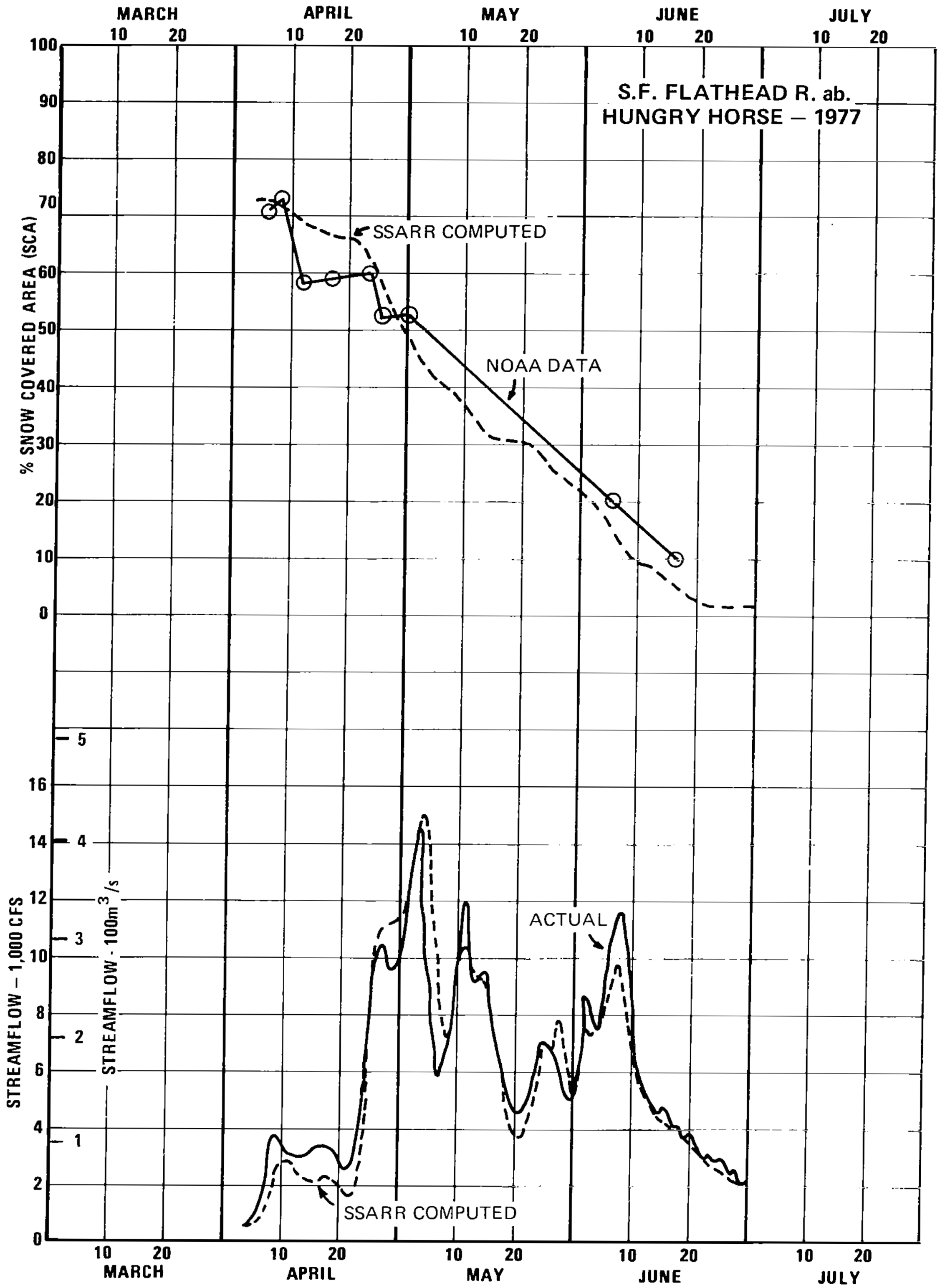
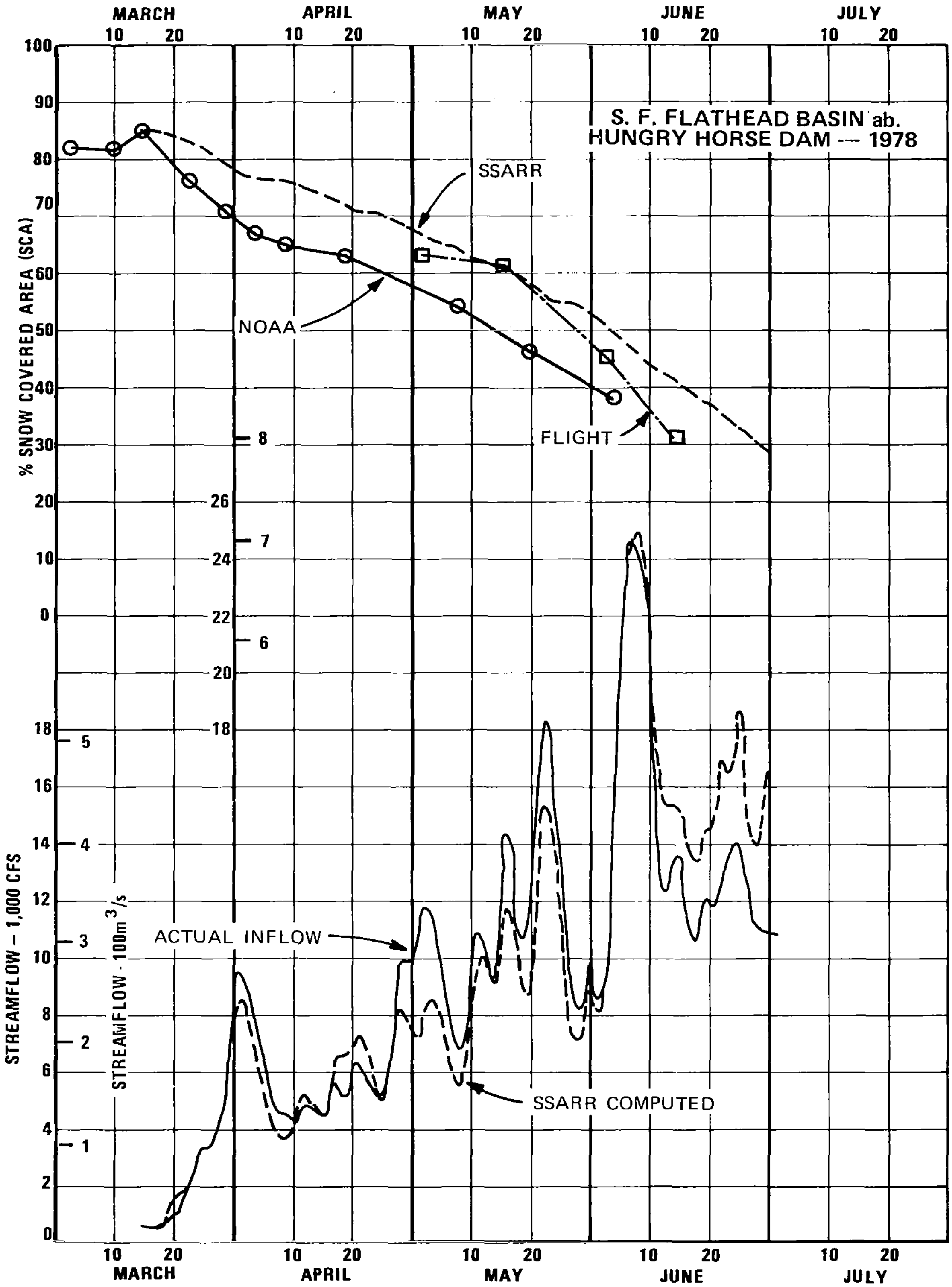
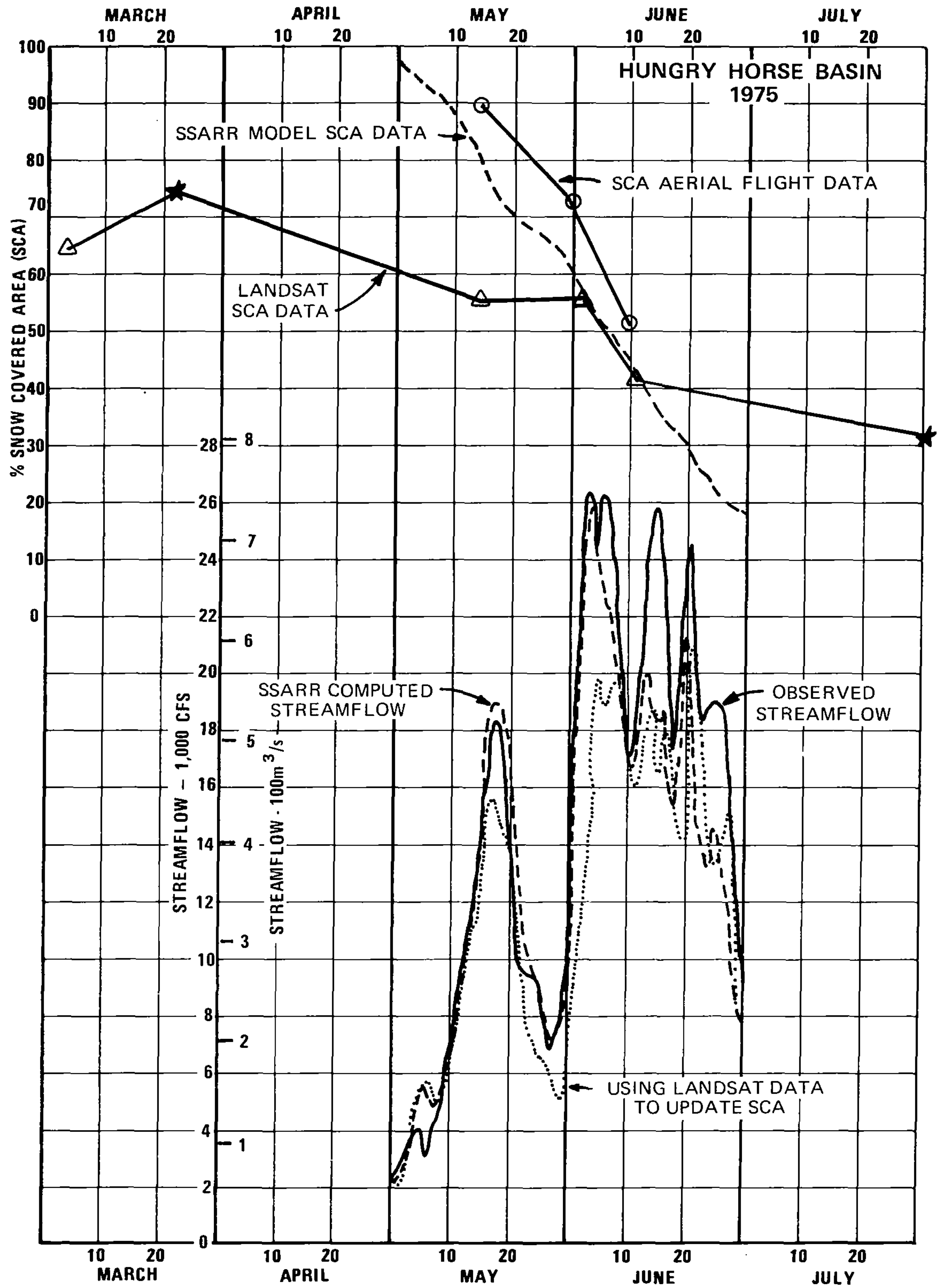

MARCH
APRIL
MAY
JUNE
JULY
10
20
S.F. FLATHEAD R. ab.
HUNGRY HORSE – 1977
% SNOW COVERED AREA (SCA)
SSARR COMPUTED
NOAA DATA
STREAMFLOW – 1,000 CFS
STREAMFLOW · 100m³/s
ACTUAL
SSARR COMPUTED

Figure 38



MARCH
APRIL
MAY
JUNE
JULY
S. F. FLATHEAD BASIN ab. HUNGRY HORSE DAM — 1978
SSARR
NOAA
FLIGHT
% SNOW COVERED AREA (SCA)
STREAMFLOW - 1,000 CFS
STREAMFLOW - 100m³/s
ACTUAL INFLOW
SSARR COMPUTED

Figure 39



MARCH
APRIL
MAY
JUNE
JULY
HUNGRY HORSE BASIN
1975
SSARR MODEL SCA DATA
SCA AERIAL FLIGHT DATA
LANDSAT
SCA DATA
% SNOW COVERED AREA (SCA)
STREAMFLOW - 1,000 CFS
STREAMFLOW · 100m³/s
SSARR COMPUTED
STREAMFLOW
OBSERVED
STREAMFLOW
USING LANDSAT DATA
TO UPDATE SCA

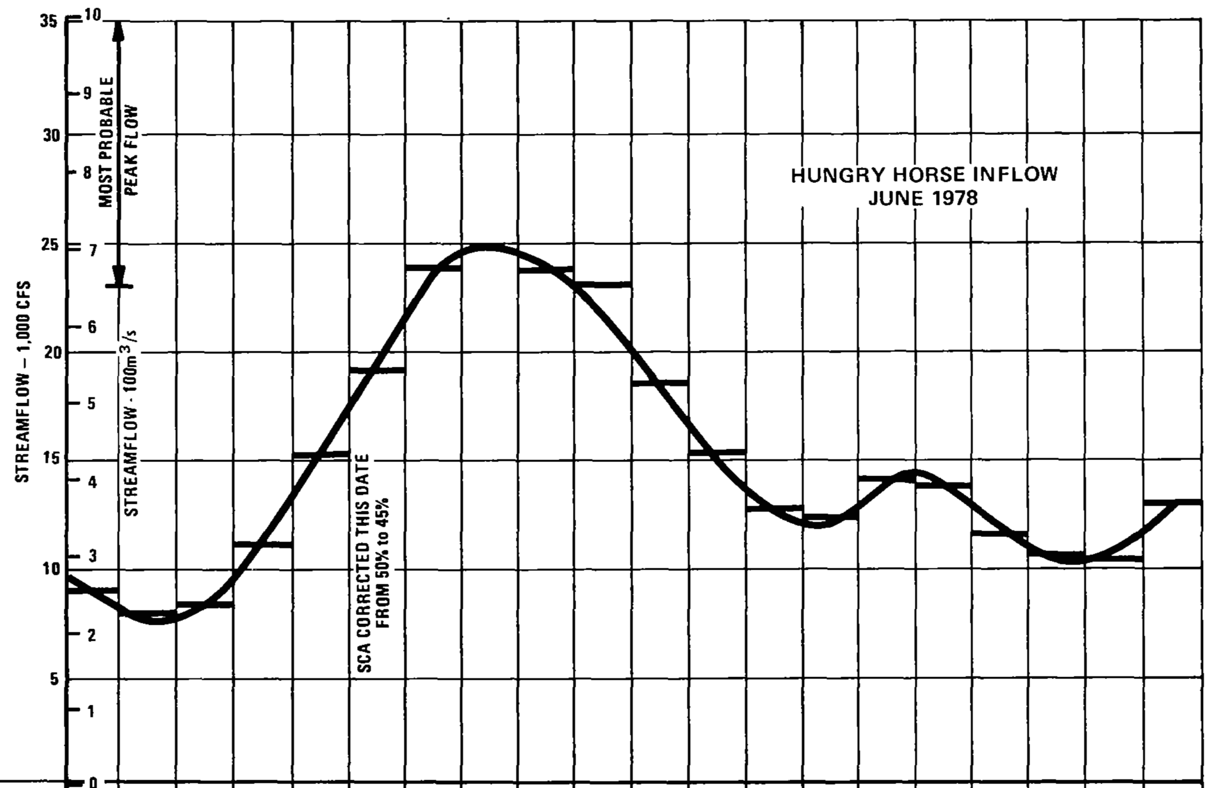
Figure 40

certain tolerance. Reliable estimates of basin snow-covered area are extremely useful during this initial adjustment period.

SSARR Adjustment Routine

Some mention needs to be made of the SSARR model adjustment routine, since the watershed adjustment factor, to a large degree, pinpoints those basins which are not computing properly. Routinely during the spring snowmelt period, the model is backed up 2 days and run with observed temperature and precipitation data for that 2-day period.

The model begins with an observed flow and a set of initial conditions and iterates to hit an observed flow 2 days later, within a certain tolerance. In the iteration routine the moisture input (snowmelt plus rain runoff) to the model is multiplied by a factor ranging between 0.5 and 2.0 until the current flow is matched within the specified tolerance. The final adjustment factor for each watershed is listed for each run. Those factors are entered daily on the hydrograph (see Figure 41), and a history of an individual basin's performance is developed.



DAY	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
ADJ. FACTOR		0.6	0.8	0.6	0.6	1.0	1.2	1.2	1.1	1.0	1.5	1.3	1.0		0.8	1.0	1.2			0.6

Figure 41

A series of adjustment factors less than 1.0 or greater than 1.0 indicate that the parameters for that basin have some bias and need to be inspected for subsequent daily runs. Snow-covered area is one of the parameter values that might be changed to improve the performance of an individual basin.

An additional aspect of this adjustment routine needs to be considered here. Often, the watershed adjustment factors may be near 1.0, indicating that the basin parameters are in proper adjustment. A satellite snow-covered area report may be received which shows a snowline different than that carried in the model. In general, when this occurs only a token adjustment is made in the model unless some compensating parameter changes can be made to continue the good fit for that particular watershed. Conversely, when the SCA carried by the model and a satellite report are disparate, and the basin adjustment factors indicate that a change to the satellite snow-covered estimate would improve the model's fit, the satellite estimate would be used to directly update the basin parameter.

SSARR Volume and Peak Check

Another form of checking an individual watershed's operation is also utilized. One of the basic inputs to the model is the total volume of runoff from rain and snowmelt that is expected for a particular period (e.g., April-July for much of the Snake River area) for a particular basin. These seasonal volumetric runoff forecasts are prepared from different data than that used by the SSARR model for daily streamflow forecasting and are volumetric forecasts as opposed to the model's flow forecasts. In operational forecasting the SSARR model is routinely run for a 60- or 90-day period using several historical temperature sequences to test the validity of the parameter values.

Two main aspects of a watershed's fit can be checked in this manner. First, the ability of a watershed to generate the total forecast volume in the proper period can be ascertained. The two primary parameters that can be adjusted to improve the volume fit are initial soil moisture and initial snow-covered area. The importance of the snow-covered area parameter increases as one advances into the main snowmelt period. Second, a series of volume-peak relations (see Figure 42) are available. When the seasonal volume is available from the water supply forecasts, estimates can be made of the expected peak flow for an individual basin. Here again the SSARR model can be run 60-90 days into the future, and each basin can be checked to see if the individual basin is generating a peak within the expected range. The model parameters which are most effective in adjusting the peak flow for a basin are snow-covered area and melt rate. Thus, it can be seen that the snow-covered area parameter is highly important in assessing the proper performance of the SSARR model.

SSARR Winter Forecast Runs

The estimates of snow-covered area from satellites are also important during the fall and winter season. In some ways the importance of satellite winter snow cover estimates may even be greater since no winter snow flights are made, and the only information on snow cover otherwise available is from

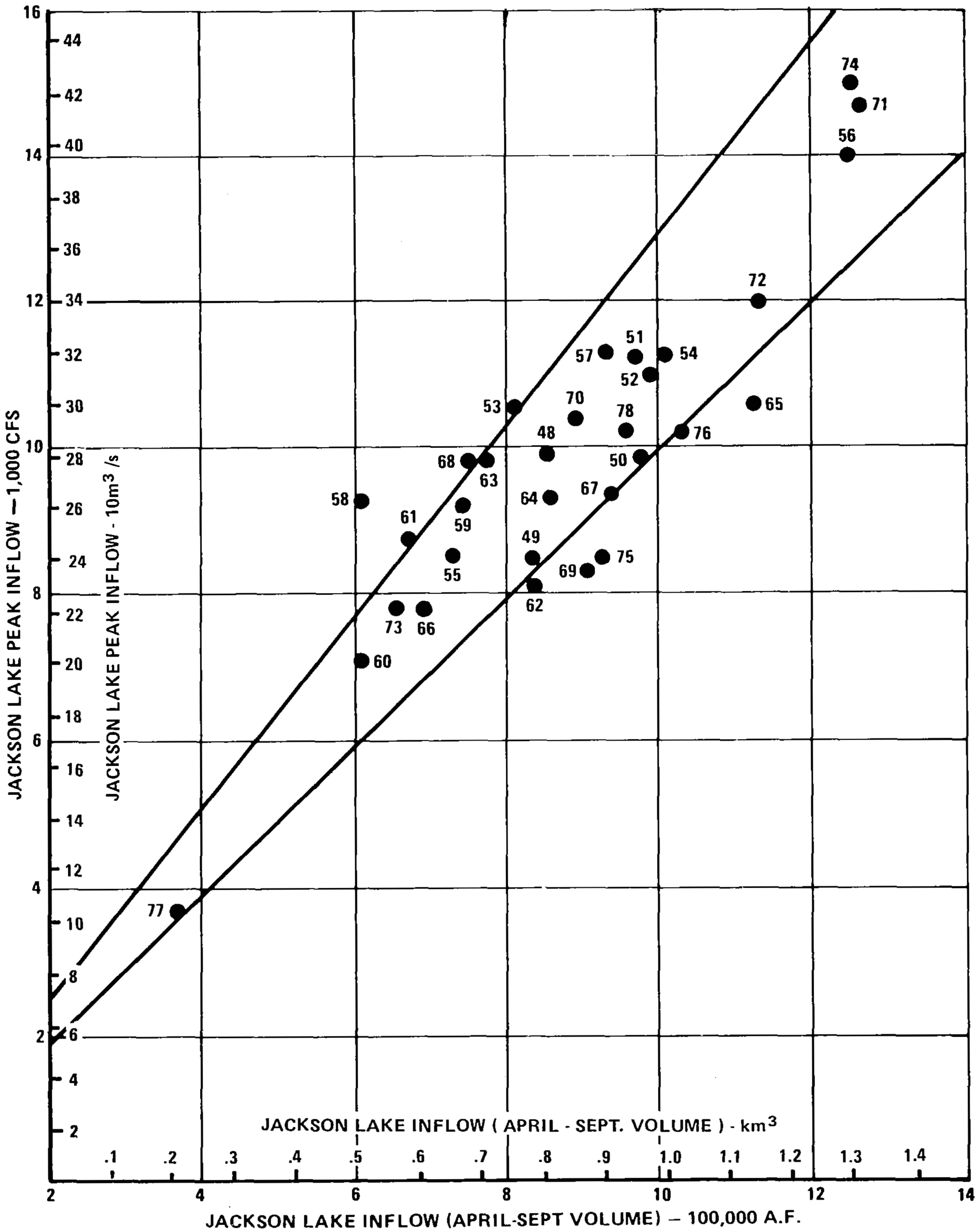


Figure 42. Jackson Lake - peak vs. volume

scattered point value reports from the various watersheds. Equal in consideration is the fact that for many basins the snowline can be highly variable during the winter period.

During a heavy runoff event, the actual snow-covered area can make a marked difference in the runoff that results (see Figure 43). It can be seen that when rapid warming accompanied by heavy rain occurs, the resulting runoff will be markedly different depending upon the basin's initial snow-covered area. The example shown is for the Weiser River Basin in central Idaho. In the one case a 5,000-foot snowline (20 percent snow-covered area) results in a rise slightly above flood stage which would cause only minor flood problems. In the extreme case with a 2,000-foot snowline and 100 percent of the basin snow covered, a flood of record would occur.

SSARR Daily Operational Forecast Improvement

A quasi-operational test was made with 1978 satellite SCA data in the Boise Basin to see what improvement could be made to the SSARR's daily streamflow forecasts. In this test, a dummy basin was set up in the model identical to the standard basin in all respects and for all data, except that satellite estimates of SCA were used exclusively in the dummy basin, and all available SCA data (including some satellite estimates) were used in the standard basin. These SCA data were input into the model upon its next run. These forecasting runs were made three times a week beginning in April, and were increased to five times a week as the streamflows were about to peak in late May and early June. Due to a long sustained runoff (of average magnitude), these runs were continued through June 30.

The Boise Basin was selected because it tends to be cloud free, because NESS personnel were making daily operational analyses of the satellite SCA data, and because there had been generally good agreement in past years between satellite SCA data and ground-truth SCA data. In the Boise Basin above Lucky Peak Dam, the quality of the ground-truth runoff data for any given day is not of the highest quality. The runoff is computed as the observed streamflow below Lucky Peak Dam, plus or minus the change of contents of three reservoirs; specifically Anderson Ranch, Arrowrock and Lucky Peak, and therefore tends to be less accurate than data from a natural basin.

Both forecasts from the standard basin and the dummy basin had a positive bias and overforecasted. It is possible that some of this deviation is due to the method of computing inflow. Because both basins used the same forecasting equation and because the bias was positive for both basins in all months, it is also very possible that the SCA was overestimated. Another contributing factor to the overcomputation of the two basins was the volume forecast. The April-July volumetric runoff forecast was biased to the high side which results in overestimating the runoff potential.

The chi-square values (Table 7) indicate that the dummy basin outperformed the standard basin forecasts for the 7-, 5-, and 3-day forecasts, but worsened the 14-day forecast. Both the dummy and standard basin forecasts degraded from the 14-day to the 7-day forecast, and then improved steadily as they went to a 3-day forecast. Based upon the absolute average values, the dummy basin

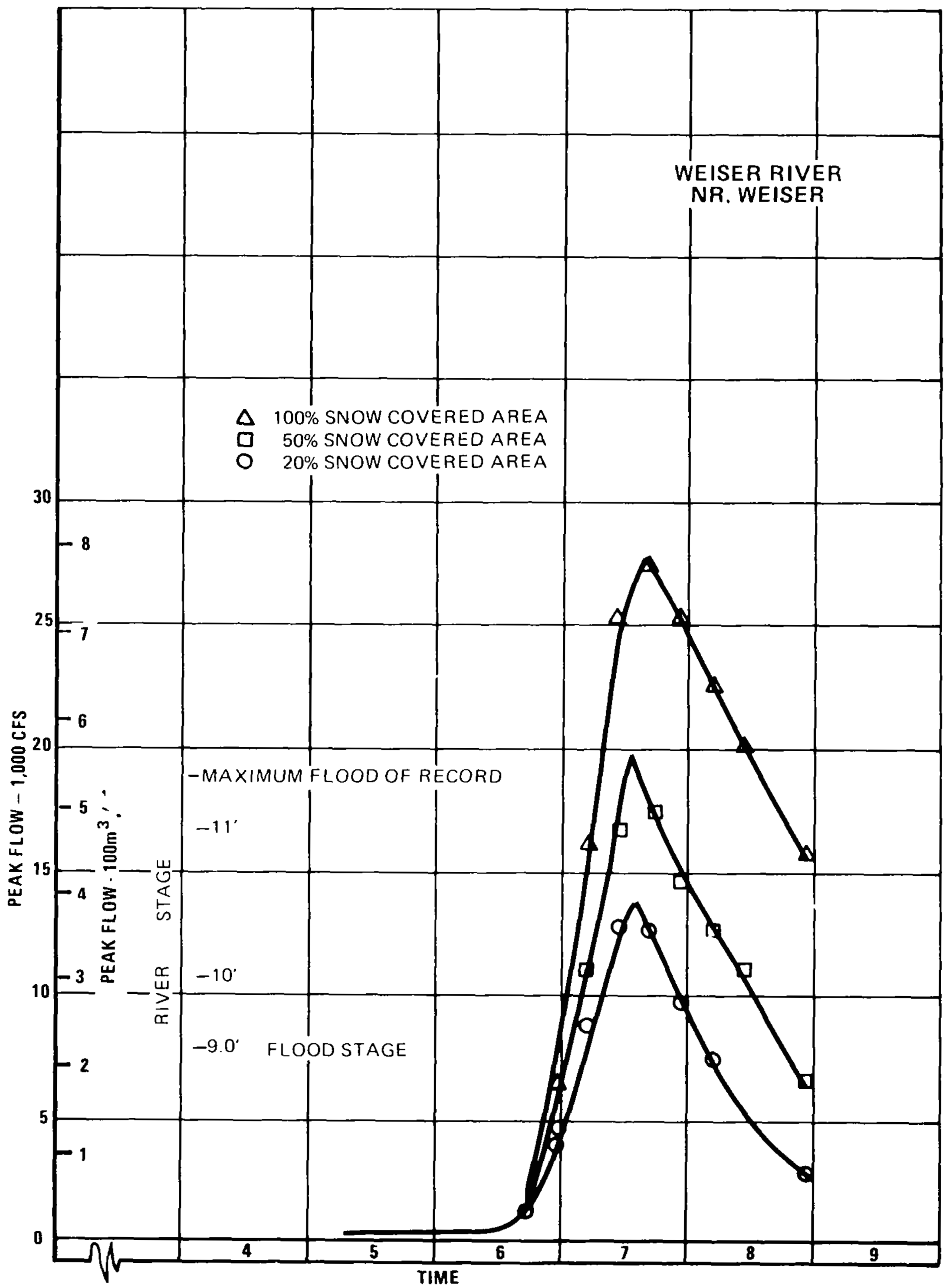

WEISER RIVER
NR. WEISER
100% SNOW COVERED AREA
50% SNOW COVERED AREA
20% SNOW COVERED AREA
PEAK FLOW – 1,000 CFS
RIVER STAGE
–MAXIMUM FLOOD OF RECORD
–11'
–10'
–9.0' FLOOD STAGE
TIME

Figure 43

TABLE 7

LUCKY PEAK BASIN - 1978 FORECASTS

FORECASTED VALUES ARE RECORDED FOR THE DATE
THEY WERE TO OCCUR, AND WERE MADE X-DAYS PRIOR

		---THREE DAY FORECAST-----				----FIVE DAY FORECAST-----				---SEVEN DAY FORECAST-----				--FOURTEEN DAY FORECAST---			
DATE	NATURAL FLOW	FCST LUCNAT	FCST ERROR	FCST LUCNATD	FCST ERROR	FCST LUCNAT	FCST ERROR	FCST LUCNATD	FCST ERROR	FCST LUCNAT	FCST ERROR	FCST LUCNATD	FCST ERROR	FCST LUCNAT	FCST ERROR	FCST LUCNATD	FCST ERROR
APR 6	5600																
APR 7	5270																
APR 8	5550	6665	1115	6064	514												
APR 9	5110																
APR 10	5120	6829	1709	6679	1559	6809	1689	5974	854								
APR 11	5780																
APR 12	6700					7927	1227	7193	493								
APR 13	6590	7752	1162	6989	399					5201	-1389	4579	-2011				
APR 14	5930									8052	2122	7020	1090				
APR 15	6160	5530	-630	5482	-678	7394	1234	6430	270								
APR 16	6240																
APR 17	7030	6155	-875	6139	-891	4749	-2281	4669	-2361	7466	436	6294	-736				
APR 18	6200																
APR 19	5550					5362	-188	5295	-255					4476	-1074	3652	-1898
APR 20	5440	5087	-353	5000	-440					3774	-1666	3693	-1747	6793	1353	5502	62
APR 21	5760									5474	-286	5552	-208				
APR 22	5510	7764	2254	7355	1845	4900	-610	4724	-786								
APR 23	5130													6806	1676	5416	286
APR 24	4520	4907	387	4890	370	7451	2931	7012	2492	4853	333	4601	81				
APR 25	4690																
APR 26	5700					5216	-484	5143	-557	7754	2054	7233	1533	4668	-1032	4566	-1134
APR 27	6560	6860	300	6759	199												
APR 28	7020									5310	-1110	5779	-1241	5599	-1421	5426	-1594
APR 29	7440	8392	952	8275	835	6631	-809	6482	-958								
APR 30	7840																

TABLE 7
LUCKY PEAK BASIN - 1978 FORECASTS

FORECASTED VALUES ARE RECORDED FOR THE DATE
THEY WERE TO OCCUR, AND WERE MADE X-DAYS PRIOR

		---THREE DAY FORECAST-----				----FIVE DAY FORECAST-----				---SEVEN DAY FORECAST-----				--FOURTEEN DAY FORECAST---			
DATE	NATURAL FLOW	FCST LUCNAT	FCST ERROR	FCST LUCNATD	FCST ERROR	FCST LUCNAT	FCST ERROR	FCST LUCNATD	FCST ERROR	FCST LUCNAT	FCST ERROR	FCST LUCNATD	FCST ERROR	FCST LUCNAT	FCST ERROR	FCST LUCNATD	FCST ERROR
MAY 1	7640	6516	-1124	6409	-1231	10084	2444	9786	2146	7015	-625	6792	-848	7012	-628	6389	-1251
MAY 2	7140																
MAY 3	6920					7001	81	6794	-126	10890	3970	10482	3562	8904	1984	8179	1259
MAY 4	8890	8213	-677	8063	-827												
MAY 5	8160									7741	-419	7440	-720	8287	127	7910	-250
MAY 6	6680	6742	62	6621	-59	8126	1446	7899	1219								
MAY 7	7350																
MAY 8	7140	6684	-456	6629	-511	7300	160	7090	-50	8730	1590	8425	1285	9062	1922	8642	1502
MAY 9	6030																
MAY 10	6820					8170	1350	7985	1165	8368	1548	8072	1252	10358	3538	9968	3148
MAY 11	7580	8790	1210	8758	1178												
MAY 12	9000									10032	1032	9730	730	9962	962	9543	543
MAY 13	7320	8326	1006	8166	846	9685	2365	9487	2167								
MAY 14	7360																
MAY 15	7620					8839	1219	8617	997	10351	2731	10059	2439	10631	3011	10287	2667
MAY 16	11300																
MAY 17	9240									9703	463	9440	200	10690	1450	10376	1136
MAY 18	7930	7710	-220	8059	129												
MAY 19	7160													11377	4217	11096	3936
MAY 20	6060	7937	1877	8442	2382	8279	2219	8997	2937								
MAY 21	6590																
MAY 22	7730	8931	1201	9541	1811	9806	2076	10797	3067	9314	1584	10352	2622	11514	3784	11077	3347
MAY 23	9070	9155	85	9824	754												
MAY 24	9980	7781	-2199	9073	-907	9792	-188	10732	752	10990	1010	12240	2260	11447	1467	11075	1095
MAY 25	9020	7755	-1265	8183	-837	8238	-782	8960	-60								
MAY 26	7780					6196	-1584	7418	-362	9407	1627	10398	2618				
MAY 27	6450	6436	-14	6447	-3	6601	151	7047	597	8046	1596	8860	2410				
MAY 28	6080	7502	1422	7766	1686					6015	-65	7552	1472				
MAY 29	5870	8096	2226	7592	1722	6633	763	6977	1107	6950	1080	7585	1715	9781	3911	10936	5066
MAY 30	6400	8372	1972	7616	1216	8650	2250	9208	2808								
MAY 31	7150	9223	2073	8472	1322	9926	2776	9026	1876	7633	483	8311	1161	10090	2940	11166	4016

TABLE 7
LUCKY PEAK BASIN - 1978 FORECASTS

FORECASTED VALUES ARE RECORDED FOR THE DATE
THEY WERE TO OCCUR, AND WERE MADE X-DAYS PRIOR

		---THREE DAY FORECAST-----				----FIVE DAY FORECAST-----				---SEVEN DAY FORECAST-----				--FOURTEEN DAY FORECAST---			
DATE	NATURAL FLOW	FCST LUCNAT	FCST ERROR	FCST LUCNATD	FCST ERROR	FCST LUCNAT	FCST ERROR	FCST LUCNATD	FCST ERROR	FCST LUCNAT	FCST ERROR	FCST LUCNATD	FCST ERROR	FCST LUCNAT	FCST ERROR	FCST LUCNATD	FCST ERROR
JUN 1	6410	8934	2524	8225	1815	10418	4008	9247	2837	9732	3322	10488	4078				
JUN 2	6540	7306	766	6821	281	12240	5700	10967	4427	11527	4987	10350	3810	9858	3318	10930	4390
JUN 3	6620	8757	2137	8247	1627	11926	5306	10656	4036	11858	5238	10457	3837	9684	3064	10746	4126
JUN 4	6800	10283	3483	9541	2741	10598	3798	9515	2715	13503	6703	12054	5254	7937	1137	10560	3760
JUN 5	7330	11306	3976	10280	2950	11569	4239	10413	3083	13879	6549	12350	5020	9566	2236	10619	3289
JUN 6	8630	11188	2558	10275	1645	12902	4272	11607	2977	12833	4203	11421	2791				
JUN 7	9850	11885	2035	11868	2018	14631	4781	12986	3136	13158	3308	11689	1839	9825	-25	10825	975
JUN 8	10830					14381	3551	12868	2038	13787	2957	12319	1489	10510	-320	11316	486
JUN 9	11420	13802	2382	13772	2352	13572	2152	13510	2090	15214	3794	13472	2052	12206	786	11028	-392
JUN 10	11900	12494	594	12757	857					15016	3116	13365	1465	12301	401	11046	-854
JUN 11	11260	12980	1720	12918	1658	13126	1866	13047	1787	13249	1989	13153	1893	12024	764	10835	-425
JUN 12	9930	10907	977	11076	1146	12888	2958	13204	3274					12180	2250	10990	1060
JUN 13	6750	9902	3152	9830	3080	11887	5137	11799	5049	12625	5875	12528	5778	11908	5158	10686	3936
JUN 14	8120	10495	2375	10892	2772	10207	2087	10437	2317	11954	3834	12206	4086	12039	3919	10739	2619
JUN 15	8800	10486	1686	10454	1654	10312	1512	10236	1436	11613	2813	11521	2721	11682	2882	10495	1695
JUN 16	8350					9442	1092	9823	1473	10108	1758	10369	2019	11806	3456	10593	2243
JUN 17	7340	9210	1870	9604	2264	9222	1882	9169	1829	10559	3219	10483	3143	11322	3982	10269	2929
JUN 18	7130									9381	2251	9777	2647	10337	3207	10232	3102
JUN 19	7160	8030	870	8411	1251	9368	2208	9944	2784	9794	2634	9743	2583				
JUN 20	7140													10040	2900	9953	2813
JUN 21	6630					8564	1934	9087	2457	9207	2577	9835	3205	9400	2770	9480	2850
JUN 22	7510	7662	152	8014	504									9630	2120	9558	2048
JUN 23	6910									8587	1677	9156	2246	8930	2020	9114	2204
JUN 24	7220	7651	431	8041	821	7964	744	8486	1266					9226	2006	9158	1938
JUN 25	7300													8413	1113	8712	1412
JUN 26	6900	7712	812	8102	1202	6996	96	7420	520	7958	1058	8540	1640	8802	1902	8754	1854
JUN 27	5950																
JUN 28	5660					7123	1463	7592	1932	7302	1642	7794	2134	7815	2155	8333	2673
JUN 29	5640	6655	1015	6924	1284												
JUN 30	6090									7218	1128	7750	1660	7582	1492	8048	1958

sheet 3 of 4

TABLE 7

LUCKY PEAK BASIN - 1978 FORECASTS

FORECASTED VALUES ARE RECORDED FOR THE DATE
THEY WERE TO OCCUR, AND WERE MADE X-DAYS PRIOR

		---THREE DAY FORECAST-----				----FIVE DAY FORECAST-----				---SEVEN DAY FORECAST-----				--FOURTEEN DAY FORECAST---			
DATE	NATURAL FLOW	FCST LUCNAT	FCST ERROR	FCST LUCNATO	FCST ERRCR	FCST LUCNAT	FCST ERROR	FCST LUCNATO	FCST ERROR	FCST LUCNAT	FCST ERROR	FCST LUCNATO	FCST ERROR	FCST LUCNAT	FCST ERROR	FCST LUCNATO	FCST ERROR
JUL 1	6460	7236	776	8041	1581	7297	837	7711	1251								
JUL 2	6450																
JUL 3	5690	5629	-61	6894	1204	6639	949	7399	1709	7458	1768	7915	2225	7240	1550	7747	2057
JUL 4	5820																
JUL 5	6220					5310	-910	6819	599	5144	-1076	5702	-518	7007	787	7444	1224
JUL 6	5070																
JUL 7	4570									5319	749	7003	2433	6715	2145	7182	2612
JUL 8	4770																
JUL 9	5080																
JUL 10	4660													6435	1775	6785	2125
JUL 11	4720																
JUL 12	4640													5839	1199	6412	1772
JUL 13	3930																
JUL 14	3920													4776	856	6068	2148
AVG	6900	8380	1009	8373	1002	8946	1655	6851	1560	9340	1963	9223	1846	9194	1861	9099	1767
ABS AVG	6900	8380	1330	8373	1262	8946	1975	8851	1785	9340	2234	9223	2174	9194	2045	9099	2085

POPULATION SIZE = 100, AND SIGMA SQUARED =2692323.96

SS	4051853.42	3935148.85	6528379.37	5209234.72	8153070.43	6126832.46	4777988.79	4188977.94
XX	13855.11	11748.72	27787.46	22776.85	33013.05	30628.85	27594.58	29835.22

sheet 4 of 4

increased the standard basin's 14-day forecast error by 2.0 percent but was able to decrease the forecast errors for the 7-, 5-, and 3-day forecasts by 2.7 percent, 9.6 percent, and 5.1 percent respectively.

Of these various forecasts, the 3- and 5-day forecasts had forecasted values of temperature and precipitation. Instead of forecasted values of temperature and precipitation, the 7-day forecasts had only normal values, and the 14-day forecasts had a seasonally dependent "wow" imposed upon temperature and precipitation to account for other variables such as melt rate. Thus the 7-day forecast is not as accurate as the 3- and 5-day forecasts, and the 14-day is purposefully high or low to be used as a "what-if" operational planning tool. Based upon this, the degradation from the 14- to the 7-day forecast is not surprising.

The dummy basin was able to reduce the forecast error of the standard basin's 5-day forecast by 9.6 percent. This is an absolute average error reduction of 5.4 m^3/s (190 cfs). The average computed inflow of the 49 values corresponding to the 5-day forecast is 206.5 m^3/s (7,291 cfs (8,946 minus 1,655)). The Geological Survey would give, at best, an accuracy to this measurement of $\pm$ 5 percent or 10.3 m^3/s (365 cfs). Thus, since the error reduction of 5.4 m^3/s (190 cfs) is less than the overall accuracy of 10.3 m^3/s (365 cfs), the improvement gained by the exclusive use of satellite SCA data, unfortunately, is not statistically significant.

CONCLUSIONS AND RESULTS

The ultimate objective of this study was to develop or modify methods in an operational framework that would allow incorporation of satellite derived snow cover observations for prediction of snowmelt derived runoff. This objective was directed toward the SSARR model which had been developed as a streamflow forecasting tool, utilized snow cover data as basic input, was fully operational, and highly successful. Based on this objective, the study's results and conclusion are given below.

(1) Cloud cover is very much a problem in acquiring SCA data for the Pacific Northwest. Because of persistent cloud cover, forecasting routines should not be totally dependent upon the satellite data.

(2) The satellite data improve forecasts, but not a statistically significant amount and, therefore, should not be used exclusively.

(3) Landsat data cannot be used operationally here in the Pacific Northwest because of a 48-hour time constraint for data acquisition. Also, because of this 48-hour time constraint, NOAA data cannot be analyzed locally.

(4) Although the satellite derived estimates of SCA integrate patchy snow into the snowline and thus are generally higher than aerial snow flight data, the satellite derived SCA data can be used to augment aerial snow flight data, and vice versa.

(5) The satellite data definitely provide many more SCA estimates than could be gathered from ground truth data alone.

(6) Based upon reconstitution runs, satellite derived SCA data can be used to augment aerial snow-flight data in the Upper Snake, Boise, Dworshak, and Hungry Horse Basins.

(7) The satellite data do not compare well with aerial snow flight data in the Libby Basin. Because of heavy tree cover, and the forest canopy hiding the snowline, satellite estimates of SCA in the Libby Basin should not be attempted until the SCA is 50 percent or less.

(8) The satellite data are invaluable in fall and winter streamflow forecasting. It can clearly be seen that the satellite derived SCA data have utility in the operational forecast scheme during all periods of the year. At times the satellite data can make a critical difference in the forecasted streamflow hydrograph.

(9) Portland's Columbia River Forecast Service has been subjectively using the satellite SCA data in conjunction with available ground truth data in its operational forecasts and will continue to do so. The CRFS looks forward to an expansion of satellite derived information such as soil moisture.

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7. Author(s) John P. Dillard		8. Performing Organization Report No. 81F0064
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16. Abstract

The study objective was to develop or modify methods in an operational framework that would allow incorporation of satellite derived snow cover observations for prediction of snowmelt derived runoff.

Data are reviewed and verified for five basins in the Pacific Northwest. The data are analyzed for up to a 6-year period ending July 1978, and in all cases cover a low, average, and high snow cover/runoff year.

Cloud cover is a major problem in these springtime runoff analyses and have hampered data collection for periods of up to 52 days. Tree cover and terrain are sufficiently dense and rugged to have caused problems.

The interpretation of snowlines from satellite data has been compared with conventional ground truth data and tested in operational streamflow forecasting models. When the satellite snow-covered area (SCA) data are incorporated in the SSARR (Streamflow Synthesis and Reservoir Regulation) model, there is a definite but minor improvement. Satellite SCA data are being used operationally for daily streamflow forecasting here in the Pacific Northwest via the SSARR model.

17. Key Words (Selected by Author(s))	18. Distribution Statement
aerial flight, cloud cover, forecast model, forest cover, hydrograph, runoff, satellite, shadow, snow cover, snowline, streamflow forecasting, SSARR	Star Category 43 Unclassified - Unlimited

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