USE OF SATELLITE DATA IN RUNOFF FORECASTING IN THE HEAVILY
FORESTED, CLOUD-COVERED PACIFIC NORTHWEST

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ABSTRACT

Data are reviewed for five basins in the Pacific North-
west and 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.

Tree cover and terrain are sufficiently dense and rug-
ged to have caused problems. Cloud cover is also a
perennial problem in these springtime runoff analyses.
Data periods of up to 30 days are obscured by clouds.

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 data are incorpor-
ated in the Streamflow Synthesis and Reservoir Regula-
tion (SSARR) model, there is a definite but minor
improvement. However, this improvement is not statis-
tically significant. Satellite snow-covered area data
are being used operationally for streamflow forecasting
here in the Pacific Northwest via the SSARR model.

INTRODUCTION

The Portland River Forecast Center has relied, for a number of
years, upon infrequent aerial flights to update the snow-covered
area (SCA) parameter in the Streamflow Synthesis and Reservoir
Regulation (SSARR) snowmelt model. In recent years, estimates of
snow cover have been made from the satellite imagery and the Fore-
cast Center has been using them in the operational model in con-
junction with the aerial flight data. The advantage of the satel-
lite estimates of snow cover is that they are available at more
frequent intervals than flight data.
The Pacific Northwest was one of four Application Systems Veri-
fication and Transfer (ASVT) areas chosen by the National Aeronau-
tics and Space Administration (NASA) to test methods to incorporate
satellite-derived snow cover observations into the prediction of
snowmelt-derived streamflow. The five test sites chosen in the
Pacific Northwest were: the Upper Snake basin above Palisades Dam,

the Boise basin above Lucky Peak Dam, the North Fork Clearwater basin above Dworshak Dam, the Kootenai basin above Libby Dam, and the South Fork Flathead basin above Hungry Horse Dam. These basins give diversity in location, elevation, aspect, slope, size, and tree cover.

DATA REDUCTION AND VERIFICATION

Data for all five of these basins were collected and analyzed for the 4-year period 1975-1978. This period included two average snow-cover years, a near-maximum year (1975), and an extreme drought year (1977). In addition, some data were collected in 1973 and 1974 for the Upper Snake and the Boise basins.

Landsat data were collected and reduced by a subcontractor using an interactive console and single-band radiance tresholding, and in-house using an optical zoom transfer scope. NOAA satellite data were collected and analyzed for snow-covered area using a zoom transfer scope by either National Oceanic and Atmospheric Administration/National Environmental Satellite Service (NOAA/NESS) or Bonneville Power Administration (BPA). Using NOAA imagery with good contrast, there was good agreement between the same image analyzed by both NOAA/NESS and BPA personnel. Cross-checks were also made between the Landsat and the NOAA data. There was excellent agreement when the operator was familiar with the basin, but there were also instances where, due to unfamiliarity with the basin, the satellite data had to be completely reanalyzed. This was the case in 1975 for the Dworshak, Libby, and Hungry Horse basins.

Aerial flights are one of the ground truths available to verify the satellite SCA 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.

The other ground truth available is the SSARR streamflow model. 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 perfor-

mance, and therefore, gives credance to the SCA curve generated by the model. In general, the satellite SCA data were equal to, or slightly greater than, the SSARR generated snow cover curve.

DATA REDUCTION PROBLEMS

Forest Cover and Shadow

In the Upper Snake and the Boise basins there were no problems interpreting the snowline from satellite imagery. 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. Figures 1-5 are 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, figures 1 through 5 (and the appropriate discussion for each figure) are shown separately on the next 5 pages.

In figure 1 (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 1: Hungry Horse Basin, 7 Mar 76, ERTS Imagery, MSS 5.

In figure 2 (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.
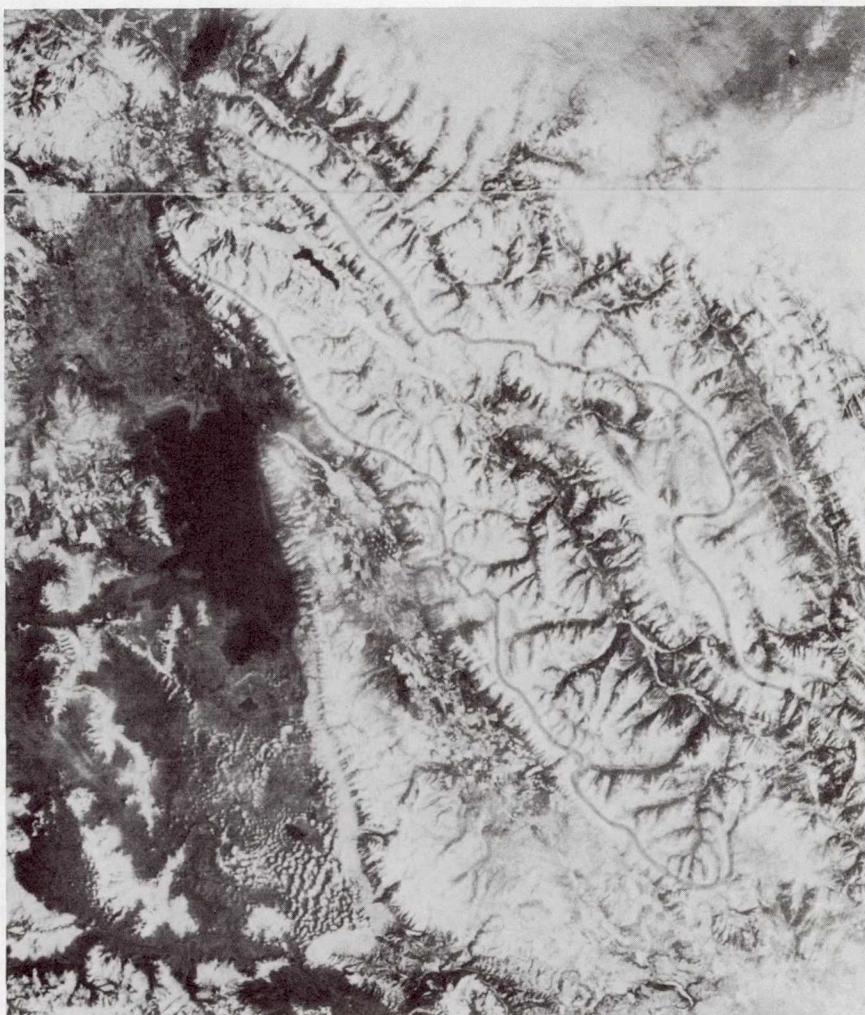

Figure 2: Hungry Horse Basin, 3 Apr 76, ERTS Imagery, MSS 5.

In figure 3 (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 intermit-
tently visible on 7 March 76 has disappeared. Snow still shows in
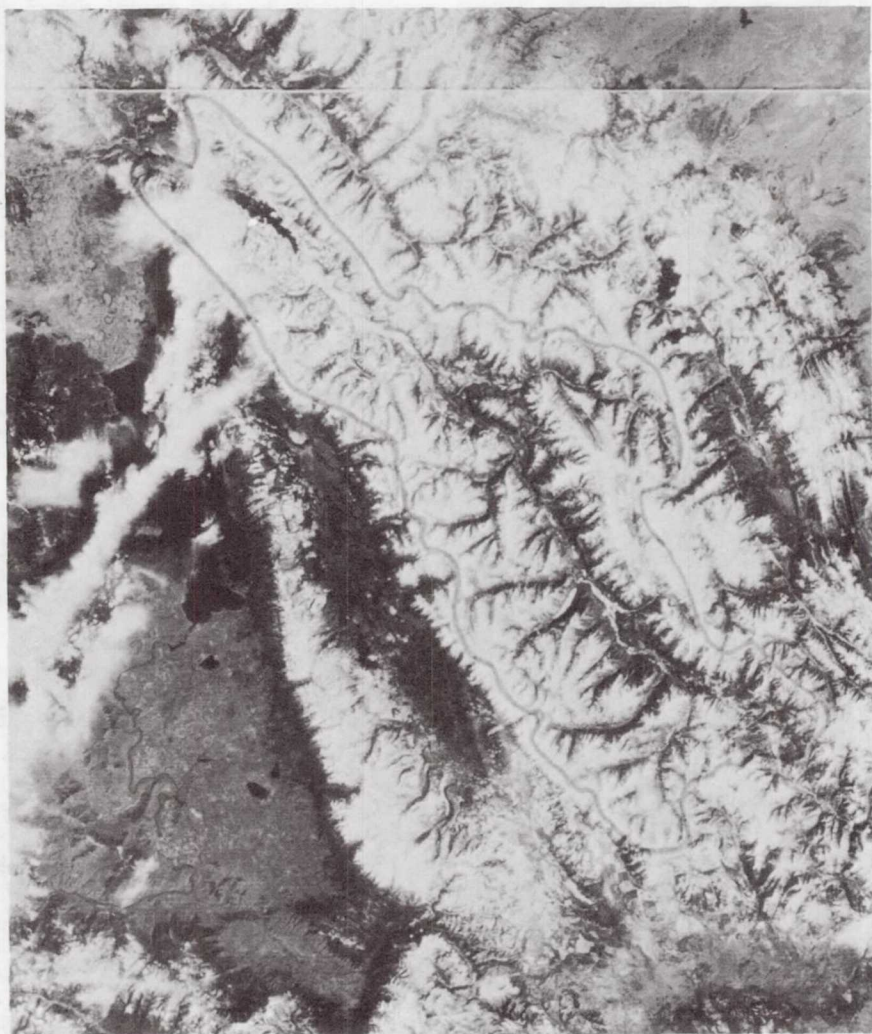the clearcut areas. SCA is 74 percent.

Figure 3: Hungry Horse Basin, 12 Apr 76, ERTS Imagery, MSS 5.

In figure 4 (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 4: Hungry Horse Basin, 30 Apr 76, ERTS Imagery, MSS 5.

In figure 5 (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 grey. SCA in the Hungry Horse basin is 48 percent.

Figure 5: Hungry Horse Basin, 18 May 76, ERTS 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 the 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 to as infrequent as 54 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-maxiumum snow cover year.

To be usable operationally, SCA data should be no older than about 48 hours. The average mail lag to receive Landsat "quick-look" imagery was 5 days. To alleviate the problem of having adequate satellite-derived SCA data, and receiving it in a timely manner, Landsat data was dropped and NOAA satellite data was used exclusively for operational purposes.

Even using NOAA data there were extended periods each year when one or more of the basins were obscured by clouds. These periods could be 34 or 36 days, and in 1977 for the Upper Snake was 43 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.

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 then aerial flights and will have direct usefulness in the forecast model.

SSARR OPERATIONAL FORECAST MODEL

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 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 runs 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 6) and a history of an individual basin's performance is developed.

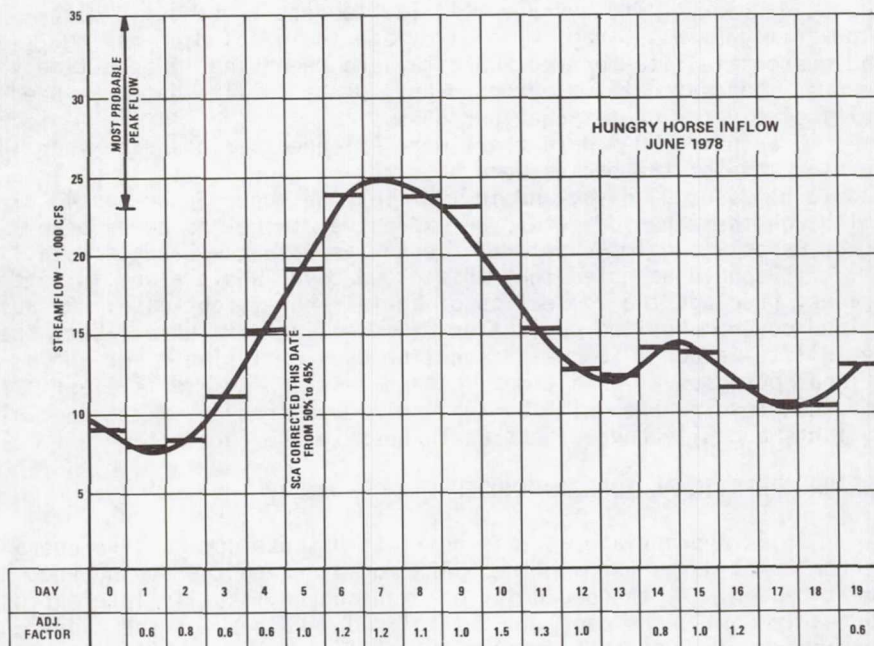| DAY	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
ADJ. FACTOR		0.6	0.8	0.6	0.6	1.0	1.2	1.2	1.1	1.0	1.5	1.3	1.0		0.8	1.0	1.2			0.6

Figure 6.

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. Snow-covered area is one of the parameter
values that might be changed to improve the performance of an indi-
vidual 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 con-
tinue 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 par-
ticular period (i.e., April-July for much of the Snake River area)
for a particular basin. 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 impor-
tance of the snow-covered area parameter increases as one advances
into the main snowmelt period. Secondly, a series of volume-peak
relations (see figure 7) 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 Reconstitutions

Let us now discuss some of the reconstitutions run for the
1975-78 water years. In each case, the initial parameters were set
at the beginning of the reconstitution, observed temperature and
precipitation were input, and the model then run without inter-
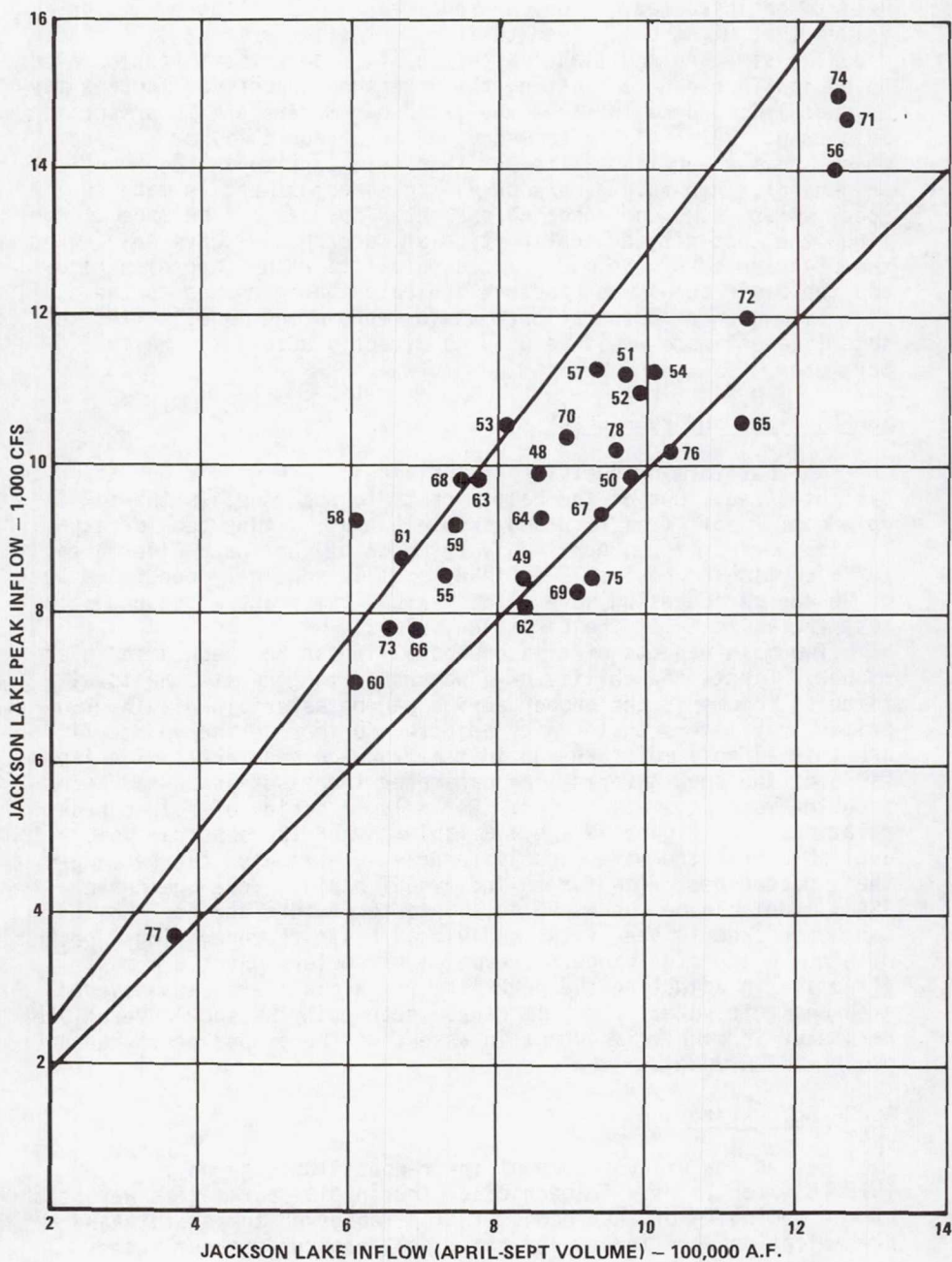vention through the whole snowmelt season. Comparisions can then

Figure 7.   Jackson Lake Inflow Peak to Volume Relationship

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be made between the model snow-covered area parameters, aerial snow-flight data, and the snow-covered area from the NOAA satellite. Figure 8 is a sample reconstitution plot which shows the interrelation of the SSARR model, snow flight, and NOAA satellite SCA data.

The early season snow-cover estimates from NOAA data exceeded the SSARR model snow-cover estimates for Snake above Palisades, 1977 (see figure 8); Boise above Lucky Peak, 1975 (figure 9), 1976 (figure 10), and 1977 (figure 11); and Clearwater above Dworshak, 1976 (figure 12) and 1977 (figure 13). In all of these cases the reconstitution fit early in the melt season was good, and using the satellite SCA estimate would not have improved the model performance. Using the NOAA data early in the season in 1977 would have caused overcomputing of runoffs in a year when runoff was at a record low. This was particularly true in the Lucky Peak and Dworshak basins. The probable cause of these overestimates was the large areas of thin snow cover which contributed little to runoff in this low year.

In the Hungry Horse and Libby basins there was a disparity of estimates in the opposite direction. In the early melt season for both Libby and Hungry Horse, NOAA satellite estimates of snow cover were lower than the model estimates, with the model reconstitutions fitting well in the early season. The heavy forestation in these two basins obscures some of the snow and easily causes underestimation of the snow-covered area.

Satellite SCA estimates also improve reconstitutions. The reconstitution for the Snake above Palisades in 1976 (figure 14) is a case where the early season reconstitution was not a good fit, and using the NOAA satellite SCA estimate would have improved the streamflow reconstitution. Also, the 1976 reconstitution for the Libby basin (figure 15) would have been improved using the satellite data. During the peak of the season the model tended to overcompute, and using the NOAA snow-cover data would have improved the reconstitution. At the end of the season the SSARR model was undercomputing, and using the satellite SCA estimates would have improved the model fit.

SSARR Winter Forecast Runs

Heretofore, discussion has only been about the spring snowmelt season and the usage of satellite estimates of springtime snow cover. 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 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 16). It can be seen that when rapid warming accompanied by heavy rain occurs, the resulting runoff will be markedly different depending
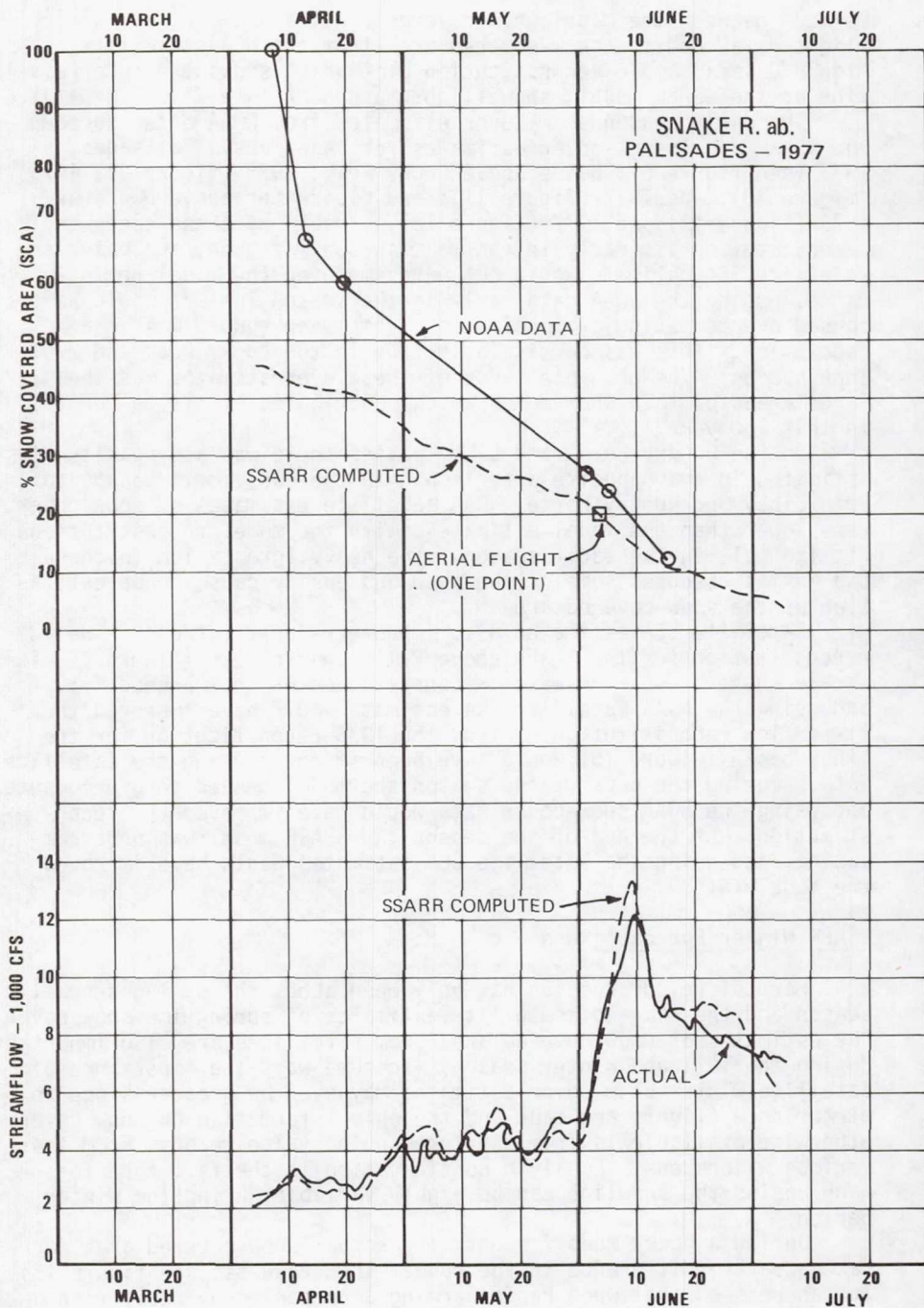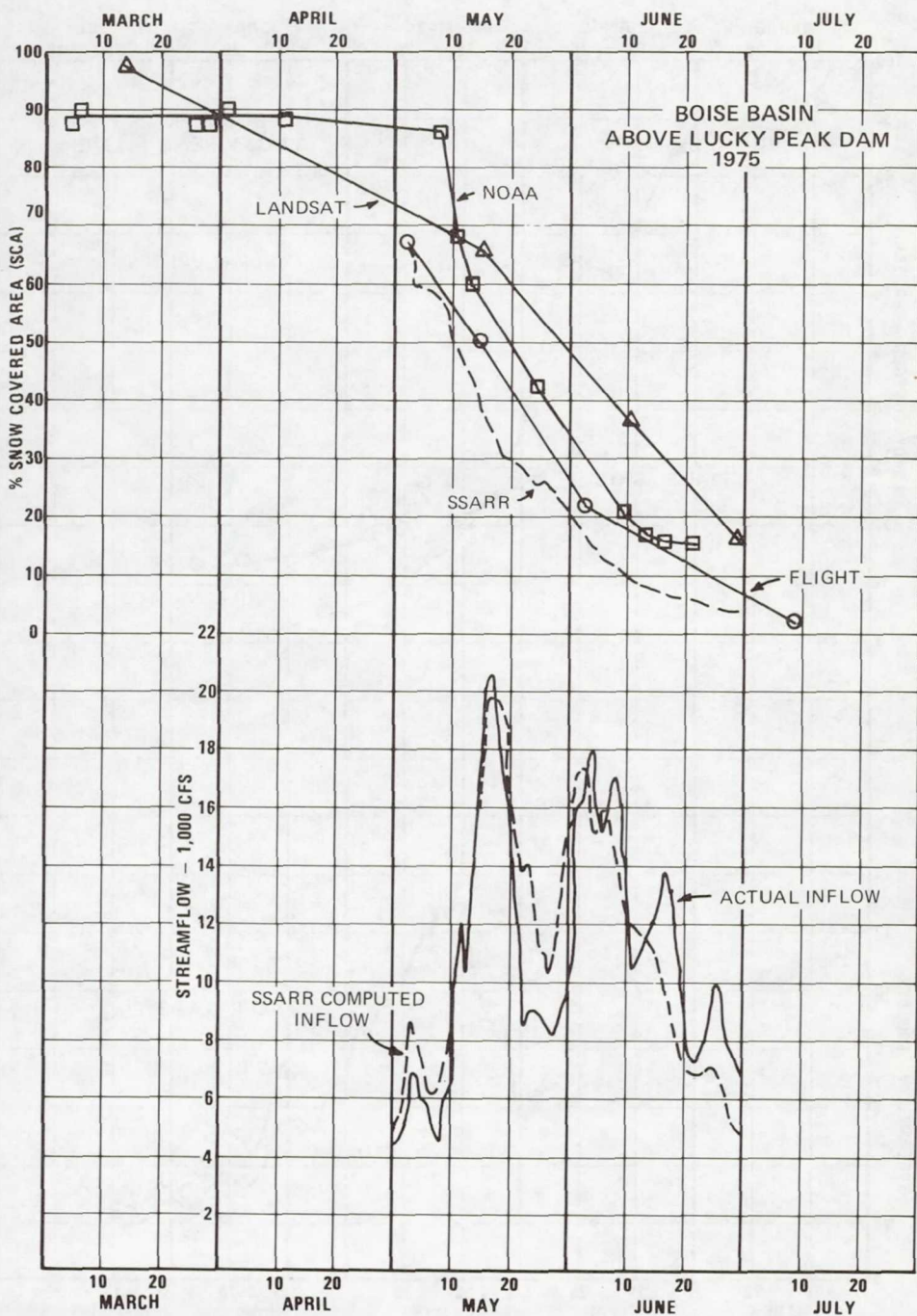
Figure 8. Snake River above Palisades - 1977

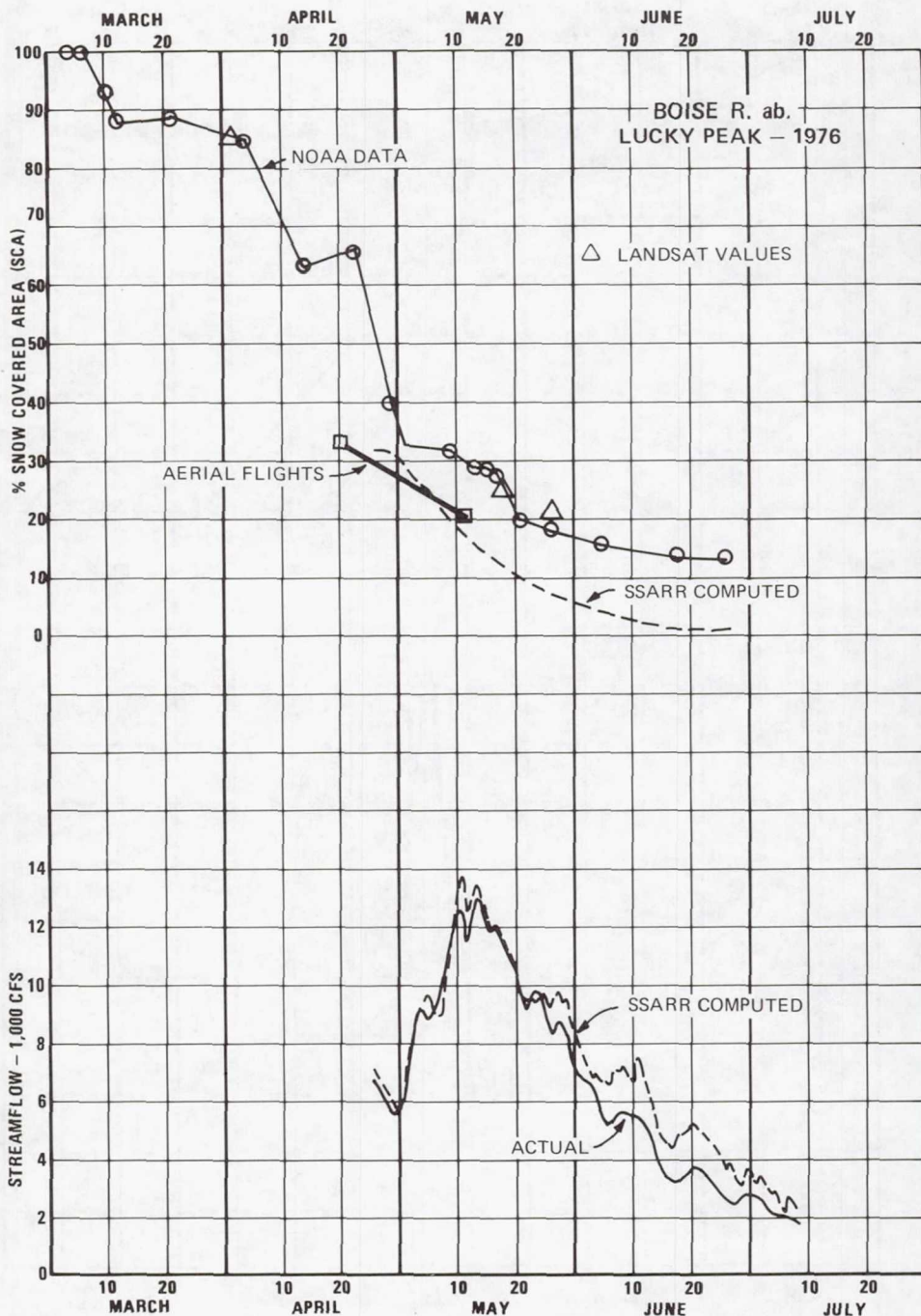Figure 9. Boise Basin above Lucky Peak Dam - 1975

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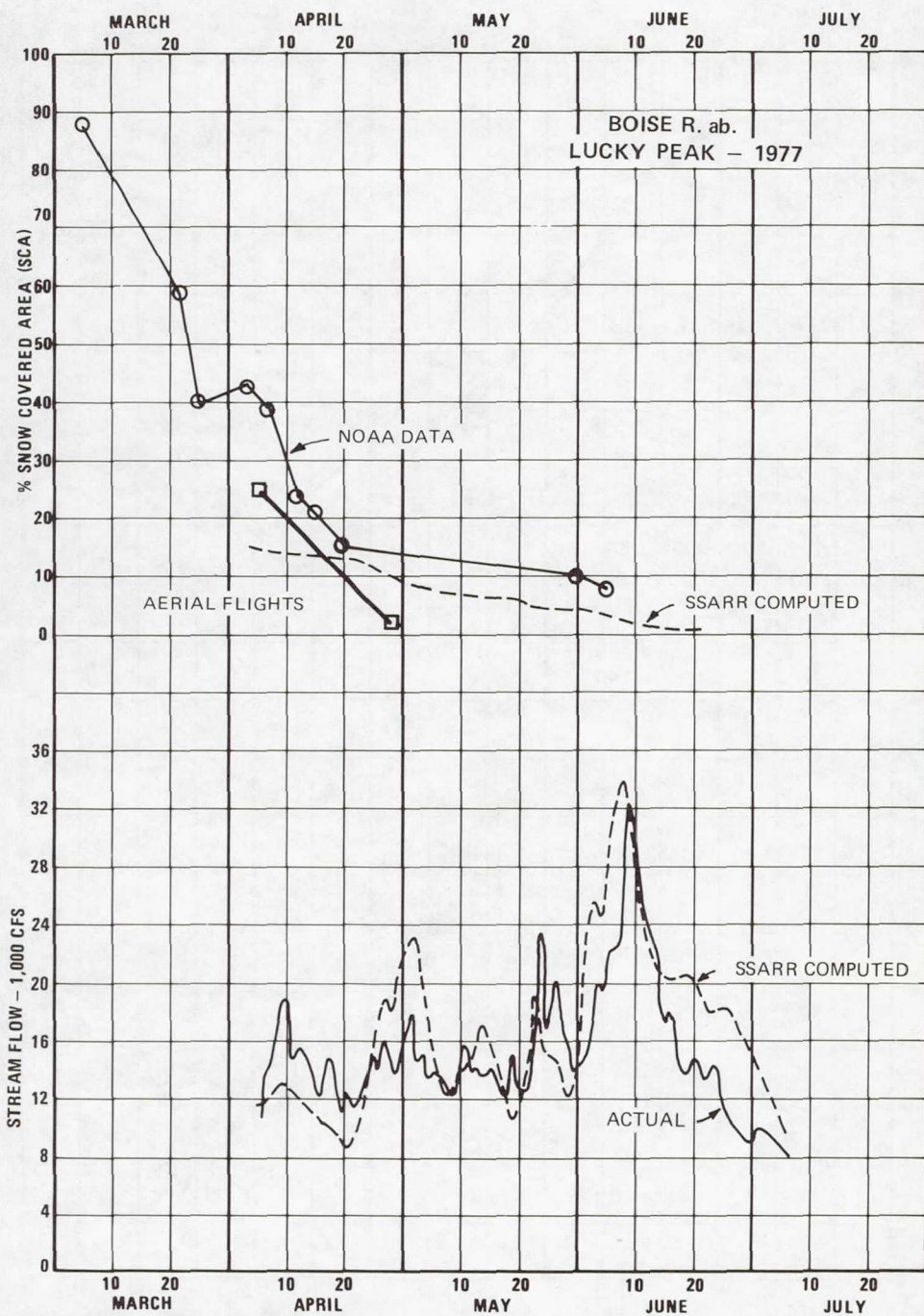Figure 10. Boise River above Lucky Peak - 1976

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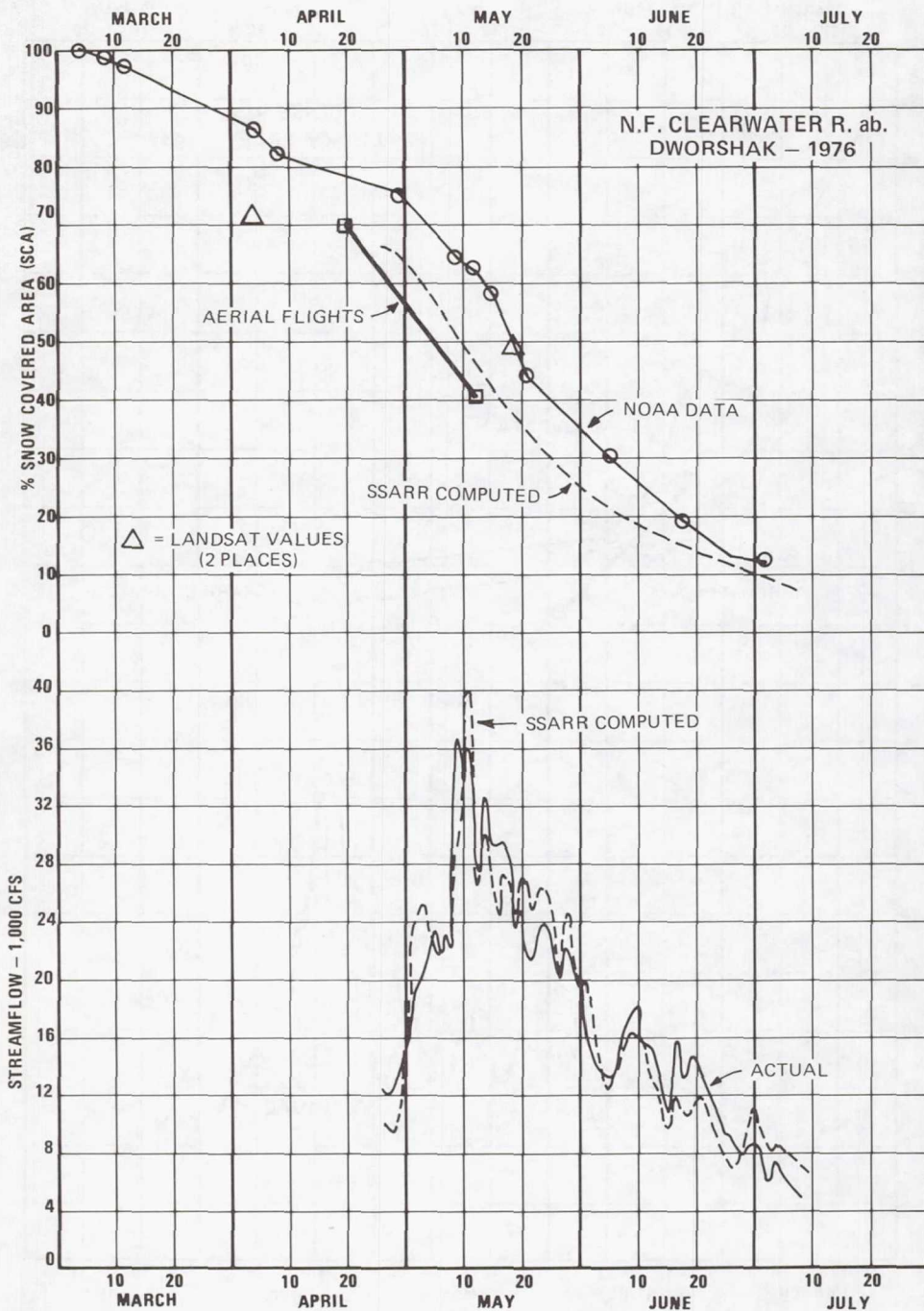Figure 11. Boise River above Lucky Peak - 1977

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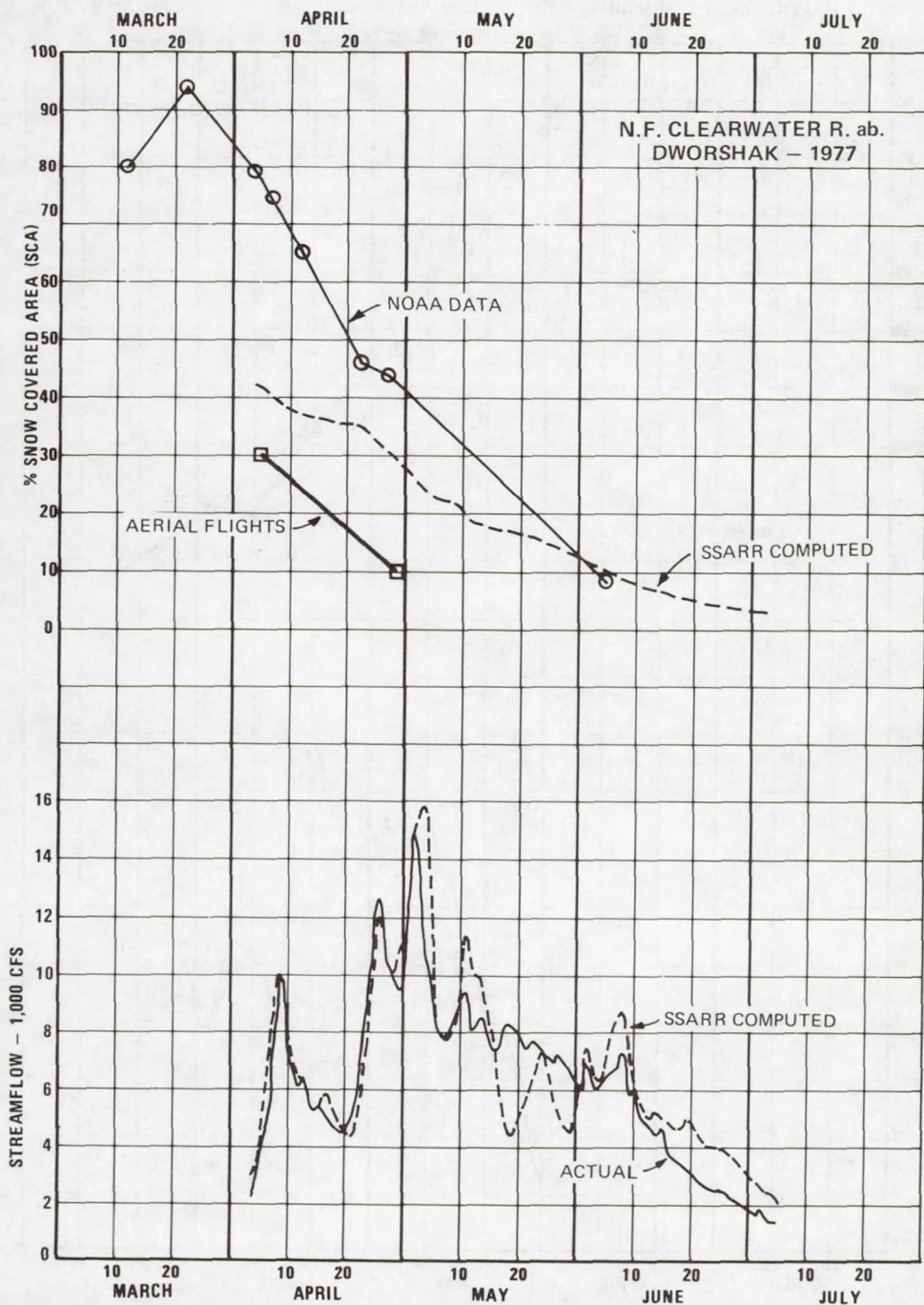Figure 12. North Fork Clearwater above Dworshak - 1976

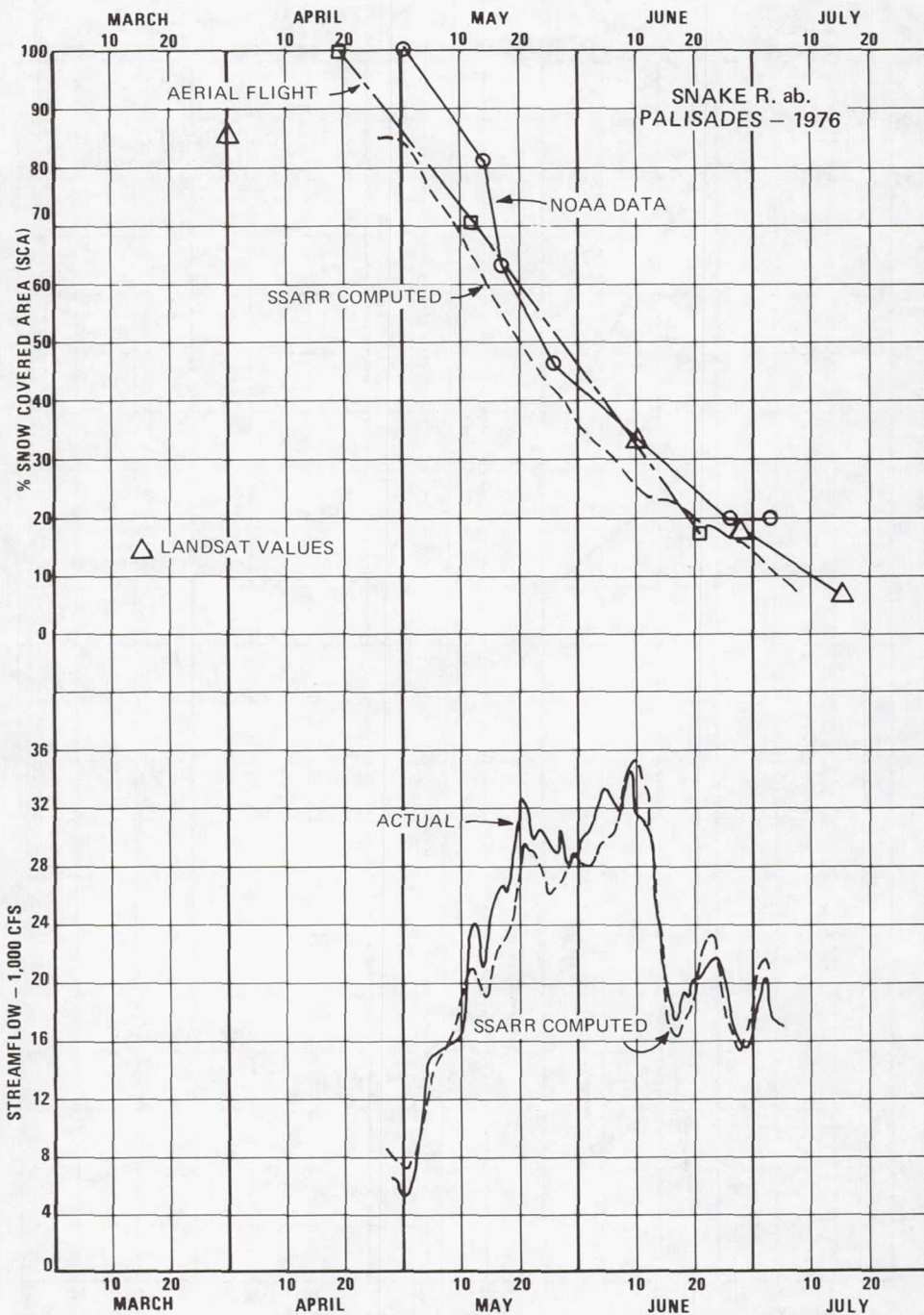Figure 13.   North Fork Clearwater above Dworshak - 1977

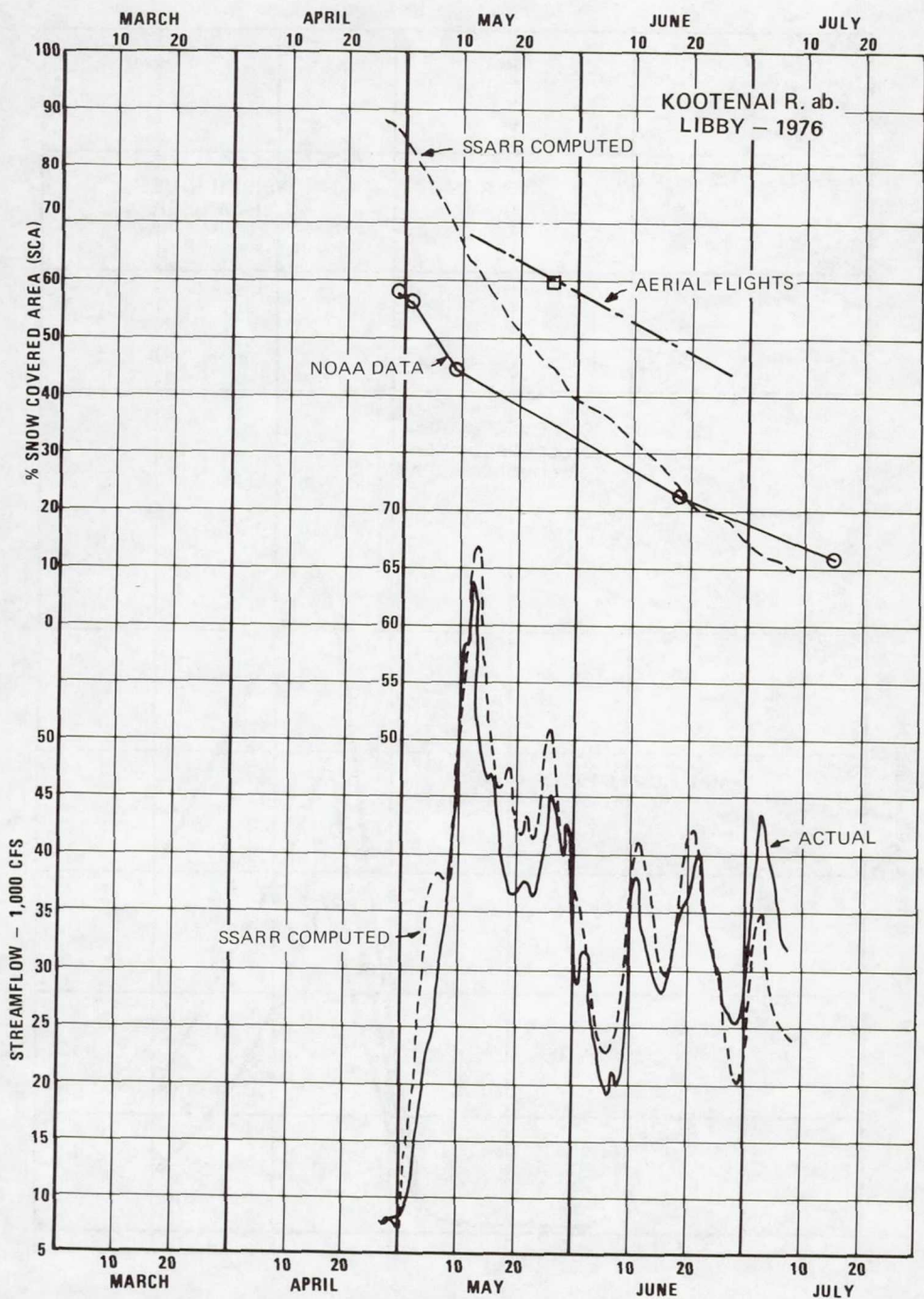Figure 14.   Snake River above Palisades - 1976

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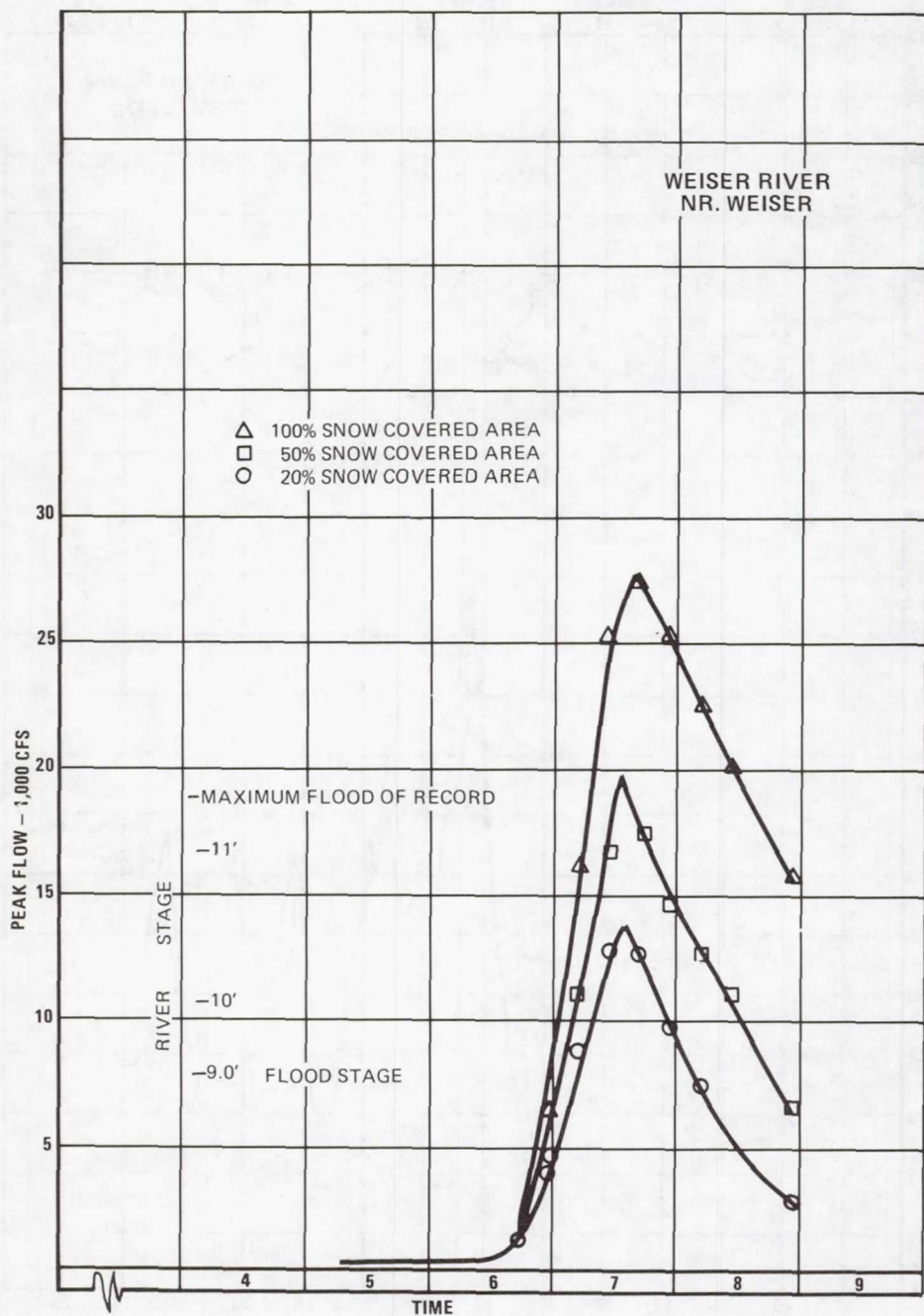Figure 15. Kootenai River above Libby - 1976

Figure 16. Weiser River near Weiser

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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 Operational Forecast Improvement

A 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 forecasting runs were made three to five times a week from April through June for a total of 49 forecasting runs. Comparisons were made for the 3-, 5-, 7-, and 14-day forecasts.

The chi-square test indicates that the dummy basin outperformed the standard basin forecasts for the 3-, 5-, and 7-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 progressed to a 3-day forecast. Based upon absolute average values, the dummy basin 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 have 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 forecast and the 14-day is purposely 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 190 cfs. The average computed inflow of the 49 values corresponding to the 5-day forecast is 7,291 cfs. The Geological Survey would give, at best, an accuracy to this measurement of ± 5 percent or 365 cfs. Thus, since the error reduction of 190 cfs is less than the overall accuracy of 365 cfs, the improvement gained by the exclusive use of satellite SCA data, unfortunately, is not statistically significant.

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CONCLUSIONS

Satellite-derived SCA data can be used to augment aerial snow-flight data, and vice versa. The satellite data provides many more additional SCA estimates than could be gathered from ground truth data alone. The satellite data improves forecasts, but not a statistically significant amount and, therefore, should not be used exclusively. Because of persistent cloud cover, forecasting routines should not be totally dependent upon the satellite data. The satellite data is an invaluable tool in fall and winter streamflow forecasting. Based upon the 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. The satellite data does not compare well with aerial snow-flight data in the Libby basin.

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. Portland's Cooperative River Forecast Center 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 River Forecast Center looks forward to an expansion of satellite snow-cover data, and also to possible use of other satellite-derived information such as soil moisture.