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AN OPERATIONAL APPLICATION OF SATELLITE SNOW COVER OBSERVATIONS - NORTHWEST UNITED STATES

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ABSTRACT

LANDSAT-1 imagery showing 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

The primary objective of this study was to map snowlines and determine the aerial snow cover using satellite data. A secondary objective was to compare satellite snow mapping products to products from conventional information sources. A long-term objective is to develop or modify methods in an operational mode to incorporate satellite-derived snow cover data to improve runoff forecasting techniques.

Available satellite data were successfully analyzed by radiance thresholding to determine snowlines and the attendant snow-covered area. Stanford Research Institute's capabilities were utilized for this task under a sub-contract from the Bonneville Power Administration. SRI utilized basin outline masks, contour elevation masks, and grid overlays as satellite data interpretation aids. The innovative use of grid overlays or boxes gives the ability to determine aerial snow cover by incremental elevations or bands.

Conventional data sources were used to verify the data obtained

from satellite imagery. A computer model capable of reconstituting streamflow was one such source used for this verification. Initialized and given daily temperature and precipitation values, the computer model accumulated and depleted the snowpack over a basin in order to generate streamflows at target locations; the snowpack over the basin expressed as a percent of basin coverage was used to verify the satellite snow cover data. Other conventional data sources used for the verification of the satellite snow cover data were the observations of extent of snow cover made by trained observers piloted over the basin in small aircraft flying at low altitude.

Verification of the LANDSAT-1 data was generally good although there were exceptions. A major problem was lack of adequate cloud-free satellite imagery of high resolution and determining snowlines in forested areas. Work to date indicates that the satellite determination of snow-covered area is a promising addition to our current forecasting methods.

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I. Introduction

This is the Final Report covering Phase 1 of Contract S-53877 and is intended to fully comply with the requirements for that phase of the contract. This study was a joint program of the Bonneville Power Administration and the Corps of Engineers, North Pacific Division. The program was funded by the National Aeronautics and Space Administration, and Dr. Mark Meier, U. S. Geological Survey, provided technical supervision.

A. Application

More than 85% of the electric energy produced in the Pacific Northwest comes from hydroelectric power generation. As of December 31, 1974, there were 159 hydroelectric plants which generate over 21 million kilowatts and 39 thermal plants which generate 3.6 million kilowatts. Both additional hydroelectric and thermal power plants are under construction. Existing, under construction, and authorized or licensed hydro plants total 34.6 million kilowatts; and thermal plants, 14.6 million kilowatts. With the addition of these new power plants, hydroelectric plants will still produce an impressive 70% of the total electric power generated. The hydro-based system in the Pacific Northwest makes this area second to none as a producer of hydroelectric power.

Streamflow in the Pacific Northwest has a highly seasonal variability. The bulk of the installed hydroelectric capability in the area is located between the Cascade Range and the Continental

Divide. In this portion of the basin, maximum runoff occurs in the late spring and early summer from melting snow when generation requirements are at a minimum. Conversely, electric loads peak in the winter when streamflows in this portion of the Columbia River Basin are at a minimum.

Storage projects in the upper portions of the Columbia River Basin capture spring runoff for release and power generation in the winter. Hungry Horse Dam, Montana; Dworshak Dam, Idaho; and Libby Dam, Montana, are typical of such storage projects. Water released from these dams generates power both at-site and at dams located downstream. At Bonneville Power Administration's (BPA's) wholesale firm power rates, one acre-foot of water released from Hungry Horse Dam generates $7.52 worth of power. A similar acre-foot of storage at Dworshak is worth $4.03, and Libby's storage is worth $4.66. If some or all of this storage can be used to displace oil-fired generation at $14.50 a barrel, an acre-foot's value is $48.52 at Hungry Horse; $30.02 at Libby; and $26.00 at Dworshak.*

Water impounded behind a hydroelectric storage project is drafted in the winter season according to the forecasted ability of the spring season snowmelt to refill that reservoir. Accurate forecasts are essential for proper reservoir operation. Libby Reservoir (Lake Koocanusa) failed to refill in 1975 by about 200,000 acre-feet because of inaccurate forecasts. Thus, forecasting

*The derivation of these values is given in the appendix.

procedures are subject to revision if any method can be found to improve the ability to predict rain or snowmelt-derived runoff.

B. Objectives

When this study was initiated late in 1974, LANDSAT-1 was the only known high resolution satellite data available for the spring of 1973 and 1974. This satellite imagery showing extent of snow cover was collected for the 1973 and 1974 snowmelt seasons for the following Columbia River Basins:

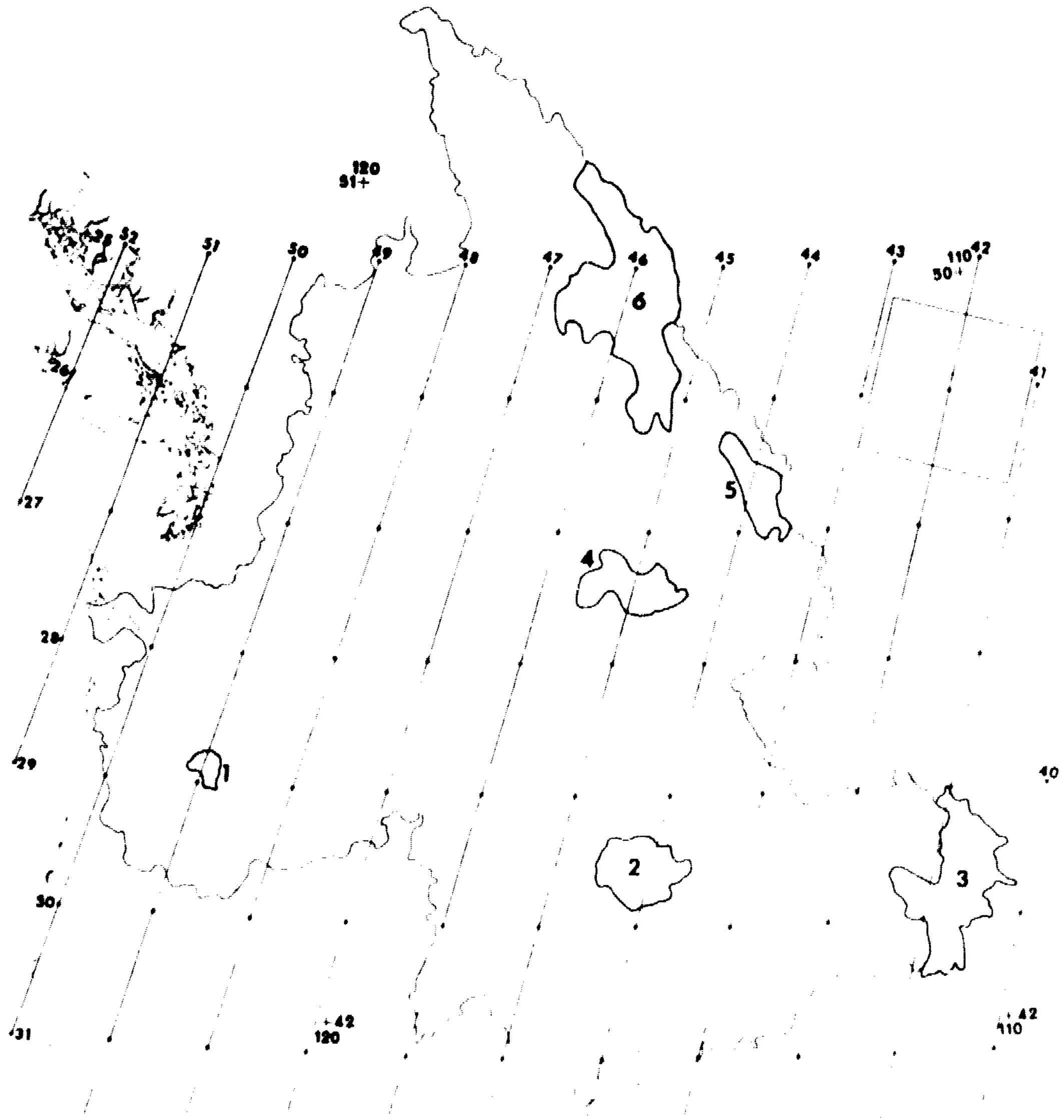
North Santiam River Basin (above Detroit Dam), Oregon

Upper Snake River Basin (above Palisades Dam), Idaho

Boise River Basin (above Lucky Peak Dam), Idaho

It was desired to include the basins above Hungry Horse, Libby, and Dworshak Dams in this program because of the value of power at these sites, and the need for improved forecasting techniques at these locations. However, because of persistent cloud cover over these basins in 1973 and 1974, the LANDSAT-1 imagery available was unusable and these basins had to be dropped from Phase 1 of this study. Satellite data from LANDSAT-1, LANDSAT-2, and SMS for 1975 is now being examined to determine adequate cloud-free coverage over the Flathead River above Hungry Horse Dam; the Kootenai River above Libby Dam; and the North Fork of the Clearwater River above Dworshak Dam, Figure 1.

The primary objective of Phase 1 was to map snowlines and determine the aerial snow cover and associated changes in snow cover using satellite data. A secondary objective was to compare satellite



Columbia River Subbasins

1. North Santiam (Detroit)
2. Boise
3. Upper Snake
4. Dworshak
5. Hungry Horse
6. Libby

FIGURE 1 NOMINAL ORBITAL TRACKS AND FRAME CENTER LOCATIONS OVER THE COLUMBIA RIVER BASIN snow-mapping products to products from conventional information sources. A long-term o' ective of this study is 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.

C. Method of Approach

LANDSAT-1 imagery was gathered for the snowmelt seasons in 1973 and 1974 for the North Santiam, Upper Snake, and Boise River Basins. A sub-contractor, Stanford Research Institute (SRI), under their SRI Project No. 4122-1, utilized this imagery to map snowlines and determine the aerial snow cover within each basin on different dates within each melt season. This snow cover, expressed as a percent of total basin area, was then used to determine the associated change in snow cover with time. SRI's final report[1] is included with this report from BPA.

Low level, over-snow aircraft flights are made by the Corps of Engineers during the spring melt season as an aid in forecasting flood peaks. Aerial snow cover data was used from these flights whenever possible as a conventional information source to compare with the satellite-gathered data.

The Columbia River Forecasting Service (CRFS) in Portland utilizes a Streamflow Synthesis and Reservoir Regulation (SSARR) computer program[2] in an operational mode as a tool to forecast reservoir inflow and river stages during the springtime flood threat. This streamflow routing program, as discussed later, uses snowpack accumulation and melt as one of the factors to determine reservoir inflow. The snow-covered area, expressed as a percent of basin drainage area, as computed in the SSARR model, was another conventional information source used to test the accuracy of the satellite-gathered snow cover data.

II. Basin Description

A. North Santiam

The North Santiam River above Detroit Dam drains an area of about 442 mi^2 (1146 km^2). The basin has a mean elevation of approximately 3865 ft MSL, and rises form 1560 ft MSL at the dam's water surface to 10,497 ft MSL atop Mt. Jefferson. Essentially all of the basin is above 2000 ft, but only about 5% of it is above 6000 ft 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. Tha basin has a relatively low mean elevation and thus snow may melt soon after falling. This basin was chosen primarily for the work being done by Dr. Mark Meier to test snow cover area methods.

B. Upper Snake

This basin includes approximately 5150 mi^2 (13,340 km^2) above Palisades Reservoir. The basin rises from 5620 ft MSL at the reservoir to 13,766 ft MSL on Grand Teton. The mean elevation is 7900 ft MSL and virtually all of the basin lies above 6000 ft. The entire basin lies high enough that snow is present year-around on a significant portion of the basin area lying above the 9000 ft elevation.

C. Boise

The Boise Basin drains approximately 2800 mi^2 (7254 km^2) above Lucky Peak Dam. Basin elevations vary from 10,651 ft MSL atop Snowyside Peak to 3060 ft MSL at the dam's water surface. Virtually all of the basin is above elevation 4000 ft with a mean elevation of 6200 ft MSL. 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.

III. Measurement Techniques

A. Satellite Snow Cover Data

LANDSAT-1 imagery was inventoried for snow coverage by single-band (MSS-5) radiance thresholding with subjective editing using basin masks, elevation contours, and other reference data as a guide. The satellite orbital tracks and the frame coverage for the three basins studied are shown on Figure 1. One LANDSAT frame will generally cover the North Santiam Basin, and this basin was used to develop detailed procedures. About two frames are needed to cover the Boise Basin and from two to four frames are required for the

Upper Snake Basin. LANDSAT imagery was entered into SRI's Electronic Satellite Image Analysis Console (ESIAC) TV screen at a scale for each view of approximately 55 x 40 km, or .5° longitude by .5° latitude. This scaling approximately matched the TV display resolution to the LANDSAT imagery resolution. This magnification required one TV view for the North Santiam Basin, four views for the Boise Basin, and eleven views for the Upper Snake Basin.

The binary thematic maps, which were generated to depict the snow cover for each date and TV view that were measured, were documented through different methods: (1) Photography; (2) a numerical pixel count representative of the total area of snow in the scene and within the basin boundary; and (3) an array of single-digit numbers depicting tenths of snow cover for each 2.5 x 2.5 km cell within the basin.

1. Data Interpretation and Verification Aids

a. Basin Outline Masks. Basin outline masks were generated by tracing the basin outline on white paper; the basin proper was painted black and photographed, producing a negative transparency at the scale of the LANDSAT imagery. In this way the original black area became clear permitting only the basin proper to show through the mask when the mask was superimposed on the satellite imagery, thus providing the basin boundary within which the binary products would appear during radiance thresholding.

b. Contour Elevation Masks. The contour elevation masks were produced using even 1000 ft increments of elevation in the same manner as the basin outline masks. When a contour elevation mask was overlaid on the satellite imagery, only that portion of the basin of higher elevation than that of the mask was viewable for radiance thresholding. No basin was subdivided by contour elevation masks at an altitude above that of the permanent snowline. In instances of partial cloudiness, these masks can establish a snowline and, assuming that the contoured snowline is similar throughout the basin, an inferred estimate of snow cover can sometimes be obtained for the total basin. (Under such cloudy conditions, this cannot be accomplished by radiance thresholding alone.)

c. Grid Overlays. The drainage pattern within a basin, including rivers, lakes, and other features identifiable in the satellite imagery, was traced onto white paper from U.S. Geological Survey (USGS) maps. The universal transverse mercator (UTM) grid was also traced from USGS maps and subdivided into 2.5 x 2.5 km grid squares. This tracing was photographed, adjusted to the appropriate scale, and developed as a positive transparency on stable film.

2. Radiometric Analysis by ESIAC. Normal data entry to the ESIAC are positive film transparencies of satellite imagery. The system scans these images with a TV camera, and, at the same time, makes available the scene radiance data in electrical form. By scanning and storing the gray-scale calibration step tablets along with the images, radiometric measurements can be made with a relatively high degree of accuracy.

a. Edited Single-Band Thresholding. Clean, well-illuminated snow exhibits radiance that is always greater than the radiance (in the visible region) of other scene constituents found in mountain regions. Thus, measurements for a significant portion of the complete snow scene could be extracted by the relatively simple process of recording only those scene elements (pixels) where the radiance or brightness exceeded some specified threshold. The first-attempt processing of these images inherently missed some snow-covered areas because of low radiance resulting primarily from shadowing due to low sun angle at this time of year, patchiness, and tree cover. Areas in a TV scene were painted black, painted white, or the radiance threshold was subjectively biased upward or downward by the ESIAC operator/analyst to compensate for these errors. The elevation contour masks were superimposed for this "second-try" to aid the analyst in making the thematic extractions.

The binary snow map created by the analyst was confined within the basin boundary by performing a logical AND operation between the snow mask and a registered full-basin outline mask stored in one of the ESIAC memory tracks. The resulting binary product was then stored on another memory track for subsequent photography and digital readout.

b. Measurement of Binary Product. The completed thematic map is composed of TRUE or FALSE (snow or no snow) pixels. The

TRUE pixels can then be totaled on a counter contained in the ESIAC to measure the total snow area.

The basin snow-covered area was also read out or totalized by grid boxes of 2.5 x 2.5 km land area. This incremental summation of snow-covered area permits objective comparisons with detailed photo-interpretation results and also permits later machine sorting of the data--for example, according to elevation bands.

Each 2.5 x 2.5 km grid box contained 625 scene elements in an array of 25 x 25 pixels; and each TV view included about 384 grid boxes in an array 24 wide by 16 high. The total pixel count in each grid box was divided by 625 (and then multiplied by 10) to arrive at tenths of snow cover within that box. An X was used to indicate a full box or 10/10's coverage. This process or reducing the pixel count to a single-digit representation of tenths of cover per grid box greatly reduced data storage requirements in the machine's disc file, while yet preserving the detail required for elevation band and photographic interpretation and verification of the data.

B. Over-Snow 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 a 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. 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.

C. Snowpack Depletion by Computer

The National Weather Service; the Corps of Engineers, North Pacific Division; and the Bonneville Power Administration are cooperators in the Columbia River Forecasting Service to pool certain resources of the agencies in the interest of improving streamflow forecasting methods, to provide uniform forecasts, and to increase the efficiency of operation. Daily operational runoff forecasts for streams in the Pacific Northwest are made using the Corps' 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:

$$m = (T_A - T_b)R\left[\frac{PH}{24}\right]$$

where

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

T_A = Period temperature 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.

Two methods are available to evaluate snowmelt from a watershed. The basin method evaluates the snow-covered area runoff relationships using a snow cover depletion function. The other method divides the watershed into elevation increments or bands with each band being examined separately with respect to snow accumulation and melt. Studies are now underway to evaluate the elevation band method of determining watershed snowmelt for some sub-basins in the region.

At the conclusion of each flood season, a streamflow reconstruction or reconstitution run is made for each basin with the SSARR model. This streamflow run has no forecasted values in it. The streamflows are initialized at target points in the basin with actual values. Thereafter, throughout the time frame of the flood season, actual 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. When compared with the observed hydrograph, a reconstitution run provides a visual check on the accuracy of the basin characteristics utilized in the model.

IV. Summary of Measurements

A. North Santiam

Measurements of snow cover from satellite imagery for the North Santiam Basin are presented in Table 1. Very adequate satellite coverage was obtained for this basin, clearly demonstrating, for this project, that satellite imagery can be utilized to map snowlines and determine aerial snow cover and associated changes in snow cover as the melt season progresses. Because the North Santiam Basin produces flooding primarily from winter rainstorms flowing in from the Pacific Ocean, and not from spring snowmelt,

Table 1

North Santiam Basin Snow Coverage

Basin Area = 442 mi^2 Average Elevation ~ 3900 ft MSL

Date	% of Basin Area Covered by Usable Imagery	Snow Coverage	
		Area (mi^2)	% of Basin Area*
1973			
6 January	100	331.4	74.9
11 February	100	344.2	77.8
6 April	100	200.4	45.3
24 April	100	183.6	41.5
12 May	100	79.2	17.9
1974			
1 January	100	376.5	85.1
6 February	100	387.2	87.5
24 February	100	417.3	94.3
12 June	100	156.6	35.4
30 June	100	73.4	16.6

*Derived by dividing the measured snow area within the basin by the viewable area within the basin.

no streamflow reconstitutions or snow flights were made for this basin. However, the satellite data were visually compared with the actual daily forecast-basis SSARR runs and with data derived by the National Weather Service and showed good correlation.

B. Upper Snake

In the Upper Snake Basin, cloud cover in 1973 rendered LANDSAT-1 imagery useless except for 29 March, 22 May, and 9 June. No aircraft snow flights were made in 1973 because this was a low runoff year and there was no flood potential. Agreement between the SSARR reconstituted data using the temperature index and the LANDSAT-1 data for 1973 was fair. The large gap between 29 March and 22 May missed the high runoff which started in mid-May and peaked on 22 May. In 1974 the only usable LANDSAT-1 image occurred on 22 June--well after any flood threat or snow flight, and too late in the season for reconstitution runs. These snow cover data for the Upper Snake Basin are given in Table 2.

C. Boise

Measurements of snow cover from satellite imagery and from the SSARR reconstitution runs for the Boise Basin are presented in Table 3. In the Boise Basin also, no snow flights were made in 1973 because of the lack of flood potential. However, the SSARR reconstitutions show very good agreement with the LANDSAT-1 data--particularly during the runoff period.

Table 2

Upper Snake Basin Snow Coverage

Basin Area = 5150 mi^2 Average Elevation ∿ 8000 ft MSL

Date	% of Basin Area Covered by Usable Imagery	Snow Coverage		
		Area (mi^2)	% of Basin Area	
			LANDSAT*	SSARR
1973				
29 March	96.9	4590.0	92.0	100
22 May	95.0	1980.1	40.5	33
9 June	94.9	671.4	13.7	19
1974				
22 June	96.8	749.9	15.3	

*Derived by dividing the measured snow area within the basin by the viewable area within the basin.

Table 3

Boise Basin Snow Coverage

Basin Area = 2800 mi^2 Average Elevation ∿ 6000 ft MSL

Date	% of Basin Area Covered by Usable Imagery	Snow Coverage		
		Area (mi^2)	% of Basin Area	
			LANDSAT*	SSARR
1973				
19 April	100	1834.1	65.5	54
7 May	100	876.6	31.3	32
12 June	100	229.3	8.2	6
30 June	100	107.6	3.7	2
1974				
14 April	100	2076.1	74.1	57
2 May	100	1007.5	36.0	34
25 June	100	194.8	7.0	6

*Derived by dividing the measured snow area within the basin by the viewable area within the basin.

The Boise Basin data for 1974 are of particular interest. Very good agreement is evident between the satellite and the SSARR data except for 14 April where the reconstitution data shows 57 percent and the satellite data shows 74.1 percent coverage. The probable cause of this disagreement was a thin skin of new snow that fell on 12 April. This new snow extended below the 4000 foot elevation and showed up on the satellite imagery; but, because of its transitory nature, provided little in the way of runoff.

Snow cover measurements were available in the Boise Basin in 1974 from satellite imagery, SSARR resonstitutions, and low-altitude aircraft flights. These data have been compared with the actual hydrograph for the Boise Basin and are depicted on Figure 2. As can be seen, the correlation is very good.

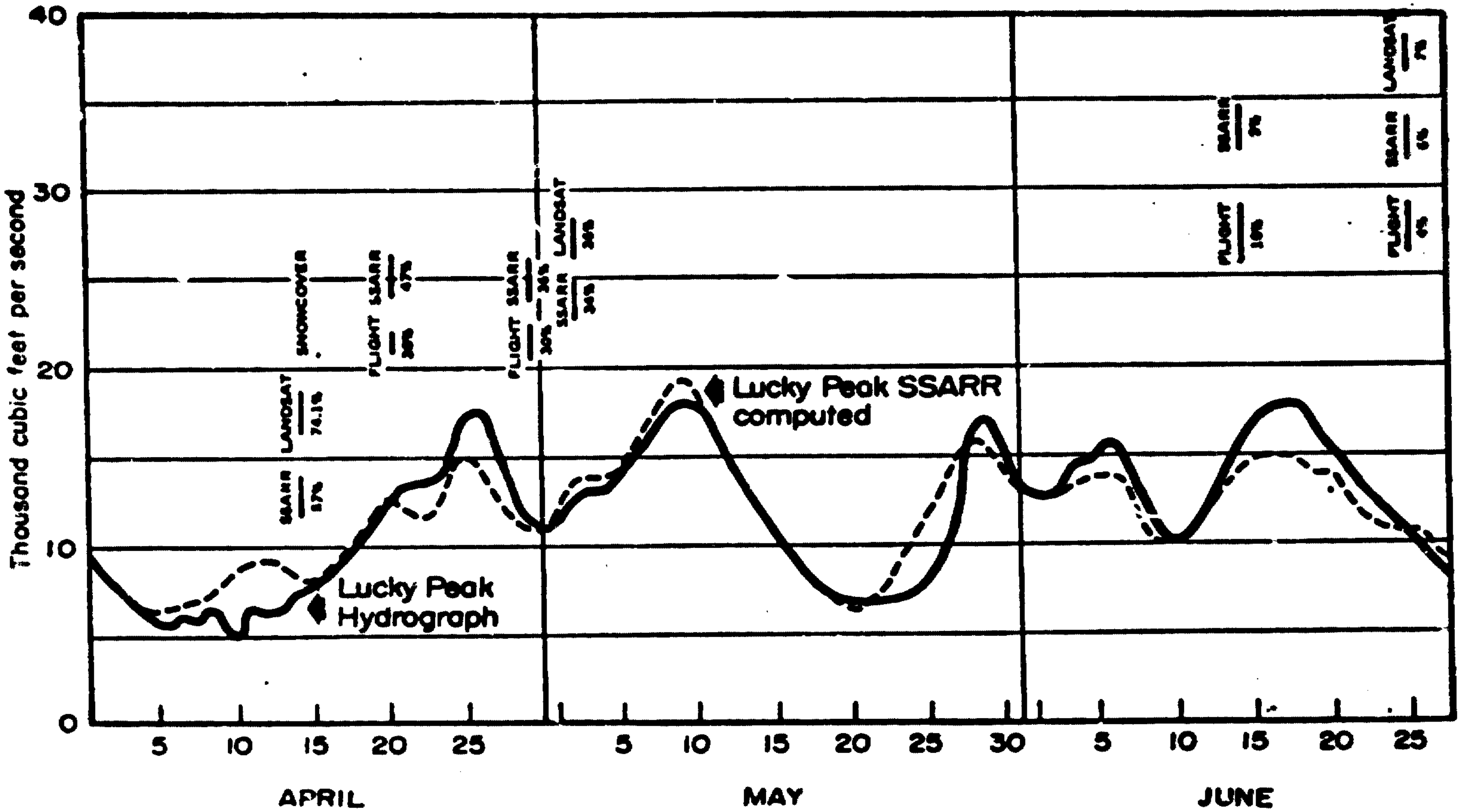
V. Conclusions and Remarks

Work in the North Santiam Basin has demonstrated that satellite imagery can be used to map snowlines and determine aerial snow cover. Work in the Boise Basin in both 1973 and 1974 shows good agreement between satellite data and that derived from conventional (SSARR reconstitution and snow flight) sources.

The unavailability of adequate satellite data for the Hungry Horse, Libby, and Dworshak Basins; and the large gaps in satellite data for the Upper Snake Basin, show that it is still too early to draw any definite conclusions on the use of satellite data for determining

Figure 2

Boise Basin above Lucky Peak Dam
Hydrograph and SSARR Computed Flows



snow cover in the Pacific Northwest region. Problems yet to be resolved include coping with the large number of cloud-covered days, determining snowlines in forested areas, and working with data from the Synchronous Meterological Satellite (SMS) which lacks high resolution.

The addition of new satellites this past year and future improvement in resolution should materially improve satellite data. We have not yet tested the turn-around time to get satellite imagery from the receiver stations to the user for a real-time application. Work to date shows that the satellite determination of snow-covered area is a promising addition to our current forecasting methods.

Continuation of this project--particularly in light of the deep snowpack and late runoff experienced in 1975--should provide us with much added information. We are much indebted to NASA/GSFC for supporting this valuable project.

Appendix

Value of Storage at Selected Reservoirs

I. H/K Sum

The generation potential of a dam, both at-site and downstream, is termed the H/K sum. System power studies are made to determine an average H/K sum over a variety of hydroelectric conditions. A study was made for FY 1976 level of electrical loads using each plant's average efficiency for critical water conditions. Reservoirs were operated on the critical rule curve which cycles from full to empty over the duration of the critical period. The values so determined were as follows:

Reservoir	H/K Sum (kWh/cfs)	
Hungry Horse	174.19	includes all Federal and non-Federal downstream
Libby	107.79	
Dworshak	93.33	
Grand Coulee	87.54	

II. Energy per Acre-Foot

$$\frac{174.19\ \text{kW}}{\text{ft}^3/\text{sec}} \times \frac{43{,}560\ \text{ft}^3}{\text{Ac-ft}} \times \frac{1\ \text{hr}}{3600\ \text{sec}} = 2.10770 \times 10^3\ \text{kWh/Ac-ft at Hungry Horse}$$

107.79 ----------------------------→ 1.30426×10^3 kWh/Ac-ft at Libby

93.33 ----------------------------→ 1.12929×10^3 kWh/Ac-ft at Dworshak

87.54 ----------------------------→ 1.05923×10^3 kWh/Ac-ft at Grand Coulee

III. Value of Energy

The energy was evaluated at BPA's firm rates, even though some is non-Federal energy and some is not firm energy but only secondary energy. This was considered a conservative estimate in that the non-Federal energy would not be wholesaled but would be retailed to the actual consumer at a much higher rate. The BPA rate employed was the EC-6 rate which has a charge for both the electrical energy delivered and for the peak amount of the energy demanded. On the overall system, this ratio of energy to peak, or system load factor, for the period July 1, 1975, through June 30, 1976, is approximately 67%. The EC-6 rate would therefore have an average annual charge of:

$$\left[\left(\frac{4.05\ \text{mills}}{\text{kWh}} \times 7\ \text{mo}\right) + \left(\frac{2.90\ \text{mills}}{\text{kWh}} \times 5\ \text{mo}\right)\right] \div 12\ \text{mo} = 3.57\ \text{mills/kWh}$$

$$\frac{2.10770 \times 10^3\ \text{kWh}}{\text{Ac-ft}} \quad \frac{3.57\ \text{mills}}{\text{kWh}} \quad \frac{\text{dollar}}{10^3\ \text{mills}} = \text{\$7.52/Ac-ft at Hungry Horse}$$

1.30426×10^3 ------------------------------→ \$4.66/Ac-ft at Libby

1.12929×10^3 ------------------------------→ \$4.03/Ac-ft at Dworshak

1.05923×10^3 ------------------------------→ \$3.78/Ac-ft at Grand Coulee

IV. Displacing Oil-Fired Generation

If storage generation is used to displace oil-fired generation, and this low-sulphur oil has a price of \$14.50 per barrel and the energy in a barrel is 630 kWh, then the value of this energy is:

$$\frac{\$14.50}{\text{barrel}} \times \frac{10^3\ \text{mills}}{\text{dollar}} \times \frac{1\ \text{barrel}}{630\ \text{kWh}} = 23.02\ \text{mills/kWh}$$

or the value of storage at various reservoirs would be:

$$\frac{2.10770 \times 10^3 \text{ kWh}}{\text{Ac-ft}} \times \frac{23.02 \text{ mills}}{\text{kWh}} \times \frac{\text{dollar}}{10^3 \text{ mills}} = \text{\$48.52/Ac-ft at Hungry Horse}$$

1.30426×10^3 ----------------------------------→ \$30.02/Ac-ft at Libby

1.12929×10^3 ----------------------------------→ \$26.00/Ac-ft at Dworshak

1.05923×10^3 ----------------------------------→ \$24.38/Ac-ft at Grand Coulee

Bibliography

(1) Weigman, E. J., W. E. Evans, R. Hadfield, July 1975: Measuring Snow Cover Using Satellite Imagery During 1973 and 1974 Melt Season: North Santiam, Boise, and Upper Snake Basins, Final Report, Phase 1, SRI Project 4122-1, Stanford Research Institute, Menlo Park, Ca., 72 pp.

(2) U.S. Army Engineer Division, North Pacific, 1975: Program Description and User Manual for SSARR Model Streamflow Synthesis and Reservoir Regulation, Program 724-K5- G0010, Portland, Or., 188 pp.

(3) Limpert, F. A., 1975: Operational Application of Satellite Snow Cover Observations--Northwest United States, paper presented at Workshop on Operational Applications of Satellite Snow Cover Observations, Aug. 18, 1975, South Lake Tahoe, Ne.