Paper No. 6

N76-16567

OPERATIONAL APPLICATION OF SATELLITE SNOWCOVER OBSERVATIONS — NORTHWEST UNITED STATES

Fred A. Limpert, *Bonneville Power Administration, Head, Hydrology Section*

ABSTRACT

A demonstration project has been undertaken in the Pacific Northwest to determine the applicability of satellite snowcover observations for operational use in three test areas of the Columbia River Basin.

INTRODUCTION

Operational application of satellite snowcover observations in the Northwestern United States is one of several demonstration projects sponsored by the National Aeronautics and Space Administration's Goddard Space Flight Center. A contract was entered into between NASA and the Bonneville Power Administration and the North Pacific Division, Corps of Engineers. BPA is the primary contracting agency with Dr. Mark Meier of the Geological Survey acting as the technical field advisor. This contract implements a study using satellite data for determining snowcover area which is a prime factor in forecasting runoff for flood control and power operation.

APPLICATION

More than 80 percent of the electric energy produced in the Pacific Northwest comes from hydroelectric power generation. As of December 31, 1974, there are 159 hydroelectric plants which generate over 21 million kilowatts and 39 thermal plants which generate 3.6 million kilowatts. An additional 8.6 million kilowatts of hydro is under construction with another 5.0 million authorized or licensed. There are 2.4 million kilowatts of thermal under construction and 8.6 million kilowatts licensed. Existing, under construction, and authorized or licensed hydro plants total 34.6 million kilowatts and thermal plants 14.6 million kilowatts.

The hydro-based system in the Pacific Northwest makes this area second to none as a producer of hydroelectric power. The hydroelectric projects of the region have been undertaken by private utilities, public agencies, municipalities, and the United States Federal Government. These developments take into consideration all of the multipurpose uses such as power, flood control, irrigation, recreation, pollution control, and navigation.

Preceding page blank

Although considerable development has been undertaken by all participating agencies, the larger multipurpose developments have been constructed by the Corps of Engineers and the Bureau of Reclamation. Nearly all of the economically feasible hydro sites have been developed and thermal power plants will be needed more and more to meet the ever growing power load of the area. Eventually thermal will carry the base load with hydro providing the peak power requirements. There are still some feasible flood control sites in the area. Under all of these conditions, an accurate forecast of volume runoff for proper scheduling of the river operation to meet all of the multipurpose project uses is of paramount importance, Figure 1.

The Columbia River Basin contains more than 668,200 km^2 (258,000 mi^2), almost twice the size of California. The Basin contains most of Washington, Oregon, and Idaho; that part of Montana west of the Rocky Mountains; small areas of Wyoming, Utah, and Nevada; and the southeastern part of British Columbia.

The Columbia River is second only to the Mississippi in average runoff for rivers in the United States. The average annual precipitation over the Basin is about 71 cm (28 in). Of this amount, 30.5 cm (12 in) is returned to the atmosphere by evapotranspiration and 2.54 cm (1 in) of the amount withdrawn for beneficial use is consumed leaving 38 cm (15 in) for runoff. This amount is equivalent to 228 billion m^3 (185 million acre-feet) of water annually or a flow of 7220 m^3 per second (255,000 cubic feet per second). Average flows for key power points in the Basin are shown in Table 1.

Flow records of the Columbia River at The Dalles, Oregon, cover a period of over 96 years. During this time, the flows have ranged from a low of 991.1 m^3/s (35,000 ft^3/s) on January 12, 1937, to a high of 35,112.9 m^3/s (1,240,000 ft^3/s) on June 6, 1894. The high flow is about six times the long-term average of 5493.5 m^3/s (194,000 ft^3/s) at The Dalles and the low flow is about one-sixth the average.

Storage projects in the Basin are used to regulate the streamflow runoff. There are 25.5 billion m^3 (20.7 million acre-feet) of storage in Federal reservoirs, 5.8 billion m^3 (4.7 million acre-feet) in non-Federal reservoirs, and 19.1 billion m^3 (15.5 million acre-feet) in the reservoirs in the Canadian portion of the Basin. Thus, usable storage capacity for power projects existing, under construction, and authorized or licensed totals about 50.4 billion m^3 (41 million acre-feet). Optimal storage in the Basin is estimated to be somewhat in excess of 61.7 billion m^3 (50 million acre-feet). The ratio of runoff to storage available provides a measure of the usability of the water available. A comparison of the Columbia, the Colorado, and the Missouri project storage capacities is shown in Table 2. From these figures it can be seen that the capacity of the Colorado and Missouri projects are several times the average annual runoff. Conversely, the reservoir storage capacity in the Columbia River system is about one-quarter the average runoff. The low ratio of reservoir capacity to average runoff in the Columbia system can produce large amounts

MAJOR POWER PROJECTS OF THE PACIFIC NORTHWEST

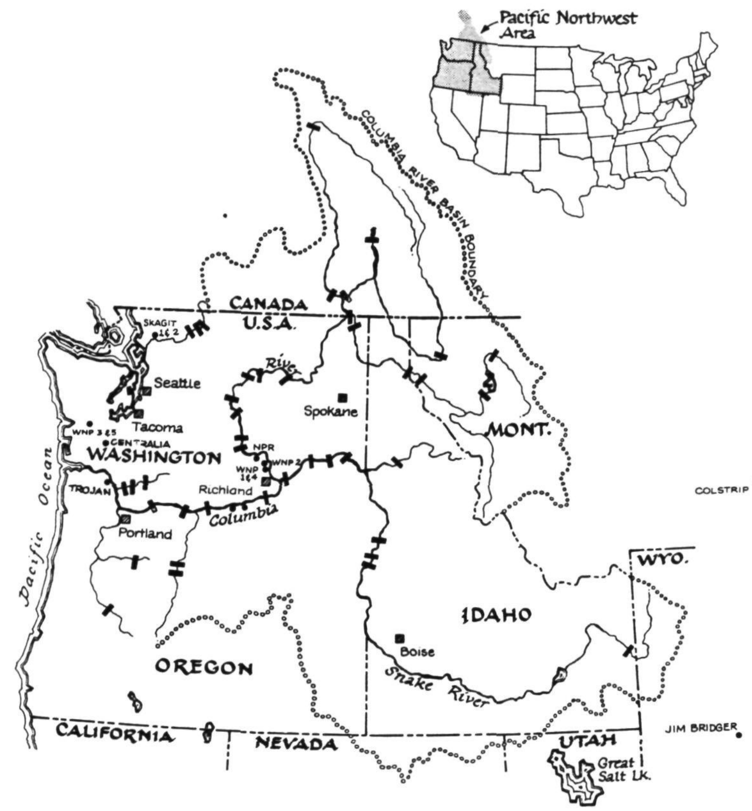

Figure 1

TABLE 1 Average Flow for Period July 1928, Through June 1968, Adjusted to 1970 Level of Development

Project	Annual Runoff Million Acre-Feet	kcfs
MOUTH OF COLUMBIA RIVER	185.0	255.0
Bonneville	132.8	183.3
The Dalles	128.9	177.9
John Day	124.9	172.4
McNary	123.0	169.8
Ben Franklin	85.9	118.5
Priest Rapids	85.8	118.4
Wanapum	85.7	118.3
Rock Island	85.6	118.2
Rocky Reach	83.1	114.7
Wells	81.5	112.5
Chief Joseph	78.2	108.0
Grand Coulee	78.0	107.7
Murphy Creek	51.4	70.9
Hugh Keenleyside	29.0	40.2
Revelstoke Canyon	20.9	28.8
Downie Creek	18.7	25.8
Mica	14.9	20.5
Calamity Curve	4.7	6.5
Luxor	1.4	1.9
DESCHUTES RIVER		
Pelton	3.1	4.3
SNAKE RIVER		
Ice Harbor	34.6	47.7
Lower Monumental	34.6	47.7
Little Goose	34.2	47.2
Lower Granite	34.1	47.1
Asotin	23.1	31.9
China Gardens	20.6	28.5
Appaloosa	12.4	17.1
Oxbow	12.0	16.5
SNAKE RIVER TRIBUTARIES CLEARWATER RIVER		
Lenore	10.2	14.1
N. F. CLEARWATER RIVER		
Dworshak	4.1	5.6
M. F. CLEARWATER RIVER		
Penny Cliffs	4.9	6.7
GRAND RONDE RIVER		
Wenaha	2.1	2.9
SALMON RIVER		
Lower Canyon	7.8	10.8
Freedom	7.7	10.6
Crevice	7.0	9.7
CHELAN RIVER		
Chelan	1.4	2.0
SPOKANE RIVER		
Long Lake	5.7	7.8
Nine Mile	5.2	7.2
Monroe Street	4.9	6.7
Post Falls	4.5	6.2
PEND ORIELLE RIVER		
Waneta	20.1	27.8
Boundary	19.4	26.8
Box Canyon	18.8	26.0
Albeni Falls	18.3	25.3
Cabinet Gorge	15.8	21.8
Noxon Rapids	14.1	19.4
Thompson Falls	14.3	19.8
FLATHEAD RIVER		
Buffalo Rapids No. 4	8.5	11.8
Kerr	8.0	11.5

TABLE 1 Average Flow for Period July 1928, Through June 1968,
Adjusted to 1970 Level of Development
(continued)

Project	Annual Runoff Million Acre-Feet	kcfs
S. F. FLATHEAD RIVER		
Hungry Horse	2.5	3.5
KOOTENAY RIVER		
Brilliant	22.2	30.6
Corra Linn	20.0	27.6
Katka	10.2	14.1
Kootenai Falls	9.0	12.4
Libby	8.2	11.3
Bull River	4.4	6.1
DUNCAN RIVER		
Duncan Reservoir	2.5	3.5
WILLAMETTE RIVER		
Sullivan	22.2	30.6
CLACKAMAS RIVER		
North Fork	2.0	2.7
OAK GROVE FORK		
Oak Grove	0.4	0.5
Timothy Meadows	0.7	0.1
NORTH SANTIAM RIVER		
Detroit	1.5	2.1
SOUTH SANTIAM RIVER		
Foster	1.8	2.5
MIDDLE SANTIAM RIVER		
Green Peter	1.2	1.6
MCKENZIE RIVER		
Walterville	3.3	4.5
Leaburg	3.1	4.3
S. F. MCKENZIE RIVER		
Cougar	0.6	0.8
M. F. WILLAMETTE RIVER		
Lookout Point	2.1	2.9
Hills Creek	0.8	1.1
COWLITZ RIVER		
Mayfield	4.4	6.1
Mossyrock	3.7	5.1
LEWIS RIVER		
Ariel	3.5	4.8
Yale	2.8	3.9
Swift No. 2	2.1	2.9
BAKER RIVER		
Lower Baker	1.9	2.6
Upper Baker	1.4	2.0
SKAGIT RIVER		
Gorge	3.3	4.5
Diablo	3.0	4.1
Ross	2.5	3.4
NISQUALLY RIVER		
La Grande	1.0	1.4
SKOKOMISH RIVER		
Cushman Nol 2	0.6	0.8

BPA - Branch of Power Resources
April 22, 1975

TABLE 2 Flow and Storage - Columbia, Colorado and Missouri Rivers

	Storage Capacity Billion m^3 1/	Annual Runoff Billion m^3 1/			Headwater Elevation meters 2/	Drainage Area Billion m^2 3/
		Average	Maximum	Minimum		
Columbia	50.6 (41)	228.2 (185)	315.8 (256)	149.3 (121)	807.7 (2.65)	668.2 (258)
Colorado	66.6 (54)	17.3 (14)	27.1 (22)	4.9 (4)	2652.0 (8.70)	626.8 (242)
Missouri	92.5 (75)	29.6 (24)	45.6 (37)	13.6 (11)	2134.0 (7.00)	1364.9 (527)

1/ Figures in ( ) are x 10^6 acre-feet.
2/ Figures in ( ) are mean sea level in feet x 10^3.
3/ Figures in ( ) are miles^2 x 10^3.

of secondary energy. This low storage to runoff ratio and the large difference in average and maximum streamflow at The Dalles, Oregon, shows the need for accurate volume runoff forecasting and optimum use of storage for flood regulation.

The National Weather Service (NWS), the Corps of Engineers, North Pacific Division (USCE, NPD), and the Bonneville Power Administration (BPA) are cooperatives in the Columbia River Forecasting Service (CRFS). The overall goal of the CRFS is 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 unsing the Streamflow Synthesis and Reservoir Regulation (SSARR) computer model. The program description and user manual along with associated publications referenced in the manual provide detailed background on the development of the model and how it is used for operational river forecasting and river management activities (1).

One of the major factors in runoff in the Columbia River Basin is snowmelt. Snowmelt calculation with the SSARR model is made by the temperature index method or by the use of the generalized snowmelt equation for a partly forested area. At the present time we are using the temperature index method for day-to-day forecasts. In general, the snowmelt equation is not used for daily operational forecasts because of the lack of real time energy budget data.

Snowmelt runoff in inches is determined for the snow area using the temperature index method:

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

where

- m = Snowmelt runoff in inches of water over the snowcover 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 to either minimum, mean, or maximum daily temperature daily temperature data. Melt rates can be specified for each day of the run 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 snowcover depletion function. The other method divides the watershed into elevation bands with each band being examined separately with respect to snow accumulation and melt. Studies are now underway to evaluate this second method for some of the sub-basins in the region.

Snowcover observations in the United States portion of the Basin are made 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 the British Columbia Hydro and Power Authority. Observations of this type are made by experienced personnel and must, of necessity, be subjective. Two to four flights are generally made each season for each area depending upon the type of season and flying conditions. In the United States portion of the Basin, flights generally occur in April, May, and June and in the Canadian portion in May and June. Though quite effective, these flights may present a safety problem and are relatively expensive.

The satellite data collection program provided an excellent opportunity for testing aerial snowcover observations as an alternate to such determination by small aircraft. BPA and the Corps of Engineers formulated a proposal to the National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/GSFC) to study snowcover observations which would hopefully improve forecasting procedures.

The primary contracting agency was BPA. A Memorandum of Understanding was signed to cover contractual work for one year by BPA and the Corps of Engineers for NASA/GSFC. Work included: (1) the mapping of snowcover in three candidate areas for the 1973 and 1974 spring melt seasons, (2) imput of snowcover information in the SSARR model for reconstitution of the temporal distribution of the spring melt runoff, and (3) compare results with reconstitutions made with the conventional data for the past two seasons.

The basins studied are: the Boise River above Lucky Peak Dam, drainage area 7254 km^2 (2800 mi^2); North Santiam River above Detroit Dam, drainage area 1132 km^2 (437 mi^2); and the upper Snake River above Palisades Dam, drainage area 13,489 km^2 (5208 mi^2). These three basins were chosen initially because of some associated work being done by Dr. Mark Meier of the Geological Survey on the Santiam Basin, reconstitution work already done by the Corps of Engineers and the National Weather Service on the Boise and Snake River Basins, and because it was expected that adequate satellite imagery would be available. Satellite data for 1975 is being examined now 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 2.

Imagery from the Earth Resources Satellite, LANDSAT-1, was assembled for the 1972-73 and 1973-74 snowmelt season. This imagery was processed under a subcontract with Stanford Research Institute (SRI) utilizing its Electronic Image Analysis Console (ESIAC) to determine the percentage of snowcover area (2). The SRI ESIAC greatly expands the capability of the human analysts, particularly their ability to effectively use time-sequence, multispectral imagery and provide objective and repeatable mea-

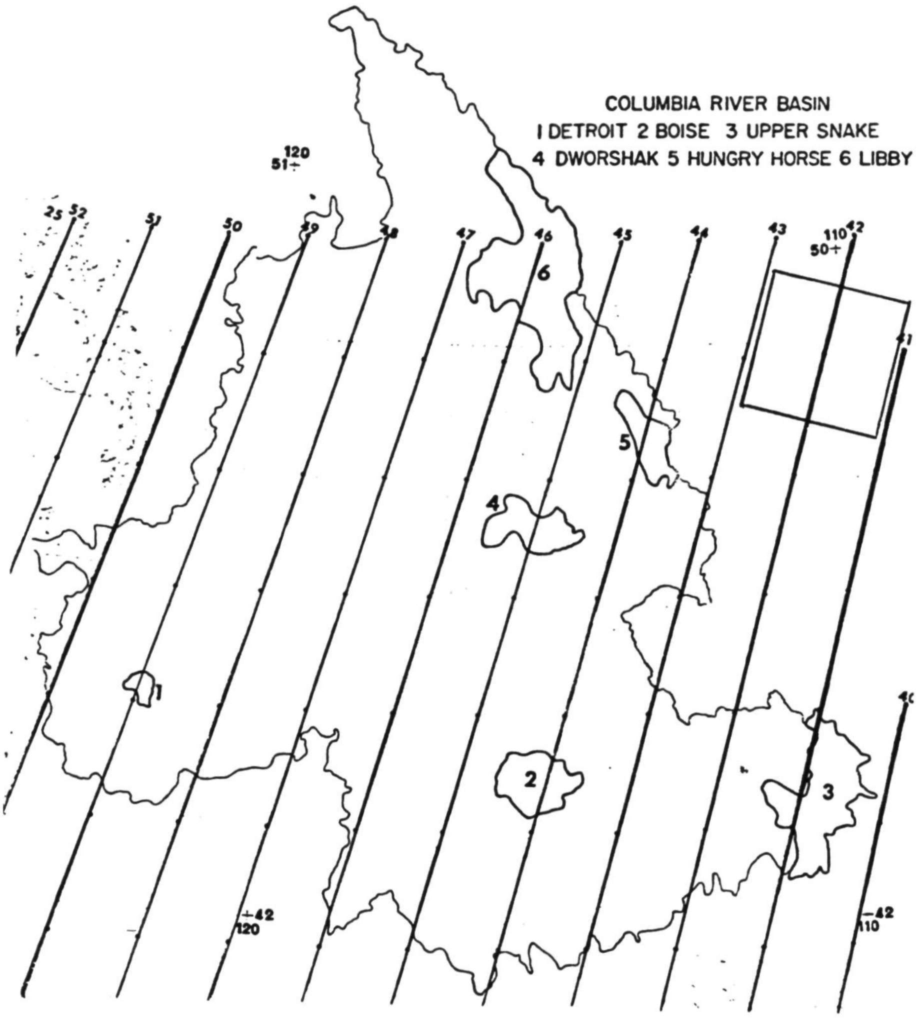

FIGURE 2

LANDSAT Orbital Tracks Over Test Basins
Using Canadian Numbering System

surements. It also provides a bridge between manual photo interpretation and machine processing. SRI presented three main options, in ascending order of cost and degree of refinement, for analyzing the imagery: manual photo interpretation, ESIAC classification from one spectral band, and advanced ESIAC analysis using two spectral bands and use of variable area, above threshold elevation masks to establish localized snowline elevations and to predict shadow regions. The second option using ESIAC classification from one spectral band (MSS-5) was chosen.

The satellite orbital tracks using the Canadian numbering system and the frame coverage is shown on Figure 2. 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.

Snowcover area was determined from a program that combines an objective classification using single-band (MSS-5) radiance thresholding with subjective editing using elevation contours and other reference data as a guide. LANDSAT imagery was scaled to the ESIAC TV screen, about 55 x 40 km or 0.5° by 0.5° longitude and latitude. This scaling approximately matched the 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. A binary basin outline map and a Universal Transverse Mercator (UTM) grid in 2.5 km x 2.5 km boxes were superimposed over each view. All of these data were spacially registered to each other during the entry process.

Registered color, time-lapse sequences were created for each basin. A mask of the snowcover area was generated for each view based on radiance thresholding, localized threshold adjustments, and superimposed elevation contours with final editing when necessary. The masks were documented by photography, by numerical pixel count of the total area, and by a digital array depicting tenths of snowcover for each 2.5 x 2.5 km cell. The cell-by-cell numerical documentation provides a convenient means for machine recording and manipulating the data, comparing with other methods of determining snowcover, and, more importantly, for use with advanced modeling techniques such as elevation bands as mentioned earlier.

Final results of the work on the measurement of snowcover from satellite imagery are not as yet available. Very adequate data were obtained for the North Santiam Basin; however, this basin was chosen primarily for the work being done by Dr. Mark Meier to test snowcover area methods. The North Santiam Basin is a coastal basin and the runoff is, for the most part, during the winter season from rain. Thus, it is not included as a primary snow runoff basin in the SSARR model. Data for the North Santiam Basin is shown in Table 3.

The Upper Snake Basin snowcover is shown in Table 4. During 1973, because of persistent cloud cover, LANDSAT-1 images were usable for only three dates, 29 March, 22 May, and 9 June. More-

TABLE 3 N. Santiam Basin Snow Coverage

Basin Area = 1146 km^2 Average Elevation ∿ 3900 ft MSL

Date	% of Basin Area Covered by Usable Imagery	Snow Coverage	
		Area (km^2)	% of Basin Area*
1973			
6 January	100	858.4	74.9
11 February	100	891.4	77.8
6 April	100	519.1	45.3
24 April	100	475.6	41.5
12 May	100	205.1	17.9
1974			
1 January	100	975.2	85.1
6 February	100	1002.8	87.5
24 February	100	1080.7	94.3
12 June	100	405.7	35.4
30 June	100	190.2	16.6

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

TABLE 4 Upper Snake Basin Snow Coverage

Basin Area = 13,339.6 km^2 Average Elevation ∿ 8000 ft MSL

Date	% of Basin Area Covered by Usable Imagery	Snow Coverage Area (km^2)	% of Basin Area* LANDSAT	SSARR
1973				
29 March	96.9	11888.0	92.0	100
22 May	95.0	5128.4	40.5	33
9 June	94.9	1738.8	13.7	19
1974				
22 June	96.8	1942.2	15.3	

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

over, no aircraft snow flights were made in 1973 as this was a very low year for precipitation and runoff. Agreement between the SSARR depleted data using the temperature index and the LANDSAT data are fair. The large gap between 29 March and 22 May misses the high runoff which started in mid-May and peaked on 22 May. In 1974 only one usable image was available for 22 June. This was much too late in the season and efforts are being made to secure additional coverage from overlapping imagery to the east that would cover most of the basin.

The Boise Basin snowcover is shown in Table 5. Again, there were no aircraft snow flights in 1973 but the SSARR depleted coverage shows good agreement with LANDSAT-1 data particularly during the runoff period. Of particular interest are the data for 1974. Very good agreement is evident between the satellite and SSARR data except for 14 April where the SSARR data shows 57 percent and the satellite data 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; but, because of its transitory nature, provided little in the way of runoff.

Comparison of the actual hydrograph and the reconstitution of satellite and SSARR data for runoff from the Boise Basin is shown on Figure 3. As can be seen, the correlation is very good.

It is still too early to draw any definite conclusions on the use of satellite data for determing area of snowcover in this region; particularly with the large number of cloud-covered days, the problem of determining the snowline in forested areas, and the lack of high resolution with the Synchronous Meteorological Satellite (SMS) data. The addition of new satellites this past year and future improvement in resolution should materially improve satellite data. Yet to be tested is the turn around time in getting the satellite data from the receiver sites to the user for real-time application. Nonetheless, what we have seen to date shows that satellite determination of snow coverage is a promising adjunct to our current methods. Continuation of our project, particularly with 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.

REFERENCES

(1) 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.

(2) Wiegman, E. J., Wm. E. Evans, R. Hadfield, 1975: Measurement of Snow Coverage From Satellite Imagery During 1973 and 1974 Melt Season: N. Santiam, Boise, and Upper Snake Basins, Draft of Final Report under BPA-SRI Contract No. 53442, Stanford Research Institute, Menlo Park, CA., 63 pp.

TABLE 5 Boise Basin Snow Coverage

Basin Area = 7254 km^2 Average Elevation ~ 6000 ft MSL

Date	% of Basin Area Covered by Usable Imagery	Snow Coverage		
		Area (km^2)	% of Basin Area*	
			LANDSAT	SSARR
1973				
19 April	100	4750.4	65.5	54
7 May	100	2270.4	31.3	32
12 June	100	594.0	8.2	6
30 June	100	278.6	3.7	2
1974				
14 April	100	5377.0	74.1	57
2 May	100	2609.5	36.0	34
25 June	100	504.5	7.0	6

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

Figure 3 : Boise Basin above Lucky Peak Dam, Hydrograph and SSARR Computed Flows