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Volume I: Operational Applications of Satellite Snow-Cover Observations - Executive Summary

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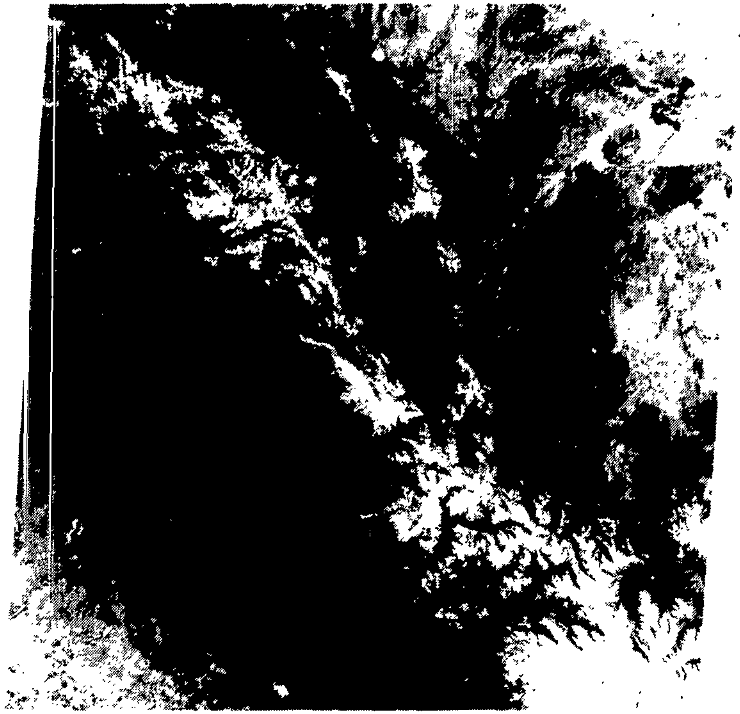
National Aeronautics
and Space Administration

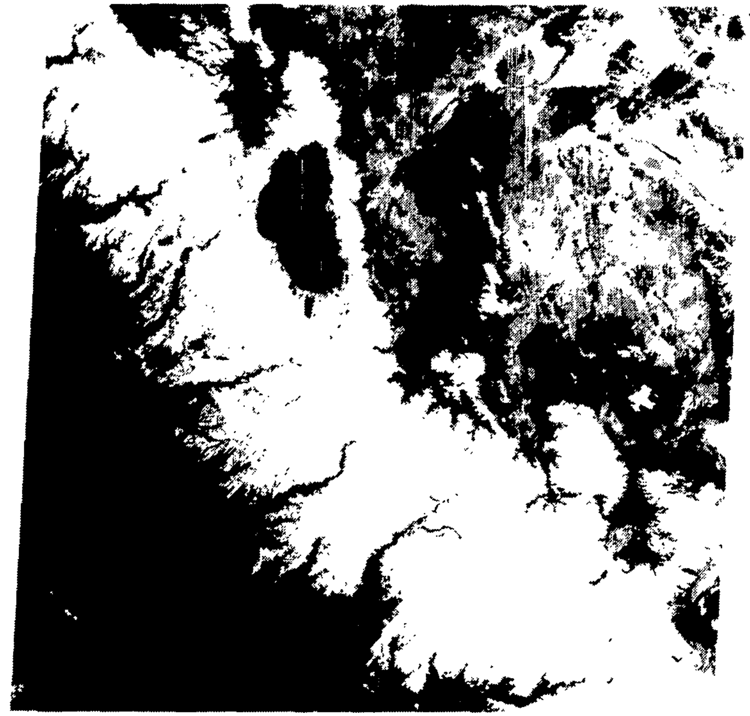
**Scientific and Technical
Information Branch**

All measurement values are expressed in the International System of Units (SI) in accordance with NASA Policy Directive 2220.4, paragraph 4.



15 APRIL 1977

AVERAGE SNOWLINE ELEVATION = 6700 FT.



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AVERAGE SNOWLINE ELEVATION = 4900 FT.

Frontispiece. Snow cover differences between a drought year (1977) and an above normal runoff year (1978) in the Sierra Nevada Mountains near Lake Tahoe, California as observed by Landsat.

ABSTRACT

A NASA Applications Systems Verification and Transfer (ASVT) project on the Operational Applications of Satellite Snow Cover Observations was begun in 1975 and completed in 1979 in cooperation with nine operational water management agencies. Both Landsat and NOAA satellite data were supplied to these agencies for use in improving snowmelt runoff forecasts. When the satellite snow cover data were tested in both empirical seasonal runoff estimation and short-term modeling approaches, a definite potential for reducing forecast error was evident. A cost-benefit analysis run in conjunction with the snow mapping ASVT indicated a $36.5 million annual benefit accruing from a one percent improvement in forecast accuracy using the snow cover data for the western United States. The annual cost of employing the system would be $505,000. The snow mapping ASVT has proven that satellite snow cover data can be used to reduce snowmelt runoff forecast error in a cost effective manner once all operational satellite data are available within 72 hours after acquisition. This Technical Paper presents executive summaries of the individual snow mapping ASVT projects, and subsequent Technical Papers in this series present the specifics of these projects.

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INTRODUCTION

Research has shown the potential for certain benefits resulting from the application of remote sensing technology to water resources management (Reference 1). When a significant body of positive research results has been acquired in a particular subdiscipline, testing of the operational usefulness of the new technology is the next logical step. In NASA such testing is carried out in cooperation with operational organizations under an Applications Systems Verification and Transfer (ASVT) program. Undertaken only when most necessary supporting research has already been completed, an ASVT is an integrated test of the capability of a remote sensing-based system to accomplish a specific applications objective on an operational basis. To accomplish this, ASVT's directly involve the user community, provide a user-oriented assessment of the system, and provide in summary form the information necessary for a potential user to make effective decisions concerning the implementation of the technology in an operational framework. Mandatory products from an ASVT are a documented methodology suitable for widespread distribution, a comprehensive user evaluation of the system's accuracy and reliability, and a cost-benefit or cost-effectiveness study.

Since 1972 when the Landsat-1 and NOAA-2 satellites were launched, it has been hypothesized that satellite data could be used to measure snow covered area and, subsequently, to assist in snowmelt runoff prediction (Reference 2). As the methods for extracting snow cover information from satellite data became well defined, it was proposed to test the usefulness of this new technology for the prediction of snowmelt-derived streamflow under the ASVT program. The snow ASVT project was entitled the "Operational Applications of Satellite Snow Cover Observations."

The snow ASVT was begun in 1975 and completed in 1979. Four different study areas were chosen for the project in order to assure variability of snow conditions, vegetation characteristics, cloud cover, and snowmelt climatology, and to more easily extrapolate project results to other snowmelt regions. The study areas were designated as Arizona, California, Colorado, and the Pacific Northwest, and the specific watersheds studied are shown in Figure 1. Agencies participating in the experiment included the U.S. Geological Survey (USGS) and the Salt River Project in Phoenix; the California Department of Water Resources (DWR) in Sacramento; the Soil Conservation Service (SCS), Bureau of Reclamation, and the Colorado Division of Water

Figure 1. Study watersheds for the snow mapping ASVT.

Resources in Denver; and the Bonneville Power Administration (BPA), Corps of Engineers, and the National Weather Service in Portland. In addition, the National Environmental Satellite Service (NESS) provided NOAA satellite data in support of the study center investigations.

At the start of the ASVT, a handbook of techniques for satellite snow mapping was compiled to assist the operational agencies in extracting the snow measurements from the satellite data (Reference 3). Throughout the project progress reports were published both quarterly and annually. Early results of the analyses were documented in the proceedings of a workshop held in 1975 at Lake Tahoe (Reference 4). A final workshop was held in coordination with the Western Snow Conference in Reno in April 1979. The proceedings of this final workshop have been published as NASA Conference Publication 2116 (Reference 5). As a final form of documentation, this series of NASA Technical Papers is being published and includes an executive summary, the final reports of each of the study areas, a project cost-benefit study, and an updated snow mapping and runoff prediction handbook. Wide distribution of these documents is planned.

OBJECTIVES

At the start of the snow ASVT, both overall project objectives and specific study area objectives were formulated. These objectives are as follows:

General Objectives

1. Map snow lines, areal snow cover, and associated changes in snow cover, using satellite data for the 1972-1973 and 1973-1974 snow seasons in four separate Western U.S. study areas in order to evaluate the usefulness of the data had they been available in near real-time.

2. Map snow cover changes through 1979 in each of the study areas in a near real-time mode (data to user $\leq$ 72 hours) so that the data base can be extended for as long a period as possible.

3. Compare and evaluate satellite-derived snow-mapping products with reference to products from conventionally-derived snow data.

4. Develop or modify methods in an operational framework over the study period that will allow incorporation of satellite-derived snowpack observations into the prediction of snowmelt-derived streamflow for specific areas.

5. Produce a documented methodology and cost-benefit analysis sufficient for user organizations to make Go/No Go decisions concerning the use of this satellite-assisted snowmelt runoff methodology in their operational responsibilities.

Arizona Objectives

1. Map snowlines and areal snow cover on the Salt and Verde River watersheds for 1972-1973 and 1973-1974, using repetitive existing satellite imagery. These snow-mapping products will be compared to existing snow cover maps prepared from conventional information sources.

2. Evaluate repetitive satellite imagery together with aerial surveys in an attempt to develop an operational capability in Arizona for using satellite imagery for mapping the distribution of snow cover on the Salt and Verde River watersheds to aid in water management. This phase of the experiment will be conducted in close coordination with the Salt River Project.

3. Develop techniques and procedures for systematic monitoring of snow cover and moisture conditions using remote sensor methods, including repetitive satellite and aerial observations, and photography of selected areas together with the use of the Landsat Data Collection System to relay ground truth observations in near real time.

4. Continue the study through 1979 to allow a total of at least seven years of data collection, and develop or modify methods in an operational framework that would allow incorporation of satellite-derived snowpack observations into procedures used by the Salt River Project for predicting both short-term and seasonal snowmelt-derived runoff.

California Objectives

1. Develop techniques for reducing, editing, and preanalyzing area of snow cover for specific watersheds.

2. Develop techniques to apply satellite snow covered area to snow covered area derived by conventional means, as well as to other hydrologic parameters required for forecasting.

3. Develop techniques to apply satellite snow covered area to forecast procedure for seasonal water supply, time distribution of runoff, and rates of snowmelt in the following drainage basins: San Joaquin, Kings, Kaweah, Tule, Kern, Feather, and Upper Sacramento Rivers.

4. Analyze results obtained from inclusion of satellite snow covered areas in the program in terms of: increased forecast accuracy; improved confidence regarding adjustments in forecasts made in the late snowmelt season; and the value of continuous reporting of snow covered area to the overall California Cooperative Snow Survey Program.

5. Investigate the potential for the use of other satellite-derived hydrologic data in addition to snow covered area.

Colorado Objectives

1. Determine if snow cover as determined from Landsat and other satellites can be used to improve water supply forecasts for the Rio Grande, Conejos, Culebra, and Arkansas Rivers.

2. Determine if snow cover analysis can be used to update streamflow forecasts on a continuing short-term basis during the snowmelt period.

3. Use Landsat snow cover observations in forecast models to increase forecasting accuracy in order to allow maximum delivery of water to Colorado users and to still permit Colorado to meet its obligations to New Mexico in the Rio Grande Compact.

4. Use Landsat and other satellite data to correlate the area of snow cover and the days of cloud seeding conducted by the U.S. Bureau of Reclamation in the San Juan Mountains.

Northwest Objectives

1. Map snow lines and determine the areal extent of snow cover and associated changes in snow cover using satellite data for 1972-73 and 1973-74 for the Boise, Upper Snake, Kootenai, Flathead, and Clearwater Rivers.

2. Continue the study through 1979 and extend the mapping in objective 1 to a total of at least seven years.

3. Compare satellite snow-mapping products to products conventionally obtained from observations made by an observer flying in a low-altitude aircraft.

4. Develop or modify methods in an operational framework that would allow incorporation of satellite snow cover observations for prediction of snowmelt derived runoff, perhaps utilizing the U.S. Army Corps of Engineers Streamflow Synthesis and Reservoir Regulation (SSARR) model.

ORGANIZATION

Project management and scientific support was performed at NASA's Goddard Space Flight Center in Greenbelt, Maryland. Each of the study centers had project leaders who directed the specific work in the study area. The project leaders, participating agencies, and applications of the data are shown in Table 1.

DATA

When the snow mapping ASVT project was conceived, a basic assumption was made, namely, that it would be more efficient and effective to transfer photointerpretation techniques for analyzing satellite snow cover than comparable digital techniques. Underlying this assumption was the knowledge that few operationally oriented agencies had access to the necessary

Table 1
Snow ASVT Study Area Details

Study Area	Study Basins	Project Leader	Participating Agencies	Applications
ARIZONA	Salt River Verde River	Herbert H. Schumann USGS	U.S. Geological Survey Salt River Project	Reservoir Regulation for power, irrigation, water supply, and flood control (in order of priority) Short-term runoff forecasting
CALIFORNIA	Kings River Kern River Kaweah River San Joaquin River Tule River Feather River Upper Sacramento River	A. J. Brown DWR	California Department of Water Resources	Supply various California Snow Survey Cooperators with seasonal runoff forecast to be used in water management for irrigation, power, and flood control
COLORADO	Rio Grande River Conejos River Culebra River Arkansas River	Bernie Shafer SCS	Soil Conservation Service Colorado Division of Water Resources U.S. Bureau of Reclamation	Improved flow forecasts on the Rio Grande drainage to be used by the State of Colorado in improving scheduling of water releases to the State of New Mexico under the Rio Grande River Basin Compact. Reservoir regulation for irrigation and power requirements
Northwest	Boise River Clearwater River Flathead River Kootenai River Snake River	John Dillard BPA	Bonneville Power Administration Corps of Engineers National Weather Service	Power generation and flood control
NOAA/NESS	Large western basins	Stan Schneider NESS	National Environmental Satellite Service	Supply NOAA data products and services to each of the study areas

computer facilities for digital analysis. In addition, snow-covered area was an easily analyzed parameter using photointerpretation, and the associated techniques were straightforward and easily understood. The additional advantage to photointerpretation was the fact that user personnel would physically handle and analyze the data, thus retaining a high degree of first-hand knowledge of the information content. Experience during the project has shown these to be valid and important considerations. Although digital interpretation may eventually become a universally adopted technique for snow cover measurement, especially when a large number of watersheds are involved, photointerpretation will still remain an important step for familiarization with the satellite data characteristics.

Data for analysis were obtained from both Landsat and NOAA satellites in the photographic format. The Landsat spacecraft are polar-orbiting satellites that survey the earth from an altitude of approximately 900 km (560 mi). Landsat views a data swath 185 km (100 mi) wide with a ground resolution of 80 m (260 ft) for the multispectral scanner. Because of the relatively narrow data swath width, the satellite provides repeat coverage only once every 18 days (or 9 days with two satellites operating). The primary spectral interval of the multispectral scanner used for snow mapping is the 0.6 to 0.7 μm visible red band. On the NOAA series of environmental satellites the primary sensor used was the Very High Resolution Radiometer (VHRR), and specifically the 0.6 to 0.7 μm visible band. The spatial resolution of the VHRR is about 900 m (0.56 mi), an order of magnitude poorer than Landsat, but still sufficient for snow mapping. In addition, visible band coverage is available once a day from the NOAA satellites. The Geostationary Operational Environmental Satellite (GOES) of NOAA also was used to provide snow mapping information. The Visible and Infrared Spin-Scan Radiometer (VISSR) on GOES was able to provide 0.54 to 0.70 μm channel data at 1 km (0.62 mi) resolution as often as every hour. Because the viewing angle of GOES becomes more oblique as latitude increases, the resolution deteriorates with latitude, and as a result, the data were most useful in the southerly test areas.

The zoom transfer scope (ZTS) was a major snow mapping tool used in the ASVT project and the standard against which any other techniques tested were judged. Both Landsat and NOAA images were analyzed by personnel of the ASVT study centers using the ZTS. In using the ZTS, the image (either a print or a transparency) is superimposed optically through a series of lenses and mirrors onto a base map. Through adjustment of the size of the projected image and through stretching of the image along either axis, the original image can be rectified to fit the base map scale. The snow line is then mapped directly onto the base map and watershed overlay. Subsequently the watershed area covered by snow can be determined by manual or automatic planimetering of the area bounded by the snow line. Landsat data, because of their high level of cartographic fidelity, are analyzed very effectively and efficiently using the ZTS technique. Because of their small scale, poorer resolution, and inherent distortion, the NOAA data are much more difficult to interpret than Landsat images. To facilitate use of the NOAA data, NESS interprets snow cover from the satellite images and supplies snow cover maps to selected users. Several large watersheds in each of the ASVT study areas were snow mapped at NESS and the resulting snow cover charts and statistics were transmitted to the study centers (Reference 6). In the snow ASVT project, these NOAA snow charts were then further interpreted by study center personnel to derive snow cover measurements for subbasin areas.

In as dynamic a situation as snowmelt runoff forecasting, the timeliness of data receipt is an extremely important consideration. The goal for the snow ASVT project was 72 hours from data acquisition to delivery to the user. Because of their operational mandate, NESS was well suited to meeting this goal and did so most of the time with both image products and the snow cover charts. Delivery of Landsat data seldom met the established goal of 72 hours because the Landsat program remains entirely research-based. By making use of both the Canadian quick look facility at Prince Albert, Saskatchewan, and the quick look system at Goddard Space Flight Center, the average delivery time for Landsat data was about seven days. In order to be truly useful for operational water resources management, this delivery time for Landsat data must be improved to less than 72 hours through the establishment of a reliable and operational data production system.

The data sources employed by each study area are shown in Table 2 along with an indication of which study areas used data collection systems for the relay of conventional hydrologic information to be used in conjunction with analysis of the remote sensing data. Table 3 presents a tabulation of the satellite scenes employed in the snow ASVT from 1973 through 1977 by study area.

Table 2
Data Systems Used in the Snow ASVT

Data System	Arizona	California	Colorado	Northwest
Landsat	X	X	X	X
NOAA	X	X	X	X
GOES	X	X	X	
Data Collection Systems:				
- Satellite	X			
- Meteor-Burst	X		X	

Table 3
Landsat (LS) and NOAA (NO) Photographic Scenes Shipped to ASVT Study Centers for the 1973-1977 Snow Seasons

	1973		1974		1975		1976		1977		Total	
	LS	NO	LS	NO	LS	NO	LS	NO	LS	NO	LS	NO
Arizona	37	11	32	17	112	33	79	33	64	90	324	184
California	65	15	64	28	202	65	187	155	162	74	680	337
Colorado	40	11	24	28	87	8	90	0	79	16	320	63
Northwest	125	0	120	0	203	0	292	200	227	107	967	307
Total	267	37	240	73	604	106	648	388	532	287	2291	891

RESULTS AND CONCLUSIONS

A summary of results from each of the ASVT study areas is included in the Appendixes of this volume. The additional volumes of this Technical Paper series treats these results specifically. Rather than reiterate the work in each study area, the following capsulized version of the snow ASVT results is presented.

The snow mapping ASVT was designed to evaluate the operational usefulness of satellite snow-cover data for water yield prediction. The results of the ASVT indicate that snow-cover information is a valuable ancillary data source for improving snowmelt runoff predictions. When satellite snow-cover data were tested in both empirical seasonal runoff estimation and short-term modeling approaches, a definite potential for reducing forecast error was evident. As an example, over a three-year period, errors in seasonal stream flow estimates for three basins in California were reduced from 15 percent to 10 percent by using satellite snow-cover data (Reference 7). In modeling studies in the Northwest on the Boise River basin, satellite data produced decreases in forecast error for various short-term periods (3-14 day forecasts) ranging from -2.0 percent to 9.6 percent. Colorado investigators have estimated that over an extended period of time satellite snow-cover data will provide a relative improvement in forecast accuracy of 6-10 percent.

A benefit/cost analysis run in conjunction with the snow-mapping ASVT considered the two most important snowmelt water uses, hydropower and irrigation. Potential benefits from improved satellite snow cover-based predictions across the 11 western states total 10 million dollars for hydropower and 26.5 million dollars for irrigation for a grand total of 36.5 million dollars annually. Snow mapping and prediction costs were estimated at $505,000; a benefit/cost ratio of 72:1 was obtained.

The snow-mapping ASVT has proven that satellite snow-cover data could be used to reduce snowmelt runoff forecast error in a cost-effective manner. The use of the satellite data is not fully operational, however, because there is too long a time lag between Landsat data acquisition and receipt by the user. In addition, the frequency of coverage from Landsat is not optimum. NOAA satellite data are available with the required frequency and quick turnaround, but the resolution is much poorer than Landsat and as a result more difficult to manipulate for snow mapping. By using both Landsat and NOAA in combination, however, it would be possible to obtain sufficient snow cover data for use in operational snowmelt runoff forecasting. This truly operational application will only be possible in the 11 western states when the turnaround time is reduced to 72 hours for all data, and the water management agencies can be assured of continuing supply of operational snow-cover data from space.

EXECUTIVE SUMMARIES

The executive summaries included in the Appendixes cover each study area plus the NOSS/NESS support, the cost-benefit study, and the final handbook. For more detailed information on each study, the reader is referred to the appropriate Technical Paper of this series.

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APPENDIX A

EXECUTIVE SUMMARY: ARIZONA STUDY CENTER
(See NASA Technical Paper 1823)

OPERATIONAL APPLICATIONS OF SATELLITE SNOW-COVER OBSERVATIONS AND DATA-COLLECTION SYSTEMS IN THE ARIZONA TEST SITE

EXECUTIVE SUMMARY

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INTRODUCTION

Snowfall provides an important renewable source of water for irrigation, hydroelectric-power generation, and municipal and industrial uses in the southwestern United States. The efficient operation of multipurpose reservoirs in semiarid central Arizona requires timely and dependable information on snowmelt and runoff rates.

Historically, snow cover conditions in the 34,000 km^2 Salt-Verde watershed in central Arizona were evaluated by ground surveys and aerial reconnaissance flights. Near-real time information on streamflow rates was provided by a network of observers and by land-based telemetry systems. Since 1974, the U.S. Geological Survey and the Salt River Project, working in cooperation with the National Aeronautics and Space Administration (NASA), have evaluated repetitive aerial and satellite snow cover observations and tested satellite data-collection systems for telemetry of hydrometeorological data in central Arizona. The Arizona Test Site is one of four major test sites included in the NASA Applications Systems Verification Transfer (ASVT) project on satellite snow cover observations. The purposes of the project were to develop operational applications of satellite observations for mapping snow cover distributions, to test satellite data-collection systems to relay hydrometeorological data, and to perfect methods to predict runoff volumes derived from snowmelt.

AERIAL SNOW COVER OBSERVATIONS

Aerial snow cover observations require experienced observers, many hours of hazardous mountain flying, and considerable expense. The availability of snow cover maps, derived from satellite snow cover observations, has greatly reduced the necessity for routine aerial snow reconnaissance flights over central Arizona. Significant cost savings have resulted, and the time that flight crews must be exposed to hazardous low-level flying over the mountains has been greatly reduced.

Low-level aerial observations have provided and will continue to provide valuable information on snow cover distributions and snow depths during periods of cloud cover that preclude effective satellite snow cover observations. The use of low-cost 35-mm oblique photography of aerial snow markers provides a permanent record of snow depths.

SATELLITE SNOW COVER OBSERVATIONS

Satellite imagery can provide the synoptic coverage necessary to quickly map large snow covered areas. Photographic imagery taken by the Apollo-9 astronauts over central Arizona indicated the general feasibility of using satellite-acquired snow cover observations to provide a rapid means for mapping snow cover distributions over the Salt-Verde watershed. However, aerial observations indicated frequent repetitive coverage was required to monitor the rapid changes in snow cover that occur in the Salt-Verde watershed.

Landsat System and Imagery

Snow cover distributions, mapped from repetitive Landsat multispectral scanner (MSS) imagery, were in close agreement with snow cover distributions mapped by experienced aerial observers. Landsat MSS imagery can be considered virtually orthographic at the 1:1,000,000 scale commonly used for snow cover mapping. The use of Landsat MSS band 5 (0.6-0.7 μm red band) imagery permits rapid, direct preparation of accurate snow maps at low cost using simple overlay techniques. The Landsat MSS band 7 (0.8 to 1.1 μm) images also are useful for snow cover mapping, because these wave lengths penetrate thin clouds and most haze.

A variety of image-enhancement techniques can be used to help evaluate the Landsat MSS imagery. However, these techniques require use of relatively expensive and highly specialized image-interpretation equipment. False-color infrared color composite images prepared from two or more bands of Landsat MSS imagery (bands 5 and 7 or bands 4, 5, and 7) can provide increased contrast between snow covered ground and snow-free areas and greatly facilitate snow cover mapping in densely forested areas.

Digital computer analysis of Landsat imagery, recorded on computer-compatible tapes (CCTs), can be used to develop high-precision snow cover maps at slow to moderate speeds. The high cost of the digital tapes and digital image processing and the delays involved in acquiring the Landsat ditigal tape limits the utilization of this technique for operational snow cover mapping at this time.

The principal limitations of Landsat imagery for snow cover mapping in central Arizona are that only one observation is provided each nine days for part of the Salt-Verde watershed. Six Landsat images taken on three consecutive days are required to cover the entire Salt-Verde watershed. Most of the thin snow cover over the lower and middle portions of the watershed can melt in less than nine days. Winter cloud cover over the mountains of central Arizona can often prevent effective Landsat snow cover observations for long periods of time.

Improved TIROS System and Imagery

Imagery from the improved TIROS operational satellites (ITOS), NOAA series, were used to produce areal snow cover maps of selected river basins including the Salt-Verde watershed. Very High Resolution Radiometers (VHRRs) aboard the satellites provide daily coverage of the western United States in the visible part of the spectrum (0.6 to 0.7 μm) and twice-daily coverage in the thermal infrared (10.5 to 12.5 μm) part of the spectrum. Daily coverage is believed necessary to monitor the rapid changes in snow cover that occur in central Arizona.

The low-resolution VHRR imagery provides a highly distorted panoramic view of the earth's surface. Moderately expensive equipment must be used to enlarge and optically stretch the imagery before it can be projected onto watershed maps. Snow-covered areas can then be quickly mapped directly on the watershed maps.

SMS/GOES System and Imagery

The Synchronous Meteorological Satellites (SMS) now in geostationary orbit are prototypes for the satellite series Geostationary Operational Environmental Satellites (GOES). The SMS/GOES satellites acquire imagery in the visible (0.55 to 0.75 μm) and thermal infrared (10.5 to 12.6 μm) parts of the spectrum by means of Visible and Infrared Spin Scan Radiometers (VISSRs). Although these sensors can image almost the entire Earth (full disk) per scanning cycle, sectors of limited and specified geographical areas are extracted for detailed study.

The VISSR imagery produces a distorted view of the surface of the Earth that changes in scale and resolution with increasing distance north and south of the equator. The Zoom Transfer Scope can be used to correct the VISSR imagery and to project it onto watershed maps. The position of the snow-line can then be plotted, and measurements of snow covered area can be obtained either by manual or electronic-planimeter methods.

The main advantage of using the VISSR imagery for snow cover mapping is that imagery is available as frequently as every 30 minutes. This capability allows afternoon viewing of mountainous areas that may have had fog or mist when imaged in midmorning by the NOAA or Landsat systems. The system also allows the hydrologist to monitor rapidly changing snow cover distributions and weather systems. Current research indicates that geometric corrections and measurements of snow covered area can be obtained by computer processing of the SMS/GOES digital data.

SNOW-COVER DEPLETION AND RUNOFF

The rate at which snow cover is depleted from the watershed can be considered as an index of the volume and rate of runoff that will be generated by snowmelt. As snow begins to melt at the lower altitudes, runoff increases to a peak that is governed by the extent of the ripe snowpack and the amount of thermal energy added to the snowpack. Runoff then begins to recede until the remaining snowpack disappears, the melt rate changes, or additional precipitation occurs.

Short-Term Runoff Predictions

Careful examination of the rates at which snow cover is depleted from the watershed indicates that short-term predictions of changes in snow-covered area can often be made on the basis of snow-cover depletion rates determined from daily satellite snow-cover observations. Statistical analysis of snow-cover depletion rates and corresponding runoff volumes during selected short observation periods indicates that short-term runoff volumes can be predicted successfully from sequential snow-cover observations. However, additional precipitation or large temperature changes during the prediction period will cause significant changes in the snow-cover depletion and runoff relationship.

Seasonal Runoff Predictions

Seasonal runoff predictions for the Salt-Verde watershed are important to the economy of the Salt River Valley near Phoenix, Arizona. Seasonal runoff predictions require careful consideration of many hydrologic parameters, such as antecedent precipitation and runoff amounts and basin storage; basin storage includes soil moisture, ground water in storage, and the volume and distribution of water stored in the snowpack. The probability of post-prediction precipitation and energy exchange, which may affect snowmelt and evapotranspiration rates, also should be considered. These parameters are difficult to measure and monitor in areas as large as the Salt-Verde watershed. As a result, index methods often are used to describe moisture conditions for use in making seasonal runoff predictions.

Operational runoff prediction models have been developed by the Soil Conservation Service and the Salt River Project using index methods to describe watershed moisture conditions. These models have provided reasonably accurate seasonal runoff predictions during years of low to average runoff volumes. These models tend to seriously underestimate runoff volumes during years of very large runoff volumes.

The Hydrometeorological Streamflow Prediction Model (HM), developed by the U.S. Geological Survey, was modified and adapted for use on the Salt-Verde watershed. This model provides improved seasonal runoff predictions, especially during periods of unusually large runoff volumes. The use of daily precipitation amounts, runoff volumes, and air temperatures allows relatively short-term runoff predictions (about 15 days in duration).

Additional research is needed to allow effective utilization of snow-covered area measurements in existing runoff prediction models. Repetitive satellite snow-cover observations concurrent with hydrometeorological data relayed from remote snow-monitoring sites should facilitate that research.

TELEMETRY OF HYDROMETEOROLOGICAL DATA

Rapid changes in winter runoff rates in response to rainfall and snowmelt present serious water-management problems in central Arizona. Telemetry systems are used to relay hydrometeorological data from selected sites in the Salt-Verde watershed to assist in the operation of multipurpose reservoirs and to provide flood-warning information. The systems include microwave telemetry, two satellite telemetry systems, and a meteor-burst communication system.

Microwave Telemetry System

The conventional microwave telemetry system operated by the Salt River Project can provide data from seven key streamflow gages in real time. However, the use of this type of telemetry system involves both large equipment costs and relatively large maintenance costs.

Landsat Data Collection System

The experimental Landsat Data-Collection System (DCS) was tested to relay hydrometeorological data from selected streamflow gages and snow-monitoring sites. On several occasions this system provided valuable information that was used by the Salt River Project to guide reservoir-management decisions during periods of critical reservoir operations.

The low-cost Landsat data-collection platforms proved to be reliable under a wide range of environmental conditions and were simple to operate. The main disadvantages of using the Landsat DCS to relay hydrometeorological data were the limited volume of data relay per transmission (64 bits) and the small number of transmissions received each day.

SMS/GOES Data-Collection System

The operational SMS/GOES Data-Collection System (DCS) was tested to relay data from three streamflow gages and precipitation and air temperature data from one snow-monitoring site in central Arizona. This system has the capability to relay large volumes of hydrometeorological data with relatively low equipment and operational costs.

The data-collection platforms (DCPs) used to transmit hydrometeorological data to one of the SMS/GOES satellites are microprocessor controlled, and when powered by batteries that are recharged by solar panels, these DCPs can operate unattended for long periods of time. The DCPs were operated in the self-timed mode and relayed data to the satellite each three hours.

The SMS/GOES telemetry data are routinely computer processed into engineering units and then relayed to Arizona on a weekly basis via high-speed computer terminals. Unprocessed data are available from the NOAA computer center in near-real time through the use of low-speed computer terminals. The value of the near-real time satellite telemetry data was dramatically demonstrated during the March 1978, December 1978, and January 1979 storm periods that produced major flooding in central Arizona. Streamflow data relayed by the SMS/GOES-DCS was used to monitor upstream runoff into the Salt River. These data were used by Salt River Project personnel to make reservoir-management decisions.

Snotel System

The telemetered snowpack system (Snotel), now being implemented by the Soil Conservation Service, will utilize a meteor-burst telemetry technique to relay hydrometeorological data from snow-monitoring sites in the Salt-Verde watershed. Snow-water equivalents and other data relayed from these sites and snow-covered area measurements provided by satellite snow-cover observations may permit improved estimates of the total volume of water stored within the snowpack on the Salt-Verde watershed.

CONCLUSIONS

Frequent satellite snow-cover observations have reduced the need for routine aerial reconnaissance flights over the Salt-Verde watershed, and significant savings have resulted. Aerial observations will continue to provide valuable information on snow-cover distributions during periods of cloud cover.

Satellite imagery provides the synoptic coverage needed for operational mapping of large snow-covered areas. High-resolution multispectral Landsat imagery permits rapid snow-cover mapping at low cost. However, the experimental Landsat system provided only one observation every nine days for a part of the Salt-Verde watershed. Low-resolution imagery acquired by the operational ITOS and SMS/GOES meteorological satellites provide the daily synoptic observations of the entire Salt-Verde watershed that are necessary to monitor the rapid changes in snow-covered area that occur in this semi-arid region.

Short-term runoff predictions can be made on the basis of snow-cover depletion rates determined from daily satellite observations. Additional research is needed to allow the effective use of snow-covered area measurements in seasonal runoff predictions in southern Arizona.

Hydrometeorological data were successfully relayed by the Landsat and SMS/GOES satellite data-collection systems from remote sites under a wide range of environmental conditions. Hydrometeorological data relayed in near-real time by satellite and conventional telemetry were used to provide early warning during the spring floods of 1978 and 1979.

APPENDIX B

EXECUTIVE SUMMARY: CALIFORNIA STUDY CENTER
(See NASA Technical Paper 1824)

OPERATIONAL APPLICATIONS OF SATELLITE SNOW-COVER OBSERVATIONS IN CALIFORNIA

EXECUTIVE SUMMARY

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INTRODUCTION

The National Aeronautics and Space Administration (NASA) has cooperated with operational agencies in investigations into the utility of applying the measurement of snow-covered area (SCA) derived from satellite imagery to water supply forecasting. In California, such studies have been conducted under the Applications Systems Verification and Transfer (ASVT) program. The Snow Surveys Branch of the California Department of Water Resources (CDWR), which has evaluated water conditions and forecast snowmelt runoff in the State for the past 50 years, has had the prime responsibility for management of the California ASVT program. Sierra Hydrotech, an engineering consulting firm in Placerville, California, under subcontract, assisted CDWR in data reduction and technical application of this program.

OBJECTIVES AND GENERAL DESCRIPTION OF INVESTIGATION

Water supply forecasting is vitally important to the yearly management of water in the Central Valley of California. This has required the development of techniques to forecast volume and time-distribution of snowmelt runoff from the Sierra Nevada, a range of mountains that form the eastern boundary of the valley. Average water year runoff to the valley totals about 30 million cubic dekametres (24 million acre-feet). Continual surveillance of streamflow and updating of forecasts each spring are necessary to make sound management decisions.

This investigation focused on five major basins in the southern Sierra Nevada and two major basins in the northern Sierra and the Cascade Range. Particular study was given to the Kings and Kern Rivers watersheds in the southern Sierra Nevada, where as much as 75 percent of the average annual runoff occurs during the April-July snowmelt season.

The objective of this investigation has been to explore the feasibility of applying SCA data obtained from satellite imagery to California's water supply forecasting procedures. Four specific topics were studied.

Data Interpretation. This work involved:

Developing techniques and training interpreters in reduction of satellite imagery

Mapping SCA and snow lines from historic satellite and aircraft observations

Mapping SCA and snow lines on a real-time basis from satellite observations.

Editing and Pre-Analysis of Data

Developing and applying techniques to estimate and check data

Comparing satellite-derived SCA with conventional SCA observations.

Basic Data File

Generating a file of SCA data for use in developing forecasting procedures by CDWR

Developing a data format to be made available to others.

Application of the Data

Developing and testing procedures for application of the data obtained from interpreted satellite imagery to CDWR forecasting procedures

Using satellite SCA operationally in forecasts of snowmelt runoff.

The region of the state that was investigated was chosen to meet two objectives: (1) to test the capability of reducing and using SCA in areas having differing geographic and hydrologic conditions and (2) to obtain a data base of SCA that would effectively test the value of SCA in hydrologic analysis.

RESULTS OF DATA INVESTIGATION

Techniques for interpretation of SCA from satellite imagery were adapted to problems of particular importance to California. The technique for estimating operational forecasting data when only limited satellite data were available was to use Landsat data on a nine-day cycle as a basic input for analysis, then adjust to specific dates of forecast with data from NOAA imagery, or other sources such as temperature data, highway data, and so forth.

A basic data file of satellite observations has been developed throughout California's snow zone for application to development of water supply forecasts. Approximately 12,000 basin-observations from 53 major basins and sub-basins throughout the snow zone have been interpreted and filed on computer cards. Extensive work has been done with regard to checking and refining the interpreted data sets for future application. Although observations have been interpreted throughout the entire period of snowcover, the greatest effort has been concentrated on the snowmelt period which extends from approximately mid-March through midsummer.

RESULTS OF THE APPLICATION OF SATELLITE DATA

Data on snow-covered area appears to have the greatest value in the Sierra Nevada during the period of snowmelt runoff (subsequent to April 1) when snow-cover is rapidly depleting and only limited historical data are available to update forecasts. Analyses suggested that SCA observed during the period of snowpack accumulation had little relationship to runoff observed during the period of snowmelt.

Consequently, SCA was tested as an additional parameter in updating water supply forecasts during the period of snowmelt in the Kings River and Kern River Basins in the southern Sierra Nevada. Results indicated that the accuracy of water supply forecast updates during the period of snowmelt was increased, particularly in the Kern River watershed. Forecast procedures were used operationally during the snowmelt seasons of 1977, 1978, and 1979. The operational forecasts that included SCA as an additional parameter in updating the snowmelt season appeared to give more reliable results than conventional procedures used by CDWR.

More important, however, SCA provides on additional parameter which may readily be obtained from direct observation in the watershed and used to increase forecast confidence as the snowmelt season progresses.

Review of application results suggested that SCA would prove most useful in water supply forecast updating during the period of snowmelt when:

- Other data during the snowmelt period were unavailable or at least not indicative of basin-wide conditions,
- Watershed area was not uniformly distributed with elevation,
- Areal distribution of snowpack for a given season was substantially different from the "normal" condition.

Although SCA is a potentially valuable tool in water supply forecasting, its use does not obviate the requirement for other data defining conditions within the watershed. These data include snowpack water content, precipitation, observed runoff and other information related to volume and time-distribution of snowmelt runoff.

CONCLUSIONS

SCA obtained from satellite imagery provides an additional input parameter to updating water supply forecasts as the snowmelt season progresses. Results of the study suggest that forecast accuracy will be increased and that the scope of forecast service will be widened and the levels improved.

Input on SCA is not readily available from other sources over extensive mountainous areas. When results appeared promising during the progress of the investigation, CDWR proceeded with reducing SCA data to develop a suitable base for future use. CDWR intends to continue interpretation of SCA from satellite imagery, and utilization of SCA as an additional parameter in the updating of operational water supply forecasts.

APPENDIX C

EXECUTIVE SUMMARY: COLORADO STUDY AREA
(See NASA Technical Paper 1825)

OPERATIONAL APPLICATIONS OF SATELLITE SNOW-COVER OBSERVATIONS AT THE COLORADO FIELD TEST CENTER

EXECUTIVE SUMMARY

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INTRODUCTION

As part of their Applications Systems Verification and Transfer (ASVT) program, the National Aeronautics and Space Administration (NASA) funded four demonstration projects in the western United States to study the ways in which Landsat-derived snow maps could be constructed and incorporated into existing schemes for forecasting snowmelt runoff. Evaluations were to be made at each study center to ascertain the potential improvement in forecast accuracy which could be ascribed to use of snow-cover data. The four demonstration study centers chosen were Arizona, California, Colorado, and the northwestern United States.

In Colorado, three agencies were involved in carrying out the intent of the ASVT program. The USDA Soil Conservation Service was given lead responsibility with assistance provided by the Colorado Division of Water Resources (State Engineer's Office) and the U.S. Bureau of Reclamation. Charles F. Leaf, consulting hydrologist, was also retained to incorporate satellite snow-cover observations into a hydrologic simulation model.

The study approach in Colorado involved a four-step analysis: (1) identify specific drainage basins and acquire the Landsat imagery to cover them; (2) examine various techniques of mapping and snow cover and determine which technique was most useful in an operational mode; (3) develop a methodology for including snow-covered area in a forecast of snowmelt runoff, and (4) evaluate the adequacy of the forecasting techniques which employed snow-cover.

The Rio Grande Basin in Colorado was chosen as the primary drainage for study and the Upper Arkansas Basin as a secondary study basin. Within the Rio Grande Basins, five watersheds ranging in size from 107 mi^2 (277 km^2) to

1336 mi^2 (3460 km^2) were selected for detailed analysis. Watersheds in the Rio Grande included Culebra Creek, Conejos River, Alamosa River, South Fork Rio Grande, Rio Grande Mainstem above Del Norte. The Arkansas River above Salida, Colorado was the sixth watershed studied. In these watersheds, snowmelt runoff accounts for 70 to 80 percent of the annual flow.

Accurate forecasts of streamflow, for several reasons, are essential in both the Rio Grande and Arkansas basins. Agricultural interests which rely on the snowmelt waters for irrigation require planning information on their prospective water supply to effectively manage their operations. Second, waters of both streams are regulated and distributed according to interstate compact agreements between Colorado and downstream states. Administration of the compact agreements in an equitable and timely manner depends upon reliable estimates of streamflow both before and during the runoff season.

SNOW-MAPPING TECHNIQUE

Six years of Landsat imagery for the period 1973-78 were available during the course of the project. During this period, seven standard methods of mapping snow cover were investigated on one or all watersheds. These included zoom transfer scope, low-level aerial photography, density slicing, color-additive viewer, computer-assisted classification, grid sampling, and National Oceanic and Atmospheric Administration/National Environmental Satellite Service (NOAA/NESS) basin snow-cover maps.

The zoom transfer scope technique was found to be the most reliable, accurate and cost-effective of the methods explored. With it, basins as small as 100 mi^2 (259 km^2) can be successfully mapped. Time requirements to map snow cover on the watersheds in the study varied from one hour to four hours with an average of two hours. Best results were obtained when mapping was performed at a scale of 1:250,000, using MSS band 5 and 185 mm positive transparencies. Problems such as distinguishing clouds from snow, and boulder fields from snow, as well as determining the location of the snow line in heavy forest cover were generally easier to resolve with the zoom transfer scope than in other methods. A set of snow mapping criteria and a handbook were developed and instituted to standardize snow-cover interpretation. As much as 50 percent of the images in the March-June period were wholly or partially obscured due to cloud cover. A baseline index method of snow-cover estimation was developed to ameliorate this problem. Basin snow-cover depletion curves were constructed for each of the study watersheds for all of the years for which data were available. The curves depict the gradual loss of snow-cover as a percent of the basin area with time. The snow-cover depletion curves served as the foundation for all forecast analyses which included snow cover as a predictor variable.

Although the six-year period of the study was relatively short, it spanned a fairly wide spectrum of hydrologic conditions. 1973 and 1975 were moderately high snowpack and runoff years which had a probability of occurrence of once every 10 years. 1977 was an extremely low year which a frequency analysis predicted should only occur once in every 100 years. Both above normal and below normal spring and summer precipitation events were experienced during the study as well.

FORECAST PROCEDURE DEVELOPMENT

Three schemes in forecasting runoff using snow cover were investigated and evaluated. A graphical procedure which relates the relative displacement in time between snow-cover depletion curves and annual runoff was successfully developed for two of three watersheds on which the methods was tested. The technique is primarily suited for use in regions were limited or no corroborative hydrometeorologic data is available upon which to base more sophisticated forecast analyses. It is insensitive to abnormal weather or hydrologic conditions which occur during the runoff season and can only be applied after snowmelt has progressed to the point where approximately 20 percent of the basin is bare of snow. The method is, however, useful in serving as an independent check of other forecast estimates.

A statistical treatment of snow cover derived from Landsat revealed a high correlation between basin snow cover and April-September seasonal volume streamflow. Comparisons of interbasin snow-cover values were also found to be correlated highly enough to be useful for making estimates in the event cloud cover or missing imagery prevents actual measurements on a specific drainage. The nature of snowmelt generated peak streamflows has been shown to be related to basin snowcover. A moderate to good relationship is apparent between snow cover and daily peak flow volume. Prediction of the timing of the snowmelt peak from snow-cover depletion curves is less precise but still of value. A combined snow course index/snow-cover variable applied to May 1 conditions was shown to be exceptionally well correlated to seasonal volume flow for the short period of the study. A reduction of 10 percent in the average forecast error over present techniques on the May 1 forecast is estimated if the snow index/snow-cover method could be employed operationally. Unfortunately, the lag in delivery of Landsat imagery has been on the order of 10 days for Quick-Look products and 30 days for standard imagery. More prompt receipt of imagery is needed before Landsat derived snow cover will appreciably benefit forecast procedures. Snow cover is of negligible value in the period January through early April for most of the basins in the Colorado study. During this period the watersheds in the study area are normally 80 to 100 percent snow-covered. Maximum snowpack is generally observed near the first of April.

A computerized hydrologic simulation model developed by the U.S. Forest Service was used with satellite-derived snow-covered area for making residual volume forecasts in the Colorado study. The model was calibrated to five index watersheds varying from 73 mi^2 (189 km^2) to 1218 mi^2 (3155 km^2) in the Rio Grande and Arkansas River Basins.

Operational computerized streamflow forecasts which utilize the Subalpine Water Balance Model are keyed to real-time telemetered snowpack (Snotel) data and satellite imagery. Snotel and satellite systems such as Landsat are used to update the model at any time by means of "control curves" for a given drainage basin which relate: (a) Snotel data to areal water equivalent on the basin, and (b) snow cover extent to residual area water equivalent on the basin.

Operational studies in 1977 and 1978 have confirmed that the simulation model forecasting system responds well to unforeseen weather changes during a given snowmelt season which can greatly alter the timing and volume of runoff. It is especially well suited for short-term forecasting.

COST ANALYSIS

A cost analysis of employing Landsat snowcover in operational forecasting has resulted in an estimate of $300/year/basin. This figure is based upon the experience gained in the four-year study and should be considered only a "ballpark" estimate. It is predicated on two major assumptions: (1) Landsat imagery will be available in an operational time frame (within four days of exposure), and (2) forecast procedures have been developed and standardized to include snow-cover data. In addition, no capital investment costs for equipment are included in the estimate.

CONCLUSIONS

Use of snow areal extent measurements in snowmelt runoff prediction shows promise, but with the short period which the study encompassed, it is difficult to assess its long range impact. However, a number of conclusions can be drawn concerning the use of snow cover in forecasting in the Rio Grande and Arkansas basins.

Currently available Landsat imagery is of sufficient quality and resolution for accurate snow mapping by photointerpretative means. Further refinement is required before digital snow-mapping techniques can approximate the degree of precision obtained with the zoom transfer scope. Delay in image delivery, occurrence of cloud cover, and a nine-day interval between satellite coverage diminish to a significant extent the amount of reliance one can place on using snow cover as a forecast parameter. Use of NOAA/NESS snow maps on large basins shows merit. However, many if not most forecast points in Colorado, as well as other western states, are for watersheds which are too small for NOAA/NESS interpretation.

A significant drawback to using snow-covered area exclusively to make streamflow predictions is the lack of applicability prior to commencement of the main snowpack recession which normally occurs after May 1. Water management decisions frequently need to be made in late March and April necessitating streamflow forecasts before snowpack depletion gets well underway. For this reason, present forecast methods utilizing snow course and precipitation data will continue to be used. Use of snow-covered area in hydrologic models and statistical prediction techniques during late spring will be valuable as an independent method of checking the standard forecasts now being produced.

As successive years of satellite imagery are accumulated covering a wider range of hydrologic and climatic conditions, forecasts can be expected to improve through the use of snow mapping. Satellite snow mapping together with improvements in remote hydrometeorological data collection systems, will enable more frequent and accurate forecasts because of increased knowledge of what is happening in the major water-producing zone above valley floors.

APPENDIX D

EXECUTIVE SUMMARY: NORTHWEST STUDY AREA

(See NASA Technical Paper 1826)

OPERATIONAL APPLICATIONS OF THE SATELLITE SNOW-COVER OBSERVATIONS IN THE NORTHWEST UNITED STATES

EXECUTIVE SUMMARY

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INTRODUCTION

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. In order to accomplish this, study basins were selected, local proficiency in reducing raw data was acquired, data timeliness requirements were determined, data were verified, the sensitivity of the forecasting model was tested, and the satellite data were operationally incorporated in a forecasting model. The satellite-derived snow-covered area data are being used in daily operational streamflow forecasts.

Rationale

It had been demonstrated by 1972 that satellite imagery could be used to measure the extent of snow in a basin. The next logical step was to determine if this satellite snow-covered area (SCA) information could be used to predict snowmelt-derived runoff. The National Aeronautics and Space Administration at Goddard Space Flight Center (NASA), as a part of its interest in applications of space technology, 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 because of the possible problems of persistent cloud cover, heavy tree canopy, and steeply sloping terrain that often occur in the Pacific Northwest.

Application

The Pacific Northwest has a large complex of single and multipurpose reservoirs that are operated as a system for flood control, irrigation, and hydropower generation. The streamflow in the Pacific Northwest has a high seasonal variability with maximum runoff occurring in the late spring and early summer from melting snow, while conversely, maximum water needs for irrigation and power generation occur at other times of the year. Efficient operation is highly dependent upon the accuracy of seasonal volumetric runoff forecasts and also upon accurate daily streamflow forcasting. Forecasting procedures are therefore 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 study were to map snow lines, compare satellite products, and then incorporate these satellite products in forecasting models.

STUDY APPROACH

A systematic approach was taken in this study to answer the question "Can satellite-derived snow-cover observations be incorporated in forecasting model in an operational mode?" Data were analyzed for the years 1973-78. 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.

Gain Local Proficiency

When the study was begun, 1973 and 1974 Landsat data were used exclusively and were analyzed by a subcontractor on an interactive analyzer. Beginning in 1975, the National Oceanic and Atmospheric Administration, National Environmental Satellite Service (NOAA/NESS) began collecting and analyzing satellite data from the NOAA series of polar-orbiting satellites. The NOAA satellite data were available on a daily basis, whereas the Landsat orbits over a given area were only every nine days, and because of cloud cover, scenes were seldom obtained every nine days. It was decided to use primarily NOAA data for the balance of the study because of the cloud cover problem and the high cost of having Landsat imagery analyzed by a subcontractor. It was later determined that the subcontractor's unfamiliarity with the basins had produced erroneous results for 1975, which then had to be reanalyzed.

Because of the switch to the NOAA data, it became necessary to develop an in-house proficiency for reducing and analyzing the NOAA data. In January 1977, local personnel were instructed in the use of an optical zoom transfer scope (ZTS) to determine snow lines from satellite imagery.

Data Timeliness

The allowable time delay to receive satellite-determined SCA data is either 24 or 48 hours. A computer model which was used for daily operational streamflow forecasting, the Streamflow Synthesis and Reservoir Regulation (SSARR), was already operational. This model uses, as one item of input, SCA data. The model is initialized with data for the 48-hour period antecedent to the start of the run, and allowed to "tune-up" itself, 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. 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 prior. In the wintertime, the initializing period for the forecasting runs is reduced to 24 hours.

Since the mail time to receive NOAA satellite imagery locally can exceed 48 hours, the NOAA data cannot be analyzed locally for operational forecasts.

STUDY AREAS

Basins were selected that would test the usability of the data under differing conditions of location, elevation, forest canopy cover, slope, and shadow parameters. The availability of ground truth data was also considered. The study period was 1973 through 1978. The five basins selected for study were:

Upper Snake River Basin (above Palisades Dam), Idaho,

Boise River Basin (above Lucky Peak Dam), Idaho

North Fork Clearwater River Basin (above Dworshak Dam), Idaho

Kootenai River Basin (above Libby Dam), Montana

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

Because of the persistent problem of cloud cover, the Dworshak, Libby, and Hungry Horse Basins were not studied for 1973 or 1974.

DATA REDUCTION

The raw data consisted of both satellite imagery and ground truth. Analysis of information was dependent upon the source of the raw data.

Satellite Data

Landsat Imagery

Landsat data were reduced either by the subcontractor, Stanford Research Institute (SRI), or by Bonneville Power Administration (BPA). Landsat data reduction by SRI was either from band MSS-5, or from bands MSS-5 and MSS-7. Analysis was performed on an interactive analyzer using radiance thresholding. Editing was done in conjunction with basin outline masks, control elevation masks, and drainage pattern maps. A binary thematic map was created from the satellite imagery and stored in a "scratch pad" computer memory, where, by subjective editing, the percent of snow cover for each cell could be revised. The SCA for the basin was then determined by summing, and the percent of basis that was snow-covered was calculated.

BPA did its analysis of Landsat data from band 5 utilizing a zoom transfer scope. The snow line traced onto a basin overlay map as planimetered to determine the snow-covered area.

NOAA Imagery

The NOAA imagery was collected and analyzed during the spring snowmelt seasons by either BPA or NOAA/NESS personnel. Visible imagery was taken from the Very High Resolution Radiometer (VHRR) and snow lines were traced onto a basin overlay map using an optical zoom transfer scope. A ZTS was required to stretch the image and remove the lateral distortion, and to enlarge the image to a traceable size. The snow lines, transferred onto the basin overlay, were then traced by planimeter to determine percent of basin area that was snow-covered.

Over Snow Aircraft Flights

Snow flights are made in small aircraft flying at low altitude to determine changes in SCA during the spring snowmelt season. An experienced observer riding in the plane determines the snow line elevation, and then plots the snow line on a map as the flight is made, excluding low-lying patchy snow which is not considered to contribute to runoff. Although the snow-flight observers are experienced, the data gathered are entirely subjective.

Snowpack Depletion by Computer

Daily operational runoff forecasts for streams in the Pacific Northwest are made using the SSARR computer model. The SSARR model computes the snowmelt portion of streamflow by a temperature index method, and routes the snowmelt, along with the other components of runoff, to determine streamflows at key points in a basin. Snowmelt determination in the model requires that the snow-covered area be updated daily. This can either be input to the program or computed by the model.

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

The SCA data generated by the SSARR model are in turn used to cross-check and verify the SCA data gathered for the aerial flights and computed from the satellite, thus providing a three-way check on the data.

DATA REDUCTION PROBLEMS

In the Upper Snake and Boise basins there were no problems interpreting the snow line from satellite imagery. In the Sworshak, Libby, and Hungry Horse Basins, forest cover, steep slopes, and sun angle/shadow caused problems in determining the snow line from the satellite imagery. This forest cover and shadow caused only minor problems in the Dworshak Basin, but was a major problem in the Libby and Hungry Horse Basins. The Libby Basin is steep, heavily forested and extremely difficult to map. NOAA/NESS personnel do not feel confident mapping the Libby Basin until the snow-covered area has dropped to below 50 percent.

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

Cloud cover was the greatest problem in data reduction. Because the snowline changes rapidly during the spring snowmelt season, Landsat's nine-day optimum coverage is less then ideal. 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. 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 30 to 40 days, and in 1978 for the Dworshak Basin was 52 days. Although these periods could be extensive, there was never a case of only one image per melt season as with the Landsat data.

DATA VERIFICATION

Ground Truth Data

As already noted, a comparison of the computed and actual hydrographs on a SSARR reconstitution run provides a visual check on the model's performance, and therefore gives credence to the SCA curve generated by the model. In addition to the general fit of the two hydrographs, there are also two other factors of a watershed's fit that can be checked by the hydrographs, again lending credence to the SCA curve generated by the model. The first of these is the volumetric runoff. The second check is the ability of the model to match the peaks on the two hydrographs. Both the volumetric runoff and the generation of the peak are highly dependent upon the SCA input parameter. Since the SCA parameter is so vitally important to the SSARR calculations, the SSARR reconstitution runs critically assess a basin's SCA during a given melt season.

The snow-covered area data determined from the aerial flights are checked by comparing the data to the SCA data generated in the SSARR reconstitution runs. The aerial flight SCA data are also compared to the satellite data. In the aerial flights, discontinuous patchy snow below the continuous snowline is disregarded. Conversely, the satellite data integrates patches into the overall snowline. Thus the satellite data are generally larger than the aerial flight SCA data. When, however, the 50 percent snow line (50 percent of patchy snow) is plotted in a flight, there is perfect agreement between the flight and satellite data.

Satellite Data

Satellite-derived SCA data were verified by comparing them with both the aerial flight and the SSARR-generated SCA data. In addition, several cross-checks were made on the satellite SCA data itself.

Retracing and measuring the same day's satellite scene on three separate occasions resulted in a good comparison, as did measuring a given day's scene with that of another satellite pass made one or two days later. When the snow lines were independently traced and measured by both BPA and NOAA/NESS personnel, the agreement was good when the image was sharp; where the image had a poor grey-scale definition, the results were variable.

The 1976 (Fig. D1) satellite data for the Hungry Horse Basin were analyzed from both Landsat and NOAA imagery. The SCA values determined from the two different sets of imagery compared very favorably.

SUMMARY AND COMPARISON OF SATELLITE DATA

In general, 1975 had a maximum SCA, 1977 had a minimum SCA, and 1973, 1974, 1976, and 1978 had average SCA. The satellite photos integrate the snow line and thus include areas of low-lying patchy discontinuous snow. This discontinuous snow is ignored in the aerial flight SCA data. Thus there is a bias between the satellite data, snow-flight data, and the SSARR-generated data, wherein the satellite data generally show a greater SCA for a given point in time.

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.

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.

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.

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 snow line. 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.

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, so as not to include bare rock in the SCA estimates.

MODEL VERIFICATION

As a test of the sensitivity of the SSARR model to SCA data, two separate reconstitution runs were made for the Hungry Horse Basin using 1975 data. These runs are shown on Figure D2. In the first run, the model was run in a standard mode wherein the SCA was initialized and then not changed throughout the time frame of the run. The initializing value of SCA was chosen

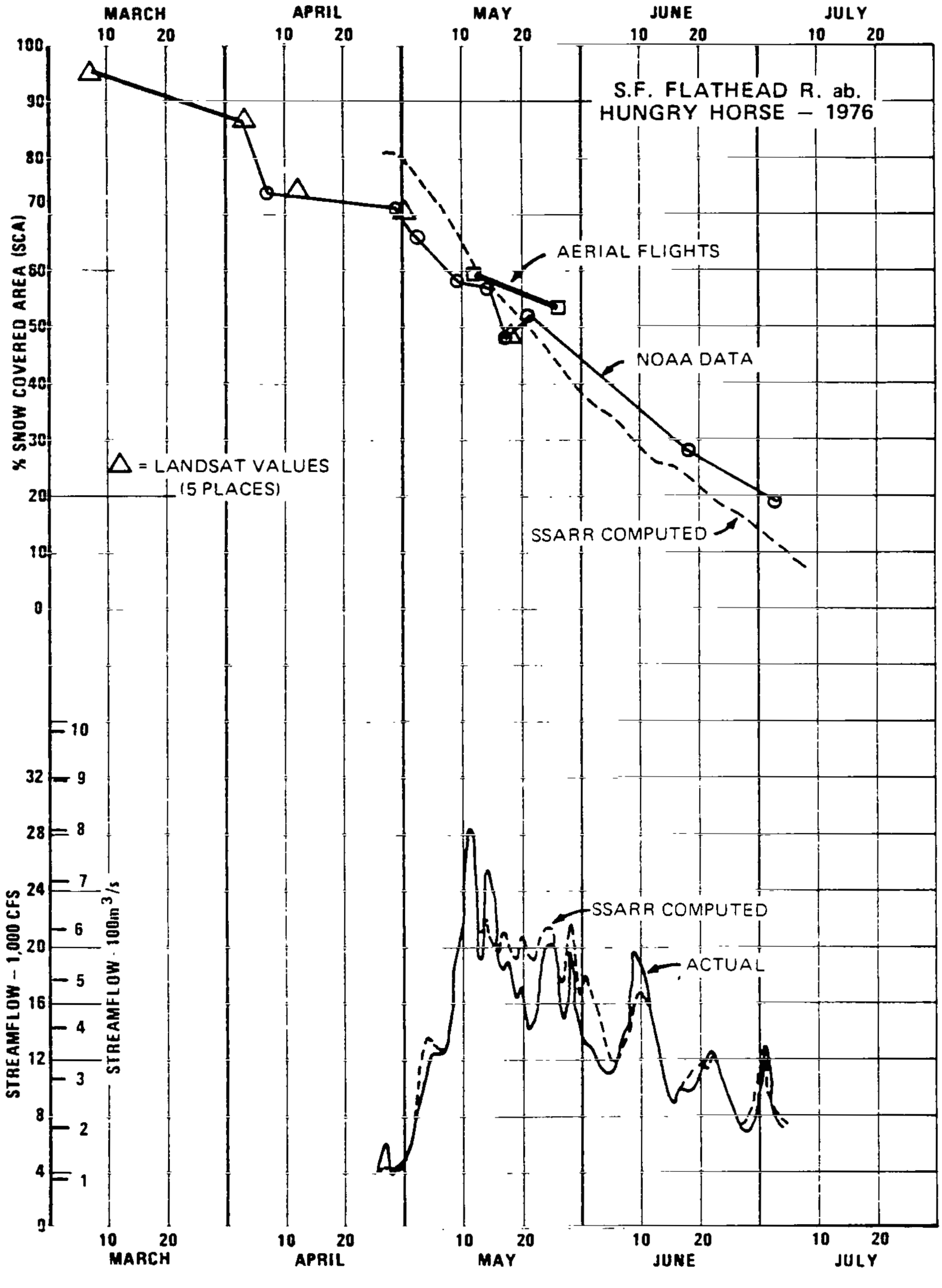

Figure D1. Satellite data for Hungry Horse Basin, from Landsat and NOAA imagery.

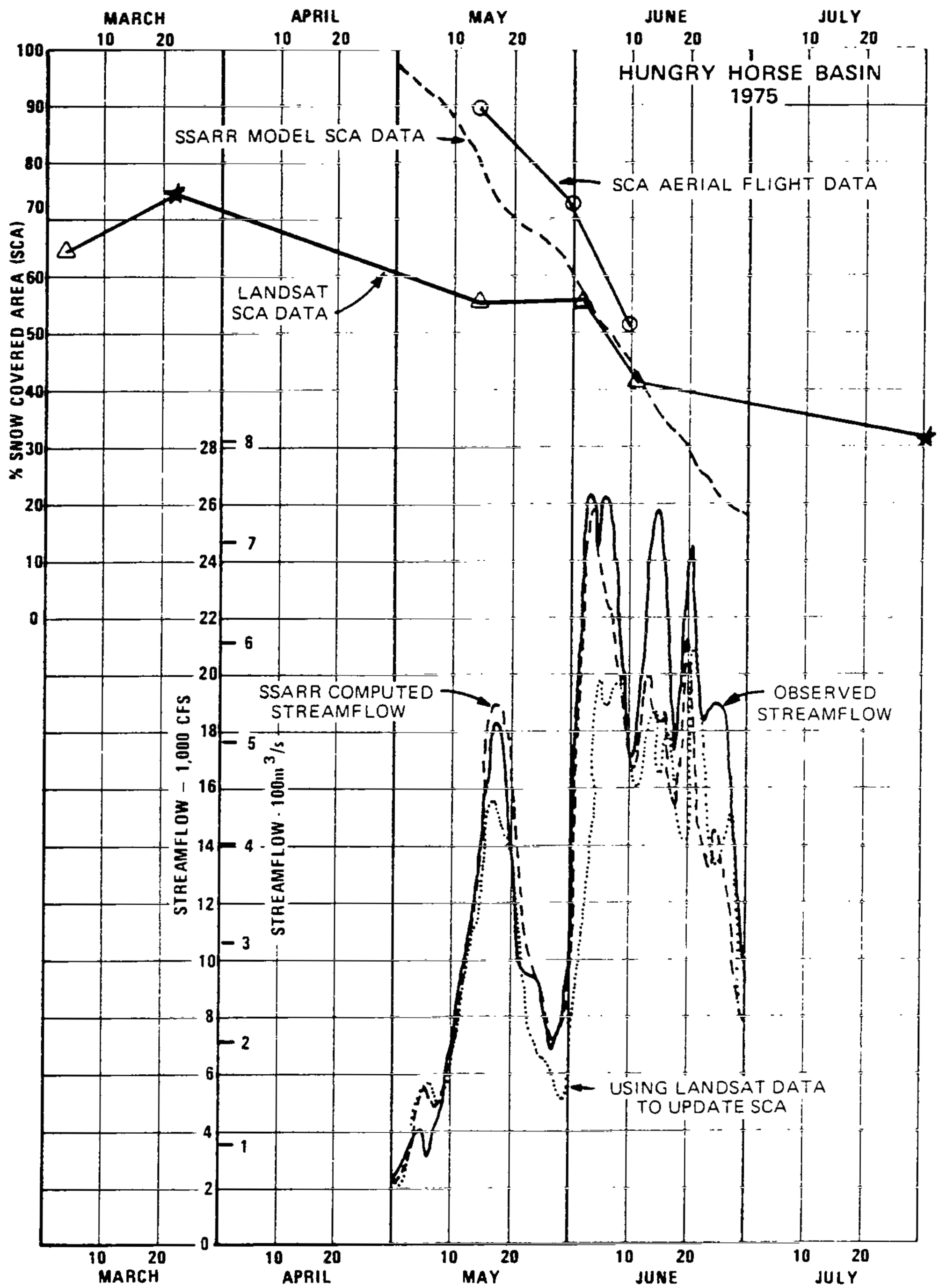

Figure D2. Reconstitution runs for Hungry Horse Basin, using 1975 data.

from the several trial runs and was the one that would produce the best hydrograph fit. In the second run, the SCA was initialized with the satellite value and updated throughout the run with each new satellite SCA data point. It was later determined that these Landsat SCA values were in error, and that the 1975 Hungry Horse data had to be revised, but as can be seen, the Landsat updated hydrograph could never match any of the peaks because of insufficient initial snowpack, and the test did indeed portray the sensitivity of the SSARR model to snow-covered area data.

SSARR DAILY OPERATIONAL FORECAST MODEL APPLICATION

The SSARR model is allowed to "tune-up" itself for a 48-hour data period before commencing daily operational streamflow forecasts.

SSARR Adjustment Routine

The SSARR model has a watershed adjustment factor, which ranges from 0.5 to 2.0, and is a multiplier for the moisture input (snowmelt plus rain runoff), and used to have the forecasted inflow and the current inflow match within a specified tolerance. When this factor deviates up or down from 1.0, it indicates those basins which are not computing properly. A current satellite SCA report can be used to update the model, and better its performance.

SSARR Volume and Peak Check

The SSARR model is periodically run during the spring runoff season for a future or forecasted period of 60 to 90 days to determine if the model is able to generate the total forecasted volumetric runoff for the particular basin. A peak-to-volume graph is available for each basin that brackets the probable peak flow, given the total seasonal volumetric runoff. Since both the runoff and the peak flow are highly dependent upon snow-covered area, a current satellite SCA report is most useful in daily operational streamflow forecasting.

SSARR Winter Forecast Runs

The satellite estimates of SCA are extremely important in the fall and winter season when ground truth are not available. Many basins are susceptible to rain-on-snow events during these two seasons. Whether a basin is still essentially snow free, or whether it is practically 100 percent snow covered can mean the difference between a moderate rise in river stage and a major flood. Information on basin SCA warns river forecasters of those basins having a potential for a major fall or winter flood.

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. Forecasts were made for 3, 5, 7, and 14 days into the future. The dummy basin with satellite SCA data used exclusively, was able to outperform the standard basin for the 3-, 5-, and 7-day forecasts, and the forecast error of the 5-day forecast was reduced by 9.6 percent. However, the absolute error reductions were less than the overall accuracy of the data, and the improvements were, therefore, 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 to 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 snow line 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 snow line, 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.

APPENDIX E

EXECUTIVE SUMMARY: NOAA/NESS SUPPORT STUDY

(See NASA Technical Paper 1827)

OPERATIONAL APPLICATIONS OF SATELLITE SNOW-COVER OBSERVATIONS--NOAA/NESS SUPPORT STUDY

EXECUTIVE SUMMARY

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NESS AND THE SNOW ASVT PROGRAM

Positive research results in both snow mapping and runoff correlations led to a decision at NASA in 1975 to operationally test the use of remotely sensed snow-covered area for improving runoff forecasts in a four-year duration Applications Systems Verification Test (ASVT). A contract was let that same year to NOAA/NESS to promote a study in support of the snow ASVT. Since that time data from NOAA/NESS have been regularly shipped on request to the ASVT test sites in Arizona, California, Colorado and the Pacific Northwest. These data have been in the form of satellite imagery, digital tapes and completed snow maps. Daily NOAA snow-cover data have been used at the four test sites to fill in the gaps created by the less frequent coverage of Landsat-1 and 2.

As the ASVT program now comes to an end, it becomes obvious that its major benefit to operational snow mapping at NESS has been to make the user community aware of the availability and usefulness of satellite snow-cover data. In fact, several of the basins (Rio Grande, Feather, Sacramento) originally targeted for limited-duration study in support of the ASVT have now been added to the ongoing Operational Snowmapping Program at NESS.

SATELLITES AND SENSORS

NOAA/VHRR

From 1973 to 1978, the primary sensor used to obtain data for the NESS Snowmapping Program was the Very High Resolution Radiometer (VHRR) on board the NOAA series of polar-orbiting satellites. The VHRR was sensitive to two portions of the spectrum, a 0.6 to 0.7 μm (visible) and a 0.5 to 12.5 μm (thermal infrared) channel. Coverage over most basins at 1 km resolution was available once daily in the visible and twice each day in the thermal infrared portions of the spectrum. Each standard VHRR frame was printed at a scale of 1:10,000,000 and covered an area approximately 2100 km square with three frames usually available per pass. Distortions in the imagery were corrected either through optical rectification or by further computer processing utilizing a geometric correction algorithm.

GOES/VISSR

Five satellites in the GOES series have been launched thus far. The first two Synchronous Meteorological Satellites, SMS-1 and SMS-2, were NASA-sponsored prototypes. The most recent three, Goes-1, 2 and 3, were entirely NOAA funded (the acronym stands for Geostationary Operational Environmental Satellite). The satellites are dubbed geostationary because their position relative to the earth's surface remains fixed. One of these satellites is always stationed off the U.S. east coast at an altitude of 37,500 km over 0°N, 75°W; another monitors the western U.S. from 0°N, 135°W. The imaging sensor on board the GOES is the Visible and Infrared Spin Scan Radiometer (VISSR). The sensor can provide imagery in both the visible (.55-.75 μm) and thermal infrared (10.5-12.5 μm) portions of the spectrum as often as every half-hour. Visible imagery from the VISSR can be obtained an optimum resolution of 1 km. The data are rectified by optical means for snow mapping.

TIROS-N/AVHRR

The first of a new generation of polar-orbiting satellite, TIROS-N, was launched on October 13, 1978. A second satellite in this series, NOAA-A, was launched on June 27, 1979. Together, the satellites are able to provide coverage four times daily (0300, 0730, 1500, 1930 Local Standard Time) over most areas in the United States and Canada. Each satellite has an Advanced Very High Resolution Radiometer (AVHRR) on board which provides coverage in the following four channels:

Channel 1	.58-.68μm
Channel 2	.725-1.1μm
Channel 3	3.55-3.93μm
Channel 4	10.5-11.5μm

The availability of simultaneous AVHRR visible (Channel 1) and near-infrared (Channel 2) imagery may allow NESS investigators to give operational reports on the age and condition of river basin snow cover as well as its areal extent.

THE NESS SNOWMAPPING PROGRAM

Snow maps are produced at NESS by first enlarging and rectifying a visible VHRR or VISSR image to overlay a hydrologic basin map. A Bausch and Lomb Zoom Transfer Scope (ZTS) is utilized for this purpose. Percentage snow cover for the basin is then determined by using an electronic density slicer.

Areal snow-cover measurements are now being routinely made at NESS for thirty critical basins in the United States and Canada. The data are disseminated to water resource managers in numerous federal, state and local agencies. The snow-cover percentages are dispatched over the RAWARC teletype circuit to National Weather Service River Forecast Centers (RFCs) in Sacramento, Fort Worth, Salt Lake City, Kansas City and Portland and River District Offices in Great Falls, Phoenix and Albuquerque. Snow maps are sent over telecopier or through the mail to other agencies including the

U.S. Geological Survey, Bureau of Reclamation, Corps of Engineers, Soil Conservation Service and U.S. Forest Service. Analyses of snow cover in the Northeast are transmitted over telecopier to the Weather Service Eastern Regional Hydrologist in New York and then rerouted to RFCs in Hartford, Harrisburg and Cincinnati.

Basin snow maps are made on an average of once a week beginning November 1st and terminating when the snowpack appears almost totally depleted on the imagery. The analyses can only be made when the basin is free of obscuring clouds. Accordingly, basins in the southwestern United States and California's Sierra Nevada are mapped more often than those in the less cloud-free Pacific Northwest.

Over six hundred snow-cover measurements were made at NESS during the 1978-1979 snow season. Totals for the past four years are as follows:

Snow Year	Number of Snow Maps
1974-1975	441
1975-1976	520
1976-1977	494
1977-1978	606
1978-1979	646
TOTAL	2707

The snow-cover data are generally provided to users within 30 hours of a satellite overpass so they can be incorporated into watershed runoff forecast models. Quality control techniques include checks of the operational snow maps with higher resolution Landsat satellite data, computer-enchanced imagery, ground-based snowpack measurements and aerial-survey maps.

DEVELOPMENT AT NESS

Interactive Snowmapping

Two new interactive computer systems named VIRGS (VISSR Interactive Registration and Gridding System) were delivered to NESS in June 1978. To use the system for snow mapping, basin perimeters drawn on standard aeronautical charts are first converted into grid points through the use of an electronic digitizing board, and are then read into the VIRGS. The basin outlines can then be displayed on the system video screen at any time by typing a single command on the keyboard. A joy-stick cursor is used to outline snow cover on the video screen; area statistics software on the VIRGS are invoked to calculate and print out the basin snowcover percentages.

All Digital Snowmapping

A project is underway at NESS to check the feasibility of doing all digital snow mapping using 4 km visible GOES data. The test area includes nine contiguous basins in the Sierra Nevada. These basins offer a wide variety of terrain characteristics and ground cover for control purposes; they are also of ideal size and location as viewed from the west coast geostationary satellite. Data used in this experiment are stored on computer disk packs for 24 hours. Snow maps for all nine basins can be done as often as five times daily. The model involves the thresholding of each individual basin pixel for snow cover and takes into account solar illumination angles as well as the nature of ground cover.

CONCLUSIONS

An operational satellite snow mapping program for selected river basins is now in place at the National Environmental Satellite Service. Owing to the combined success of this program and the NASA Snow ASVT, a larger number of requests for support have been received than can be handled, given present manpower and fiscal restraints. Expansion of the program can therefore only come about through the development of more efficient (i.e., automated) techniques for snow mapping. This is the goal towards which satellite snow specialists must now direct their efforts.

ACKNOWLEDGEMENTS

The author wishes to thank Mr. Russell Koffler for his support of the operational snow-mapping program. The meteorologists, hydrologists and technicians of the NESS Environmental Sciences Group, Interactive Processing Group and Synoptic Analysis Branch are thanked for their diligent monitoring of snow cover in the various operational river basins over the years.

APPENDIX F

EXECUTIVE SUMMARY: COST/BENEFIT STUDY
(See NASA Technical Paper 1828)

COST/BENEFIT STUDY FOR THE ASVT ON THE OPERATIONAL APPLICATIONS OF SATELLITE SNOW-COVER OBSERVATIONS (OASSO)

EXECUTIVE SUMMARY

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INTRODUCTION

Since the early 1970's, technology has been capable of providing high-quality satellite imagery with sufficient frequency to indicate to hydrologists the practicality of using these data to estimate snowpack areas. Techniques for measuring snowpack area and their exploration for improved seasonal runoff predictions have been demonstrated.[1,2,3] In 1976, NASA established an Applications Systems Verification and Transfer (ASVT) program to analyze the value of operational Satellite Snowcovered Area Measurements (SATSCAM) to water resources activities within the 11 western states.

Four ASVT sites were defined in Arizona, California, Colorado and the Pacific Northwest. The ASVT's primary objectives were to: 1) evaluate the operational capability of using satellite imagery in mapping snow-cover area; 2) develop techniques and procedures for systematically monitoring snow cover from remotely sensed imagery; and 3) perfect methods to incorporate satellite snow-cover area measurements into operational streamflow forecasts.

This report summarizes the results of the cost/benefit analysis of the operational applications of SATSCAM. The effort's purpose was to quantify the potential benefit and associated cost of operationally utilizing SATSCAM throughout the 11 western states, using data provided by ASVT personnel and a methodology acceptable to them.

THE RESULTS FROM THE ASVT'S

Two approaches were used by the ASVT's to determine the physical contribution of satellite snow-cover observations to runoff forecasting. The first employed linear regressions between snowmelt runoff volume, snow-covered area and snow water equivalent. The second used hydrologic models with SATSCAM inputs.

The ASVT sites used, in various combinations, snow-cover data obtained from: Landsat and SMS/GOES imagery; NOAA/NESS snow-cover maps; and aerial snow flights.

All ASVT's concluded that SATSCAM represented a valuable contribution to operational snow survey forecasting:

- In Arizona where the snowpack below 7,000 feet (2,100m) is generally thin and transient and energy input for snowmelt is intense, SATSCAM was of significant value for short-term runoff prediction.

- In California, SATSCAM was indicated to be most effective in reducing forecast errors in basins characterized by: 1) erratic precipitation; 2) snowpack accumulation pattern not related to elevation; and 3) poor coverage by precipitation stations or snow courses with consequent inadequate indexing of water supply conditions.[4] SATSCAM was also hypothesized to result in significant contributions to runoff forecast accuracy in other basins during unusual snowpack distribution conditions.

- In Colorado, a high degree of correlation between satellite determined snowcover area on April 1, May 1, June 1 and the April-September streamflow was noted. 66.7% of the cases investigated exhibited a significant increase in forecast accuracy; only 15.8% exhibited decreased accuracy. The balance was substantially unaffected.[5]

- In the Pacific Northwest, use of SATSCAM in preparing streamflow forecasts resulted in apparently increased accuracy; however, this increase was not found to be statistically significant. Nevertheless, Pacific Northwest ASVT personnel indicate that in their experience SATSCAM is a valuable input for fall and winter forecasting.[6]

While forecast improvements from SATSCAM were indicated by all ASVT's, precise estimations of the exact level of this improvement were compromised by limitations such as the short history of satellite data, and problems of cloud obscuration. The Colorado ASVT site personnel indicated that 5 to 10 more years of SATSCAM data are required to finalize the evaluation. They concluded, based upon their operational forecasting experience and the currently available SATSCAM data record, that it is reasonable to expect a 6% to 10% relative improvement of forecast from the operational use of SATSCAM.

POTENTIAL AREAS OF BENEFITS FROM IMPROVED INFORMATION

The major benefits of improved snowmelt runoff forecasting relate to the principal usages of water.

In the United States these are:

- Hydropower
- Irrigation
- Municipal and Industrial
- Navigation
- Recreation, Land and Wildlife Management

An additional area of benefit is flood damage reduction. Direct benefits originate from reduced losses to public and private property, and from increases in net income arising from more continuous use of property. Indirect benefits stem from alleviation of interruptions of public and private activities. Major intangible benefits accrue from preventing loss of human life and from augmenting the general welfare and security of the populace.

Table F1 depicts the principal direct and indirect benefits accruing to each water use.

Hydroelectric energy production is the largest use of water in the 11 western states. They produce annually (1976) 190 terawatt-hours of hydroelectric energy, requiring over two billion acre-feet of water. Annual dollar sales of hydroelectric energy at current prices exceed $6 billion (1978).

Irrigation is second to hydropower in quantity of water used. Twenty-five percent ($12 billion) of all crops sold in the United States are produced on irrigated land. Irrigation accounts for approximately 40% of all the water withdrawn annually in the U. S. (with hydropower excluded since it does not withdraw water). Sixty percent of the irrigation water is consumed as evapotranspiration from crops and soil surfaces, making irrigation the largest consumptive user of water. The 11 western states account for approximately 58% of the nation's irrigation requirements.

The next largest user of water is municipal and industrial water supply. Recent reports on annual withdrawal for various uses in the 11 western states indicate that municipal and industrial uses require only 10% of the water required by irrigation and less than 1% of that required by hydroenergy. Consequently, the central focus of this study was directed at estimating the benefit of improved streamflow forecasting to hydropower production and to irrigated agriculture.

THE ECONOMIC IMPACT OF IMPROVED RUNOFF FORECASTING

The less perfectly known the future (quantity and timing) of the water supply, the less efficient can be the water management activities. This is illustrated conceptually in Figure F1.

Curve A represents the locus of benefits accruing to perfect forecast. It reflects optimal management of water-dependent activities at each level of water supply. For example, "value" from a perfectly managed volume of water X_o is given by Y_o. Curve B_1 is the locus of the values accruing to water volume lower than the forecasted quantity X_o. Curve B_2 is the analogous locus to water volumes greater than that forecasted.

To illustrate: If the volume X_o is forecast and the lesser volume X obtained, then the corresponding value is Y_1. Had X been forecasted correctly, the benefit would have been Y'_1. The benefit lost is the difference between these "values" or $Y'_2 - Y_1$.

Table F1

Generic Benefits of Improved Information

Uses	Direct Benefits	Indirect Benefits	Intangible Benefits
Hydroenergy	Cost savings due to optimal mix of hydro-energy and thermal energy. Value added by optimal production at upstream/ downstream sites. Improved power production scheduling, hence improved overall plant efficiency.	Conservation of fossil energy supplies Conservation of labor	Improved level of life due to lower cost energy production
Irrigation	Increase in net farm income due to lower production costs Increase in net farm income due to optimal crop selection Improvements in operational efficiency of in place irrigation projects	Increases in net income to Agri-business suppliers Reduction in food costs to populace Reduction in energy required to provide irrigation	Improved community facilities and services Increased level of living
Municipal/ Industrial	Improved surface water withdrawal scheduling, hence improved overall waterworks efficiency Cost saving by reduction of high cost ground water withdrawal	Reduction of fire insurance rates Cost savings to populace due to increased availability of water Expansion of industry due to increased availability of water	Improved standard of living within area
Navigation	Reduction in cost of transport through improved scheduled releases of reservoirs' water storage to improve or expand navigable waterways Increased value of transport services resulting from expanded demand for the improved service	Increased industrial and commercial activity Increased utilization/value of land along waterways	Enhanced strategic value of inland waterways
Recreation, Fish & Wildlife	Increased revenues from increased utilization of recreational lands and facilities Increased population of higher value fish and wildlife Reduction of fish embolism through better control of reservoir releases	Increased revenues from the sale of recreational equipment Improved health of recreationally active populace	Esthetic value of improved waterways and wildlife habitat Ecological value of improved waterways and wildlife habitat Scientific value of improved water ecosystems

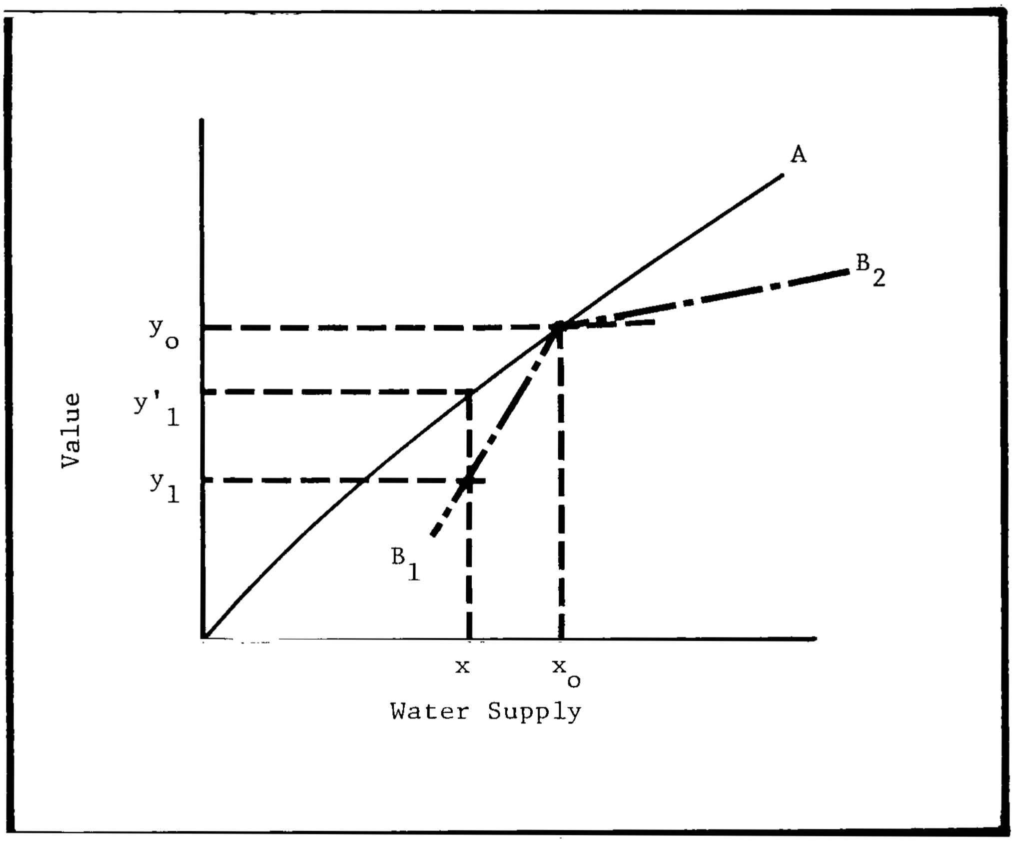

Figure F1. Conceptual description of benefits to improved forecasting.

The physical explanation of this loss of benefit is that in an attempt to maximize benefits, activities are planned which will utilize the forecasted quantity of water most efficiently. If subsequently, the supply of water actually obtained differs from that forecasted, efficiency suffers and the results obtained are less than optimal. This conceptual model was adapted to compute the benefits of improved forecasts due to the addition of satellite snow-covered area measurements to irrigated uses and hydroenergy.

IRRIGATION

The average annual benefit of improved forecasting by SATSCAM to irrigated agriculture is dependent upon: the variability of streamflow, as indicated by the coefficient of variation; the variability of streamflow forecast accuracy, as indicated by the standard deviation of % forecast error; the amount of irrigated area impacted by snow survey forecasting; the average annual revenue generated per irrigated acre; and the average increase in forecast accuracy attributable to SATSCAM.

Empirical data required to estimate irrigation benefits were obtained from many sources. ASVT personnel and local hydrologic experts were primary sources of accurate, up-to-date data.

Estimation of the benefit to irrigation from SATSCAM required the assembly of two extensive geographic data bases; one for specifying the areas impacted by snow survey forecasting, the second to provide the inputs to the irrigation benefit model. These data bases contain geographically specific information at as fine a level of granularity as is presently available and consistent with the total area covered.

The Snow Survey Forecast Unit of the Soil Conservation Service provided data on average streamflow variation, and forecast accuracy for 361 primary snow survey forecast points covering the 11 western states. Data for twenty additional forecast points were supplied by the California Department of Water Resources (CDWR).

Flow-weighted values of streamflow CV and 1σ forecast error were calculated for each hydrologic region.

The wide range of streamflow variability from region to region illustrates the varying hydrologic characteristics of the major basins. The Pacific Northwest hydrologic region shows the smallest variability of streamflow at CV = 0.22, while the Lower Colorado shows the greatest variability at CV = 1.15. Streamflow forecast errors also vary considerably; the lowest 1σ error is 10.0% (California hydrologic region); the highest is 89.9% (Lower Colorado hydrologic region).

The SCS data, the CDWR data and other information obtained from hydrologic experts in the 11 western states were used to identify the basins impacted by snow survey forecast. A total of 52 hydrologic subregions (USGS '74) are partially or totally impacted by snow survey forecasts. Within these, approximately 20 million irrigated acres can potentially benefit from an improvement in streamflow forecasting. These utilize surface water instead of ground water for irrigation.

The irrigated acreage which can potentially benefit from improvement of forecast accuracy is shown in Figure F2. Three hydrologic regions account for 80.1% of the total 20 million irrigated acres: the Pacific Northwest (29.5%); the Missouri (30.9%); and the California (19.7%).

The average annual crop values per acre were extrapolated from 1976 crop value/acre statistics[13] of the Bureau of Reclamation for each of its irrigation projects, and were used to produce an annual crop value/acre for each subregion. Figure 5 indicates these.

The crop values were generally higher within hydrologic regions whose variability of streamflow was high.

BENEFITS OF SATSCAM FOR IRRIGATION

The irrigation benefit model computes the potential increase in crop revenues attributable to improved streamflow forecast information. The model is derived from the application of linear programming techniques to evaluate the value of planting mixes of crops tailored to make optimum use of forecasted volumes of water under various conditions of forecast accuracy. The benefit attributable to SATSCAM is computed as the difference between crop revenues obtained under current forecast accuracy conditions and the revenues obtained under the improved accuracy conditions afforded by SATSCAM.

The computed annual benefit to irrigation from forecast improvements due to SATSCAM was $26.5 million per year, using the conservative estimate of 6% relative forecast error improvement supplied by the Colorado ASVT.

Figure F3 shows the total benefit and the benefit per irrigated acre for each hydrologic region. Note that three hydrologic regions account for 74% of the total potential benefit to irrigation: the Pacific Northwest; the Missouri; and the California region.

HYDROENERGY

The benefit of improved runoff forecasting to hydroenergy is a function of: the standard deviation of percent forecast error; the average annual amount of hydroelectric energy generation within the snow survey impacted area; the difference in primary and secondary hydroelectric tariffs; the difference in hydroelectric and steam-electric production costs; and the increase in stream-flow forecasting attributed to employing SATSCAM.

A hydroenergy data base was developed for all the generating plants within the 11 western states listed by the Federal Energy Regulator Commission (FERC), the Energy Information Administration (EIA) and the former Federal Power Commission (FPC). These data, reorganized into a subregional basis, included: 1) 1978 average annual hydroelectric energy generation (MWH)[14]; 2) current estimates of hydroelectric costs (mills/KWH); and 3) current estimates of the revenues obtained from the sale of prime and secondary energy (mills/KWH). Production expenses, initially based on 1976 figures [15,16] and the energy sales revenue, initially based on 1975 figures [17] were adjusted for inflation.

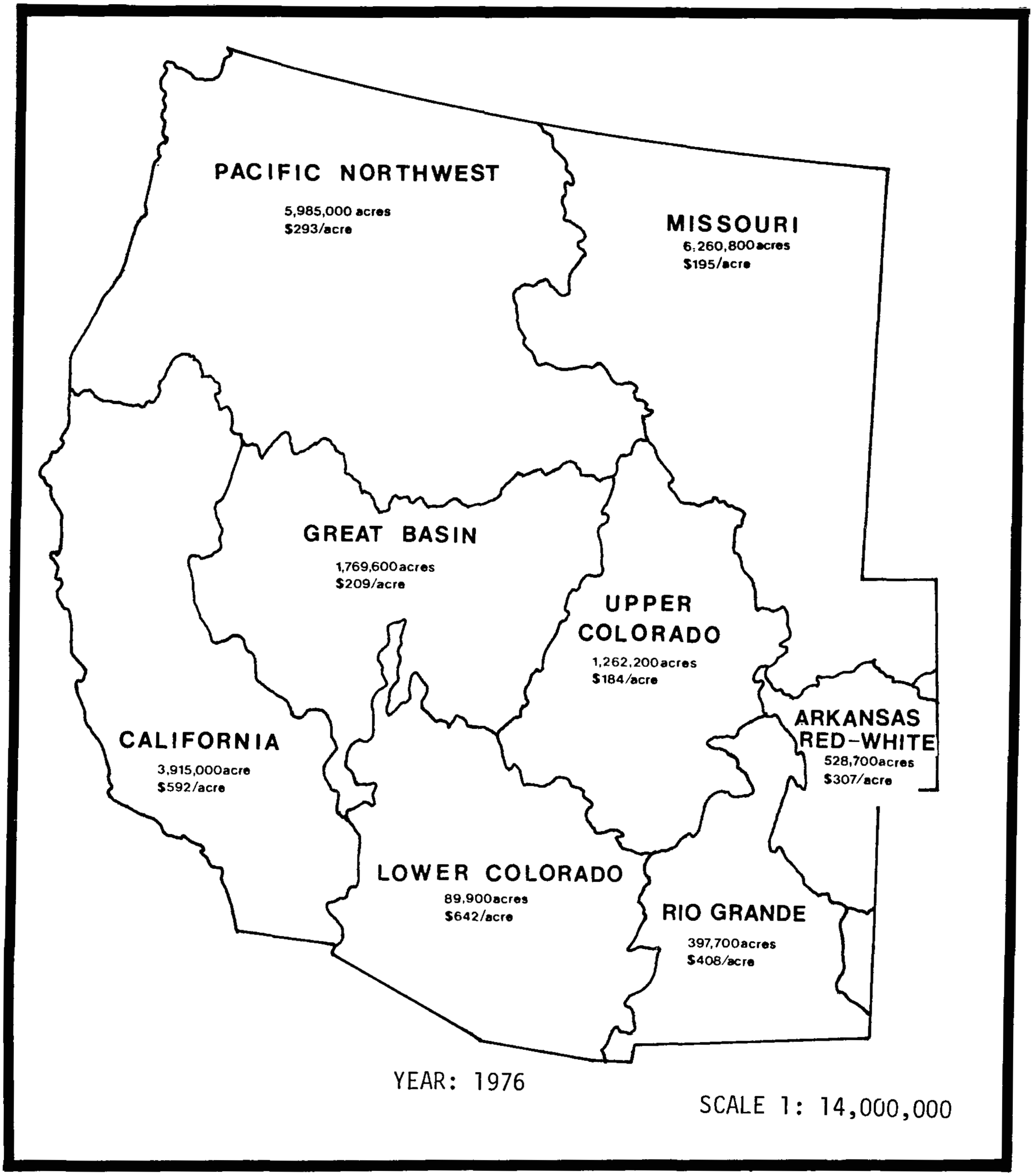

Figure F2. Surface water irrigated acreage and its average crop value ($/acre) in the eleven western states by hydrologic region.

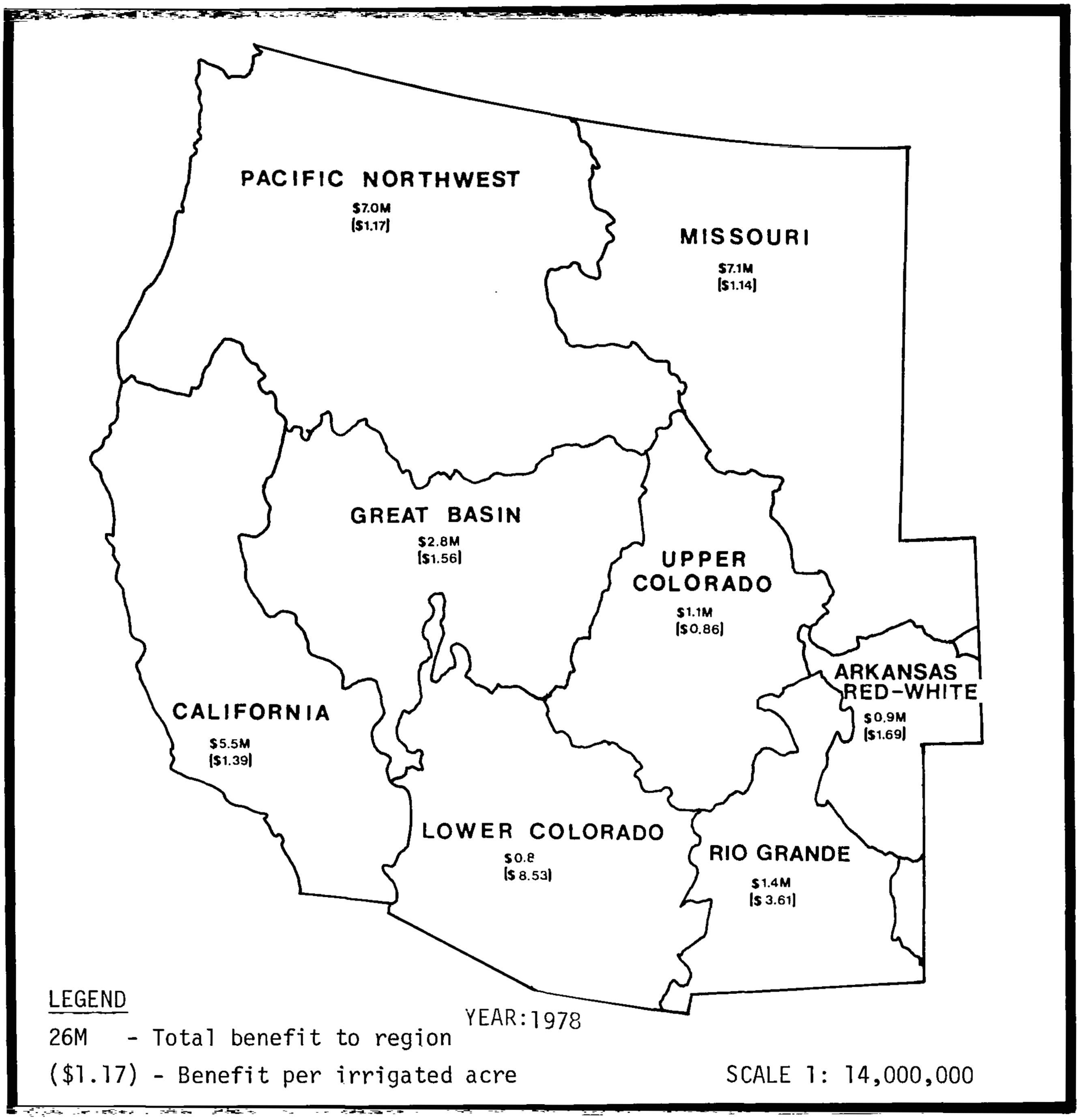

Figure F3. Annual benefit of SATSCAM to irrigated agriculture in the western United States by hydrologic region.

Approximately 180 terawatt-hours of hydroelectric energy were generated in 1976 by plants located within 52 subregions of the 11 western states. The total average generation by hydrologic region is illustrated in Figure F4. The Pacific Northwest generates 73%; California accounts for 18%; Missouri and Upper Colorado for approximately 3% and 2%, respectively.

The cost of producing hydroelectric energy varies significantly across the western states. It is highest in basins whose streamflow variability is large. For example, 1976 production costs of Lower Colorado were 2.23 mills/KWH, while those of the Pacific Northwest were 0.39 mills/KWH. The coefficient of variation of streamflow in the Lower Colorado is roughly 1.15 while that of the Pacific Northwest is roughly 0.22. Regional costs data are presented in Figure F5.

The cost of producing steam-electric energy is also highly variable. EIA data (1976) indicates that production costs were least in the Upper Colorado (5.95 mills/KWH) and the Pacific Northwest (6.65 mills/KWH) regions and greatest in the California region (22.67 mills/KWH).

The revenues from sales of prime energy were obtained from statistics collected by the former FPC on publicly-owned electric utilities in the U.S. Since this data was last published for 1975, the values were upgraded in relation to increases in the consumer price index (1.26) in order to reflect "current" values. Similar data for secondary energy were not available; FERC personnel indicated that revenue for this is legally set at a maximum of 85% of the cost of producing steam-electric energy.

BENEFITS OF SATSCAM FOR HYDROENERGY

The hydroelectric energy benefit model derives from standard electric energy marketing practices. It evaluates the benefit of improved forecast accuracy attributable to SATSCAM in terms of increased energy sales and decreased generation costs.

The estimated 6% relative forecast improvement supplied by the Colorado ASVT personnel when used in the hydroelectric benefit model yields an average annual SATSCAM benefit of $10 million. Regional distribution of the benefits is shown in Figure F6.

The Pacific Northwest, with its heavy concentration of hydropower (132 terawatt-hours annually, 73% of the total in the western United States), receives the largest portion of the benefit (38% of the total), roughly twice that of California, the second largest energy-producing region. The Pacific Northwest exhibits the smallest benefit per KWH of generation, 0.03 mills/KWH. This is primarily the result of the small difference between the revenues obtained for prime and secondary hydroelectric energy (3.62 mills/KWH). Other factors which cause the benefit per MWH to be low are the relatively small differences between hydroelectric and steam-electric production expenses (7.57 mills/KWH) and the relatively low forecast error in this region (11.9%).

LEGEND

SCALE 1: 14,000,000

96,000 MWH	- Total 1978 average annual hydroelectric energy generation
28.9 mills/KWH	- 1975 revenues obtained from the sale of prime hydroenergy
(36.4 mills/KWH)	- Current revenues (Revenues adjusted using an inflationary factor of 1.26)

Figure F4. Average annual hydroelectric energy and revenues obtained from the sale of prime hydroelectric energy in the eleven western states by hydrologic region.

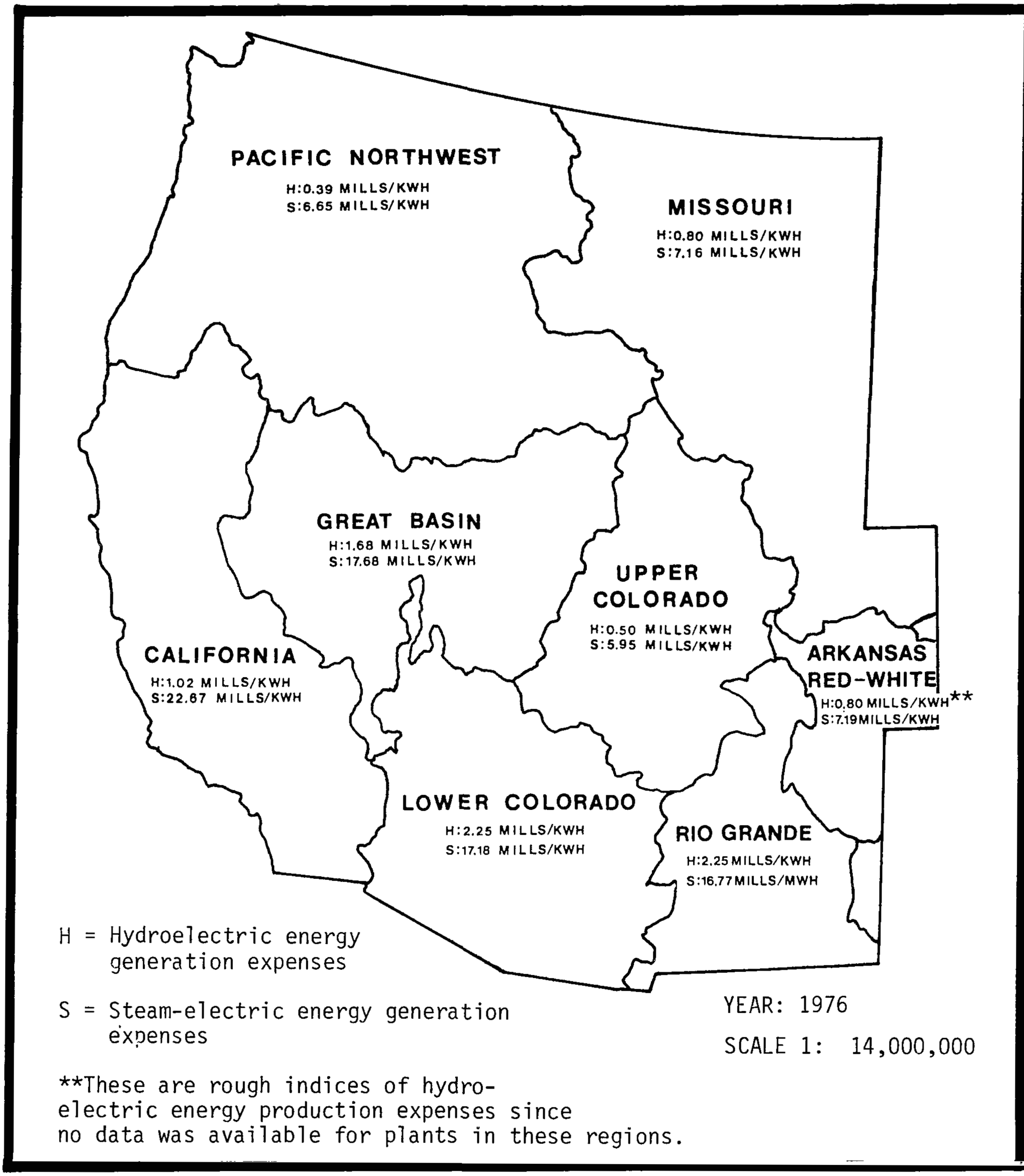

Figure F5. 1976 hydroelectric and steam-energy production expenses in eleven western states by hydrologic region.

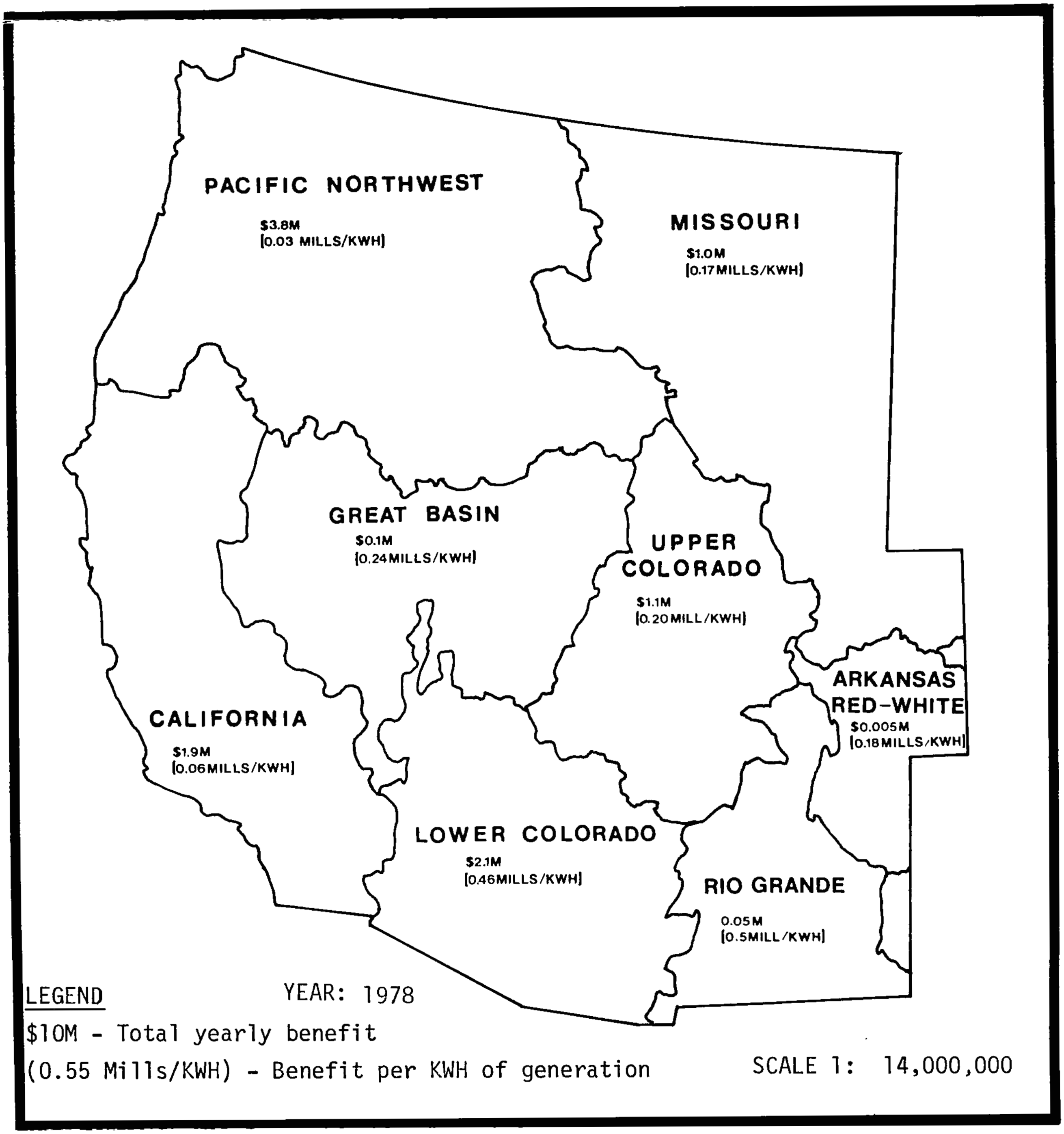

Figure F6. Annual benefit of SATSCAM to hydroelectric energy in the western United States by hydrologic region.

The second highest beneficiary is the Lower Colorado, which has an average annual benefit of \$2.1 million. In this region, the difference between prime and secondary hydroelectric energy tariffs (18.07 mills/KWH, adjusted for inflation) and the difference between hydroelectric and steam-electric production expenses (15.33 mills/KWH, adjusted for inflation) are relatively high. This combined with the strong influence of the high forecast error ($1\sigma = 89.9\%$) drives up the benefit/KWH of SATSCAM to 0.46 mills/KWH. Since the average annual hydroelectric energy generated in the Lower Colorado is on the order of 4.5 terawatt-hours, the computed annual benefit is relatively high.

Although the market of hydroelectric energy in the Rio Grande region is influenced by similar conditions, its computed total benefits differ significantly from that computed for the Lower Colorado. The Rio Grande's 1σ forecast error is relatively high and consequently the benefit/KWH value is also high (0.50 mills/KWH). Yet the amount of hydroelectric energy generated in this region is very low (96,000 MWH/year); the total hydroelectric energy benefit potentially derived from the use of SATSCAM is low at \$0.05 million/year.

SATSCAM IMPLEMENTATION COSTS

Costs associated with research and development and with the operational "start up" of SATSCAM forecasting schemes have been considered sunk for the purposes of these estimates. Thus, the cost associated with operationally employing SATSCAM comprises four components:

$$C = C_{SDP} + C_A + C_{AP} = C_E$$

C = Total cost of operationally employing SATSCAM

C_{SDP} = Cost of Satellite data products used

C_A = Cost of Satellite data analysis

C_{AP} = Cost of incorporating analysis results into the forecasting scheme

C_E = Cost of equipment needed for analysis

Cost details were derived from data supplied by the Colorado ASVT.

The Colorado ASVT effort focused on six watersheds covering a total area of 8876 km^2. Five Landsat frames were required to provide adequate basin coverage for each date. The forecast period during which SATSCAM was used extended from mid-March to mid-June. Eight observations (image dates) were used during this period. Using a Landsat per-frame cost of \$10, the total cost of image procurement was \$400. Image interpretation for the six basins required 16 man-days per season and resulted in a total cost of \$800.

Implementing the data into the forecasting scheme required an additional eight man-days/season of effort at a cost of \$600. The total seasonal costs, exclusive of equipment was \$1,800 or \$0.20/km^2.

ASVT experience has shown the stereo-viewing zoom transfer scope to be the most widely used and generally accepted basic piece of equipment required for performing operational snow-cover mapping. This instrument was identified by Colorado ASVT personnel as being the primary piece of equipment utilized at their site. It provides the necessary scaling and distortion elimination capabilities required for the task. Bausch and Lomb, Inc., a leading company in the manufacturing and sale of zoom transfer scopes, indicates that the current market price of a zoom transfer scope is approximately \$10,000.

A reasonable equipment turnover or replacement rate upon which to base the period of amortization is of the order of 10 years even though optical equipment such as the zoom transfer scope is designed to last 27 years or more without need of major repair or replacement. Using an equipment utilization factor of 25% (Colorado ASVT) and amortizing the cost over 10 years, the annual equipment cost will experience similar costs.

Adding the equipment cost to the \$1,800 seasonal operations cost indicated by the Colorado ASVT brings the total annual cost of employing SATSCAM at the Colorado ASVT to \$2,050 or \$0.23/km^2. Discussions with the other ASVT sites indicate that they experienced similar costs.

Extrapolating to the 2,195,250 km^2 area impacted by snow survey forecasting in the western United States, the total yearly cost of employing SATSCAM is approximately \$505K.

SUMMARY AND CONCLUSIONS

The Applications System Verification and Transfer Study on the Operational Applications of Satellite Snowcover Observations covering the western United States offered NASA the possibility of developing credible cost benefits derived from data supplied by operationally cognizant experts.

With interaction and guidance by the ASVT experts, a benefit assessment technique was developed which estimated the major benefit and cost drivers for 52 snow runoff subregions over the western states.

With significant input and direction from the ASVT's, an up-to-date data base was accumulated and validated containing data on runoff, forecast accuracy, irrigation, and hydroelectric energy at granularity sufficiently fine to permit distributed modeling of benefits by regions.

Since the result of improved snow-cover area measurement is improved information, the bottom line technical question posed to the ASVT experts was the level of improvement of forecast attributable to SATSCAM.

The Colorado ASVT projected a 6-10% relative forecast improvement based upon its operational forecasting experience. Since only limited results from the performance of present satellites are available specifying the improvement attributable to SATSCAM, this estimate may not represent the full potential of near-future SATSCAM systems.

Using the most conservative improvement estimate, i.e. 6%, the yearly irrigation benefit to the 11 western states was computed as $26.5 million. The three regions most benefitted are the Pacific Northwest with $7.0 million, Missouri with $7.1 million, and California with $5.5 million.

The calculation of benefit per irrigated acre eliminates the effect of the uneven distribution of irrigated land. The largest benefit/irrigated acre accrued to the Lower Colorado ($8.53/acre) and the Rio Grande ($3.61/acre) regions. Intermediate benefits accrued to the irrigated lands in the Arkansas-Red-White ($1.69/acre), the Great Basin ($1.56/acre), the California ($1.39/acre). The lowest per acre benefit accrued to the Pacific Northwest ($1.17/acre), the Missouri ($1.14/acre) and the Upper Colorado ($0.86/acre) regions.

The potential hydroelectric benefit from the operational application of SATSCAM was computed for the western United States at $10 million annually. The regions which showed the largest total benefits were the Pacific Northwest with $3.8 million; the Lower Colorado with $2.1 million; and the California with $1.9 million.

The benefit/MWH in the Pacific Northwest and that in California were computed at $0.03/MWH and $0.06/MWH, respectively. The regions with the greatest unit benefit ($/MWH) were the Rio Grande ($0.50/MWH) and the Lower Colorado ($0.46/MWH). For both of these regions the driver parameters were well above the average for the western United States.

The aggregate total benefit which could potentially accrue to irrigation and hydroenergy was $36.5 million yearly. The estimated cost of SATSCAM, based upon the Colorado ASVT cost details, totalled $505K for the "Western States." The resultant benefit/cost ratio is 72:1.

The large magnitude of the benefit/cost ratio supports the utility and applicability of SATSCAM. Future developments of computer models specifically tailored or adapted for snow input such as those developed by ASVT personnel (Leaf, Schumann and Tangborn, and Hannaford) will almost certainly increase the use and desirability of SATSCAM.

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APPENDIX G

EXECUTIVE SUMMARY: FINAL HANDBOOK
(See NASA Technical Paper 1829)

SATELLITE SNOW MAPPING AND RUNOFF PREDICTION HANDBOOK

EXECUTIVE SUMMARY

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INTRODUCTION

Soon after the first meteorological satellites were providing imagery from space, scientists began to realize the potential of the earth-orbiting platforms to provide hydrologists with useful information on snow cover. By the mid-1960's, serious investigations were underway to develop techniques to map snow from satellite images, determine the accuracy with which snow could be mapped, and assess the advantages and limitations of satellite observations.

As improved spacecraft observational systems became available in the early 1970's, additional studies were performed to demonstrate that remote sensing from space could provide a more cost-effective means for monitoring snow cover. Other research provided an indication that snow-covered area, provided either by aerial or satellite surveys, can be employed as an additional parameter in the prediction of snowmelt-derived runoff. These positive research results in both mapping and runoff correlations, led to an operational test of the use of remotely sensed snow-covered area for improving snowmelt runoff forecasts in an Applications Systems Verification and Transfer (ASVT) Program.

To assist in the planning of the demonstration program, a Handbook of Techniques for Satellite Snow Mapping was prepared in 1974 as one of the initial Snow ASVT tasks. This earlier handbook included discussion of the various satellite systems with application to snow mapping, the techniques to identify and map snow from these data, and the problems inherent in using satellite observations.

Now, at the completion of the ASVT program five years later, an updated handbook has been prepared as one of the final products of the ASVT program. The purpose of this handbook is to update the various snow-cover interpretation techniques, document the snow mapping techniques used in each of the four ASVT study areas (Arizona, California, Colorado and the Northwest), and describe the ways snow-cover data have been applied to runoff prediction.

The material presented in the handbook is, to a large extent, derived from the documents produced by each of the four study centers throughout the course of the project. In addition, meetings were held with the personnel directly responsible for the project in each of the four test areas; these meetings were useful for assessing the particular methods adopted by each of the study areas for application of satellite data to improved runoff forecasts.

SATELLITE SYSTEMS USEFUL FOR SNOW MAPPING

Three satellite systems - Landsat, NOAA VHRR (Very High Resolution Radiometer), and GOES (Geostationary Operational Environmental Satellite) - have application to operational snow mapping. Visible-channel data from these three systems were used to map snow cover in the Snow ASVT program. The following paragraphs briefly describe these satellite systems.

Landsat

The Landsat spacecraft are polar-orbiting satellites that view the earth from an altitude of approximately 900 km (500 nm). The primary sensor system carried by Landsat is the Multispectral Scanner Subsystem (MSS). The MSS observes in four spectral bands, ranging from the visible to the near-infrared portions of the spectrum; the four bands are the MSS-4 (green: 0.5 to 0.6 μm), MSS-5 (red: 0.6 to 0.7 μm), MSS-6 (red to near-infrared: 0.7 to 0.8 μm), and MSS-7 (near-infrared: 0.8 to 1.1 μm). Landsat-3, launched in March 1978, also carries a fifth MSS band, which measures in the thermal infrared portion of the spectrum (10.4 to 12.6 μm).

Landsat views an area 185 km (100 nm) wide, and the MSS has a ground resolution of 80 meters (260 feet); features can be mapped accurately from the imagery to a scale of at least 1:250,000. Because of the relatively narrow swath viewed by Landsat, the satellite does not provide repeat coverage each day. In fact, at lower latitudes, the satellite repeats coverage of the same area only once every 18 days. As a result of the overlapping of orbits at higher latitudes, however, coverage of the same area (north of 60 N) can occur on two or three consecutive days during each 18-day repeat cycle of the satellite.

The Landsat series of satellites has also carried a second sensor system, the Return Beam Vidicon (RBV). The RBV failed early in the life of Landsat-1, and was used very little on Landsat-2, but is routinely acquiring data on Landsat-3. The Landsat-3 RBV is a single-channel instrument covering a spectral range of 0.50 to 0.75 μm and has an improved resolution (about 40 m as compared to the 80 m MSS resolution).

NOAA Very High Resolution Radiometer (VHRR)

The NOAA series of meteorological satellites was in operation during the period of the Snow ASVT. The primary sensor on the NOAA satellites was the VHRR (Very High Resolution Radiometer), a dual-channel radiometer sensitive in the visible (0.6 to 0.7 μm) and thermal infrared (10.5 to 12.5 μm) spectral regions. The VHRR sensor was flown on each of the NOAA satellites from January 1973 until early 1979 (through NOAA-5). The spatial resolution of the VHRR is 900 m (0.5 nm), an order of magnitude poorer than that of Landsat, but still sufficient for mapping snow cover.

The NOAA VHRR was designed primarily for direct readout with three readout stations in use. Repeat coverage was provided twice daily; near local noon (visible and infrared), and again near local midnight (infrared), allowing both rapid and longer term changes in snowcovered area to be monitored. The area that was covered when the satellite passed directly overhead was a strip about 2,200 km (1,400 nm) wide and more than 5,000 km (3,000 nm) long. The VHRR also had a limited data storage capability; eight minutes of data could be stored on each orbital pass yielding an image about 2,200 km wide and 2,200 km long.

Effective in early 1979, the NOAA satellite series was replaced by the TIROS-N satellites series, the third generation of operational meteorological satellites. The primary sensor on TIROS-N is the AVHRR (Advanced VHRR), which has a spatial resolution similar to that of the VHRR, but is a four-channel instrument.

Geostationary Operational Environmental Satellite (GOES)

The third type of satellite system with application to snow mapping is the GOES system (Geostationary Operational Environmental satellite). A geostationary, or so-called geosynchronous satellite, always remains above the same location of the equator, so continually views the same portion of the earth. The altitude of a geostationary satellite to remain in geostationary orbit is 35,903 km.

Following NASA's experimental series of the late 1960's known as ATS (Applications Technology Satellite), came the GOES satellite program, which was initially called SMS (Synchronous Meteorological Satellite). The principal sensor on the GOES is the Visible and Infrared Spin-Scan Radiometer (VISSR), which provides the capability for acquiring observations every half-hour both day and night. The visible (0.54 to 0.70 μm) channel provides albedo measurements between 0.5 and 100 percent, and the infrared (10.5 to 12.5 μm) channel provides radiance temperature measurements between 180°K and 315°K.

The GOES data can be processed at different resolutions, ranging from 4 km (full-disc) to 1 km (sectorized) in the visible channel data. The maximum resolution for the thermal IR data is 8 km. Because the viewing angle of GOES becomes more oblique as latitude increases, the resolution of the imagery deteriorates with latitude. Therefore, GOES is more useful for mapping snow in the more southern areas, such as Arizona and the southern Sierra Nevada.

OTHER SATELLITE DATA WITH APPLICATION TO MAPPING SNOW COVER

In addition to the use of satellite imagery in the visual portion of the spectrum, the application of data from other spectral regions has also been investigated. Thermal infrared observations have been available routinely for a number of years from meteorological satellites, observations in the near-infrared were made from Skylab, and the Nimbus satellite series has carried microwave sensors since the early 1970's. Studies are continuing to evaluate and develop techniques for use of each of these types of observations.

Thermal Infrared

The NOAA VHRR satellite system has a thermal infrared channel (10.5 to 12 μm) with the same resolution (1 km) as the visible channel. The thermal infrared scanner measures the radiative temperatures of the Earth's surface and cloud tops rather than the reflectances; therefore, thermal infrared imagery can only be acquired during daytime. At high latitudes, the thermal infrared scanner provides the only observations during the winter dark periods. Furthermore, the use of thermal infrared has the potential for providing information on the snow surface temperature, a parameter that can be significant with regard to snowmelt prediction.

Accurate delineation of snow boundaries using thermal infrared measurements from satellites depends on detection of small differences in radiative temperature, perhaps only 2° or 3°K. Such temperature differences could be detected for cloud-free views, if all possible "errors" arising from differences in emissivity (ϵ) of various surfaces, variations in atmospheric attentuation, insufficient resolution of the radiometer, and differences in elevation of terrain were accounted for. Unfortunately, the above "errors" are not known exactly; however, they may be approximated well enough to allow good delineation of snow boundaries and differentiation of some types of snow-covered terrain.

Further studies of the application of thermal infrared measurements to snow hydrology are currently in progress using data from the Heat Capacity Mapping Mission (HCMM), launched in April 1978. The HCMM was the first of a planned series of Applications Explorer Missions (AEM) that involve the placement of small spacecraft in special orbits to satisfy mission-unique, data acquisition requirements. The HCMM sensor is a two-channel radiometer similar to the VHRR in its spectral ranges, but with somewhat better resolution (600 m). The primary purpose of the mission is to establish the feasibility of acquiring thermal infrared remote-sensor derived temperature measurements of the Earth's surface within a 12-hour interval of times when the temperature variation is a maximum. The day-night temperature difference may provide further information on the snow condition.

Near-Infrared

Snow-cover extent measured in the Landsat near-infrared spectral band (MSS-7) is consistently less than that measured in the visible bands because of the decreased reflectance of wet or refrozen snow in the near-infrared. In a study of the characteristics of snow reflectance in the near-infrared using Skylab Multispectral Scanner (S-192) data, where measurements were made in several near-infrared spectral bands, investigators found two potential applications to snow mapping of measurements in the near-infrared spectral region: (1) the use of a near-infrared band in conjunction with a visible band to distinguish automatically between snow and clouds; and (2) the use of one or more near-infrared bands to detect melting snow. An experimental near-IR sensor is being flown on a Defense Meteorological Satellite to test further the feasibility of automated snow/cloud discrimination.

Microwave

Satellite observations in the visible, near-infrared, and thermal infrared portions of the spectrum are all affected by clouds. Microwave sensors, however, provide the capability of viewing the Earth's surface regardless of cloud conditions, so have great potential for snow mapping.

Studies of microwave properties of snow have been carried out for some time using ground-based and aircraft instruments. The microwave radiometers flown in space on the Nimbus satellites have not had sufficient resolution, however, to provide useful snow-cover data, especially for mountainous terrain regions. Recently, using data from the improved Nimbus-6 Electrically scanning Microwave Radiometer (ESMR), the utilization of space-borne microwave radiometers for monitoring snowpack properties has been investigated.

METHODS FOR IDENTIFYING AND MAPPING SNOW COVER IN SATELLITE DATA

Through careful analysis of satellite images, snow can be identified and the boundaries of snow-covered area accurately located. In nonforested terrain, all areas with a continuous brightness distinctly greater than the normal dark background, that are identified as being essentially cloud-free, should be mapped as being snowcovered. The snow line enclosing all such areas represents the limit of a snow accumulation of approximately 2.5 centimeters (1 inch) or more. Areas that appear "mottled" (alternating dark and grey) usually are indicative of less than 2.5 centimeters of snow.

In mountainous terrain, the snow line is mapped at the edge of the brighter tone without regard to brightness variations resulting from forest effects or mountain shadows within the overall area deduced to be snow covered. Because of the deeper snowpacks and steep terrain, the visible snow line in a mountainous area may represent a snow depth of considerably more than 2.5 centimeters.

In the NOAA VHRR and Landsat visible bands, snow cover and clouds both have high reflectances. Differentiating between the two is one of the major problems in the use of satellite observations for snow-cover analysis. The skill of the analyst is also essential for accurate identification of snow cover within areas of dense forest, mountain shadows, and bare rock surfaces.

The Zoom Transfer Scope (ZTS) was the primary snow mapping tool in the ASVT Study program and the standard against which the performance of other techniques were judged. Major advantages of the ZTS are its simplicity of operation, relative inexpensiveness, short training time for use, and speed in which mapping can be accomplished. A major disadvantage is the restricted field-of-view requiring several registrations and/or images for larger drainage basin areas. Analysts have found that, in general, snow can be identified and mapped more readily using Landsat transparencies, rather than prints, with the ZTS.

Machine processing techniques using imagery and digitized data can also be used for snow-cover mapping. Experimentation with some of these techniques was performed at the various study centers and at the NOAA/National Environmental Satellite Service as part of the Snow ASVT. The machine processing techniques include the use of density slicing and a color-additive viewer to analyze imagery. Computer-assisted classification has been carried out using GOES and Landsat digitized tape data.

PRINCIPAL RESULTS OF SNOW ASVT

The four ASVT study areas (Arizona, California, Colorado, and the Northwest) provide excellent examples for describing methods to map snow cover from satellites and to incorporate snow-covered area into runoff prediction schemes. Each study area has differing characteristics with regard to the type of terrain, forest cover, and climate. Thus, these four areas present a wide-range of characteristics, which can be extrapolated to other geographic locations. The principal results of the Snow ASVT were as follows:

Arizona

Results of the snow mapping ASVT in central Arizona indicate that multispectral Landsat imagery permits rapid and accurate mapping of snow-cover distribution in small to medium-sized watersheds. Low resolution meteorological satellite imagery provides the synoptic daily observations necessary to monitor the large and rapid changes in snowcover. Satellite and microwave telemetry systems were used to furnish near real-time data from streamflow gages and snow monitor sites.

Seasonal runoff predictions by conventional index models and a modified hydrometeorological model (HM) were compared. Significant reductions in the standard-error fractions for seasonal runoff predictions (March-May) were obtained using the HM model. Short-term runoff predictions using snow-cover depletion models were also tested. Statistically significant correlations between short-term snowcover depletion rates and runoff rates were determined for selected periods.

California

Results of the California study indicate that snow-covered area (SCA) can be determined from Landsat using the zoom transfer scope for watersheds as small as 100 km^2 (40 mi^2) and snowpack depletion may be determined within reasonable limits of accuracy even as the area of snowpack becomes fragmented. Cross-basin plots were developed for the various major basins and sub-basins, making it possible to estimate SCA on watersheds that were partly or completely cloud covered from data available on adjacent basins or sub-basins. The best results were obtained when mapping was performed using Landsat MSS-5 band positive transparencies at a scale of 1:250,000.

Information on SCA for estimation of both rate and volume of snowmelt runoff was obtained from aircraft and satellite. In many cases, aircraft observations varied considerably from the satellite observations. The aircraft observations in 1978 appeared to show less snow cover than did the satellite observations.

A multiple regression technique was utilized to relate runoff subsequent to the date of forecast to causitive parameters. The analysis was predicated on the operational requirement for accurate updating of water supply forecasts throughout the period of snowmelt runoff. The analysis indicated that use of SCA as a parameter in forecasting snowmelt runoff may result in significant improvement for forecasting procedures under certain circumstances. Simulated mean daily runoff for the Kings River, computed as output from a hydrologic model, has given results which are entirely acceptable in analysis. In addition, the conceptual model appears to be more consistent with known hydrologic relationships than a previously used snowmelt submodel. Water supply forecasts utilizing SCA as a forecast parameter verified well, while conventional procedures tended to over-forecast.

Colorado

In the Colorado snow-mapping ASVT study, six methods of mapping snow cover were investigated. The technique that proved to be the most accurate, least expensive, and least time-consuming from an operational point of view, was the Zoom Transfer Scope (ZTS).

Two methods of using SCA in forecasting were explored and proved successful. A statistical regression model relates snow cover to seasonal volume flow directly. A computerized simulation model provides short-term and seasonal forecasts using snow cover as an input variable. Results indicating about a ten percent reduction in average forecast error can be realized through use of satellite-derived snow cover in forecast procedures.

Linear regression analysis of six years of snow-cover data on six watersheds revealed that snow cover is highly correlated with seasonal streamflow. Combining snow course water equivalent information with Landsat derived areal extent data is extremely promising as a forecast tool when used during the first of May when melt is well underway. Forecasts of the magnitude of the snowmelt peak flow, and to a lesser degree, the date of the peak flow, can be predicted from Landsat snowcover data.

Satellite snow-cover data used in combination with Snotel and the Subalpine Water Balance Model have been used to develop an extremely flexible system for making continuous short-term streamflow forecasts in the Rio Grande and Arkansas basins.

Northwest

The results of the Northwest snow-mapping ASVT have shown that snow-covered area measured from NOAA and from Landsat satellite data agree within a few percent. The satellite data have provided many more SCA estimates than could be gathered from ground truth data alone, and the satellite-derived SCA data can be used to augment aerial snow survey data.

The interpretation of snow lines from satellite data have been compared with conventional ground truth data and tested in operational streamflow forecasting models. When the satellite SCA data were incorporated into the streamflow synthesis and reservoir (SSARR) model, there was a definite but minor improvement. This improvement was not felt to be statistically significant.

CONCLUSIONS

The results of the ASVT as reported by each study center have demonstrated that the areal extent of snow cover as derived from satellite imagery does have potential for improving the timeliness and frequency of hydrologic forecasts in the four study areas. The greatest potential for water-supply forecasting is probably in improving forecast accuracy and in expanding forecast services during the period of snowmelt. Problems of transient snow line and uncertainties in future weather conditions are the main reasons that snow-covered area (SCA) appears to offer little in weather supply forecast accuracy improvement during the period of snowpack accumulation. The greatest improvement in forecast acuracy with the addition of SCA as a parameter can be expected for basins not already well-instrumented.

Existing, visible-channel satellite sensor systems have certain inherent limitations, and there are certain problems in the interpretation of snow cover. A critical problem is the time period for delivery of satellite imagery from the source to the interpreter. Operational experience during the snow-mapping ASVT suggests that much more rapid dissemination of available satellite imagery will be required before totally effective use can be made of SCA in operational forecast procedures.

From an operational standpoint, the use of SCA can become restricted when there is considerable cloud cover over mountainous regions for extended periods of time. During these times, neither the Landsat nor the daily NOAA imagery may be suitable for even partial snow mapping of individual watersheds. The experience of the interpreter is extremely valuable in estimating SCA during partial cloud cover conditions. The skill of the analyst is also important when interpreting snowcover in areas of heavy forest cover, mountain shadows, and bare rock terrain. In fact, because subjective decisions must be made by the analyst, and because of the cost involved in computer processing, photointerpretive techniques were found to be the most useful for the purposes of the ASVT. Continued development of automated analysis techniques should certainly be encouraged, however, and offer promise for eventually providing a more efficient means for mapping snow cover from satellites.

Because of the demonstrated potential usefulness of satellite-derived SCA data in operational forecasting procedures, each of the ASVT study centers plan to continue to utilize the interpretation of satellite data in conjunction with available ground truth data. As successive years of satellite imagery are accumulated covering a broader range of hydrologic and climatic conditions, forecasts can be expected to improve through use of satellite snow-mapping.

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16. Abstract

A NASA Applications Systems Verification and Transfer (ASVT) project on the Operational Applications of Satellite Snow-Cover Observations was begun in 1975 and completed in 1979 in cooperation with nine operational water management agencies. Both Landsat and NOAA satellite data were supplied to these agencies for use in improving snowmelt runoff forecasts. When the satellite snow-cover data were tested in both empirical seasonal runoff estimation and short-term modeling approaches, a definite potential for reducing forecast error was evident. A cost-benefit analysis run in conjunction with the snow-mapping ASVT indicated a $36.5 million annual benefit accruing from a one percent improvement in forecast accuracy using the snow-cover data for the western United States. The annual cost of employing the system would be $505,000. The snow-mapping ASVT has proven that satellite snow-cover data can be used to reduce snowmelt runoff forecast error in a cost effective manner once all operational satellite data are available within 72 hours after acquisition. This Technical Paper presents executive summaries of the individual snow mapping ASVT projects, and subsequent Technical Papers in this series present the specifics of these projects.

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