NASA

Technical Memorandum 78109

(NASA-TM-78109) PILOT TESTS OF SATELLITE SNOWCOVER/RUNOFF FORECASTING SYSTEMS (NASA) 17 p HC A02/MF A01 CSCL 08L
N78-20577
Unclas
G3/43 12579

Pilot Tests of Satellite Snowcover/Runoff Forecasting Systems

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MARCH 1978

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Space Administration

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TM78109

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CONTENTS

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By

Albert Rango[2]

Background

Since 1972 when Landsat-1 and NOAA-2 were launched, speculation that high resolution satellite data could be used to measure snowcovered area and, subsequently, to assist in runoff prediction has been optimistically proposed (Salomonson and Rango, 1974). The use of photographic methods for interpreting snowcovered area has been favored over digital methods, and a handbook describing the various snowcover photointerpretive methods has been compiled (Barnes and Bowley, 1974). Various snowcover analysis techniques, successful in different areas, have been reported at a workshop at Lake Tahoe (Rango, 1975).

Although methods for extracting snowcover information from satellite data are now well established, the means by which snowcovered area data can be used for runoff prediction are still being developed. Using long-term meteorological satellite data, Rango, Salomonson, and Foster (1977) demonstrated that snowcovered area at a particular point early in the snowmelt season is highly correlated with seasonal streamflow. Various investigators are now exploring means by which remotely-sensed snowcovered area data can most effectively be used in runoff prediction. In order to assure a thorough test directly applicable to water resources users, NASA entered into a cooperative, quasi-operational, four-year test program with various agencies in four major Western U.S. snow zones. This project, entitled "Operational Applications of Satellite Snowcover Observations" (OASSO), is part of NASA's Applications Systems Verification and Transfer (ASVT) program designed to demonstrate and test the usefulness of developing technology in remote sensing.

Project Description

The OASSO project was begun in late 1974 and is planned to be completed in early 1979. Four different areas were chosen for the project in order to assure variability in snow conditions, vegetation characteristics, cloud cover, and

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[1] Presented at the Western Snow Conference, April 18-20, 1978, Otter Rock, Oregon.

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snowmelt climatology and to extrapolate project results to other snowmelt regions. In the central Arizona mountains the Salt and Verde River systems are under study (see Figure 1). This area generally has a thin, transient snowpack, and, because the tree cover is sparse, vegetational obstructions to observation of the snowcover are few. Cloud cover frequency is low resulting in near optimum satellite observing conditions, and energy input for snowmelt is intense with significant melt possible throughout the snow season. The U.S. Geological Survey and the Arizona Salt River Project in Phoenix are cooperatively testing the data acquired over this study area as reported by Kirdar, Schumann, and Warskow (1977).

Two separate areas are being studied in California by the Snow Surveys Branch of the California Department of Water Resources in Sacramento as shown in Figure 1. The southern Sierra portion experiences cloud cover and snowmelt climatology conditions similar to Arizona but with slightly denser tree cover and a much greater accumulation of snow. In the northern California study area more extensive tree cover is prevalent with an increasing incidence of clouds that can lead to a reduction in the number of useable satellite observations acquired. In this area, the temperature of the deep snowpack is normally near 0°C and runoff usually does not occur until after April 1.

In Colorado several watersheds are under study as shown in Figure 1, and several agencies are participating in the project. The primary watershed under study is the upper portion of the Rio Grande Basin with some additional work being done on the Arkansas and San Juan Rivers. Participants include the U.S. Soil Conservation Service, the U.S. Bureau of Reclamation, and the Colorado Division of Water Resources in Denver. Moderately dense forest areas and occasionally cloudy conditions prevail in the Colorado study area. The snowpack generally remains cold, dry, and of low density until after about April 1 when clear sunny skies can produce wet snow conditions and significant runoff.

Figure 1 also shows the five watersheds under study in the Pacific Northwest. In this region the forest canopies are extremely dense, only broken in some areas by clearcuts and power lines. Persistent cloudiness presents a major obstacle to obtaining clear satellite views of the study area, although cloudiness decreases from the northern to the southern watersheds. Snowpacks are deep and in many areas significant snowmelt runoff can occur throughout the winter. Rain on snow in these areas is common, resulting in an increased potential for flooding. The Bonneville Power Administration and the U.S. Army Corps of Engineers in Portland are the major participants with some assistance provided by NOAA's National Weather Service.

When these study areas are combined a wide spectrum of snow type, depth, and wetness, vegetation type and density, frequency of cloudiness, and spring melt conditions are represented. With a few exceptions, snowmelt in these study areas contributes greater than 70 percent of the total annual streamflow. The results from the different areas should provide a rational means for extrapolation of the techniques and results to other potential western study sites.

In addition to the above mentioned agencies, NOAA's National Environmental Satellite Service (NESS) has been supplying standard photographic satellite scenes to the study areas. NESS has also been providing real time snowcover interpretations for selected watersheds associated with this project.

Objectives

Because of the large number of agencies involved in the OASSO project and the diversity of snowmelt runoff conditions between study areas, no two study sites have the same specific objectives. There are certain overall project objectives, however, which are listed below.

1. Map snowlines, areal snowcover, and associated changes in snowcover using satellite data for the 1973-1977 snow seasons in order to evaluate the usefulness of the data had they been available in near real-time.
2. Map snowcover changes in 1978 in a near real-time mode (data to user ≤ 72 hours), thus extending the data base to six years.
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 period of study that will allow incorporation of satellite-derived snowpack observations into the prediction of snowmelt-derived streamflow for specific watersheds.
5. Produce a documented methodology and cost/effectiveness 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.

Approach

When the OASSO project was conceived a basic assumption was made, namely, that it would be more efficient and effective to transfer photointerpretation techniques for analyzing satellite snowcover than comparable digital techniques. Underlying this assumption was the knowledge that few operationally oriented agencies had access to the necessary computer facilities for digital analysis. In addition snowcovered area was an easily analyzed parameter using

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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 snowcover measurement, especially when a large number of watersheds are involved, photointerpretation will still remain an important step for familiarization with the satellite data characteristics.

Various types of photographic data products are being subjected to analysis. Landsat standard 1:1,000,000 scale images are most suitable for interpretation but are not received in a real-time mode. In order to meet the required time frame of 72 hours or less images from the Canadian Quick Look Facility at Prince Albert, Saskatchewan, Canada are acquired, supplemented by Goddard Space Flight Center quick look products. The images from these facilities have slightly variable map scales and degraded photographic clarity, but they seem to be acceptable for mapping snowcovered area. Additionally, NOAA (and GOES) satellite images are sent to the study centers. Because of their smaller 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, the National Environmental Satellite Service interprets snowcover from the satellite images for 27 large watersheds across the United States and is supplying snowcover maps of these watersheds to interested users. In the OASSO project these large watershed snowcover maps are further interpreted by study center personnel to derive snowcover measurements for sub-basin areas. Both the original NOAA imagery and the initial map interpretations are available to the user within 72 hours.

In Arizona Landsat imagery is operationally analyzed for snowcovered area using a density slicer which enables the operator to select a snow reflectance threshold in order to separate snow from non snowcovered area. Automatic planimetering of the snowcovered area is one available option. Additional Landsat snowcover interpretation using a zoom transfer scope and a color additive viewer has been attempted. Because of the rapidly changing nature of the snowcover in Arizona, NOAA VHRR and GOES data have been quite valuable. These data are primarily interpreted using the zoom transfer scope which allows removal of distortion, scale change, and registration of the original imagery on a base map through the use of a system of lenses and mirrors. The snowcovered area thus delineated can then be measured using a manual planimeter.

Direct overlay interpretation of snowcover from the original 1:1,000,000 scale Landsat imagery is employed in California. In special situations, the zoom transfer scope is used to transpose the imagery to 1:500,000 scale.

NOAA data is used to supplement the snow coverage and the zoom transfer scope is used to transpose the 1:3,000,000 scale imagery to an interpretation scale of 1:1,000,000.

In Colorado, Landsat imagery is used on a zoom transfer scope and interpreted at 1:250,000 scale. For special problem areas and examination of the quick look imagery, a color additive viewer and 70 mm chips are employed. The NOAA interpreted snowcover maps are used to fill in between Landsat passes, and overlays of small basins are used to extract more detailed data from this large area map.

In the Northwest, because of cloud cover problems Landsat imagery has only been used to verify snowcover data obtained from NOAA imagery. Both the primary data source, NOAA, and supplemental Landsat data are reduced using the zoom transfer scope.

In addition to developing and refining snowcover interpretive approaches for use in a particular area, each study center has undertaken the task of incorporating the snowcover data into their operational runoff predictions. The goal is to be using the snowcovered area data in a quasi-operational method by the completion of the project. There are generally two distinct approaches being investigated. First, seasonal streamflow estimation is being examined using snowcovered area as a predictor variable in conventional regression analysis. Second, the use of snowcover data as an input to watershed models for short term snowmelt runoff prediction is being evaluated.

The development of successful regression techniques is of course directly affected by the period of record of snowcover data. By the end of the project six years of satellite record (1973-1978) will be available for the study watersheds. Although this time period would normally be only marginally useful, certain advantages of the data set have become apparent. In the six year period, both high and low runoff extremes have been approached. For most of the study watersheds 1977 was the minimum runoff of record, whereas 1973 and 1975 were extremely high runoff years in some areas. As a result any regression relation between snowcover and seasonal streamflow will be applicable over a wider range of data than normally possible with a short period of record. In addition, in a few watersheds aircraft snowcover data extend back considerably prior to the satellite coverage, thus greatly increasing the effective period of record. This is especially true for California and to lesser degree for the Northwest.

As opposed to regression approaches, the use of snowcovered area in runoff models does not require long periods of record. Five to six years of data should be sufficient to calibrate and verify a model using satellite-derived snowcovered area. In the OASSO project several study centers are incorporating snowcovered area into runoff prediction techniques using various modeling approaches. In the Northwest snowcovered area is directly input to the Streamflow Synthesis and Reservoir Regulation (SSARR) model used for forecasting flows in the Columbia River Basin. Daily forecasts of streamflow are possible, and the model automatically depletes snowcovered area until the next satellite update. In California the Kings River hydrologic model has been modified to use snowcovered area in combination with temperature for calculation of the non-dimensional melt factor. This factor is critical for calculating daily snowmelt amounts. In Colorado the Sub-Alpine Water Balance Model developed by Leaf and Brink (1973) has been used with satellite-derived snowcovered area for the estimation of daily streamflow. In fact the use of snow water equivalent as an input to the model is being updated on a regular basis before snowmelt begins with SNOWTEL and with snowcovered area after the snowpack covers less than 100% of the basin in the spring. Modification of an existing hydrometeorological model to accept snowcovered area is being completed by Arizona personnel. The use of models greatly improves water management flexibility because of the option for daily flow estimates.

Results

California. — Satellite imagery was initially reduced on seven major basins and 31 sub-basins covering both the northern and southern project study areas. Results from California indicate that snowcovered area can be determined from Landsat for watersheds at least as small as 50 mi^2 (129.5 km^2), and snowpack depletion may be determined quite accurately, even as the area of the snowpack becomes fragmented. From a practical standpoint it was decided that beginning with the 1977-1978 water year snowcovered area would be interpreted for the 20 major basins throughout California for which the Department of Water Resources provides forecasts. This not only serves to eliminate much of the detailed analysis on some of the very small sub-basins but also to assure continuity of analysis if and when the switch to operational use of snowcover data is made. It is estimated that during snowmelt (after April 1) snowcovered area may provide significant improvement in the updating of runoff forecasts on approximately one-half of the major basins.

Regarding use of the satellite information, snowcover data interpreted from quick look imagery were published on a timely basis in the California Department of Water Resources (1977), Bulletin No. 120, Water Conditions in California, which appeared on the first of each month (February through May). Quick look imagery received during the 1977 snowmelt period was of generally better quality and more timely than that received during the 1976 water year.

For runoff prediction the availability of U.S. Army Corps of Engineers aerial snowcover observations over Southern California watersheds has proven to be a valuable data source. These low altitude visual observations were initiated in 1952 and terminated in 1973. As a result, only one year of concurrent aerial and satellite snowcover observations were available for comparison. It appeared that the aerial and satellite data were compatible with a consistently greater snowcovered area (about 6%) being estimated from the satellite due to transient, thin snow not being recorded by the aerial observers (Barnes and Bowley, 1974). Supplemental ground observations have been used by the California investigators to adjust both data sources to a comparable base for analysis with runoff data from 1952-1977. More conventional predictor variables such as snow water equivalent and precipitation have also been assembled for the same period.

As reported in Rango, et al. (1977) the long-term snowcovered area data from aircraft and satellite observations have proven useful in reducing seasonal runoff forecast error on the Kern River watershed when incorporated into regression procedures to update water supply forecasts as the melt season progresses. Similar use of snowcovered area on the Kings River watershed produced results that were approximately equivalent to methods based solely on conventional data. The results of the study indicate that snowcovered area will be most effective in reducing forecast procedural error on watersheds with: (1) a substantial amount of area within a limited elevation range; (2) an erratic precipitation and/or snowpack accumulation pattern not strongly related to elevation; and (3) poor coverage by precipitation stations or snow courses restricting adequate indexing of water supply conditions. The regression approaches developed in the study by Rango, et al. (1977), especially those used for updating the forecast every 15 days, require data delivery in 72 hours after acquisition and an assured continuity of data.

In the area of modeling the existing Kings River hydrologic model was modified to accept satellite snowcovered area inputs and used to simulate mean daily discharge and reproduce the snowmelt hydrograph (Hannaford, 1977). The snowcover data were used both in the snowmelt submodel and the calculation of elevation of prime. After the basin has become fully primed, the rate of snowmelt is primarily dependent upon area (and elevation) of snowcover and air temperature as a measure of energy available to melt snow. This has also been confirmed in Switzerland by Martinec (1975). The elevation of prime sub-routine provided a value that, when compared with the lower elevation of the snowline, defined the portion of the snowpack available to produce changes in runoff from changes in temperature. Calculation of discharge using the observed effective snowline has given results which are entirely acceptable in analysis. In addition, this conceptual model appears to be more consistent with known hydrologic relationships than the formerly used Kings River snowmelt submodel (Hannaford, 1977). Work is now underway to further refine the use of snowcover in the model by accounting and calculation on the basis of 500 foot elevation zones. Techniques are also being developed to extrapolate the snowcovered area depletion into the future so the model can be used for predictions.

Colorado. — Although zoom transfer scope analysis of the Landsat data at 1:250,000 scale supplemented by color additive viewer checks of Landsat quick look data and the use of NOAA interpreted snowcover maps is used by the Soil Conservation Service in the Colorado study, an alternative method of analysis especially useful for combatting cloudy conditions has been devised. This method, developed by the Colorado Division of Water Resources, estimates snow area extent through a network of indexed base lines covering a particular watershed and can be used when clouds obscure part of the area. The index base lines tend to be areas free of tree cover that are visible on Landsat images. The method is based on the assumption that within a basin the snowline recession will follow basically the same pattern year after year, although the time of recession will change. By observing the location of the snowline at base lines not covered by clouds, the basin snowcovered area can be inferred. This new method has produced results strikingly similar to the more conventional photointerpretive approaches mentioned earlier.

In exploring the utilization of snowcovered area in runoff prediction, the Colorado ASVT site has experimented with graphical techniques, regression analysis, and modeling. The plotting of remaining snowcovered area versus time and remaining runoff throughout the snowmelt season has indicated important similarities and differences between years that can be used to quantitatively estimate the water supply outlook. Such an approach based on Landsat data and developed by the Colorado Division of Water Resources was used to estimate the monthly flows for all of 1977 on the Conejos River as a mechanism for deciding the amount of curtailment that had to be applied to Colorado water users on the Conejos River in order to meet obligations to Texas and New Mexico under the Rio Grande Compact.

In order to more objectively quantify the use of snowcover in seasonal runoff forecasts, five years of May 1 snowcovered area data were linearly regressed against the April-September discharge on the Conejos River in southern Colorado. The R^2 value of 0.95 was significant, but because of the limited sample the equation would be marginally useful for predictions. The relationship does include the record low runoff year of 1977 (34% of normal) and a high runoff year (1973, 160% of normal) which extends the range over which the equation can be applied. As a refinement of this method, the Colorado Division of Water Resources has modified the multiple regression "Predictive Model for Upper Rio Grande Index Flows" to utilize Landsat snowcover extent.

The Sub-Alpine Water Balance Model as developed by Leaf and Brink (1973) has been modified to incorporate input data from Landsat and SNOWTEL on a real-time basis. A control curve relating snowcovered area to residual water equivalent (developed over five years of record) is used to update streamflow forecasts produced by the model. Landsat was first used on an experimental basis to update model predictions of Conejos River runoff in 1977 and should be available for operational testing in 1978. The model is currently being adapted to additional watersheds in Colorado, such as the Upper Arkansas River. To improve their management flexibility for delivery of Rio Grande water to New Mexico, the Colorado Division of Water Resources has also started to use the Sub-Alpine Water Balance Model.

Arizona. — The rapidly changing nature of the snowpack on the Salt and Verde Basins has necessitated the use of aircraft flights (initiated in 1965) for acquiring timely information on snowcover, snow depth, and snow condition. The availability of satellite snowcover maps through the OASSO project has freed the aerial snow survey team from the need for detailed mapping of snowcover extent. This permits the Arizona test site personnel to concentrate on obtaining snow depth information and low altitude photography of selected watersheds for use in developing snowpack area-runoff relationships (Kirdar, Schumann, and Warskow, 1977). Flights for snowcover measurements have only been necessary when real-time meteorological satellite imagery indicate cloud cover conditions not conducive to space mapping of snowcover.

The Arizona test site has recently been adapting a Hydrometeorological Model (HM) developed by Tangborn (1977) for use on the Salt and Verde Rivers. Necessary modifications to the model for use in Arizona include the capability to accept daily precipitation input and predict daily runoff (completed) and the incorporation of temperature and snowcovered area measurements (in progress). The final model will be called the Basin Water Storage model and will be used primarily for short-term runoff predictions.

Satellite data collection systems (DCS) have been used to relay timely hydrologic data (during the snowmelt runoff season) which are critical when predicting runoff from a rapidly changing snowpack. In addition to hydrometeorological data such as temperature, precipitation, and water equivalent from remote portions of the basins, streamflow data in response to melt conditions are also available within an hour of actual measurement. Such data would be invaluable for short-term runoff predictions using models. A new portable data terminal has recently been incorporated into the satellite relay system used in Arizona. It was pressed into real-time service for reservoir control purposes by the U.S. Geological Survey upon request of the Salt River Project during the early March 1978 floods.

Northwest. -- In this region interpretation of the snowcovered area is being done using the zoom transfer scope, although electronically assisted interpretation has also been employed. Even with the potential daily coverage afforded by the NOAA data, acquisition of useable data through cloud cover is still a problem. Although the visible imagery is certainly useful, microwave all-weather snowcover mapping may eventually be required as a complementary data source.

Aerial measurements of snowcovered area were originally used as input to the SSARR model, one of the few streamflow models that requires the direct input of snowcovered area. The use of the snowcover parameter in the model acknowledges the importance of snowcover; the question that the Northwest study site is investigating is whether the satellite snowcover data are acceptable for input into the model and provide a degree of improvement over conventional methods. Simulations of runoff hydrographs with and without the satellite snowcover input are currently being run and evaluated.

Future Work

During the 1978 snowmelt season, the satellite snowcover assisted system will be tested in an operational fashion on a number of basins so that the results of this last year will be directly pertinent to real-world application. The study centers will assess compatibility of the snowcover data to their current methods, cost of data interpretation, and potential savings from employing the snowcover data in runoff forecasting (for input to the concurrent cost-benefit study). The cost-benefit study will use ASVT study center data to estimate the west-wide impact of adopting the remote sensing technology. The actual snowcover technology that was developed in the OASSO project will be documented in updated handbook form along with the various methods used to incorporate snowcover data into runoff predictions. Final reports from each study center will be compiled and distributed in an overall project final report. Results of the OASSO project will be presented at a workshop April 16-17, 1979 in Reno, Nevada immediately prior to the 47th Annual Meeting of the Western Snow Conference.

In regard to operational use of the satellite snowcover data the following systems are available. Landsats 2 and 3 are currently operational and effectively providing coverage once every nine days (Landsat 3 was launched March 5, 1978 with the same spectral coverage of Landsat 2 except that a thermal infrared band has been added as well as a panchromatic camera system with 40 m resolution). These data are available in quick-look format in about 3-5 days after data acquisition. NOAA data can be obtained everyday and is usually received by the user within 72 hours after acquisition. Arrangements with NOAA's National Environmental Satellite Service can result in an interpreted snowcover map product, also received within 72 hours. During 1978 and 1979, several other satellites will be available that may provide supplementally useful information. The next approved earth observations satellite is Landsat-D scheduled for a 1981 launch. Subsequent Landsat satellites may follow with eventual conversion to a truly operational system. An operational snowcover observing system would benefit from subsequent Landsat satellites as well as the improved operational NOAA satellites that are planned. A large step towards an operational system would include the approval of a Synchronous Earth Resources Satellite (SERS) which could possibly be launched by 1986. Such a satellite would provide a high resolution, real-time, continuous coverage capability that would greatly improve the monitoring of snowcover. The data from this system, combined with the Landsat and NOAA data acquired up to that time, would provide the ultimate visible and infrared observing system for water resources agencies. At the same time extensive ground-based and aircraft microwave research over snow (such as by Ellerbruch, et al., 1977) should provide advances that would increase our snow monitoring capability to include mapping of snowcovered area through clouds, estimation of snow water equivalent, and the detection of free water in the snowpack. Systematic development of such capabilities should result in a quasi-operational spacecraft demonstration of the microwave capabilities by 1988. Operational microwave systems for snow monitoring could then follow in the early 1990s.

Acknowledgements

Particular thanks go to each of the OASSO project study leaders: Herb Schumann, Phoenix; Jean Brown, Sacramento; Jack Washichek, Denver; and John Dillard, Portland. Appreciation is also extended to Stan Schneider and Russ Koffler of NOAA/NESS for direct project support. In addition, I would like to thank the various personnel working on this project from the following agencies: U.S. Geological Survey, Soil Conservation Service, Bureau of Reclamation, Bonneville Power Administration, Corps of Engineers, NOAA/National Weather Service, NOAA/National Environmental Satellite Service, Arizona Salt River Project, California Department of Water Resources, and the Colorado Division of Water Resources. Finally, many private firms and individuals are playing an extremely important role in supporting the above agencies during the course of the project and their work is appreciated.

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Figure 1. Study Watersheds for the Operational Applications of Satellite Snowcover Observations Project.

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BIBLIOGRAPHIC DATA SHEET

1. Report No. TM 78109	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

Pilot Tests of Satellite Snowcover/Runoff Forecasting Systems

5. Report Date

March 1978

6. Performing Organization Code

913

7. Author(s)

Albert Rango

8. Performing Organization Report No.

9. Performing Organization Name and Address

Goddard Space Flight Center
Greenbelt, Maryland 20771

10. Work Unit No.

11. Contract or Grant No.

13. Type of Report and Period Covered

12. Sponsoring Agency Name and Address

National Aeronautics and Space Administration
Washington, DC 20546

14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the U.S. Geological Survey, U.S. Soil Conservation Service, U.S. Bureau of Reclamation, Bonneville Power Administration, Army Corps of Engineers, National Oceanic and Atmospheric Administration, California Department of Water Resources, Colorado Division of Water Resources, and the Arizona Salt River Project.

16. Abstract

NASA instituted Applications Systems Verification and Transfer (ASVT) programs to demonstrate and test the usefulness of developing technology in remote sensing. Because results from satellite snow mapping and runoff correlation have been encouraging, a cooperative, quasi-operational, four-year test program was started with various agencies in four major snow zones of the Western U.S., namely, the central Arizona mountains (U.S. Geological Survey and Salt River Project), the Sierra Nevada mountains (California Department of Water Resources), the Colorado Rockies (U.S. Soil Conservation Service, U.S. Bureau of Reclamation, and the Colorado Division of Water Resources), and the northern Rockies (Bonneville Power Administration, U.S. Army Corps of Engineers, and the National Weather Service). These areas were selected to test the capability of satellite systems for mapping snowcover in various snow, cloud, climatic, and vegetation regimes. Different satellite snowcover analysis methods are being used in each of the study areas. The snowcover data have been employed in illustrations of the effects of drought, in regression methods to forecast seasonal runoff, and in hydrologic models for simulations of daily streamflows.

17. Key Words (Selected by Author(s))

Satellites, snowcovered area, snowmelt runoff prediction, demonstration project

18. Distribution Statement

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 13	22. Price*

*For sale by the National Technical Information Service, Springfield, Virginia 22151.