THE EVOLUTION OF SATELLITE SNOW MAPPING WITH EMPHASIS ON THE USE OF LANDSAT IN THE SNOW ASVT STUDY AREAS

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ABSTRACT

The potential of the satellite for mapping snow cover was recognized soon after the launch of the first United States weather satellite nearly 20 years ago. Since then, as improved satellite systems have been developed, an increasing use has been made of remote sensing from space to monitor snow. Maps showing percentage snow cover for selected river basins are now produced on a routine basis from the NOAA operational satellite imagery, and the data from Landsat have been shown to have practical application for snow mapping. This paper reviews the types of satellite data that have been used to map snow and the interpretive techniques that have evolved. The emphasis in the review is on the application of Landsat data in the four ASVT Snow Project study areas, and the development of methods to use snow cover area from Landsat in runoff prediction. The application of remote sensing in portions of the spectrum other than the visible is also discussed.

INTRODUCTION

The year 1980 will mark the twentieth anniversary of the launch of the first United States weather satellite. As seen in Figure 1, the first television camera images from TIROS-1 were rather crude as compared to today's satellite data because of the relatively poor resolution and oblique viewing angle. These initial sensor systems were designed primarily to view clouds, and the resulting images showed patterns, such as spiral clouds associated with deepening storms, never before realized by the meteorologist.

It was not long after TIROS-1 returned its first images from space that efforts were underway to determine what information other than cloud patterns could be derived from weather satellites. In the early images, such as that shown in Figure 1, snow and ice were essentially the only terrestrial features that could be detected other than ocean-land boundaries, large lakes, and a few rivers. Thus, snow was perhaps the first "earth resource" observed from space, even before the term came into common use.

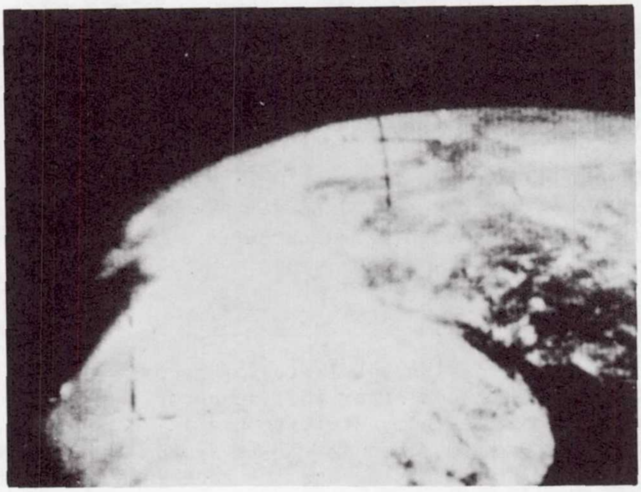


Figure 1 TIROS-1 image, 1 April 1960, viewing the mouth of the St. Lawrence River. Snow and ice can be seen in this very first image ever taken by a weather satellite.

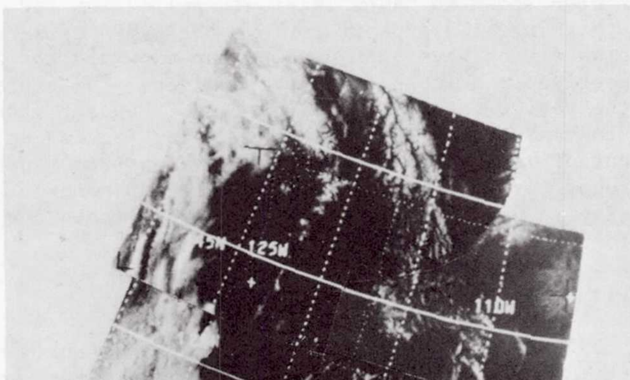


Figure 2 Cloud-free mosaic of the western United States compiled from ESSA-3 images taken in late May and June 1967. Snow cover can be seen in the Sierra Nevada, Colorado Rockies, Wind River Range, and other ranges.

Having recognized the potential of the earth-orbiting satellite to provide the hydrologist with useful information on snow cover, investigations were initiated in the mid-1960's to develop techniques to map snow from satellite images and determine the accuracy with which snow could be mapped. Following the introduction of improved spacecraft observational systems in the early 1970's, further studies were carried out to demonstrate that remote sensing from space could provide a more cost-effective means for monitoring snow cover. Moreover, these studies provided an indication that snow covered area, derived either by aerial or satellite surveys, can be employed as an additional parameter in the prediction of snowmelt-derived runoff. The positive research results in both mapping and runoff correlations led to the implementation in 1974 of the Snow Applications Systems Verifications Test (ASVT). An initial Snow ASVT workshop on applications of satellite snow cover observations was held in 1975 (Rango, 1975).

To assist personnel who would be involved in the Snow ASVT, a handbook of techniques for satellite snow mapping was prepared (Barnes and Bowley, 1974). The handbook included discussions 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 Snow ASVT five years later, an updated handbook is in preparation (Barnes and Bowley, 1979). The purpose of the updated handbook is to document the snow mapping techniques used in the various ASVT study areas and the ways snow cover data have been applied to runoff prediction. Through documentation in handbook form, the methodology developed in the Snow ASVT can be extended to other areas.

EARLY SATELLITE SNOW STUDIES

Using images from the very first satellites of the TIROS series, several early investigators showed that areas of snow cover could be delineated from space (Fritz, 1962; Singer and Popham, 1963; Tarble, 1963). Despite these studies, however, little operational application of snow cover mapping from satellite photography could be achieved with the earlier data, due in part to the uncertainty of obtaining an observation over a specified region from the TIROS series of satellites.

When satellites began to provide vertical-viewing imagery and daily global coverage, the first extensive research was carried out to assess the operational application of the data (Barnes and Bowley, 1968a). This work led to the preparation of an operational guide, applicable primarily to the Upper Mississippi-Missouri River Basins region (Barnes and Bowley, 1968b). Subsequently, studies were carried out emphasizing satellite surveillance of mountain snow in the western United States (Barnes and Bowley, 1969).

The early studies were concerned with how to identify snow in satellite imagery and, in particular, how to identify snow from cloud. Through interpretive keys, such as recognition of terrestrial features, pattern recognition, uniformity of reflectance, shadows, and pattern stability, snow could be reliably distinguished from cloud. Using these keys and taking into consideration other factors, including the effects of forest cover, it was possible to begin monitoring snow cover extent on a regular basis. Mosaicked, cloud-free images showing typical snow cover distributions in the western part of the country, such as shown in Figure 2, were prepared for use as background charts to assist in the analysis of other images.

An excellent summary report on the status of satellite snow mapping using data in existence a decade after those first TIROS-1 images was prepared by an international committee for the World Meteorological Organization (McClain, 1973).

CURRENT SATELLITE DATA WITH APPLICATION TO OPERATIONAL SNOW MAPPING

Three improved satellite systems introduced in the early 1970's have application to operational snow cover mapping: NOAA VHRR (Very High Resolution Radiometer), GOES (Geostationary Operational Environmental Satellite), and Landsat. Soon after observations from these satellites became available, researchers began investigations to evaluate the application of the improved data to snow hydrology (Wiesnet and McGinnis, 1973; Wiesnet, 1974; Barnes, et al, 1974; and McGinnis, et al, 1975). Subsequently, visible-channel data from these three satellite systems have been used to map snow cover in the Snow ASVT.

NOAA Very High Resolution Radiometer (VHRR)

The NOAA series has been the operational meteorological satellite 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 satellites from January 1973 until early 1979 (through NOAA-5). The spatial resolution of the VHRR is 900 m (0.5 nm).

The NOAA VHRR is designed primarily for direct readout use with three readout stations in use. Repeat coverage is provided twice daily; near local noon (visible and infrared), and again near local midnight (infrared), allowing both rapid and longer term changes in snow covered area to be monitored. The area that can be covered when the satellite passes directly overhead is a strip about 2,200 km (1,400 nm) wide and more than 5,000 km (3,000 nm) long.

A NOAA-5 VHRR image covering a large portion of the western United States is shown in Figure 3. The improvement in snow cover definition as compared to the ESSA mosaic shown in Figure 2 is obvious. Percentage of snow cover in several river basins in the ASVT study areas has been mapped on a routine basis from the VHRR images using a Zoom Transfer Scope (Schneider, 1975; Schneider and

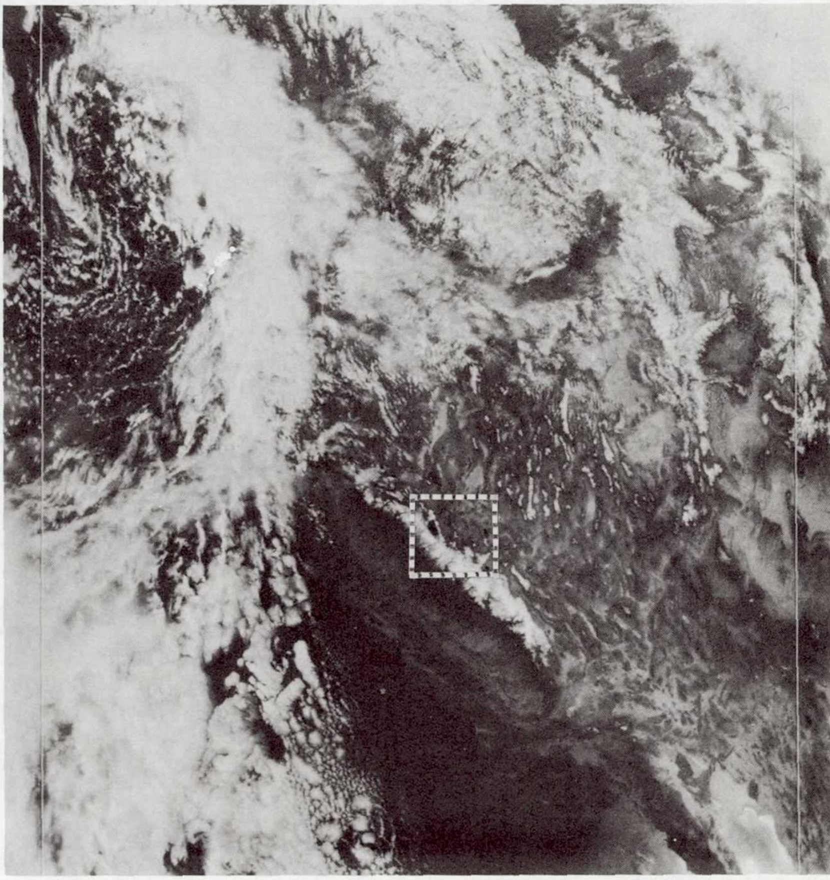


Figure 3 NOAA-5 visible-channel VHRR image, 22 April 1978, viewing the western United States. The area outlined over the Sierras is the area of the Landsat MSS scenes shown in later figures.

Matson, 1977).

Effective in early 1979, the NOAA satellite series has been replaced by the TIROS-N satellite 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. The AVHRR will now be used for the National Environmental Satellite Service's routine snow mapping.

Geostationary Operational Environmental Satellite (GOES)

Another satellite with application to snow mapping is the GOES system (Geostationary Operational Environmental Satellite). A geostationary, or so-called geosynchronous, satellite remains always above the same point on the equator, so always views the same portion of the earth. The altitude of a 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. An example of a GOES image on the same date as the NOAA VHRR image is shown in Figure 4.

Landsat

High resolution, multispectral data from space first became available in the summer of 1972 with the launch of Landsat-1, called at that time the Earth Resources Technology Satellite (ERTS). Landsat-2 was placed in operation in January 1975, and Landsat-3 was launched in March 1978; data are now being collected by Landsat-2 and Landsat-3.

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 (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

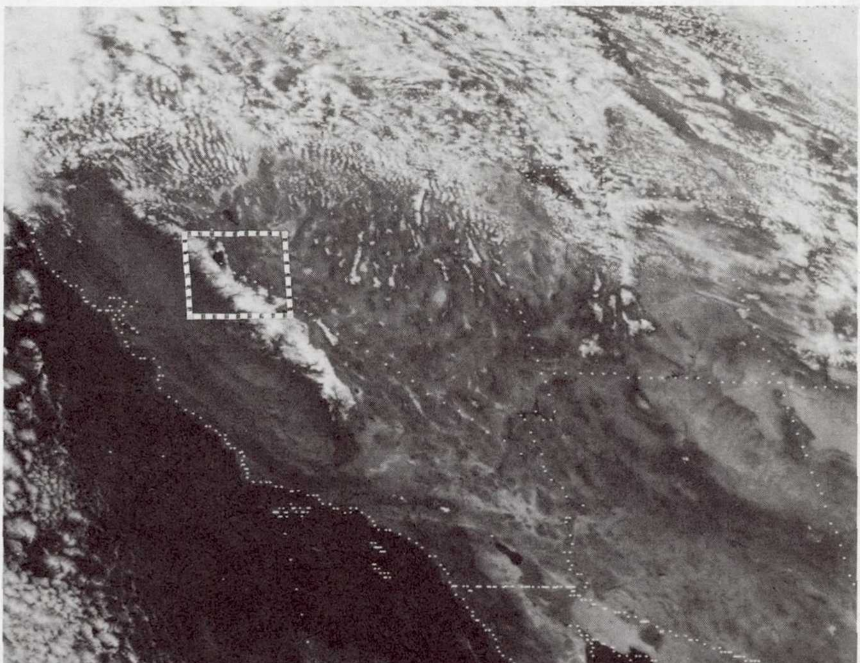


Figure 4 VISSR image from the western GOES satellite, 22 April 1978, 1945 GMT. Area covered by Landsat is indicated.

MSS-7 (near-infrared: 0.8 to 1.1 μm). Landsat-3 also carries a fifth MSS band, which measures in the thermal infrared portion of the spectrum (10.5 to 12.5 μm). Landsat views an area 185 km (100 nm) wide, and the MSS has a ground resolution of 80 meters (260 feet). Because of the relatively narrow swath viewed by Landsat, the satellite repeats coverage of the same area only once every 18 days.

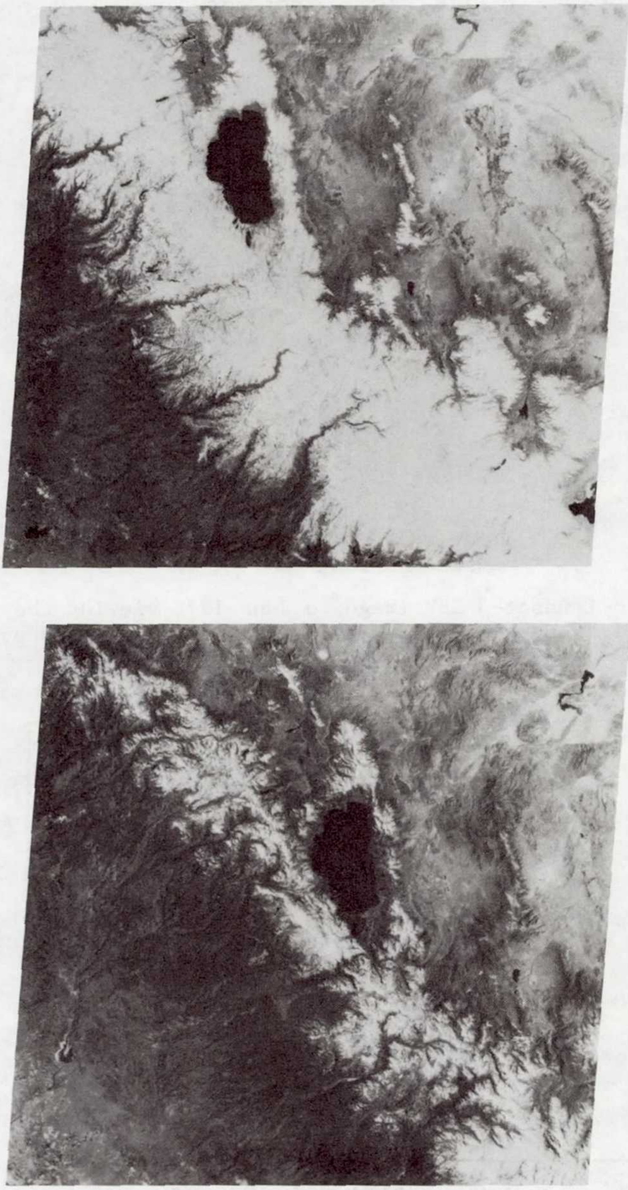
Landsat MSS-5 images showing a striking difference in snow cover extent in the Sierra Nevada in April 1978 and April 1977 are shown in Figures 5a and 5b. The 1978 image is the same day as the VHRR and GOES observations.

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. The characteristics of the Landsat-1 and Landsat-2 RBV's in terms of sensor resolution and area viewed were similar to the MSS. The RBV on Landsat-3 is a single band instrument covering a spectral range of 0.50 to 0.75 μm, and has improved resolution (about 40 m as compared to the 80 m resolution of the MSS); the standard RBV product is at a scale of 1:250,000 as compared to 1:1 million for the MSS images. Since the RBV data have not been processed routinely, the data used for snow mapping applications have been almost exclusively from the MSS sensor; nevertheless, some excellent RBV images have been acquired. An example of an RBV image viewing the Lake Tahoe area is shown in Figure 6; the scale can be compared to that of the MSS images shown in the previous figures.

The results of studies to evaluate Landsat imagery (Barnes, et al, 1974) have shown that in areas such as Arizona and the southern Sierra Nevada the extent of the mountain snowpacks can be mapped from Landsat in more detail than is depicted in aerial survey snow charts. In four river basins of the southern Sierra Nevada, for example, the agreement between the percentage of the basin snow covered as mapped from Landsat and from the aerial survey charts is of the order of 5 percent. Moreover, in both areas, significant discrepancies between the Landsat and aerial survey data could usually be explained by changes in snow cover during the interval between the two observations.

Similarly, comparative analysis with high-altitude aircraft photography indicated that although small details in the snow line that cannot be detected in the Landsat imagery can be mapped from the higher-resolution aircraft data, the boundaries of the areas of significant snow cover can be mapped as accurately from Landsat as from the aircraft photography.

In a comparison between Landsat and NOAA VHRR Wiesnet (1974) found the snow cover area from VHRR imagery to be consistently less than that mapped from Landsat for the American River Basin. He attributed the observed difference to be due primarily to the fact that the VHRR tends to integrate the snowline and eliminates small snow patches that may be detected and mapped from Landsat. In a comparative analysis for the Conejos Basin in Colorado, however, the VHRR imagery indicated more snow than Landsat (Washichek, 1978).



(a)

(b)

Figure 5 Landsat-2 MSS-5 scenes viewing the Lake Tahoe area. (a) 22 April 1978; (b) 15 April 1977. The snow cover area in 1978 is significantly greater than in 1977.

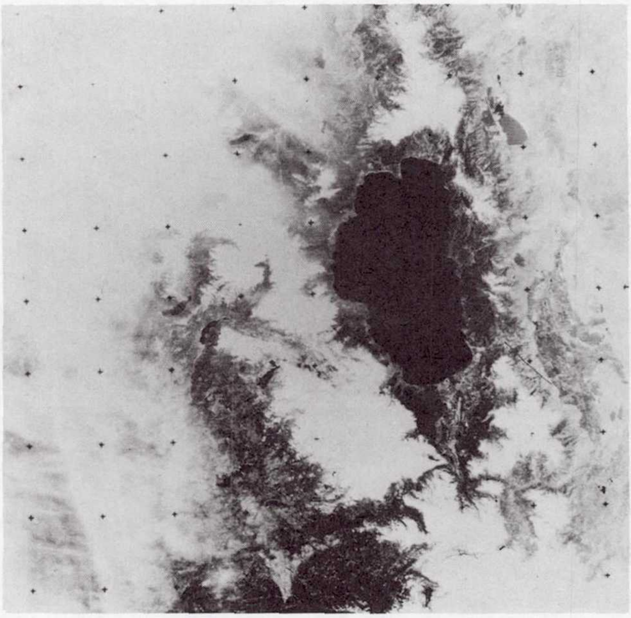


Figure 6 Landsat-3 RBV image, 6 June 1978 viewing the Lake Tahoe area. Some cloud obscures the snow cover west of the lake.

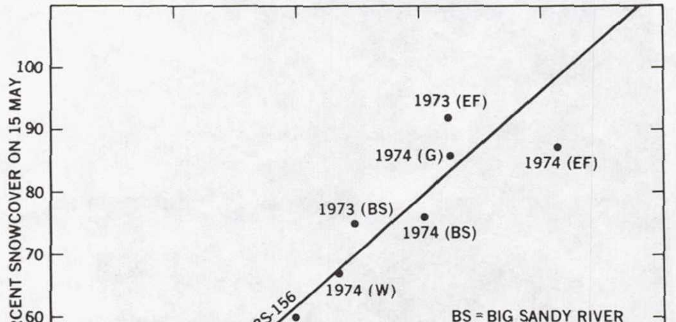


Figure 7 Landsat derived snow cover estimates versus measured runoff (1973 and 1974) for four watersheds less than 3,050 m mean elevation in the Wind River Mountains, Wyoming (from Rango et al, 1975).

Obscuration by cloud and identifying snow in heavily forested areas remain two major problems with all three types of satellite data used in the Snow ASVT. The cloud problem is more severe with Landsat, of course, because of its less frequent repeat coverage. In some years, such as 1972-73, useful data were fortunately acquired on nearly all Landsat passes over the Arizona and southern Sierras study areas; in other years, however, many of the passes have been cloud obscured. In the Arizona study area, where snow cover is extremely transient, the infrequent Landsat repeat coverage is also a drawback because significant changes in snow cover may occur between observations.

USE OF SNOW COVERED AREA FROM LANDSAT IN RUNOFF PREDICTION

Regardless of the type of satellite system, visual-channel data have application only for mapping snow cover area. Although a relationship between reflectance and snow depth has been found in certain instances (McGinnis, 1975), operationally useful information on either the depth or water equivalent of mountain snowpacks cannot be derived from existing satellite systems. The question of how to relate satellite observations to runoff prediction has, therefore, been of prime concern.

At the time that techniques to map snow from satellites were being developed, other research related to runoff prediction was being carried out using aerial photographs. In studies of certain Colorado watersheds, Leaf (1969) found that a functional characteristic existed between extent of snow cover during the melt season and accumulated runoff, and that snow cover depletion relationships were useful for determining both the approximate timing and the magnitude of seasonal snowmelt peaks. This research would provide the basis for later studies to relate satellite snow cover area to snowmelt runoff.

Studies to employ satellite snow cover observations for seasonal streamflow estimation are described in a report by Rango, et al (1975). The initial attempts were made using low resolution meteorological satellite data to map snow covered area over the upper Indus River Basin in Pakistan. For the Indus River early spring snow covered area was extracted and related to April through June streamflow from 1967-1971 using a regression equation. Prediction of the April-June 1972 streamflow from the satellite data was within three percent of the actual total.

The results of further studies for two years of data over seven watersheds in the Wind River Mountains in Wyoming indicated that Landsat snow cover observations, separated on the basis of watershed elevation, could also be related to runoff in significant regression equations. The relationship between percent snow cover and runoff for the four lower elevation watersheds is shown in Figure 7. From these results, Rango et al (1975) concluded that satellite-observed snow covered area could be usefully employed as an additional seasonal runoff index parameter or as an input into certain hydrologic models.

The earlier studies were, in part, the basis for the implementation of the Snow ASVT, where the use of snow covered area in runoff forecasts has been evaluated in each of the four study areas. In the California study area, for example, snow covered area (SCA) from aircraft and satellite observations has been shown to be useful in reducing seasonal runoff forecast error on the Kern River watershed when incorporated into water supply forecast procedures (Rango et al, 1977). Similar analysis on the Kings River indicated that SCA-produced forecasts were generally as good as conventional forecasts but no significant improvement was noted. Based on the comparison of the Kings and Kern River watersheds, these investigators conclude that SCA will most likely reduce forecast procedural error on watersheds with: (a) a substantial degree of area within a limited elevation range; (b) an erratic precipitation and/or snowpack accumulation pattern not strongly related to elevation; and (c) poor coverage by precipitation stations or snow courses restricting adequate indexing of water supply conditions.

OTHER TYPES OF SATELLITE DATA WITH APPLICATION TO SNOW MAPPING

Research has also been conducted to apply data from other satellite systems to snow hydrology. For example, data from the instruments of the Skylab Earth Resources Experiment Package (EREP) have been studied, as well as the hand-held camera photography taken by the Skylab-4 crewmen as part of the Visual Observations Project (Barnes and Smallwood, 1975; Barnes, et al, 1975). Snow mapping was also included as part of the Earth Observations Experiment of the Apollo-Soyuz Test Project (Smallwood, et al, 1979). Although not having application for collecting operational snow data, the color photography from the manned spaceflights has been shown to be very worthwhile for research purposes.

In addition to the use of satellite imagery and photography 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.

Near-Infrared Data

As reported by Barnes et al (1974) and Rango et al (1975), 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 more thorough examination 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, Barnes and Smallwood (1975) 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.

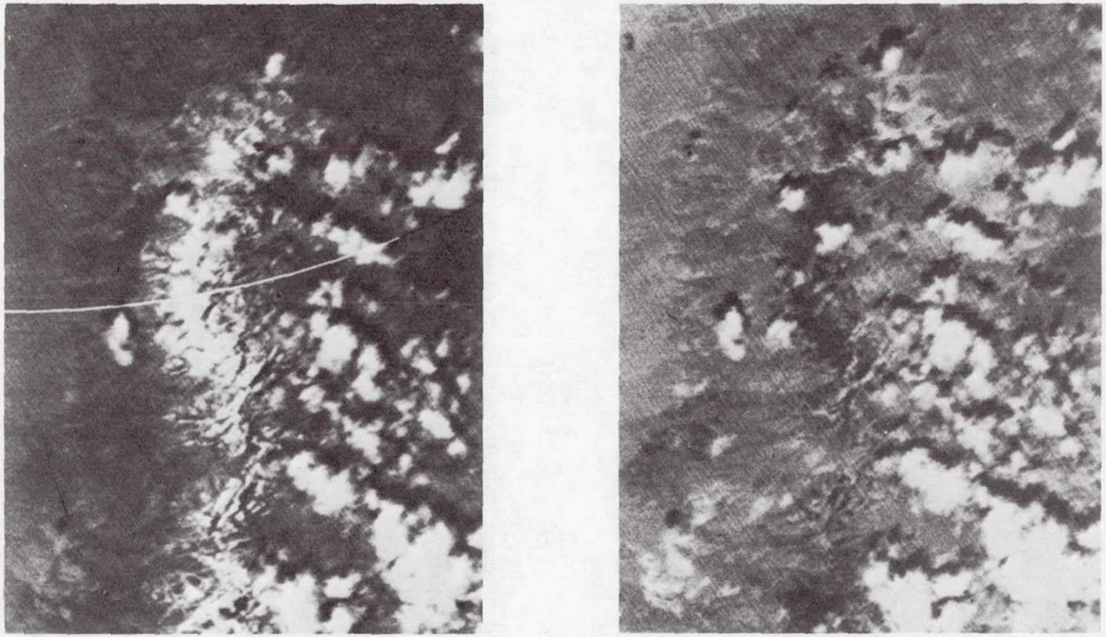
The nearly complete reversal in snow reflectance between the visible and near-infrared bands observed in the S-192 data indicates that in certain portions of the near-infrared, snow surfaces are essentially non-reflective regardless of the condition of the snow. In contrast, the reflectance of clouds (water droplet) displays no decrease in the near-infrared bands. Therefore, a technique combining two spectral bands, one in the visible and one in the near-infrared, can be used to distinguish between snow and clouds. An example of this method to distinguish snow and clouds is shown in Figure 8.

The second potential application, that of detecting melting snow, is based on the observed behavior of snow in the intermediate S-192 bands from about Band 7 (0.78 - 0.88 μm) through Band 10 (1.20 - 1.30 μm). For two spring cases examined, the apparent snow extent decreases gradually from a maximum in the visible (Band 6) to a minimum in Band 11. It was concluded, therefore, that bands in the spectral range from about 0.8 μm to about 1.30 μm should provide the most information on the condition of the snow surface.

Thermal Infrared Data

The NOAA VHRR carried a thermal infrared channel (10.5 - 12.5 μm) with the same resolution as the visible channel. The thermal infrared scanner measures the radiative temperatures of the Earth's surface and cloud tops rather than the reflectances. Studies have indicated (Barnes and Bowley, 1974) that in most instances snow cover can be delineated in the VHRR thermal data because of its lower temperature, although the thermal gradients associated with snow boundaries are considerably better defined during the spring than during the winter. Caution must be exercised when interpreting infrared data over mountainous terrain, where temperature differences due to variations in elevation may obscure the temperature differences associated with snow cover.

Further studies of the application of thermal infrared measurements to snow hydrology are 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. 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 at times when the temperature variation is a maximum, and applying the day/night temperature difference measurements to the determination of thermal inertia, that property of material to



(a) Band 3 (b) Band 11

Figure 8 Comparison between Skylab S-192 visible and near-infrared data, viewing the White Mountains in California, 3 June 1973; (a) Band 3 (0.52 - 0.56 μm), (b) Band 11 (1.55 - 1.75 μm). Because of the decreased reflectance of the snow, clouds that cannot be detected in Band 3 are distinct in Band 11.

resist temperature changes as incident energy varies over a daily cycle.

Although the satellite was designed primarily for its geological applications, snow hydrology studies using the HCMM data are being carried out. The main purpose of the studies is to determine whether the thermal measurements from HCMM, and particularly the more precise day/night temperature difference measurements, can be related to snow conditions, such as areas of melting versus non-melting snow. Examples of HCMM visual and thermal infrared imagery are shown in Figures 9a and 9b.

Microwave Data

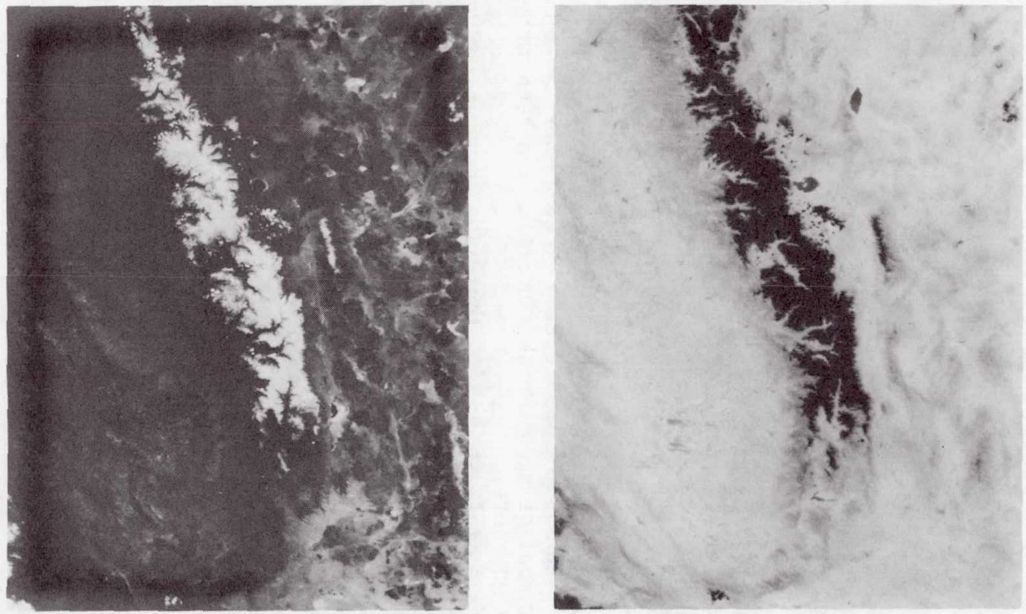
Satellite observations in the visible, near-infrared, and thermal infrared portions of the spectrum are all affected by clouds. Microwave sensors, however, provide the capability for viewing the Earth's surface regardless of cloud conditions, so have great potential for snow mapping.

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 (Rango et al, 1979).

The results of this study show that snow accumulation and depletion at specific locations can be monitored from space by observing related variations in microwave brightness temperatures. Using vertically and horizontally polarized brightness temperatures from the Nimbus-6 ESMR, a discriminant function can be used to separate snow from no snow areas and map snow covered area on a continental basis. For dry snow conditions on the Canadian high plains significant relationships between snow depth or water equivalent and microwave brightness temperature were developed which could permit remote determination of these snow properties after acquisition of a wider range of data. The presence of melt water in the snowpack causes a marked increase in brightness temperature which can be used to predict snowpack priming and timing of runoff. The authors point out that as the resolutions of satellite microwave sensors improve, the application of these results to snow hydrology problems should increase.

OUTLOOK FOR SATELLITE SNOW MAPPING

The Snow ASVT has provided a quasi-operational test of the use of satellite snow cover area in runoff prediction. Over the four-year period of the ASVT, each study center has found somewhat different methods for incorporating satellite data into runoff prediction models to be the most advantageous to the particular needs of their area. The overall results of the program indicate



(a) (b)

Figure 9 Heat Capacity Mapping Mission (HCMM) images viewing the Sierra Nevada, 31 May 1978 (daytime). (a) visible-channel; (b) thermal infrared channel (lower temperatures are darker).

without doubt that the utilization of satellite data will continue to be an integral part of operational runoff prediction procedures.

Limitations, of course, exist in making use of satellite observations. Even after 20 years, the types of satellite data most readily available for operational use are still limited by clouds, and the highest resolution data, that from Landsat, are not always available in real time. Also, for the purposes of the Snow ASVT, photointerpretive techniques to map snow cover from the satellite images were found to be the most useful; nevertheless, further development of automated analysis techniques using digitized data is essential.

New satellite systems will be providing improved data. For example, the studies using Skylab near-infrared measurements have led to the development of the snow-cloud discriminator, an instrument to be flown on an operational Air Force meteorological satellite. Undoubtedly, much emphasis in coming years will be placed on remote sensing in the microwave; as technological advances allow space-borne microwave radiometers to provide better resolution data, these sensors will have greater application to snow hydrology.

This paper has reviewed the evolution of satellite snow mapping. The continued development of improved satellite systems and mapping techniques will lead to more reliable and more cost-effective means for monitoring snow cover distribution and predicting runoff.

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