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Computer-aided analysis of satellite and aircraft MSS data for mapping snow-cover and water resources

1 INTRODUCTION

Effective management of our water resources requires current and accurate information about these resources. In some cases, the information needed concerns the areal extent, depth, and condition of the snowpack so that estimates of the quantity and regimen of the runoff can be obtained. In other instances, the resource manager is more interested in the amount and condition of the water after it has reached reservoirs, lakes and streams.

The developments in remote sensing technology during the past 15 years offer tremendous potentials for the hydrologist to obtain various types of information concerning the water resources--information that previously could not be obtained. Use of thermal infrared scanner systems from aircraft altitudes, for example, has proven the feasibility for accurately obtaining temperature measurements of the surface of water bodies over large areas. With the advent of Landsat satellites, the potential for measuring the areal extent of water bodies at frequent intervals and over very large geographic areas has been proven. Perhaps of even more importance, satellite data offers--for the first time--the opportunity to measure the areal extent of snow-cover in mountainous watersheds in an accurate and cost effective manner. Multi-spectral scanners (MSS) operated from satellite altitudes have also allowed the condition of water bodies to be assessed. For example, some studies have shown that different concentrations of non-organic suspended matter can be delineated on satellite data with a relatively high degree of accuracy.

From these comments, we see that there are several aspects of remote sensing technology which have application for mapping the extent and condition of snow-cover and surface water resources. This paper will consider the following topics:

- Mapping snow-cover using satellite MSS data and computer-aided analysis techniques.
  - Mapping snow-cover using Landsat data.
  - Snow/cloud differentiation using Landsat data.
  - Snow/cloud differentiation using Skylab data.
  - Mapping snow-cover using Skylab plus topographic data.
- Mapping water resources using satellite MSS data.
  - Areal extent of water bodies.
  - Defining water condition with Landsat data.
  - Water temperature mapping with Skylab data.
- Water temperature mapping using aircraft MSS data.

2 SNOW COVER MAPPING

For over thirty years, snow hydrologists have made numerous attempts to correlate the areal extent of snow-cover with the subsequent runoff. Parshall (1941) and Potts (1944) estimated the areal extent of snow-fields for runoff forecasting using ground photography. Later studies have involved use of aerial photography to measure the areal extent of snowcover (Parsons and Castle, 1959; Finnegan, 1962; Leaf, 1969). It was not until the early 1960's, however, that one could attain a synoptic view of large geographical areas through earth orbiting satellites. Today, a wide variety of environmental satellites are collecting an astronomic amount of data that potentially could be utilized to map the areal extent of snow-cover in a repetitive mode. Wiesnet (1974) has stated that "our capacity for collecting data on snow and ice far exceeds our ability to analyze the data". Therefore, in order to keep up the pace with the existing and highly advanced data collection technology, computer-aided analysis techniques (CAAT) have been developed and evaluated, and needs for further developments and refinements have been defined.

The Laboratory for Applications of Remote Sensing (LARS) was organized at Purdue University in 1966 with an overall goal of applying modern computer technology and pattern recognition theory to the quantitative analysis of multispectral earth resources data. Several analysis techniques have been developed since that time and applied to a variety of disciplines. However, it was not until Landsat-1 MSS data became available that any of these computer-aided analysis techniques were applied to snow/hydrology studies.

2.1 Mapping snow cover using Landsat data

A study involving the use of computer-aided analysis techniques for accurately and efficiently mapping snow cover was conducted in the San Juan Mountains of southwestern Colorado (Luther et al, 1975). Cloud-free Landsat data tapes were obtained for six dates during the 1972-1973 winter. The boundary of the Animas River Watershed was delineated on topographic maps and then transferred to the Landsat data in digital format as a series of X-Y coordinates. Such a procedure allows the total area within the watershed (145 square kilometers in this case) to be rapidly tabulated by the computer (see Figure 1).

Preliminary analysis of the data indicated that spectral responses for snow and "non-snow" areas were significantly different in all four wavelength bands of Landsat data. However, it was also found that the detectors on the Landsat scanner system were usually saturated for all resolution elements containing snow-cover. (This fact became particularly important later when we attempted to differentiate the snow from cloud-cover.) Classification of the six data sets that were cloud-free resulted in an accurate identification of the snow covered areas, so that the total area covered by snow could be tabulated by the computer, and the percent snow-cover within the entire watershed calculated. The results showed the percent snow-cover ranged from 62.6% to 87.5%, depending on the date when the Landsat data was obtained.

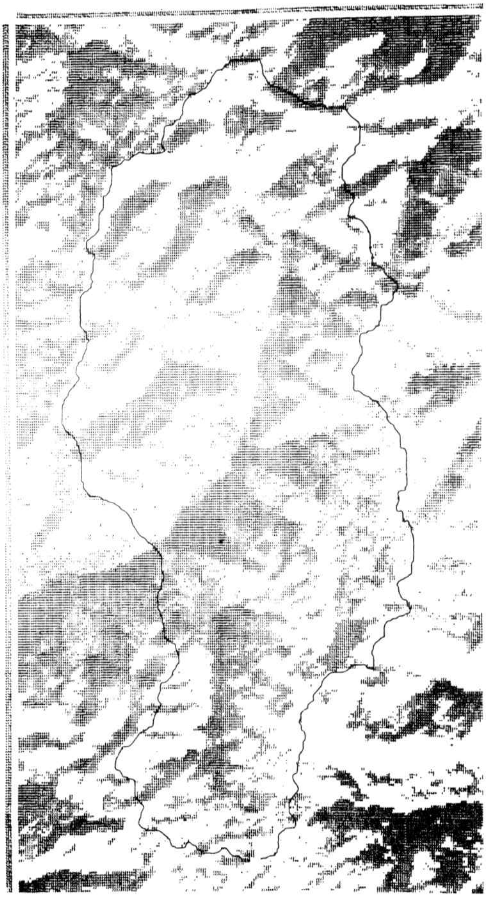

Figure 1. Digital Line-Printer Map of Landsat Data, With the Boundary of the Animas Watershed Outlined. (From Luther et al., 1975.)

Next a study was conducted to show the location of the changes in snow-cover from one date to the next. The general technique for determining changes in the condition or type of ground cover between two different data sets is known as "change detection". There are at least four change detection methods that can be used in computer-aided analysis of this type of data: Delta Transformation, Spectral/Temporal Concurrent Classification; Spectral/Temporal Layered Classification; and Post-Classification Comparison.

In this study the Post-Classification Comparison method was used because of its simplicity and cost-effectiveness. Each of the six data sets were digitally overlayed, resulting in a data tape containing 24 channels of data (i.e., four wavelength bands for each six different dates). Each of the six data sets were classified into snow and non-snow categories. Then, the Post-Classification Comparison between any two dates enabled one of four combinations to be defined: (1) snow-cover on both dates; (2) non-snow on both dates; (3) snow-cover on Date 1 changing to non-snow on Date 2; and (4) non-snow on Date 1 changing to snow-cover on Date 2. The results obtained in this phase of the study clearly indicated that if the digital overlay of the data is accurate, simple classifications such as snow and non-snow can be compared so that maps and tables showing the changes in snow-cover from one date to the next can be quickly and easily compiled.

In these initial phases of this study, each resolution element of the Landsat data was being classified. From this preliminary work, it was clear that multispectral classification of enormous quantities of data gathered by earth orbiting satellites can require a moderately large amount of computer CPU (Central Processing Unit) time, even for such relatively simple tasks as determining the areal extent of the snow-cover. Therefore, a third phase of this study was conducted to compare the accuracy of the multispectral classification of snow-cover using different data sampling rates in order to reduce the amount of computer processing time. To do this, an area including approximately 60% of a Landsat scene (therefore involving over 4.3 million data points or resolution elements) was classified into four spectral classes (one "snow" class and three "non-snow" classes) using one visible and one infrared wavelength band. The same set of statistics were utilized to classify the area five times, each classification involving a different sampling rate. After this, the areal extent of snow-cover was computed for each one of five classifications. The results are shown in Table 1.

These results indicate that the percent of the area in snow-cover is not significantly different when every sixteenth column of data is classified as compared to classifying every resolution element in the data, since the difference between the area of snow for the 16 x 16 and the 1 x 1 sampling rates was only 0.4 of one percent. Of particular importance is the fact that the computer classification time was reduced from over 54 minutes to less than one minute for the classification. This would indicate that reasonably accurate estimates of the area of snow-cover can be obtained using a sample of Landsat data rather than using every resolution element present on the data tape. Such a procedure would allow the cost of computer processing to be reduced significantly, while the percent of the area covered by snow could still be determined with a relatively high degree of accuracy. Figure 2 graphically shows the effect of the sampling rate on the computer time used.

2.2 Snow/cloud differentiation using Landsat data

In the early 1960's, the problem of differentiating snow-covered areas from cloud formations was first identified by researchers working with some of the early meteorological satellite imagery. At that time, however, the primary emphasis was on study of cloud types and patterns. For example, while studying cloud patterns as seen on TIROS satellite data, Conover (1964) stated that "clouds are easily confused by the interpreters with snow-cover". Early work with the Landsat data also indicated that snow-cover could be easily confused with clouds. Articles by Meier (1973) and Barnes and Bowley (1973) both pointed out the difficulty in separating clouds from snow on the Landsat data, based upon differences in reflectance. However, by using a manual photointerpretation approach, other characteristics in the data can often be used to advantage to separate cloud-cover from snow. As Barnes and Bowley (1973) pointed out, "although snow and clouds have similar reflectances, mountain snow-cover can be differentiated from clouds primarily because the configuration of the snow patterns is very different from cloud fields and can be instantly recognized. The snow boundaries are also sharper than typical cloud edges, and snow fields usually appear with a more uniform reflectance than do clouds, which have considerable variation in texture. Furthermore, cloud shadows are usually visible, especially with cumuliform clouds, and various terrestrial features can be recognized in cloud-free areas". However, Meier (1973) pointed out that it is often difficult for even an experienced interpreter to distinguish some types of clouds and fog from snow.

In our study, the reflectance characteristics for areas which could be positively identified as snow-cover and as clouds were summarized for data obtained on three different dates. These results are shown on Table 2 and graphically displayed in Figure 3.

Table 1. Determination of Areal Extent of Snow-Cover from Landsat MSS Data Using Different Sampling Intervals.

Sample Interval	Number Data Points	Number of Points Classified as Snow	% of Area in Snow	Classification CPU* Time (minutes)
1 x 1	4,330,561	1,385,126	31.99	54.34
2 x 2	1,083,681	345,417	31.87	13.20
4 x 4	271,441	86,433	31.84	4.21
8 x 8	68,121	21,646	31.78	1.52
16 x 16	17,161	5,422	31.60	0.65

*IBM 360 Model 67

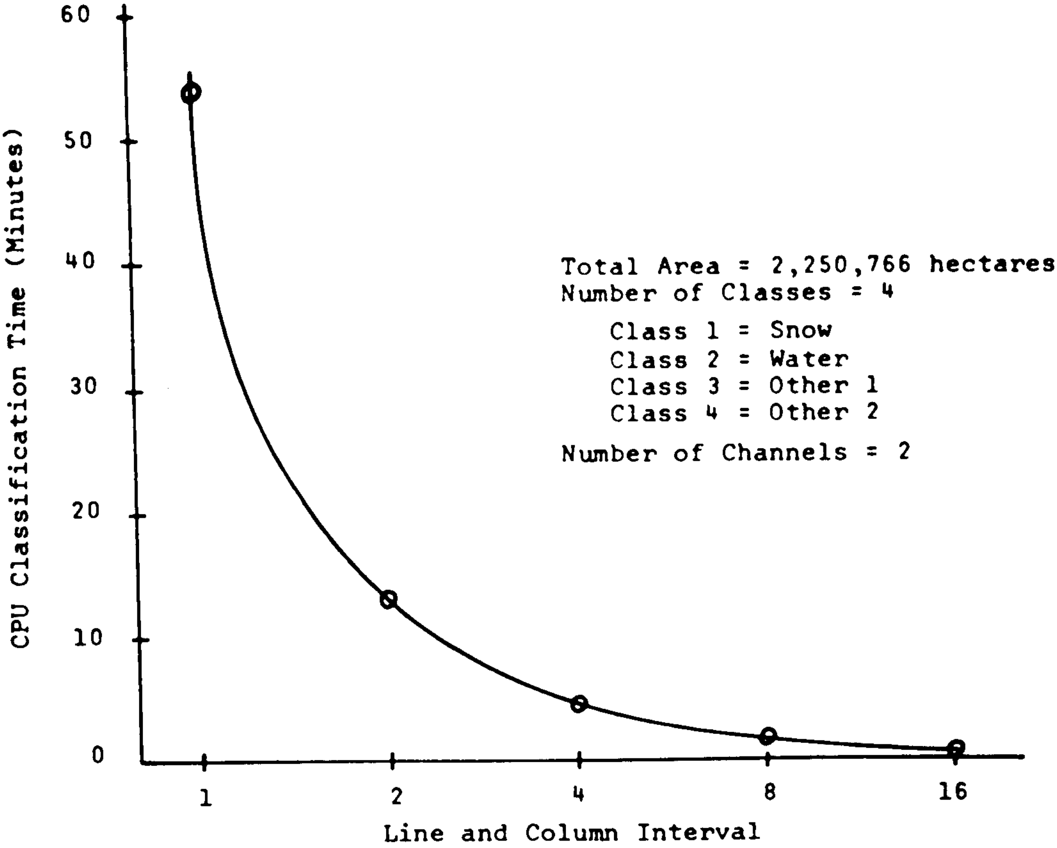

Figure 2. Computer CPU Time Required for Classification of Snow-Cover Using Different Sampling Intervals. (From Luther, et al., 1975.)

A relative response level of 127 indicates the saturation level for wavelength Bands 4, 5 and 6 of the Landsat data, and a relative response level of 63 in Band 7 indicates detector saturation. As can be seen from Figure 3, both snow and clouds saturated all four detectors on two of the dates examined and approached the saturation level for the third date. These results clearly indicate that computer-aided

Table 2. Comparison of Spectral Response of Clouds and Snow Using Landsat-1 Data.

	Wavelength Bands			
	4	5	6	7
	(0.5-0.6μm)	(0.6-0.7μm)	(0.7-0.8μm)	(0.8-1.1μm)
Clouds	126.6 $\pm$ 2.3^1	126.2 $\pm$ 2.8	118.2 $\pm$ 6.8	55.6 $\pm$ 6.7
Snow	125.4 $\pm$ 5.2	125.0 $\pm$ 5.6	116.2 $\pm$ 10.2	51.2 $\pm$ 9.0

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[1] Numbers indicate mean relative response $\pm$ 1 standard deviation using a combination of approximately 3000 data resolution elements, representing several areas of clouds and snow on each of three dates (1 Nov. '72, 6 Dec. '72, and 18 May '73).

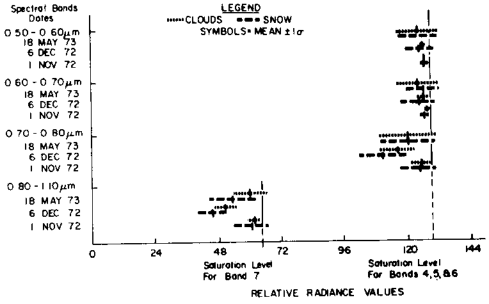


Figure B.15. Statistical analysis of the spectral response of snow and clouds.

Figure 3. Spectral Comparison of Clouds and Snow Using Landsat-1 Data From Three Different Dates. Saturation level was reached in nearly all data sets and the similarity of response indicates lack of spectral separability between those two cover types.

analysis techniques based upon spectral response cannot be reliably utilized to determine the areal extent of snow-cover using Landsat data, because of the limited dynamic range and limited spectral range of the Landsat scanner systems.

2.3 Snow-cloud differentiation using Skylab data

In 1973, the S-192 multispectral scanner was flown on the Skylab space station. This scanner contained 13 wavelength bands, operating in the atmospheric windows in the 0.41 to 12.5μm portion of the electromagnetic spectrum. Analysis of these Skylab data indicated that the limitations of the Landsat data in differentiating snow and clouds could be overcome. The extended spectral range of the Skylab S-192 Multispectral Scanner (0.41-12.5μm) proved to have significant advantages over the more limited spectral range of the Landsat MSS system (0.5-1.1μm). Examination of the Skylab imagery indicated that in the visible (0.4-0.7μm) portion of the spectrum snow and clouds had similar high reflectance values and appeared white on the imagery. In the thermal infrared band, both clouds and snow had a relatively low spectral response and appeared black on the imagery. This is because of the relatively low temperature for snow as compared to the other cover types, and the fact that in this data set, the clouds had a very similar low temperature. In the near infrared portion of the spectrum (0.7-1.3μm), the snow was white, but the snow-pack appeared to decrease in size with increasing wavelength. However, the clouds had a high reflectance throughout the near infrared portion of the spectrum and did not change in size. In the middle infrared wavelength bands (1.55-1.75μm and 2.10-2.35μm) a very striking difference in spectral response was found between clouds and snow. In this portion of the spectrum, the clouds have a high reflectance and appear white, whereas the snow has a very low reflectance and appears black on the imagery. The reason for the very low response of the snow in the middle infrared portion of the spectrum as well as for the decreased reflectance with increased wavelength in the near infrared portion of the spectrum is indicated by the typical spectral reflectance curve of snow shown in Figure 4. The quantitative spectral responses (means and standard deviations) for snow-cover and clouds in the 13 Skylab S-192 wavelength bands are shown in Table 3. (A spectral response of value of 255 indicates saturation of the detector.)

In order to accurately measure the degree of spectral separability between clouds and snow, a transformed divergence algorithm (Swain, et al., 1971; Swain and Staff, 1972) was utilized. Figure 5 is a bar graph showing the separability (based upon the transformed divergence values) between clouds and snow in the 13 wavelength bands of Skylab data. Transformed divergence

Table 3. Mean Spectral Response and Standard Deviation for Snow and Clouds, SL-2 S-192 Data, 5 June 1973.

Wavelength Region	Wavelength Band (m)	Snow		Clouds	
		Mean	S.D.	Mean	S.D.
Visible	0.41-0.46	255	0	254	4
Visible	0.46-0.51	250	16	248	19
Visible	0.52-0.56	229	38	229	37
Visible	0.56-0.61	255	0	254	1
Visible	0.62-0.67	254	6	254	8
Near Infrared	0.68-0.76	246	22	246	22
Near Infrared	0.78-0.88	230	38	230	35
Near Infrared	0.98-1.03	181	44	222	41
Near Infrared	1.09-1.19	165	33	228	32
Near Infrared	1.20-1.30	106	22	210	43
Middle Infrared	1.55-1.75	33	16	163	33
Middle Infrared	2.10-2.35	39	15	160	31
Thermal Infrared	10.2-12.5	67	18	61	14

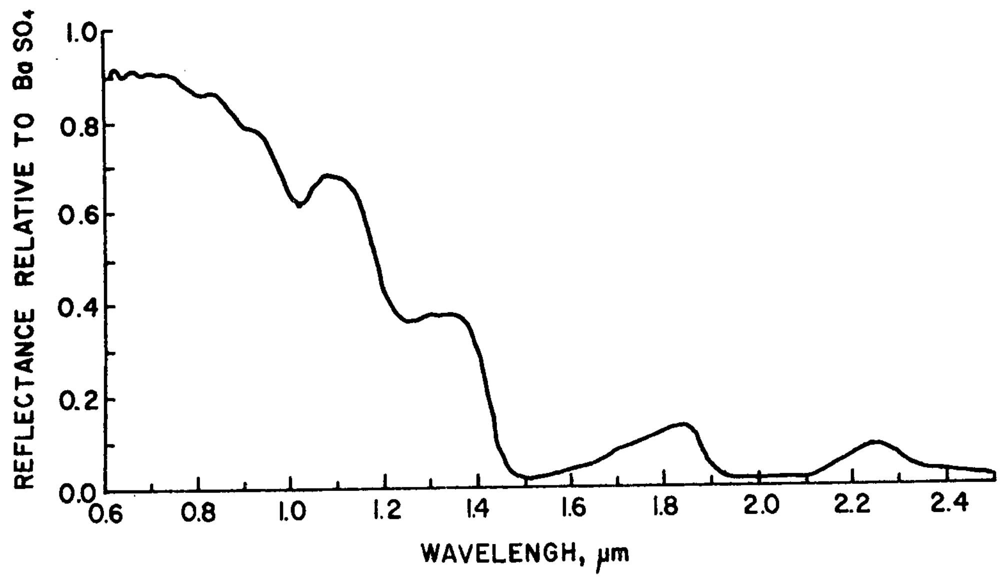
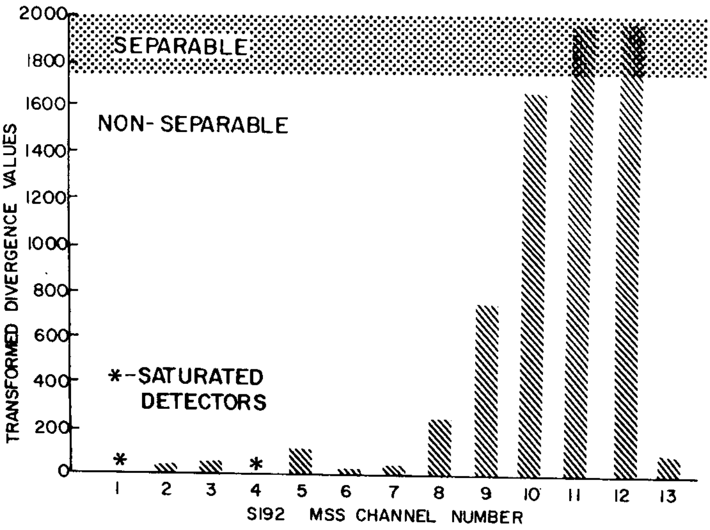


Figure 4. Typical spectral reflectance curve for snow. (After O'Brien and Munis, 1975.)

values of greater than 1750 indicate reliable separability between the spectral classes involved (Swain and King, 1973). The most relevant aspect of Figure 5 is that clouds and snow can be spectrally separated only in the two middle infrared wavelength bands (1.55-1.75μm and 2.10-2.35μm). These results clearly show the advantage for obtaining multispectral scanner data in the middle infrared (1.3-3.0μm) portion of the spectrum when the application involves the mapping of snow cover. These results, as well as others involving computer-aided analysis of vegetative cover types, indicate the need for scanner systems carried by future satellites to contain at least one wavelength band in the middle infrared portion of the spectrum.

2.4 Mapping snow-cover using Skylab plus topographic data

The computer-assisted analysis of the Skylab MSS data for mapping snow-cover involved several processing steps. The first consisted of the definition of the maximum number of spectrally separable classes or categories of snow-cover present in the scene. A clustering or "non-supervised"



CHANNEL	WAVELENGTH (μm)
1	0.41-0.46
2	0.46-0.51
3	0.52-0.56
4	0.56-0.61
5	0.62-0.67
6	0.68-0.76
7	0.77-0.88
8	0.98-1.03
9	1.09-1.19
10	1.20-1.30
11	1.55-1.75
12	2.10-2.35
13	10.20-12.50

Figure 5. Spectral separability of snow and clouds in the 13 Skylab-2 S-192 wavelength bands. (From Bartolucci, 1975.)

approach was utilized for this phase of the analysis, and five distinct spectral classes of snow-cover were defined. The training statistics thus defined were then used in a "supervised" classification of the entire data set using the maximum likelihood algorithm.

As indicated in Table 4, these five spectral classes of snow-cover were related to differences in reflectance in the individual wavelength bands in the near infrared portion of the spectrum, particularly in this 1.09-1.19μm and 1.2-1.3μm bands. Comparison of the snow-cover classification results with aerial photos taken from two different altitudes one day after the Skylab data was obtained indicated that the five different spectral classes of snow-cover were closely related to different proportions of snow and forest cover present within the individual resolution elements (pixels) of the Skylab MSS data. The S-192 scanner integrates the reflectance from the entire area on the ground within a resolution element (approximately 0.46 hectares). Therefore, a relatively high proportion of coniferous forest cover and a relatively low proportion of snow within a single resolution element will result in a relatively low reflectance as compared to a resolution element containing fewer trees and therefore having a larger proportion of snow-cover.

The spatial distribution of the five spectral classes of snow-cover mapped by the computer was found to be highly correlated to the topography of the area. The "snow-1" spectral class was found only at higher elevations in the areas of alpine tundra. The other four spectral classes were found in lower elevation ranges which generally have an increasing density of coniferous forest cover with decreasing elevation.

To establish a more quantitative correspondence between the spectral classes of forest cover and the topography of the area, digital topographic data were overlaid onto the multispectral scanner data. Tapes of elevation data obtained from 1:250,000 scale USGS topographic maps were reformatted to match the scale the Skylab MSS Data. Then, an interpolation procedure was developed and applied to the digital elevation data in order to obtain data on slope and aspect for each resolution element. This produced a digital data tape containing 13 channels of Skylab data and three channels of topographic data (elevation, slope, and aspect).

To show the value of the topographic overlay data, the elevation data were combined with results of the snow-cover classification, and the area of each of the five classes of snow-cover were determined as a function of elevation, using 100 meter elevation increments. This type of calculation can be accomplished rapidly and effectively using such multiple data sets which have been overlaid in a

Table 4. Mean Spectral Response of Five Snow-Cover Classes and a Forest Class in Skylab S-192 Data.

Band (μm)	Spectral Classes Snow 1	Snow 2	Snow 3	Snow 4	Snow 5	Forest
(0.41-0.46)	255*	255*	255*	255*	255*	205
(0.46-0.51)	255*	255*	255*	197	162	110
(0.51-0.56)	254*	252*	219	120	93	56
(0.56-0.61)	255*	255*	255*	253	251	131
(0.62-0.67)	255*	255*	255*	255*	237	72
(0.68-0.76)	255*	255*	255*	240	166	89
(0.78-0.88)	255*	255*	255*	193	148	113
(0.98-1.08)	255*	255*	194	138	108	102
(1.09-1.19)	251	196	137	104	89	92
(1.20-1.30)	185	148	98	76	68	83
(1.55-1.75)	64	61	56	54	59	72
(2.10-2.35)	19	17	14	11	13	21
(10.2-12.5)	99	100	101	105	110	124

* - Denotes detector saturation

format suitable for computer-aided analysis. The results of this analysis sequence are shown in Table 5. The results in Table 5 indicate the potential for rapidly summarizing the area of the snowpack as a function of elevation and as a function of the spectral class of snow. Such information could be of tremendous help to hydrologists in predicting the amount and timing of runoff from the snowpack in mountainous regions throughout the world.

3 MAPPING WATER RESOURCES USING SATELLITE MSS DATA

In water management, as well as many other areas of resource management, effective planning is dependent upon the accuracy and the reliability of the data which is available for the various planning and management activities. An accurate knowledge of the quantity of water stored in natural and artificial lakes is required to reach sound decisions regarding the conservation and allocation of water for different applications such as recreation, municipal and industrial water supplies, flood control, hydroelectric power generation, and agricultural irrigation.

Because the reflectance characteristics for water are distinctly different from those of other earth's surface features in the near infrared portion of the spectrum, use of remote sensing data in the near infrared region has long been recognized as a very valuable method for locating, mapping, and monitoring water features. Figure 6 shows the distinctly low reflectance of water as compared to soil or green vegetation in the near infrared portion of the spectrum. Figure 7 shows that the reflectance characteristics of clear water are even lower than for turbid water, particularly in the near infrared and red visible wavelength regions.

3.1 Areal Extent of Water Bodies

The availability and frequency of coverage by Landsat therefore leads to many questions and investigations involving the use of this data for mapping water bodies over large geographic areas of interest. In one study at LARS, it was shown that water bodies of more than three hectares in size could be identified with 100% reliability on the Landsat data through the use of computer-aided analysis techniques (Bartolucci, 1976).

Work and Gilmer (1976) used two different analysis techniques to map open water as an indicator of waterfowl habitat. At present, waterfowl management decisions are based in part on an assessment of the number, distribution, and quality of ponds and lakes in the primary breeding range, which covers a very large geographic area of North Central United States and South Central Canada. At the present time, surveys are conducted annually from low flying light aircraft to monitor the water conditions and provide key information for the necessary management decisions. The results of this study showed that areas of more than 1.6 hectares were nearly always recognized, but ponds smaller than that size were sometimes recognized and sometimes not, depending upon the location of the water body in relation to the resolution element of the Landsat scanner system. Thus, it is problematic as to whether

Table 5. Snowpack Area (in hectares) Within 100 Meter Elevation Increments.

Elevation (meters)	Spectral Class of Snowcover 1	2	3	4	5	Total Area (hectares)
Above 3700	1179	2464	308	108	7	4086
3600-3700	400	1914	694	135	37	3180
3500-3600	129	1868	1858	517	61	4433
3400-3500	45	904	1858	1266	280	4353
3300-3400	13	378	1305	1417	812	3925
3200-3300	7	94	922	1258	1298	3579
3100-3200	6	22	529	793	1540	2890
3000-3100		9	213	433	1041	1893
2900-3000		1	38	188	535	752
2800-2900			4	54	289	347
2700-2800			1	13	147	181
2600-2700				1	95	96
Below 2600					79	79
Totals	1779	7651	7730	6183	6221	29564

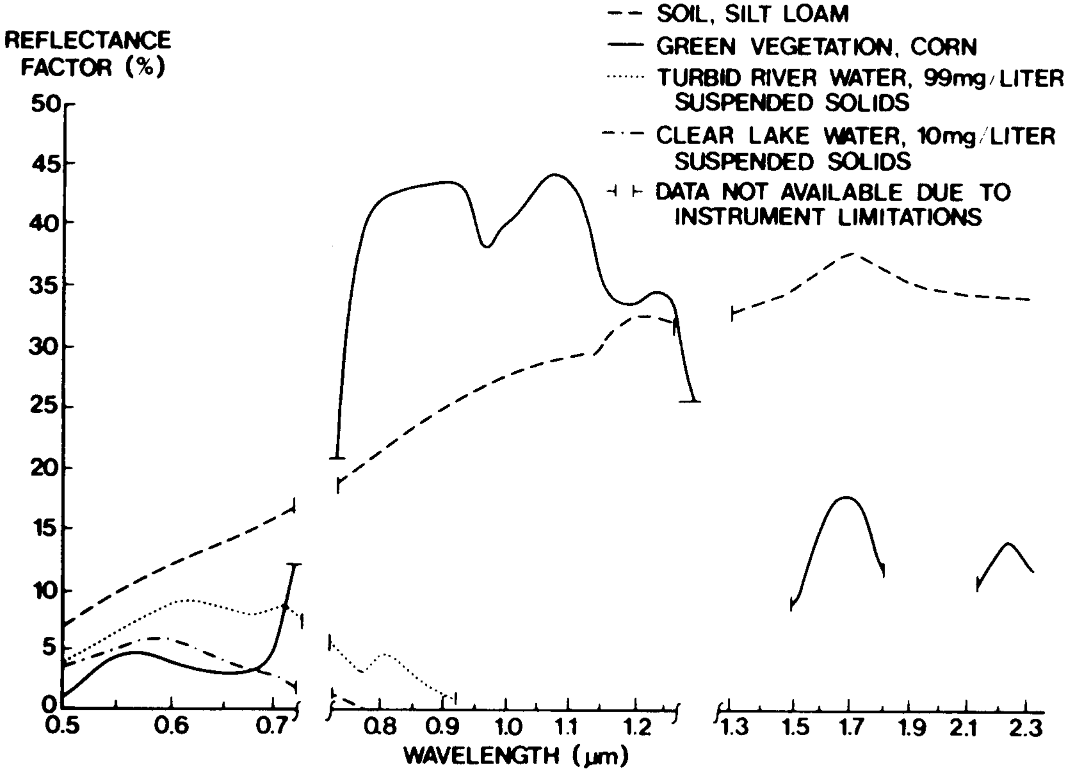


Figure 6. Spectral characteristics of turbid river water, soils, and vegetation. (After Bartolucci, et al., 1977.)

very small ponds will or will not be recognized on Landsat data. Other studies have shown some similar results. Future satellite systems, such as the Thematic Mapper on Landsat D, or the French SPOT scanner system will have much better resolution spatial resolution, and therefore may provide a capability to map smaller ponds (e.g., < 1 hectare) with a reasonable degree of reliability.

One difficulty in the use of satellite

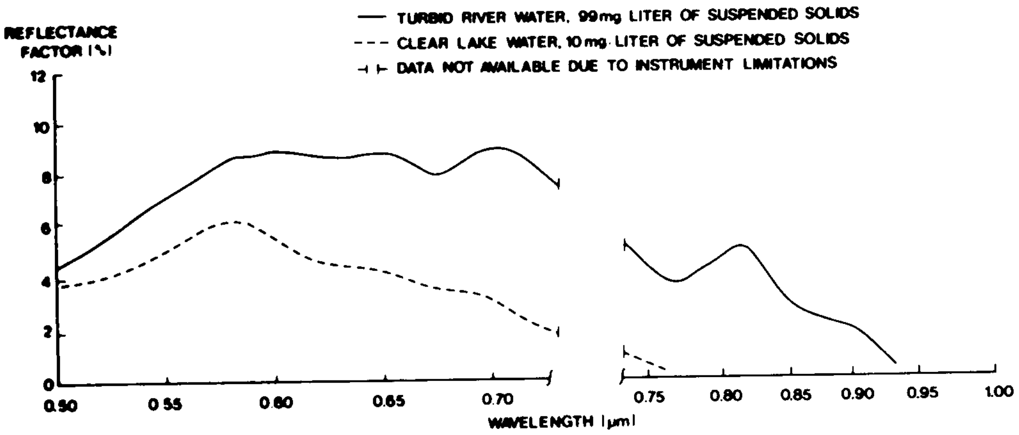


Figure 7. Spectral characteristics of turbid river water and clear lake water. (After Bartolucci, et al., 1977.)

data to identify and map water bodies that should not be overlooked is that in areas of mountainous terrain, topographic shadows have a very low spectral response and can be confused with the low spectral response found in bodies of clear water. Even in flat-land terrain areas, cloud shadows are sometimes confused with water bodies because of the low spectral response. Figure 8 shows the spectral response obtained from Landsat data on four different dates, and shows that the differences between cloud shadows and water are very small, particularly in the near infrared portion of the spectrum. In two visible wavelengths, cloud shadows tend to be slightly lower in spectral response than the water bodies and could be discriminated with reasonable reliability. It is important to recognize, however, that computer-aided analysis of Landsat data for mapping water bodies must take into account the effect of shadow areas present in the data so that these are not mapped as surface water features.

3.2 Defining Water Condition With Satellite Data

In the natural world, water bodies are usually not clear but contain a variety of organic and inorganic materials, some of which are in suspension. These materials cause scattering and absorption of the incident energy, resulting in significant differences in both the transmission and reflectance of incident energy from water bodies. Turbidity caused by suspended sediments is one of the major factors affecting the spectral response of water

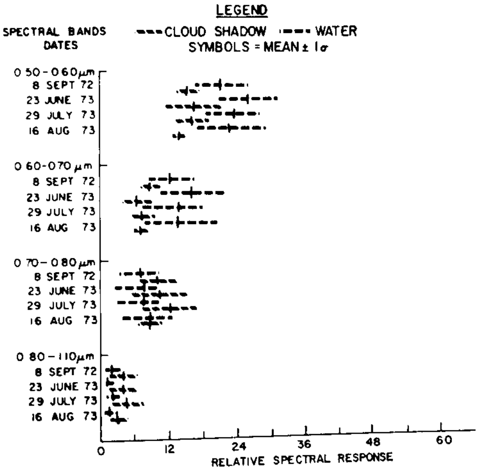


Figure 8. Spectral response of shadows and water bodies. (After Hoffer, et al., 1975.)

features. Previously, in Figure 7 we saw the spectral response for turbid and clear waters under natural conditions. As was seen in this figure, turbid water has a significantly higher reflectance than clear water, and it is also apparent that the peak reflectance for turbid water is at a longer wavelength than the peak reflectance for clear water. In the study by Bartolucci et al, (1977), they found that the reflectance characteristics of the river bottom did not influence spectral response of the turbid water when the water was mere than 30 centimeters in depth. This is a particularly significant finding, in that it indicates that whenever one is interpreting Landsat data for areas in which water is over 30 centimeters in depth, differences in reflectance measured by the Landsat scanner system are due to differences in the water quality rather than reflectance characteristics of the bottom.

A study by Weisblatt (1973) indicated that increased levels of turbidity produce almost a linear relationship with the radiance values measured by the Landsat scanner system in the two visible wavelengths, and a curvilinear relationship in the near infrared wavelength bands. The best relationship between spectral response and water turbidity was found in band 5 (0.6-0.7μm) of the Landsat data. Figures 9a and b show these relationships between Landsat data and turbidity, and for measurements obtained with a reference data source (Exotech 100 C) and water turbidity.

3.3 Water Temperature Mapping With Skylab Data

During the Skylab satellite mission, thermal infrared scanner data was obtained in the 10.2-12.5μm portion of the spectrum for Vallecito Reservoir in the San Juan Mountains of Colorado. The Skylab S-192 Multispectral Scanner System contained a set of internal calibration sources, consisting of two "black bodies" which were maintained at constant and known temperatures, so that while MSS data were being gathered, the rotating scanner mirror viewed these two black bodies during each rotation. Thus, in every scan line of data, a set of two radiance values are recorded which correspond to the energy emitted by the black bodies as a function of their temperatures. Both linear and non-linear calibration procedures were applied to the thermal band of Skylab data. At the time the Skylab satellite passed overhead, a team of researchers were in a boat on the surface of the reservoir taking temperature measurements in a variety of locations. These temperature measurements ranged from 12.0 to 13.1 degrees Centigrade. The linear calibration procedure applied to the Skylab data indicated that the temperature of the surface of Vallecito Reservoir was approximately 8.6 degrees Centigrade, whereas the non-linear calibration procedure indicated a surface temperature of 12.7 degrees Centigrade, which was a better indication of the true surface temperature of the reservoir.

Although limited in scope, this study indicated the value of the non-linear calibration procedure for use with thermal infrared scanner data. It also indicated that for mountainous areas at high elevations, the need to apply correction factors to account for atmospheric attenuation is minimized, thereby allowing reasonable and accurate surface temperature measurements to be obtained directly from the satellite scanner data.

4 WATER TEMPERATURE MAPPING USING AIRCRAFT MSS DATA

There is a great deal of controversy concerning many of the federal and state guidelines involving quality standards. Often this is because the legislative bodies and the industry both lack accurate and comprehensive factual information about the streams, reservoirs, and lakes with which they are concerned. This is particularly true in situations involving the setting of safe temperature standards for streams affected by the discharge of large quantities of waste heat from power plants. The discharge of heat into the water of the streams and the resulting thermal alteration is one aspect of power generation that is particularly amenable to study by thermal infrared scanner systems operated from aircraft altitudes. Thermal infrared scanner measurements are especially suitable for flowing water systems where no thermal stratification exists and where distinct thermal input may occur at numerous points along the length of the river.

In a study along the Wabash River, two different sets of data were collected and analyzed to determine the accuracy of calibrated remote sensor measurements to determine surface water temperature. One set of the data were collected in 4.5-5.5μm and 8.0-13.5μm portions of the spectrum, and from both 3000 meter and 600 meters altitudes. A second set of data were collected using only 9.3-11.7μm wavelength band from an altitude of 1,500 meters. At the time the scanner data were collected, measurements were also made from a boat on the surface of the river, so that a comparison could be obtained between the temperatures calculated from the scanner data (radiant temperatures) and the temperatures actually measured at the water surface (kinetic temperatures).

Table 6 shows the means for the radiant

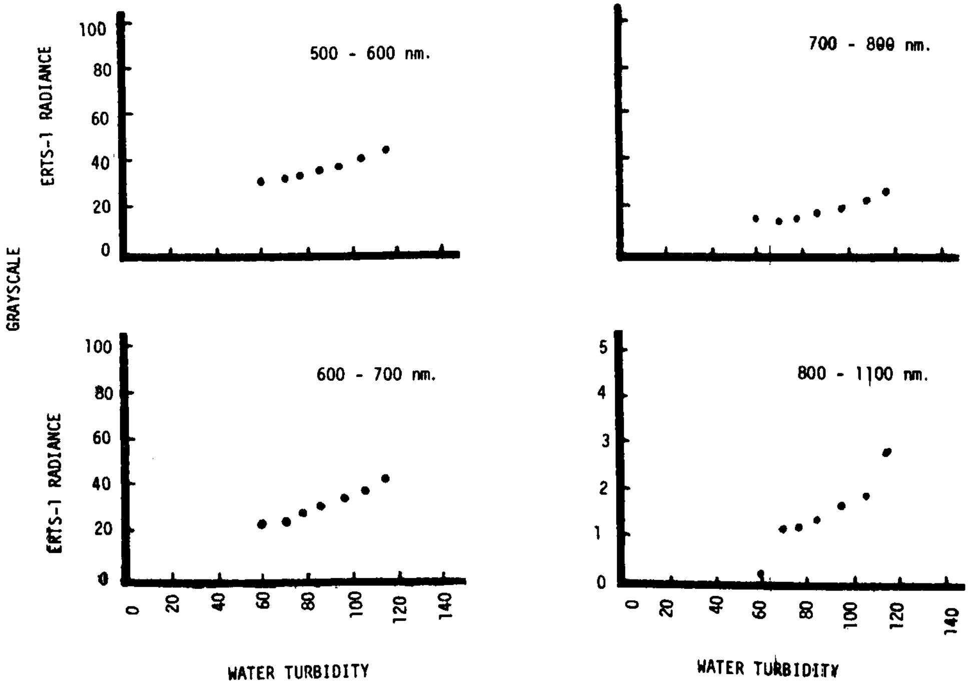


Figure 9a. Landsat Radiance as a Function of Water Turbidity. (From Weisblatt, 1973.)

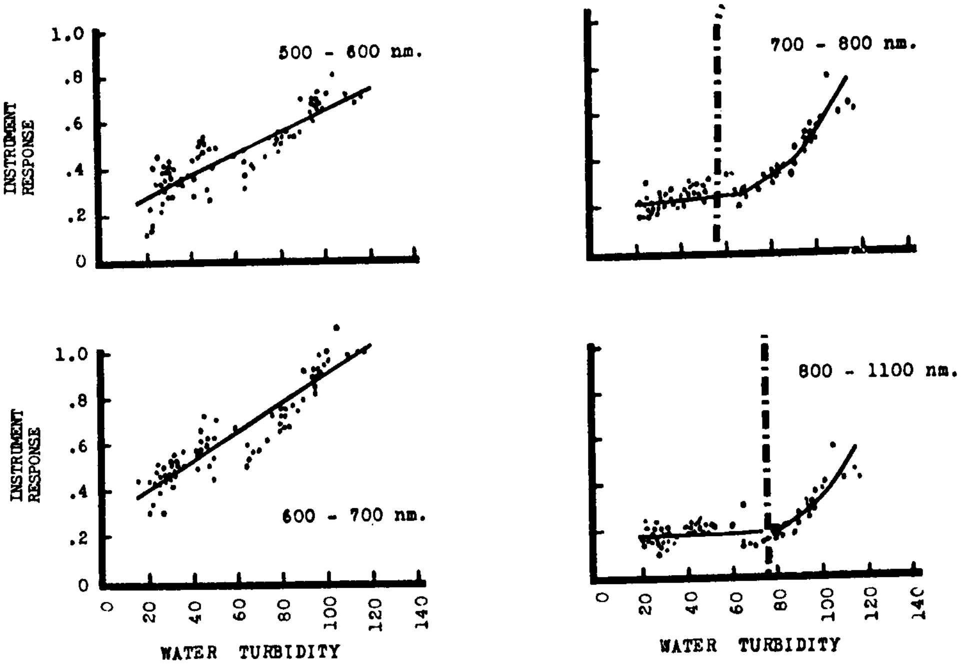


Figure 9b. Reference Data Showing Response as a Function of Water Turbidity of Bay Waters. (From Weisblatt, 1973.)

Table 6. Altitude Effects on Radiant Temperatures.

Measurement Site	Radiant Temperatures[1] (°C) 3000 M. Alt. 4.5-5.5µm	8.0-13.5µm	600 M. Alt. 4.5-5.5µm	9.0-13.5µm	Kinetic Temp.[2] (°C) (Contact Thermometer
1st River Bend	19.3	24.6	25.8	26.2	26.5
Above Intake	19.2	24.4	25.9	26.2	26.5
Intake	19.3	24.6	25.9	26.1	26.2
Outlet	19.2	24.4	25.8	26.1	26.0
1/2 Mile Below	19.3	24.4	25.6	26.1	26.2

[1] The standard deviation for the radiant temperatures is ± 0.2°C.

[2] All the surface measurements of temperatures listed above were obtained within half an hour from the time the aircraft passed overhead.

temperatures obtained from the thermal scanner data at both the 3000 and 600 meter altitudes, and also for the two wavelength bands (4.5-5.5 and 8.5-13.5µm) that were available during the first data collection mission. The kinetic temperatures measured at the water surface are also shown. From these results, it is quite evident that the aircraft altitude, or more correctly, the atmospheric path length between the target and sensor, plays an extremely important role in the degree of accuracy with which radiant temperatures can be determined from airborne scanner data. For the 600 meter altitude data, water surface temperatures could be determined in the 8.0-13.5µm wavelength band to an accuracy of approximately 0.2 degrees Centigrade. However, at the 3000 meter altitude, the radiant temperatures for the same wavelength band appear to be approximately 2° C. lower than they should be. For the 4.5-5.5µm band, the altitude effects are so pronounced that for the 3000 meter data, the radiant temperatures measured from the scanner data are approximately 7° C. lower than the actual surface temperatures.

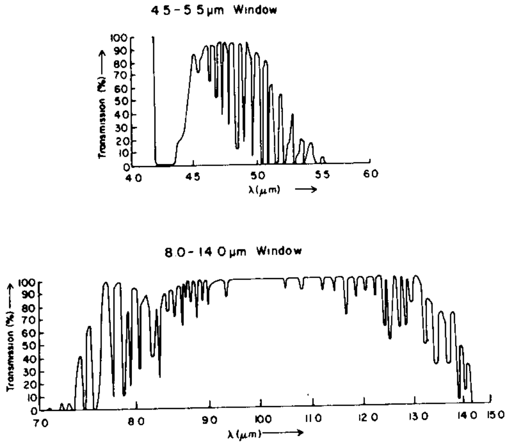


Figure 10. Transmission characteristics of the atmosphere at sea level for a 300 meter pathlength in the two thermal infrared atmospheric windows (4.5-5.5µm and 8.0-14.0µm). (From Bartolucci, et al., 1973.)

The impact of the transmission characteristics of the atmosphere on the data is shown in Figure 10. As can be seen, the so-called 4.5-5.5µm "atmospheric window" has a moderate amount of attenuation. Sensitive detectors, such as the Mercury Cadmium Telluride (Hg: Cd: Te), can obtain thermal infrared scanner data effectively in very narrow wavelength bands and thereby take advantage of the very good transmission characteristics in the 9.3-11.7µm portion of the spectrum. Such very clear transmission characteristics of the 9.3-11.7µm region indicate why accurate measurements of water temperatures could be obtained with the Skylab S-192 satellite data.

An evaluation of the use of aircraft scanner data for measuring the effluent from a hydroelectric power plant was conducted in conjunction with the Cayuga Power Plant on the Wabash River. This is a fossil fuel plant which utilizes water from the Wabash River for cooling purposes at an approximate rate of 2,200 cubic meters per minute. The temperature of the cooling water is increased by approximately 8° C. as it passes through the power generating units and is discharged back into the Wabash River. Use of the 9.3-11.7μm thermal infrared scanner data from 1,500 meters altitude showed that after the water was discharged into the Wabash River, the river temperature was approximately 4° C. higher than the temperature of the river above the discharge point. A distinct thermal plume could be mapped downstream from the power plant for a distance of approximately 6 kilometers. Use of the 9.3-11.7μm data allowed the water temperatures in the river to be mapped from aircraft altitudes with an accuracy of 0.2° C., as indicated in Table 7.

Table 7. Comparison of Kinetic and Radiant Temperatures at Six Different Locations.

Site & Date	Kinetic Temp. (°C)	Radiant Temp.[1] (°C)
Cayuga 8/9/72	22.1	21.9
	22.5	22.4
	25.7	25.6
Junction 8/10/72	19.8	19.8
	21.5	21.3
	20.4	20.3

[1] From an altitude of 1,500 meters using the 9.3-11.7μm band.

Work with fisheries biologists also indicated that there were distinct changes in the population of various fish species normally found in the Wabash River. Comparisons with data prior to the time the power plant went into operation indicated that large increases in the number of catfish were found in the heated portions of the river where the impact of thermal effluent was the greatest, while the populations of sauger and redhorse decreased in the heated areas.

It is clear from these results that remote sensing techniques involving the use of computer-aided analysis of thermal infrared aircraft scanner data allow an effective method determining the extent and magnitude of thermal effluents from hydroelectric power plants on river ecosystems.

5 SUMMARY AND CONCLUSIONS

Research results such as reported in this and other papers clearly indicate that remote sensing technology can be effectively utilized in mapping and monitoring of snow-cover and water resources. Computer-aided analysis techniques are becoming more cost-effective each year as new hardware and data processing capabilities are developed. Such computer-aided analysis techniques are particularly useful in conjunction with multispectral scanner data collected from satellite altitudes.

Studies such as those reported in this paper involving Landsat and Skylab data have indicated the potential for mapping snow-cover using satellite data and computer-aided analysis techniques. However, the limited spectral range and spatial resolution of the current Landsat scanner systems make them of limited value for mapping snow-cover and small bodies of surface water, but both of these limitations will be overcome by satellites to be launched in the early 1980's. The use of computer data bases for digitally combining topographic data with the satellite scanner data offers additional promise for evaluating and monitoring snow-pack conditions in mountainous areas.

The ability to accurately map surface temperatures of lakes and rivers using calibrated thermal infrared scanners from aircraft altitudes has been developed. The use of this technology will become more common as the availability of calibrated thermal infrared scanners increases, and as the data processing using standardized hardware systems and analysis techniques becomes more cost-effective.

From these comments, one sees that the development and the utilization of remote sensing (and other technologies) must follow a sequence in which there is a proper balance among (1) the research involved in defining the energy/matter interactions involved, (2) availability of appropriate instrumentation to collect and analyze the data, and (3) the refinement of the data processing techniques necessary for providing a cost-effective capability for operational utilization of the technology. It is also apparent that the demand for certain types of information and the time requirements involved will determine the ultimate utilization of remote sensing technology. In the case of the utilization of remote sensing technology for the mapping and assessment of snow-cover and water resources, it is clear that in some areas the technology are ready for operational application and utilization, whereas other aspects of remote sensing technology (particularly the utilization of satellite data) will be considerably improved with the next generation of scanner systems. Analysis techniques have been reasonably well developed, but work remains on the development of cost-effective hardware to be utilized with the data collection systems which will come into existence in the early 1980's. In summary, it seems clear that there are many aspects of remote sensing technology that can and will be utilized in the assessment and monitoring of our water resources.

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