THE INFLUENCE OF SCALE IN REMOTE SENSING OF SNOW COVER

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ABSTRACT

During the winter of 1972-73, the distribution of snow in southern Ontario was studied at four different scales using ground measurements, low altitude photography, high altitude photography and ERTS-1 imagery. The results show that low altitude photography permits a detailed examination of snow drift patterns associated with different types of agricultural land use. On high altitude photography, the proportions of vegetation to snow produced by different land uses are recorded as variations in image density and texture. Thus, the influence of vegetation on patterns of snow accumulation can be readily studied over fairly large areas. With ERTS-1 imagery, it was found that the appearance of snow cover is greatly influenced by the physiographic/land use characteristics of an area. Some of the problems of comparing ERTS-1 imagery and ground measurements are discussed.

INTRODUCTION

A series of studies has been undertaken to investigate the feasibility of using certain remote sensing systems for snow hydrology. The major emphasis in the research has been to evaluate the capability of ERTS-1 imagery for interpreting the distribution and depths of snow cover. At the same time, however, ground measurements, low altitude photography and high altitude photography have been obtained during passes of the ERTS-1 satellite.

By obtaining photography and imagery from different altitudes, a view of the ground surface at a variety of scales is produced. At the same time, the pictures recorded have different ground resolutions and spatial coverages, thus presenting information at various levels of detail. In general, the amount of detail recorded by a sensor decreases with increasing altitude. Thus, with the ground resolution of ERTS-1 imagery (approximately 70 m), it is apparent that integration of information over a considerable area takes place. By examining photography and imagery obtained simultaneously from a variety of altitudes, it was hoped to achieve a greater understanding of the characteristics of the snow cover being recorded by ERTS-1 imagery. At the same time, it was hoped to illustrate the types of information, of value to the snow hydrologist, that can be obtained from the different sensing systems.

This paper presents an analysis of ground conditions, low altitude photography, high altitude photography, and ERTS-1 imagery recorded simultaneously over part of southern Ontario on February 17, 1973. In addition, some of the advantages and limitations of using the ERTS-1 system for snow studies are discussed.

REMOTE SENSING OF SNOW COVER

The distribution and depths of snow cover have been studied from both airborne and spaceborne platforms. Finnegan (1962) using a hand-held camera from a light aircraft photographed graduated snow markers in a mountainous area of the State of Washington, U.S.A., and Cooper (1965) used photogrammetric measurements to determine snow depths from large scale vertical photography. A number of snow studies have also been undertaken using sensor systems operating in regions of the electromagnetic spectrum other than the visible and the near infrared. Such studies have concentrated on sea ice and the differentiation of snow covered terrain from sea ice (e.g., Poulin and Harwood, 1966; Leighty, 1966), but their fields of interest are beyond the scope of this present paper.

With the advent of weather satellites in the early 1960's, we had for the first time a broad view of the earth's surface. Although designed to record cloud distributions, snow cover could also be identified on the imagery. Early work in the U.S.A. by Barnes and Bowley (1968, 1969) and in Canada by Ferguson et al. (1969) discussed such problems as distinguishing between snow and cloud and the identification of the snow line. Attempts were also made to estimate depths of snow cover and it was found that for non-forested areas a threefold classification could be obtained based on the image density or tonal characteristics of the satellite pictures.

The lack of resolution was a problem using the early weather satellite pictures for snow studies. The situation, however, changed in 1973, "the year of the hydrological satellite" as Weisnet (1974b, p. 156) has described it. This year saw the start of data collection for snow studies from sensors with improved ground resolution mounted on new satellites. In Canada, ERTS-1 imagery was available in 1973, but NOAA-2 winter imagery has only been received for the first time during the 1974-75 season.

A number of studies involving ERTS-1 imagery have been reported in the literature and the capabilities and limitations of the system have been discussed (e.g., Barnes and Bowley, 1973; Barnes et al., 1974; Lauer and Draeger, 1973; Meier, 1973; Wiesnet, 1974a; Wiesnet and McGinnis, 1974). The majority of studies have been concerned with the monitoring of snow cover and have concentrated on the mountainous regions of North America. In contrast, this present paper discusses snow cover in an area of low relief and makes use of data obtained from aerial photography as well as ERTS-1 imagery.

AREA OF STUDY

The area chosen for study was southern Ontario. Although the major research effort was concentrated in the Niagara Peninsula, ground measurements and ERTS-1 imagery for an area bounded by Lake Ontario, the Niagara River, Lake Erie, Lake Huron, Georgian Bay and Lake Simcoe (Figure 1) were also studied.

For a number of reasons, this area was considered a suitable one for study. First, it is a local area for the investigators, which aided in obtaining ground information. It was found, too, that a general knowledge of the characteristics of the landscape was of great assistance in interpreting the photography and the imagery. A second reason is that in comparison with other parts of Canada, southern Ontario has a fairly dense network of ground stations at which snow depths are measured. These data have been used in certain aspects of the study. Also, during the period of study, parts of the area were flown with a gamma ray spectrometer to investigate the feasibility of measuring snow water equivalent from an airborne platform (Loijens, 1974). Finally, southern Ontario has a comparatively large population. The fact that much of the land has been developed for urban and agricultural uses means that information on snow cover from as many sources as possible can provide a valuable input to the planning of water resources.

In spite of the advantages of studying southern Ontario, the general characteristics of the area present a number of problems which complicate the study of snow cover. First, the area is bounded by water. The influence of the lakes on the

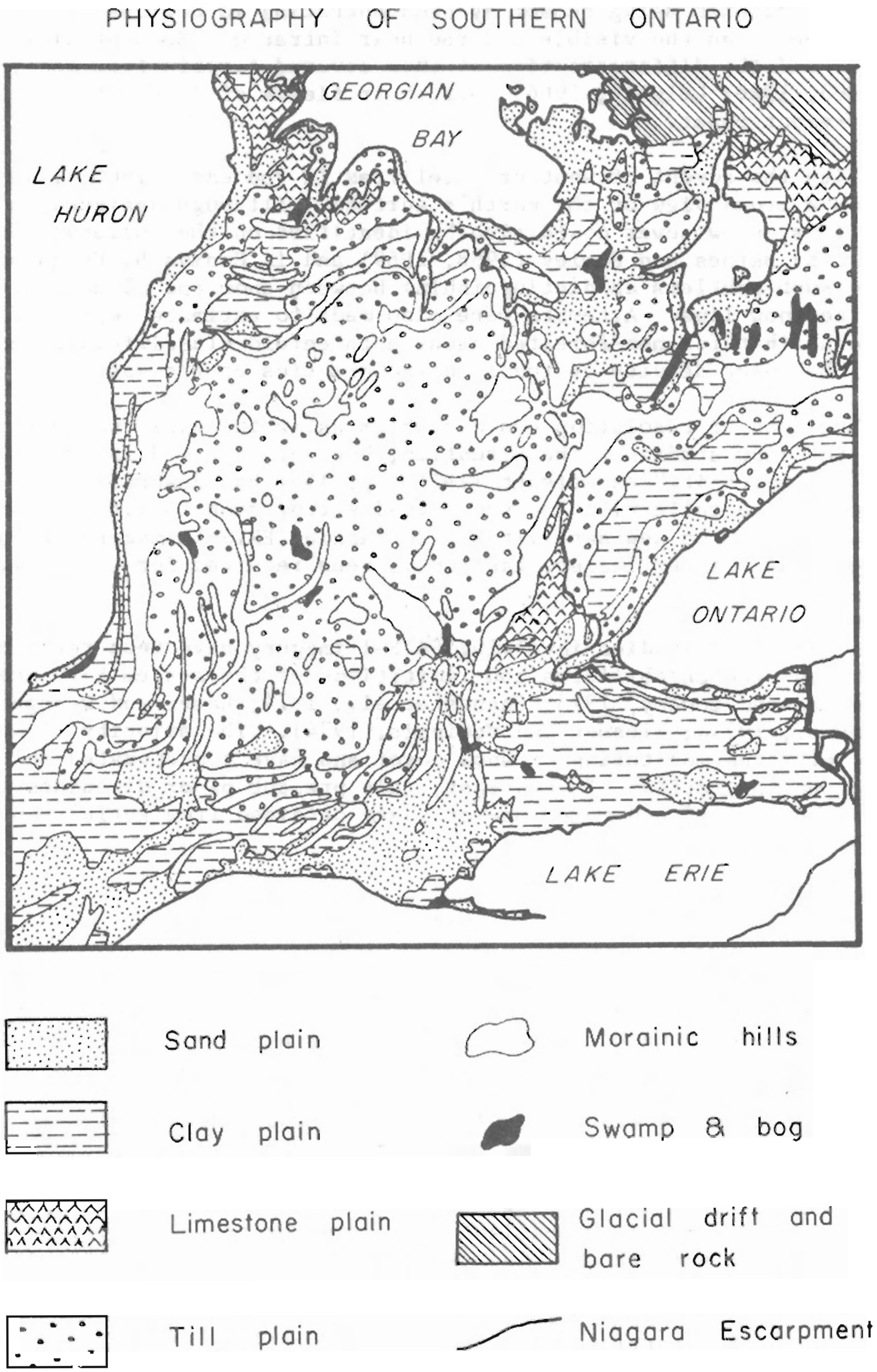

FIGURE 1. Location of the study area in southern Ontario. Physiography based on Chapman and Putnam (1966).

land area can result in a local warming influence and can also affect the distribution of precipitation (Brown et al., 1968; Webb and Phillips, 1973). A second problem is the southerly location of southern Ontario within Canada. This means that the area is likely to be influenced by many temperature fluctuations during the winter period, resulting in melting between snowfall events and rapid changes in the characteristics of the snow pack.

The physiographic characteristics of the area also present problems. Elevations range from less than 100 m near Lake Ontario to over 500 m in the northern parts of the study area. In addition, the Niagara Escarpment, with a height of generally 100 m, runs from northwest to southeast across the area. These variations in elevation can lead to differences is snow cover over short distances, particularly when temperatures are round about 0°C. The terrain itself is primarily a product of the effects of the retreat of the Wisconsin ice (Chapman and Putnam, 1966). The frequent variations in terrain (Figure 1) affect the land use patterns, both natural and modified by man, which in turn can affect the pattern of snow cover. As pointed out later, the variations in land use also influence the patterns that are observed on the photography and the ERTS-1 imagery.

SNOW COVER IN SOUTHERN ONTARIO

Southern Ontario has the densest snow survey network in Canada. Results of snow surveys have been published by the Atmospheric Environment Service as "Snow Cover Data" since 1954. The majority of survey sites are maintained by the Ontario Ministry of Natural Resources which conducts snow survey at half-monthly intervals, using ten sample points at each site. The remaining sites are operated by the Atmospheric Environment Service. These are all located at airports, with snow depths taken at daily intervals.

The data were analyzed to obtain an indication of the temporal pattern on an annual basis. In addition, the spatial patterns for several representative years (i.e., high snowfall, low snowfall and "average" snowfall) were plotted to give an indication of the seasonal variations. These provided a standard against which the data for the 1972-73 season could be compared.

The Winter of 1972-73

Snow surveys conducted at the beginning and the middle of winter months by the Ontario Ministry of Natural Resources happened to be close to several of the dates when ERTS-1 passed over southern Ontario. Of these dates, only January 31 and February 17-18 showed fair weather which permitted a view of the ground from the satellite.

Five separate plots of snow depth conditions over southern Ontario were made from ground survey data (Figure 2). Since snow survey is carried out over a period of several days, some sites would be recording snow conditions before a storm, while others would include snowfall from that particular storm. No attempt has been made to rectify this difference because the amount of fresh snow was not recorded. Partly because of this, isolines for snow depth were plotted at 100 mm intervals so that any inconsistency of data from one site to another could be glossed over and would not seriously affect a generalization of snow cover distribution.

Like most other winters, the heaviest snowfall occurred in the northern sector and the snowbelt was again prominent. The southern sector was devoid of snow for a larger number of days than the rest of the region. During this winter, westerly winds prevailed, but on several occasions when easterlies blew, the western shore of Lake Ontario received more snowfall than the snowbelt area. On the whole, there were more warm periods than usual which punctuated the winter cold, bringing about excessive amounts of melt between snow storms. As a result, at no time did the pack attain a thickness comparable to an "average" year.

FIGURE 2. Snow depths in southern Ontario based on surveys by the Ontario Ministry of Natural Resources.

Measurements at Test Sites

In addition to government data sources, snow surveys at several sites in the Niagara Peninsula were carried out during or around the days of ERTS-1 passes, mainly to determine the effect of the land use pattern upon the disposition of snow. In all cases the effect was similar and results from measurements recorded at two sites on February 17, 1973 illustrate the effects of the land use variations. The first site was at Elfrida to the southeast of Hamilton and the second in a zone between Grimsby and Grimsby Centre (Figure 3). In both cases the areas chosen had a very low relief, so this was not a factor in influencing the snow depths observed.

At each site a series of snow depth measurements was taken in a number of fields. When the pack was over 0.1 m deep, snow depths were measured with a Meterological Service of Canada snow sampler. If the depth was less than 0.1 m, sample plots consisting of "blocks" of snow 300 mm x 300 mm were marked out and several depths averaged for the "block". Depending on the variability of snow depth, 5 to 25 sample points were used to determine the mean snow depth for a particular field.

It was apparent from these and other studies that the nature of the land use has a considerable influence on the snow depth patterns that occur in any area. For this reason, measurements were taken in examples of all types of fields that occurred in the area of study. In Figure 4, average depth measurements for the different cover types that were encountered are shown. The pattern that occurs is as one would expect. The shallowest snow depths occurred in ploughed fields, where there was usually considerable drifting into dunes. In the higher parts of the fields bare patches were frequently encountered. In contrast, in fields containing uncut corn with little chance for snow drift and the greatest possible chance for interception of the snow by the corn, the least variability and the greatest depths were encountered. In such areas, too, as was determined from field measurements, density of the snow pack was the lowest.

LOW ALTITUDE PHOTOGRAPHY

In studying aerial photography, one has to consider what ground parameters are going to influence the image as we see it on the aerial photograph. From the field studies and also from the low altitude photography, it became apparent that the relative proportions of vegetation cover to snow cover and the characteristics of the vegetation were having a considerable influence on the photographic image.

The overall tone observed for a field will depend primarily on the proportion of vegetation on the ground surface that is visible through the snow. It will be found also that textural variations will occur depending upon the relative distributions of the snow and non-snow covered areas on the ground. In addition, patterns can be introduced in two ways; first, by the growth of the crops in the fields, and second, by the distribution of snow cover over the surface. These points can be illustrated from the low altitude photography flown on February 17, 1973.

From a light aircraft at flying heights of 300 to 600 m, oblique photographs were taken with a hand-held 35 mm camera. The camera was loaded with panchromatic film (Ilford Pan F) and a haze filter was used. Photographs were taken of sites in the two study areas as well as other parts of the Niagara Peninsula and the Hamilton region.

Figure 5 shows part of the Elfrida site. Across the centre of the photograph is a field of uncut corn, producing an overall dark tone and fairly coarse texture. This contrasts clearly with the adjacent fields of cut corn, still containing stubble, in the upper half of the photograph. The field at the bottom of the

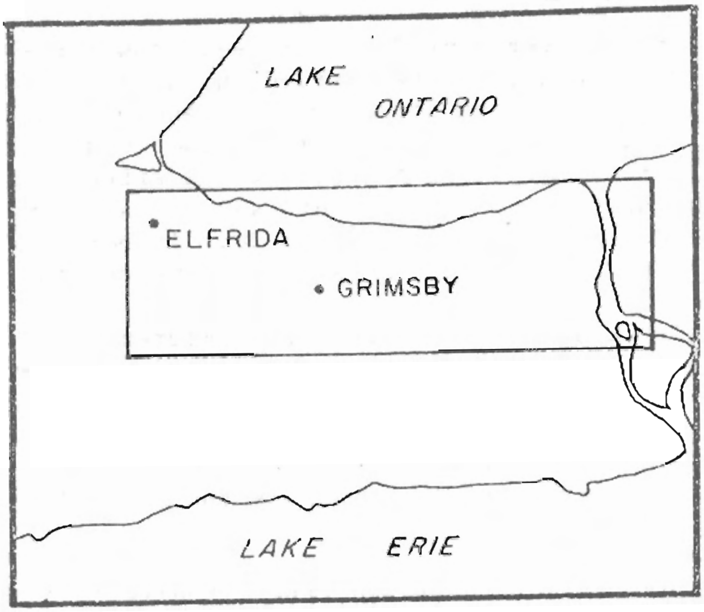

FIGURE 3. Locations of the Elfrida and Grimsby test areas in the Niagara Peninsula. High altitude aerial photography covered the area enclosed by the rectangle.

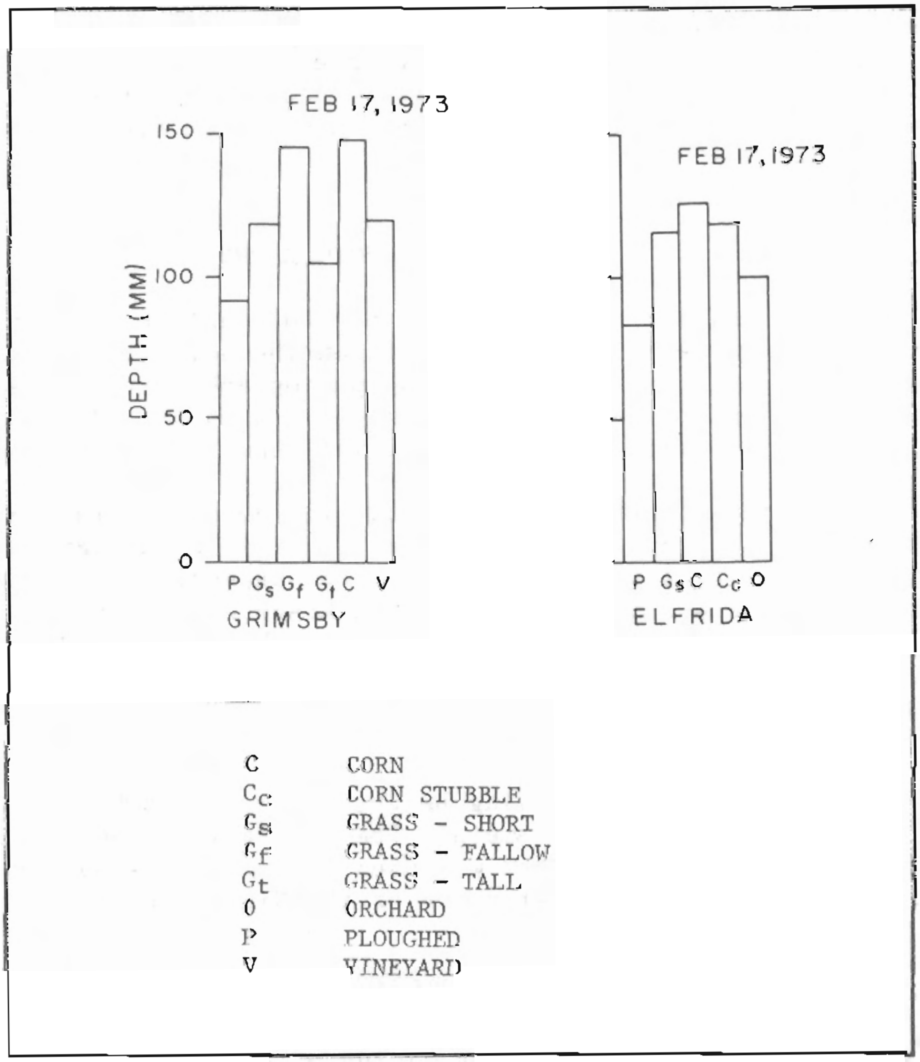

FIGURE 4. Average depth measurements of snow cover in areas of different land use.

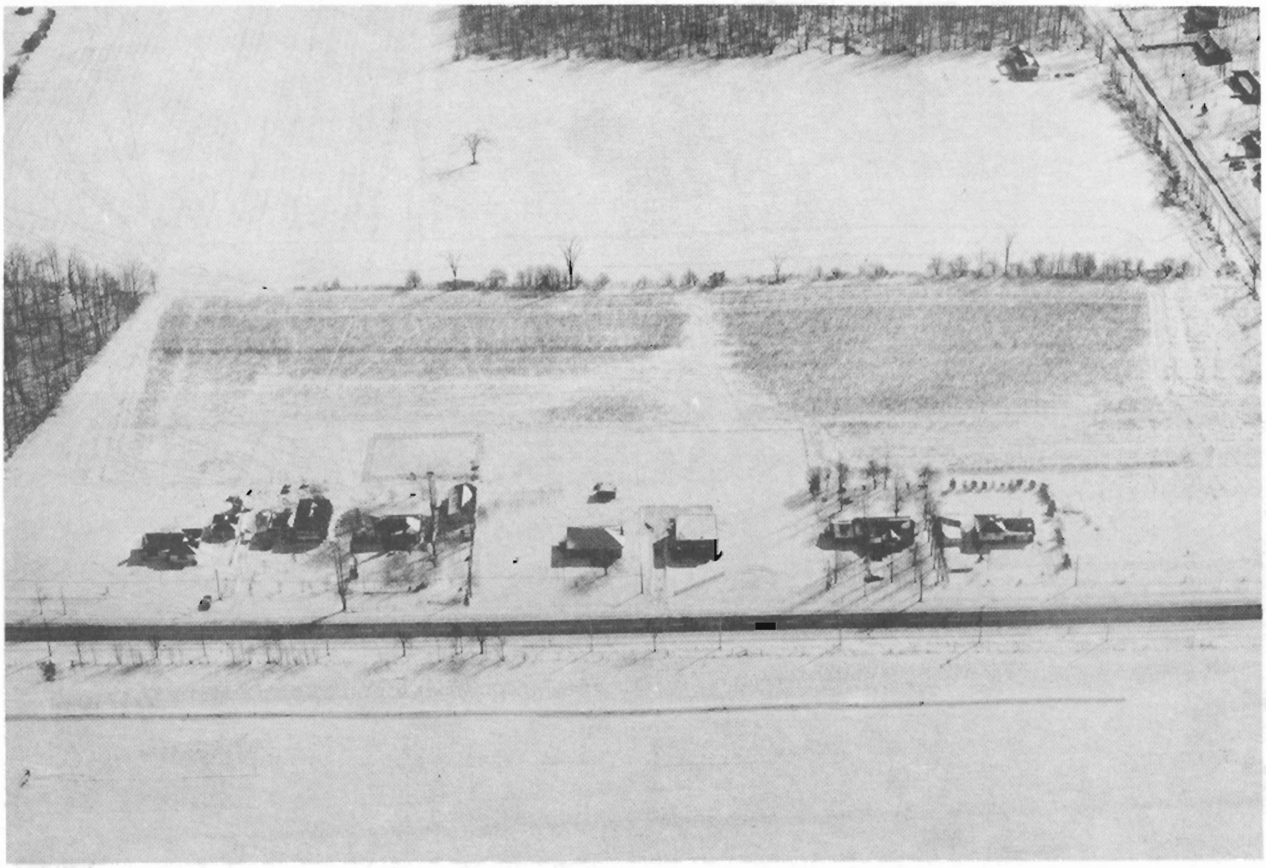

FIGURE 5. Part of the Elfrida test site. The dark tone field in the centre contains uncut corn. Fields in the background contain corn stubble and in the foreground is small grain stubble and low grass.

FIGURE 6. A ploughed field at the Grimsby test site. Note the dunes and the influence of the field boundary on the left. The field on the right contains tall grasses.

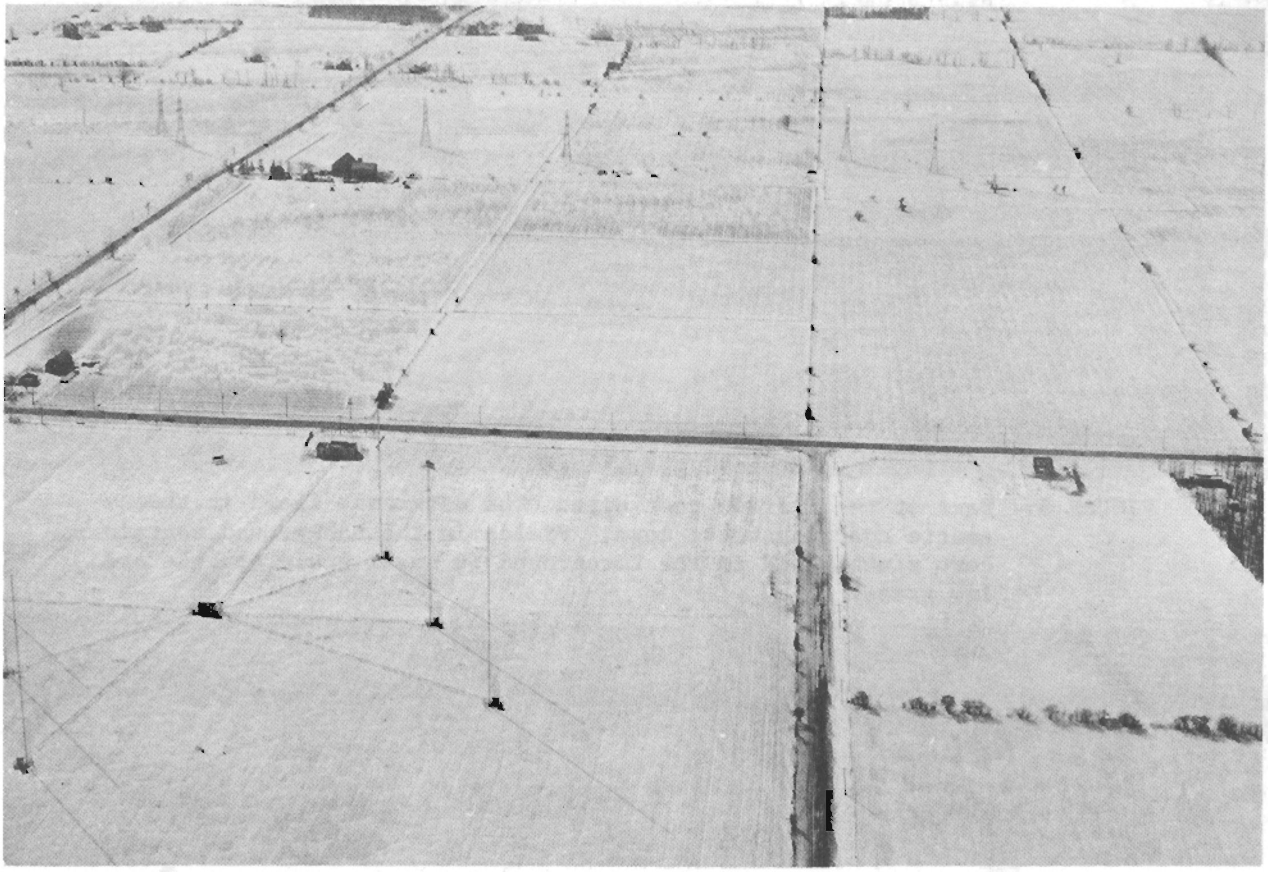

FIGURE 7. General view of the Elfrida test site. Note the tonal differences that occur between the fields. Plough fields produce the darker tones; small grain stubble and low grass result in lighter tones.

photograph contains small grain stubble and a low grass cover that grew during the fall.

The variability of snow distribution over a ploughed field is shown in Figure 6 taken at the Grimsby site. Dunes cover part of the surface, but there are many areas of bare soil with snow occupying the depressions between the furrows. Wind effects on snow distribution produced by the field boundary at the left side of the photograph can be seen as lines of snow accumulation adjacent to the boundary. The field at the left, displaying medium tones and a coarse texture, contains tall grasses in an area of fallow.

An overall impression of tonal variations in different fields is illustrated in Figure 7, taken at the Elfrida site. The fields with darker tones have been ploughed, while the lighter tones are fields containing small grain stubble with low grass.

From these few examples, it can be observed that the land use characteristics, influencing the proportions of snow to vegetation in the different fields, result in different tones, textures and patterns observed on low altitude photography. In addition, it can be seen that the microscale features of snow distribution can be readily identified from the aerial view. Such photography might help to solve some of the problems of "lack of detailed information on the vegetative cover and exposure at snow course sites", reported by Ferguson and Goodison (1974, p. 109).

HIGH ALTITUDE PHOTOGRAPHY

High altitude photography to coincide with a pass of the ERTS-1 satellite was requested through the Airborne Operations Section of the Canada Canada Centre for Remote Sensing. Four 70 mm cameras equipped with 3 inches (76 mm) focal length lenses were used to obtain the photography. The film and filter combinations for three of the cameras were selected to cover the same spectral regions (green, red and infrared) as recorded by Bands 4, 5 and 6 of the ERTS-1 system. The fourth camera contained colour infrared film, but this was overexposed and had to be discarded. Details of the photography obtained are shown in Table I and the area of coverage for the photography is shown in Figure 3.

TABLE I

AERIAL PHOTOGRAPHY OF THE NIAGARA PENINSULA, FEBRUARY 17, 1973

NAPL* Roll Nos.	Frame Nos.	Film	Filter	Spectral Range
BN 2193 IR	#1-111	2424	89B	Near Infrared
BN 2194	#1-111	2405	25A	Red
BN 2195	#1-111	2405	12+58	Green

Altitude: 35,000 feet.
Approx. scale: 1:140,000

Format: 70 mm. f = 3 inches
Index: RS 30M"W"

*National Air Photo Library, Ottawa, Canada.

The photography was examined as 70 mm transparencies using a Bausch and Lomb Zoom 240R stereoscope. All films were of good quality. The two films recording in the visible portion of the spectrum proved to be the most suitable for detecting tonal variations in the snow cover, and of these two the red band gave slightly better detail. Similar observations have been put forward in the literature evaluating ERTS-1 imagery for snow cover mapping (e.g., Barnes and Bowley, 1973).

Analysis of the photography covering the Elfrida and Grimsby sites indicated that in the cultivated areas five different tonal and textural images could be identified. Maps were made to indicate these different images and the results for the Elfrida site are shown in Figure 8. An enlargement of the area that was mapped is shown in Figure 9. (There is some loss of detail due to using a print for the illustration).

A field check was made of the vegetational types in many of the fields in the study areas. It was found that there was a good correspondence between the type of vegetation in the field and the tonal and textural characteristics of the photographic image, as shown in Figure 8. As is to be expected, orchards and ploughed fields (which in parts are bare) had the darkest tones, while fields of short stubble with low grass and also winter wheat imaged the lightest. These observations emphasize the results of the study of the low altitude photography in which the proportions of vegetation to snow were shown to influence the tonal characteristics of the photography.

As snow depth increases, it can be appreciated that in any one area, the overall tones will become lighter as more of the vegetation is buried by the snow. At the scale of the high altitude photography, the image density variations are seen in individual fields. On ERTS-1 imagery, however, integration of ground characteristics occurs and individual fields cannot be observed, but the results of the high altitude analysis suggest that tonal variations indicating changes in snow depth should be recorded by the ERTS-1 imagery.

ERTS-1 IMAGERY: FEBRUARY 17, 1973

Nearly cloud-free ERTS-1 imagery of the Niagara Peninsula, as well as other parts of southern Ontario, was obtained on February 17, the same day on which the photography was flown and field measurements were made. An enlargement of the area covering the Elfrida and Grimsby sites is shown in Figure 10. Comparing the two sites on the ERTS-1 imagery, the Grimsby site appears to be slightly lighter in tone than Elfrida. The same impression is gained from the high altitude photography of the two areas. This is because the photograph of the Elfrida site shows a larger portion of the fields with darker tones than is observed near Grimsby. Whether this relates directly to different proportions of land use types in the two areas, or whether it relates to the differences in depth of snow cover is not known. Overall, however, the field measurements do show a slightly deeper snow cover in the Grimsby area, which could be significant.

Extending the analysis of the ERTS-1 imagery to other portions of southern Ontario, attempts were made to map tonal and textural variations that were observed. Obvious vegetational changes were ignored, but the boundaries produced were still found to correspond more with the physiographic boundaries than with variations in snow depth indicated by the data shown in Figure 2. It is suggested that the reason for this is the different land use patterns that are related to the physiographic regions. This problem illustrates some of the complexities of attempting to map variations in depths of snow cover.

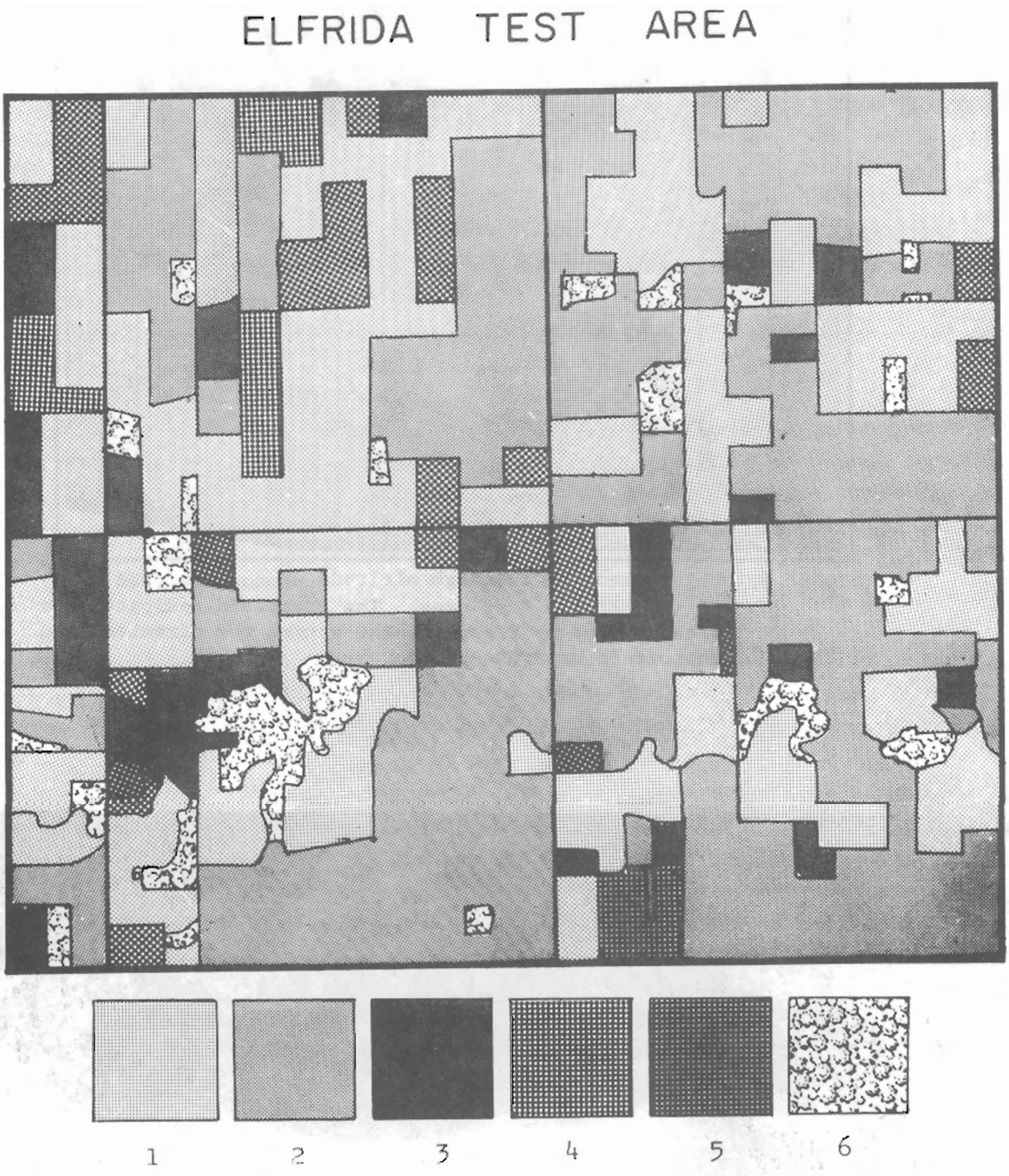

FIGURE 8. The Elfrida test area mapped from high altitude photography. From lighter tones to darker tones the key is 1 - Small grain stubble, winter wheat, low grass; 2 - Permanent pasture, low grass; 3 - Uncut corn; 4 - Ploughed fields; 5 - Orchards; 6 - Woodlots.

FIGURE 9. Enlargement of the high altitude photograph (red band) of the Elfrida test area. The trapezoid indicates the area covered by Figure 5, the arrow, the direction the photograph was taken.

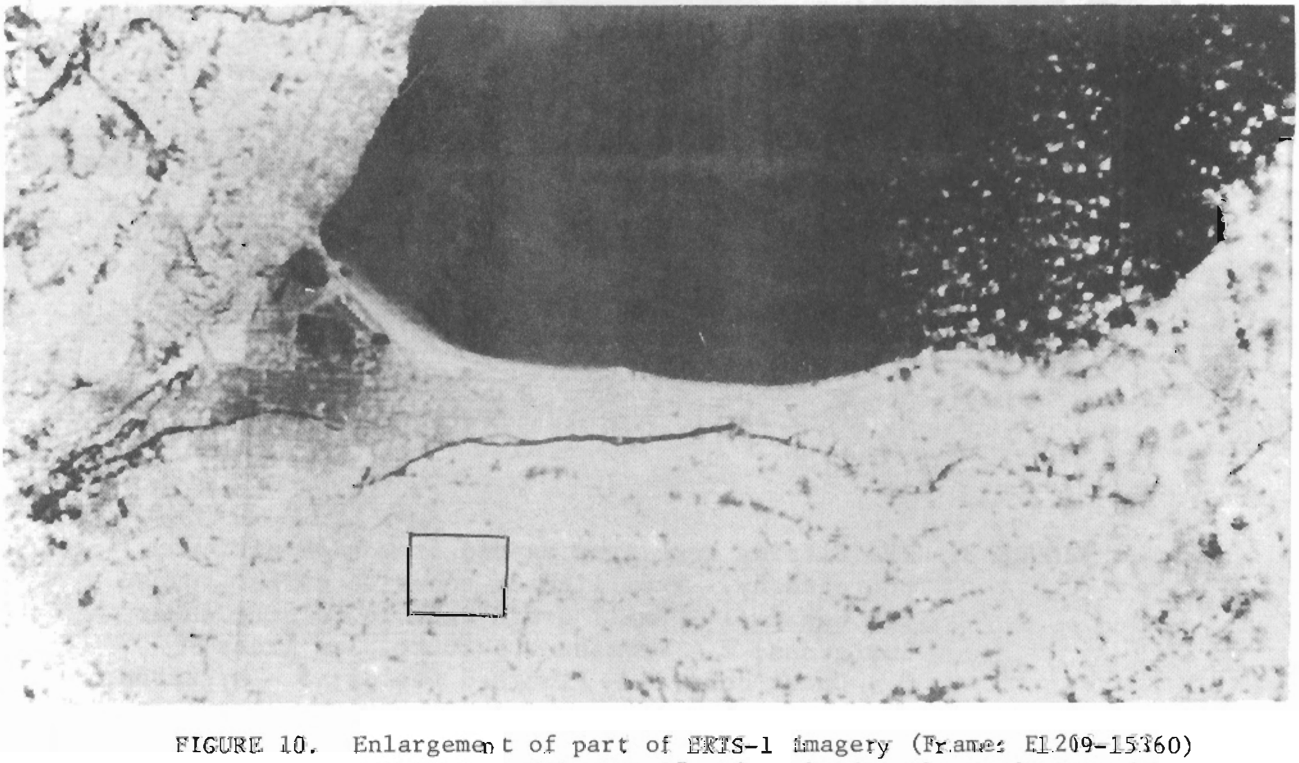

FIGURE 10. Enlargement of part of ERTS-1 imagery (Frame: E1209-15360) recorded on February 17, 1973 showing the study area in the Niagara Peninsula. The square indicates the area covered by Figure 9.

ERTS-1 IMAGERY: JANUARY 31, 1973

On January 31, 1973, ERTS-1 imagery was obtained for the northwestern portion of the study area, bounded by Georgian Bay to the north and Lake Huron to the west. Apart from February 17, this was the only other date on which suitable ERTS-1 imagery was obtained at the same time as ground data were recorded by the Ontario Ministry of Natural Resources. The ground data were collected over the period January 31 to February 2, most of the data for the area covered by the imagery being obtained on February 1.

From the plot of the snow depths produced from the ground data (Figure 2) it would appear that there is little or no snow cover over much of the area shown on the ERTS-1 image. Inspection of the ERTS-1 image, however, presents the appearance of a definite snow cover over the whole area (Figure 11).

In this case, there is an apparent discrepancy between ground information and information from the ERTS-1 imagery. In part this can perhaps be explained by the fact that the snow survey was conducted over a period of three days and snow conditions can change rapidly in that time. Snow flurries occurred on January 29 and 30 with below normal temperatures and highs not reaching freezing point. On February 1 and 2, however, highs were approximately 5°C and rain occurred throughout southern Ontario. Such conditions would lead to rapid depletion of snow cover, which could account for the zero readings at the snow courses. At the same time it must be remembered that snow course readings are taken at point locations and results may not be indicative of wider areas, as pointed out by Ferguson and Goodison (1974).

An illustration of the rapid changes in snow cover which can occur from one day to the next is provided by portions of two ERTS-1 images recorded on successive days (Figure 12). The area shown is centred on Peterborough, Ontario and the dates the images were recorded were April 11 and 12, 1973.

SUMMARY AND CONCLUSIONS

In this study an attempt has been made to look at the different types of information that can be obtained from airborne and spaceborne platforms. As the altitude changes, so the level of detail that is recorded on the photography or imagery changes. It is suggested that a valuable input to a number of hydrologic problems at various spatial scales can be provided by using the most appropriate sensor system.

Low altitude, large scale photography taken from a light aircraft with a hand-held camera can provide an inexpensive method of obtaining information about microscale features of snow distribution and the relationship of snow cover to land uses in an area. The possibility of providing more detailed information about the characteristics of snow courses has already been mentioned.

In the past, very little aerial photography was flown when snow cover was on the ground, the reason being that the photography was usually acquired for mapping purposes. It has been shown that even very small scale high altitude photography is capable of detecting land use variations which correspond with different depths of snow cover. It is suggested that high altitude photography, or even conventional altitude photography, provides a good basis for a detailed view of the characteristics of smaller drainage basins during the winter period.

ERTS-1 imagery presents a regional view of the landscape, clearly indicating the presence or absence of snow cover. Although not demonstrated in this paper, it is possible to delineate the snow line more accurately than interpolating between the point readings provided by snow cover data. The estimation of snow depths,

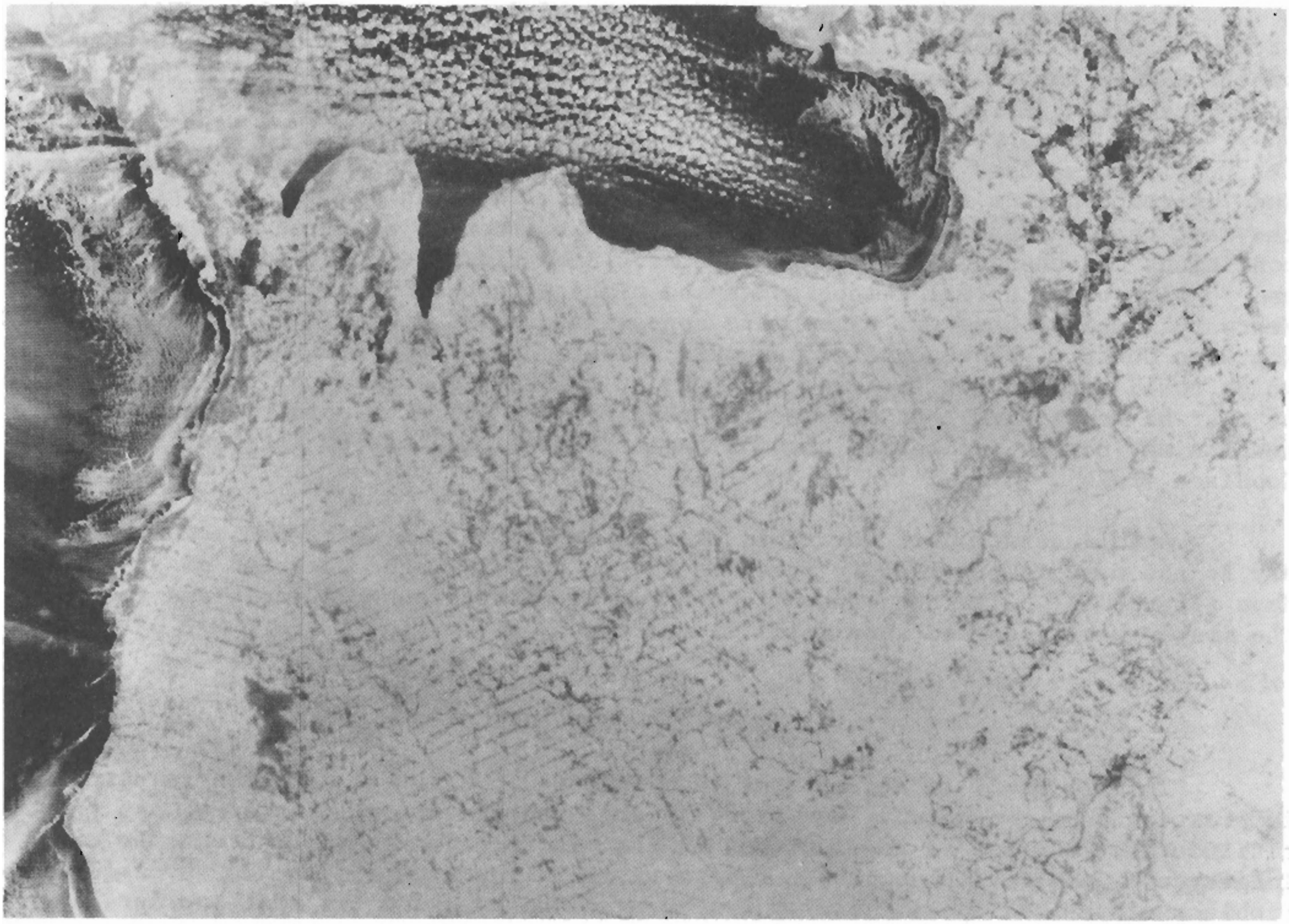

FIGURE 11. Part of ERTS-1 imagery (Frame: E1192-15411) recorded on January 31, 1973. Snow cover is apparent, although not indicated by the snow cover data in Figure 2.

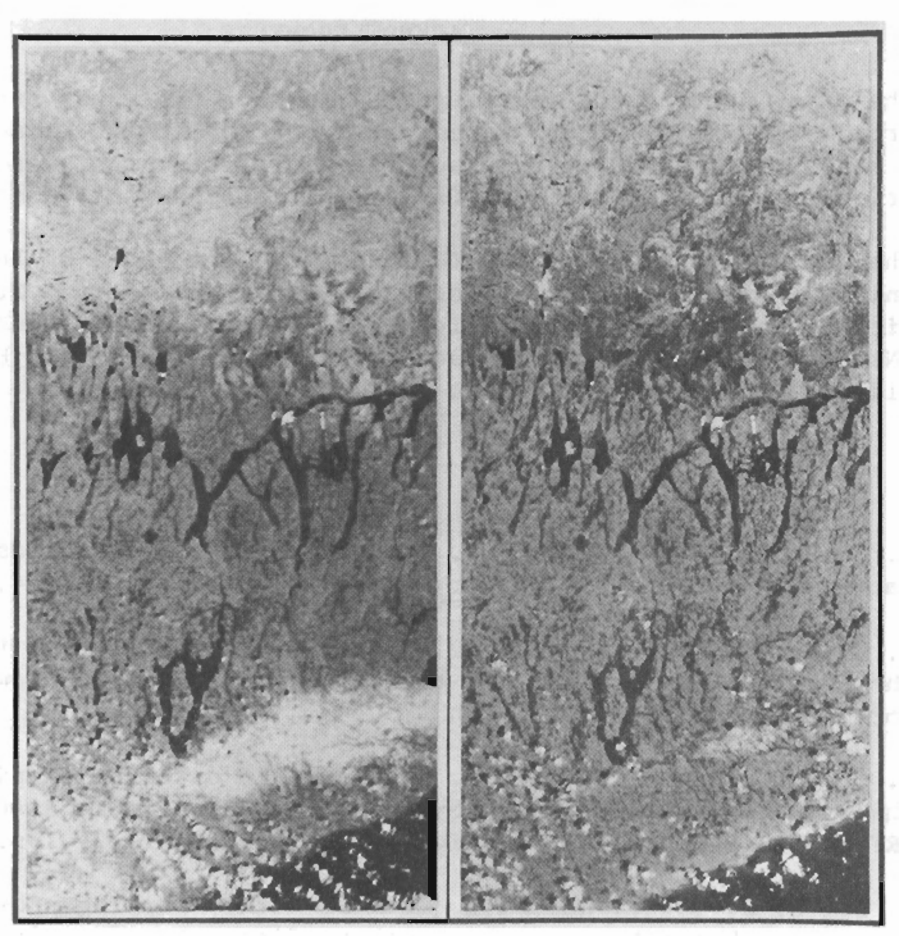

FIGURE 12. Part of ERTS-1 imagery (Frames: E1262-15300 and E1263-15355) recorded in an area near Peterborough, Ontario on April 11 (left) and April 12 (right). Note the changes in snow cover in the Oak Ridges moraine (lower section) and in the Shield areas (upper section).

however, is a difficult task due to the influence of the physiographic/land use characteristics of an area.

It was demonstrated that as the depth of snow increases, the image density observed on the photography decreases. This is due to the relative portions of the snow and vegetation recorded by the sensor. Further studies, on a quantitative basis, to investigate the relationships between image density and depth of snow cover would be valuable.

At the present time, the 18 day cycle of ERTS-1 greatly limits the amount of data on snow cover that can be obtained from space. This virtually precludes the use of ERTS-1 for obtaining information for operational snow mapping, but it is important that techniques for handling the data be devised now. In the future, more satellites, with a greater frequency of coverage and specialized sensors, will become available. It is expected that information obtained from the satellites will provide a valuable aid to the snow hydrologist.

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