

Snow Depth Estimates for Shallow Snowpacks From GOES Visible Imagery

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ABSTRACT

The spatial variation of snow cover depth is an important input to distributed hydrologic models. Meteorological satellites are used to map the areal extent of snow at this resolution but they are not normally used to determine snow cover depth. This paper examines the potential of GOES imagery to map snow cover depth in southern Ontario. GOES visible data for December 29, 1987 and March 1, 1990 are compared with snow course data. Results show the image brightness to be uniform where mean snow depths exceed 20 cm or the snowpack is fresh and correlate well with shallower snow depths when the snowpack is not fresh. This relationship between image brightness and snow depth is also examined in a field scale experiment. Results of the experiment show the relationship between brightness and snow depth resulting from discontinuities in the snowpack at the field scale to be consistent with that observed at the integrated scale of the GOES visible sensor.

INTRODUCTION

The spatial variation of snow cover properties, such as areal coverage, depth, density and water equivalent, is an important data requirement for distributed hydrologic models. Snow surveys provide detailed information on such snow pack properties but their site specific nature and infrequent occurrence limit their potential for use in operational models. In order to provide distributed information characterizing the snow cover of a watershed, snow survey measurements must be extended to regions where no snow survey data are available.

Snow has a high albedo in the visible wavelengths of the electro-magnetic spectrum compared to most natural surface cover. For this reason snowcover area maps were one of the first satellite remote sensing applications and now percent snowcover area estimates on a basin scale from classified NOAA imagery can now be obtained in real-time (Carrol, 1990). This information has proved useful in simulating the snowmelt runoff from alpine snowpacks, where the melt occurs over a long period of time and is strongly related to the percent snow covered area along basin elevation zones (Rango and Martinec, 1981; Rango and van Katwijk, 1990).

In low relief regions such as southern Ontario snowcover maps cannot be binary. The snowpack is often

discontinuous and both distributes and melts in a very heterogeneous fashion. Classification of a basin into distinct snow/no snow regions is difficult and would be of little use in hydrologic modelling of the snowmelt runoff. The snowpack is usually quite heterogeneous at the sub-pixel level, with the percentage of snow covered area and depth of coverage varying according to land cover types and linear snow accumulation zones such as fence lines and ditches (Schroeter and Whitely, 1987). Pixel brightness is therefore an integrated response to high albedo snow and lower albedo bare surface and vegetation cover protruding through the snowpack and will vary from one limit to the other depending on the percent snow covered area in a pixel.

Pixel brightness also appears to contain information about snow depth. Studies by Kung et.al. (1964), McGinnis et.al.(1975) indicate that the integrated surface albedo is related to average snow depth, with brightness increasing with depth to a limiting value once the snow depth reaches 20-30 centimetres (Figure 1 and Figure 2).

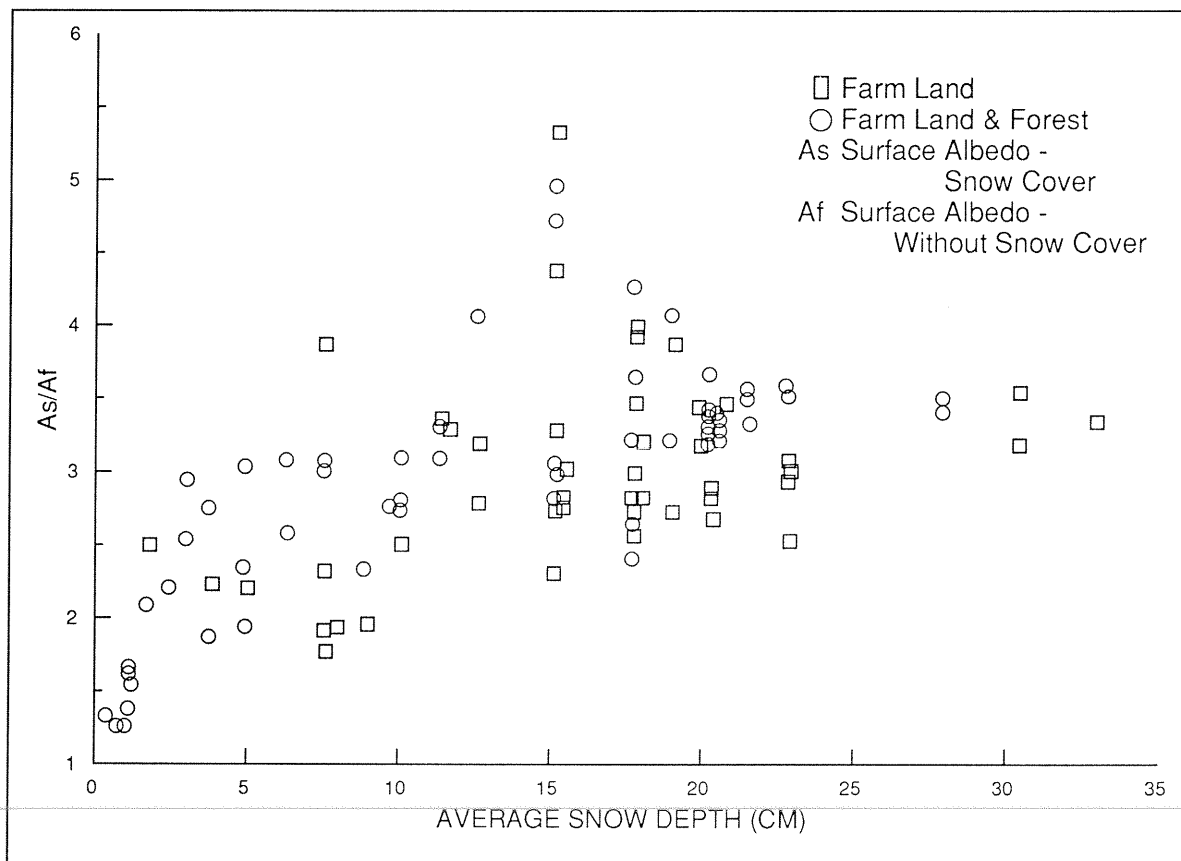


Figure 1 Surface albedo related to depth of ground snow cover (after Kung et.al., 1964)

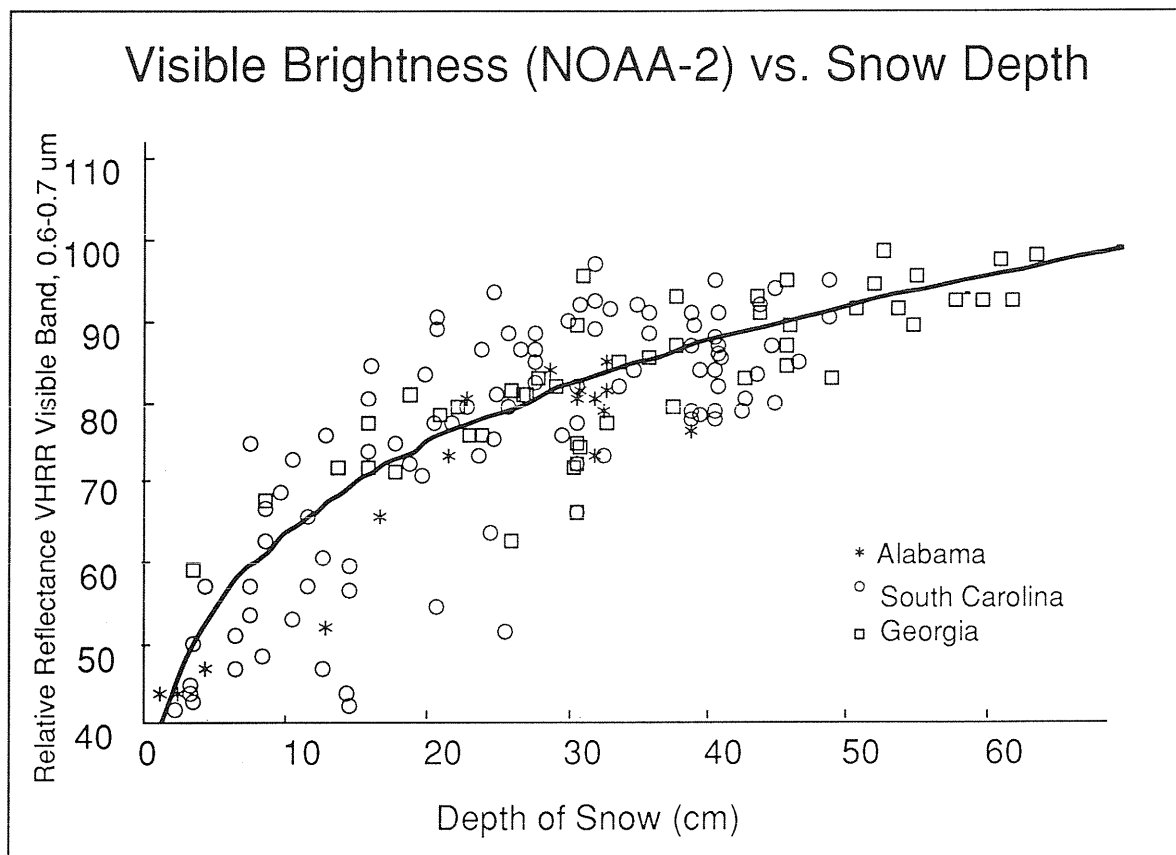


Figure 2 Visible Brightness (NOAA 2) vs. Snow Depth (after McGinnis et.al, 1975)

The occurrence of the relationship is likely to be the result of two phenomena:

- 1) as the snow cover depth gradually increases, brightness increases as more and more vegetation is covered. Eventually the vegetation is covered completely and no increase in brightness is observed as depth of snow continues to increase.
- 2) the snowcover fills in depressions on the surface first, with brightness increasing as bare areas are covered until the average depth level is reached where the field is completely covered and no increase in brightness occurs with increasing depth.

Donald et.al. (1990) found a similar relationship for southern Ontario. The purpose of this paper is demonstrate that this relationship is consistent with the field scale behaviour of the snowpack in the region. The brightness-depth relationship and its dependence on snow covered-area is examined in a detailed field study of snow covered area vs. average snow depth to show the relationship that exists between brightness, snow depth and snow covered area at the field scale.

GOES imagery is used in this study because images can be acquired on a daily basis (provided cloud-free conditions exist) at adequate spatial resolution for use in distributed hydrologic modelling of large watersheds.

FIELD SCALE RELATIONSHIP BETWEEN BRIGHTNESS AND AVERAGE DEPTH

Site Location

A field study was conducted from January through February, 1991 to examine the relationship that exists at the satellite scale between brightness and average snow depth. The parameter of percent snow covered area (SCA) is used in this study to represent the brightness that would be observed remotely with the rationale that if the albedo of the snow and soil are assumed constant, there will be a linear relationship between snow covered area and brightness. The site used in the study is located on farmland owned by the University of Waterloo, adjacent to the existing campus as shown in Figure 3. The land is cultivated for corn. The study site was ploughed in late November 1990, leaving the fields in a very rough ploughed condition with little to no exposed corn stubble. The ploughed furrows ran in approximately east-west direction, with distance between the peaks of approximately one metre and furrow depths of 10 to 20 centimetres. An open field was chosen for the study because open fields comprise the bulk of the land cover of watersheds in southern Ontario. Also, ploughed fields display the greatest internal heterogeneity in snow cover and visible band satellite sensors clearly "see" the snowpack in open areas, because the forest canopy masks the snow cover in wooded areas.

The snowpack depth measurements were established along four lines, radiating from a hydro pole in the middle of the ploughed field. Measurements were taken in north-south and northwest-southeast directions in order to cut across the furrows that existed in the field prior to snowfall.

Field Roughness

The field roughness along each of the four snow survey lines was measured in December 1990, before the onset of snow cover, to provide a physical basis for evaluating the distribution of the snowpack throughout the winter. The survey was carried out using a tape measure and ruler. To establish the field roughness along each of the survey lines, one end of the survey tape was attached to the hydro pole and the other was held one metre above the ground approximately 20 metres from the hydro pole. A metal ruler was then used to measure the distance from the tape to the top of the ground surface at 10 cm intervals along each of the four lines. This interval was chosen because the small-scale roughness of the furrows was of interest in this experiment and the redistribution of the snowpack is mainly influenced by the small-scale in the field.

The general trend and measuring tape sag were removed from the profile as follows:

- 1) the readings were averaged for each one metre interval along the line. This distance is the approximate furrow width and is an appropriate scale for evaluating the micro-roughness.
- 2) These averages were subtracted from individual field heights within each 1-metre interval to yield a net height of the micro-topography along the profile.

A typical corrected line profile, is shown in Figure 4.

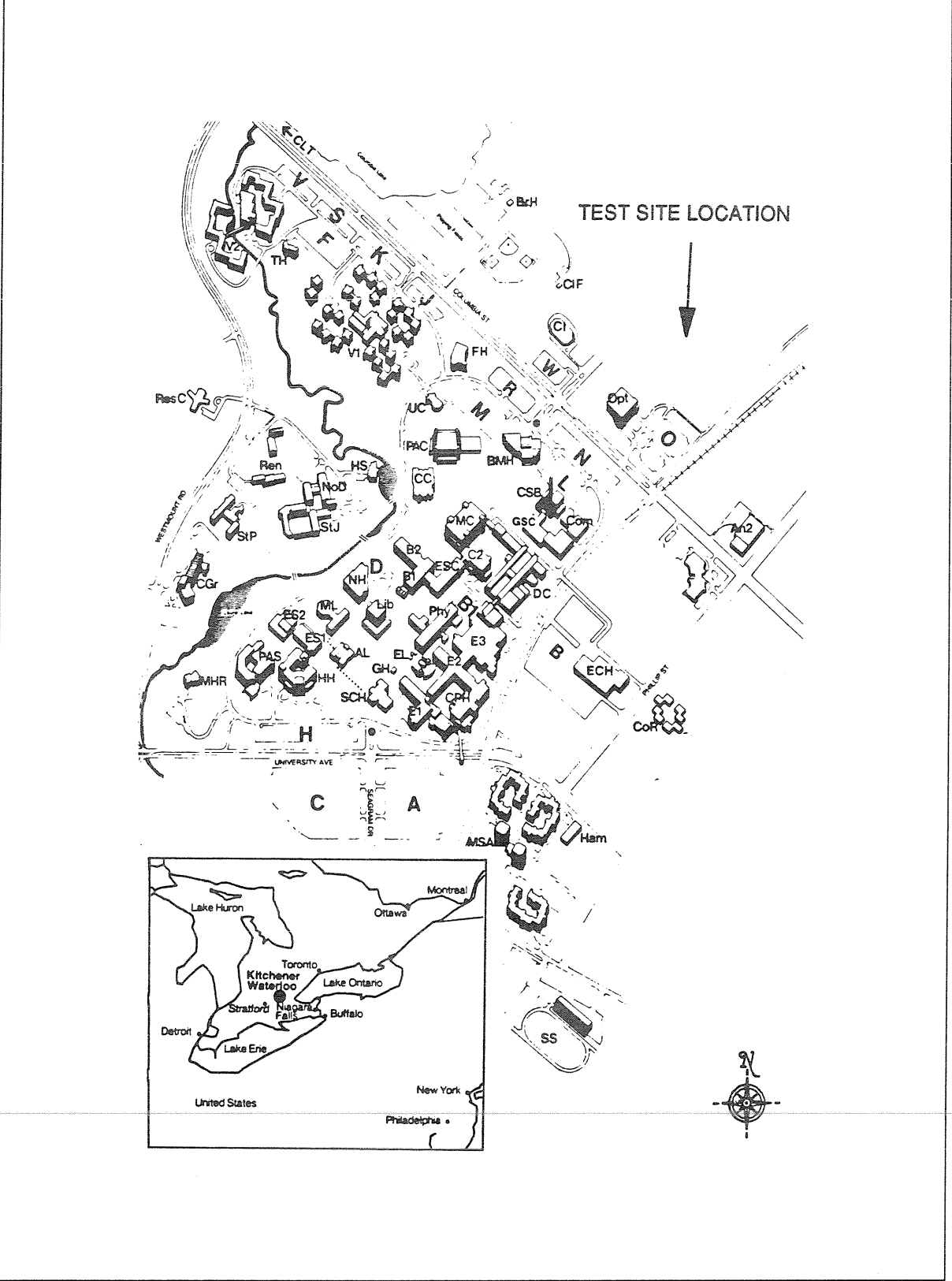


Figure 3 Field Study Site Location

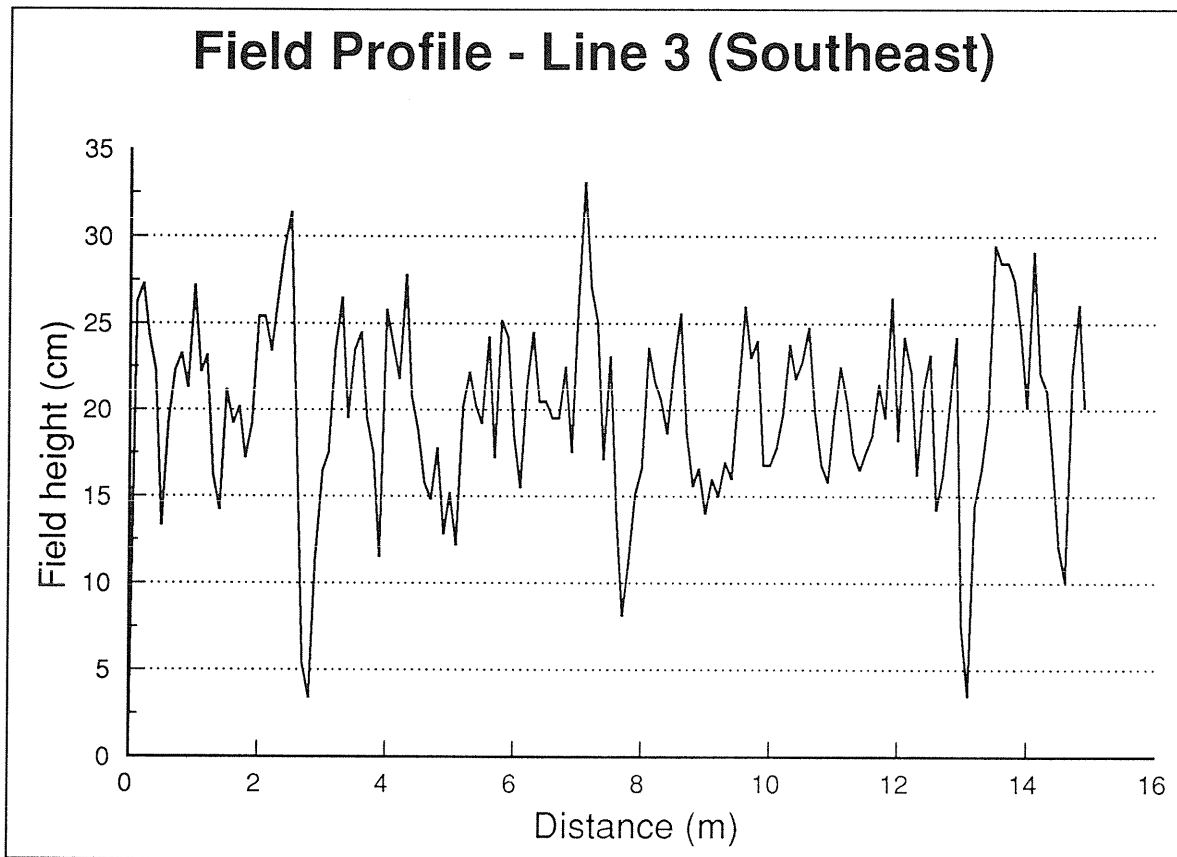


Figure 4 Corrected Profile - Ploughed Field

Snow Depth Measurements

Measurements along each of the four survey lines were taken on 13 different dates, at approximately three-day intervals, from January 4 through February 6, 1991. During this period the snow cover went through a cycle that started as bare field at the beginning of January, oscillated between 90-100% snow cover in the following 3-4 weeks and then returned to almost bare field during a mid-winter thaw in early February.

Snow depth profiles along each of the four lines were surveyed in the following manner. One end of the measuring tape was attached to the centre hydro pole and then the tape was laid out onto the ground to a distance of approximately 20 metres. Starting far enough from the pole to be clear of local drifting effects (3 to 7 metres) snow depth readings were taken every 10 centimetres for a distance of 15 metres. The exact locations for the readings were not repeatable from day to day due to the roughness of the field. However, the important characteristics used in the analysis are average snow depth and percent cover, which can easily be inferred from the 150 depth readings taken on each line.

Snow Cover Relationships

To demonstrate the relationship between percent snowcover (i.e. brightness) and average snow depth for the

ploughed field, the percent snow cover was calculated, for each day on each line, by counting the number of readings which were not zero and dividing by the total number of readings. The readings were taken every 10 cm, thus any significant bare area along the line was easily identified. The average depth was calculated as the average of the 150 readings taken along each line, including the zero-depth readings. The resulting percent snow cover to average snow depth relationship is shown in Figure 5.

In the remote sensing studies of Kung et.al. (1964) and McGinnis et.al. (1975), brightness increased with increasing snow depth until it levelled off at some value when presumably all the depressions in the surface were filled with snow. Figure 5 shows the same basic relationship with the percent snow cover increasing until a depth of about 15 cm when the percent snow cover reaches 100%. The four outliers in the diagram, which appear to have an abnormally high value of percent snow cover, were all measured on January 4, 1991. On this date, little redistribution of the snow had taken place before the readings were taken, resulting in a high percent snow cover for a shallow snow depth.

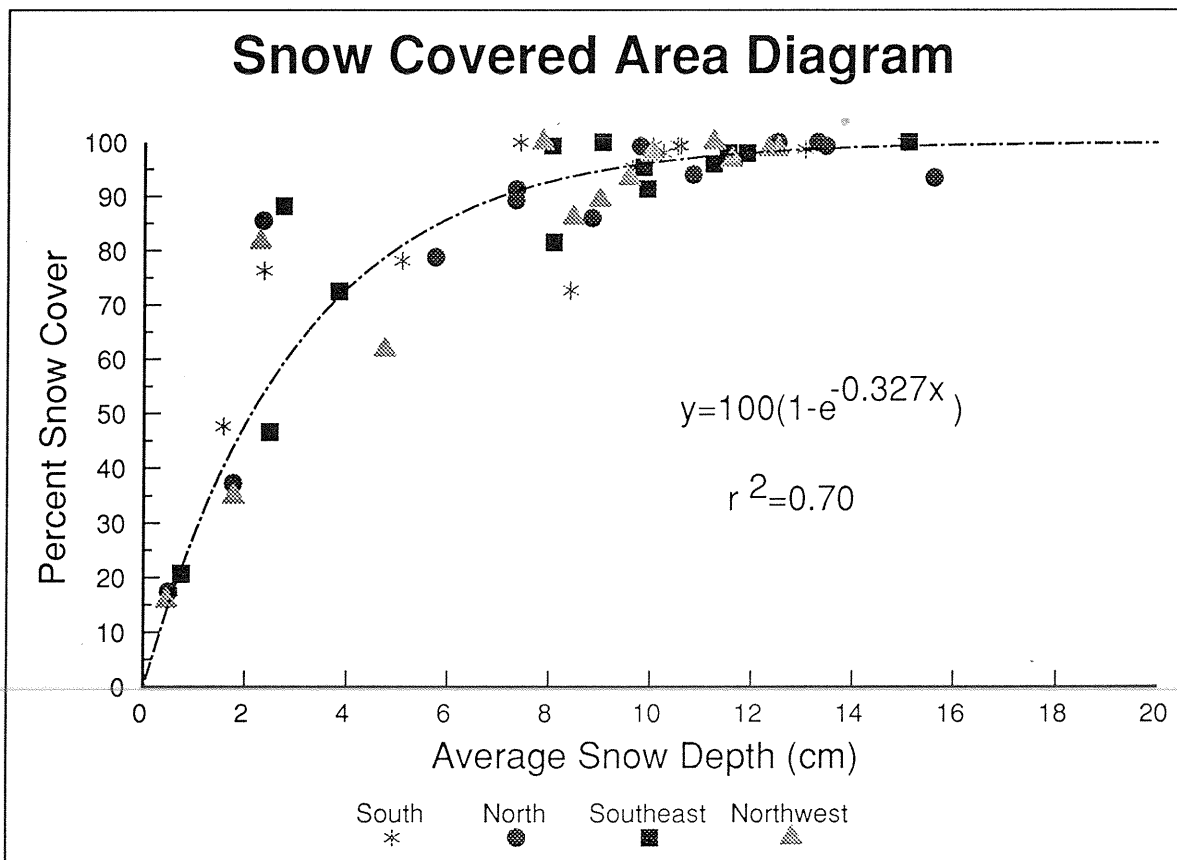


Figure 5 Measured Percent Snow Covered Area vs. Average Depth Relationship
University of Waterloo Ploughed Field

To relate the observed profile in Figure 5 to field topography, a computer simulation was conducted to model the filling of the depressions in the observed field profile in a manner that closely reflects the way in which the snow redistributes after a snowfall. For a given snowfall, there is a maximum depth, h_{\max} , to which depressions tend to fill. In the model all the depressions in the actual field profiles are filled with snow simultaneously to this height. However, if the depression depth is less than the maximum fill depth, then the depression is only filled to the depression height (i.e. snow is assumed to be scoured or melted to meet the peaks of the field profile). In the algorithm, the depressions are filled starting at the highest depression and proceeding downward. If a depression at a higher elevation has already been filled as the algorithm proceeds to lower depressions, then the lower depression can fill it further. Example results of the filling procedure are shown in Figure 6 for maximum filling depths of 4, 8 and 14 cm with their respective average snow depths and percent snow covered area.

Application of the coverage program to the actual field profiles yields the result shown in Figure 7. This figure indicates that the theoretical depression filling routine describes both the observed and regressed (from Figure 5) percent snow cover versus snow depth very well. This is significant because the filling routine was used to calculate the percent snow covered area independently of the observed field results and was based only on the actual field profiles and a hypothesis regarding the filling of depressions.

It is also apparent, from the set of outliers on January 4, 1991, that the average snow depth to snowcover relationship is only valid when the snow has redistributed according to the pattern characteristic of the field.

SATELLITE REMOTE SENSING OF AVERAGE SNOW PACK DEPTH

The relationship between image brightness and average snowpack depth for southern Ontario was demonstrated by Donald et.al. (1990) using GOES visible imagery from December 29, 1987 and snow course data. The resulting relationship, reproduced in Figure 8, shows that the brightness indicated by the satellite digital number (DN) increases with average snowpack depth as measured in the snow courses, levelling out in the 15 to 20 centimetre range. The shape of the relationship is the same as found by Kung et.al. (1964) and McGinnis et.al (1975) and is very similar to that obtained in the field experiment as shown in Figure 5, exhibiting higher scatter and greater asymptotic depth. The similarity in the field and satellite relationships is not surprising as southern Ontario is primarily agricultural with 70-90 percent of the land cover being non-forested (Tao, 1988).

The satellite relationship (Figure 8) is derived from satellite brightness on a specific day at various snow course locations in southern Ontario. This results in a greater degree of scatter in the relationship than seen for the field scale experiments (Figure 5) because of the varying percentages of topographical features such as land cover and slope that occur at the scale of the satellite pixel. The higher asymptotic depth in the satellite relationship is likely a result of most snow courses in southern Ontario being in forested areas, which normally have deeper snowpacks than open fields.

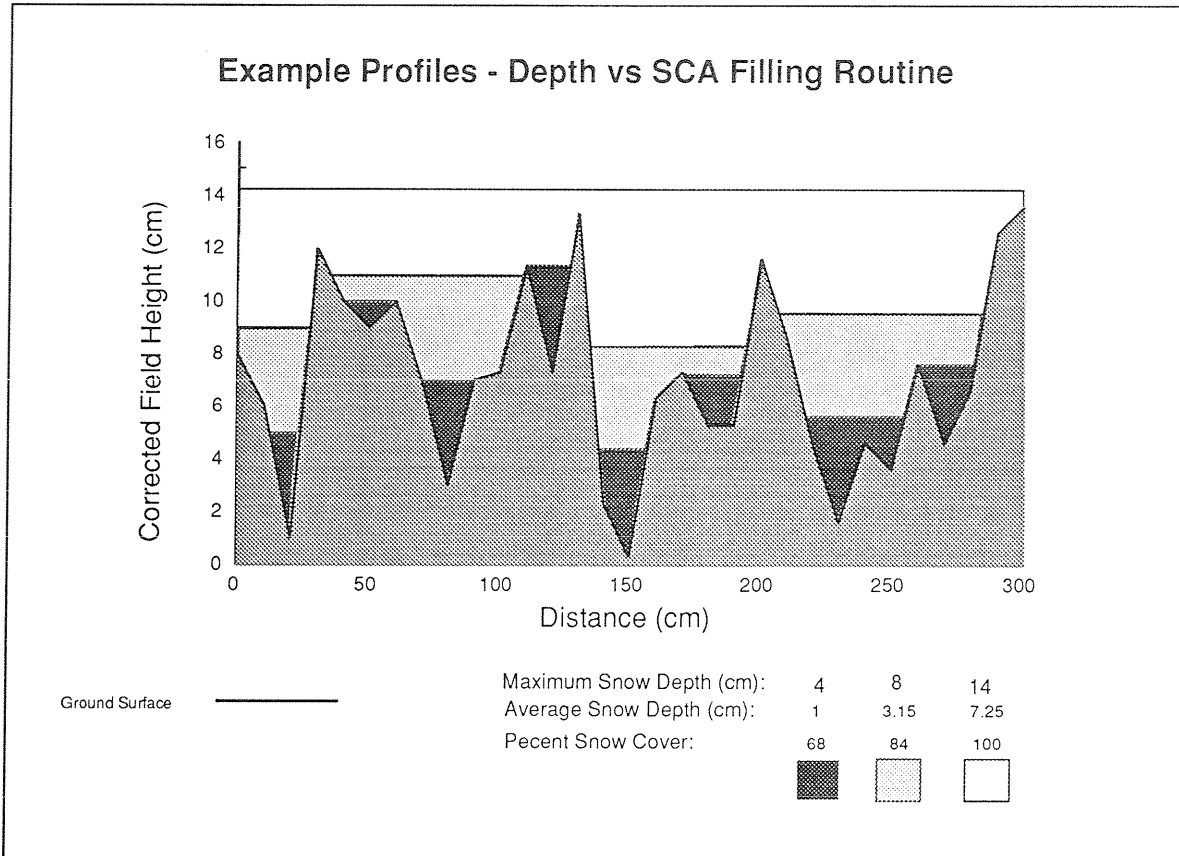


Figure 6 Example Filling Depths for Snow Covered Area Estimation Program

THE EFFECT OF FRESH SNOW

A second GOES image, dated 18:00 GMT, March 1, 1990, was acquired over southern Ontario to further examine the visible brightness vs depth relationship. Satellites in the GOES series follow a geosynchronous orbit, sampling in two operational bands: visible (0.55 μ m to 0.75 μ m) and thermal infrared (9.7 μ m to 12.8 μ m). The visible band of this image has a ground resolution of approximately 1 kilometre by 1 kilometre at the latitude of the study region. The major contrast with the December 29, 1987 image is that this is taken after a fresh snow-fall.

Radiometric correction of the images, for comparison with the digital image of December 29, 1987, was made using the maximum snow reflectance and Lake Ontario as linear transformation references. The resulting image (Figure 9) is clear and shows an extensive snowpack covering most of southern Ontario. Snow survey information was obtained for Mar. 1, 1990 (Dept. of Transport, 1990) at 29 locations in the region of the image, as shown by the boxes on Figure 9. The snow courses report average depth and average snow water equivalent on a bi-weekly basis throughout the winter season.

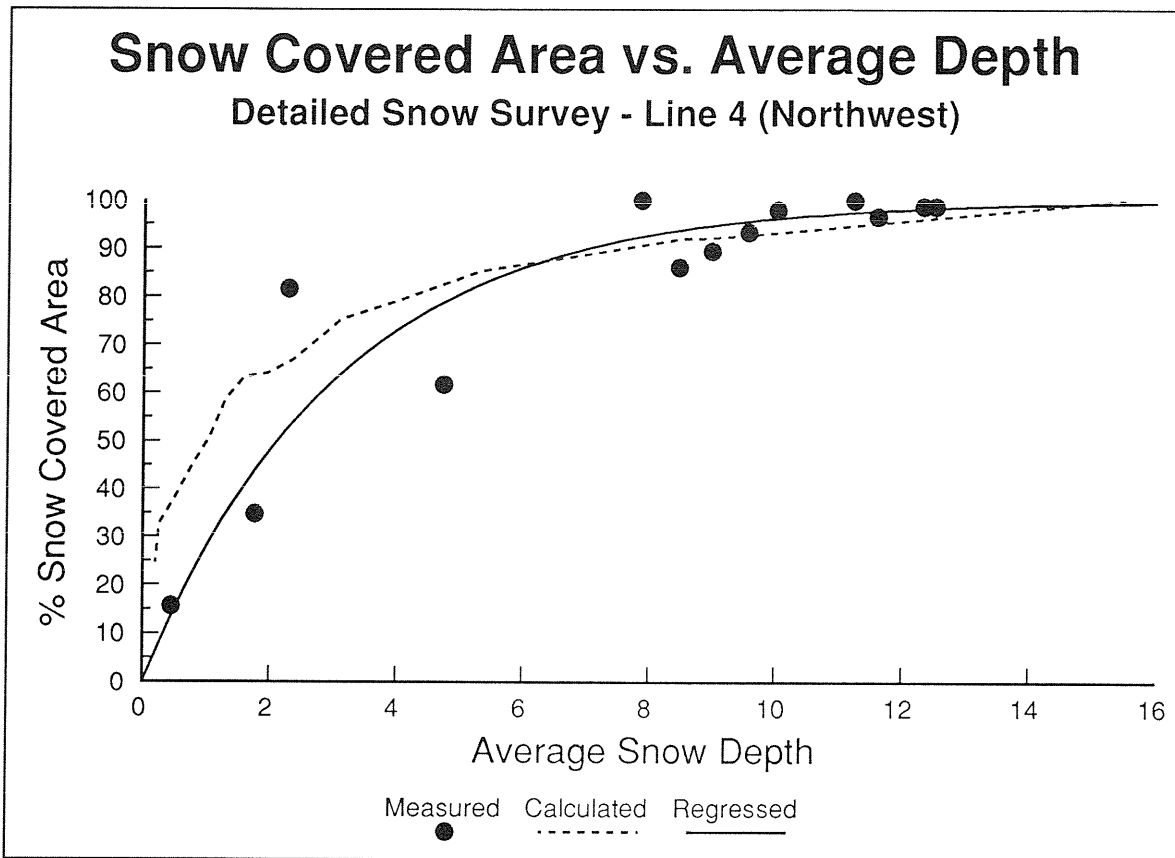


Figure 7 Comparison of Measured to Calculated Snow Covered Area vs Snow Depth

The corrected image brightness vs average snow depth relationship for March 1, 1990 is displayed along with the December 31, 1987 relationship in Figure 8. It is clear in Figure 8 that the brightness-depth relationship developed for the 1987 image does not hold for the 1990 image. This is due to a fresh snowpack resulting from a series of snowfalls on February 28 and 29, and the lack of snowpack redistribution before the date the image was taken. This is also consistent with Figure 5, in which the points that are significantly different from the regressed relationship corresponded to fresh snowfalls. This problem was also encountered by Kung et.al (1964), who consequently designed their data acquisition program to eliminate or reduce the effects of fresh snow by acquiring their data only after the snowpack was a few days old.

CONCLUSIONS

Operational hydrologic modelling of snowmelt events requires real-time input of the snow cover parameters. The results of this study indicate that a relationship exists between reflectance values measured from meteorological satellites and average snow depth in southern Ontario, perhaps to an average snow pack depth of 20 cm. Snowpacks with depths of this order are very important in southern Ontario, as packs are shallow, discontinuous and ephemeral in nature. The results of the field study confirm that the relationship is consistent with snow pack

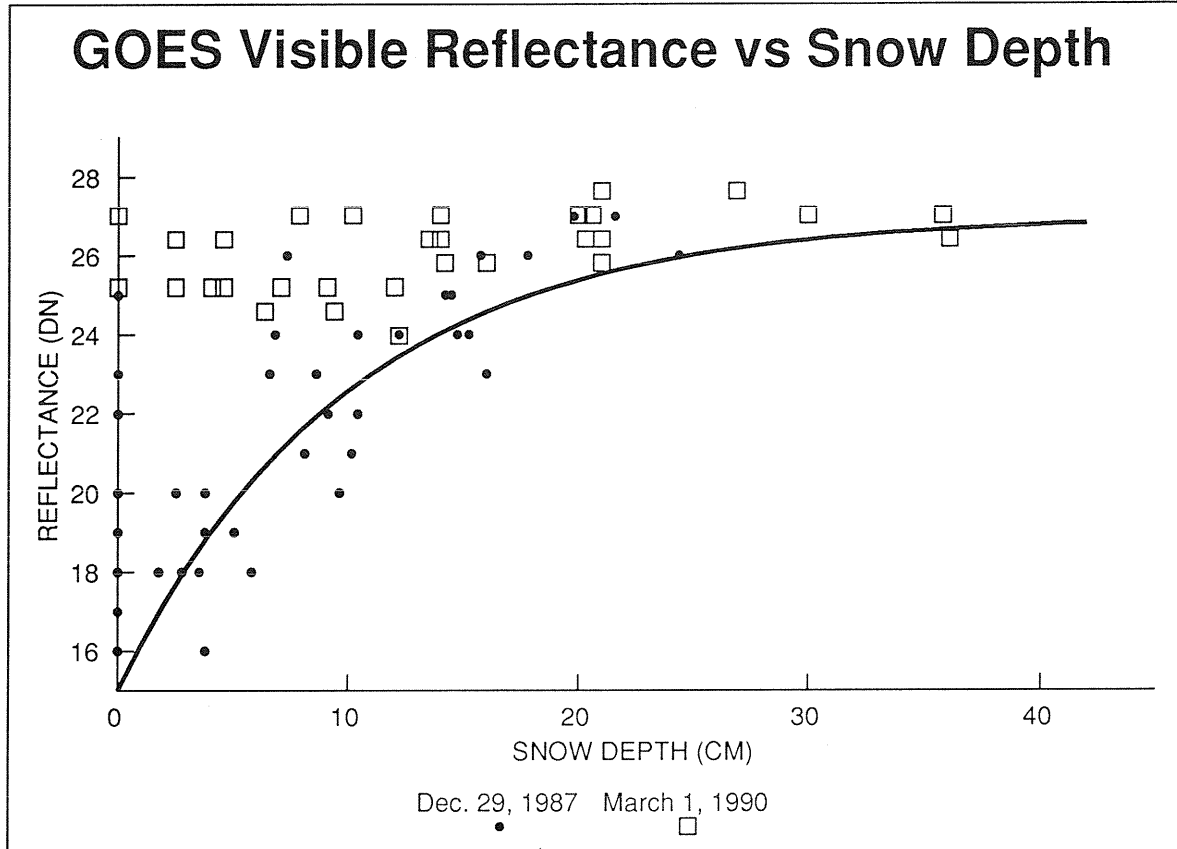


Figure 8 GOES Visible Reflectance vs. Average Snow Course Depth
December 29, 1987 and March 1, 1990

redistribution patterns and therefore brightness can be related to both snow covered area and depth. The brightness vs. depth relationship is only valid if the snow has redistributed through wind or melt processes (i.e. if snow depth is a valid index of snow covered area).

The close agreement between the observed and calculated percent snow cover vs average depth relationship, as well as the fact that the shape of the curve closely approximates that observed in the remotely-sensed brightness vs snow depth relationship, provides a physical basis for the shape of the relationships observed in the literature that to date has only been speculative. The potential application of the relationships in deriving snow cover area maps and perhaps even snow depth and water equivalent maps for use as input to distributed snowmelt runoff models should improve operational snowmelt hydrology, as it already has for alpine snowmelt hydrology, by providing daily information regarding the snow pack on a basin scale.

The operational difficulty in the application of satellite visible brightness to snow depth or snow covered area relationship in southern Ontario is the necessity of cloud-free coverage. Significant snowmelt events are often accompanied by rain or cloud coverage for periods of days, inhibiting the utility of the meteorological satellite coverage. However, even one or two images in the course of a melt, especially if the timing of the standard snow course surveys is poor, could aid in the initialization or updating of a snowmelt model.

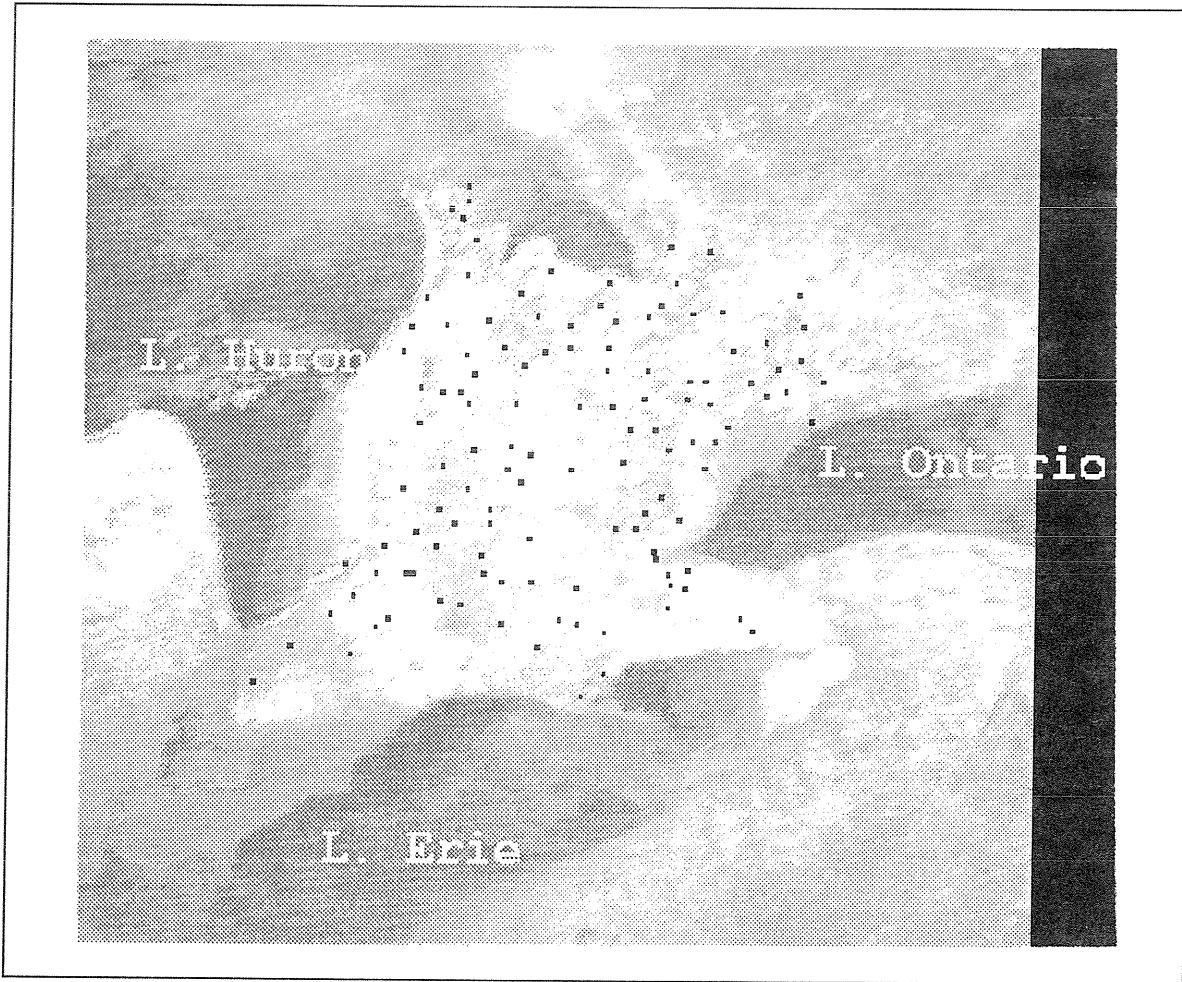


Figure 9 GOES Visible Image of Southern Ontario
March 1, 1990

The concepts and techniques presented in this paper can be applied to any sensor that is sensitive to changes in the areal coverage of the snowpack. For example, active microwave sensors can detect wet snow but have not shown the ability to map snowpack properties such as depth directly from backscatter (Bernier, 1987). Therefore, during the melt period at least, the return signal for microwave imagery should be a function of the areal distribution of the snowpack at a sub-pixel level. This distribution could then be used as an indirect measure of snow depth.

ACKNOWLEDGEMENTS

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