The Usefulness of Standard Hydrometeorological Data for Snowmelt Calculations

by

H.R. Whiteley, W.T. Dickinson, & T. Core
Assistant Professor, Associate Professor, & Research Associate.
School of Engineering, University of Guelph, Guelph, Ontario.

Introduction

The importance of the snowmelt contribution to streamflow and groundwater recharge is well established for regions with significant winter snow. Equally well known is the difficulty of describing analytically the ablation of shallow and intermittent snow covers which occur over considerable areas in the southern part of Canada and adjacent regions of the United States.

Modelling of the snowmelt process can be divided into two distinct parts: (i) estimation of snow ablation at each point as a function of time, and (ii) routing of the various melt inputs through a watershed model to an outlet point of interest. In the estimation of snow ablation, "point" values are generally used to represent areas and time periods for which important variables are taken as constant. Routing of the "point" or "area" melt values to an outlet point takes into account transmission and storage effects experienced by the meltwater in the flow regime.

The first part of this modelling is considered here, with attention given to the usefulness of some standard hydrometeorological data for the estimation of snowmelt. Sample data from the Blue Springs I.H.D. Basin, located in Southern Ontario near Guelph, have been utilized. The basin and associated data networks have been described previously by Dickinson and Whiteley (1970, 1973).

Areal Variability of the Snowpack

For the purpose of determining the occurrence of ablation over various portions of a watershed, it is essential to be able to describe the areal variability of the snowpack. Where is the snow? What is the pattern of snow density and depth over the basin?

To date the most effective manner of describing snow distribution has been the use of representative snow surveys and detailed snow survey grids, as discussed by McKay (1970) and Golding (1970). Snow courses may be shown to be representative of the basin pattern by means of aerial photo and interpretive techniques. They may also be compared to the results of more detailed snow survey grids performed as spot checks. Once a set of snow courses has been confirmed to be representative, the measurements may be used to ascertain the areal pattern of snow water in a basin. Remote sensing data from satellites can be expected to be an increasingly important source of information on both the areal distribution of the snow and the physical properties of the pack.

Dickinson and Whiteley (1971) have described patterns of snow cover which occur in open and cedar bush areas on the Blue Springs Basin. Examples of the distributions are shown in Figures 1 and 2. It may be noted that the distribution for open conditions is considerably less uniform than that for the forested regions. Such a distribution results in the rapid development of large regions devoid of snow early in the ablation period, and ever decreasing areas contributing to melt runoff.

Variables Significant to Melt

Not only are the snowpack characteristics and their distribution over an area required for modelling the snowmelt process, but also the hydrometeorological variables and their areal and temporal patterns must be known. Although the physics of ablation is not fully understood, and explicit expressions noted in the literature for describing ablation may vary, the prime hydrometeorological variables affecting melt have generally been accepted. They include net radiation, air temperature, vapour pressure of the air, saturated vapour pressure, wind speed, and rainfall. One manner in which a melt model

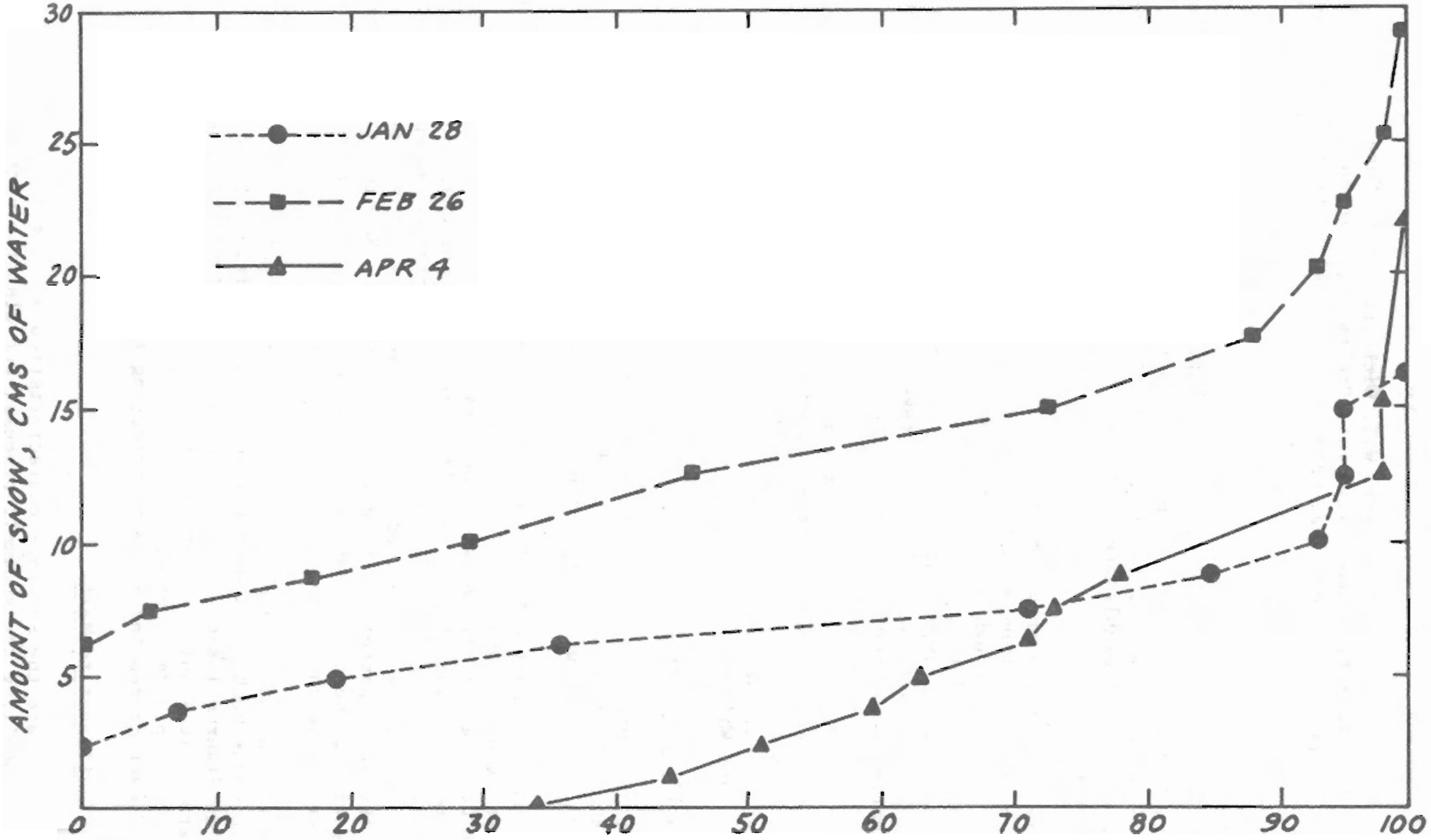


FIG. 1- PERCENTAGE OF AREA WITH SNOW COVER LESS THAN AMOUNT INDICATED
AREAL DISTRIBUTION OF SNOW IN OPEN AREAS, BLUE SPRINGS BASIN, 1971

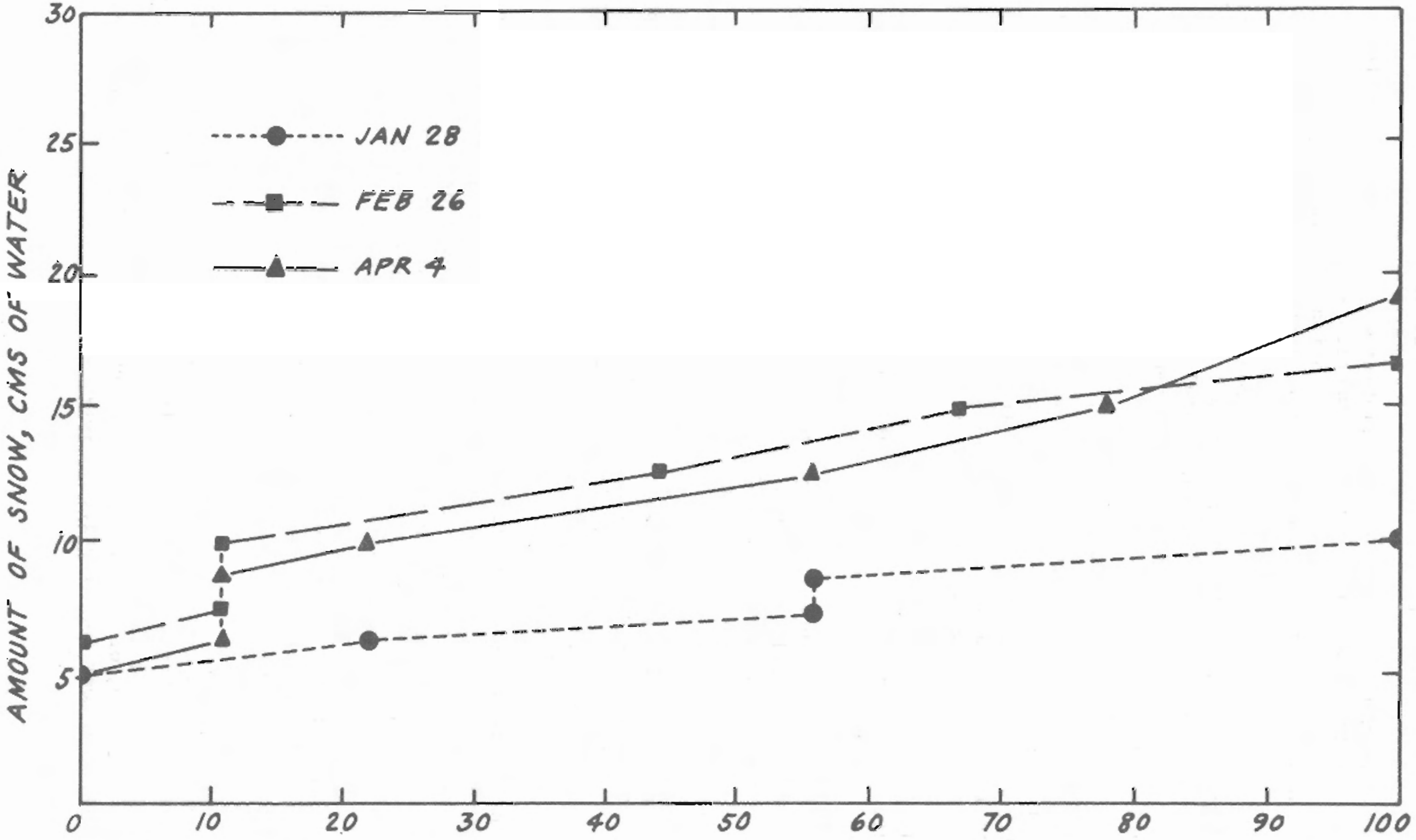


FIG. 2 – PERCENTAGE OF AREA WITH SNOW COVER LESS THAN AMOUNT INDICATED
AREAL DISTRIBUTION OF SNOW IN FORESTED AREAS, BLUE SPRINGS BASIN, 1971

can be constructed on the basis of these variables has been developed by Provart (1970) and is presented in Figure 3. Such a model is useful for evaluating ablation due to melt and vapour transfer (ie. evaporation, sublimation, or condensation).

Therefore, the essential meteorological variables which must be specified for a point in space and a specific time period are air temperature, relative humidity, wind speed, precipitation, and net radiation. A brief discussion is offered below on the first four variables, and net radiation is considered at more length.

(a) Air Temperature. This variable can be readily measured with standard hydrometeorological instruments. Recording thermograph data are useful for the monitoring of rapid temperature changes, and provide more useful information than twice a day maximum temperature readings. The height at which temperature measurements are taken should be clearly specified.

With regard to the areal variability of air temperature, a comparison of data from the Blue Springs Basin with observations taken at Elora, a station fifteen miles to the west, reveals very close correlation for monthly mean values ($r^2 = 0.99$). It appears that temperature means may be transferred at least this distance without loss of accuracy, as long as the general snow distribution is the same at the two locations and topographic differences remain insignificant.

(b) Relative Humidity. A recording hygrothermograph can supply an accurate record of relative humidity and temperature variation at a point. It is important to have both measurements made at the same height above the snow surface.

Relative humidity values appear to vary over an area somewhat more than temperature readings. The Blue Springs vs Elora data for monthly mean relative humidity reveals a fair correlation, with $r^2 = 0.81$. It is not known what effect the use of average six hour values at Blue Springs and the average of twice daily readings at Elora has on the correlation.

(c) Wind Speed. Calculations for both convective heat transport and vapour transport require estimates of wind speed. Setting aside the extremely difficult problem of estimating appropriate transport coefficients for these quantities, there remains the difficulty of obtaining the areal distribution of wind. Williams (1959, 1961) has discussed this latter problem.

In the absence of feasible observational methods to obtain areal wind distributions, a minimum requirement is a measurement of wind at the same site and height as that utilized for temperature and relative humidity. This requirement was not recognized for the Blue Springs Basin for some years after the initial instrumentation was installed. Indeed, the absence of wind as an important standard measured variable at I.H.D. stations appears in retrospect to be a serious omission.

(d) Precipitation. An estimate of the precipitation occurring within the time period utilized for each ablation calculation is important as it represents input to the mass balance for the period. Rain and snow also influence the physical properties of the snowpack.

There being no standard hydrometeorological instrument which can distinguish between solid and liquid precipitation in the temperature range near 0°C, one must rely on the physical senses of a careful observer. In storms characterized by mixtures of rain and snow, or various forms of each, differentiation can be extremely difficult for even the most conscientious observer.

Net Radiation

Snow ablation calculations require estimation of the combined net downward radiation, including both the shortwave component (wavelengths less than four micrometres) and the longwave component. Such radiation data can be provided by a pyrradiometer, e.g. the Middleton Company's version of the Funk net radiometer, discussed by Latimer

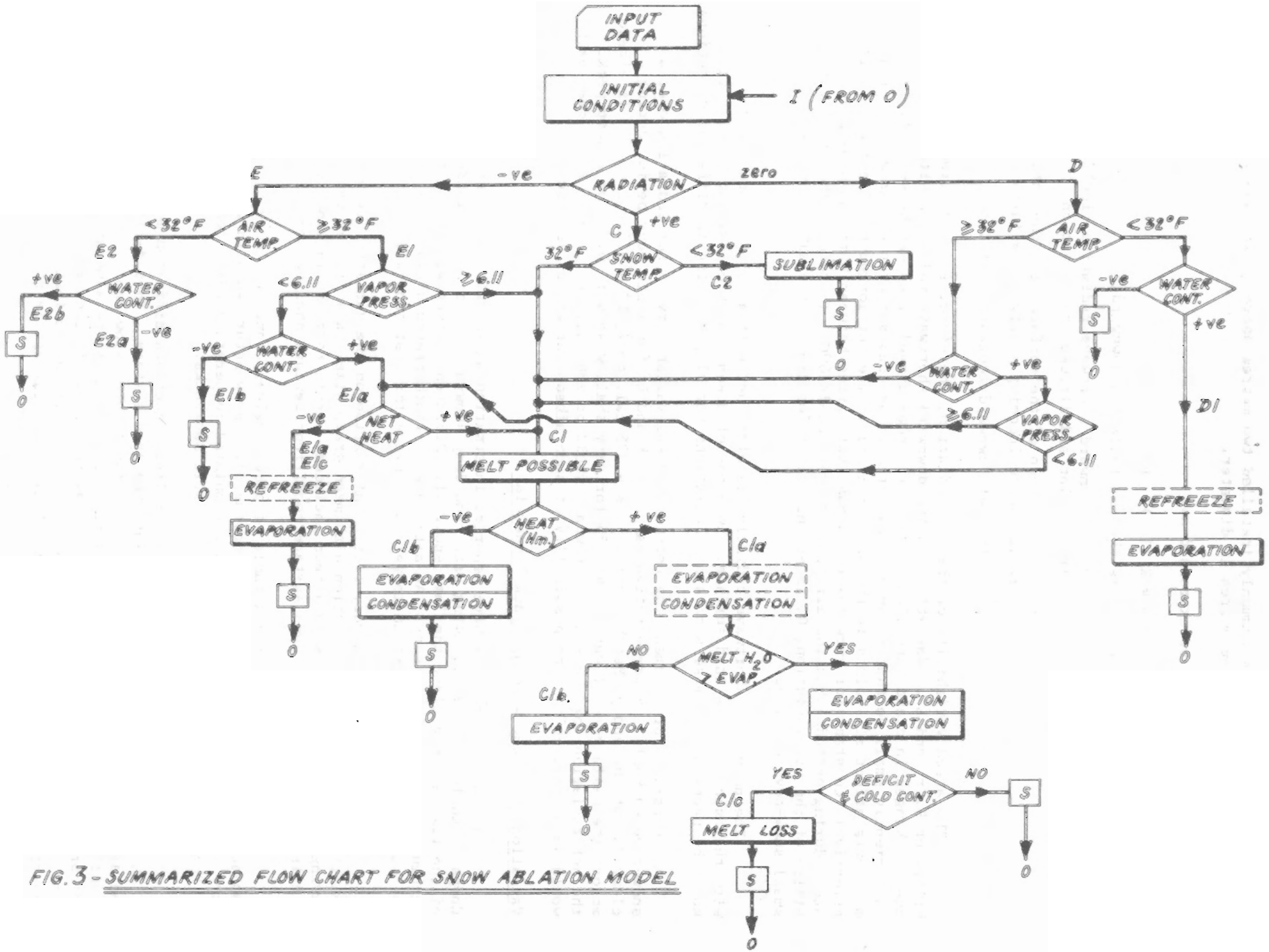


FIG. 3 - SUMMARIZED FLOW CHART FOR SNOW ABLATION MODEL

(1972). The instrument is commonly installed two metres above ground and views an area of ground approximately ten metres in diameter.

Net radiation can be expressed as,

$$Q = K\ (1-r) + L^*$$

where Q is the net radiation downward,

K is the downward shortwave radiation, including direct solar and diffuse sky radiation,

r is the albedo of the surface, ie. the ratio of reflected to incoming shortwave radiation,

L^* is the net downward longwave radiation.

The areal variability of the net radiation, therefore, is a function of the variability of K, r, and L^*. Variations in the downward shortwave radiation within a day are due to changes in cloud conditions. Usually, snow-covered areas can be selected to be sufficiently small so that K can be considered to be constant over the area, ie. cloud movements affect all points in the area similarly. The net longwave radiation, L^*, is effectively constant for snow-covered areas, but varies between bare-and snow-covered areas during periods when the air temperature exceeds 0°C. Therefore, the areal variability of the net radiation, Q, is essentially a function of the albedo, r, for relatively small snow-covered areas.

The amount of shortwave radiation received per unit area of ground surface varies with the aspect of the land surface. In areas of steep slopes of varying aspect, it would be necessary to make separate calculations for slopes facing in different directions.

Consider for a moment the potential areal variability of net radiation over a snow-covered basin. Representative values of K and L^* for a six hour period during a clear day at the end of March might be: $K = 225$ cal. cm^{-2}, $L^* = -10$ cal cm^{-2}. If albedo across the basin were to vary from 0.35 for very shallow snow to 0.75 for a deep pack, the net radiation for the shallow snowpack would be 136 cal. cm^{-2}, and for the deep pack would be 46 cal. cm^{-2}. The possibility of such albedo variations is discussed below.

Variation of Albedo with Snowpack Properties

A number of authors have reported information on the albedo of snow. The U.S. Corps of Engineers (1956), using data from deep snowpacks, expressed albedo as a function of the time elapsed since the last snowfall. Different curves were found to exist for accumulation and melt seasons. An alternate approach presents albedo as a function of the summation of daily maximum temperatures since the last snowfall.

Mellor (1964) found very little information on the variation of albedo with snow density, and none on the variation with mean grain size. His list of snowpack properties having important influences on albedo included: grain form, solid impurities, macroscopic irregularities, and ground surface conditions beneath shallow snowpacks.

Gray (1970) presented a table of albedo values, ranging from 0.86 to 0.95 for compact clean dry snow, to 0.37 for porous dirty snow saturated with water. He noted that the relation between albedo and accumulated temperature suggested by the U.S. Corps of Engineers did not apply to shallow prairie snowpacks.

Giddings and Lachapelle (1961) applied a modified diffusion model to the process of short wave radiation penetration into the snow surface. They derived an equation for the albedo of a finite depth snowpack as a function of snow depth, absorptivity of the underlying surface, albedo of an infinitely deep pack of the same properties, and physical properties of the pack. The properties deemed significant included average grain size, free water content, depth, type of ground surface, laminations within the snowpack, and distributed or layered dirt. The Giddings and Lachapelle equations are:

$$r = \frac{1 - \frac{W}{2}(1-y)}{1 + \frac{W}{2}(1-y)}$$

$$\text{where} \quad y = \frac{e^{-bd}\left[A + W\left(\frac{A}{2} - 1\right)\right]}{W\left(\frac{A}{2} - 1\right)\cosh bd - A \sinh bd}$$

$W = 2(1-r^*)/(1 + r^*)$

r^* = the albedo of an infinitely deep snowpack,

r = the albedo of a pack of depth d,

b = an extinction coefficient, cm^{-1},

d = the depth of snowpack, cm,

A = the absorptivity of the underlying surface.

Giddings and Lachapelle further concluded that albedo decreases with increasing grain size of the snow. The extinction coefficient also depends on grain size and might be expected to decrease as grain size increases. A value of b for clean dry snow with an average grain size of 0.5 mm. was noted to be 0.54 cm^{-1}. O'Neill and Gray (1972) reported a value of b of 0.42 cm^{-1} for clean dry snow with an average grain size of 0.7 mm, and a value of 0.43 for snow of about the same size distribution experiencing slight melt conditions. U.S. Corps of Engineers values ranged from 0.28 to 0.106 cm^{-1} as density varied from 0.26 to 0.45.

The available literature confirms that albedo may vary significantly with snowpack properties. However, the information falls short of providing an explicit relationship between albedo and readily measurable properties. An attempt to utilize standard hydrometeorological data to examine the dependence of albedo on snowpack characteristics is presented below.

Estimation of Albedo at Blue Springs

Data available from the Blue Springs hydrometeorological station comprised average air temperature, total net radiation, total rain, and total new snow for the six hour intervals 0 to 6, 6 to 12, 12 to 18, and 18 to 24 hours. For convenience, these intervals are coded 1, 2, 3 and 4 respectively. Snow depth was measured about 50 metres from the net radiometer in an area of short grass or bare soil, while the radiometer viewed an area of pasture with an average summer grass height of 20 cm. Snow depth measurements were usually obtained once a day in the morning, although twice daily readings were taken during the last two years. The period of analysis was November 1967 to April 1972.

Incoming solar radiation data was initially available from Guelph, and later from Elora when the instrument was moved to the latter location. Both stations were situated about fifteen miles from the Blue Springs meteorological station.

Albedo was estimated from an analysis of the radiation components. Rewriting the equation for net radiation in terms of albedo,

$$r = \frac{K + L^* - Q}{K} ,$$

the terms being defined earlier. With measurements of net radiation and incoming solar radiation available for six hour intervals, the term requiring estimation is net longwave radiation.

During the night-time periods, 1 and 4, the incoming solar radiation is very small or zero. For these periods, the net shortwave radiation was assumed to be one half of the incoming solar radiation. Then the net longwave radiation could be estimated from the expression,

$$L^* = Q - 0.5 K.$$

For periods 2 and 3, net longwave radiation values were determined from an interpolation between the values obtained for periods 1 and 4. With these estimates, and the measured values of net and incoming shortwave radiation, albedo was estimated for each daytime period.

Analysis of Albedo Data

For the analysis of albedo vs snowpack properties, the following variables were defined:

(i) Snow age. The snow age represents the number of time periods since the last snowfall, a snowfall being defined as the occurrence of 0.02 inches of water equivalent of snow in a six hour period. Therefore, snow age assumes the value zero for any period in which a snowfall occurs, and increments by one for each succeeding 6 hour period of no snow.

(ii) Snow depth. The snow depth was measured and recorded to the nearest inch.

(iii) Degree period. This variable represents the number of fahrenheit degrees of temperature above freezing point for the time period.

(iv) Net shortwave radiation. This variable was used as a control variable. For a given period, to be considered in the final analysis, the net shortwave radiation total had to be equal to or greater than ten cal. cm^{-2}. It was felt that smaller values of net shortwave radiation did not allow accurate estimates of albedo.

With regard to both snow age and snow depth, it was found useful to further classify the variables. The data was partitioned into 6 classes according to snow depth. Classes of 0, 1, 2 and 3, 4 and 5, 6 to 11, and 12 to 18 inches were used. With reference to snow age, each time period analysed was specified as falling within one of three main divisions. These divisions were identified as:

(i) uninterrupted antecedent aging periods, ie. periods in which the mean temperature was less than or equal to 32°F and during which no rain occurred, and before which all periods since the last snowfall exhibited the same temperature and precipitation properties;

(ii) interrupted antecedent aging periods, ie. periods with the mean temperature less than or equal to 32°F and no rain, but with at least one period with either rain or mean temperature greater than 32°F since the last snowfall; and

(iii) melt periods ie. periods with rain or with a mean temperature greater than 32°F. A symbolic representation of snow aging conditions is shown in Figure 4.

The melt periods were divided into two segments, one containing those periods of melt with uninterrupted antecedent aging and the other periods with interrupted antecedent aging. Further, each melt period with uninterrupted antecedent aging was characterized with an accumulated degree period term. At the beginning of a melt period the accumulated degree period was considered to be -5 DP, based on the assumption that a snowpack could have a maximum free water content of 0.10 inches and that a melt of 0.02 inches per six hour period per degree fahrenheit was possible. Subsequent degree periods for succeeding melt periods were cumulated with night-time periods included. A cumulate melt period was ended when two successive day-time periods exhibited zero degree periods, and the accumulated degree period was reinitialized to -5 DP.

Albedo vs Snow Age and Snow Depth

A correlation model between albedo and snow age was analysed, the data having

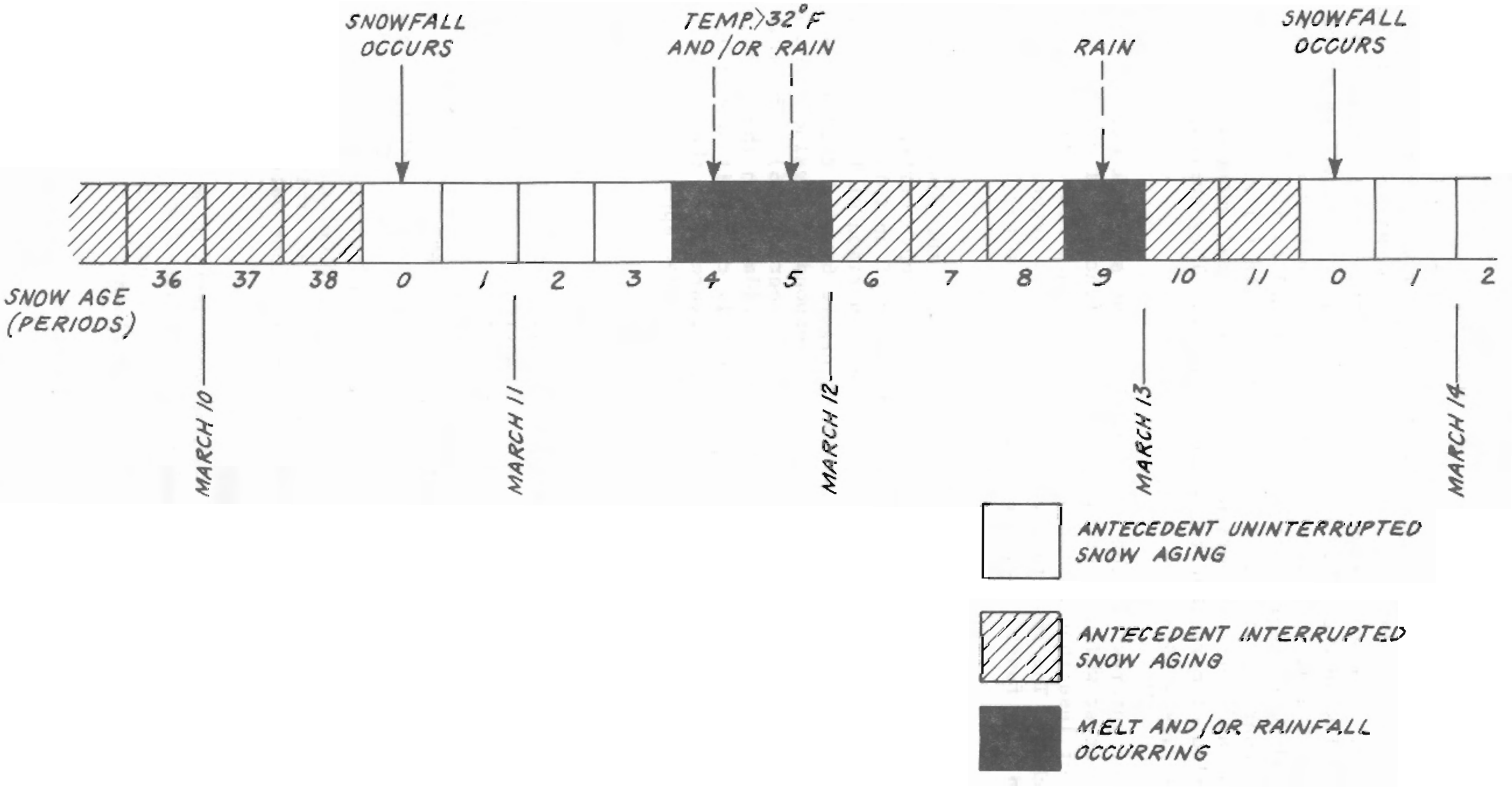


FIG. 4 - SYMBOLIC REPRESENTATION OF SNOW AGING CONDITIONS

been grouped according to the three main conditions caused by temperature and rainfall during a snow aging event. The data points exhibited little if any correlation. Some trend toward decreasing albedo with increasing snow age existed, but a meaningful regression model was not permissible.

Possible relationships between albedo and snow depth were considered. The regression lines of best fit for selected groupings of data are presented in Figure 5. Although there is considerable scatter of the plotted mean values for each depth class, three snow conditions tend to evolve. The time periods identified by uninterrupted antecedent aging are characterized by small grained, clean, dry snow, and the albedo for such periods remains quite high to shallow snow depth. Data for time periods identified by interrupted antecedent aging appear similar to data for melt periods with uninterrupted antecedent aging and an accumulated degree period of less than or equal to ten DP. Such periods represent a condition of coarse-grained, clean, dry snow. Data for melt periods with interrupted antecedent aging and for melt periods with uninterrupted antecedent aging with an accumulated degree period of more than ten DP are similar. They correspond to conditions of coarse grained, dirty, wet snow.

Another point of interest is the depth at which the snowpack might be considered to be deep, ie. the point at which albedo is no longer a function of depth. Gray (1970) has suggested a value of less than six inches, and O'Neill and Gray (1972) have noted approximately four inches. The results presented in Figure 5 suggest that the depth at which the pack is deep is a function of the aging process, and may be as much as ten inches for dirty, wet snow.

To enable a comparison of the Blue Springs data with the equation presented by Giddings and Lachapelle (1961), a family of albedo vs snow depth curves were prepared using selected values of extinction coefficient and albedo of an infinitely deep snowpack. Four of these relationships are shown in Figure 6. A comparison of Figures 5 and 6 reveals that a line situated between the upper two curves of Figure 6 would correspond approximately to the upper curve of Figure 5. Such a line would correspond to a value of extinction coefficient in the range reported by the U.S. Corps of Engineers (1956). The third curve on Figure 6 (ie. $b = 0.0375$, $r^* = 0.77$) is virtually coincident with the second curve on Figure 5. The lower curves reveal more departure. In this regard it should be noted that Giddings and Lachapelle (1961) predicted large departures from their theory for albedo values of less than 0.5, as the diffusion approach does not apply to wet and dirty snowpacks.

Verification of Derived Relations

The applicability of the derived curves was verified by calculating daytime net radiation values for the month of March 1970 using measured values of snow depth, snow condition (as specified by antecedent snow aging condition, temperature, and degree period values), and incoming solar radiation. For the first 27 days of the month, including one significant melt period, agreement between measured and calculated values of net radiation was reasonable. For the morning period, period 2, the average measured Q value was 28 cal. cm^{-2} while the calculated value was 26 cal. cm^{-2}. For the afternoon period, the average measured value was 39 cal cm^{-2} while the calculated value was 28 cal cm^{-2}. The latter discrepancy suggests a possible systematic decrease in albedo during the afternoon, perhaps due to increased free water content. An arbitrary increase of 0.10 in the afternoon albedo estimates raises the mean afternoon value of calculated net radiation to 43 cal. cm^{-2} for the 27 day period.

On the last days of the month, the measured snow depth 50 m from the net radiometer was three inches. For these days the measured net radiation values were much larger than the calculated values for both morning and afternoon periods (106 cal. cm^{-2} vs. 39 cal. cm^{-2}). Much of this difference would be explained if the snow depth under the radiometer was less than three inches.

Utility of Results in Modelling

A family of relationships linking albedo to readily identifiable snowpack

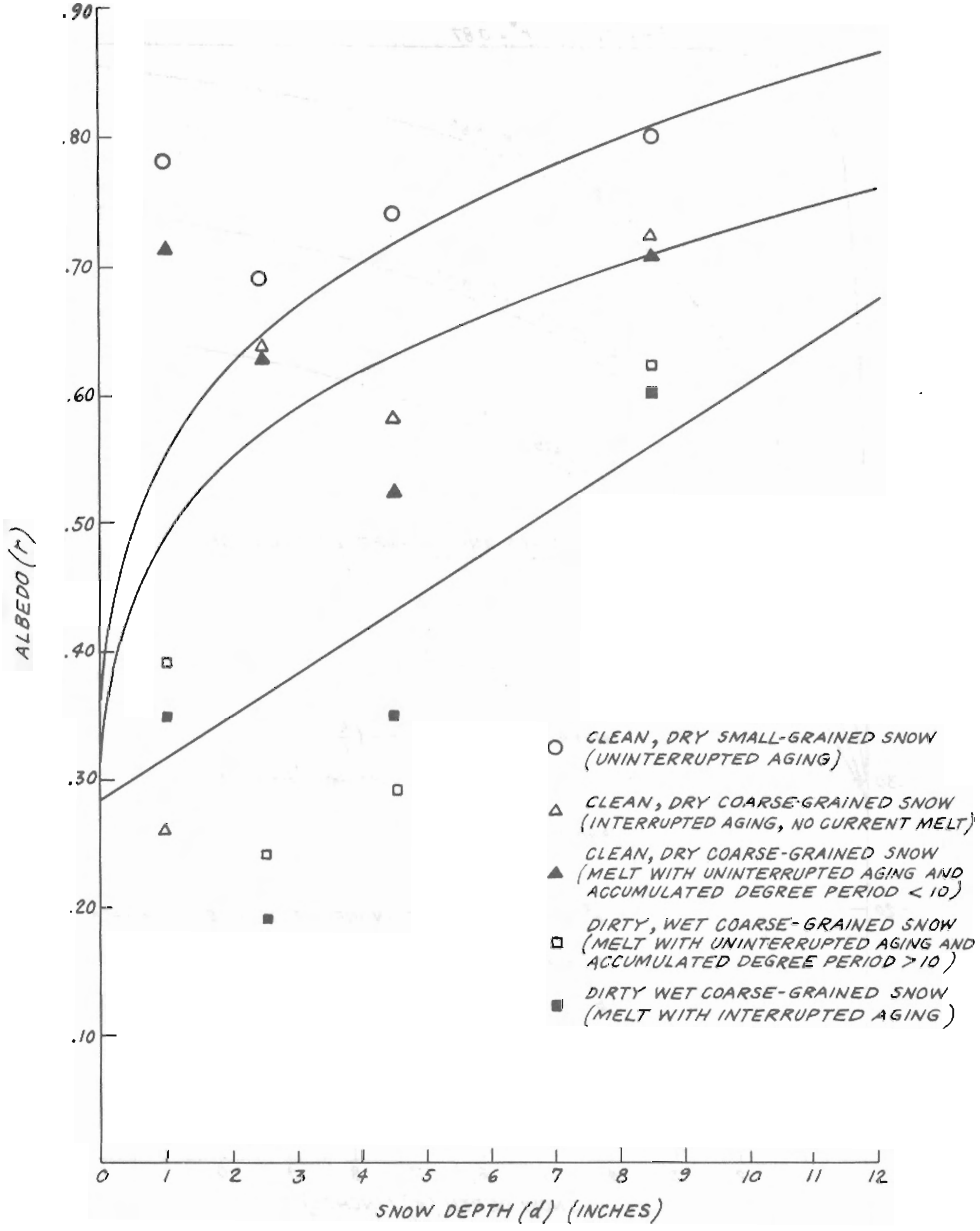
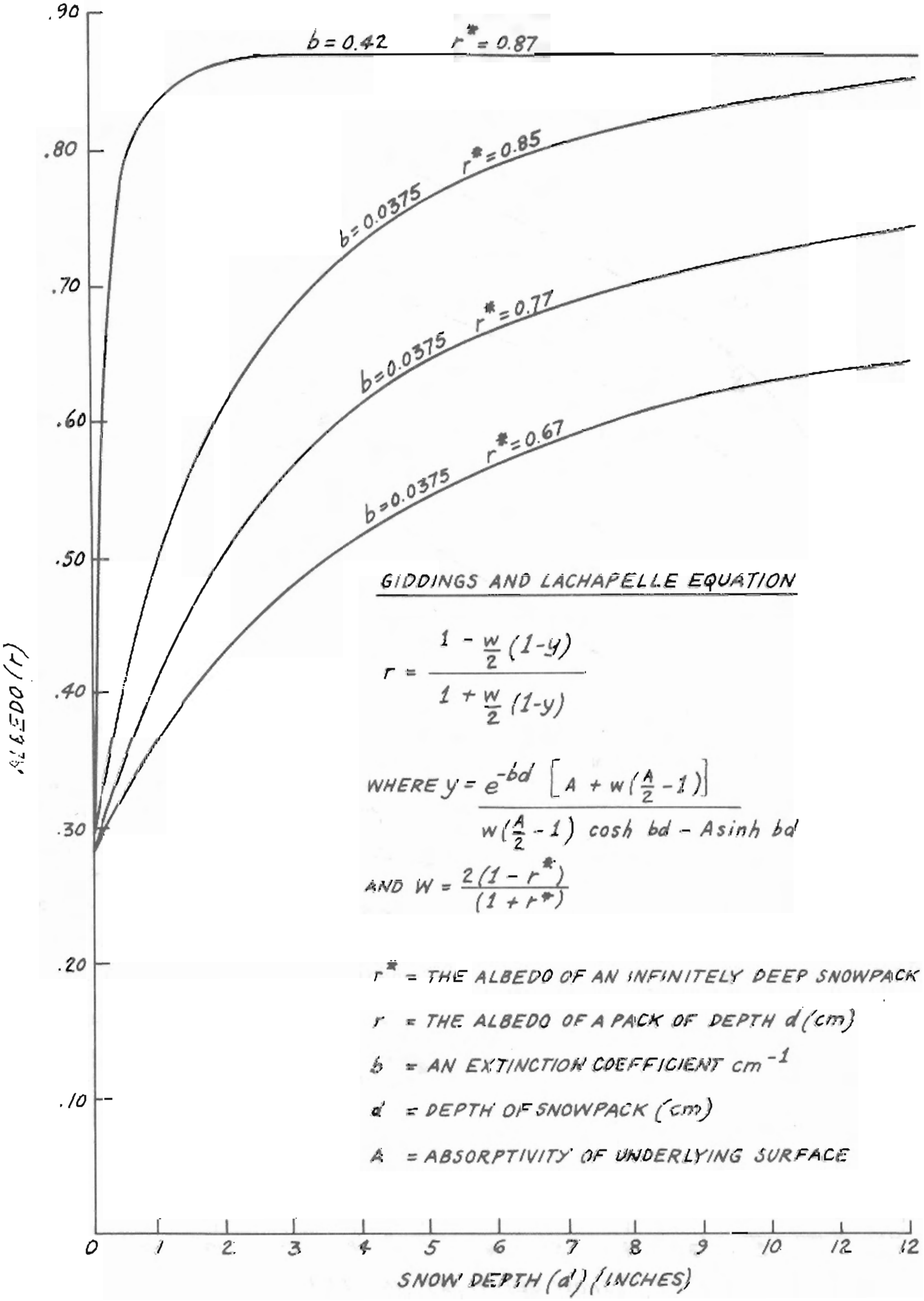


FIG. 5- EMPIRICAL ALBEDO VERSUS SNOW DEPTH RELATION.



GIDDINGS AND LACHAPELLE EQUATION

$$r = \frac{1 - \frac{w}{2}(1-y)}{1 + \frac{w}{2}(1-y)}$$

WHERE $y = \dfrac{e^{-bd}\left[A + w\left(\frac{A}{2} - 1\right)\right]}{w\left(\frac{A}{2} - 1\right)\cosh bd - A \sinh bd}$

AND $W = \dfrac{2(1 - r^*)}{(1 + r^*)}$

r^* = THE ALBEDO OF AN INFINITELY DEEP SNOWPACK

r = THE ALBEDO OF A PACK OF DEPTH d (cm)

b = AN EXTINCTION COEFFICIENT cm^{-1}

d = DEPTH OF SNOWPACK (cm)

A = ABSORPTIVITY OF UNDERLYING SURFACE

FIG. 6 - THEORETICAL ALBEDO VERSUS SNOW DEPTH RELATION

characteristics such as snow depth and snow condition (as reflected in the snow aging sequence) would be extremely useful for the modelling of watershed response from snowmelt. Two approaches to such utility are noted below.

For the purpose of a lumped basin model (ie. lumping in area), it would normally be required to describe the areal distribution of snow, such as presented in Figures 1 and 2. Dividing the pack into percentages of the area covered by selected snow depths, one could estimate the albedo for each portion.

The general tendency for albedo to decrease with decreasing snow depth results in shallow parts of the snowpack melting more rapidly than deeper portions, accentuating the skewness of the areal distribution curve. Such an effect is observable in Figure 1.

A subsequent computation of net radiation for each areal extent would allow melt estimates to be made and lumped as the melt input to the model.

For the case of a distributed basin model, the snow properties would be known for specific basin locations. Albedo estimates and net radiation values could be determined for selected areas and the individual melt determinations would serve as distributed inputs to the model.

Concluding Remarks

Of the standard hydrometeorological variables involved in snow ablation estimation, it has been suggested that special attention should be given to the areal distribution of snowpack characteristics, to measurements of wind, and to areal variations in net radiation. In order to obtain useful values for net radiation at points of differing snow characteristics, it is important to have measured incoming shortwave radiation and measured net radiation at one point, along with knowledge of the variation of snow albedo with snowpack properties.

There is no adequate description of the variation of albedo of shallow packs with snow properties in existing published results. The relationships resulting from the analysis of data from the Blue Springs Basin show promise in this regard and correspond to current theory on the subject. Further research in this area appears warranted as the range of albedo values is large and has considerable effect on the net radiation energy available for melt.

References

Dickinson, W.T. & H. Whiteley. Watershed areas contributing to runoff. I.A.S.H. Symposium on the results of research on representative and experimental basins. Publ. 96. Wellington, N.Z. 1970.

Dickinson, W.T. & H. Whiteley. Snowpack sampling for the estimation of liquid water equivalent. Proc. 8th Canadian Hydrology Symposium. Quebec City. 1971.

Dickinson, W.T. & H.R. Whiteley. A sampling scheme for shallow snowpacks. Bulletin of the I.A.H.S. XVII. 1972.

Giddings, J.C. & E. Lachapelle. Diffusion theory applied to radiant energy distribution and albedo of snow. Journal of Geophysical Research, Vol. 66 No. 1. p.181-189. 1961.

Golding, L. Research results from Marmot Creek experimental watershed. I.A.S.H. Symposium on the results of research on representative and experimental basins. Publ. 96. Wellington, N.Z. 1970.

Gray. Snow hydrology of the prairie environment in Snow Hydrology Proceedings of workshop seminar 1968 Queen's Printer, Ottawa. 1970.

Latimer, J.R. Radiation measurement. International field year for the Great Lakes Technical Manual Series No. 2. Information Canada, Ottawa. 1972.

McKay, G.A. Problems of measuring and evaluating snowcover. In Snow Hydrology Proceedings of workshop seminar 1968. Queen's Printer, Ottawa. 1970.

Mellor, M. Properties of snow. Cold Regions Science & Engineering Part III: Engineering, Section A: Snow Engineering, U.S. Army Material Command, Cold Region Research & Engineering Lab., Hanover, New Hampshire. 1964.

O'Neill, A.D.J. & D.M. Gray. Solar radiation penetration through snow. International Symposia on the Role of Snow & Ice in Hydrology. Banff. 1972.

Provart, M.R. An analytical model for snow ablation. M.Sc. Thesis, University of Guelph, 1970.

U.S. Corps of Engineers. Snow hydrology. U.S. Government Printing Office, Supt. of Documents, Washington, D.C. 1956.

Williams, G.P. Evaporation from snow covers in Eastern Canada. Research paper no. 73, Division of Building Research, National Research Council, Ottawa. 1959.

Williams, G.P. Evaporation from water, snow and ice. Proceedings of Hydrology Symposium No. 2, Queen's Printer, Ottawa. 1961.