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Preliminary results of a study on active layer hydrology in the discontinuous zone at Schefferville, Nouveau-Québec
Résultats préliminaires de l'étude de l'hydrologie du mollisol dans la zone de pergélisol discontinu, Schefferville, Nouveau-Québec
Vorläufige Resultate einer Forschungsarbeit über Auftauzonen-Hydrologie in der unterbrochenen Dauerfrostzone von Schefferville, Québec

Richard K. Wright

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Article abstract

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PRELIMINARY RESULTS OF A STUDY ON ACTIVE LAYER HYDROLOGY IN THE DISCONTINUOUS ZONE AT SCHEFFERVILLE, NOUVEAU-QUÉBEC

Richard K. WRIGHT, Department of Geography, McGill University, 805 Sherbrooke W., Montréal, Québec H3A 2K6.

ABSTRACT A detailed study of the water balance of a lichen tundra underlain by permafrost was started in September 1976. Data collection at the 9 000 m² site near Schefferville, Québec includes air and ground temperatures, precipitation, evapotranspiration, and changes in soil moisture storage as well as incoming short-wave and net all-wave radiation. It is shown that the development of the active layer is strongly influenced by the amount and distribution of moisture in the soil at freeze-up. Moisture transfer within the unsaturated zone is shown to be strongly influenced by the temperature field within the active layer during freeze-up. During the thaw season the confinement of infiltrated water by permafrost is not only a major soil moisture reservoir and medium for suprapermafrost ground water flow, but it is also shown to maintain evapotranspiration at or near the equilibrium rate for the tundra as well as causing a significant increase in evaporation from permafrost induced wetlands.

RÉSUMÉ *Résultats préliminaires de l'étude de l'hydrologie du mollisol dans la zone de pergélisol discontinu, Schefferville, Nouveau-Québec.* En septembre 1976, une étude détaillée du bilan hydrique d'une toundra à lichen fut entreprise. Sur un site de 9 000 m², nous avons colligé les données suivantes: températures de l'air et du sol, précipitations, évapotranspiration, variations du degré d'humidité du sol et rayonnement solaire brut et net. Cette étude démontre que le degré d'humidité du sol pendant la période d'engel a une forte influence sur le développement du mollisol. L'étude démontre, en outre, que la répartition des températures dans le mollisol pendant la période d'engel influence grandement le transfert de l'humidité dans la zone non saturée. Pendant la période de dégel, l'eau d'infiltration emprisonnée dans la zone saturée au-dessus du pergélisol constitue un important réservoir d'humidité et un milieu d'écoulement de l'eau souterraine. De plus, cette nappe perchée contribue à maintenir le niveau d'équilibre de l'évapotranspiration de la toundra tout en provoquant une augmentation sensible de l'évaporation des marécages provoqués par la présence du pergélisol.

ZUSAMMENFASSUNG *Vorläufige Resultate einer Forschungsarbeit über Auftauzonen-Hydrologie in der unterbrochenen Dauerfrostzone von Schefferville, Québec.* Im September 1976 wurde ein eingehendes Studium der Wasserbilanz in einer von Dauerfrost unterlegenen Lichen-Tundra begonnen. Die Datensammlung auf dem 9000 m² grossen Forschungsgebiet in der Nähe von Schefferville, Québec, umfasst Luft- und Bodentemperaturen, Niederschlag, Evapotranspiration, Wechsel in Bodenfeuchtigkeitsgehalt, sowie eintretende Kurzwellen und Netto-Allwellen Radiation. Es zeigt sich, dass die Entwicklung der Auftauzone von der Feuchtigkeitsmenge und -verteilung des Bodens beim Gefrieren stark beinflusst wird. Feuchtigkeits-übertragung innerhalb der ungesättigten Zone erscheint durch das Temperaturfeld in der Auftauzone während des Gefrierens stark beeinflusst zu sein. In der Tausaison stellt das eingefangene Wasser des Dauerfrostbodens nicht nur ein wichtiges Feuchtigkeitsreservoir dar, sondern auch ein Medium für Superdauerfrost-Grundwasserfluss, aber es erhält auch die Evapotranspiration im Gleichgewicht für die Tundra, sowie eine bedeutende Zunahme der Verdunstung in vom Dauerfrost hervorgerufenen nassen Gebieten.

INTRODUCTION

Although there has been a notable increase in recent years in the amount of hydrologic research in the North, both outside Ungava (*e.g.* DINGMAN, 1971; MARSH and WOO, 1977) as well as within it (*e.g.* NICHOLS, 1966; LEWIS, 1977), there is still a serious lack of detailed studies of hydrologic processes in northern environments (HARLAN, 1974). For this reason, a project was started in September, 1976 to study the water balance of a lichen tundra underlain by permafrost.

The ultimate aim of the project is a detailed examination of the components of the water balance and their relative magnitudes during the thaw season, but the results reported here are considered tentative and the discussions will be restricted to the reciprocal influences of the water balance and the development of the active layer. The first section gives a brief overview of the study area and the site while the second discusses the role of water in the development of the active layer. The final section considers some of the ways in which the presence of permafrost and the development of the active layer can affect the water balance in central Ungava.

THE STUDY AREA

GENERAL

The project is being carried out near Schefferville, Québec (54°51′ N. 67°01′ W.; 520 m a.s.l.) in central Ungava (Fig. 1). Located within the Labrador Trough, the Schefferville area is characterized by broad, permafrost-free valleys and long, narrow ridges underlain by extensive permafrost, the depth of which exceeds 100 m in some areas (NICHOLSON and GRANBERG, 1973). Lichen woodland and muskeg in the valleys grade into scattered spruce and lichen tundra on the ridges. Mean annual air temperature at the nearby Timmins 4 Permafrost Experimental Site is −6.2° C. The mean annual precipitation at the Schefferville townsite (15 km SE of the main research site) is 745 mm of which 433 mm falls as rain between May and October, and the rest falls as snow, primarily from October to May (NICHOLSON and LEWIS, 1976).

THE SITE

Located approximately 15 km NW of the Schefferville townsite at an altitude of 685 m, the research site (Hematite) represents a typical area of lichen tundra. The surface cover over 80% of the site consists of a 5-10 cm lichen mat (primarily *Cladonia* spp.) and scattered dwarf birch (*Betula glandulosa*) and the remaining 20% is bare frost scar. To minimize the lateral inflows of suprapermafrost groundwater and the associated sensible heat the site selected is a large (9 000 m^2) hillside with a well-defined watershed (Fig. 2). The site is underlain by several members of the Sokoman Formation and the Ruth Formation, both of which are weakly metamorphosed Proterozoic sediments that have been folded and faulted. The rocks range from a ferruginous, carbonaceous slate to banded, partly-leached iron formation (HARRISON, HOWELL and FAHRIG, 1972). These rocks are covered by a very stony till (20% to 30% by weight larger than 2 mm with a silty or sandy loam matrix) approximately one metre thick. Permafrost underlies the entire site to a depth of at least 10 m and probably in excess of 30 m with an annual depth of thaw that range from 2.0 m under lichen mat to 2.5 m under bare frost scar.

Data collection at the site began in September 1976 with the installation of the thermistor cables, and comprehensive data collection began in early June, 1977. The study concentrates on the thaw season, but some winter data has been collected, notably temperature and moisture readings during the winter of 1977-78. Figure 2 shows the instrumentation at the site during the 1978 thaw season.

ROLE OF WATER IN THE DEVELOPMENT OF THE ACTIVE LAYER

INTRODUCTION

It would be desirable to be able to describe (and model) the development of the active layer by such simplistic approaches as the general equations for sinusoidal temperature variations in a homogeneous medium, but such approaches require several assumptions that have been shown to be invalid in northern environments. A number of authors (*e.g.* LACHENBRUCH, 1959; NAKANO and BROWN, 1972) have demonstrated that active layers in very simple northern soils can be successfully modelled using complex instrumental and analytical methods. However, very little work has been applied to describing the development of the active layer under more complex field conditions and its effect on active layer hydrology. The following sections will use the data collected in this study, as well as others in the Schefferville area, to illustrate the problems of adequately describing the development of the active layer under field conditions.

CHANGES IN THERMAL PROPERTIES

The most important property affected by water in cold regions is the volumetric specific heat (C) of the soil. In general, the aggregate value of C for a soil can be obtained by summing the individual values of C for each of the soil components (solid, liquid, and gaseous

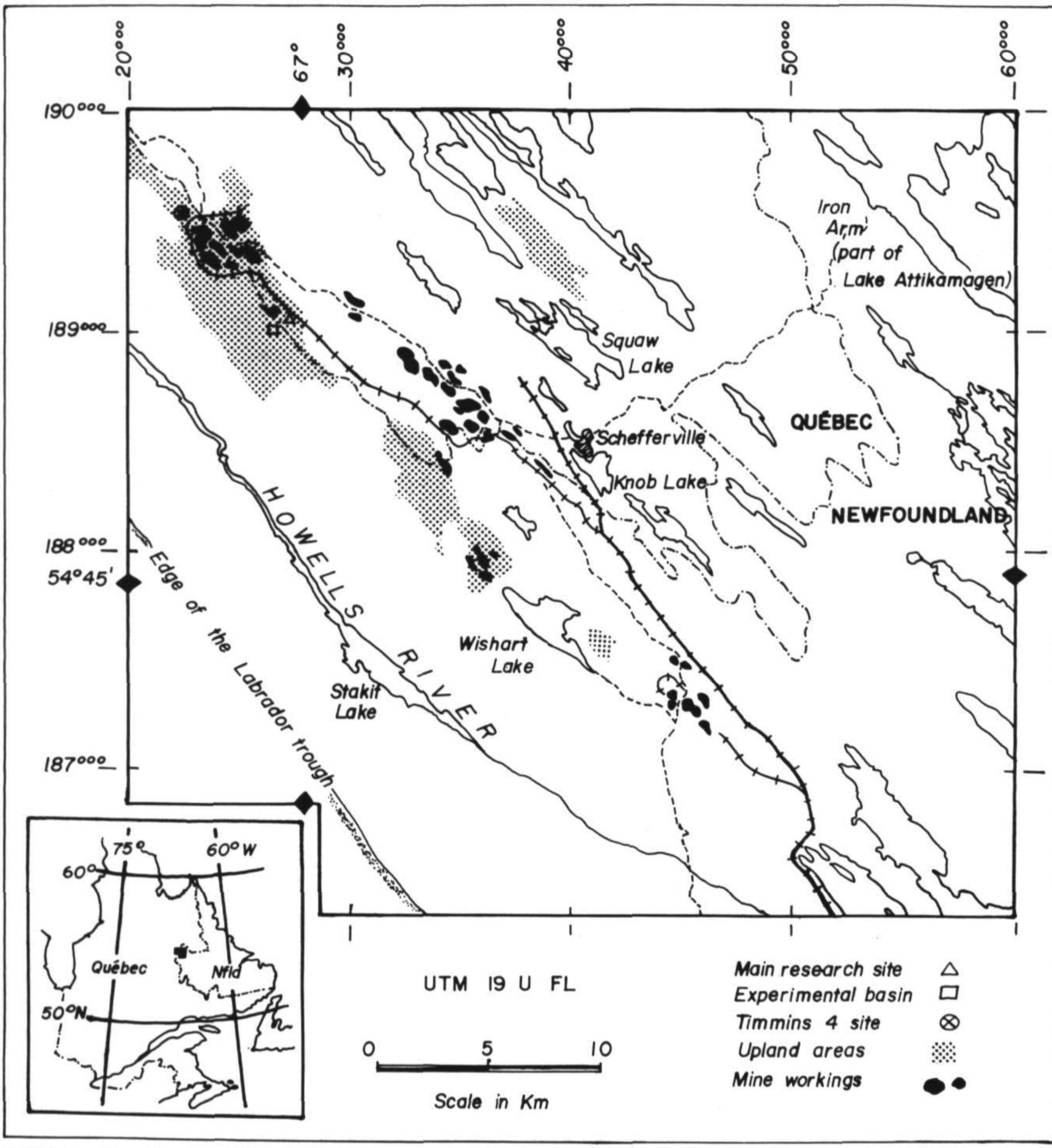

FIGURE 1. Location map of research sites and the Schefferville region.

Carte de localisation de la région de Schefferville et des sites étudiés.

phases). However, when the temperature passes through 0°C. the value for C must include the heat of fusion of water and is therefore much larger than the value in either the thawed or frozen state. WILLIAMS (1967), working with samples of iron ore from the Schefferville area, found that the apparent volumetric specific heat (C') was approximately 25 times that of the iron ore in either the thawed or frozen state. LEWIS (1977), working at Timmins 4, found that up to 80% of the energy entering the ground had to be allocated to melt-

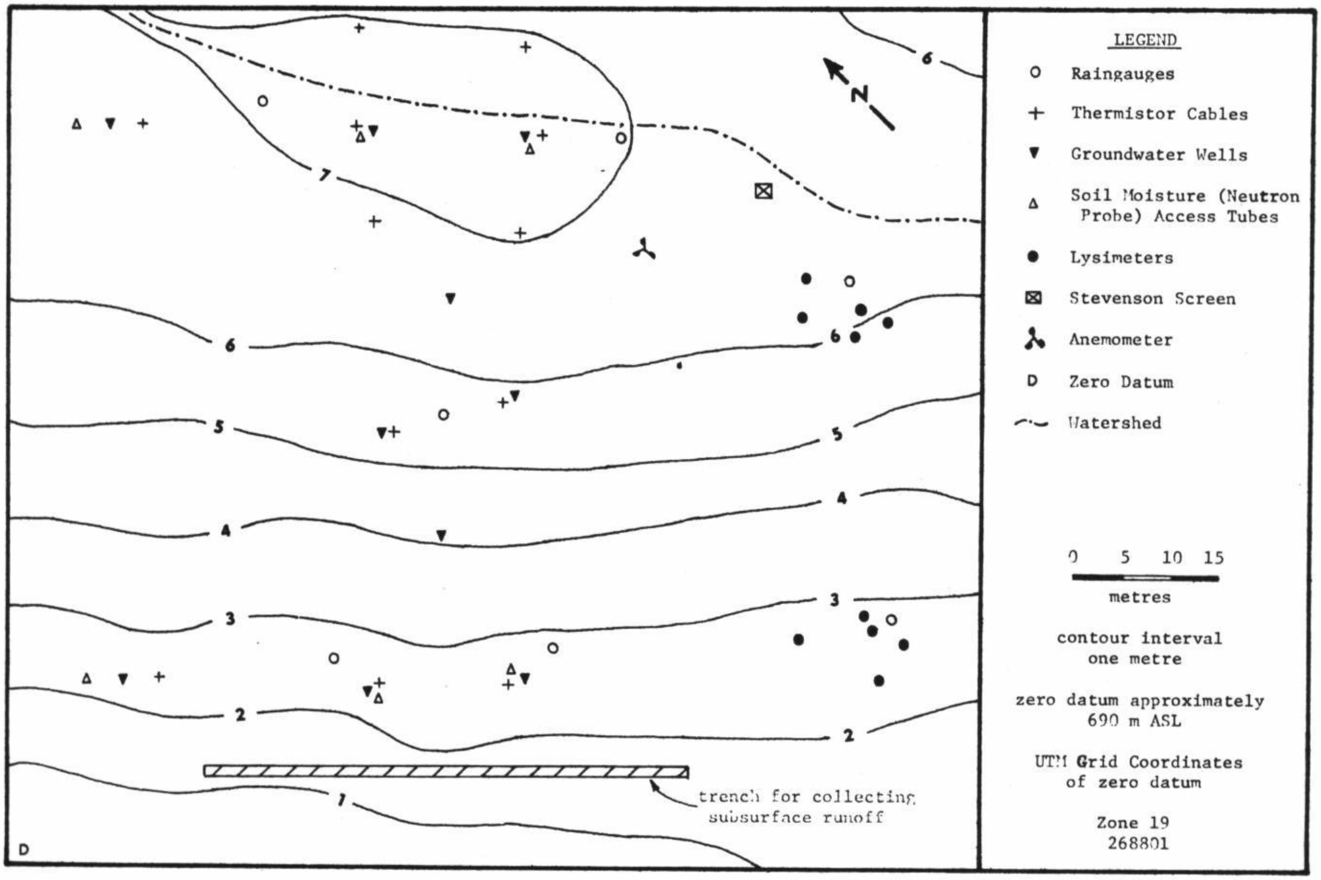

FIGURE 2. Topography and instrumentation of the site (Hematite) during the summer of 1978.

La topographie du site et la localisation des instruments de mesure, Hematite, été 1978.

ing the estimated ice content of the active layer to explain the observed ground temperature profiles. Even minor variations in the moisture content at freeze-up can have a significant impact on the annual depth of thaw as a resúlt of the very high proportion of the available energy budget used to melt ice.

Although theoretical considerations indicate that the freezing of a soil should increase its thermal conductivity (λ) due to the fourfold increase in the thermal conductivity of ice compared to water, there is very little field data to support this. ANNERSTEN (1964) found that measured annual thermal diffusivities (λ/C) in the Schefferville area were up to five times higher in the permafrost than in the active layer despite the active layer being frozen more than half the year. These values are probably misleading since C tends to be lower in the active layer due to lower density and λ higher in the permafrost due to the higher iron content. YAPP (1972), working in the laboratory with rock samples from the Schefferville area, found that freezing increased by a average of 73%. Both sets of results are higher than would be predicted by the geometric model of GOLD and LACHENBRUCH (1973), probably because of the better intergranular contact provided by the relatively expanded volume of ice within the pores (ANNERSTEN, 1964).

TRANSPORT OF LATENT AND SENSIBLE HEAT

The transport of sensible heat by water can occur in either or both the gas or liquid phase. The former is probably of little importance in cold regions, but the transport of heat by liquid can be of major importance. Although it can be shown that, in most cases, the vertical transfer of heat is of little moment, LEWIS' (1977) work at Timmins 4 indicates that the lateral concentration of sensible heat associated with suprapermafrost groundwater can be significant. The percolation of the suprapermafrost groundwater into the very permeable wetlines (areas of slight to moderate topographic depression and concentrated subsurface flow) can lead to active layers up to 10 m deep, in contrast to 2 to 3 m on adjacent slopes. NICHOLSON (1978) has also suggested that this concentration of groundwater may be sufficient to maintain taliks and has been able to improve his model of permafrost distribution in the Shefferville area by introducing a groundwater component.

The problem of latent heat transfer, either vapour/liquid or liquid/ice, is one that has received much attention in recent years, but a satisfactory solution has not been acheived (deVRIES, 1976), particularly with respect to liquid/ice transfers. The primary problem is that the theoretical basis is still uncertain, particularly the mode and relative magnitudes of the exchanges of heat in the vicinity of the freezing front (HARLAN, 1974). Studies at Hematite have clearly detected such transfers (see below), but it is doubtful that they are of major importance to the development of the active layer except in fine-grained materials containing massive ground ice.

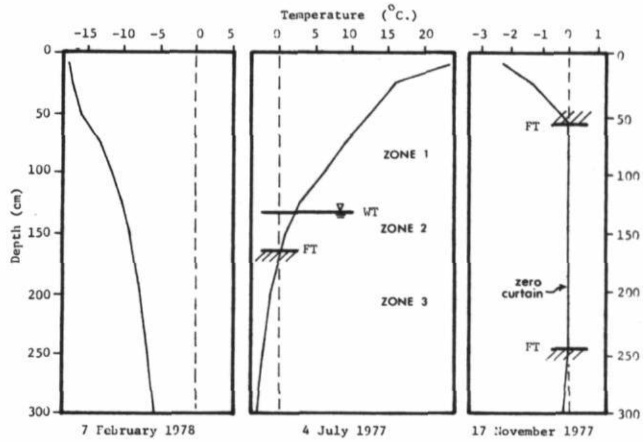

FIGURE 3. Three ground temperature profiles from cable 2, Hematite, including frost (FT) and water (WT) levels, during 1977-78.

Trois profils thermiques enregistrés par le câble n° 2, incluant les profondeurs du niveau supérieur du pergélisol et de la nappe phréatique, site Hematite, 1977-1978.

HETEROGENEITY OF THE ACTIVE LAYER

In addition to modifying the thermal properties of the soil through time, the relative changes in moisture content and phase at different depths within the soil column also play a major role in the development of the active layer. At the beginning of the thaw season, just after snowmelt, the ground is completely frozen and usually contains a higher ice content near the surface (Fig. 3a). As the active layer begins to develop there are two thermally distinct zones: a thawed surficial layer and the underlying, still-frozen material with relatively higher values of land C′. In addition, as thawing continues, a saturated zone normally develops and there are then three zones: unsaturated unfrozen (zone 1, Fig. 3b), saturated unfrozen (zone 2), and unsaturated unfrozen (zone 3) — each layer having different thermal properties.

During the fall the ground begins to freeze from the surface downwards (freezing upwards is normally far slower due to the much smaller temperature gradients at the base of the active layer). The energy exchange is concentrated at the freezing front because of the relatively large heat of fusion, but, in contrast to the thawing period, the unfrozen portion of the active layer is between two freezing planes and has little or no temperature gradient. As a result, the unfrozen part of the active layer slowly approaches 0°C. (Fig. 3c and Fig. 4), remaining at that temperature for a period up to several weeks as the freezing front slowly descends. This effect, known as the "zero curtain", is most strongly pronounced during freeze-up in permafrost regions due to the presence of two freezing fronts and the consequent diminution of the temperature gradient. Although studies at Hematite have clearly detected the presence of a zero curtain during the thaw period, a more detailed examination of this phenomenon as well as its implication for active layer studies will be dealt with in a later publication.

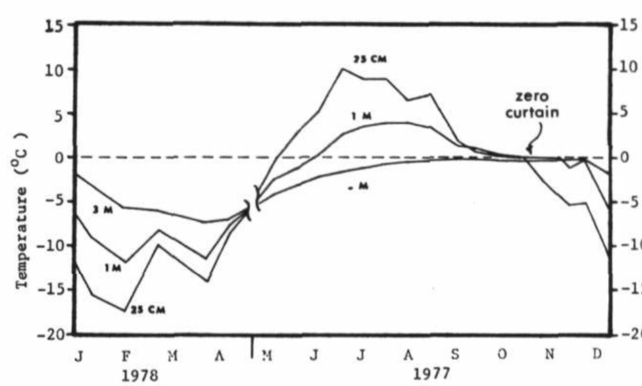

FIGURE 4. Annual ground temperature cycle at cable 2, Hematite (80% lichen cover within 1 m radius of cable head) during 1977-78.

Le cycle thermique annuel enregistré par le câble à thermistor n° 2, site Hematite, 1977-1978; 80% de la surface adjacente est recouverte de lichen (rayon = 1 m).

EFFECT OF PERMAFROST ON THE WATER BALANCE

GENERAL

Because of the relative impermeability of most perennially frozen earth materials, water infiltrating the active layer in excess of field capacity is confined to a saturated zone on top of the frost table. In many permafrost areas this saturated zone exceeds the active layer depth and results in extensive wetlands that are either continually saturated or covered by a free water surface. This perched water body (suprapermafrost groundwater) and resulting wetlands are the key characteristics that distinguish northern from southern hydrologic regimes.

In the discontinuous permafrost zone (such as the Schefferville area) the low-lying wetlands are not the direct result of permafrost since they tend to be permafrost-free, but at higher altitudes and latitudes the wetlands are largely the result of impeded drainage.

The following sections will use data collected at Hematite, as well as other areas near Schefferville, to indicate how the presence of permafrost affects the components of the water balance in central Ungava.

PRECIPITATION AND EVAPOTRANSPIRATION

Although the effect of permafrost on precipitation is almost certainly negligible, the formation of wetlands has a significant effect on evapotranspiration rates. It has been shown that in some northern regions actual evapotranspiration (ET) rates can be predicted quite accurately with the equilibrium form of the combination model,

$$ET = \left[\frac{s}{(s+\gamma)L}\right]\left[R_n - G\right]\alpha \qquad \text{Eq. 3.1}$$

where α is a constant dependent on the type and wetness of the surface, L is the latent heat of evaporation, R_n is the net all-wave radiation, G is the soil heat flux, s is the slope of the saturation vapor pressure — temperature curve, and γ is the psychometric constant. Data collected at Hematite for mixed bare and lichen-covered surfaces suggests that a value of $\alpha = 1.0$ is appropriate under moderately dry conditions (Fig. 5), as has been found for similar surfaces in the eastern subarctic (ROUSE *et al.*, 1977). In contrast, freely evaporating surfaces (such as ponds, sedge meadows, or other wet surfaces) have a value of $\alpha = 1.26$ (PRIESTLY and TAYLOR, 1972; ROUSE *et al.*, 1977). It follows, then, that because of the higher value of α, as well as that of $(R_n - G)$ (ROUSE *et al.*, 1977), the formation of ponds and wetlands by permafrost would tend to increase evaporation by more than 26%. This has a significant impact on the regional water balance since large areas of central Ungava (as well as many other areas of the North) are lakes and wetlands.

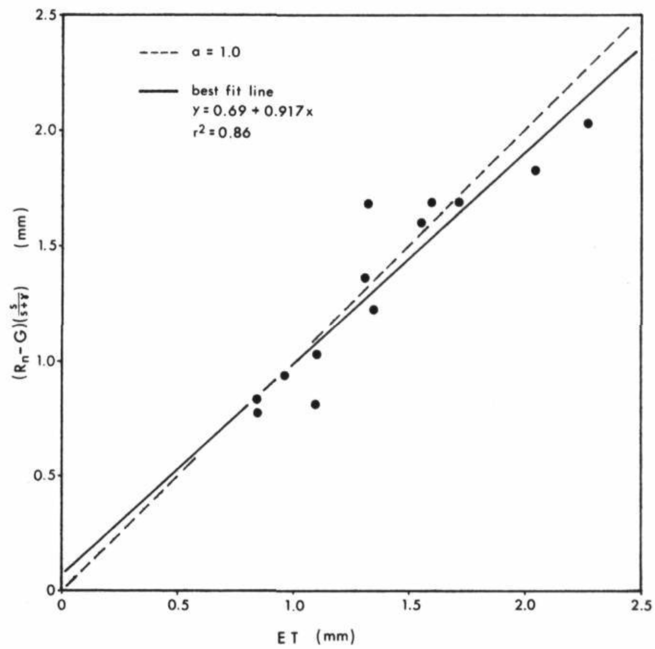

FIGURE 5. Comparison of ET estimated from lysimeters and the equilibrium form of the combination model. Data points represent mean values for 3 to 6 day periods during July and August 1977.

Comparaison entre le taux d'évapotranspiration estimé par les lysimètres et le taux prédit au moyen du modèle de combinaison. Les points représentent des valeurs moyennes pour une période de 3 à 6 jours pendant les mois de juillet et août 1977.

SOIL MOISTURE STORAGE

Saturated Zone

In addition to being the principal medium for the suprapermafrost groundwater flow, the saturated zone also represents a very large soil moisture reservoir. The amount of stored water is strongly controlled by the relative rates of precipitation and ET and is therefore quite variable, responding particularly to precipitation, which is more variable than the rate of ET. Depletion of the zone occurs as a result of both ET and groundwater flow. Figure 6 depicts the thickness of the saturated zone and depth to the frost table during June, July, and August, 1977. It can be seen that the layer did not become well developed until the heavy rains in early July and that it was fairly sensitive to the rainfall events thereafter. Variations in the amount of stored water within the saturated zone do not seem to be related to the rate of ET, as is the case in other northern regions (DINGMAN, 1971; WOO, 1976).

Despite the relatively large storage capability of the saturated zone, its overall importance to the water budget is small on a seasonal basis. Over shorter periods, however, the change in the amount of water stored in the saturated zone can be the largest component in the budget, particularly late in the thaw season (LEWIS, 1977).

Unsaturated Zone

In contrast to the amount of water stored in the saturated zone, the soil moisture storage in the unsaturated zone is relatively constant in central Ungava as well as many other permafrost areas. This is largely due to the rarity of moisture deficits and the relatively shallow depth to the saturated zone. The infrequency of deficits is a result of the low ET rates and the cool, drizzly summers characteristic of central Ungava. The

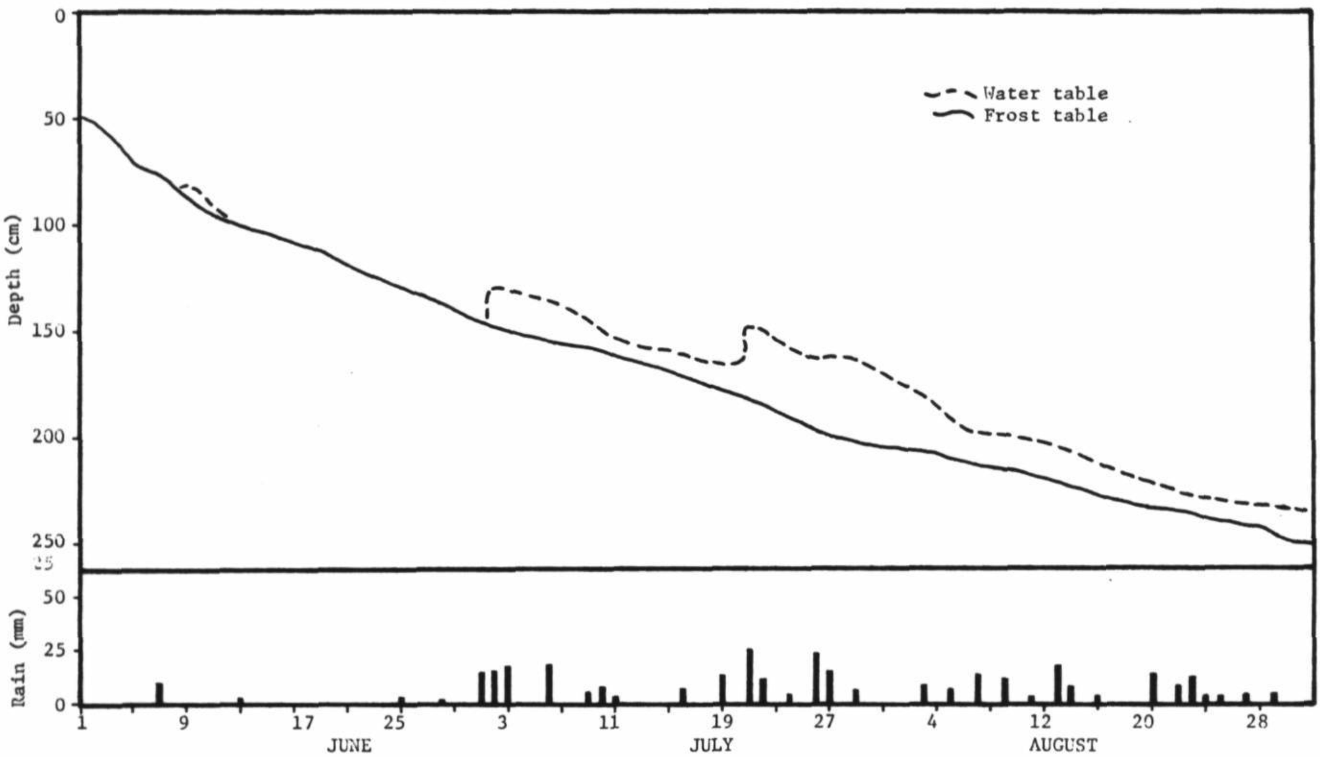

FIGURE 6. Depth of the frost and water tables and daily precipitation during the summer of 1977 at cable 5 (30% lichen cover within 1 m radius of cable head), Hematite.

Profondeur de la nappe phréatique et du niveau supérieur du pergélisol ainsi que les précipitations quotidiennes, câble n° 5, site Hematite; 30% de la surface adjacente (rayon = 1m) est recouverte de lichen.

shallowness to the saturated zone is important, particularly in fine-grained materials, because a significant proportion of the active layer can be within the capillary fringe developed by the saturated zone. Despite this, very dry periods, such as June, 1977 (when less than 20% of the normal monthly rainfall was recorded at Schefferville), can lead to significant short-term depletion, especially since ET and groundwater flow tend to exhaust the saturated zone storage during those periods.

Frozen Soil Moisture

Although moisture storage in the frozen state is not a characteristic unique to permafrost areas, the annual changes in the phase of water within the active layer play a major role in the water balance as well as the development of the active layer. When the mean daily temperature drops below 0°C in the fall the surface freezes and forms an essentially impermeable barrier to further moisture exchanges between the active layer and the atmosphere. It does not, however, eliminate either reduction of total moisture storage in the saturated zone or redistribution of moisture within the unsaturated zone.

The soil is often at or just below field capacity because the period prior to freeze-up tends to be very cool and moist in central Ungava (rainfall often being augmented by the melting of an early snowpack). It is unlikely that complete freeze-up occurs with soil moisture in excess of field capacity except in very fine-grained soils where gravity drainage is relatively slow. For example, the complete melting of a 15 cm snowpack and heavy rain in late October, 1977 produced a saturated zone almost 2 m thick at Hematite. Despite a relatively rapid freeze-up in succeeding weeks the saturated zone disappeared, presumably by suprapermafrost groundwater flow.

The reduction of the saturated zone during freeze-up is largely due to suprapermafrost groundwater flow, but there is probably a minor amount of transfer to the unsaturated zone. These upward transfers from the saturated to the unsaturated zone, as well as within the unsaturated zone, occur as the result of a water potential gradient set up by the attenuation of the interfacial films on the soil particles (DIRKSEN and MILLER, 1966). Because the thickness of the interfacial films is a function of temperature, the temperature field within the soil can be considered to act in a manner analogous to the hydraulic gradient in an unfrozen soil (HARLAN, 1974). Thus, in very fine-grained soils the rate of flow might be sufficiently slow that a significant pro-

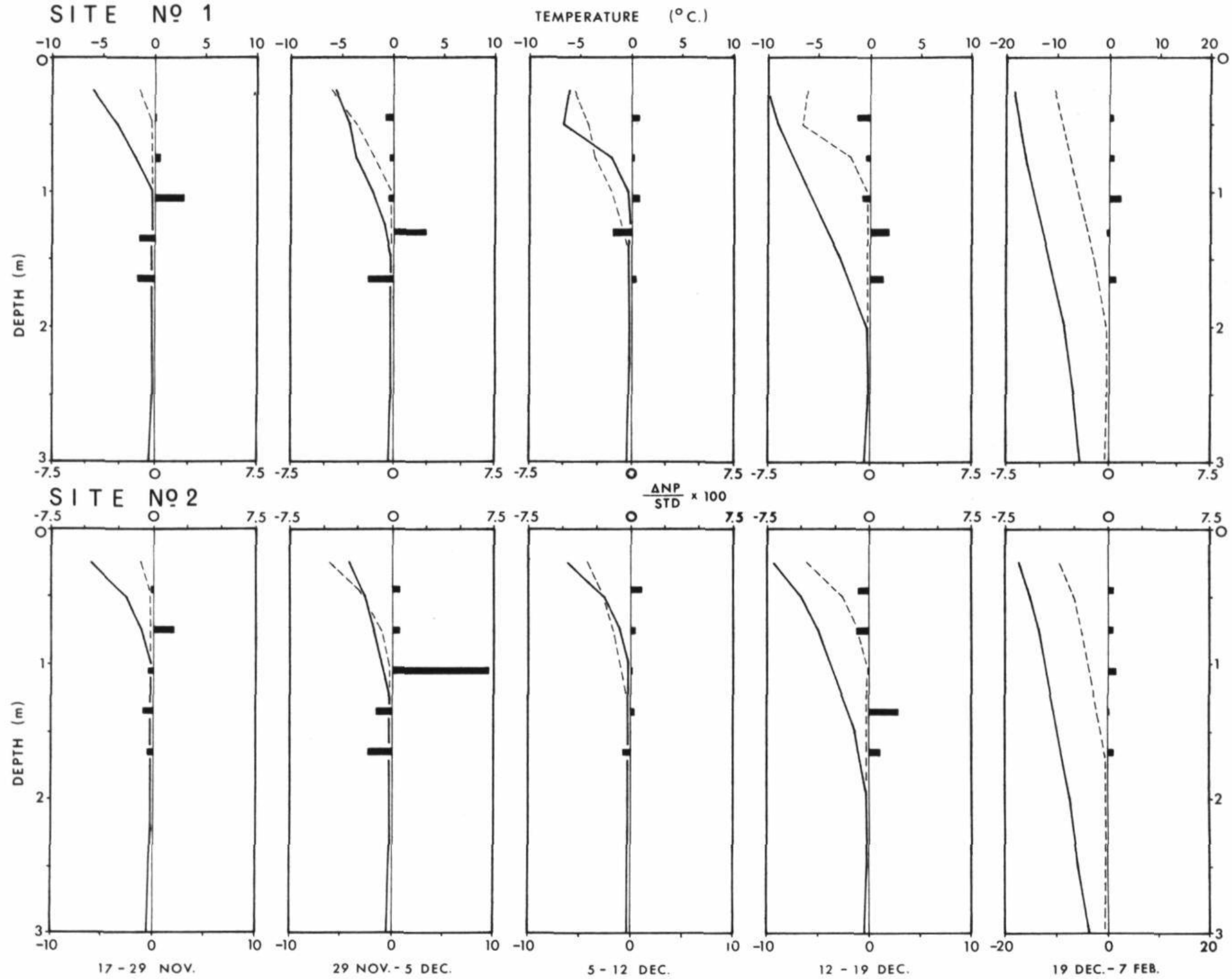

FIGURE 7. *Ground temperature profiles and change in* neutron probe counts during freeze-up, 1977-78 at sites 1 and 2. Dotted line represents temperature profile at the beginning of the indicated period while solid line indicates profile at end of the period. Bars represent the change in the ratio (expressed as a percentage) of thermalised neutrons counted (Δ NP) *relative to the standard count* (STD). Manufacturer's calibration indicates that 1.0% change in ratio equals 0.3% change in volumetric moisture content. Ratio changes greater than 0.5% are significant with $\alpha = 0.025$.

Profils thermiques et changements dans les calculs de la sonde à neutrons pendant la période d'engel (1977-1978) aux sites nos 1 et 2. La ligne brisée correspond au profil thermique au début de la période d'observation tandis que la ligne pleine représente le profil thermique à la fin de cette période. Les traits horizontaux représentent les changements dans la proportion du nombre de neutrons calculés (Δ NP) par rapport au calcul habituel (STD). Le calibrage de la sonde montre qu'une variation proportionnelle à 1% équivaut à un changement volumétrique de l'humidité du sol de l'ordre de 0,3%. Les variations de proportions supérieures à 0,5% ont une valeur significative lorsque $\alpha = 0{,}025$.

portion of the moisture could be frozen *in situ* or transferred to the unsaturated zone by the potential gradient induced by the temperature field.

Data in support of this concept is depicted in Figure 7[1], which shows values of water contents (as neutron probe measurements) from early November, 1977 to February, 1978 at Hematite. It can be seen that until early December there is a tendency for an increase in moisture content at or just above the freezing front and for a decrease below it. However, there was a relatively warm period in early December and this led to changes in the temperature field and a halt in moisture transfers, indicating that the temperature field is a significant

1. Changes in neutron probe count rates cannot be directly related to changes in volumetric moisture content because the presence of iron minerals distorts the instrument's calibration. Nevertheless, count rate changes are proportional to moisture content changes.

force in effecting the moisture transfers. After 19 December the ground remained solidly frozen and there was little significant moisture transfer until the ground began to thaw in the spring.

Runoff

After the field capacity of the active layer is exceeded and a saturated zone develops, the rate of subsurface runoff (suprapermafrost groundwater flow) is controlled by the thickness of the saturated zone (d), the topography of the frost table, and the hydraulic conductivity of the saturated material (k). Although it would be desirable to be able to describe the flow of suprapermafrost groundwater by Darcy's Law, that approach is infeasible in most field situations because d and k are difficult to assess, especially k since the bulk of the groundwater flow often moves along very small zones of very high permeability such as joints and/or zones of intense leaching. It is probable that most wetlines represent such areas of relatively high permeability and a mass-budget analysis by J. S. Lewis (pers. comm., 1978) indicated that this was the case at Timmins 4.

SUMMARY

The role of water in modifying the development of the active layer can be considered on two levels. If the vertical exchanges alone are considered then the role of water lies in modifying the values of λ and C, particularly with respect to the energy exchanges involved in the heat of fusion of water. Because the active layer is defined as that rock or soil which annually cycles through 0°C., these parameters, and their relationship to the moisture content, become of critical importance to the rate of development of the active layer. Alternatively, the lateral transfer and subsequent percolation along the wetlines of the suprapermafrost groundwater and the associated sensible heat can lead to active layers several times the depth of adjacent areas not subject to the lateral heat transfers.

In turn, the rate of development of the active layer partially controls the degree to which the infiltration in excess of field capacity is confined to a satured zone on top of the frost table. The presence of the saturated zone means that more water is available for surface moisture exchanges, keeps soil moisture in the unsaturated zone close to field capacity, and plays a major role in sustaining runoff through suprapermafrost groundwater flow, as well as in the formation of wetlands which significantly increase the amount of evaporation in northern environments.

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