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The Effects of Frozen Soils on Groundwater Recharge and Discharge in Granitic Rock Terrane of the Canadian Shield

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Hydrologic measurements on groundwater flow systems of the Canadian Shield during the winter period provide insight into groundwater dynamics and can support conclusions based on measurements of the more "active" spring-to-fall, open-water period. To illustrate this, we present the results of detailed and continuous year-round measurements of parameters such as groundwater levels, air/soil temperatures, soil heat flux and soil moisture content which were made in upland recharge and wetland discharge areas of a local groundwater flow system in granitic terrane of the Canadian Shield.

Recharge to the groundwater flow system in the rocks of the study area occurs as rain or snowmelt waters infiltrate exposed vertical and/or sub-horizontal soil-infilled fractures in outcrops of the upland area. During winter, soils in the fractures of the recharge area do not normally freeze below 0.5 m depth and shallow (5-20 cm depth) soil temperatures are most often only 1-2°C below freezing. During the spring melt period the temperature of these frozen soils remains near 0°C for several weeks as the pore ice absorbs thermal energy necessary for the phase transition from ice to water. However, despite these soils being completely or partially frozen, infiltration and recharge to the groundwater flow system in the rock occurs as shown by large and rapid rises in watertable and piezometric levels.

In the groundwater discharge area of this flow system, near-surface soil temperatures (5 cm depth) reached minimums of about -12°C during the 1996 winter and freezing soils extended downward to more than 75 cm depth. During the spring melt period, as meltwaters add heat to the substrate, these shallow soil temperatures also rise to near 0°C and remain frozen for several weeks as latent heat of fusion of ice becomes a factor. However, during the spring melt period, while ice covers the surface and soils are still frozen in the discharge area, groundwater level rises are recorded in both the overburden and bedrock of the discharge area. This is attributed to hydraulic pressure being rapidly transmitted to the discharge area through the low storativity groundwater flow system in the rock from the large waterlevel increases occurring in the rock of the adjacent upland recharge area.

Introduction

As part of the process of evaluating the potential of crystalline rocks to serve as a medium for nuclear fuel waste disposal, Atomic Energy of Canada Limited has conducted geological, hydrological and hydrochemical investigations in granitic terrane environments of the Canadian Shield. In Southeastern Manitoba, a 4.8 km area of leased land, referred to as the URL lease area (Fig. 1), has been extensively studied since the early 1980's as part of the Canadian Nuclear Fuel Waste Management Program (CNFWMP). An important component of these investigations has been the evaluation of the hydrological processes, timing, and quantities of groundwater recharge and discharge in granitic terrains (Thorne 1992; Thorne and Gascoyne 1993; Thorne and Gascoyne 1995).

To better understand the hydrological processes that control groundwater recharge and discharge in Shield terranes, a study area was chosen on the URL Lease Area for additional investigations. The study area included an upland area of exposed rock outcrop where recharge to a local flow system occurs and adjacent lowland wetland area where discharge occurs. Instrumentation was installed in the upland recharge area in 1989 and continuous monitoring and data analysis showed that study of winter period hydrological phenomena was important for obtaining a better understanding of groundwater dynamics in these terranes (Thorne *et al.* 1994). These studies also indicated that to better define the hydrological processes and associated groundwater recharge and discharge during winter periods similar instrumentation would have to be installed in the bedrock and overburden deposits of the discharge area of this flow system. In 1993, dataloggers and sensors for the measurement of soil and air temperatures, soil heat flux, and groundwater levels were installed in the wetland discharge area of the study area.

This paper describes the winter and spring melt period measurements and observations made during 1994/95 and 1995/96, and discusses the interaction between climatic conditions, the thermal regime of rock and soils, and the control that factors such as frozen soils have on groundwater recharge/discharge and flow patterns for this local groundwater flow system.

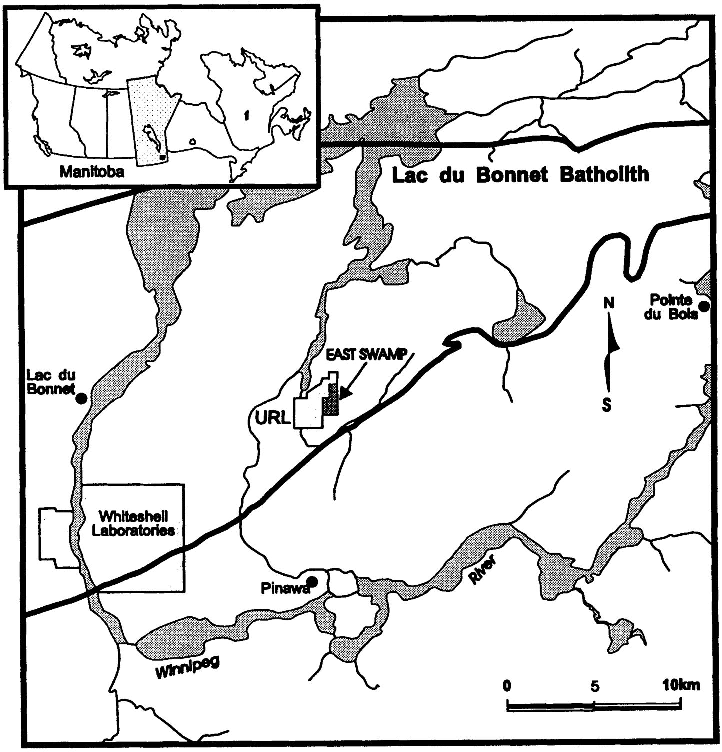

Fig. 1. Location Map.

Study Area Description and Hydrology

The study area is located on the Lac du Bonnet Batholith, a large granitic intrusion which is covered with Paleozoic and Quaternary deposits to the west but has large areas of outcrop exposure in the east. The small groundwater flow system chosen for this study has an upland recharge area that consists of a ridge of rock outcrop which has scattered depressions filled mainly with either clay-rich lacustrine sediments or shallow organic soils and peat. Vertical and sub-vertical fractures are exposed on the outcrop of the upland recharge area. Some of these have apparent open apertures of 10-15 cm and are 10's of metres in length, striking normal to the outcrops eastward slope. The wider-aperture fractures are infilled at the outcrop surfaces with soil having a composition of 80% sand, 19% silt and 1% clay (Thorne *et al.* 1994). Other sealed fractures, with little or no open aperture, are also present in the outcrop recharge area , but have much less potential of being conductive pathways for infiltrating surface waters. While some of the wider-aperture fractures may be capable of rapidly transmitting infiltrating surface waters, the overall hydraulic conductivity of the rock of the upland recharge area is relatively low. Sixteen single-well response tests were completed in various boreholes drilled into the upland area and these yielded hydraulic conductivity values of 5.0×10^{-10} to 7.0×10^{-7} m/s (Thorne and Gascoyne 1995). Vegetation in the upland area is sparse and mainly limited to soil filled depressions of the bedrock. Thicker soil deposits of the topographically higher areas support the growth of stands of jackpine. Some of the wider aperture, soil infilled fractures, support vegetation such as willow, grasses and peat.

The adjacent low-lying discharge area is mainly covered with clay-rich lacustrine sediments and glacial till deposits. These are usually about 5 m thick although thicknesses of 16 m have been intersected by boreholes in the northeast parts of the study area. Single-well response tests were performed in boreholes drilled into the overburden deposits of the discharge area and yielded hydraulic conductivity values of 10^{-9} to 10^{-6} m/s. The watertable within the discharge area is a subdued replica of the topography ; it is often near ground surface, and normally fluctuates less than 0.5 m annually. Several perennial ponds, some controlled by beaver dams, occupy the eastern margins of the study area. Vegetation in the wetland discharge area is denser, with coarse grasses, sedges and willow being the predominant ground cover and occasional clumps of black spruce as the main tree species.

Instrumentation and Methods

Groundwater monitoring instrumentation was initially installed in boreholes (B-series) of the recharge area of this study area as part of the URL site characterization program of the early 1980's (Davison 1984). Since then, additional boreholes (R-series) have been drilled up to a depth of 50 m into the bedrock of the upland recharge area. In the adjacent lowland discharge area, boreholes (O-series) have been augered into overburden deposits, and shallow boreholes (< 10m length) have been drilled into bedrock (Fig. 2 A,B). All boreholes have been completed with groundwater monitoring instrumentation to allow determination of vertical and horizontal hydraulic gradients. Manual or continuous water level monitoring has been maintained since the groundwater monitoring wells were installed.

Meteorological instrumentation was installed, and a concrete dike was constructed , to create a 1,175 m^2 catchment area (Fig. 2A) on an eastward sloping outcrop of the upland recharge area. A 60° v-notch weir, pressure transducer and Campbell Scientific datalogger are used to measure stage and record runoff from the catchment area. Meteorological parameters such as air temperature and relative humidity are recorded continuously within a Stevenson Screen. A tipping bucket rain gauge connected to a data logger records rainfall intensity and duration.

Separate instrument packages, consisting of air/soil thermistors, a CSIRO heat flux plate, soil moisture wafers and pressure transducers for water level measurement were coupled to Campbell Scientific dataloggers to continuously monitor the various parameters. In the upland recharge area, measurements of soil heat flux, soil

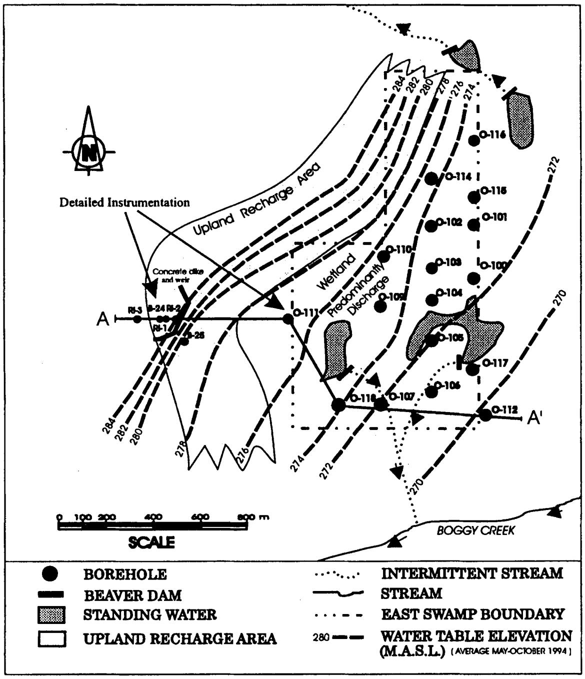

Fig. 2a. Instrumentation and recharge/discharge areas of the East Swamp.

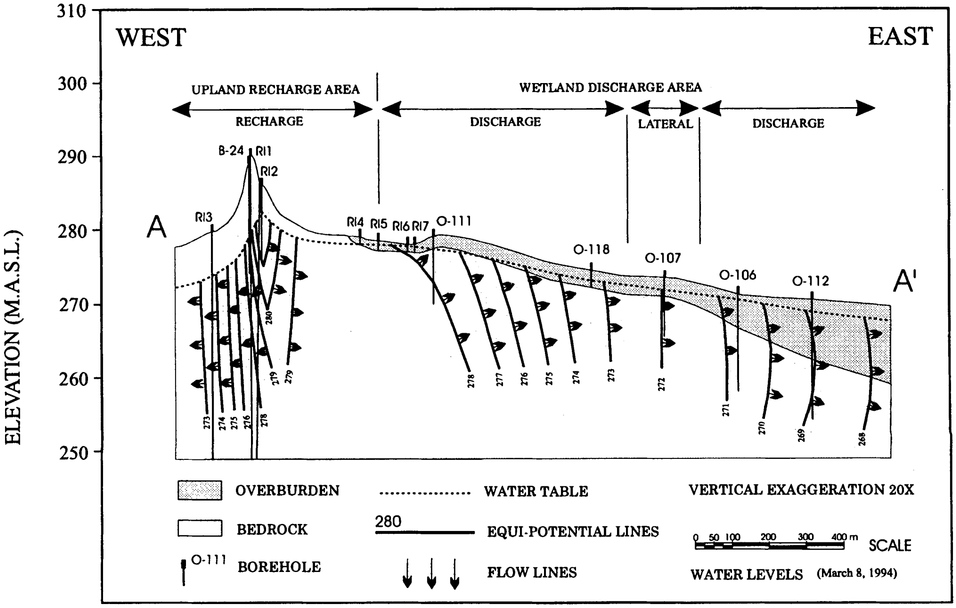

Fig. 2b. Groundwater flow patterns for the study area.

temperatures and soil moisture content were made in the infilling soils of a 10-15 cm aperture fracture, while water level measurements were made in adjacent groundwater monitoring wells. In the groundwater discharge area , soil temperatures and heat fluxes were measured in clay-rich sediments (4 m thick) adjacent to piezometer nest O-111, (Fig. 2B) in which continuous water level recordings were taken.

The programmable dataloggers allowed for frequent parameter sampling and recording (*e.g.*, hourly averages) to facilitate a comparison between hydrological processes and groundwater level fluctuations. Data was transferred from dataloggers deployed in the field to office computers via portable tape recorder transfer, VHF radio transmission or overland cable link.

Frozen Soils, Infiltration and Recharge in Upland Recharge Area

Daily-mean air/soil temperatures, snow pack depths, soil heat flux, daily mean soil moisture potential and groundwater levels for a bedrock borehole collected during the 1994/95 winter period are shown in Fig. 3. Air temperatures recorded in the study area dip below 0°C in mid-November and remain below freezing until March 9, except for two brief (mid-day) periods in December. These short, above-freezing air temperature spikes did not cause snowmelt within the snowpack. This is shown by continuous negative soil heat flux and soil moisture measurements made at the soil-snowpack interface within the upland recharge area. The soil moisture did not increase at even shallow depth (10 cm) during these brief periods of above freezing temperatures. This indicates that no snowmelt waters, or large enough ground heat flux or air temperature that could add a positive heat gain to the soil overlying the fractures, occurred during this period.

The most negative heat fluxes from the shallow soil infilling the bedrock in the upland recharge area are recorded during the autumn to mid-December period. This is due to the combined effects of cold temperatures and the lack of snow cover (Thorne *et al.* 1994).

Coincident with daily mean freezing temperatures, snow accumulated at a relatively even rate over the winter period. When the snowpack attained a depth of 20 cm, the negative soil heat flux (representing a loss of heat) became rather constant regardless of daily mean temperatures. During this winter period (mid-January to mid-March) the daily mean air temperatures remained well below freezing (-5 to -25°C) for extended periods.

Temperatures in the soil within the fracture reflect the combined effects of snow pack accumulation, soil heat flux and air temperature. As air temperatures decrease during the fall and early winter period, rather rapid decreases in the soil temperatures were recorded. However, freezing of soils in the fracture was not recorded at even the shallow depth (5 cm) until late November. From mid-December until March 9, the soil temperatures at this depth were at -2 to -3°C with a decrease to

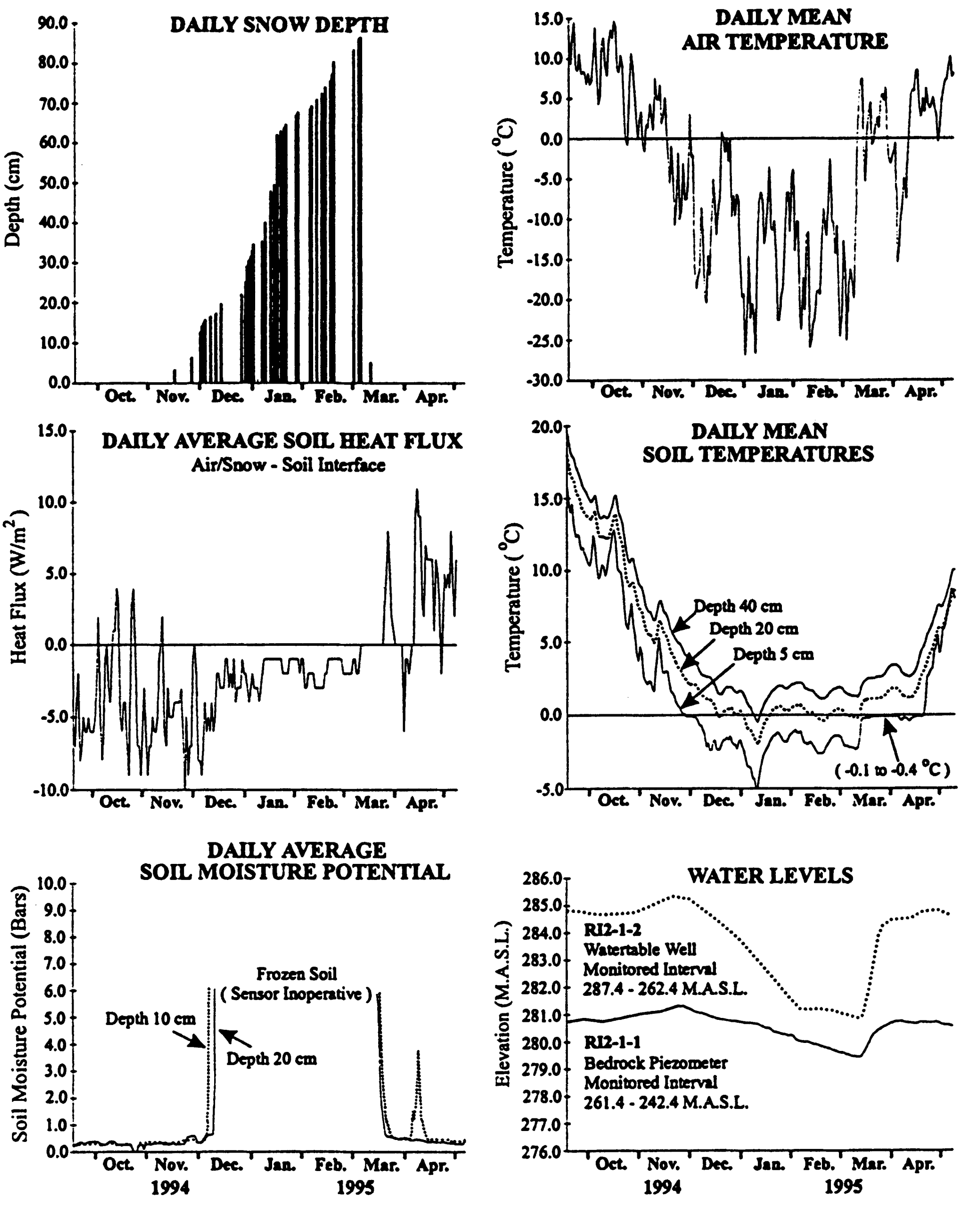

Fig. 3. Snow depth, air and soil temperatures, soil heat flux, soil moisture potential and water levels for the outcrop groundwater recharge area.

about -5°C in early January. The reduced rate of freezing or heat loss is coincident with snowpack accumulation and results in soil freezing to only shallow depths within the soil infilled fractures. At 20 cm depth, the soil temperature remained

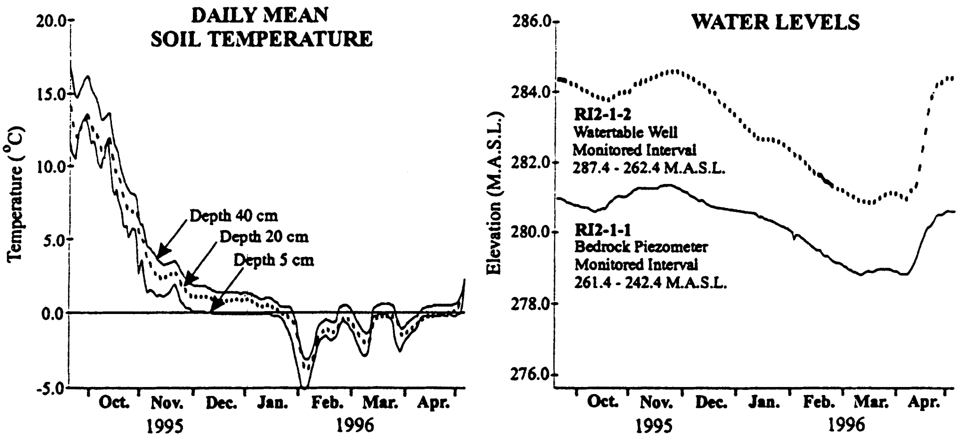

Fig. 4. Soil temperature and groundwater levels for the upland recharge area for the winter of 1995/96.

rather constant around 0°C and at a depth of 40 cm frozen soils are recorded for only a few days in mid-January. During the remainder of the winter period, soils at 40 cm depth were above freezing at temperatures of 2-3°C.

The winter of 1995/96 had well-below normal temperatures, including a near record 20-day cold period when the daily maximum temperature did not rise above -20°C. However, in spite of the prolonged low temperatures, the soils infilling the fracture at the upland recharge area did not freeze below 5 cm depth, until late January (Fig. 4). The reason for the lack of freezing is the insulating properties of the snowpack. For the 1995/96 winter period, snow began to accumulate early (October) and by late December the snowpack was about 35 cm thick.

Water levels within the bedrock of the upland recharge area showed a rise during the late autumn in response to a wet period just prior to freeze-up. During early winter of 1994/95 large vertical hydraulic gradients about (0.1) existed in the rock of the upland area as there was a 4-m elevation difference between the water table and deeper bedrock monitoring intervals. From late November until early January February, the water table (RI21-2) decreased about 4 m (a normal winter recession as the rock fracture network is drained) until it leveled off at about 1 m of hydraulic head above the piezometric level (RI21-1, Fig. 3). The water level declined when snow and/or ice accumulated on the outcrop. Despite the lack of infiltration, groundwater recharge to the deeper fractures within the rock continued to persist throughout the winter. These hydraulic head differences and water levels were relatively stable until the onset of recharge from snowpack melt during mid-March.

The snowmelt during 1995 March was exceptionally rapid and there was nearly a complete loss of the accumulated 90 cm depth of snow in the study area during a 3-day period (March 11-13). During this rapid melting period, maximum air temperatures reached 15°C and daily means ranged from 5-7°C. Normally snowmelt occurs in the study area over a 2-3 week period during late March or early April. Observations of the soil temperatures at 5 cm depth in the soil infilled fractures are of particular interest, as snowmelt waters infiltrate the soils and recharge the groundwater flow system. While the soil temperatures at 20 and 40 cm depth are about 2 and 4°C respectively, the soil temperatures at 5 cm depth remain at -0.1 to -0.4°C from March 12 to April 18 (Fig. 3). These soils which are near 0°C can be either completely or partially frozen. This is due to the potential depression of the freezing point due to solutes within the soil (Freeze and Cherry 1979). However, given the long period (5 weeks) of near-freezing temperatures and a measured decrease in soil temperatures during the springmelt period, it is likely that ice and ice lenses were present within the soils infilling the fractures. This pattern of soil heat gain, (where shallow soil temperatures remain near 0°C followed by a longer period before complete thawing occurs) was repeated in the upland recharge area during the spring melt period of 1996 (Fig. 4). This is attributed to the heat of fusion of water amounting to 80 cal/gm of pore ice within the frozen soils (Weast 1987).

The rapid snowmelt produced an excess of moisture available for infiltration into the large-aperture fractures at the upland rock outcrop area and runoff occurred. However, despite the fact that frozen or partially frozen soils still existed within the larger-aperture fractures of the outcrop, there was not any significant limitation on surface water infiltration in the rock of the upland recharge area during the melt period. The type of soils, amount of ice and the moisture content of the soils at time of freezing would affect the infiltration rate (Kane and Stein 1983). In response to the infiltration, the watertable (RI2-1-2) in the rock of the upland area rose about 3.5 m during a one week period of both 1995 and 1996. This rapid water level rise measured in 1995 and 1996 is common to other boreholes of the recharge area and long-term water level records also show that the hydraulic head difference between the water table and deeper piezometric monitoring intervals has persisted. This indicates sustained groundwater recharge conditions in the upland area. At depth, the piezometric water level rise (RI2-1-1) was less, about 1 m. This corresponding piezometric increase at depth indicates the interconnectivity of the larger aperture surface fractures with the water table and the hydraulic coupling of the water table to deeper parts of the groundwater flow system in the upland recharge area.

Frozen Soils and Groundwater Discharge in Wetland Area

Daily mean air/soil temperatures, snowpack depth, weekly average soil heat flux, and groundwater levels for both the overburden and bedrock for 1994/95 winter period are shown in Fig. 5.

As with the shallow soils of the upland recharge area, the largest soil heat losses (fluxes) are measured in the early winter period, prior to the accumulation of signi-

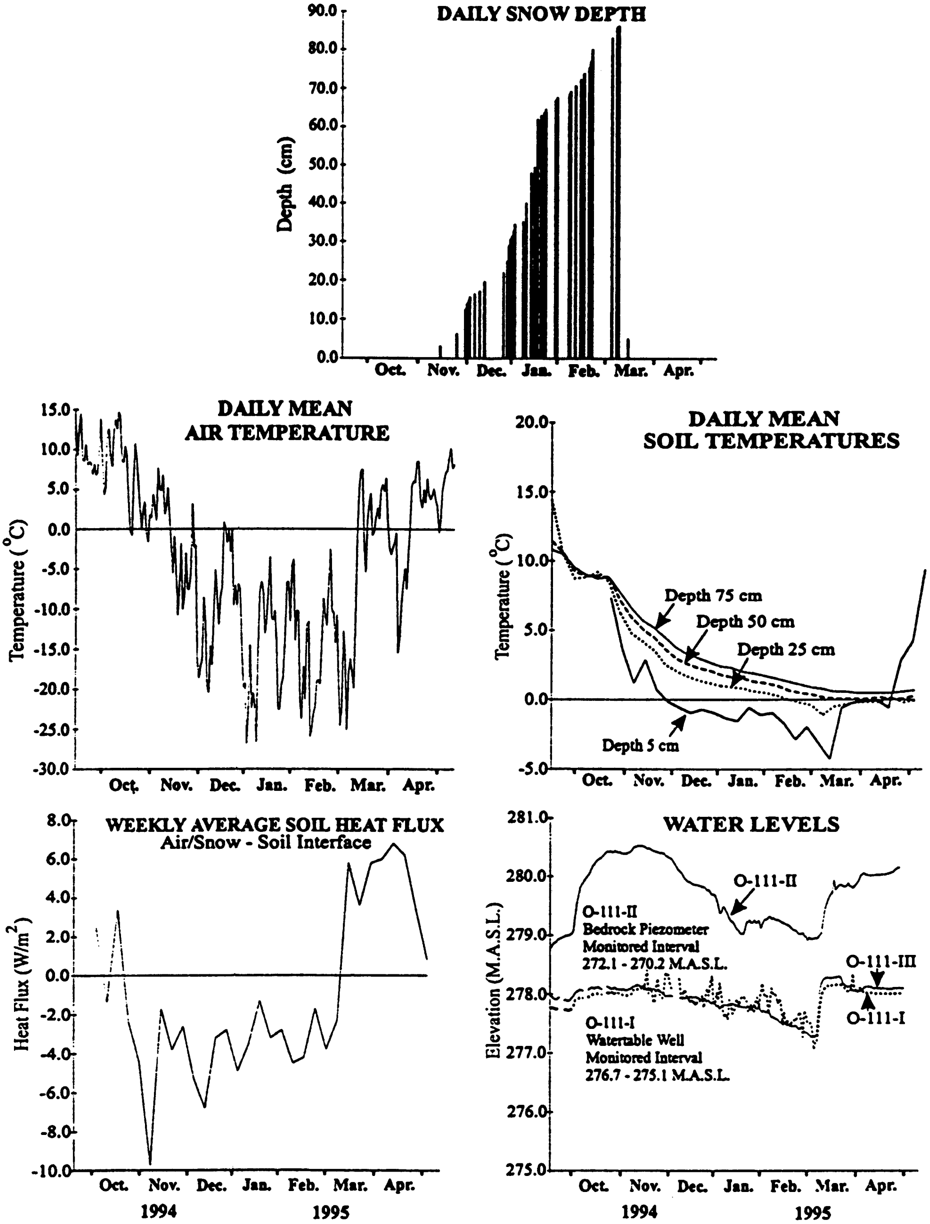

Fig. 5. Snow depth, air and soil temperatures, soil heat flux and groundwater levels for the wetland discharge area.

ficant snowpack. Once a snow pack is established the rate of heat loss is reduced and the soil heat flux begins to respond to air temperatures on a periodic basis (longer-term). This is reflected in the time and depth of freezing of the organic mat and clay soil of the discharge area. While the organic soils at 5 cm depth froze by mid-November, the clay soil at a depth of 25 cm did not freeze until mid-February. The soils at a 50 cm depth attained a near freezing temperature for brief periods during March and April and the temperature of the soils at 75 cm depth never decreased below about 0.5°C. Therefore, for this winter period the depth to which soil in the discharge area froze was shallow.

With the commencement of the springmelt, a positive soil heat flux was recorded at the snow pack-soil interface as the soil temperatures at a depth of 5 cm increased in temperature. However, the shallow soils remained frozen and the recorded temperatures at this depth ranged from -2.0 to 0°C during the March 11 to April 14 period. The reason for the extended period of frozen soils related to the fact that the pore ice in the saturated soil absorbs thermal energy at a rate of 80 cal/gram for the phase change from ice to water. Therefore, during this snow melt period while surface waters were ponding in the discharge area and groundwater levels were rising rapidly, the soils in the discharge area remained frozen or partially-frozen near the ground surface.

The pattern of soil freezing observed in the discharge area during 1994/95 (where the shallow soils of the wetland discharge area remain near 0°C during the spring melt period) followed a similar pattern during the 1995/96 winter period (Fig. 6). However some differences, such as the depth to which soil was frozen, were evident. The entire soil profile reached lower minimum temperatures (-12°C) and froze to depths greater than 75 cm during 1995/96. With the onset of springmelt in 1996, which was much later than normal, the soil temperatures within the near surface soils (25-50 cm depth) showed a temperature response similar to the previous year, *i.e.*, attaining a temperature near 0°C and maintaining the temperature for several weeks. However, the shallow soil temperatures (5 cm depth) did not follow the same

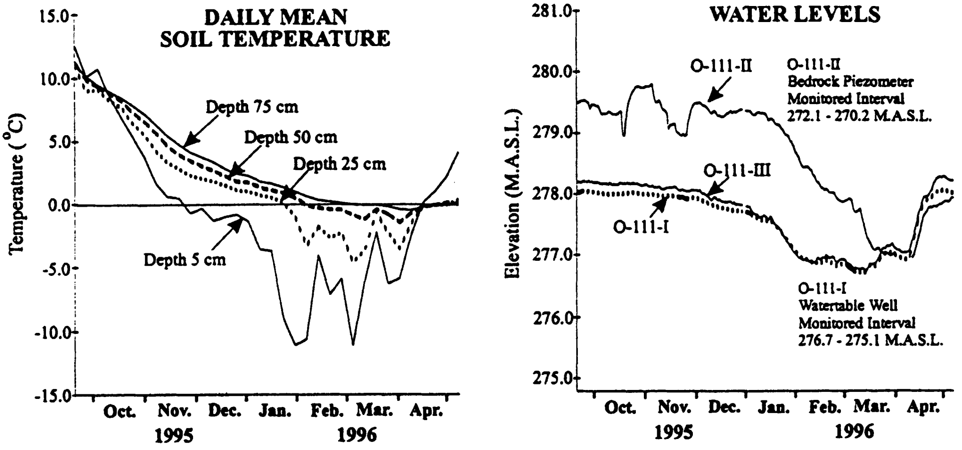

Fig. 6. Soil temperature and groundwater levels for the wetland discharge area for the winter of 1995/96.

heat gain pattern as observed in the deeper soil temperatures during the 1995 spring-melt period. The temperature of soils at 5 cm depth rose rapidly during the spring-melt period, attaining a temperature of 5°C by late April. Meanwhile the soil temperatures at 25 and 50 cm depths remained near 0°C (being frozen or partially frozen) for several weeks as the ice within the pores absorbed energy. Field observations made during this period attribute the rapid rise in temperature at the 5 cm depth to energy exchange with melt waters (Marsh and Woo 1984) and/or direct solar heating.

The waterlevels for a piezometer nest in the wetland discharge area are shown in Fig. 5. The hydrographs show a vertical hydraulic head distribution where the hydraulic heads measured in the bedrock (O-111-II) are greater than those in the overburden deposits (O-111-I, O111-III), indicating groundwater is discharged from bedrock into the overlying sediment and till deposits. Of particular interest for the spring melt period are the rapid and large hydraulic head increases observed in both the bedrock and overburden of the groundwater discharge area. As noted previously, during this period of rapid water level increases in the shallow subsurface thawed zone, the overburden deposits at surface and at shallow depths (<25 cm) remained partially or completely frozen. Similar depths of frozen soils (about 30 cm) and existence of ice crystals for several days after snowmelt was complete have been observed in other study areas of the Canadian Shield (Price and Hendrie 1983). Other field investigations, (*e.g.* by augering into peat and overburden deposits) have confirmed the existence of discontinuous frozen shallow soils and the presence of ice lenses in this study area as late as mid-June. Within the groundwater discharge area of this study most soils are clay-rich and saturated. Completely frozen soils would act as an aquitard and prevent groundwater flow from reaching the ground surface (Freeze and Cherry 1979; Everdingen 1990). When these soils are partially frozen they would restrict groundwater discharge from depth to ground surface within the wetland discharge area.

The large water level increases measured in the groundwater monitoring wells of the groundwater discharge area correlate to the even larger water level increases that occurred in the rock of the upland recharge area of this flow system. The near simultaneous rises in the water levels at both the recharge and discharge ends of the flow system leads to the conclusion that the hydraulic head increases of the discharge area are a direct result of water pressure being transmitted rapidly through the shallow groundwater flow system in the rock. These observations reveal the rapid hydraulic coupling of groundwater recharge in the upland recharge area to groundwater discharge in the adjacent, lower-lying wetland discharge area. This rapid coupling is probably caused by an interconnected network of the wide-aperture fractures in the rock that provide high hydraulic conductivity and low storativity. It also indicates that while the subsurface flow system is dynamic during this period, the shallow layers of frozen soil control or limit the actual discharge of groundwater to ground surface in the low lying discharge area.

Summary and Conclusions

These observations show that groundwater recharge at the upland recharge area was not significantly restricted or controlled by the shallow organic soils that infill the larger-aperture vertical or sub-vertical fractures that are exposed in the rock outcrop. For some winters, soils at shallow depths (5 cm) in these fractures are frozen for only a part of the freeze-up to springmelt (November-March) period while soils at depths of 20-40 cm depth are most often only near to slightly below freezing. The depth and duration to which soils in the fractures in the recharge area are frozen are controlled mainly by the depth and duration of snow cover. In the 1995/96 winter period, the depth of soil freezing within the fractures did not extend much below the depth of freezing during much less severe winters. However during the spring melt period, as air temperatures rise and meltwaters come in contact with the frozen soils, the temperature of the soil rises to near 0°C. The temperatures of these frozen soils can remain near freezing for several weeks due to the phase change (pore ice to liquid) with no concurrent increase in temperature.

In the adjacent wetland discharge area, frozen soils and surface ice cover control both lateral surface water flow and groundwater discharge. As with soils of the upland recharge area, shallow soils (5 cm depth) in the discharge area remain frozen for most of the winter period. At depths of 20 cm freezing soils are not recorded until mid-winter (January) for some years, however during extremely cold periods such as during the 1995/96 winter, soils in the discharge area freeze to a depth of over 75 cm. During springmelt, as in the recharge area, these soils remain frozen due to the phase change (pore ice to liquid) with no increase in temperature.

Comparison of hydraulic head measurements of watertable and piezometric levels in both the recharge and discharge areas of the study area show that the water level increases during the springmelt period are nearly simultaneous. The magnitude of these hydraulic head responses and the time correlation between them support the conclusion that the water level increases measured in the discharge area are due to hydraulic pressure increases that are rapidly transmitted through the groundwater flow system in the rock. This shows a rapid hydraulic coupling of groundwater recharge in the upland area to groundwater discharge in the adjacent lower-lying discharge area. These analyses also show that the actual discharge of groundwater to surface during this period is controlled by the surface layer of ice and the shallow frozen soils in the wetland discharge area.

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