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Field Observations of Small Scale Spatial Variability of Snowmelt Drainage and Infiltration

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De-icing chemicals (containing 1,2 propane diol and potassium acetate) used on airports in winter time mix with snow and start infiltrating along the runways in spring. The distribution of the chemicals over the area, and the infiltration pattern during the snowmelt period will strongly affect the efficiency of the unsaturated zone for degradation of these chemicals before entering the groundwater. Transport of de-icing chemicals and tracers in the unsaturated zone was studied in a lysimeter trench at Gardermoen, Norway during the snow melt periods of 1994 and 1995. Simultaneously, volumes of meltwater were registered from melt plates. Observations in 1994 indicated a typical diurnal process in contrast to observations in 1995 where large volumes of meltwater entered from each melt plate within a limited number of days. Temperature seemed to be the main regulating factor and cause for the observed differences between years. The overall melt pattern was well captured by a simple model based on air temperature and global radiation. Large differences in melt volumes collected from melt plates on the surface indicated a spatially variable drainage pattern strongly related to micro-topography. Infiltration rates estimated from breakthrough curves of tracers moving through the unsaturated zone at the same location were in the same order of magnitude as drainage rates found from melt plates.

Introduction

The new main airport at Gardermoen, Norway will use large quantities of chemicals for de-icing runways and aeroplanes throughout the winter season (October-April).

The chemicals potassium acetate (KAc) and 1,2 propane diol (PG) are the main constituents of the de-icing chemicals Clearway 1 and Kilfrost. By the process of mechanically removing snow from the runways, and by the drift of chemicals from the aeroplanes at take-off, the de-icing chemicals are mixed with snow and infiltrate at the soil surface along the runways when the melt begins about April. Most of the groundwater recharge in this area occurs during the snow melt period (Jørgensen and Østmo 1990). Furthermore, this is the time when the chemicals may enter soil and groundwater. Hence, the infiltration process during this period is of great importance.

We examine the heterogeneity of the drainage pattern over an area of approximately 68 m^2, at a field site near the new main airport at Gardermoen. Heterogeneity on such a small scale is relevant in situations similar to the airport situation as the potential groundwater pollutants will have a limited distribution. If a heterogeneous melt pattern causes variations of the infiltration it may affect the fate of de-icing chemicals in the unsaturated zone. It has been shown that soil can be an adequate rinsing medium for water containing de-icing chemicals (Efraimsen and Laake 1992; French *et al.* 1996 a). The concentration of the chemicals in the infiltrating water, soil temperature and the density of biologically active sites are important factors for the efficiency of the degradation in soil (Bunnell *et al.* 1977; French *et al.* 1996 a; Mørkved 1998). Several experiments have shown that concentrations are highest in the first melt water that comes from snow containing pollutants, for instance ions and de-icing chemicals (Johannessen and Henriksen 1977, 1978; French *et al.* 1996 b). It is therefore relevant to know the infiltration distribution of the first meltwater. Two-dimensional simulations of transport in heterogeneous permeability fields have shown the presence of preferential flowpaths in this type of soil even with a homogeneously distributed infiltration over the surface (French *et al.* 1996 c). A heterogeneous infiltration pattern (caused by restricted infiltration by ice and ground frost) may further reduce the volume taking part in the water flow. A reduction in the number of preferential flowpaths and higher velocities through the unsaturated zone determines the degree of degradation at the groundwater level. Correlations between measurements above and below the melting snowcover, and between the snow melt pattern and the micro-topography have been examined. All melt water is infiltrated locally as the area is flat and the soil has a large hydraulic conductivity. Ground frost, small differences in elevation (in the order of cm) and basal ice can however give local redistribution of melt water.

Snow melt and infiltration during the melt season is a complex process because it involves coupled heat and mass flow with phase changes. The climatic history of the snow-cover will affect the internal structure of the snow and the formation of ice layers or lenses within the snowpack, which in turn can give lateral flow of melt water (Gerdel 1954; Tseng *et al.* 1994). This will also affect the formation of ice lensing in the soil (Konrad and Duquennoi 1993). As the snowpack is a continuously changing medium, because of varying energy fluxes above and below the snowpack, it is difficult to monitor the various physical parameters determining the flowpattern. Various one-dimensional models have been developed which couple physical processes in the snow pack and in the ground: SOIL (Jansson 1991); SHAW (Flerchinger and Saxton 1989); FROST (Benoit 1974; Benoit and Mostaghimi 1985). The models have shown more or less good agreement with field data (Kennedy and Sharratt 1997). Such models however are unable to predict heterogeneous melt patterns and lateral flow. Tseng *et al.* (1994) developed a theoretically based model in two dimensions and simulated various heterogeneities within the snowpack. Models simulating snow melt infiltration have also been developed (Zhao and Gray 1997). One of the general conclusions from this work was that a transient regime at the beginning of infiltration was followed by a quasi steady state regime with a diurnal melt cycle. Practical problems in field work includes describing the snow-water characteristic curves as a function of time, quantifying snow grain sizes as a function of position and time *etc*. Several factors can explain a heterogeneous infiltration pattern during the melt season: heterogeneities within the snowpack, micro-topography underneath the melting layer of snow and variable frost layer in the ground below the melting snow cover. Focused recharge has been observed on silty soil at several locations (Baker and Spaans 1997; Knuteson *et al.* 1989; Derby and Knighton 1997). At these sites the focused recharge and ponding were mostly explained by topographical effects and the reduced permeabilities caused by ground frost and a thin ice layer on the ground surface. A large variation in runoff and soil percolation during the melt period was also observed by Johnsson and Lundin (1991).

This work was aimed at quantifying the redistribution of melt water that occurs during snow melt caused by small scale differences in surface elevation and ice formation on the surface. Melting rates observed on the surface and infiltration rates indirectly estimated from breakthrough curves of tracers measured at 35-90 cm depth are compared to show how the processes are related.

Method

The experimental site, Moreppen, is located in a flat, partly forested area with coarse glaciofluvial sediments (French *et al.* 1994). The geology is further documented in Østmo (1976) and Tuttle (1997). During the experimental periods of 1994 and 1995 we monitored melting underneath the snow cover, tracer transport, soil temperatures and soil water tension in the unsaturated zone, as well as climatic factors, such as air temperature, precipitation, global radiation and wind. A detailed map of the micro-topography next to the instrumentation was also made.

Before the winter season of 1993/94, one melt plate was placed on the ground surface next to the lysimeter trench (next to area C in Fig. 1) to monitor the snow melt during the transport experiments performed in the unsaturated zone during the melt period of 1994. The next year before snow fall, eight plates where placed in a regu-

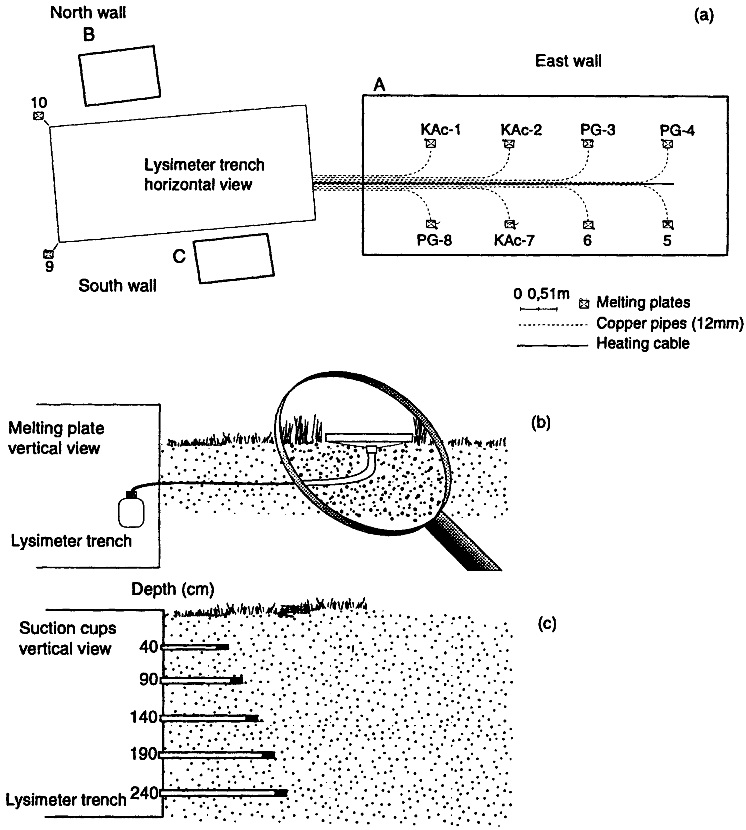

Fig. 1. System for collecting melt water (a and b). Ten collecting plates were placed as indicated, potassium acetate (KAc) and 1,2 propane diol (PG) were added to snow above plates as shown (a) and melt water drained through copper pipes (b). Collecting plates were 20 × 25 cm^2, with edges 2 cm high. Along the north and south walls of the lysimeter trench 40 and 30 suction cups are installed accordingly. Suction cups are installed horizontally and depths from the surface are indicated (c). Areas A, B and C refer to areas where the spatially varying melt pattern has been described.

lar grid within area A (Fig. 1) and two plates west of the trench covering a total area of 68 m^2. The collecting plates made of steel were 20 by 25 cm, with edges 2 cm high (Fig. 1). The plates had an angle of 1:24 towards a drainage hole 1 cm in diameter. A coarse filter (holes 2.2 mm in diameter, 1.5 mm apart, one bigger hole in the centre 1 cm in diameter) was placed on each plate to avoid particles blocking the drainage hole. Copper pipes lead the melting water through a 50 cm deep trench with a heating cable into the lysimeter trench which remains above freezing point throughout the winter season. Each pipe ended in a 10 litres collecting can. No suction was applied to the plates. No chemicals were applied above the melt plate in 1994, while chemicals were applied to the snow above some of the plates in 1995.

This may have affected the initial time of the melt. Concentration of chemicals in melt water is further documented in French *et al.* (1996 b).

Micro-topography

The micro-topography of the surface around the melt plates and above the lysimeter walls was registered in a dense grid of measuring points. The separation of grid lines ranged from 10 to 40 cm in both directions. The relative elevation at 889 points was registered and the correlation structure analysed by semivariogram modelling in Variowin (Pannatier 1994).

Monitoring of Water and Solute Movement below the Ground Surface

To ascertain whether the drainage values registered at the melt plates represent actual infiltration values, flow through the unsaturated zone at the same location was monitored. The transport of inactive tracers, through the unsaturated zone was studied in a lysimeter trench at the same site (Fig. 1) (French *et al.* 1996 a). Changes in concentration of tracer in the passing soil water was monitored by continuously exerting a suction of 0.2 bars to 70 suction cups and sampling every week during the melt period. Suction cups were placed in two different walls at depths from 35-240 cm. From breakthrough curves observed at 35-90 cm depth it is possible to obtain an independent measure of the infiltration rates. By comparing drainage volumes obtained from melt plates and estimated infiltration from breakthrough curves, we assess whether or not the observed drainage pattern on the surface is reflected in the soil infiltration. The programme CXTFIT (Toride *et al.* 1995) is a code for estimation of transport parameters from laboratory or field tracer experiments. It was used to estimate pore water velocities, v in Eq. (1) from breakthrough curves of tracers (Cl^- in '94 and Br^- in '95) found from 16 suction cups (spread out over 1m parallel to the lysimeter trench at 35 and 85 cm depth in the north wall and at 40 cm depth in the south wall). The distance from the wall to the suction cups is increased by 10 cm for each successive depth (Fig. 1 c), therefore the two top layers represent an area of 1m x 0.2 m. Assuming steady state conditions and a homogeneous soil in the top part of the soil profile the simple relation

$$v = \frac{P}{n_w} \qquad (1)$$

where v is pore water velocity, P is precipitation and n_w is water filled porosity, was used to get an estimate of P (in this case as a measure of the infiltration rate). Zhao and Gray (1997) showed that quasi steady state prevailed during snow melt infiltration. The assumption of homogeneity will be discussed later. Soil tension at 50 and 80 cm depth was measured continuously during the melt period of 1995, soil temperatures were measured at 5 depths from 40 to 240 cm depth during the period July 1994 to June 1995 and soil water content was measured in three vertical profiles at various times in April 1993 and 1994 (Kitterød *et al.* 1997). An average soil water content of $n_w = 0.2$ was used in Eq. (1).

Simulations with Melt Function in SOIL

A simple model was chosen to describe the melting of the snowpack during the experimental period. SOIL is a one-dimensional transport model for soil water and heat conditions (Jansson 1991), which also includes a snow melt function. As the Penman estimated evaporation during both melting periods was less than the precipitation it has not been considered here. Daily amount of snow melt, M (mmd^{-1}), is described by three parts: a temperature function M_T, a function accounting for solar radiation M_R, and soil surface heat flow $q_h(0)$

$$M = M_T T_a + M_R R_{is} + \frac{q_h(0)}{L_f} \tag{2}$$

Where T_a is air temperature, R_{is} is global radiation, $q_h(0)$ is heat flux through the soil surface and L_f is the latent heat of freezing (3.34E+05 Jkg^{-1}). The heat flux is positive going from air to soil and negative in the opposite direction. Reflection of shortwaved radiation decreases with increasing age of the snow. The melt rate is therefore a function of the age of the snow, t_{age}, which is defined as the number of days since last snowfall larger than 5 mm, for which the temperature was less or equal to 1.6 °C.

$$M_R = m_{R\min}\left(1 + s_1\left(1 - e^{-s_2 t_{age}}\right)\right) \tag{3}$$

$m_{R\min}$, s_1, s_2 are parameters where $m_{R\min}$ is the minimum value of global radiation influence in snow melt function (1.5E-07 mmJ^{-1}) which means 6.67 MJ is required for melting the snow equivalent of 1mm , s_1 is the radiation factor for old snow with a recommended default value of 2 which means 2.2 MJ is the energy needed to melt 1 mm of water, s_2 is the snow age coefficient, with a recommended value of 0.1. The temperature dependence, M_T, is described by

$$\begin{aligned} M_T &= m_T, & T_a &\geq 0 \\ M_T &= m_{T\min}\left(1, \frac{m_f}{\Delta z_{snow}}\right), & T_a &< 0 \end{aligned} \tag{4}$$

where m_T, is the temperature coefficient in the snow melt function (mmd^{-1}°C^{-1}). A value of $m_T \equiv 2$ is recommended by Jansson (1991) for forested areas, this coefficient was adjusted to 2.64 to fit the results of 1994. The same value was used for 1995. Parameter m_f is the refreezing efficiency coefficient in the snow melt function (m), which regulates which depth of snow is necessary for an efficient refreezing to occur. Δz_{snow} is the snow depth. The recommended value of m_f is 0.1 m which means that the refreezing is more efficient when the snow depth is less than 0.1 m. Assuming a total cover of snow and absence of ground frost the heat flux at the soil surface $q_h(0)$ (Jm^{-2}d^{-1}), can be estimated in one dimension from the temperature gradient in the soil

$$q_h(0) = -\kappa \frac{dT}{dz} \tag{5}$$

Where κ is the thermal conductivity. A tabular value of 1.5 x 10^5 $Jm^{-1}d^{-1}{}^{\circ}C^{-1}$ for sand with a volumetric water content of 0.2 was chosen (Hillel 1982). The sensitivity of Eq. (2) to temperature, solar radiation and heat flux at the soil surface was tested. All parameters were kept constant the two years.

Results and Discussion

Both years, the melt occurred during April after a winter with a stable snow cover. Still, the melt periods of 1994 and 1995 represented two "extreme" situations. A diurnal melt pattern was clearly observed from the melt plate in 1994 while this was not the case in 1995. In 1994, daily average temperatures increased throughout April, in 1995, temperatures fluctuated more and were below freezing on several occasions during April (Fig. 2). This gave rise to structural changes in the snow pack throughout the melt. In 1995 the warmer periods seem to correspond with the melt flushes observed from the melting plates (Fig. 3).

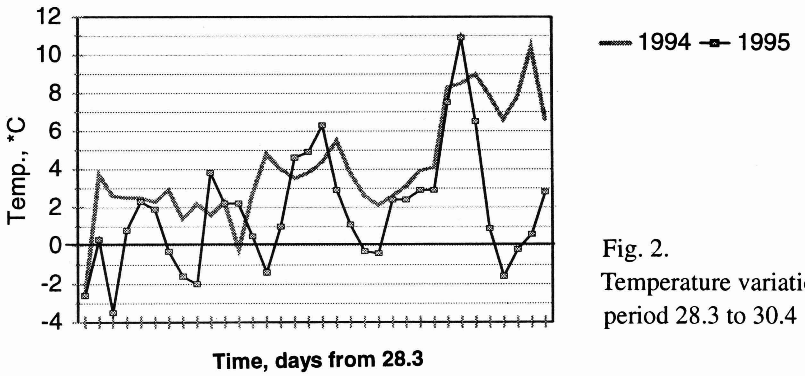

Fig. 2.
Temperature variation during the period 28.3 to 30.4 1994 and 1995.

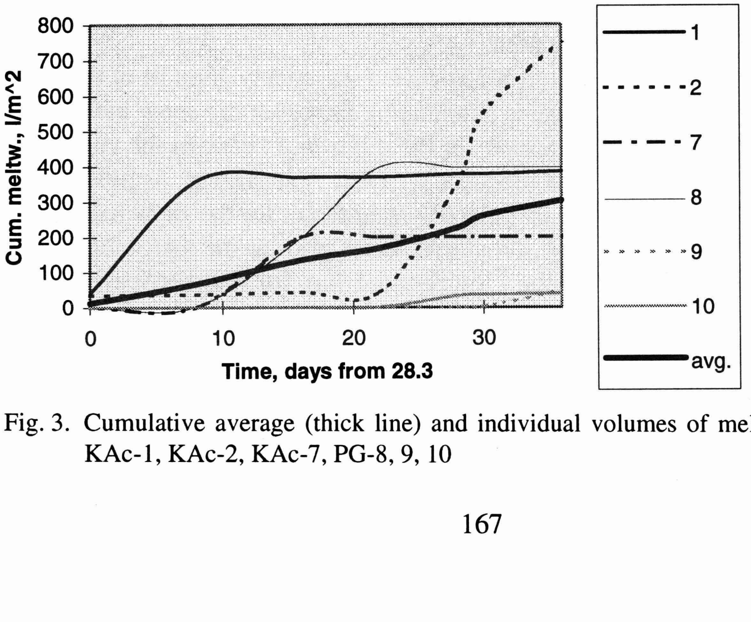

Fig. 3. Cumulative average (thick line) and individual volumes of melt water from plates KAc-1, KAc-2, KAc-7, PG-8, 9, 10

Table 1 – R squared values of linear regression analysis.

	Air temperature 1994	Air temperature 1995	Soil tension 1995
Melt volume	0.99	0.51	0.73
Air temperature			0.47

Correlations between Observations on and below the Ground Surface

Correlation analysis and linear regression between various parameters were used to examine the data (Table 1). This was done as previous work done on thermal properties of soil and in the field of snow hydrology (*e.g.* Kersten 1949 and Anonymous 1956) has shown various mechanistic and empirical relations between factors such as snowmelt, radiation, heat flux at the soil surface and so forth. An example of a combination of mechanistic and empirical relations is formulated in the melt function of the model SOIL Eq. (2).

A good correlation between air temperature and melt volumes was observed for the data from 1994, the reduced correlation in 1995 is explained by more fluctuating temperatures, and temperatures below 0°C occurring throughout the whole melt period (Fig. 2). The single tensiometer and the melt plates were separated by several metres, still a linear fit of average melt volumes *versus* tension gave a good correlation (Table 1). This could indicate a less heterogeneous infiltration process than what was expected from the melt plate observations. The correlation was reduced for individual plates. As we had limited data, the correlations are of an indicative quality only. No continuous tensiometer readings were available for 1994. Averaged daily air temperatures and soil tension showed some degree of correlation (Table 1) indicating that temperature constitutes a key factor for both the melt process and infiltration during snow melt, retention times in the snow and soil are factors which reduce the correlation.

Simulations with Melt Function in SOIL

Simulations using the melt function in SOIL gave a reasonably good fit of the overall melt pattern (Fig. 4). Temperature is a regulating factor for the snow melt development, and is probably the main reason for the difference between the two years. This was well captured by the melt function in SOIL. A sensitivity analysis of the model showed that the temperature is the dominating factor for the snow melt. Solar radiation had hardly any effect. The soil temperatures prior to the melt month were stable. We therefore assume a constant temperature flux for the melt period. This was done to obtain measure of the potential heat flux during the melt period if ground frost was absent. The temperature gradients, calculated by a linear regression through soil temperatures measured at depths ranging from 35 to 235 cm depth, at the beginning and the end of the melt period (Fig. 5), were 1.6 °Cm^{-1} and 1.26 °Cm^{-1} accordingly. We used an average value for $q_h(0)$ (Eq. (2)) of -0.2 Jm^{-2}d^{-1} for

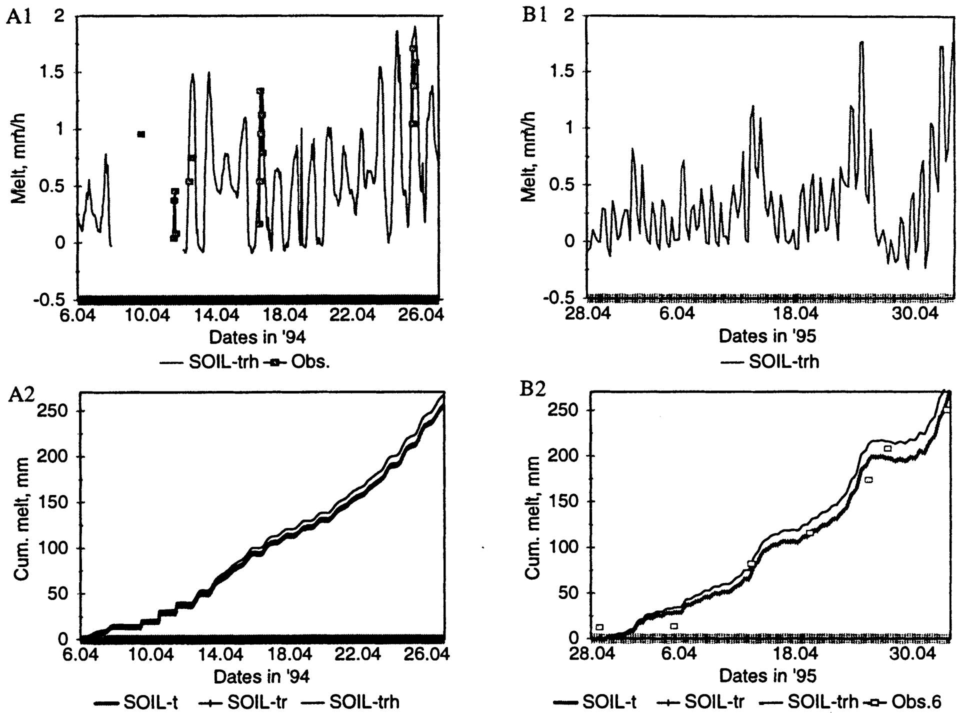

Fig. 4. Results from simulations with melt function in SOIL plotted with field results from 1994 and 1995, simulations based on 1h measurements of climatic data in 1994 (A1 and A2), and on 6h observations in 1995 (B1 and B2). The subscripts *t*, *h* and *r* indicate whether the temperature function, *t*, the heat flux at the soil surface, *h*, and the radiation, *r*, was included in the model.

the whole period for both years. The estimated value indicates an average influence of soil heat flux where ground frost is absent. Eq. (2) shows that heat flux at the soil surface can have a significant, but not dramatic, effect on the snow melt as shown in Fig. 4 A2 and B2.

In 1994, diurnal changes in temperatures were reflected in observations of meltwater from the melt plate. The simulated diurnal changes fit well with the observed values (Fig. 4 A1). Simulations of the 1995 conditions showed a less regular diurnal pattern of melt than in 1994 (Fig. 4 B1). In 1995 there were 4 or 5 main melt periods. These periods were also reflected in the cumulative curve which is a more stepwise function than what was the case in 1994 (Fig. 4 A2, B2). On the basis of cited literature and from the experience with 1D model of snowmelt there seems to be a need for a three dimensional model able to predict the thickness and heterogeneity of the ground frost, the ice formation on the ground surface, and lateral flow of melt water for more realistic simulations of spatial and temporal heterogeneity. Often field monitoring of infiltration is limited. Simple models such as the one tested for these experiments however could provide estimates of average infiltration rates for the use as boundary conditions in simulations of particular field experiments.

Temporal and Spatial Snowmelt Drainage Heterogeneity

The volumes recovered from the ten melt plates in 1995 varied from 0 to 271% of the expected volumes (Table 2) strongly indicating a heterogeneous drainage pattern. The time averaged drainage rates varied between 0 to 20.8 mm/d (Table 2). The drainage pattern could be described as large flushes of meltwater draining from different melt plates over a five to ten days period (Fig. 3). These flushes spread out over a period of approximately 30 days.

Plates number PG3, PG4, 5 and 6 (Fig. 1) all gave very low recoveries which might have been caused by a malfunctioning of the equipment. The results from these plates are therefore left out of the rest of the discussion. The varying recoveries of the applied chemicals (not shown) supported the impression from the melt water recovery, that we had little control of where the melt water drained. All melt plates, with or without applied chemicals, showed the same melt pattern. A heterogeneous ground frost was registered by piercing a metal rod through the ground surface at the end of the melt period. Ground frost had a depth of at least 40 cm during the period January-March (Fig. 5) and the ice layer on the ground surface (basal ice) varied between 5-10 cm. A heterogeneous ground frost and the resulting heterogeneous ice cover may have caused less permeable areas where there was run-off to areas of higher permeability, as observed by Lissey (1971), Baker and Spaans (1997), Brooks *et al.* (1997), Derby and Knighton (1997). Also heterogeneity within the snow pack affect the melt/drainage pattern. Our results are also supported by Tseng *et al.* (1994) who showed that, in layered volumes of snow, thin layers of denser snow or ice can form within a snowpack, giving horizontal flow of melt water. Granger *et al.* (1984) found that the snowmelt-infiltration curves may exhibit a multitude of different shapes. Infiltration to a frozen soil is strongly dependent on snowmelt rate, the water transmission and storage properties of the snow cover and the presence of impermeable ice lenses on or within the soil profile. A general conclusion from their work, was that the amount of infiltration during snowmelt varied directly with the snow-cover, and inversely with the frozen water content of the soil at the time of the melt. They also found that the infiltration could exceed the snow water equivalent because of direct contributions from surface and interflow water.

Table 2 – Amount of melt water collected in percentage of total volume expected from each plate (1995) and time average melt/drainage rates (mm/d).

Plate no.	KAc-1	KAc-2	PG-3	PG-4	5	6	KAc-7	PG-8	9	10
Water %	138.0	271.0	0.32	3.6	0.81	0	70.0	135.0	14.0	16.3
Melt/drainage rates, mm/d	1.9	20.8	0.025	0.21	0.05	0.0073	5.56	11.03	1.27	1.08

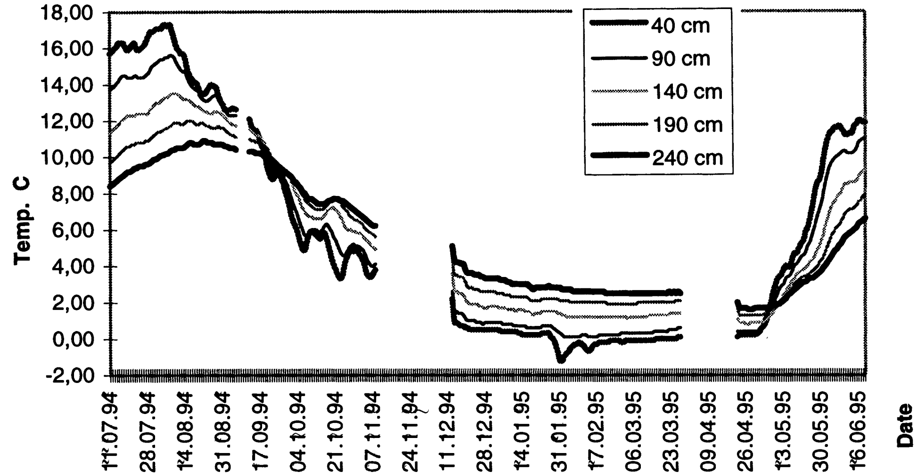

Fig. 5. Soil temperatures measured at 5 depths throughout the year July '94 to June '95.

Variations in Observed Breakthrough Curves

The good agreement between observed drainage rates and independent estimates of infiltration rates from breakthrough curves of tracer flow through the unsaturated zone gave circumstantial evidence that there was a close relationship between water collected on the surface and flow in soil. From breakthrough curves of tracers sampled at 35-90 cm depth, estimated infiltration rates were in the same order of magnitude as the melt/drainage rates found from the melt plates. With the depth of the measuring point and the time period for the tracer application as input data, the parameter estimation programme, CXTFIT, estimated values of velocity and dispersion to give the best fit to the field data (Fig. 6). We were unable to get good fits for breakthrough curves at larger depths in the profile. The reason for this is probably that the steady state flow assumption was no longer valid at these depths. The sudden drop in infiltration after the snow had melted, gave a transfer to a more transient situation. Melt and infiltration above each suction cup was calculated from Eq. (1). Data from 4 suction cups in the south wall (at 40 cm depth) and 8 in the north wall (4 at 35 cm depth and 4 at 85 cm depth) were examined. Simulations with CXTFIT with a pulse application of tracer lasting 4 days, gave average velocities ranging from 2 to 10 cmd^{-1}, and infiltration rates, P (Eq.1), between 4-9 mmd^{-1} above the 4 suction cups on the south wall and 6-20 mmd^{-1} above the 8 suction cups in the north wall. The sensitivity to the water filled porosity for the variation of P, n_w, was tested for values between 0.17 to 0.22. This did not affect the variability of the estimated infiltration to a great extent.

One of our assumptions for using CXTFIT, was that we were working with homogeneous conditions. As we know the soil is heterogeneous we compared the variation in estimated velocities with the velocity field obtained from two-dimensional

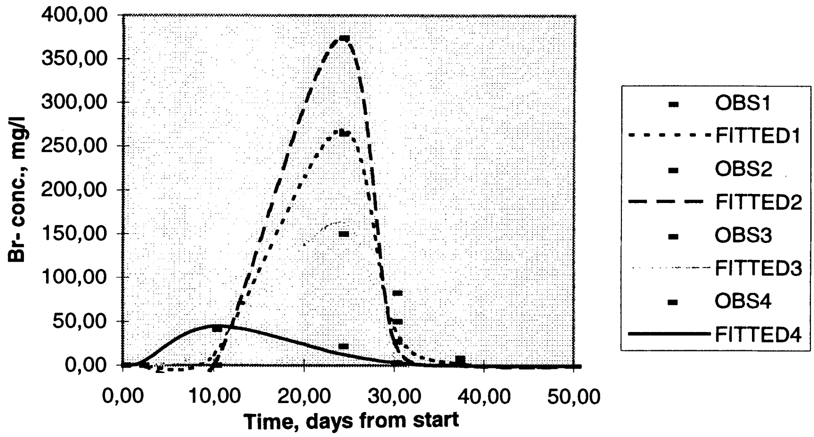

Fig. 6. Fitted breakthrough curves (CXTFIT) for Bromide sampled at 4 different suction cups at 40 cm depth at the south wall during the snow melt period of 1995.

simulations of transport in a heterogeneous profile. The simulations indicated that because of the soil heterogeneity, the variation in velocities might be larger than that found from the breakthrough curves. With this limitation in mind, we still think it is useful to know that the indirect approach gives a variation in the same order of magnitude as that found in the melt plate experiment. The observed variation in velocities could have several underlying reasons: micro-topography, soil heterogeneity and the distribution of an ice layer, it is not possible to separate these factors from the indirect method only.

Influence of Micro-topography

There was a good correlation between micro-topography and melt/drainage volumes registered from the melt plates. A linear fit gave an R squared value of 0.69 with a 95% confidence level. Visual observations in the field also pointed towards infiltration in local depressions. Although the area is relatively flat, there are large enough variations in the micro-topography (maximum elevation difference of 29 cm) to give rise to lateral water movement on the surface when ground frost and basal ice reduce the infiltration capacity. At other locations on the field site, ponding on the surface, was observed. The largest pond was 18 cm deep with an area of approximately 4 m^2. It therefore seems reasonable that some plates could have served as local drainage locations. A drainage volume 2.5 times larger than the expected (the case for plate 2) is not dramatic compared to observations made at other locations (Lissey 1971; Derby and Knighton 1997). The semi-variogram analysis of the micro-topography gave a range of 3 m in the east-west direction and a range of 1 m in the north-south direction. These values were used for interpolation with Kriging to make contoured maps of micro-topography, shown as shadings in grey in Fig. 7. The semi-variances of the time averaged drainage at the melt plates were analysed, and although

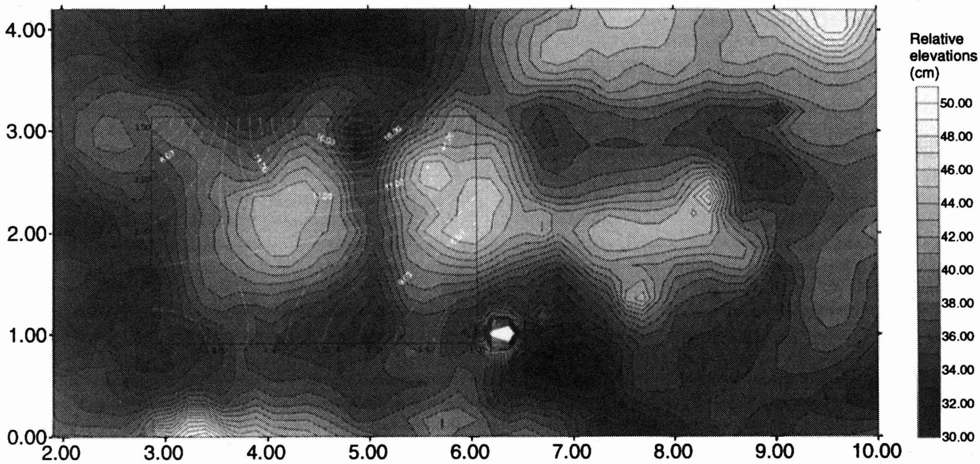

Fig. 7. Kriged interpolated map of micro-topography, overlain by contours of time averaged melt rates in area A with reference to Fig. 1a (based on 4 melting plates). Scale on x and y axis is in m.

more uncertainty was involved, they gave ranges of 4 m in the east-west direction and 2 m in the north-south direction. The cross-semivariance was also tested and gave a correlation length in the range of 1.5 to 2 m. Data from the melt plates (Table 2) were used for interpolation with Kriging to make a contoured map of time averaged melt rates as white ISO-lines placed on top of the micro-topography map (Fig. 7 with reference to area A indicated in Fig. 1).

Conclusions

The large difference between melt observations in 1994 and 1995 was mainly caused by the temperature differences during the melt month. The two years represented "extreme" situations, a steadily increasing temperature in 1994 and large temperature fluctuations in 1995, giving rise to several freeze thaw cycles. This difference was well captured by a simple snowmelt model based on air temperature and global radiation. The experiment in 1995 showed a temporally and spatially variable drainage pattern, even though the area is relatively flat. The drainage pattern was strongly related to the micro-topography. Circumstantial evidence point towards a relation between flow in soil and collected melt volumes on the surface. At our particular site with maximum elevation differences of 29 cm over a few metres, the drainage/infiltration rate seemed to vary between 2-20 mmd^{-1} during the melt period. As chemicals mixed with snow have a tendency to leach out in the first melt water, especially when it concerns de-icing chemicals, the redistribution of melt water and temporal variability of drainage should be taken into account for estimating velocities through the unsaturated zone.

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