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Infiltration into a Frozen Heavy Clay Soil

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The infiltration of snow melt water on arable land influences both the water storage and the nutrient budget. The infiltration rate during thawing was assumed to depend on the ice content of the soil. Field measurements of soil temperature, water content and infiltration rate were made and used to test a numerical model. Efforts were made to create different ice contents in three plots by adding different amounts of water before freezing as well as during winter. The total water content in spring was not influenced by the pre-freezing addition of water, but slightly increased by water added during the winter. The simulated total water content was constant throughout the winter. The measured infiltration rates were high, at maximum 8 mm/min, and the differences between the plots were small, although lower infiltration rates were found in plots with higher amounts of added water. Simulated infiltration rates never exceeded 0.1 mm/min. The discrepancy was probably due to water flow in the partially unfrozen crack system, which the model was not capable to simulate, and to a time lag in the simulated soil temperature during thawing. Low infiltration rates were probably caused by high ice content in the cracks, originating from the added water. It should be possible to predict the infiltration capacity during thawing using a simple model which treats the crack system, the water content before freezing, and the number and intensity of warm spells during the winter.

Introduction

Swedish agricultural land is largely situated on heavy clay soils. The infiltration patterns in such soils govern the transport of plant nutrients to groundwater and surface waters. A low rate of infiltration over a long period generally causes nitrate to leach from the soil, whereas a rapid infiltration through the crack system is likely to cause less leakage because in this case the water in the aggregates is not participating in the drainage. A low infiltration capacity and surface runoff during the thawing period may lead to large losses of nitrogen and phosphorus especially if manure has been applied to the soil surface. Persistent high soil water contents delay spring farming operations and cause deterioration of the soil structure in some areas, while in other areas snowmelt into the soil represents an important source of plant available water.

Komarov and Makarova (1973) and Steenhuis *et al.* (1977) state that water flow through frozen soil is more or less restricted to macropores. For soils with no cracks, there is a general consensus that infiltration capacity is lowered by high amounts of ice in the soil profile (Willis *et al.* 1961; Kane 1980; Granger *et al.* 1984). High ice contents are caused by high pre-freezing water contents in the soil or by the freezing of infiltrated meltwater during winter. The properties of the snow cover and the actual distribution of ice and ice lenses in the soil profile are additional factors governing the infiltration process.

In situ infiltration rates in frozen soils are reported to range from 0.004 to 5 mm min^{-1} (Kapotov 1972, cited by Motovilov 1979; Kane 1980; Kane and Stein 1983; Karvonen *et al.* 1986; Engelmark 1987). These values refer to silts and sands of various water contents; the high values being obtained in the drier soils. Granger *et al.* (1984) found that cracked Prairie soils had a higher infiltration capacity than uncracked soils, but no rates were presented.

Numerical modeling of soil moisture movements and infiltration in frozen soils has been performed by Harlan (1973), Guymon and Luthin (1974), Motovilov (1977), Sheppard *et al.* (1978) and Jansson and Halldin (1979) among others. Most of these models have been developed on the basis of laboratory measurements, and many have not been tested (Lundin 1989a). The model by Jansson and Halldin, however, has been tested under frozen field conditions by Halldin *et al.* (1979), Troedsson *et al.* (1982), Jansson and Gustafson (1987) and Lundin (1989b).

The objective of this paper was to measure the infiltration rate into a frozen heavy clay soil and to study the relationship between infiltration rate and ice content. The physically based numerical model of Jansson and Halldin (1979) was used to interpret the soil temperature, water content and infiltration rate measurements.

Materials and Methods

The Site

The site was located in an experimental field south of Uppsala (59°49′ N, 17°39′ E). The soil is a post-glacial, heavy clay, similar to those described by Wiklert *et al.* (1983) and Sandsborg and Wiklert (1976), with a well developed macrostructure. The clay content is around 50 % in the profile, while the humus content is about 4 % in the topsoil and 2 % in the subsoil.

Field Measurements

On three plots, each one covering 1 m^2, measurements of total volumetric soil water content and soil temperature were made from Nov. 1985-April 1987, *i.e.* two winter periods, in a profile down to 1 m depth. The plots were shielded from precipitation with aluminium plates. In order to produce a colder thermal regime the plots were frequently cleared of snow. During the first winter there was no crop at the site but from the summer of 1986 a grass ley was cultivated.

In a manner similar to Kuznik and Bezmenov (1963) the plots were prepared so that no lateral water flow could occur. Rubber sheets were installed in trenches, dug to 1 m depth around the plots. The trenches were then carefully backfilled with sand. In this way a soil monolith of 1 m^3, in hydraulic contact with surrounding soil through its base, was created. To minimize water flow along the sheets, fine silt soil was washed down between the rubber sheets and the soil monoliths. The sheets extended about 10 cm above the soil surface to prevent surface runoff.

Pt-500 probes were installed in the soil monoliths from 5 to 50 cm depth. Temperature data were stored automatically every 3 h. At deeper levels the temperature was measured manually with thermistors. Total water content profiles were measured every 5-10 days with a neutron probe.

Infiltration Experiment

A pilot study was made during April 1986 in which equal amounts of water were supplied to all three plots (Table 1). Further preparations for the infiltration experiment were then undertaken in autumn 1986 and late winter 1986/87. The actual experiment took place in spring 1987. Monthly mean values (1951-80) of air temperature at the climatological station of the Swedish University of Agricultural Sciences, about 200 m from the site, show that the winter of 1987 was much colder than normal (Fig. 1). The preparations consisted of autumn irrigating 0, 100 and 200 mm to the three plots as an effort to create different pre-freezing water contents. In order to enhance the differences in ice content, two of the plots were irrigated in late winter prior to the start of the infiltration experiment (Table 1). In the infiltration experiment, the plots were ponded to the same height and the time needed for the water to infiltrate was measured. Since the measurements were made momentarily the results will be referred to as infiltration rates. However, the

Table 1 – Amounts of water (mm) supplied to the plots.

Time		Plot 1	Plot 2	Plot 3
1986	15/4*	70	70	70
	17/4*	150	150	150
	20/11	–	50	100
	2/12	–	50	100
1987	23/3	–	2	4
	25/3	–	2	3
	27/3	–	2	–
	30/3	–	2	2
	31/3	–	2	4
	1/4	–	2	4
	2/4	–	2	4
	3/4*	4	4	4
	6/4*	4	4	4
	7/4*	10	10	10
	8/4*	4	4	4
	9/4*	4	4	4
	10/4*	4	4	4
	13/4*	10	10	10
	14/4*	4	4	4
	15/4*	4	4	4
	16/4*	4	4	4
	21/4*	10	10	10
	22/4*	20	20	20
	23/4*	20	20	20
	24/4*	20	20	20

* Infiltration rate was measured.

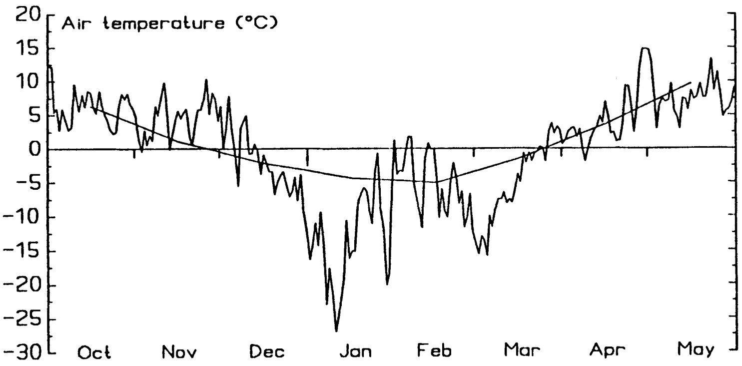

Fig. 1. Air temperature, presented as daily mean values for the winter of 1986/87 and as monthly mean values for the period 1951-1980.

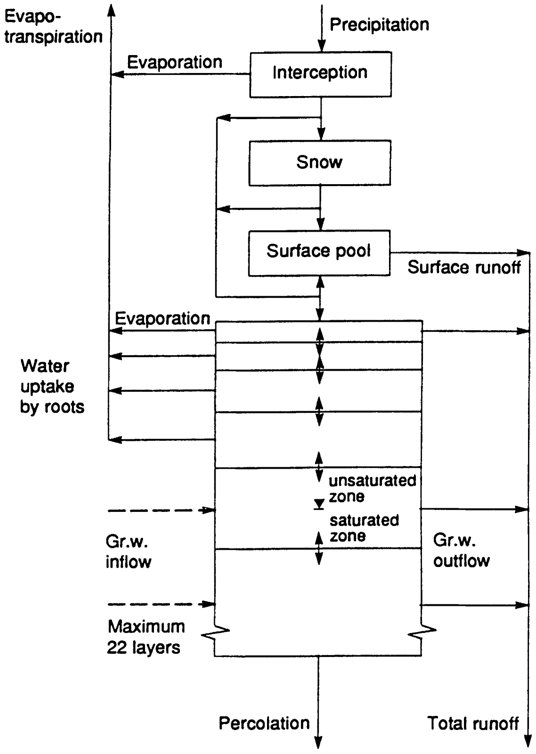

Fig. 2. Model structure of the water flows in SOIL (Jansson and Gustafson 1987).

amounts of water supplied were generally large enough so that the obtained infiltration rate values could be considered to be close to infiltration capacity of the soil.

Model Description

The SOIL model (Jansson and Halldin 1979) used in the analysis simulates the coupled heat and water flow in a soil profile (Fig. 2) with an explicit finite difference method. A detailed description of the model and the model code is given by Jansson and Halldin (1980). The flow equations of the model are

$$\frac{\partial (CT)}{\partial t} - L_f \rho_i \frac{\partial \theta_i}{\partial t} = \frac{\partial}{\partial z}\left(k_h \frac{\partial T}{\partial z}\right) - C_w \frac{\partial (T q_w)}{\partial z} \qquad (1)$$

$$\frac{\partial \theta}{\partial t} = \frac{\partial q_w}{\partial z} + s_w \qquad (2)$$

Eq. (1) describes the heat flow and Eq. (2) the water flow. The symbols are as follows: C – soil heat capacity; T – temperature; t – time; L_f – latent heat of freezing; ρ_i – ice density; θ_i – volumetric ice content; k_h – thermal conductivity; z – depth; C_w – water heat capacity; q_w – flow of water; θ – volumetric water content and s_w – water source/sink.

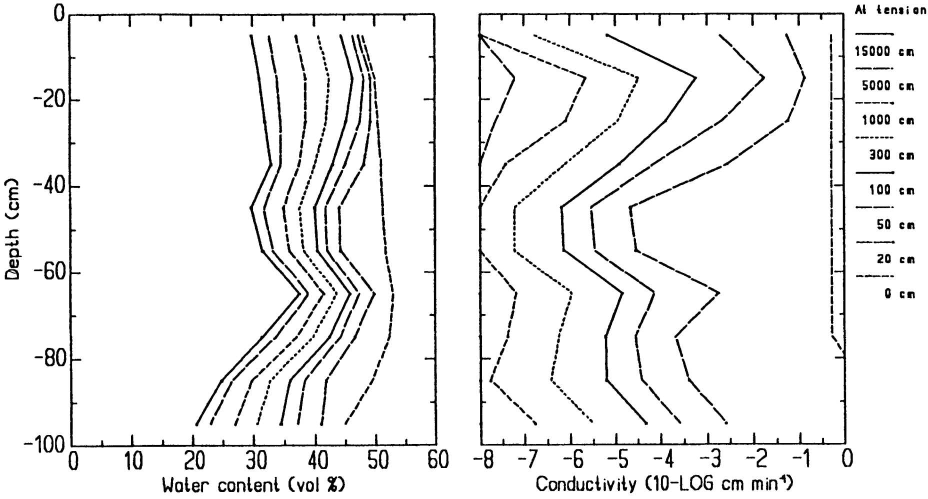

Fig. 3. Water retention properties and unsaturated hydraulic conductivity of the heavy clay soil at Ultuna.

Similarity is assumed between drying-wetting and freezing-thawing under frozen conditions. A freezing-point depression function, based on the soil-moisture characteristic curve, is used to estimate the unfrozen water content of the partially frozen soil. The hydraulic conductivity of the frozen soil is treated according to the procedure suggested by Lundin (1989b). The water-retention function is estimated by a modified version of the Brooks and Corey (1964) equation. Following Mualem (1976), the unsaturated hydraulic conductivity is estimated from the retention properties and an estimated saturated conductivity. In addition, a logarithmic dependence of the conductivity on water content suggested by Jansson and Thoms-Järpe (1986) is used for water contents close to saturation. Thermal conductivity is estimated from Kersten's (1949) equations, based on porosity, water content and a particle density of 2.65 g cm^{-3}. A surface-water pool was introduced in the model by Jansson and Gustafson (1987) in order to account for surface runoff. The water in the surface pool can either infiltrate during the following timestep or be lost as surface runoff. If water cannot continue downwards, *e.g.*, because of frost in the ground, it will be directed as surface runoff.

In our application, daily mean values of the measured soil temperature at 5 cm depth were used as the upper thermal boundary condition, whereas the irrigations made were used as an upper water flow boundary. The model treated the irrigation as a daily variable, thus interpreting the irrigated amount as a daily total and not as a ponded volume. Soil physical measurements in a similar profile, located about 200 m from the current site, were made by Sandsborg and Wiklert (1976). Functions for water retention and unsaturated hydraulic conductivity were estimated from their data (Fig. 3).

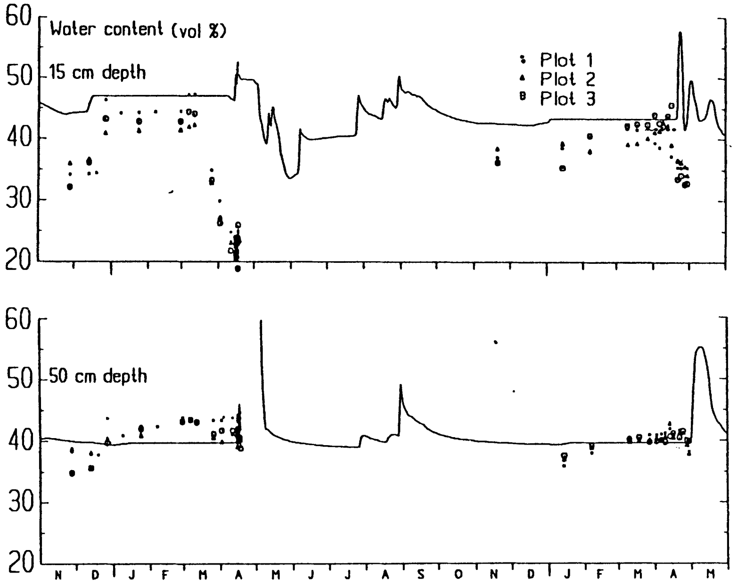

Fig. 4. Measured (symbols) and simulated (solid line, plot 1) total water content at 15 and 50 cm depths, from Nov. 1985 to May 1987.

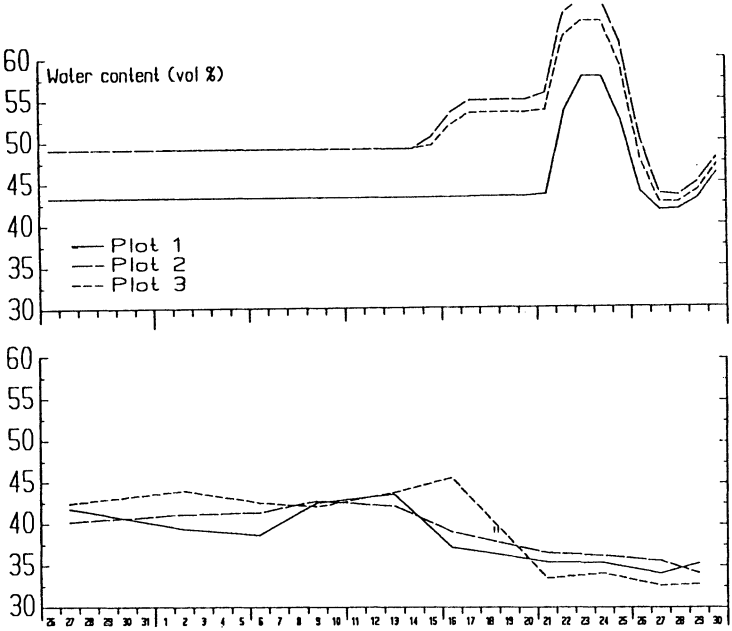

Fig. 5. Simulated (upper diagram) and measured (lower diagram) total water content at 15 cm depth from 26 March to 30 April 1987.

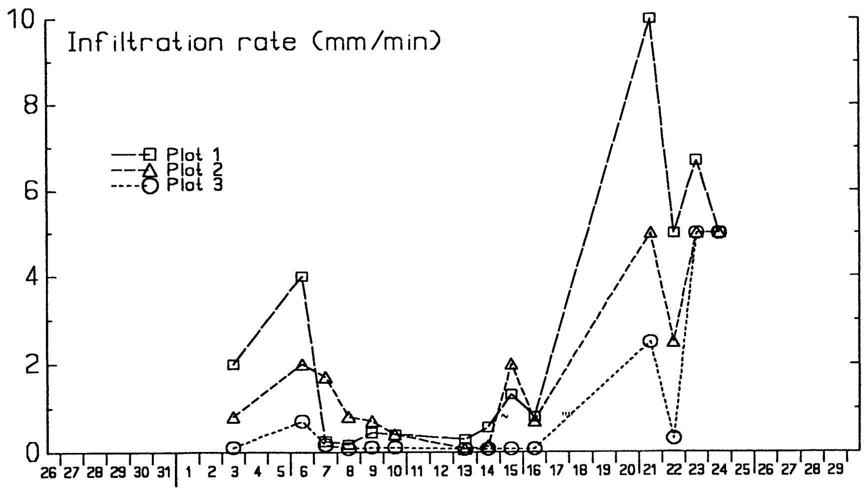

Fig. 6. Measured infiltration rate from 3 April to 24 April 1987.

Results

Both measurements and simulations showed that the water content in the upper layers increased during the early part of the winter and decreased during the thawing period (Fig. 4). There was no influence of the autumn irrigation on the total water content during winter, whereas the late winter irrigation on plots 2 and 3 seemed to have resulted in somewhat higher total water contents in the upper layers in the end of March 1987 (Fig. 5). There were differences in measured infiltration rates between the plots in the beginning of April 1987, but infiltration rates had decreased to such low levels after a few days that only small differences remained (Fig. 6). Around mid April these differences reappeared for about a week. Temporal variation in the magnitude of the differences seemed to be related to variations in soil temperature (Fig. 7), giving small differences in connection with low soil temperatures.

The difference between simulated and measured total water content was greatest during the thawing period (Fig. 4), and was especially pronounced in the upper layers. The simulated decrease in total water content was less pronounced than the observed decrease. A delay in the simulated response to the infiltrations, not seen in the measurements, is demonstrated in Fig. 5. The simulated water content at 15 cm depth remained constant until 15 April when, contrary to the measurements, it increased rapidly. Simulated soil temperatures (Fig. 8) lagged behind the measured ones when the soil was in the process of freezing or thawing.

Simulated and measured infiltration rates did not generally agree. When the soil

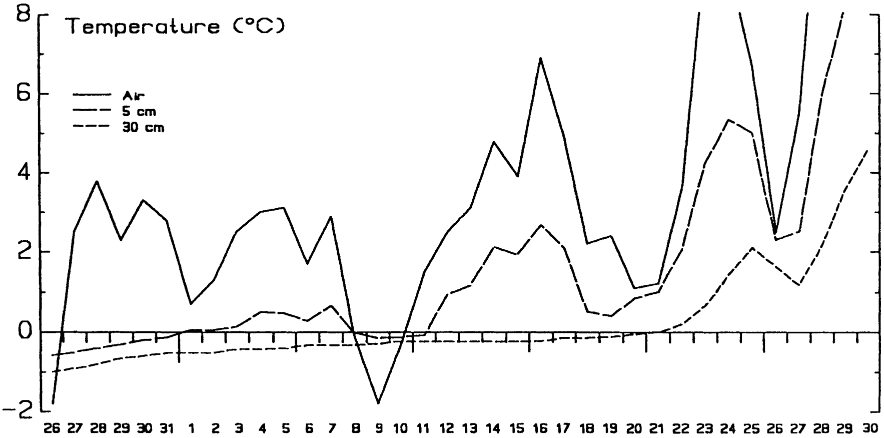

Fig. 7. Measured air temperature and measured soil temperature at 5 and 30 cm depths in plot 2 from 26 March to 30 April 1987.

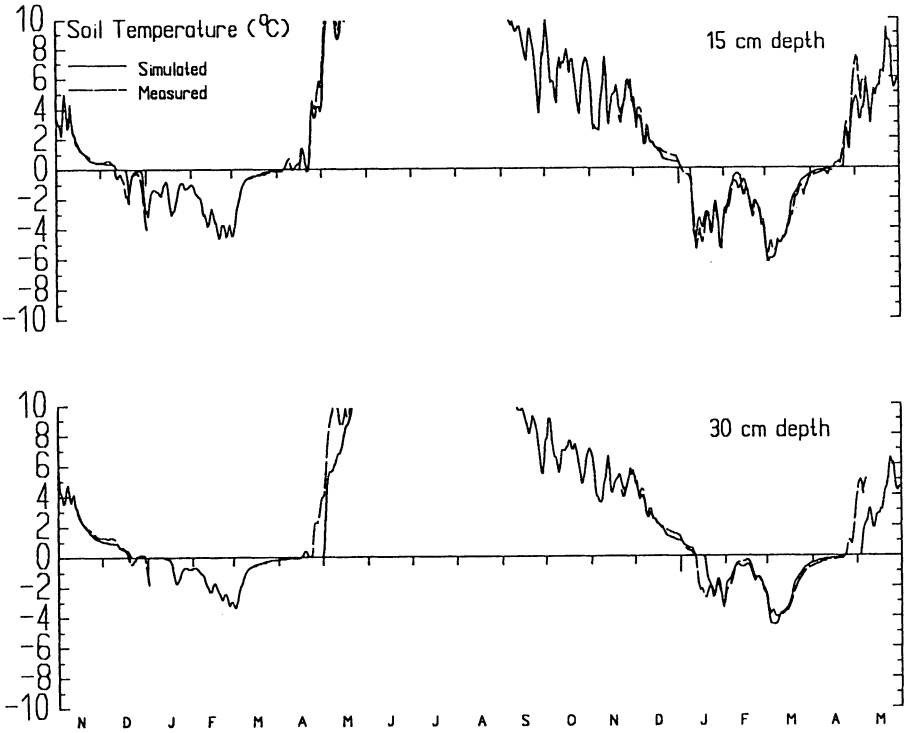

Fig. 8. Measured and simulated soil temperature at 15 and 30 cm depths in plot 1 from Nov. 1985 to May 1987.

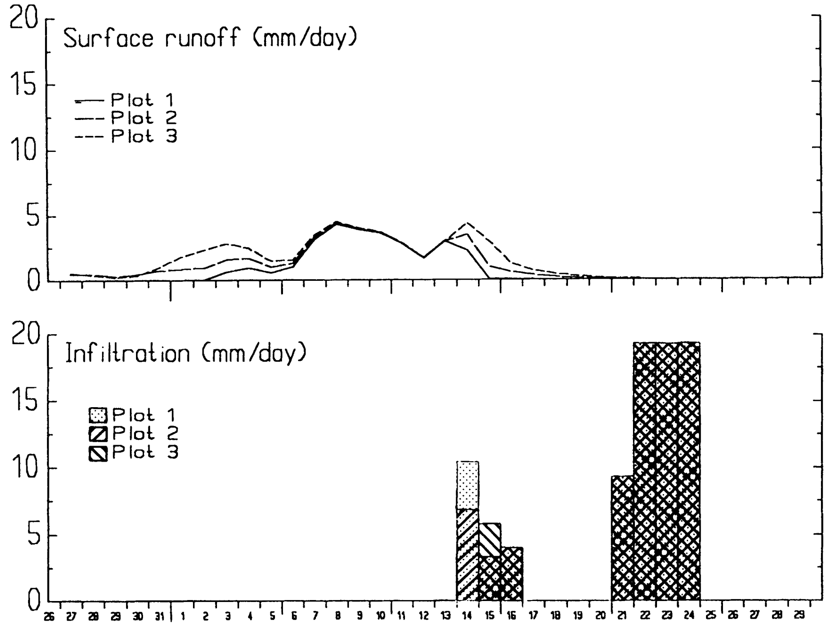

Fig. 9. Simulated surface runoff (upper diagram) and simulated infiltration (lower diagram) from 26 March to 30 April 1987.

was frozen, the infiltration capacity was considered too low by the model and most of the added water was stored on the ground and lost as surface runoff (Fig 9). The infiltration started on 14 April in the simulation, *i.e.,* 11 days after infiltration actually began. The supplied water had been routed to the surface pool and lost as surface runoff up until this time. The surface pool was then emptied in a single day, yielding an infiltration of 8 mm in plot 1. Simultaneously, 2.5 mm of the 4 mm supplied that day infiltrated, giving the total of 10.5 mm seen in Fig. 9. No infiltration runs were performed during 17-20 April. The 21 April was the last day of frost. No surface runoff was simulated after this day.

Discussion

The discrepancies between simulated and measured total water contents may be attributed to the inability of the model to describe aggregates and cracks. The rapid decrease in measured water content during thawing was very likely a consequence of the expulsion of water from the aggregates during winter. Because clay swells slowly, the influence of drying on the soil-moisture characteristic curve can be long-lasting.

The highest infiltration rate measured in this experiment, 10 mm min^{-1}, was about two times higher than any previously reported on frozen soils. Differences in measurement procedure and the fact that no measurements in cracked soils were found can probably explain this discrepancy.

The macropore system in a heavy clay soil is normally filled with air. This is also the case when the soil freezes (Kenny and Saxton 1986). When the water expulsed from the aggregates upon freezing fills some of the macropores, the remaining crack system is still capable of conducting infiltrated water through the frozen layer. Thus, a considerable infiltration capacity may be sustained throughout the winter. If the soil is partly thawed and refrozen, or if snowmelt infiltrates into frozen soil, the infiltrating water may freeze in the cracks and fill them with ice, thereby reducing the infiltration capacity. This is probably what happened during the first infiltration runs in April 1987. When the temperature dropped on 7 April, the infiltration rates were probably decreased in response to the freezing of previously added water.

Simulated soil temperatures lagged somewhat behind those measured during thawing periods so that the simulated ice content was overestimated. Even a small discrepancy is crucial if it occurs close to the freezing point. The infiltration capacity was therefore underestimated. The time lag might be explained by the choice of the 5-cm soil temperature as the upper boundary condition. This caused an underestimation of the actual soil surface temperature during thawing. Another reason for the discrepancies between measured and simulated infiltration rates was the fact that the model handled the irrigations made on a daily basis. Thus, the infiltration rates were calculated as the amounts of infiltrated water per day. However, this should only contribute to an overestimation of the infiltration capacity by the model. The most important reason for the poor performance of the model was that the model did not consider the water flowing through the empty macropores of the soil. Large discrepancies in magnitude and timing between measured and simulated infiltration rates should be expected in frozen soils, where infiltration occurs through cracks, as long as the model treats soil water flow uniquely as a capillary process.

Jansson and Gustafson (1987) used the SOIL model for a silt loam with a well developed structure to study surface runoff and discharge through drainage pipes. The inability of the model to correctly depict observed drainage flows was attributed to problems associated with the spatial variation of soil properties. Gorkov (1983) points out that the increase in permeability during thawing takes place in a patchlike manner, partly caused by spatial variation in snow depth. Although we acknowledge that variability problems exist, it still appears more likely that the consistent delay observed in simulated pipe discharge compared with the measured discharge was due to water flowing through cracks. If snowmelt drains through the cracks, water should start to flow in the drainpipes as soon as the snow starts melting. Water flowing through the micropore system of the soil can contribute to the pipe discharge only when the soil is fully thawed.

Concluding Remarks

Our results support the general consensus that an inverse relationship exists between ice content in the soil and infiltration rate. Warm spells during winter cause snow to melt and lead to repeated freezing and thawing of the soil. The ice content in macropores can be increased by such periods of thawing and refreezing and by freezing of infiltrated snowmelt during the winter. We propose that the most important factors to consider when predicting infiltration of snowmelt into aggregated soils are the number and intensity of warm spells during winter.

The high measured infiltration rates were probably the result of waterflow in the crack system of the soil. The results emphasize the need to consider both aggregates and cracks of frozen soils.

In soil water flow models it would be beneficial to include flows in macropores separately. The impact of freezing on the soil-moisture characteristic curve should also be included. Such a model could be developed based on knowledge of ice content in cracks and the aggregate stabilities of different soil types.

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References

Brooks, R. H., and Corey, A. T. (1964) Hydraulic properties of porous media, Colorado State University, Hydrology Paper No. 3, 27 pp. Fort Collins, Colorado.

Engelmark, H. (1987) Rates of infiltration into frozen and unfrozen fine sand, *Can. J. Earth Sci, Vol. 25,* pp. 343-347.

Gorkov, V. P. (1983) Effect of primary cultivation on the permeability of frozen soils, *Soviet Soil Science, Vol. 15(2),* pp. 99-103.

Granger, R. J., Gray, D. M., and Dyck, G.E. (1984) Snowmelt infiltration to frozen Prairie soils, *Can. J. Earth Sci., Vol. 21,* pp. 669-677.

Guymon, G., and Luthin, J. N. (1974) A coupled heat and moisture transport model for arctic soils, *Water Resour. Res., Vol. 10,* pp. 995-1001.

Halldin, S., Jansson, P.-E., and Lundkvist, H. (1979) Ecological effects of long-term soil heat pump use. Proc. Nordic Symp. Earth Heat Pump Systems, Suppl., Univ. of Technology, pp. 14-23, Gothenburg.

Harlan, R. L. (1973) Analysis of coupled heat-fluid transport in partially frozen soil, *Water Resour. Res., Vol. 9,* pp. 1314-1323.

Jansson, P.-E., and Gustrafson, A. (1987) Simulation of surface runoff and pipe discharge from an agricultural soil in northern Sweden, *Nordic Hydrology, Vol. 18,* pp. 151-166.

Jansson, P.–E., and Halldin, S. (1979) Model for annual water and energy flow in a layered soil. In: Halldin, S. (ed.). Comparison of Forest Water and Energy Exchange Models, Int. Soc for Ecological Modeling, pp. 145-163, Copenhagen.

Jansson, P.-E., and Halldin, S. (1980) SOIL water and heat model. Technical description, Swedish University of Agricultural Sciences, Swedish Coniferous Proj., Technical Rep. 26, 81 pp., Uppsala.

Jansson, P.-E., and Thoms-Hjärpe, C. (1986) Simulated and measured soil water dynamics of unfertilized and fertilized barley, *Acta Agric. Scand., Vol. 36,* pp. 162-172.

Kane, D. L. (1980) Snowmelt infiltration into seasonally frozen soils, *Cold Reg. Sci. Techn., Vol. 3,* pp. 153-161.

Kane, D.L., and Stein, J. (1983) Water movement into seasonally frozen soils, *Water Resour. Res., Vol. 19,* pp. 1547- 1557.

Kapotov, A. A. (1972) Laboratory investigations of the infiltration capacity of frozen and unfrozen soils (According to the data of the Permafrost Laboratory), *Trudy GGI 194,* pp. 32-45.

Karvonen, T., Lemmelä, R., and Sucksdorff, Y. (1986) Infiltration into seasonally frozen soil and modeling of soil freezing and thawing phenomena. In: Saavalainen, J., and Vakkilainen, P. (eds.). Proc. Int. Seminar on Land Drainage, Helsinki University of Technology, Department of Civil Engineering, pp. 324-347, Otaniemi.

Kenny, J. F., and Saxton, K. E. (1986) Air permeability as an index to infiltration of frozen, tilled soil. Summer Meeting of the ASAE, Paper No. 86-2012, 26 pp., St. Joseph, Mi.

Kersten, M. S. (1949) Thermal properties of soils. University of Minnesota, Inst. of Technology Engineering, Exp. Station, Bull. 28, 226 pp., Minneapolis.

Komarov, V. D., and Makarova, T. T. (1973) Effect of the ice content, cementation and freezing depth of the soil on meltwater infiltration in a basin, *Soviet Hydrology, Selected Papers, Vol. 12,* pp. 243-249.

Kuznik, I. A., and Bezmenov, A. I. (1963) Infiltration of meltwater into frozen soil, *Soviet Soil Sci., Vol. 7,* pp. 665-670.

Lundin, L.-C. (1989a) Water and heat flows in frozen soils. Basic theory and operational modeling. Acta Universitatis Upsaliensis. Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science, 186, 49 pp., Uppsala.

Lundin, L.-C. (1989b) Hydraulic properties in an operational model of frozen soil. Accepted for publication in *Journal of Hydrology.*

Motovilov, Y. G. (1977) Numerical modeling of the infiltration of water into frozen soils, *Soviet Meteorology and Hydrology, Vol. 9,* pp. 55-62.

Motovilov, Y. G. (1979) Simulation of meltwater losses through infiltration into soil, *Soviet Hydrology, Selected Papers, Vol. 18,* pp. 217-221.

Mualem, Y. (1976) A new model for predicting the hydraulic conductivity of unsaturated porous media, *Water Resour. Res., Vol., 12,* pp. 513-522.

Sandsborg, J., and Wiklert, P. (1976) Soil physical investigations in four soil profiles, *Grundförbättring, Vol. 27,* pp. 89-109.

Sheppard, M. I., Kay, B. D., and Loch, J. P. G. (1978) Development and testing of a computer model for heat and mass transfer in freezing soils. Proc. 3rd Int. Conf. on Permafrost, Nat. Research Council of Canada, pp. 76-81, Edmonton, Alberta.

Steenhuis, T. S., Budenzer, G. D., and Walter, M. F. (1977) Water movement and infiltration in a frozen soil: Theoretical and experimental considerations. Meeting of the American Society of Agricultural Engineers, Dec. 13-16, 1977, Paper 77-2545, Chicago, Ill.

Troedsson, T., Jansson, P.-E., Lundkvist, H., Lundin, L., and Svensson, R. (1982) Ekologiska effekter av ytjordvärmeuttag. Markkemi, markfysik, markbiologi, markhydrologi och växtodling (Ecological effects of soil heat extraction. Soil Chemistry, soil physics, soil biology, soil hydrology and plant husbandry, in Swedish). Swedish Council of Building Research, R51:1982, 76 pp., Stockholm.

Wilkert, P., Andersson, S., Weidow, B., Karlsson, I., and Håkansson, A. (1983) Studier av markprofiler i svenska åkerjordar. En faktasammanställning. I. Ultunajordar (in Swedish). Swedish University of Agricultural Sciences, Department of Soil Sciences, Division of Hydrotechniques, Report 132, 126 pp., Uppsala.

Willis, W. O., Carlson, C. W., Alessi, J., and Haas, H. J. (1961) Depth of freezing and spring run-off as related to fall soil-moisture level, *Can. J. Soil Sci., Vol. 41,* pp. 115-123.

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