Preferential water flow in a glacial till soil

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Abstract Measured and simulated response of runoff during snowmelt has suggested that preferential water flow occurs as part of the infiltration process in glacial till. However, only a few quantitative studies have been presented. TDR measurements of soil water content were performed during the growing period in a till slope (7–10%) outside Stockholm. Soil cores were used to determine the water retention curve and the saturated hydraulic conductivity. A physically based one-dimensional model was used to simulate soil water dynamics in the slope. Two simulation approaches were used: a strict one-domain Darcian approach and a two-domain approach accounting for a bypass of the matrix flow system. The measured response of soil water content occurred within the first few hours after rainfall. This was best represented by the two-domain approach, while the response for the one-domain approach was significantly delayed with time and depth. The general behaviour of the soil water content throughout the season was, however, best simulated with a one-domain approach. The results indicated that preferential flow patterns through the unsaturated zone does not need to be considered to describe the seasonal pattern in glacial till soil. However, the results also point out that the purpose of the simulation is decisive when choosing a simulation approach, depending on whether the general soil water content over the season or the instant behaviour immediately after rainfall is of major interest.

Keywords Infiltration; macropore; runoff; two-domain; unsaturated

Introduction

When compared to soils of more assorted texture, there have been few investigations concerning hydraulic properties of glacial till (Espeby 1989). This is due to the tough penetration and excavation nature of such soils and to the difficulties in measuring soil hydraulic properties. However, glacial till is the most common soil type in Sweden (Lundqvist 1977), covering more than 95% of the country, so there is a need to gain knowledge of the hydraulic properties of till soils. Observed rapid responses of runoff in till catchments indicate preferential water flow in glacial till soils during heavy rains and snowmelt events (Espeby 1992; Beldring 2002). For assorted soils a number of investigations have described the importance of preferential flow for similar events (see, for example, Aubertin 1971; Thomas and Phillips 1979; Andersson 1988). For glacial till there have been few investigations demonstrating preferential flow.

At a research site NW of Stockholm called Lund, a till slope has been investigated concerning soil physical properties (stratification, texture, porosity, water retention characteristics and saturated hydraulic conductivity) by field and laboratory investigations (Espeby 1989). Some visual macrostructures in the form of old root channels were found during the filed investigations. A tracer experiment conducted at the slope during snowmelt (Espeby 1990*a*) indicated that preferential flow paths contributed to the response of runoff from the slope. The role of preferential flow patterns was further demonstrated by a simulation study where runoff from a quasi-two-dimensional soil water flow model was compared to observed runoff from the slope (Espeby 1992). Runoff was modelled as groundwater discharge and was observed in a ditch in the slope that formed a small watershed. In the simulation study two model approaches were used: a strict one-domain

Darcian approach where water is transported only through the soil matrix, and a two-domain approach accounting for bypass flow (a model representation of preferential flow) of the matrix system. One finding of the study was that a strict one-domain Darcian model approach could not fully describe the observed rapid response of runoff from the slope during heavy rains and snowmelt events. During these events it seemed as if the observed water movement was quicker than that which could be explained by the gradient forced matrix flow. Better agreement with the observations was obtained when the bypass flow was introduced. The results indicated that preferential flow paths conduct water rapidly through the unsaturated part of the soil to the groundwater and thereby contribute to the fast response of groundwater discharge from the slope.

However, preferential flow is not necessarily what causes the rapid response of runoff. For example, the outflow area could be connected via bedrock fissures with an inflow area having no or shallow soil cover. Infiltrating water would then quickly reach the bedrock and the hydraulic response in the outflow area could be rapid. Also, it was mainly during the extreme infiltration events causing runoff that preferential flow was indicated. Field-based knowledge of preferential flow in the unsaturated part of the soil profile is, to a large extent, still lacking.

In this study we look at the soil water dynamics in a till slope during the growing season. Soil water dynamics by the means of soil water content were observed at the Lund site from June to October 1993. The observations are evaluated using a physically based soil water flow model. Similar to Espeby (1992) two simulation approaches were used, with and without taking preferential flow into account, and compared with observations. The objective of this paper is to present measurements of field water dynamics and a recently made evaluation. The purpose is to present new estimated parameters that can be used for water flow modelling in till soils.

Materials and methods

The LUND research site (2.3 ha) is located 35 km NW of Stockholm on a gentle forest slope (7–10%). Around 85% of the area is covered with 60–70 year old coniferous trees: spruce (*Picea abies*) and pine (*Pinus silvestris*). The dominant soil is a clayey silty sandy basal till. The study area is situated at an altitude between 20 and 45 m a.s.l. For more detailed information of the study area see Espeby (1989).

Soil properties

Soil physics of the slope were investigated by Espeby (1990*b*, 1992) by laboratory analysis of core and soil samples taken from six soil pits in the slope (Fig. 1). For each location saturated hydraulic conductivity, texture and bulk porosity were measured.

A schematic view of the soil stratification presents five major soil horizons. The organic layer (horizon 1) covers a wave-washed beach gravel and sand layer (horizons 2 and 3), which has a high saturated hydraulic conductivity ($k_s = 10^{-4}\,\mathrm{m\,s^{-1}}$). Underlying these horizons is a fine textured layer (horizon 4) with a silty-sand character (average $k_s = 10^{-6}\,\mathrm{m\,s^{-1}}$). The fifth layer is a clayey silty-sandy till (horizon 5) having a very low saturated hydraulic conductivity (average $k_\mathrm{s} = 2.5 \times 10^{-8}\,\mathrm{m\,s^{-1}}$).

The saturated hydraulic conductivity shows a decreasing average and an increasing variability with depth, which is a common feature for this kind of soil (Lundin 1982). Water retention properties were determined in the laboratory using soil cores (70 mm diameter, 50 mm or 100 mm high) collected from different depths within the upper 1 m of soil at soil pit nos. 1, 4 and 6 (Fig. 1). Fig. 2 shows the retention values obtained from soil pit no. 1.

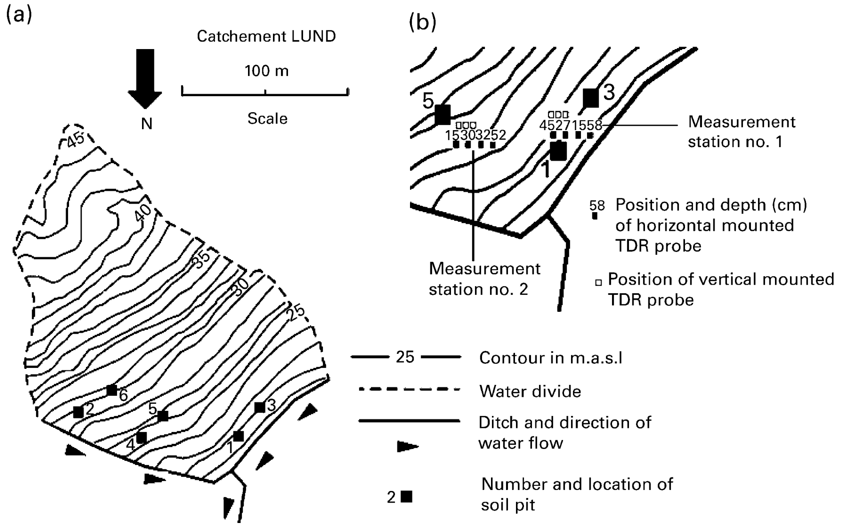

Figure 1 (a) Map of the Lund catchment with soil pit locations. (b) Location of the TDR measurements (from Espeby 1990)

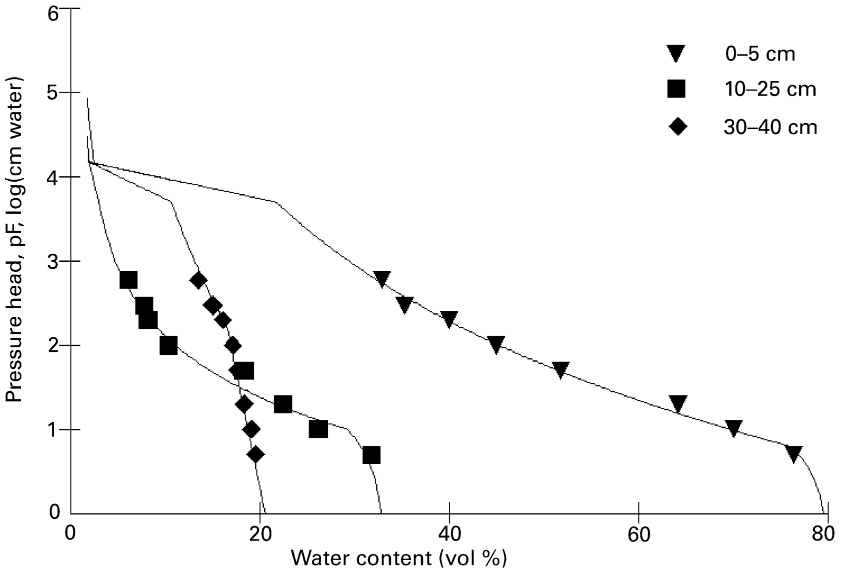

Figure 2 Measured water retention values at different depths for soil samples taken from soil pit no. 1 with fitted Brooks and Corey functions. A selection of measured depths is shown (from Espeby 1992)

Soil water measurements

Two sites within the catchment were equipped with Time Domain Reflectometry (TDR) probes (Fig. 1). At each site, called measurement station Nos. 1 and 2, soil moisture content was measured in two ways: as a depth profile from 15 cm to approximately 60 cm by 4 horizontally mounted TDR probes; and as an integrated value for the uppermost 30 cm of the soil by vertically mounted TDR probes. The vertically mounted TDR probes were 30 cm long and set within a few metres of each other to show the spatial variation on a small scale. The measurements were conducted during mid-June to October 1993 and data were sampled every second hour for the profile measurements and every hour for the vertically mounted probes. The soil moisture content was estimated from the TDR signal by the Topp equation

(Topp *et al.* 1980). The same algorithm has previously been used for TDR observations for similar soils (Jansson *et al.* 1999). Meteorology data except for global radiation was taken from the Swedish Meteorology and Hydrology Institute (SMHI) station 9720, located 25 km from the research site. Global radiation was taken from the neighbouring SMHI station 9873. Temperature, dew point temperature and wind speed were sampled every third hour while global radiation was measured every hour and precipitation was measured twice a day.

Model description

A soil–plant–atmosphere model, the COUP model, was used as a tool to simulate soil water dynamics. The COUP model is a coupled heat and mass transfer model used for soil–plant–atmosphere systems. The main part of the model describes water and heat transfer in a one-dimensional vertical soil profile using two coupled differential equations. These equations are solved with an explicit numerical method. The soil profile is divided into layers with certain thickness and soil properties. Submodels accounting for interception, snow, surface water, evaporation and transpiration give upper boundary conditions for the model. Lower boundary conditions can be given in a number of ways, including unsaturated, saturated and groundwater flow. A technical description with references to different applications in which the model has been used is available in Jansson and Karlberg (2001). A former version of the COUP model, the SOIL model, was first presented by Jansson and Halldin (1979).

The two flow equations for water and heat describe the dynamics in water content and temperature at different depths. The soil water content is calculated by Darcy's law as generalised for unsaturated flow by Richards (1931):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(k_w(\theta)\left(\frac{\partial \psi}{\partial z} + 1\right)\right) + S_w \tag{1}$$

where k_w is the hydraulic conductivity which varies with the soil water content θ; ψ is the soil water tension and S_w is a sink-source term accounting for root water uptake.

The water retention characteristics in the matrix pore region are calculated by an analytical expression derived by Brooks and Corey (1964):

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{\psi}{\psi_a}\right)^{-\lambda} \tag{2}$$

where λ is a parameter accounting for the pore size distribution; ψ_a is the air-entry tension; θ_r is the residual water content; and θ_s is the water content at saturation. In the macropore range close to saturation, the water retention is estimated as a simplified linear function.

Unsaturated hydraulic conductivity is determined using the analytical expression of Mualem (1976):

$$k_w = k_{mat}\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{n+2+\frac{2}{\lambda}} \tag{3}$$

where k_{mat} is the saturated matrix conductivity, i.e. the conductivity when the largest pores are drained; and n is a parameter accounting for pore correlation and path tortuosity. In the macropore region, defined as θ_s minus the macropore volume (θ_m), a log-linear function is used to account for macrostructures:

$$k_w = 10^{\left(\log(k_w(\theta_s - \theta_m)) + \frac{\theta - \theta_s + \theta_m}{\theta_m}\log\left(\frac{k_{sat}}{k_{w(\theta_s - \theta_m)}}\right)\right)} \tag{4}$$

The model also includes an optional empirical bypass flow concept to represent preferential flow that is not driven by the water potential gradient in the matrix pore region. The basic idea is that the matrix pore system is restricted to fluxes lower than a maximal rate that is controlled by a sorption capacity. Flow rates that exceed this threshold may be bypassed to lower levels assuming transport in the macro pore region. This type of two-domain approach, or dual porosity approach, is often used for modeling water flows in soils with macrostructures (see, for example, Gerke and van Genuchten 1993). However, other simpler and more complex approaches exist (see, for example, Jarvis *et al.* 1991; Ross and Smettem 2000; Tuller and Or 2002). At each model iteration, water entering a soil layer at a rate greater than the sorption capacity S_{mat} will be routed as a bypass flow to the next underlying layer. The matrix flow q_{mat} and the bypass flow q_{bypass} are expressed as (Eckersten and Jansson 1991)

$$q_{mat} = \begin{cases} \max\left(k_w(\theta)\left(\frac{\partial\psi}{\partial z}+1\right), q_{in}\right) & 0 < q_{in} < S_{mat} \\ S_{mat} & q_{in} \geq S_{mat} \end{cases} \tag{5}$$

$$q_{bypass} = \begin{cases} 0 & 0 < q_{in} < S_{mat} \\ q_{in} - q_{mat} & q_{in} > S_{mat} \end{cases} \tag{6}$$

where q_{in} is the sum of q_{mat} and q_{bypass} entering the layer from above. S_{mat} is given as

$$S_{mat} = a_{scale} a_r k_{mat} pF \tag{7}$$

where a_r is the ratio between layer thickness and the unit horizontal area represented by the model; pF is $^{10}\log$ of ψ; and a_{scale} is an empirical bypass scaling coefficient accounting for the geometry of soil aggregates. The a_{scale} parameter was assumed to be a common value for the whole profile. Infiltration to the soil is calculated based on the total infiltration capacity, taking both the matrix pore region and the macropore region into consideration. Surface runoff is also considered in the model but was never simulated because of the high infiltration capacity in the present application.

Parameter choice and simulation technique

Espeby (1992) used the former version of the COUP model, the SOIL model, when simulating groundwater discharge from the Lund site. Several parameters, especially those controlling the upper and lower boundary conditions, were set similar to the ones used previously. Table 1 shows the hydraulic related parameters used in this study.

Parameters in the Brooks and Corey expression were obtained from calibration of the function to fit the measured retention values. Model layers below the measured horizons used extrapolated retention properties assuming decreasing total porosity from the measured layers to the bedrock.

Saturated conductivity, k_s, was given a value near its measured average (within the 95% confidence limit). Saturated matrix conductivity, k_{mat}, was given a value between k_s and about 1/10 of k_s. The n parameter in the conductivity expression was tuned together with k_s and k_{mat} so that the conductivity at field capacity (-100 cm pressure head) was in the range of 0.1–1 mm/d for all layers below the organic horizon (Fig. 3). The initial soil water tension was set as uniform through the soil layer at -40 cm pressure head. The macropore volume range was defined as the 4% before saturation. Within this range a linear function and a log-linear function was used for estimation of water retention and hydraulic conductivity respectively.

The bypass scaling coefficient, a_{scale}, was the only parameter calibrated during the simulations. This parameter can be set anywhere from a value giving almost no bypass to a value where almost all water was bypassed leaving nearly no soil water in the upper soil layers. The parameter was set at 0.2, a value in between these extremes giving some bypass of water to lower model layers whereas the soil water content in the upper soil layers still remained in the magnitude of the observed.

Table 1 Parameter values at measured horizons used for retention and conductivity calculations

Depth below soil surface (cm)	Parameter in the Brooks and Corey retention expression λ	Air entry tension ψ_a (cm)	Residual soil water content θ_r (%)	Saturated water content θ_s (%)	Macropore volume (%)	Matrix conductivity k_{mat} (mm/d)	Saturated conductivity k_s (mm/d)	Parameter in the Mualem conductivity expression n
0–0.05	0.19	4.7	0.3	80	4	4800	20020	1
0.05–0.10	0.19	1.5	11.1	56	4	1000	3400	−3
0.1–0.25	0.46	7.5	1.4	33	4	1000	3400	0
0.25–0.30	0.06	0.4	0.1	24	4	1000	3400	−8
0.3–0.40	0.13	30.0	0.1	21	4	100	3400	8
0.4–0.55	0.13	5.4	0.1	24	4	100	100	−3

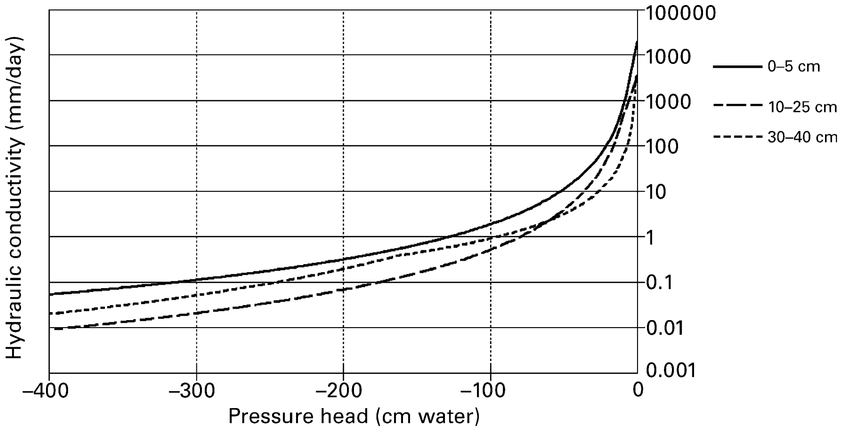

Figure 3 Model representation of hydraulic conductivity for a selection of model layers

Two simulation approaches, a strict one-domain Darcian approach and a two-domain approach accounting for a bypass of the matrix flow system, were performed and compared to measurements. Both approaches were performed with retention and hydraulic properties derived from soil physical measurements from soil pit no. 1 (Figs. 2 and 3).

Results

Measurements

The period was considered to be a wet summer, receiving 210 mm of rainfall between 1 July and 1 October (Fig. 4). The profile measurements and the measurements for the upper 30 cm showed similar dynamic tendencies with increases in soil water content often occurring simultaneously. Plateaus at maximum observed soil water content at measurement station no. 1 seemed to indicate that saturation was sometimes reached. This was especially evident

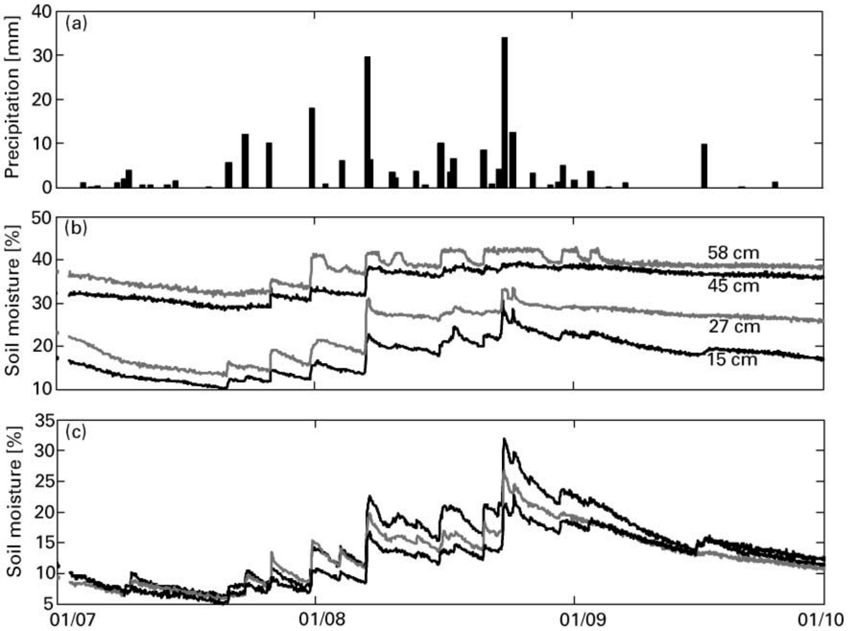

Figure 4 (a) Precipitation, (b) soil moisture content at different depths for measurement station no. 1 and (c) soil moisture content for the upper 30 cm of the soil for measurement station no. 1

during August, when the soil at 58 and 45 cm depths appeared to reach saturation at 42% and 39% soil water content, respectively. Similar plateaus were not observed at measurement station no. 2. The local spatial variability for the upper 30 cm of the soil seemed small and showed similar dynamics to the 15 and 27 cm profile measurements.

It seems as if the response of soil water content often occurs at the same time at all measured depths (Fig. 4). Looking in detail at two infiltration events, on 31 July and 7 August, showed that within the first two hours (the sampling rate of the profile measurements) after rainfall, the response of increased soil water content was instantaneous at all measured depths (Fig. 5 and Table 2).

Simulations

The correlation between measured soil water content and simulated soil water content decreased with increasing depth (Fig. 6 and Table 3). At a depth of 15 cm, simulations with and without bypass followed the measured soil water content reasonably well whereas at the 45 cm depth both simulations with and without bypass followed the measured values less

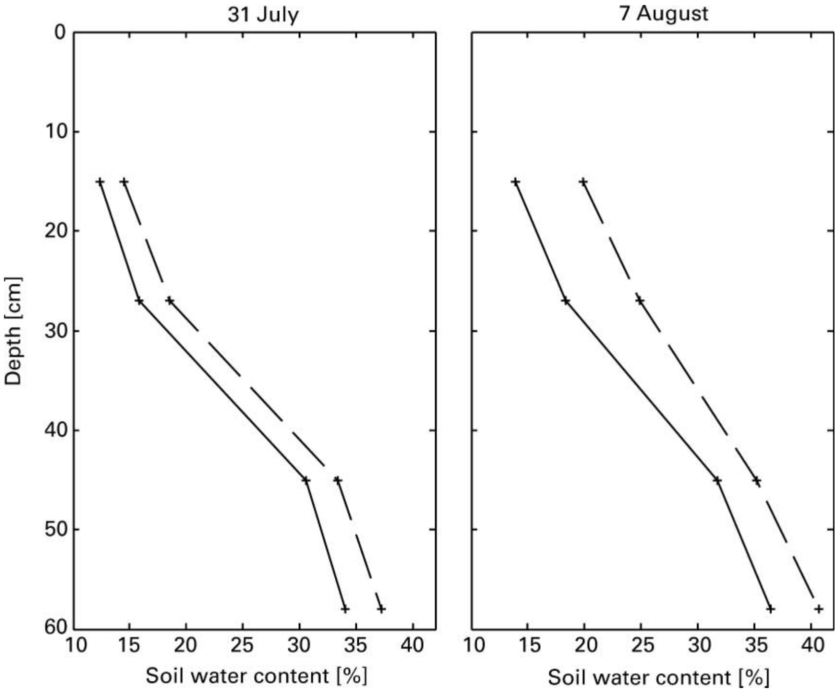

Figure 5 Measured response of soil water content after rainfall at measurement station no. 1. The solid line represents the soil water content before rainfall and the dashed line represents the soil water content 2 hours after rainfall. The " + " symbols show the measured values at 15, 27, 45 and 58 cm depths

Table 2 Soil water content (%) after rainfall measured by the three vertically mounted TDR probes at measurement station no. 1

	31 July			7 Aug		
	Probe no. 1	Probe no. 2	Probe no. 3	Probe no. 1	Probe no. 2	Probe no. 3
Time 0	10.6	10.1	8.5	13.8	10.8	9.5
1 hour	12.3	12.5	9.5	16.6	12.8	11.9
2 hour	13.9	14.8	10.4	19.4	14.8	14.2

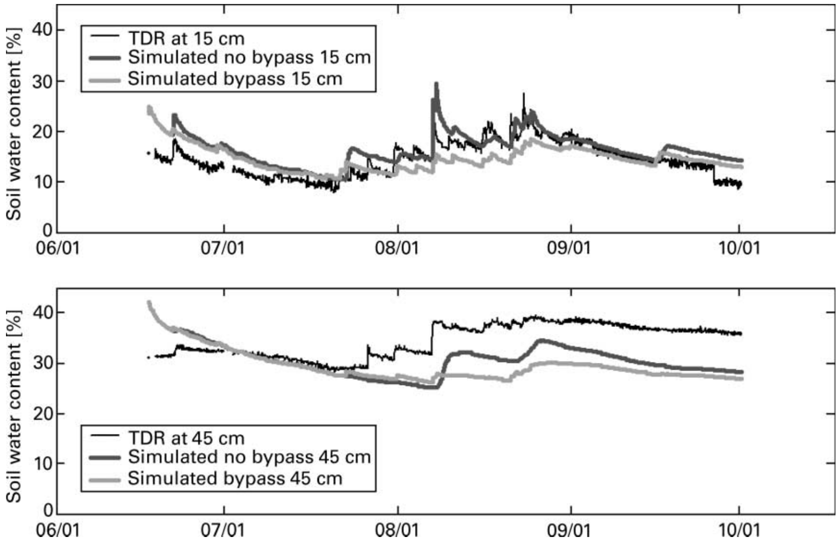

Figure 6 Simulated soil water content, with and without bypass flow, and measured soil water content at measurement station no. 1. The simulated 15 and 45 cm values represent the 12–18 and 40–50 cm model layers

Table 3 Linear regression values (r^2, intercept and slope) and Root Mean Square Error values (RMSE) when comparing simulated and measured soil water contents. The measured 0–30 cm value used for the statistics is an average value for the three TDR probes

	No bypass				With bypass			
Measurements	r^2	**Intercept**	**Slope**	**RMSE**	r^2	**Intercept**	**Slope**	**RMSE**
Station no. 1								
0–30 cm	0.67	12.0	0.5	6.2	0.67	11.6	0.4	5.2
15 cm	0.67	6.8	1.1	8.0	0.71	5.6	1.4	9.2
27 cm	0.74	−18.0	2.5	7.9	0.71	−18.5	2.7	8.7
45 cm	0.53	10.7	1.5	19.0	0.31	15.2	1.3	19.8
58 cm	0.48	16.5	1.5	23.4	0.22	21.6	1.2	24.1
Station no. 2								
0–30 cm	0.80	11.2	0.7	7.4	0.74	11.2	0.5	6.3
15 cm	0.67	4.9	1.0	5.0	0.54	5.3	1.1	6.3
30 cm	0.75	−16.3	2.1	3.7	0.63	−14.6	2.1	4.4
32 cm	0.39	−10.6	1.4	5.2	0.42	−17.4	1.9	4.6
52 cm	0.35	−23.7	2.5	5.8	0.10	−7.8	1.7	6.5

well. The simulated values at 15 cm show how the bypass function reduced the peak of increased soil water content after rainfall events as water was bypassed to the lower model layer.

Looking in detail at the same two infiltration events as the measured events presented in Fig. 5 showed that the response of increased soil water content seemed to be delayed with depth when a strict one-domain Darcian approach was used, while the response was more instantaneous throughout the profile when the bypass flow was introduced (Fig. 7). Overall, the Darcian approach seemed to correlate better with the measured values than the bypass approach (Table 3).

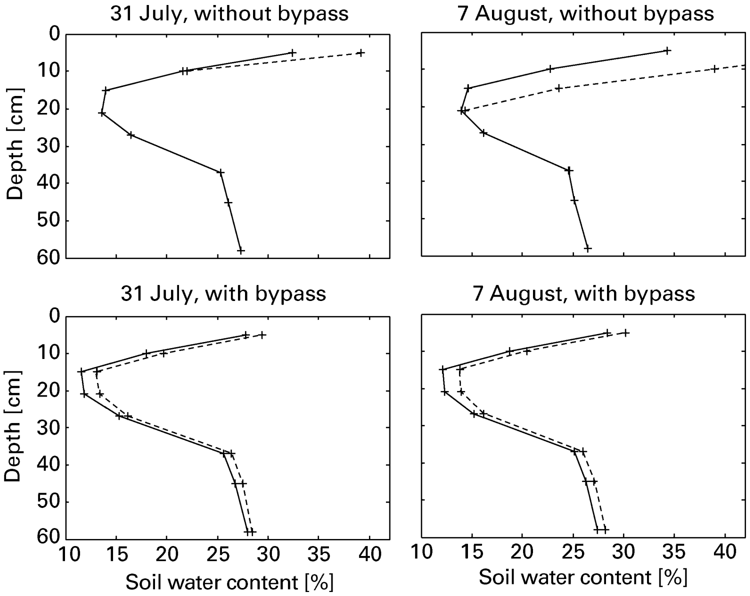

Figure 7 Simulated response of soil water content after two rainfall events. The solid line represents the soil water content before rainfall and the dashed line represents the soil water content 2 hours after rainfall. The " + " symbols represent the middle of the model layers

Discussion and conclusions

The soil samples used to determine the hydrological properties that were used in the simulations were not taken from the same location where the TDR probes were mounted. It is therefore hard to tell to what extent the deviations between observed and simulated soil water contents are due to poor observations, poor simulations or caused by the heterogeneity of the soil. Nevertheless, the dynamics of the soil water contents seems to have been captured by the observations and also to different extents by the two model approaches.

The measured increase in soil water content during the first few hours after rainfall was rapid throughout the measured soil profile (Figs 4 and 5). This suggests that water was quickly transported from the upper soil layers downward through the soil. A two-domain modelling approach accounting for bypass flow of the matrix system could resemble this response, while a strict one-domain Darcian approach accounting only for matrix flow could not (Fig. 7). This indicates that infiltration into a glacial till is not well explained as a strict Darcian process. The results therefore give strength to the theory that water is drained from the upper soil layers via a preferential flow system that is not in equilibrium with the matrix pore system.

When looking at the general soil water content over time, a strict one-domain Darcian approach seemed better than the approach with added bypass (Table 2). The purpose of the simulation must therefore play a decisive role when choosing a simulation approach. For instance, if the amount of water available for transpiration during the growing season is of interest, one should choose a strict Darcian approach that describes the soil water variability over the season reasonably well. However, if the concern is a measure of how fast water is transported to the groundwater, one would want to use a model that also considers preferential water flow. This is the case when looking at solute transport, where it is of interest to know how long water is retained in the buffering unsaturated part of the soil profile.

Preferential water flow through the unsaturated soil matrix has been indicated in glacial till during heavy rains and snowmelt events by runoff observations and physically based modelling. The results from this study strengthen those indications and suggest that preferential flow also occurs in glacial till during less extreme infiltration events.

Acknowledgements

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