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Saturated Hydraulic Conductivity of Scandinavian Tills

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There is a distinctive difference in hydraulic properties between the upper horizons of Scandinavian till soil and the deeper C-horizon. The hydraulic conductivity has been studied in different soil profile types, mainly Podzolic variants. In the topsoil there are correlations from grain size and porosity to hydraulic conductivity. Both porosity and hydraulic conductivity are stratified with depth. Often high conductivity appears in the upper soil horizons decreasing with depth to low values at about one metre. This pattern varies with soil type. The soils vary with topographic location as does the groundwater level.

Published data on hydraulic conductivity in the C-horizon of sandy-silty tills in Scandinavia covers a wide range, from about 5×10^{-9} m/s to 5×10^{-4} m/s, with a mean of 3×10^{-6} m/s. The correlation between porosity and hydraulic conductivity, as well as between mean grain size and hydraulic conductivity, is weak in the C-horizon. It is concluded that the sediment structure has a decisive influence on the hydraulic conductivity of till. A model of the relationship between fabric (in relation to water flow direction), the porosity in the pore-size interval 30-95 μm and the hydraulic conductivity is presented.

Introduction

Different hydrological and geological conditions have caused characteristic soils to develop in till. These are influenced by the distance between soil surface and the groundwater level (Tamm 1931, Troedsson and Nykvist 1973). Several typical hydropedological properties can be identified in the different soils. In Northern

Fennoscandia there are often poorer sites where Podzols prevail, while in the more loamy and clayey soils in Southern Scandinavia Cambisols occur more frequently. The most common soils in Nordic tills are Podzols. In dry and mesic soil types, Orthic Podzols prevail turning towards Humic Podzols in downslope locations and Gleyic Podzols further down. In wet and waterlogged locations, Gleysols and Histosols occur. The Cambisols present are often Dystric, Humic or Gleyic. The soils are classified according to FAO-UNESCO (1974).

The hydraulic conductivity in the C-horizon of till is related to the sediment properties in a very complicated way. For sorted sediments there is known to be a correlation between grain-size distribution, pore-size distribution and hydraulic conductivity (*e.g.* Gustafson 1983). In diamicton sediments, such as till, this is not equally evident. The importance of elements such as, porosity, grain dispersion, fabric, orientation of domains, and grain shape has often been suggested but the documentation on the influence on the hydraulic conductivity is sparse.

Hydraulic Conductivity within the Soil Profile

Considering the common till deposited above the highest marine border, without secondary impacts such as from wavewashing, there is often a textural and porosity stratification with depth in the soil profile. Due to pedological processes, loose layers have developed mainly in the upper one metre of the soil (Andersson and Wiklert 1970, Lundin 1982). In this context freezing/thawing, root and soil fauna activities are important together with chemical processes. The latter both improving and deteriorating the hydraulic conductivity.

In the ordinary forested till of at least Northern Fennoscandia bulk density is relatively low in the upper soil layers consecutively increasing with soil depth (Högbom and Lundqvist 1930, Andersson and Wiklert 1970, Lundin 1982). This influences the hydraulic conductivity that decreases with soil depth (Fig. 1) (Knuts-

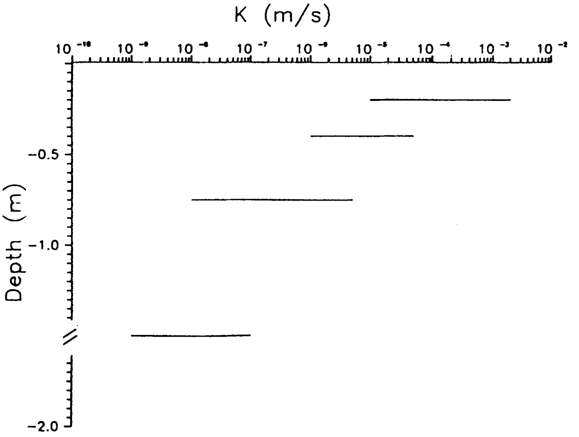

Fig. 1.
General variation in hydraulic conductivity (K) with soil depth in till.

son 1971, Lundin *et al.* 1981, Lundin 1982, Johansson 1986, Espeby 1988). There are, however, morainic formations with large heterogeneities both within short distances and disorderly organized with depth. In fine-grained till, *e.g.* clayey till, the conductivity is generally low but may locally be high in the upper soil layers due, for instance, to cracks. In the unsaturated zone hydraulic conductivity, roughly, decreases with decreasing grain size (Jenssen and Køhler 1986).

Variation in Hydraulic Conductivity between Soil Types

Few investigations distinguish between hydraulic conductivity of different till soils, *i.e.* at different locations within the hill slope. In forested areas, the main soils concerned are Podzols, Gleysols and Histosols. Of these, the last is strongly influenced by peat which has a low conductivity. This is also the case in mineral soil layers mixed with organic material. Since the mixing with organic material mainly occurs in the upper soil layers this may cause the conductivity to increase with depth in the upper horizons of these soils (Hauhs 1986).

At locations with thick organic layers of peat or layers with peat character, these are often underlain by a stony and boulderly layer which has a high hydraulic conductivity. In a depth of a few decimetres this coarse layer may abruptly change to a fine-grained layer with low conductivity (Lundin 1982). This fine-grained layer might also exist directly beneath the organic material, causing only small water movements throughout the whole soil profile. The water flow is low but there might occur "funnel-like“ flows with high velocities although only concerning small amounts of water. These "funnel-like" water movements are indicated by gleyic formations formed during aerobic conditions. The normal anoxic conditions prevailing in these profiles occasionally change to aerobic during dry periods when the groundwater level is lowered. Till of this character often have a high content of silt and especially clay and are common in Southern Scandinavia.

In contrast to low-lying locations with Podzols and Gleysols, upslope locations, often with Orthic Podzols, have lower bulk densities and relatively high porosities. The densities also increase more slowly with soil depth than in the wet soil types (Lundin 1982). These conditions have caused hydraulic conductivities which are comparably high throughout the whole soil profile but none the less decrease with depth. The described distribution of hydraulic conductivities in the soil profiles of different hillslope locations is exemplified by Lundin (1982) Fig. 2.

The groundwater flows are determined by the groundwater levels and hydraulic conductivities. At upslope locations, groundwater in till seldom occurs closer to the soil surface than two metres while at the slope foot, in wet soil types, the groundwater level is often found in the uppermost soil layers (Fig. 3).

From the high conductivities in the upslope soil types it follows that there is a rapid drainage of water there, supplying downslope soil types. In these there often

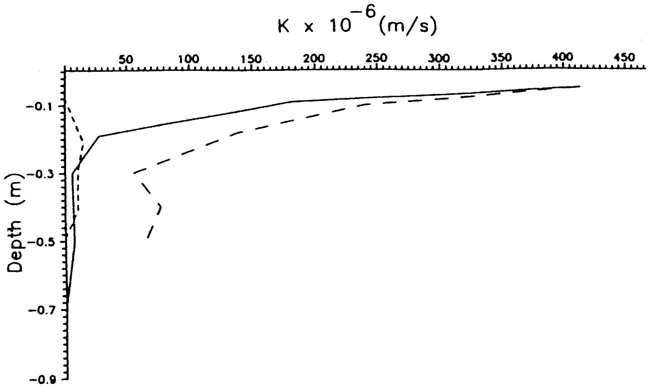

Fig. 2. The saturated hydraulic conductivity (*K*), with depth in the soil, at three soil types in a sandy, silty till. (From Lundin 1982). Mesic soil type -- Moist - Wet ---.

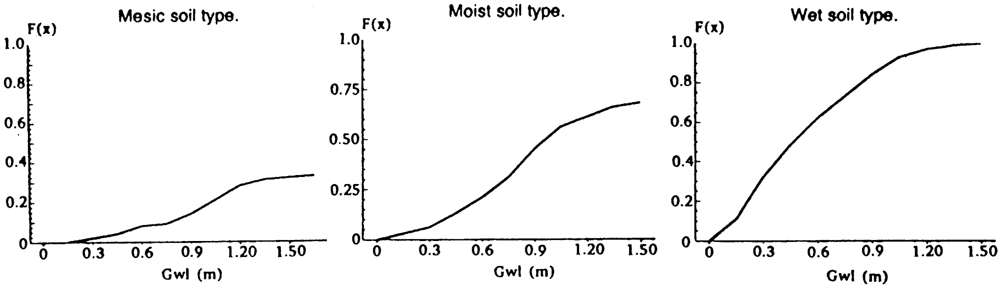

Fig. 3. The cumulated relative frequencies, *F*(*x*), of groundwater levels below soil surface (*Gwl*) in mesic, moist and wet soil types during the period May-October. (From Lundin 1982).

are slow-moving or stagnant water at depths deeper than 0.5 m. When the groundwater appears in the upper soil layers a considerable flow occurs there. Especially important are the stony and boulderly horizons in the wet soils of swales and drogs (Table 1).

Table 1 – The groundwater flow at three groundwater levels (*Gwl*) in three different soil types on till.

	Flow in $m^3/s \times 10^{-7}$, a crossection of one metre with!		
Gwl (m)	Mesic soil	Moist soil	Wet soil with a stony layer
0.2	510	70	180
0.4	250	25	2.7
0.8	30	0.7	0.4

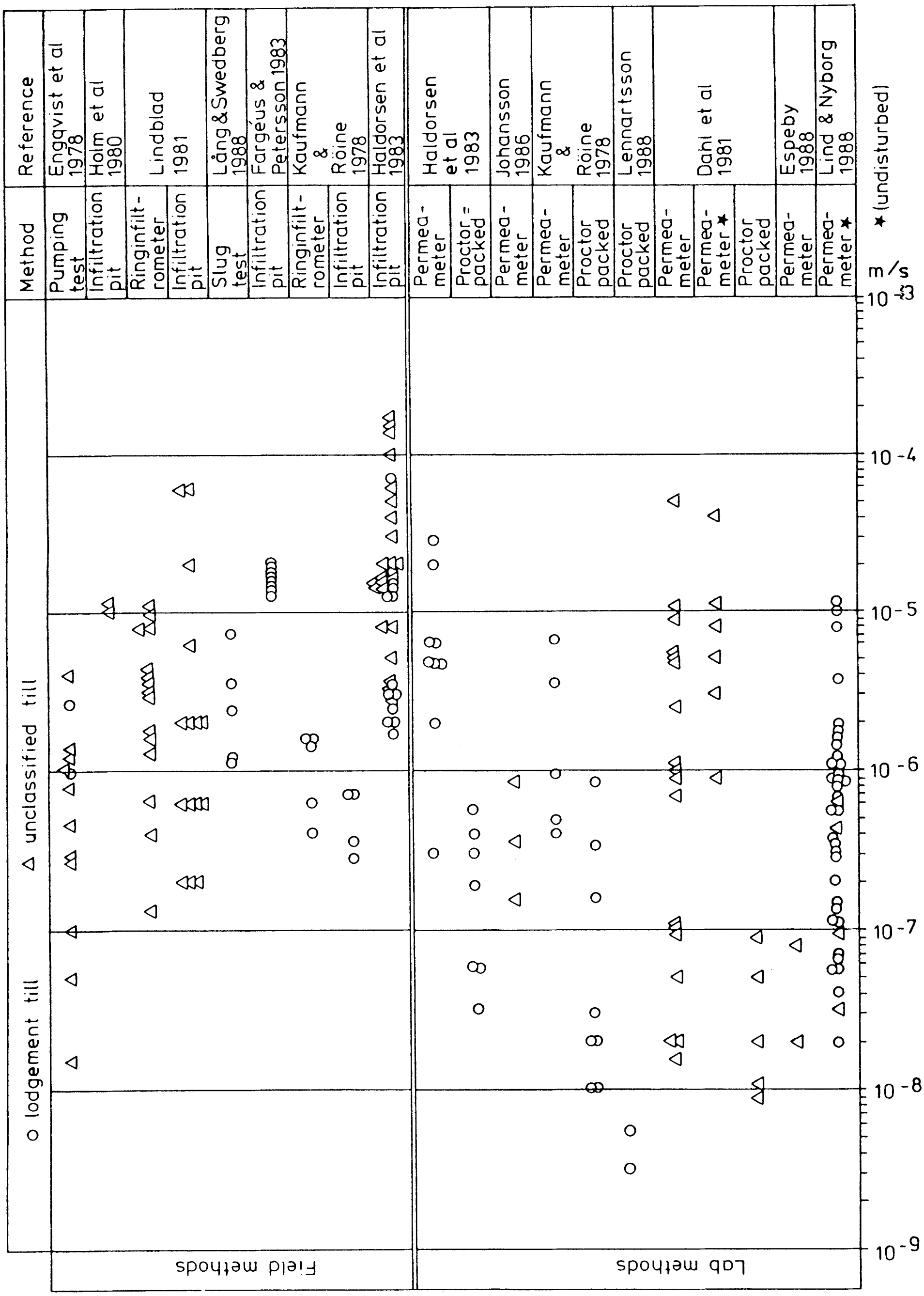

Fig. 4. Hydraulic conductivity of Swedish and Norwegian tills determined by different methods.

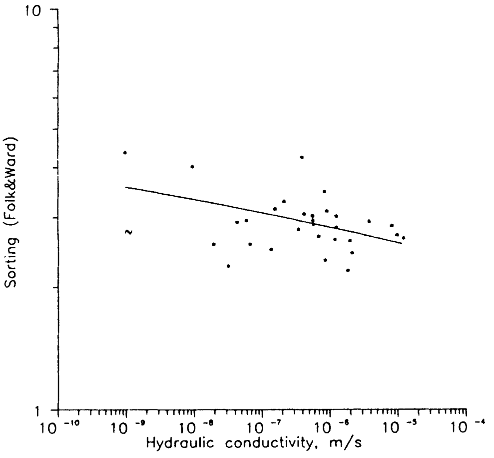

Fig. 5. Hydraulic conductivity and grain sorting of undisturbed samples from Swedish tills.

Hydraulic Conductivity in the C-Horizon

The hydraulic conductivity of sandy-silty till in Scandinavia varies within wide limits. The situation is illustrated in Fig. 4, which summarises 210 measurements of hydraulic conductivity at depths of more than 40 cm in Swedish and Norwegian till. The measurements were performed in different till types and with different methods, in the field or on intact or weakly disturbed samples in the laboratory, except for the proctor packed samples. The distribution is essentially lognormal and gives a mean hydraulic conductivity of 3×10^{-6} m/s. Of great importance is the very wide range in hydraulic conductivity, from 5×10^{-9} to 2×10^{-4} m/s. Studies of sandy-silty tills in Norway and Sweden have shown great variations in hydraulic conductivity, variations that could not be correlated to the mean grain-size (Haldorsen *et al.* 1983, Lind and Nyborg 1988). It has been shown, however, that variations in hydraulic conductivity in samples from the C-horizon of sandy-silty till, at least to some extent, may be influenced by the grain sorting (Lind and Nyborg 1988). The diagram in Fig. 5 shows that a lower sorting factor (Folk and Ward 1957), *i.e.* a better sorting, corresponds to a higher hydraulic conductivity. The uncertainty in predicting hydraulic conductivity of soils from particle size distributions has recently been underlined by Mishra *et al.* (1989).

The saturated water flow occurs in pores and the grain-size distribution is just a substitute for the description of pore structure. Figs. 6 and 7 show the relationship between the total porosity and the mean grain size, M_z (Folk and Ward 1957), and sorting, $\sigma 1$, respectively, on samples taken at 2-3 m depth in lodgement till (Lind and Nyborg 1988). In the same way, M_z and $\sigma 1$ are compared with the effective porosity (at pF 2.0) in Figs. 8 and 9. From this comparison it is evident that the porosity of the till is more or less independent of the grain size, expressed as M_z,

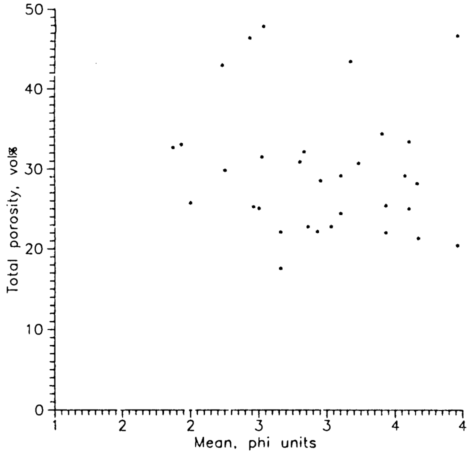

Fig. 6. Mean grain-size and total porosity of undisturbed samples from Swedish tills.

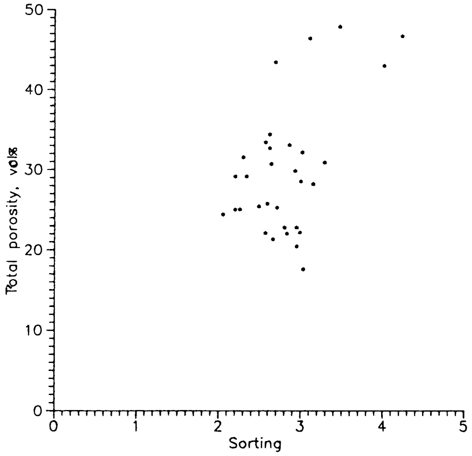

Fig. 7. Grain sorting and total porosity of undisturbed samples from Swedish tills.

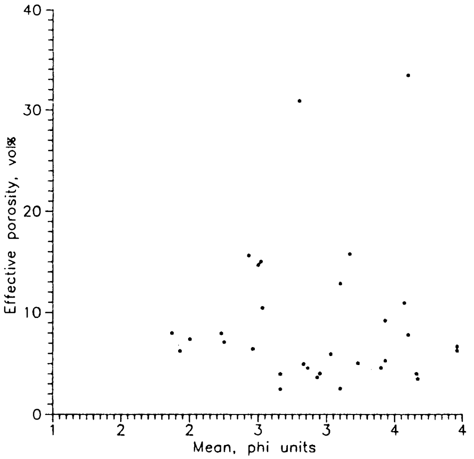

Fig. 8. Mean grain-size and effective porosity of undisturbed samples from Swedish tills.

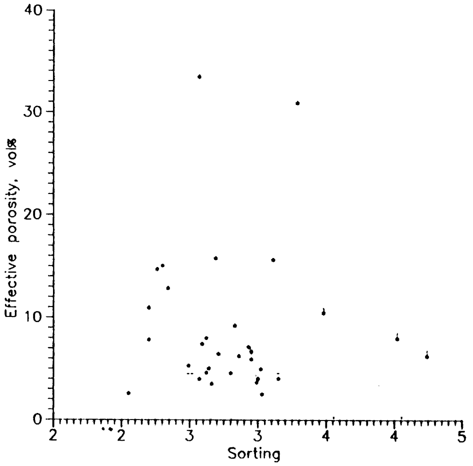

Fig. 9. Grain sorting and effective porosity of undisturbed samples from Swedish tills.

but correlated to the grain sorting, σ1, a finding that has earlier been shown for sand by Beard and Weyl (1973).

Knutsson (1971) has shown that there are characteristic differences in flow pattern, velocity of flow, storage and yield between different moraine types. He concluded that the ground-water flow, due to the sediment structure, was greater in drumlin terrain than in hummocky moraine. The results coincide with those by

Engqvist *et al.* (1978) who, from pumping tests in southern Sweden, found the hydraulic conductivity of drumlin terrain to be about 3.5 times that of the till in the surrounding area.

The influence of till genesis on the hydraulic conductivity has also been studied in Norway by Haldorsen *et al.* (1983). In this study calculations from 42 infiltrometer tests showed that lodgement till had a lower hydraulic conductivity than meltout till.

Further studies on the relationship between pore-size distribution and hydraulic conductivity of till have indicated that a certain pore interval, between 30 and 95 μm, has the most significant influence on the hydraulic conductivity (Lind 1989). A pore-size between 30 and 95 μm is characteristic for well-sorted fine sand (Odén 1957, Andersson and Wiklert 1972). Sediment layers of fine sand should have great numbers of pores of this size and should also have an important impact on the hydraulic conductivity. Moreover, microstructure studies by Van der Meer (1987) and Lind (1989) have shown that a number of elongated voids can be associated with the fissility planes that commonly occur in lodgement tills of the investigated type. The confined sections of these voids seem to be of the order of about 50-100 μm in width. This leads to a model for lodgement till with preferential saturated flow in pores of about 30-95 μm at the fissility planes and in thin fine sand layers.

Comparisons between single structural or textural elements and the hydraulic conductivity have proved to be very difficult. A more fruitful approach can often be to study the multiple correlations between three separate factors. Nyborg (1989) has presented a model for the relationship between a characteristic porosity (pore-geometrical factor), fabric and the hydraulic conductivity. The model shows a strong correlation between fabric and hydraulic conductivity. It can also be shown that there is a strong correlation between fabric (in relation to the water flow), the pore interval 30-95 μm and the hydraulic conductivity. A multiple linear regression analysis has been made on 29 undisturbed till samples (Fig. 10). The significance level for the fabric variable is almost 100 % and for the pore segment about 70 %. The coefficient of determination (r^2) for the whole model is very high 97 %. It appears from the model that if the fabric is near parallel to the flow, which means low logfabric values, the porosity in the relevant interval has a greater impact on the hydraulic conductivity than if the fabric is more transverse to the flow direction.

Primary Sedimentary Structures and Hydraulic Conductivity

It may be concluded that the sediment structure has a decisive influence on the hydraulic conductivity of till. A great deal of the variation in hydraulic conductivity in Fig. 4 may be due to structural differences, whereas the texture may be similar. This concept harmonises with the difference in hydraulic conductivity between undisturbed and packed till and it also explains the differences between horizontal

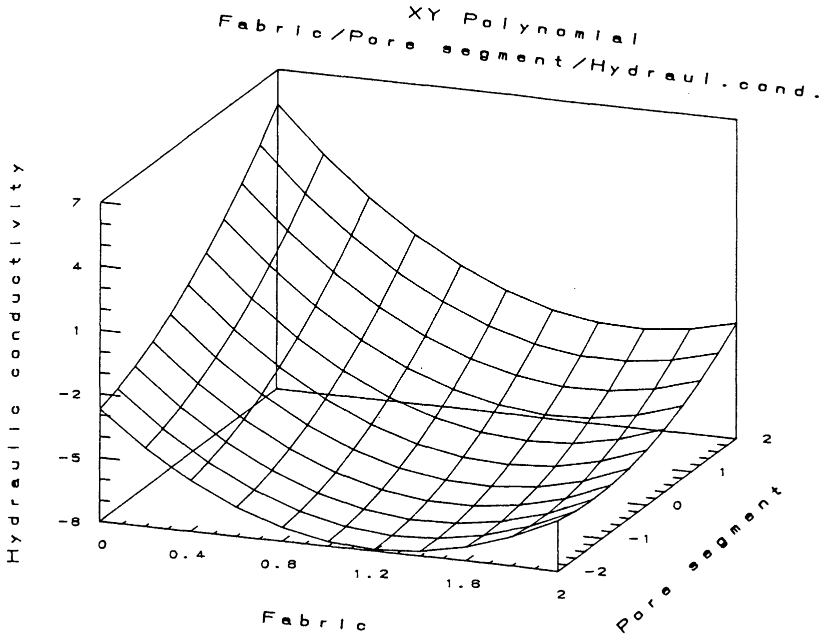

Fig. 10. Response surface plot of the multiple regression analysis between the hydraulic conductivity, fabric and the pore segment 30-95 μm. The fabric-values are a measure of the log 3D-angle between the mean grain orientation and the direction of water flow. The pore segment values are presented as the log vol-% of the pore interval 30-95 μm. The Hydraulic conductivity is presented as log-values in m/s. The up-bend of the surface in the lower right corner is due to the algorithm and should not be considered. (Partly compiled from Nyborg 1989).

and vertical conductivity (Haldorsen *et al.* 1983, Lind and Nyborg 1988).

From the diagram in Fig. 4, two orders of sediment structures can be discussed in relation to hydraulic conductivity. If excluding the proctor packed measurements the diagram could be interpreted as if the field measurements generally give hydraulic conductivity values higher than 10^{-7} m/s, whereas the laboratory measurements go down to 10^{-8} m/s. If this difference is significant it indicates that there are large sediment structures, affecting the hydraulic conductivity, that are not captured in the small laboratory samples. On the other hand the variations in the laboratory series show that structural elements within the samples have a decisive effect on the hydraulic conductivity. This is supported by the proctor packed measurements, provided that the proctor packed samples had a bulk density comparable to the undisturbed samples. It is indicated that the pattern of saturated flow, in small samples from the C-horizon of sandy-silty till, is comparable to the large scale pattern. Good agreement between small and larger structural elements in till has also been shown by Krüger (1979) and Åmark (1986). Further studies on hydraulic conductivity in till should consider the interconnection between small and large scale sediment structures.

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