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### **SURFACE RUNOFF AND SOIL PHYSICAL PROPERTIES AS AFFECTED BY SUBSURFACE DRAINAGE IMPROVEMENT OF A HEAVY CLAY SOIL**

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**ABSTRACT** The percent of total runoff as surface runoff is an indicator of soil structure and functioning of subsurface drainage system in clay soils. Water logging due to low infiltration and low hydraulic conductivity of wet soil increases the risk of surface runoff, and thereby the risk of soil erosion and phosphorus leaching. Lowering groundwater table by efficient subsurface drainage has been found to enhance physical and biological processes that improve the structure of clayey soils. The effects of drainage improvement on surface runoff and soil physical properties have seldom been reported. We have studied the long-term effects of subsurface drainage improvement on soil physical properties and surface runoff on a heavy clay soil under boreal conditions. The runoff determinations were carried out for five years before and nine years after the drainage improvement. During the study period, the soil was autumn ploughed annually to 20 cm depth and spring cereals were grown. Before the drainage improvement, surface runoff constituted 60–80% of the total runoff but it declined to 10–40% after improvement. Mean values of macroporosity and saturated hydraulic conductivity for subsoil (20–60 cm layer) measured ten years after drainage improvement were higher than the mean values measured two years before drainage improvement, indicating that the processes relevant to the formation of clay soil structure were enhanced.

**Keywords:** groundwater table management, soil structure response, environmental impact, boreal conditions

**INTRODUCTION** Subsurface drainage affects the water fluxes in the soil. In boreal conditions, subsurface drainage systems are installed primarily to provide trafficable conditions so that field operations can be conducted in a timely manner, and to protect plant roots from anaerobic conditions. Subsurface drainage is designed to remove excess water from soils to reduce the residence time and improve soil aeration (Van de Graaff, 1979; Grazhdani et al., 1996). However, subsurface drainage is increasingly perceived nowadays in terms of its water quality impacts, e.g. surface runoff, erosion and nutrient leaching control or increase. It has been found to reduce surface runoff and increase the amount of water infiltrating into soils compared to undrained soil (e.g. Skaggs et al.,

1994; Bengtson et al., 1995; Augeard et al., 2005) with subsequent decrease in the risk of sediment and particulate phosphorus losses (Turtola and Paajanen 1995).

Lowering groundwater table by subsurface drainage enhances unsaturated conditions favouring the processes essential to the development of clay soil structure, e.g., shrinking and cracking, root growth, and the activity of soil organisms. Van de Graaff (1979) reported that cracking was less intensive in poorly drained soils. Of the biological factors with important implications for soil structure formation, earthworm activity, for instance, is known to be enhanced by the drainage of wetlands and water-logged soils (van Rhee, 1969; Carter et al., 1982; Baker, 1998). Soil structure, i.e. porosity and aggregation, markedly affects the cultivability, workability and hydrological properties of clay soils. Subsurface drainage has been reported to improve the aggregation and aggregate stability of clay soil (Baker et al. 2004) and to increase the volume of air-filled pores (Hundal et al., 1976) and saturated hydraulic conductivity (Bouma et al., 1979) of clay soils. According to Mokma et al. (2000) and Yli-Halla et al. (2009), the lowering of the groundwater table by subsurface drainage has markedly affected the structure development of Finnish clay soils.

In Finland, the most important agricultural region of annual crops is the southern and southwestern part of the country between latitudes 60° and 61° N. In this area, clayey (> 30% of particles smaller than 0.002 mm) subsoil is found in more than 60% of the arable land (Puustinen et al., 1994). Subsurface drainage, consisting of perforated pipes or tiles installed at depths typically ranging from 70 to 100 cm, is a common agricultural water management practice in boreal conditions of Finland. In south and southwestern part of the country, 54–82% of the arable area is subsurface drained (Yearbook of Farm Statistics, 2007).

Despite the subsurface drainage system, problems of surface water ponding and heavy surface runoff are common on the clay soils of southern and southwestern Finland. Thus, a need for improving the drainage systems of clay soils has been expressed. Even though the improved subsurface drainage is expected to be beneficial for the reduction of surface runoff generation and for the structure development of clay soils, the effects of drainage on the surface runoff and soil physical properties related to soil macroporosity have seldom been examined. Modifications in soil macroporosity are very important since they clearly affect essential physical, chemical, and biological soil properties and processes which also have marked economic and environmental consequences. We addressed the question by studying the share of surface runoff and examining soil physical properties related to soil macroporosity before and after the improvement of the drainage system. The study was performed in a long-term leaching field located on a heavy clay soil.

## **MATERIAL AND METHODS**

**Experimental site and subsurface drainage system** The Kotkanoja experimental field was instrumented for non-point source pollution studies by the MTT Agrifood Research Finland in 1975. The site is located at Jokioinen, southwest Finland (60°48.94' N, 23°30.84' E), with a mean slope of 2% (1–4%). The soil in the area is clay and classified (Soil Survey Staff, 1998) as a very fine, mixed Typic Cryaquept, and according to FAO (1998) classification as a Vertic Cambisol. Soil texture is heavy clay (at least 60% of the particles in the clay fraction, < 0.002 mm), the surface layer (0–25 cm) being silty clay

(Turtola et al., 2007). The content of total C, 2.5–3.0%, considered to be organic C and soil pH, 6.0–6.5 (measured in 1:2.5 (v/v) water suspension) were typical for the soil type in the area (Turtola et al., 2007).

The original subsurface drainage system with tile pipes was installed in 1962. Since the subsurface drainage did not function well in 1980s, the system was reconstructed using plastic pipes in summer 1991. The new pipe lines were laid at the same depth (about 1 m) but 30 cm from old ones, and were connected to the same plastic cross pipes delivering water to the observation hut (Fig.1, Turtola and Paajanen, 1995). To enhance the water conductivity of the backfill material of the drain trenches, the pipes were covered with a 15 cm layer of gravel, and additionally five short, 40–60 cm thick gravel deposits per a drain of 33 m long was installed. Finally, the trenches were backfilled with topsoil in the upper part of the field and with wood chips in the lower part (Turtola and Paajanen, 1995).

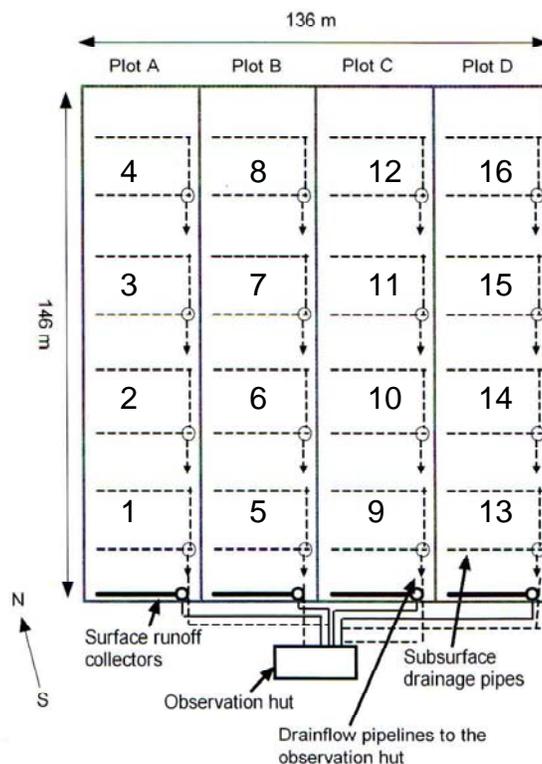


Figure 1. Layout of the Kotkanoja experimental field. Surface runoff is collected from plots A to D and subsurface drainflow from plots 1 to 16 (Uusitalo et al., 2007).

The leaching field was established on the Kotkanoja field in 1975. The experimental field is divided into four 0.5-ha plots, which are hydrologically isolated by plastic sheet curtains that extend 1 m below the soil surface, by open ditches and by 20–30 cm high barriers of mounded soil (Fig. 1; Turtola and Paajanen, 1995; Uusitalo et al., 2007). Collection of surface runoff was done at the lower ends of the four field plots A–D whereas subsurface drainflow was separately collected from each plot (1 to 16) by 4 pairs of pipe drains laid at about 1 m depth (Fig.1). Surface runoff and subsurface drainflow

flowed through PVC pipes to an observation hut where the volume of water was measured throughout the years by tipping buckets equipped with a data logger.

**Field cultivation and determination of surface runoff** To determine the effect of subsurface drainage improvement on the share of surface runoff the water flow measurements were done 10 years (in 1980–1990) before and after (in 1991–2001) the drainage improvement. The total runoff for plots A to D was calculated by summing the surface runoff of a plot and the subsurface drainflow of the four separate drainage systems in the surface runoff plot (Fig. 1). Surface runoff comparison was made for periods (spring to spring) for plots under similar tillage and crop (autumn ploughing, spring barley (*Hordeum vulgare* L.) or spring oats (*Avena sativa* L.)). Before subsurface improvement surface runoff and subsurface drainflow were compared for three periods (in 1980–83, 1988–89, 1990–91), with two periods (1991–92, 1994–2002) after the improvement. During these years before and after the drainage improvement the mean precipitation was 673 and 624 mm, respectively.

**Soil sampling and determination of physical properties** The effects of subsurface drainage improvement on soil physical properties were investigated by determining the saturated hydraulic conductivity and soil macroporosity two years (in 1989) before and ten years (in 2001) after the improvement in 1991. In autumn 1989, three undisturbed soil samples (PVC pipe with a diameter of 15 cm and length of 60 cm) were taken for laboratory analysis from each subsurface plot (1 to 16 in Fig. 1) midway between two subsurface drains. In autumn 2001, two replicate samples per plot were taken, one about 50 to 100 cm from the subsurface drain and the other midpoint between two drains. Before analysis the samples were stored at +4–5°C. The samples were cut into three subsamples: the plough layer (0–20 cm), the middle layer (to 15 cm below the plough layer) and the bottom layer (the rest of the sample). The depths of these subsamples also approximately correlate with the depths of the three uppermost genetic horizons of the Kotkanoja soil: Ap (0–24 cm), Bw1 (24–32 cm), and 2Bw2 (32–56 cm) (Peltovuori et al., 2002).

To obtain a sample surface with open macropores, cut surfaces were prepared by removing any smeared or damaged soil with a knife and vacuum cleaner. The subsamples were saturated with boiled water from bottom to upwards to avoid air entrapment. Samples were then soaked for five days and saturated hydraulic conductivity ( $K_{\text{sat}}$ , constant head method; Youngs, 1991) of soil was determined. Soil macroporosity (theoretical diameter > 300  $\mu\text{m}$ , largest macropores relevant to preferential flow) of the subsamples was determined by measuring the volume of water out flowed from a saturated soil sample at -1 – -0.75 kPa water potential (at the middle of the sample height) as described by Alakukku (1996).

In 1989, the plots A, B and C (Fig. 1) had been ploughed in previous autumns but perennial grass had been cultivated (three years before sampling) on plot D. Since 1994, spring cereals were cultivated in the field, and plots A and C were annually ploughed and plots B and D were stubble cultivated in autumn. Therefore, the comparison before and after the drainage improvement was made for plots under similar tillage before and after the operation, i.e. for plots A (subsurface 1 to 4) and C (9 to 15, Fig. 1). In analysing how the drainage improvement influences  $K_{\text{sat}}$  and macroporosity, median values of the replicated measurements from a subsurface were used as observations.

**RESULTS AND DISCUSSION** The share of the surface runoff of total runoff during the experimental period is shown in Figure 2. Since the establishment of the experimental field in 1975, the share of surface runoff from the field had been increasing (Turtola and Paajanen, 1995). Before the subsurface improvement, surface runoff constituted 60–80% of the total runoff but after the improvement 10–40% (Fig. 2). The result is in agreement with the findings of Skaggs et al. (1994) who report that subsurface drainage reduced surface runoff by 34% to 55% in comparison with similar undrained soils.

Before the drainage improvement, the water movement in wet soil conditions occurred through tilled topsoil and in macropores. In wet conditions, the permeability in subsoil of the heavy clay was very low. In summer time, cracks provide fast routes to ponded water to subsurface drains. The clear increase of subsurface drainflow immediately after the drainage improvement (Fig. 2) was mainly affected by the good permeability of the backfill material (gravel, topsoil/wood chips) of the drain trench allowing the water infiltrate and drain quickly from surface and topsoil to deeper layers as discussed in Turtola and Paajanen (1995) and Montagne et al. (2009). We can also presume that the ploughing of the soil (normal to drain pipelines) enhanced the subsurface drainflow by increasing the temporal water storage capacity of wet soil during rainy and snow melting periods, and by conducting the topsoil layer runoff (in 0–20 cm) towards drain trench. Relevant to this, Turtola et al. (2007) found that omitting autumn tillage or replacing ploughing (to 20 cm) by shallow stubble cultivation (to 5–8 cm) reduced clearly the subsurface drain flow on this field.

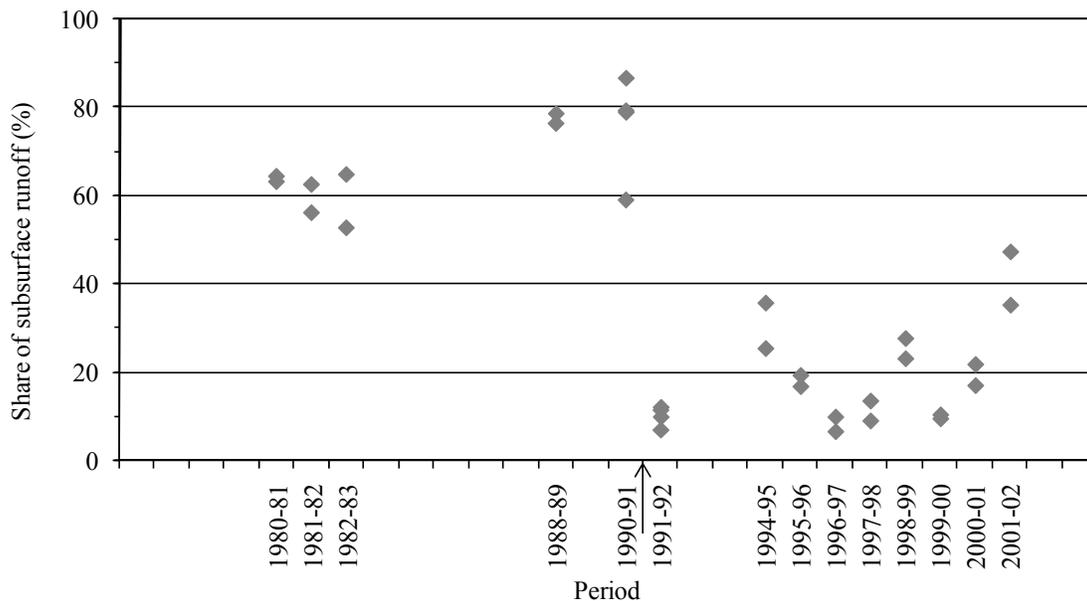


Figure 2. Share of surface runoff from the total runoff (surface runoff + subsurface drainflow) for annual periods (spring to spring) before and after subsurface drainage improvement in summer 1991 (↑) in Kotkanoja field. Comparison was made for plots under autumn ploughing and spring cereal cultivation.

Before drainage improvement in 1991, the mean volume of the biggest macropores being relevant for preferential flow was small and also the mean  $K_{sat}$  of the heavy clay subsoil was low (Table 1). However, ten years after the drainage improvement, the mean volume of macropores had increased in subsoil. Moreover, in agreement with the macroporosity

values, the mean  $K_{\text{sat}}$  in the 20–35 cm layer was clearly greater than before the drainage improvement (Table 1). After the improvement,  $K_{\text{sat}}$  in the upper part of the subsoil was just above the limit assessed for good soil structure (Aura 1990) instead of the low value before the operation. The measurements thus show that during the ten years the structure of the soil had been improved also between the drain trenches to allow less surface runoff

Table 1. Medians (Md) and quartile deviations (QD) of saturated hydraulic conductivity ( $K_{\text{sat}}$ ) and soil macroporosity (> 0.3 mm) before (in 1989) and after (in 2001) subsurface drainage improvement in 1991 in Kotkanoja field. n = 8.

Depth	$K_{\text{sat}}$ (cm/h) <sup>a</sup>				Macroporosity (m <sup>3</sup> /100 m <sup>3</sup> )			
	1989		2001		1989		2001	
	Md	QD	Md	QD	Md	QD	Md	QD
0–20	43	24	33	45	4.6	1.7	6.8	1.2
20–35	0.04	0.06	1.64	1.00	0.3	0.3	0.6	0.3
35–60	0.003	0.001	0.007	0.027	0	0	0.3	0.1

<sup>a</sup>Limits recommended for good structure of clay soils in Finland:  $K_{\text{sat}}$  in topsoil  $\geq 30$  cm/h, in subsoil  $\geq 1$  cm/h (Aura 1990)

than before. While the effects of subsurface drainage improvement on soil properties have been seldom reported, subsurface drainage as such has been found to increase the volume of air-filled pores (Hundal et al., 1976) and saturated hydraulic conductivity (Bouma et al., 1979) of undrained clay soils.

By removing the excess water subsurface drainage reduces the residence time of water in soils and increases soil aeration (Van de Graaff 1979, Bentson et al. 1995, Grazhdani et al. 1996). This favours the processes essential to the development of clay soil structure, e.g, shrinking and cracking, root growth, and the activity of soil organisms. In several experimental summers, we observed intensive soil cracking nearby the drain trenches. Moreover, in several years before subsurface drainage improvement, soil wetness hampered the growth of spring barley while the crop yields were clearly greater after the subsurface drainage improvement indicating better root growth and more intensive evapotranspiration (data not shown). Mokma et al. (2000) and Yli-Halla et al. (2009) suggested that lowering the groundwater table by subsurface drainage has markedly enhanced the structure development of Finnish clay soils. Soils having subsurface drains tend to dry up to a greater depth than those without drains, and this is presumed to cause irreversible changes in the soil structure.

**CONCLUSIONS** Subsurface drainage improvement of a heavy clay soil clearly reduced the share of surface runoff of the total runoff when soil was annually ploughed. Higher values for subsoil macroporosity and saturated hydraulic conductivity were determined ten years after than two years before the drainage improvement indicating that the operation clearly enhanced the processes relevant to the formation of clay soil structure.

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