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Simulating 3-D water flow in subsurface drain trenches and surrounding soils in a clayey field

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ABSTRACT

Subsurface drain trenches are important pathways for water movement from the field surface to subsurface drains in low permeability clayey soils. The hydrological effects of trenches installed with well conducting backfill material and gravel inlet patches are difficult to study with only experimental methods. Computational three-dimensional soil water models provide additional tools to assess spatial processes of such drainage system. The objective was to simulate water flow pathways with 3-D FLUSH model in drain spacing and trench depth scale with two model configurations: (1) the total pore space of soil was treated as a single continuous pore system and (2) the total pore space was divided into mobile soil matrix and macropore systems. Both model configurations were parameterized almost solely with field data without calibration. Data on soil hydraulic properties and drain discharge measurements were available from a clayey subsurface drained agricultural field in southern Finland. The effect of soil hydraulic variability on water flow pathways was assessed by generating computational grids in which the hydraulic properties were sampled randomly from five measured soil sets. Both model configurations were suitable to describe the recorded drain discharge, when model was parameterized in finer scale than drain spacing and the parameterization described highly conductive subdomains such as macropores in a dual-permeability model or the trench in a single pore system model. Models produced similar hourly discharge and water balance results with randomly sampled soil hydraulic properties. The results provide a new view on consequences of soil heterogeneity on subsurface drainage. The practical implication of the results from different drainage scenarios is that gravel trench appears to be important only in soils with a poorly conductive subsoil layers without direct macropore connections to subsurface drains. Solely drain discharge data was not sufficient to determine the differences in water flow pathways between the two model configurations and more output variables, such as groundwater level, should be taken into account in making assessments on the effects of different drainage practices on field drainage capacity.

1. Introduction

Cultivated clayey soils are abundant in the coastal areas of the Baltic Sea and they are routinely subsurface drained to remove excess water from the fields during wet autumn and spring snow melt periods. Efficient drainage reduces the risk of soil compaction due to machine traffic during field operations after moist periods (e.g. Alakukku et al., 2003) and prevents waterlogging in the root zone during the growing season. In Nordic countries, subsurface drains are installed mainly with the trenchless or trench installation methods (e.g. Ritzema et al., 2006). In the trench installation method, a trench is excavated with a machine, and simultaneously the drain pipe is laid at the bottom of the trench. The pipe is covered using an envelope material such as gravel and the trench is filled with a mixture of tilled topsoil and subsoil (e.g. Stuyt et al., 2005).

In low permeability soils, such as clays, the main function of envelope material is to improve permeability around the pipe

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(Stuyt et al., 2005) and the drain trenches provide a well conducting pathway for water from the field surface to the subsurface drains. Gravel inlets, created by pouring gravel into the trench up to the topsoil layer, are often used to increase the conductivity of the backfill material even though their effect is somewhat controversial (Aura, 1990). The functioning of the trench and drain envelope material appears to depend on the characteristics of the surrounding soil (Ritzema et al., 2006; Stuyt et al., 2005) but this has only rarely been studied in detail. Turtola and Paajanen (1995) noticed that drain installation with wooden chips and topsoil in the drain trenches increased drain discharge compared to the situations with impermeable subsoil and gravel envelope around the drain pipe. Messing and Wesström (2006) found that differences in soil properties between the trench material and the surrounding soil layers control the formation of drain discharge in old drainage systems, as fast flow through the drain trench was combined with a more gradual release of water from the surrounding soil layers.

The clay soil matrix usually conducts water poorly but cracks, pores between aggregates, and macropores composed of plant root channels and earthworm burrows provide additional flow capacity for percolating water. The tilled topsoil layer is well conductive due to the impact of tillage operations on soil hydraulic conductivity and macroporosity (e.g. Turtola et al., 2007). Field drainage affects the soil structure development in heavy clay soils and enhances the formation of soil aggregates and preferential flow pathways (e.g. Alakukku et al., 2010). Preferential flow pathways allow rapid movement of water (Jarvis, 2007) and generate the main part of drain discharge in clayey soils (e.g. Frey et al., 2016; Warsta et al., 2013). When gravel envelope material is used in macroporous soil, the role of preferential flow and the envelope for field drainage is unclear.

Macroporosity of soils appears to vary spatially and it has been shown with soil sample analyses and tracer experiments that more earthworm burrows and root channels exist above the drains, partly due to more suitable moisture conditions than elsewhere in the field (Alakukku et al., 2010; Shipitalo et al., 2004; Nuutinen and Butt, 2003). Direct connections between the drains and the soil surface have been verified by injecting smoke into drainpipe outlets and mapping the locations where the smoke billowed out of the soil (Nielsen et al., 2015). Messing and Wesström (2006) reported that in fields with 2 to 45 years old drain systems hydraulic conductivities were higher in the trench backfill soil compared to the soil between the drains. Alakukku et al. (2010) studied a heavy clay field with 50-year-old drainage system and demonstrated spatial variability in soil macroporosity and hydraulic conductivity, but found no notable differences in these variables between locations above the drain line and in the midpoint of the drain lines. The literature reports about spatial differences in preferential flow paths and provides some conceptual understanding of their implications on subsurface flow, but quantitative assessment of their role calls for application of simulation models. Messing and Wesström (2006) suggest that simulations of water flow in these heterogeneous soils should take into account the quick water flow to drainpipes in the permeable backfill material and slower, more continuous water flow from the soil layers between the trenches.

Hydrological models are regularly used to analyze the performance of field drainage systems (e.g. Nousiainen et al., 2015; Turunen et al., 2013). Two-dimensional (2-D) and three-dimensional (3-D) models can take into account the topography and spatial variability of soil hydraulic characteristics (e.g. Haws et al., 2005; Hansen et al., 2013; Klaus and Zehe, 2010; Henine et al., 2014; De Schepper et al., 2015; Turunen et al., 2015a Henine et al., 2014; De Schepper et al., 2015; Turunen et al., 2015a) and thus simulate the hydrological effect of a trench (Gärdenäs et al., 2006) and features such as mole drains or gravel inlets that lie in the trench at regular intervals (Filipović et al., 2014).

Several 1-D (Jarvis and Larsbo, 2012; Jansson and Karlberg, 2004; van Dam et al., 2008), 2-D (Abrahamsen and Hansen, 2000) and 3-D (Danish Hydraulic Institute, 2007; Šimůnek and van Genuchten, 2008; Warsta et al., 2013; Brunner and Simmons, 2012) models which include descriptions of preferential flow processes have been developed. A common approach to simulate preferential flow is to divide the soil porosity into two or more pore systems, e.g. soil matrix and macropores that conduct water at different rates and can exchange water between the systems (e.g. Köhne and Mohanty, 2006). Another approach to take preferential flow into account in computational models is to apply single pore system models with explicit representation of the macropores as high flow numerical units (e.g. Klaus and Zehe, 2010; Vogel et al., 2000 Vogel et al., 2000). Parameterization of preferential flow models can be challenging because the related parameter values can be difficult to derive from laboratory data (e.g. Gärdenäs et al., 2006; Haws et al., 2005; Köhne and Mohanty, 2006). Previous studies have successfully simulated water flow in clay soils, but challenges remain with model parameterization and description of preferential flow processes (Beven and Germann, 2013).

Models that include a preferential flow description can give insight whether the effect of macropores on water flow is crucial in the simulated soil domain (Gärdenäs et al., 2006; Klaus and Zehe, 2010). According to Vogel et al. (2000), the effect of soil heterogeneity could be described with a dual-permeability model or with a single pore system model where soil hydraulic parameters are randomized. There is a need to compare the suitability of different pore system approaches.

In this study we strived to clarify the role of drain trenches, gravel envelope material and soil macropores in the formation of drain discharge in clay soil with different hydraulic properties. We simulated 3-D water flow in drain spacing scale with the FLUSH model that supported direct parameterization of drain trenches in heterogeneous clayey soils. Our objective was to investigate if the model can reproduce the drain discharge with 1) a single pore system and 2) dual-permeability configurations when the values of the hydraulic parameters are taken from measurements and are not calibrated. The study setup enabled us to investigate if the application of the two model configurations using the same data set can give insight on water flow pathways in drain spacing scale. Our hypothesis is that in clayey soils water initially flows laterally in the tilled topsoil layer towards the trench and to the drainpipe. Presumably the effect of the drain trench increases as the saturated hydraulic conductivity of the surrounding soil decreases.

2. Materials and methods

2.1. Site and data description

The Nummela experimental site is a subsurface drained clayey field located in Jokioinen (60°51′ 59″N 23°25′ 50″E) southern Finland (Fig. 1a), administrated by the Natural Resources Institute Finland. The total field area is 9.2 ha and the field is relatively flat (slope $< 1\%$). The experimental field was originally subsurface drained in 1952 with the trench installation method. The drainage system was composed of tile drains (inner diameter 0.05 m), and the drains were installed into a depth of approximately 1.0 m with drain spacings of 16 m (5.8 ha) and 32 m (3.4 ha).

The field area was divided in 2006 into four separately monitored sections (A, B, C and D), where impact of different drainage installation methods on field hydrology, nutrient losses and crop yield were studied before and after the installations (Vakkilainen et al., 2008, 2010; Äijö et al., 2014). The field sections were delineated on the basis of subsurface drainage networks