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Analyzing subsurface drain network performance in an agricultural monitoring site with a three-dimensional hydrological model

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SUMMARY

Effectiveness of a subsurface drainage system decreases with time, leading to a need to restore the drainage efficiency by installing new drain pipes in problem areas. The drainage performance of the resulting system varies spatially and complicates runoff and nutrient load generation within the fields. We presented a method to estimate the drainage performance of a heterogeneous subsurface drainage system by simulating the area with the three-dimensional hydrological FLUSH model. A GIS analysis was used to delineate the surface runoff contributing area in the field. We applied the method to reproduce the water balance and to investigate the effectiveness of a subsurface drainage network of a clayey field located in southern Finland. The subsurface drainage system was originally installed in the area in 1971 and the drainage efficiency was improved in 1995 and 2005 by installing new drains. FLUSH was calibrated against total runoff and drain discharge data from 2010 to 2011 and validated against total runoff in 2012. The model supported quantification of runoff fractions via the three installed drainage networks. Model realisations were produced to investigate the extent of the runoff contributing areas and the effect of the drainage parameters on subsurface drain discharge. The analysis showed that better model performance was achieved when the efficiency of the oldest drainage network (installed in 1971) was decreased. Our analysis method can reveal the drainage system performance but not the reason for the deterioration of the drainage performance. Tillage layer runoff from the field was originally computed by subtracting drain discharge from the total runoff. The drains installed in 1995 bypass the measurement system, which renders the tillage layer runoff calculation procedure invalid after 1995. Therefore, this article suggests use of a local correction coefficient based on the simulations for further research utilizing data from the study area.

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1. Introduction

Subsurface drains are commonly used in aggregated soils such as clay to provide sufficient soil moisture conditions for cultivation operations and crop growth after snowmelt in the spring and during autumn rains in high latitude conditions. Artificial drainage of clayey soils can improve the soil structure by accelerating aggregate formation (e.g. Yli-Halla et al., 2009) and increasing earthworm activity in the soil (e.g. Alakukku et al., 2010). Water movement in clayey soils is complicated due to preferential flow in the interaggregate space, and dynamic volume changes of the aggregates caused by swelling and shrinkage processes in wetting and drying soil, respectively. Effectiveness of the drainage networks reduces during their lifetime of several decades due to compaction of the soil, clogging of the pipes, and decrease of conductivity in the drain trenches (e.g. Grismer et al., 1988; Turtola and Paajanen, 1995; Alakukku et al., 2003; Sikkilä, 2014; Äijö et al., 2014). Soil compaction can decrease the hydraulic conductivity in both the upper parts of the soil profile and the drain trench, reducing water flow into the drains. However, results of recent dye tracing experiments indicated that persistent compaction may enhance preferential flow (Etana et al., 2013). Clogging is often caused by accumulation of silt and formation of iron ochre in the pipelines (e.g. Luoma and Puustinen, 1986; Stuyt et al., 2005). Clogged drains can be cleaned by jet flushing but there is little evidence on practical benefit of the procedure (Stuyt et al., 2005). It is also possible that the drains in some sites were originally installed incorrectly resulting in decreased performance. Pehkonen (1986) noted that in Finland 24% of the drainage deficiencies were associated with problems in the installation of the system. Inefficient drainage is often fixed by installing supplemental drains between

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the old drains or by installing new drains over the old ones (e.g. Luoma and Puustinen, 1986; Vakkilainen et al., 2010). Typically additional drains are installed in locations where water ponding or high soil moisture conditions occur to ensure sufficient drainage in the whole field area (e.g. Äijö et al., 2014). The old drains are commonly left in the ground, and they can influence the drainage efficiency even though they are not directly connected to the new system. The result is that with time the drainage networks become spatially heterogeneous with areas of varying drainage densities and effectiveness. Such spatial heterogeneity of overlapping new and old drainage system complicates the hydrological performance and nutrient transport within the field.

The changing performance of subsurface drainage systems with time has been studied in several long term measurement campaigns (e.g. Grismer et al., 1988; Turtola and Paajanen, 1995; Äijö et al., 2014). While it is possible to assess the drainage performance based directly on drain discharge observations, mathematical models are helpful for estimating the extent to which the changes in discharge are caused by annual variations in the meteorological data or changed drainage efficiency. Specifying the actual reason behind the efficiency changes is difficult (e.g. Rimidis and Dierickx, 2003; Sikkilä, 2014) and requires digging up drain lines in the field and also investigation of possible soil compaction.

Water balance and nutrient transport in field-scale have traditionally been simulated with one-dimensional (1D), process-based hydrological models, such as MACRO (e.g. Jarvis and Larsbo, 2012), SWAP (van Dam et al., 2008) and DRAINMOD (e.g. Dayyani et al., 2010). Water movement in structured soils is often simulated with models that divide the soil porosity into soil matrix and macropore systems (e.g. van Dam et al., 2008; Jarvis and Larsbo, 2012; Warsta et al., 2013a). This approach facilitates simulation of slow water flow in the soil aggregates and fast flow in the interaggregate space. However, simulation of drainage systems with 1D models can be difficult because the drains can generate different amounts of drain discharge in different parts of the field due to the varying efficiencies of the drain pipes, different soil properties and topographic differences (Hintikka et al., 2008; Turunen et al., 2013). Two-dimensional (2D) transect models can simulate drainage in field areas with a simple sloping topography and nearly uniform slope aspect (e.g. Mohanty et al., 1998; Gärdenäs et al., 2006). Three-dimensional (3D) hydrological models can explicitly describe the different branches of the drainage network and topographical variations in the area, and the resulting lateral flow processes such as water redistribution due to groundwater flow (e.g. Rozemeijer et al., 2010; Turunen et al., 2013, 2015a, 2015b; Filipović et al., 2014; Warsta et al., 2013a, 2014). Alternatively, drainage network can be presented adequately e.g. as a high-conductivity porous medium layer (De Schepper et al., 2015). Most hydrological models do not simulate water flow inside the drain pipes even though models simulating both soil water movement and pipe flow processes are becoming available (e.g. Henine et al., 2014). Network simulation tools integrate simple hydrological models and description of water movement in the drainage networks. Yang et al. (2000) presented an integrated drainage network analysis system (IDNAS) and Tiemeyer et al. (2007) described a semi-conceptual catchment scale model (MHYDAS-DRAIN) to simulate water movement in the soil and in the drainage network.

Our objective is to develop a method for evaluating the performance of subsurface drainage networks in clayey soils, and to apply the method to assess the uncertainties in the structure of the subsurface drainage system and the water balance in the clayey Hovi field in southern Finland. The Hovi field is of special interest because the measurements from the area are part of the data behind the national estimate of environmental loads from agriculture in Finland (e.g. Vuorenmaa et al., 2002). Our specific aims are (1) to produce the water balance of the field annually and during autumns with the current drainage system, and (2) to produce model realisations to assess the role of each installed drainage network in the water balance and water contributing areas in the field. The proposed method combines a GIS analysis and an application of the FLUSH model (e.g. Warsta et al., 2013a), which is a 3D distributed hydrological model developed for structured soils in Nordic conditions. We also investigate how the drainage parameters in FLUSH can be used to depict poorly functioning pipes and how the model can cope with a relatively large and complex field area having several separate drainage systems. We produce a scheme to correct the problems introduced into the data due to incomplete information on drainage system structure.

2. Site description

In Finland, national environmental loads, including sediment and nutrient losses from cultivated areas, are based on data collected from a network of small representative catchments and results of runoff and nutrient load models (e.g. Vuorenmaa et al., 2002). There are four operationally monitored catchments in Finland having large shares of agricultural areas. The Hovi catchment (12 ha, slope 2.8%), which is bordered with ditches and embankments from the surrounding fields, is the only catchment having 100% cultivated land. Hovi is located in Vihti, Southern Finland (60°25′20″N, 24°22′7″E, Fig. 1a) and the Natural Resources Institute Finland (LUKE, earlier MTT Agrifood Research Finland) manages agricultural field operations on the field. LUKE together with the Finnish Environmental Institute (SYKE) and other research organizations carries out data acquisition in the area. Several experimental and modelling studies have used the data from the Hovi area to study subsurface drainage techniques and nutrient leaching in cultivated areas (Seuna and Kauppi, 1981; Bengtsson et al., 1992; Seuna, 2004; Puustinen et al., 2007; Taskinen and Bruen, 2007a, 2007b; Vakkilainen et al., 2010; Warsta et al., 2014). The total field area is 26 ha, which includes the monitored catchment of 12 ha (Fig. 1b). During 2010–2012, the 26 ha field was divided into three smaller field sections for cultivation of different crops (Fig. 1b). Total of 21 ha of barley was cultivated in the field sections 1 and 2, and the section 3 (5 ha) was left as permanent grassland. Farming operations in the field sections are presented in Table 1.

Soil properties were most recently investigated in 2009 when soil samples were collected from three different depths in 17 locations situated in a 3.2 ha subarea of the field (part of the field section 1 in Fig. 1b). Particle size distribution, water retention properties, macroporosity and saturated hydraulic conductivity were measured from each sample. Average values of clay and silt contents and macroporosity of the tillage layer (0–0.20 m) and the bottom soil (0.2–0.35 and 0.35–0.60 m) are presented in Table 2.

An artificial catchment (12 ha) delineated by ditches and embankments was built in the field during the 1970s. Since then the field has been subject to several drainage operations. During our study period, three partly overlapping subsurface drainage networks existed in the field area (Networks 1–3 in Fig. 2a). The oldest Network 1 was installed in 1971 (e.g. Seuna and Kauppi, 1981; Warsta et al., 2014) and it is connected to the drain discharge measurement well (Point A in Fig. 2a). The drainage efficiency of the old network is likely decreased. The second newest Network 2 found in this study was installed in 1995 and it is currently not connected to the drain measurement system. The newest Network 3 was installed in 2005 and it is connected to the original Network 1 and the measurement well.

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