<https://helda.helsinki.fi>

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

Salo, Heidi

2017-05

Salo , H , Warsta , L , Turunen , M , Nurminen , J , Myllys , M , Paasonen-Kivekäs , M , Alakukku , L & Koivusalo , H 2017 , ' Simulating 3-D water flow in subsurface drain trenches and surrounding soils in a clayey field ' , Soil & Tillage Research , vol. 168 , pp. 20-32 . <https://doi.org/10.1016/j.still.2016.12.002>

<http://hdl.handle.net/10138/308485>

<https://doi.org/10.1016/j.still.2016.12.002>

cc_by_nc_nd

acceptedVersion

Downloaded from Helda, University of Helsinki institutional repository.

This is an electronic reprint of the original article.

This reprint may differ from the original in pagination and typographic detail.

Please cite the original version.

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

3 Heidi Salo^a, Lassi Warsta^b, Mika Turunen^b, Jyrki Nurminen^c, Merja Myllys^d, Maija Paasonen-
4 Kivekäs^e, Laura Alakukku^f, Harri Koivusalo^b

5

6 ^a Corresponding author information: tel. +358 505307604, email: heidi.salo@aalto.fi, Aalto
7 University School of Engineering, Department of Built Environment, P.O. Box 15300, FI-00076
8 Aalto, Finland.

9 ^b Aalto University School of Engineering, Department of Built Environment, P.O. Box 15300, FI-
10 00076 Aalto, Finland.

11 ^c The Finnish Field Drainage Association, Simonkatu 12 A 11, FI-00100 Helsinki, Finland.

12 ^d Natural Resources Institute Finland, Tietotie 4, FI-31600 Jokioinen, Finland.

13 ^e Sven Hallin Research Foundation, Simonkatu 12 A 11, FI-00100 Helsinki, Finland.

14 ^f University of Helsinki, Dep. of Agricultural Sciences, P.O. Box 28, FI-00014 University of
15 Helsinki.

16 **Abstract**

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

41

42 **Keywords**

43 3-D modeling; preferential flow; supplementary drain installation

44

45 **1. Introduction**

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

55 In low permeability soils, such as clays, the main function of envelope material is to improve
56 permeability around the pipe (Stuyt et al., 2005) and the drain trenches provide a well conducting
57 pathway for water from the field surface to the subsurface drains. Gravel inlets, created by pouring
58 gravel into the trench up to the topsoil layer, are often used to increase the conductivity of the
59 backfill material even though their effect is somewhat controversial (Aura, 1990). The functioning
60 of the trench and drain envelope material appears to depend on the characteristics of the
61 surrounding soil (Ritzema et al., 2006; Stuyt et al., 2005) but this has only rarely been studied in
62 detail. Turtola and Paajanen (1995) noticed that drain installation with wooden chips and topsoil in
63 the drain trenches increased drain discharge compared to the situations with impermeable subsoil

64 and gravel envelope around the drain pipe. Messing and Wesström (2006) found that differences in
65 soil properties between the trench material and the surrounding soil layers control the formation of
66 drain discharge in old drainage systems, as fast flow through the drain trench was combined with a
67 more gradual release of water from the surrounding soil layers.

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

78 Macroporosity of soils appears to vary spatially and it has been shown with soil sample analyses
79 and tracer experiments that more earthworm burrows and root channels exist above the drains,
80 partly due to more suitable moisture conditions than elsewhere in the field (Alakukku et al., 2010;
81 Shipitalo et al., 2004; Nuutinen et al., 2003). Direct connections between the drains and the soil
82 surface have been verified by injecting smoke into drainpipe outlets and mapping the locations
83 where the smoke billowed out of the soil (Nielsen et al., 2015). Messing and Wesström (2006)
84 reported that in fields with 2 to 45 years old drain systems hydraulic conductivities were higher in
85 the trench backfill soil compared to the soil between the drains. Alakukku et al. (2010) studied a
86 heavy clay field with 50-year-old drainage system and demonstrated spatial variability in soil
87 macroporosity and hydraulic conductivity, but found no notable differences in these variables
88 between locations above the drain line and in the midpoint of the drain lines. The literature reports

89 about spatial differences in preferential flow paths and provides some conceptual understanding of
 90 their implications on subsurface flow, but quantitative assessment of their role calls for application
 91 of simulation models. Messing and Wesström (2006) suggest that simulations of water flow in these
 92 heterogeneous soils should take into account the quick water flow to drainpipes in the permeable
 93 backfill material and slower, more continuous water flow from the soil layers between the trenches.

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

101 Several 1-D (Jarvis and Larsbo, 2012; Jansson and Karlberg, 2004; van Dam, 2008), 2-D
 102 (Abrahamsen and Hansen, 2000) and 3-D (Danish Hydraulic Institute (DHI), 2007; Šimůnek and
 103 van Genuchten, 2008; Warsta et al., 2013; Brunner and Simmons, 2012) models which include
 104 descriptions of preferential flow processes have been developed. A common approach to simulate
 105 preferential flow is to divide the soil porosity into two or more pore systems, e.g. soil matrix and
 106 macropores that conduct water at different rates and can exchange water between the systems (e.g.
 107 Köhne and Mohanty, 2006). Another approach to take preferential flow into account in
 108 computational models is to apply single pore system models with explicit representation of the
 109 macropores as high flow numerical units (e.g. Klaus and Zehe, 2010; Vogel et al., 2000).

110 Parameterization of preferential flow models can be challenging because the related parameter
 111 values can be difficult to derive from laboratory data (e.g. Gärdenäs et al., 2006; Haws et al., 2005;
 112 Köhne and Mohanty, 2006). Previous studies have successfully simulated water flow in clay soils,

113 but challenges remain with model parameterization and description of preferential flow processes
114 (Beven and German, 2013).

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

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

131

132 **2. Materials and methods**

133 **2.1. Site and data description**

134 The Nummela experimental site is a subsurface drained clayey field located in Jokioinen (60°51'
135 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 having uniform depth and spacing within each section. Data from section C (1.7 ha) with original drain spacing of 16 m was used in this study.

In June 2008, the trench installation was applied in section C (Äijö et al., 2014) as supplementary drains were installed between the original drains resulting in a drain spacing of 8 m (Fig. 1b). Gravel was used as an envelope material (0.3–0.4 m above the drain) and gravel inlets were installed into the trench with a spacing of 7–8 m. The monitoring of the field section was started one year before the drainage installation.

Spring barley (*Hordeum vulgare*) and oats (*Avena sativa*) were cultivated in the field section during the study years. Minimum tillage (autumn stubble cultivation with cultivator to 0.10–0.15 m depth) was applied in the section in the autumns except for 2012 due to excessive wetness in the field. The crops were harvested in September except in 2012 when the harvest was postponed into October. The experimental activities and the field setup are reported in more detail in Vakkilainen et al. (2008, 2010) and Äijö et al. (2014).

Soil in section C is classified as Vertic Luvisol Stagnosols (IUSS Working Group WRB, 2014) with a mean clay content (particle size < 2 µm) of 66% in the soil layers 0–0.35m and 70–73% in the soil layers 0.35–1m (Vakkilainen et al., 2010). Undisturbed soil cores (diameter 0.15 m and length 0.6

160 m) were gathered in 2006 with a tractor auger from five locations between the tile drains (Fig. 1b)
161 with 8 m distance to the drains. The cores were divided into three soil samples with an equal height
162 of 0.2 m representing topsoil, plow pan and subsoil layers. Bulk density (Blake and Hartge, 1986),
163 soil porosity and pore size distribution (Danielson and Southerland, 1986; Williams and
164 Shaykewich, 1969), saturated hydraulic conductivity (Youngs, 1991) and water retention
165 characteristics (WRC) (Aura, 1990) were measured on the samples (Table 1). Macropores were
166 defined as pores, which drained in a suction pressure of 0.1 m (diameter >300 μ m).

167 Topsoil layer runoff and drain discharge were measured automatically from section C (Fig. 1b) with
168 a 15 min interval using Datawater WS Vertical helix meter (Maddalena, Povoletto, Italy). Topsoil
169 layer runoff was collected from the downslope side of section C with 0.4 m deep gravel-filled drain
170 trench. Groundwater levels were measured biweekly from nine observation wells (five before
171 supplementary drain installation) installed into a depth of 1.6 m and one into a depth of 2.6 m. Soil
172 (0–0.3 m) water content was measured biweekly at the locations of the groundwater wells with the
173 TRASE system I moisture meter time domain reflectometry sensor (Soil Moisture Equipment
174 Corporation, Coleta, CA, USA). Precipitation was measured on site with a 15 min interval using the
175 RAINEW 111 tipping bucket rain gauge (RainWise Inc., Bar Harbor, ME, USA).

176 For the calculation of the Penman-Monteith potential evapotranspiration (PET) hourly
177 meteorological data including air temperature, wind speed, incoming solar radiation, and relative
178 humidity were available 5 km from the study site at the Jokioinen Observatory of the Finnish
179 Meteorological Institute (FMI). Missing measurements in the meteorological data set were filled in
180 with values from the Helsinki-Vantaa Airport FMI observatory 100 km from the study site (see
181 Turunen et al., 2015b).

182

183 **2.2. Model description**

184 FLUSH is an open source 3-D hydrological model developed for simulating water flow (Warsta et
185 al., 2013; Turunen et al., 2013), soil freezing and snow processes (Warsta et al., 2012; Turunen et
186 al., 2015a) in structured soils in Nordic conditions.

187 The model divides the simulated area into 2-D overland and 3-D subsurface domains. The pore
188 space in the 3-D subsurface domain is either handled as a single continuous pore system or the pore
189 space is divided into two mobile pore systems representing the soil matrix and macropore systems.
190 The dual-permeability approach enables simulation of fast bypass flow of water in the macropore
191 system from the field surface to deeper soil layers.

192 In the overland domain, water flow on the field surface is described with the diffuse wave
193 approximation of the Saint-Venant equations. Furthermore, the overland domain handles the soil
194 surface depression water storage and sets the upper boundary condition for the subsurface domain.
195 In the model, precipitation is first stored in the soil surface depression storage and overland flow is
196 initiated only after the water depth exceeds the depression storage. Water can be removed from the
197 overland domain by open ditches and infiltration into the subsurface domain. Water can infiltrate
198 into both pore systems of the subsurface domain, but exfiltration back to overland domain is
199 prevented. Water in the subsurface domain can be removed by evapotranspiration, seepage into
200 open ditches, subsurface drains and groundwater outflow.

201 Water flow in both soil matrix and macropore systems in the subsurface domain are described with
202 the Richards equation. Unsaturated hydraulic conductivity and water retention properties of both
203 pore systems are computed with the van Genuchten (1980) model. The water exchange between the
204 pore systems is driven by pressure differences between the soil matrix and macropores. Water
205 exchange is included as a sink and source term in the Richards equations (Gerke and van
206 Genuchten, 1993):

$$\Gamma = \alpha_W(h_F - h_M) \quad (1)$$

207

208 where F [T^{-1}] is water exchange rate, α_w [$L^{-1}T^{-1}$] is the first order water exchange coefficient and h
209 [L] is the pressure head in the macropore (F) and matrix (M) systems. The first order water
210 exchange coefficient α_w is defined as follows (Gerke and van Genuchten, 1993):

$$\alpha_w = \frac{\beta}{d^2} K_A \gamma_w \quad (2)$$

211

212 where β [-] is a geometry coefficient, d [L] is the distance from soil aggregate to space between the
213 soil aggregates, K_A is the hydraulic conductivity in the matrix-macropore interface and γ_w [-] is a
214 scaling coefficient.

215 K_A can be computed with various approaches including arithmetic mean of hydraulic conductivities
216 in the soil matrix and macropore systems, minimum or maximum of the conductivities, or using the
217 conductivity of the system, which has the higher pressure head (upwind method) (e.g. An and Noh,
218 2014).

219 Computation of drain flux in FLUSH is based on the hydraulic head difference between the
220 surrounding soil and the drainpipe:

$$q_s = K A_s \frac{H_s - H}{\Omega_s} \quad (3a)$$

$$A_s = L_s 2\pi R_s \quad (3b)$$

221

222 where q_s [L^3T^{-1}] is the volumetric drain flux, K [$L T^{-1}$] is the hydraulic conductivity of the matrix or
223 macropore system in the computational cell containing the drainpipe, A_s [L^2] is the drain surface
224 area, H_s is the hydraulic head in the drain, Ω_s [L] is the flow path length, L_s [L] is the drain length

225 in the cell, and R_S [L] is the drain radius. The soil hydraulic conductivity in Eq. 3 is calculated as an
226 arithmetic mean of vertical and horizontal conductivities.

227 The model calculates evapotranspiration from the subsurface domain based on precomputed PET
228 that is divided into the soil profile according to the root mass distribution. The PET value is
229 decreased in dry conditions with the function of Feddes et al. (1978). Lateral flux of groundwater
230 outflow is removed at the computational domain borders and the hydraulic gradient at the border
231 cell is set equal to the soil surface slope (Warsta et al., 2013).

232 Implicit finite volume methods are used to discretize the computational domains and numerically
233 solve the governing partial differential equations (PDEs) (Warsta et al., 2013). The overland domain
234 is divided into rectangular cells and the subsurface domain is divided into hexahedric cells with
235 regular curvilinear grids. Unsaturated hydraulic conductivities between computational cells in the
236 subsurface domain are computed with an arithmetic mean of conductivities in two adjacent cells.
237 Backward difference method is used to solve the time derivatives in PDEs.

238 The simulations are distributed with the MPI (Message Passing Interface) parallelization (Message
239 P Forum, 1994) that divides the simulated domain into subdomains. Each subdomain is laterally
240 surrounded by ghost cells that are need to solve the lateral gradients at the subdomain boundaries
241 during each iteration round. After computing the new hydraulic heads for every cell in each
242 subdomain in one iteration round, the hydraulic head values in the ghost cells are updated with the
243 received values from a neighbor subdomain. Iteration progress information is shared between the
244 subdomains to enable them to stop the process when the hydraulic head changes in the whole
245 domain are below the iteration stop threshold value. The approach enables application of an
246 iterative and continuous solution in the whole simulated domain although each process is only able
247 to access data of the local subdomain.

248 The original subsurface water flow solver applies the pentadiagonal matrix algorithm to directly
249 solve hydraulic heads in columns of cells in 3-D grids in both pore systems at the same time, and
250 then iteration to solve the horizontal water fluxes between the columns. A new iterative solver was
251 included in the model to solve water flow in the subsurface domain due to numerical stability issues
252 experienced with the original solver. The applied solver uses a Successive Over-Relaxation
253 approach that is a modification of Gauss-Seidel method (Young, 2014).

254

255 **3. Model setup**

256 The model setup was created to simulate hourly drain discharge before and after supplementary
257 drain installation, and water balances with and without drain trenches in section C of the Nummela
258 field. Three differently parameterized 3-D computational grids (area $8 \times 4 \text{ m}^2$) were prepared for the
259 simulations: (1) a grid with a drain spacing of 16 m including the original trench (Fig. 2a), (2) a grid
260 with a drain spacing of 8 m including the original and supplementary drain trenches (Fig. 2b) and
261 (3) a grid with the drain spacing of 8 m without trenches (Fig. 2c). Since the spacing between the
262 drain lines and gravel inlets was regular and the field is relatively flat, it can be assumed that the
263 hydrological response to the drain installations was similar throughout the section. Thus the length
264 of the simulated domain was set to half of the length of the original drain spacing (8 m) and the
265 width of the domain to half of the distance between the gravel inlets (8 m) (Fig. 2b). Only half of
266 the drainpipe area (Eq. 3) is included in the simulations due to the assumption that the hydrological
267 processes were symmetrical throughout the section. The depth of the grid was 1.5 m reaching below
268 the drain depth of 1.0 m. Grid cell depths in the vertical direction were 0.02 and 0.03 m for the first
269 two layers near the surface and 0.05 m for the layers 3–32. The horizontal cell dimensions were 0.1
270 m, which was half of the drain trench width (0.2 m). The simulations were conducted with time step
271 lengths of 0.94–3.75 min.

272 To test the effect of the supplementary drain installation on drain discharge, three rainy autumn
273 periods without crop interaction on field water balance were selected to represent conditions before
274 (1 Oct–4 Nov 2007) and after the installation (14 Oct–7 Nov 2008 and 14 Oct–7 Nov 2012). A two-
275 day model warm-up period was included in the simulated periods. Drain discharge data from the
276 autumn 2007 period was used to test the parameterization of the soil in the original drain trench in
277 grid 1 (Fig. 2a). The drain discharge data from the autumn periods 2008 and 2012 were used to test
278 the capability of the model to reproduce the measured hourly drain discharge results with the
279 measured soil hydraulic properties. Performance of hourly drain discharge simulations was assessed
280 with the Nash-Sutcliffe (N-S) efficiency coefficient (Nash and Sutcliffe, 1970). The simulation
281 results from the autumn 2008 period were further analyzed to decipher differences between the
282 water balances of the grids 1–3 (Figs. 2a–c).

283 Soil hydraulic parameters (saturated and residual water contents, macroporosity, saturated hydraulic
284 conductivity and van Genuchten water retention curve parameters) required by the model are
285 presented in Table 1. Five soil sets, which included data from the three depths collected from
286 locations C1–C5 (Fig. 1b), were applied one by one to the soil layers outside the drain trench in the
287 simulated periods. The model was run with each soil set and time period for both model
288 configurations.

289 The bottom soil (1.0–1.5 m) parameterization was derived from previous modelling studies in the
290 Nummela field (Turunen et al., 2013; Salo et al., 2015). We presumed that the original trench
291 backfill material had similar soil parameters as the surrounding clay soil after several decades from
292 the installation in 1952. Hydraulic properties of the original trench soil were computed as an
293 arithmetic average of the topsoil and surrounding soil layer properties (Table 1). Gravel layer of 0.4
294 m was set on the bottom of the supplementary drain trench (Table 1). At the gravel inlet locations,
295 the depth of the gravel was increased up to the bottom of the topsoil layer. The soil hydraulic
296 parameters of the trench of the new supplemental drains was set according to the measured topsoil

297 (0–0.2 m) properties, but the gravel layer (0.6–1.0 m) was parameterized after Leij et al. (1996).
 298 WRC parameters for the macropore system were set after Köhne and Mohanty (2006).
 299 Randomized soils, where soil properties for the cells between the trenches were assigned by random
 300 sampling from Table 1, were created to analyze the hydrological impacts of soil heterogeneity. The
 301 randomization was conducted independently for topsoil, plow pan and sub soil layers, e.g. subsoil
 302 or plow pan parameterization was not applied for the topsoil layers. The parameterization for the
 303 envelope material for the supplementary drain trench and bottom soil material was not randomized.
 304 The same water retention curve was applied in the macropore domain for all the soil layers (Table
 305 1). Measured saturated hydraulic conductivity was decomposed into soil matrix and macropore
 306 fractions in the dual-permeability model according to the following equation:

$$K_{sat} = (1.0 - w)K_M + wK_F \quad (4)$$

307

$$K_F = K_{FS,MUL} w \quad (5)$$

308

309 where K_{sat} [$L\ T^{-1}$] is the measured saturated hydraulic conductivity, w [-] is the macroporosity
 310 fraction of the total porosity, K_M and K_F [$L\ T^{-1}$] are the saturated hydraulic conductivities of the soil
 311 matrix and macropore systems, respectively, and $K_{FS,MUL}$ [$L\ T^{-1}$] is the macropore saturated
 312 hydraulic conductivity multiplier. The value of $K_{FS,MUL}$ in Eq. 5 was initially set to a value of 80 m
 313 h^{-1} (Warsta et al., 2013) but was adjusted to assure that the K_M value computed with Eq. 4 was
 314 positive. Anisotropy of hydraulic conductivity in macropores was disabled. Parameter values in α_w
 315 (Eq. 2) were lumped together into a water exchange coefficient Ψ_w [L^{-2}] except for K_A . The
 316 parameter Ψ_w was set to a value of $0.01\ m^{-2}$ in the soil domain (Salo et al., 2015). K_A was computed
 317 in the simulations with the upwind method.

318 Lateral groundwater outflow was triggered at those horizontally outermost grid cells where the
319 terrain slope aspect was directed away from the simulated domain, while groundwater inflow was
320 prevented. The bottom of the grids were considered impermeable. Topsoil layer runoff collector
321 with a length of 8 m was set into depth of 0.4 m and located at the downslope boundary of the
322 domain. Subsurface drains (length 4.0 m) were set into a layer with depth of 0.95–1.0 m (Fig. 2).
323 The pressure values inside the topsoil layer runoff collector and subsurface drainpipe were set to 0.0
324 m. The value of Q_s (Eq. 3) was set to 0.1 m, which is the horizontal cell size in the grid. The PET
325 time series was calculated with The Penman–Monteith equation (Allen et al., 1998), similarly as
326 Turunen et al. (2015b).

327 As initial conditions, overland water depth was set to 0.0 m and groundwater level was derived
328 from observations at five wells in 2007 (average 0.5 m) and nine wells in 2008 (average 0.3 m) and
329 2012 (average 0.1 m). Initial soil moisture in the unsaturated soil layers was set by assuming static
330 steady state pressure head conditions. The initial conditions were the same for every soil set and
331 both model configurations in each period.

332 The simulations were run in local workstations and in the Taito supercluster (HP cluster) and Sisu
333 supercomputer (Cray XC30) administered by CSC – IT Center for Science Ltd.

334

335 **4. Results**

336 The simulation results are presented in three sections: 1) Hourly and 2) cumulative drain discharge
337 results before and after the supplemental drain installation and 3) water balance results for the 2008
338 period.

339

340 **4.1. Hourly drain discharge results before and after the supplemental drain installation**

341 Simulations of the 2007, 2008 and 2012 periods were conducted with the two model configurations
342 (single porosity and dual-permeability) and five different soil hydraulic parameterization sets (Table
343 1). Median of the simulation results with the C1–C5 parameterizations for the single pore and dual-
344 permeability models are presented in Fig. 3 together with the measured series. The two-day model
345 warm-up period is not presented in Fig. 3. Precipitation was 66 mm (33 days), 85 mm (23 days) and
346 62 mm (23 days) during the 2007, 2008 and 2012 periods, respectively. N-S efficiency coefficients
347 were computed for the median of the simulated results separately for each drain discharge event and
348 model configuration (Fig. 3). The 2007 and 2012 periods were divided into two separate discharge
349 events separated by a dry spell in the middle of the periods. In 2008 autumn precipitation was more
350 evenly distributed resulting in four distinct discharge events.

351 A clear difference can be seen between the shapes of the measured drain discharge peaks and the
352 simulated peaks (Fig. 3), while both model configurations simulated the timing of the peaks
353 accurately. The highest measured peaks in 2008 and 2012 were blunt and confined to a maximum
354 value of 0.4–0.5 mm h⁻¹, while the simulated peaks with both models were sharper and higher as the
355 single pore model gave a maximum value of 1.0 mm h⁻¹ and dual-permeability model 1.6 mm h⁻¹.
356 The peaks produced with the dual-permeability model were almost four times higher than the
357 measured values (Fig. 3d and f).

358 The largest precipitation event in the studied period occurred in 30–31 Oct 2007 (26 mm in 27 h)
359 producing the highest simulated discharge peak. During this period the simulated drains removed 4–
360 16 mm of water while the measured cumulative drain discharge was 7 mm. The highest measured
361 discharge peak in 2007 (0.32 mm h⁻¹) was clearly lower than the highest peaks in 2008 and 2012
362 (0.39–0.46 mm h⁻¹). This likely reflects the increasing drainage capacity of the field due to the
363 supplementary drain installation. The maximum measured peak decreased from 0.46 mm h⁻¹ in
364 2008 to 0.39 mm h⁻¹ in 2012 but lower precipitation amounts during the 2012 period were
365 responsible for the lower discharge peaks.

366 The hydrological effect of soil spatial heterogeneity was analyzed by parameterizing each cell with
367 the properties of a randomly selected soil sample from the corresponding depth. Fig. 4 shows the
368 average hourly drain discharge of five randomizations for both model configurations. The
369 randomization was different for each model run, but the simulation results between the different
370 model runs remained similar to each other. Also the hydrographs for different model configurations
371 were more similar to each other (Fig. 4 a and b) compared to the homogenous soil properties (Fig.
372 3). For the dual-permeability model configuration the simulations with randomized soil properties
373 produced higher N-S efficiency numbers compared to the cases with homogeneous soil properties
374 (Table 2).

375

376 **4.2. Cumulative drain discharge changes before and after the supplementary drain** 377 **installation**

378 Cumulative drain discharge results for the 2007, 2008 and 2012 periods are presented in Fig 5. The
379 discharge results simulated with the five soil sets (Table 1) are combined into a range graph by
380 selecting the minimum and maximum values from each hour. The range graph illustrates how much
381 the discharge results varied between the five different soil parameterizations and the two model
382 configurations during the autumn periods. The variation in the discharge results simulated with the
383 single pore system model was higher and the median of the results was in the upper part of the
384 range graph. The results computed with the dual-permeability model were more similar between the
385 different soil sets and the median was closer to the lower boundary of the graph than the single pore
386 system results (Figs. 5b, 5d and 5f). Even though the drain discharge peaks simulated with the dual-
387 permeability model were higher (Fig. 3), the cumulative discharge results were lower and closer to
388 the measurements than the single pore system results (Fig. 5).

389 According to the single pore system results, the soil sample set C1 with the lowest saturated
390 hydraulic conductivities (Table 1) constantly produced the lowest cumulative drain discharge values
391 (25, 46, and 41 mm) during the three simulated periods. Soils with similar low permeability values
392 beneath the tilled topsoil layer could also be responsible for the restricted drainage capacity in the
393 field. This indicates that decreasing drain spacing or increasing the amount of gravel in drain
394 trenches may not increase field drainage capacity if the drain discharge is restricted by the
395 surrounding soil properties. When the C1 parameterization was applied in the dual-permeability
396 model, the cumulative discharge results were clearly closer to the measurements than the
397 simulations with the single pore system model (lower boundary of the cumulative drain discharge
398 cloud in Figs. 5b, 5d and 5f).

399 The normalized drain discharge (drain discharge divided by precipitation) increased after the
400 supplementary drain installation (Table 3). The difference between 2007 period and the two later
401 periods is visible with both model configurations, but there was again more variation in the single
402 pore system model results between the soil sets. The normalized discharge increased from 0.32 to
403 0.54 for the C1 set (Table 1) using single pore system model and the smaller drain spacing, which
404 could indicate that supplementary drains increased drainage capacity.

405

406 **4.3. Water balance results from 2008 period**

407 The simulation results from the autumn 2008 period were further analyzed to decipher the
408 differences in the water balances between the grids 1–3 in Figs. 2a–c and the different model
409 configurations (Fig. 6). The water balances are composed of topsoil layer runoff, drain discharge
410 and groundwater outflow.

411 The variation in the simulated water balances with the different soil sample sets (C1–C5 in Table 1)
412 was clearly lower with the dual-permeability approach than with the single pore approach (Fig. 6).

413 The effect of the trench was visible when applying the single pore system model as there was a
414 clear difference in runoff components between the grids 2 and 3 (with or without the trench
415 parameterization in Fig. 6c and Fig. 6e). The drain discharge was higher and topsoil layer runoff
416 was lower in results computed with grid 2 (Fig. 6c) compared to the results with grid 3 (Fig. 6e).
417 The reason for this is that water was not able to flow from the topsoil layer to the subsurface drains
418 due to the very low hydraulic conductivity value in the subsoil layer (arithmetic mean between soil
419 sets is 0.007 m h^{-1}) when the trench was not present in the single pore system simulation. When
420 using the C4 parameterization and the single pore system model the simulated water balances
421 generated with grids 2 and 3 were similar due to the higher saturated hydraulic conductivity (0.03 m
422 h^{-1}) of the subsoil layer compared to other sample sets (average conductivity of C1–3 and C5 is
423 0.002 m h^{-1}).

424 According to the results computed with the dual-permeability model, the effect of the trench was
425 subtle, because the macropore domain was able to activate rapid preferential flow to drains in all
426 soils (Figs. 6d and 6f). We assumed that water could first infiltrate vertically via preferential flow
427 pathways down to the shallow groundwater table and then continue laterally into the subsurface
428 drain.

429 The drain discharges from the original and supplementary drains are presented separately in Fig. 6.
430 The drainpipes were parametrized similarly and although the hydraulic properties of the trenches
431 (original and supplementary) were different in the simulations, drain discharge was evenly
432 generated through both drains with grids 2 and 3 (Fig. 2b and 2c). The total drain discharge was
433 similar between grids 1 and 2 that represented the 16 and 8 m drain spacings, respectively. The soil
434 sets C4 and C5 have the highest saturated hydraulic conductivity values in the subsoil layer (Table
435 1) providing well conducting flow pathways for water to reach the trench and the drain, meaning
436 that the different grids had smaller effects on the water balance components compared to the soil
437 sets C1–C3. Our hypothesis, in which water initially flows laterally in the topsoil layer towards the

438 drain trench and then vertically down in the trench towards the drainpipe, can be correct for the soil
439 sets C1, C2 and C3 as the low saturated hydraulic conductivity beneath the tilled topsoil layer or
440 plow pan layer (Table 1) resulted in relatively high amount of tilled topsoil layer runoff when using
441 the grid without trench. The feature was not visible in the dual-permeability model results due to the
442 dominant effect of the macropore domain on soil water flow.

443

444 **5. Discussion**

445 **5.1. Hourly and cumulative drain discharge**

446 Drain discharge data and the results of the two model configurations (dual-permeability and single
447 pore system) were analyzed with the five different soil parameterizations (Table 1) that showed
448 large spatial variation within the studied area. The simulation results indicate that the limited
449 number of soil samples was enough to represent the variation of soil hydraulic properties in the field
450 section as the minimum and maximum simulated drain discharge hydrographs encompassed the
451 measured discharge during the three autumn periods. The highest simulated peaks computed with
452 the dual-permeability and the single pore system models overestimated the measured peaks. This is
453 in contrast with earlier field scale FLUSH simulations in subsurface drained clay soils, where
454 modelled hourly drain discharge peaks were lower compared to the measurements (Nousiainen et
455 al., 2015; Warsta et al., 2013).

456 The cumulative drain discharge results simulated with the dual-permeability model were more in
457 line with the measurements and included less variation compared to the discharge computed with
458 the single pore system model. Previously, Gärdenäs et al. (2006) reported overestimated drain
459 discharge peaks simulated with dual-porosity and dual-permeability models compared to data, while
460 the single porosity model underestimated the data, but the authors did not present cumulative results
461 from the simulations. Their simulations were conducted with a 2-D computational grid using data

462 from a glacial till field in southern Sweden. Models embedding descriptions of preferential flow
463 processes have been noted to have a tendency to overestimate hourly and daily drain discharge
464 (Klaus and Zehe, 2010; Vogel et al., 2000). Haws et al. (2005) reported that the single pore system
465 model produced higher discharge peaks than the dual-porosity model when simulating water flow in
466 a 2-D grid with laterally homogeneous soil properties representing 3-D heterogeneous soil with
467 macropore paths. Turunen et al. (2013) simulated the same Nummela field section as in this study
468 with FLUSH assuming horizontally homogeneous soil layer properties. Even though they did not
469 parameterize the drain trenches, the simulation results for drain discharge generated mainly by
470 preferential flow were deemed to be successful.

471 The measured hourly drain discharges were characterized by blunt peaks during 2008 and 2012
472 periods (Fig. 3), which indicated that drain discharge rates in the field section were restricted to a
473 maximum intensity (0.46 mm h^{-1} in 2008). The average soil moisture measured from nine locations
474 was near saturation in the beginning of 2008 and 2012 simulation periods. Blunting of the peaks
475 could have been caused by the wet field conditions prior to the simulation periods, but also by the
476 low hydraulic conductivities in the subsoil layers, due to lack of preferential flow pathways, flat
477 topography of the field or by limited drainpipe capacity. In fact, the maximum intensities were in
478 the order of the design value of 0.36 mm h^{-1} ($1 \text{ l s}^{-1} \text{ ha}^{-1}$) for the drainage system. According to the
479 data of Turunen et al. (2013), the hourly drain discharge peaks were smaller in the reference field
480 section without the supplementary drainage in the Nummela field but exhibited similar round
481 shapes as our data. Henine et al. (2010) noticed from field observations that flow rates through drain
482 pipes were limited due to pipe pressurization during intense rainfall events in a tile drained
483 catchment. Henine et al. (2014) were able to simulate the phenomenon with a 2-D model coupled to
484 a 1-D pipe flow description. Simulation of water flow in drain pipes have been tested in a few 3-D
485 studies with different methods, e.g. by describing the pipe network explicitly with 1-D elements (De
486 Schepper et al., 2015) or by using a well conducting soil layer emulating the effect of a drainage

487 system (De Schepper et al., 2015; Rozemeijer et al., 2010). In this study the drain nodes work as
488 sinks and water is immediately removed from the system as it enters the drainpipe. Based on our
489 results and the previous studies, inclusion of a pipe flow model would likely improve the drain
490 discharge generation process description of FLUSH.

491

492 **5.2. Water balance and effect of the drain trench**

493 The application of the model in drain spacing scale enabled us to explicitly parameterize the drain
494 trench and the surrounding soils into computational grids and to assess the effects of the
495 supplemental drain installation on water balance components in soils with different hydraulic
496 properties. The new drains clearly increased normalized drain discharges during the 2008 and 2012
497 periods compared to the period before the installation (2007) (Table 3). The share of drain discharge
498 from precipitation was in 2008 1.4 and in 2012 1.3 times the share in 2007. Aura (1990) reported
499 that their groundwater level observations in autumn showed that groundwater table was 30 to 50 cm
500 lower with the supplementary drain in a clay field. Filipović et al. (2014) conducted 2-D and 3-D
501 simulations with HYDRUS 2D/3D to test the effects of different drainage approaches in a heavy
502 clay soil and stated that also mole drainage was an efficient practice to improve field drainage. In
503 our study, the drain trenches had a clear effect on water balance components when the results were
504 simulated with the single pore system model (Fig.6c and 6e). The trenches had a much smaller
505 effect on water balance results when the dual-permeability model was applied (Fig. 6d and 6f). Our
506 results indicate that the effect of drain trenches can be taken into account by (1) explicitly
507 parameterizing the trench into a computational grid in single pore system model applications or (2)
508 by using a dual-permeability model without trench parameterization. Previous field scale studies
509 with the FLUSH model have applied the latter method (e.g. Turunen et al., 2015a; b; 2013; Warsta
510 et al., 2013; Nousiainen et al., 2015). When single pore system model is applied and the drain

trenches are not present in computational grids, water cannot reach the drains (Fig. 6e) due to the low permeability of clayey soils. The practical implication of the results is that the importance of trench decreases in soils with direct macropore connections sustaining efficient preferential flow between field surface and subsurface drains.

515

516 **5.3. The effect of soil heterogeneity on water flow**

Turunen et al. (2015b) restricted the lateral saturated hydraulic conductivity of the macropore system in soil layers closer to the surface but left the deeper layers isotropic in their 3-D field-scale simulations of the Nummela field. We did not apply anisotropic hydraulic conductivities in the computations and it is possible that in the dual-permeability simulations water movement should be restricted in the lateral directions. Otherwise water can flow laterally without restrictions in the subsoil layers to the subsurface drains. Petersen et al. (2007) stated that the variation of the anisotropy of soil saturated hydraulic conductivity in different soil layers should be accounted when modelling agricultural fields and it could explain the heterogeneous flow evident at the field scale. Vogel et al. (2000) conducted numerical experiments to assess differences in simulated water flow and solute transport results between single pore system and dual-permeability models in 2-D transects. According to the authors, soil heterogeneity could be described with dual-permeability model or with random hydraulic conductivity fields, although field evidence would be needed to verify such parameterisations (Vogel et al., 2000). Haws et al. (2005) concluded based on their single and dual porosity model results that failure in simulations can be attributed to problems with representing 3-D soil domain as 2-D domain with homogeneous soil properties in lateral directions and misrepresentation of macropore paths. In this study, the results of computational grids with randomized hydraulic properties (Table 1), showed that the different versions of the single pore system and dual-permeability model grids produced similar results and the results produced by the

two model configurations were also similar. The N-S coefficient values were higher when grids with random hydraulic properties were applied in the simulations instead of homogeneous soil layers. This indicates that our method was able to describe some features of the heterogeneity present in the soil. Both single pore system and dual-permeability models produce comparable results against measurements, when the model is parameterized at a finer scale than drain spacing and the parameterization describes highly conductive subdomains of soil (i.e. macropore pathways or trenches). Taskinen et al. (2008) described a way to create random isotropic and anisotropic conductivity fields and the authors suggested that the solution should be easy to implement also in 3-D grids. Their approach could be used to further develop the simple randomization method applied in this study.

5.4. Model parameterization based on field data measurements and future objectives

The available soil data from Nummela were sparse but sufficient to demonstrate the impacts of different subsurface drainage methods and soil heterogeneity on discharge generation. The model performance was assessed with a single outflow variable following other model applications that use a similar approach in model calibration (e.g. De Schepper et al., 2015; Henine et al., 2010; Haws et al., 2005). Haws et al. (2005) stated that assessing model success by matching simulated and measured hydrographs for single outlet should be done with caution since observations from a single outlet may not contain enough information of the other hydrological processes within the field. Direct measurements of flow routes would be more useful than an aggregated discharge measurements for the calibration of spatially variable model parameters (Rozemeier et al., 2010). The groundwater table level observations provide another measure for monitoring the functioning of drainage systems even though modelling groundwater table level in clay soils is reported to be difficult (e.g. Aura, 1995). We were able to simulate the generation of drain discharge with a single pore system model although it has been noticed that single pore system models cannot accurately describe solute transport in clay soils (e.g. Gärdenäs et al., 2006; Haws et al., 2005). To track the

560 water flow pathways with tracers, model configurations should be tested with solute transport
561 simulations.

562

563 **6. Conclusions**

564 The drain discharge data and simulation results with the single pore system and dual-permeability
565 models and different soil parameterizations were analyzed to decipher the impacts of different
566 subsurface drainage methods, model structures and soil heterogeneity on drain discharge generation
567 and water balance. Our results demonstrate that it was possible to produce plausible simulation
568 results with both single pore system and dual-permeability models when the model was
569 parameterized at a much finer scale than drain spacing and the parameterization described highly
570 conductive subdomains such as macropores in the dual-permeability model or the trench in the
571 single pore system model. If the trench is not described, a single point sample might not be enough
572 to parameterize single pore system type models for clay since the water balance results simulated
573 with the single pore system model were sensitive to soil hydraulic parameter values.

574 Parameterization based on a single soil sample may lead to biased results, when the sample
575 represents outermost range of soil conditions. Based on our simulation results with random
576 sampling of soil data, heterogeneity of clay soil should be taken into account in model
577 parameterization. Inclusion of more output variables in the simulations can further enhance the
578 reliability of the model results, as the drain discharge data was not sufficient to determine the
579 differences in the water flow pathways between the single pore system and dual-permeability
580 models. The main novelty value of the results lies in the theoretical description and data-driven
581 numerical experiments of field water balance facilitated by the 3-D FLUSH model. The water
582 balance results have practical implication on implementation of drainage through the finding that

583 gravel trench appears to be important only in soils with poorly conductive subsoil layers without
584 direct macropore connections to subsurface drains.

585

586 **Acknowledgments**

587 The study was conducted in the TOSKA (*Functioning of drainage practices in crop production*
588 *fields*) project (2014–2017) in which the functioning and the effects of different drainage methods
589 on crop production, water balance and nutrient loads have been investigated. The study was funded
590 by the Aalto University School of Engineering, Drainage Foundation sr, the Ministry of Agriculture
591 and Forestry, Maa- ja vesitekniikan tuki ry., the Sven Hallin Research Foundation, Natural
592 Resources Institute of Finland and Academy of Finland. We acknowledge CSC – IT Center for
593 Science Ltd. for the allocation of computational resources.

594

595 **References**

- 596 Abrahamsen, P., Hansen, S., 2000. Daisy: an open soil-crop-atmosphere system model. Environ
597 Modell. Softw., 15, 313-330.
- 598 Äijö H., Myllys, M., Nurminen, J., Turunen, M., Warsta, L., Paasonen-Kivekäs, M., Korpelainen,
599 E., Salo, H., Sikkilä, M., Alakukku, L., Koivusalo, H., Puustinen, M., 2014. PVO2-hanke.
600 Salaojitustekniikat ja pellon vesitalouden optimointi [Field drainage methods and optimizing water
601 management of agricultural fields (PVO2)]. Salaojituksen tutkimusyhdistys ry:n tiedote 31. Finnish
602 Field Drainage Association, Helsinki, Finland, 105 pp (in Finnish with English abstract).
- 603 Alakukku, L., Nuutinen, V., Ketoja, E., Koivusalo, H., Paasonen-Kivekäs, M., 2010. Soil
604 macroporosity in relation to subsurface drain location on a sloping clay field in humid conditions.
605 Soil Till. Res., 106, 275–284.

606 Alakukku, L., Weisskopf, P., Chamen, W.C.T., Tijink, F.G.J., van der Linden, J.P., Pires, S.,
607 Sommer, C., Spoor, G., 2003. Prevention strategies for field traffic-induced subsoil compaction: a
608 review: Part 1. Machine/soil interactions. *Soil Till. Res.*, 73, 145–160.

609 Allen, R., Pereira, L., Raes, D., Smith, M., 1998. Crop evapotranspiration – Guidelines for
610 computing crop water requirements – FAO Irrigation and drainage paper 56. Rome: FAO – Food
611 and Agriculture Organization of the United Nations. ISBN 92-5-104219-5. Available:
612 <http://www.fao.org/docrep/x0490e/x0490e00.htm>.

613 An, H., Noh, S. J., 2014. High-order averaging method of hydraulic conductivity for accurate soil
614 moisture modeling. *J. Hydrol.*, 516, 119–130.

615 Aura, E., 1990. Salaojien toimivuus savimaassa. Tiedote 10/90. MTT Agrifood Research Finland,
616 Jokioinen, Finland, 93 pp. ISSN: 0359–7652.

617 Aura, E., 1995. Finite element modeling of subsurface drainage in Finnish heavy clay soils. *Agric.*
618 *Water Manage.*, 28, 35–47.

619 Beven, K., Germann, P., 2013. Macropores and water flow in soils revisited. *Water Resour. Res.*,
620 49, 3071–3092.

621 Blake, K.R., Hartge, K.H., 1986. Bulk density. In: Klute, A.K. (Eds.). *Methods of soil analysis.*
622 *Agronomy 9, Part 1*: 363–375.

623 Brunner, P., Simmons, C. T., 2012. HydroGeoSphere: a fully integrated, physically based
624 hydrological model. *Ground Water*, 50, 170–176.

625 Danielson, R.E., Sutherland, P.I., 1986. Porosity. In: Klute, A.K. (Eds.). *Methods of soil analysis.*
626 *Agronomy, Part 1*: 443–461.

627 Danish Hydraulic Institute (DHI), 2007, The MIKE SHE User Manual, Volume 2: Reference
628 Guide, Hørsholm, Denmark.

629 De Schepper, G., Therrien, R., Refsgaard, J. C., Hansen, A. L., 2015. Simulating coupled surface
630 and subsurface water flow in a tile-drained agricultural catchment. *J. Hydrol.*, 521, 374–388.

631 Feddes, R.A., Kowalik, P.J., Zaradny, H., 1978. *Simulation of Field Water Use and Crop Yield*.
632 Pudoc, Wageningen, The Netherlands, 189 pp.

633 Filipović, V., Mallmann, F.J.K., Coquet, Y., Šimůnek, J., 2014. Numerical simulation of water flow
634 in tile and mole drainage systems. *Agric. Water Manage.* 146: 105–114.

635 Frey, S. K., Hwang, H. T., Park, Y. J., Hussain, S. I., Gottschall, N., Edwards, M., Lapen, D. R.,
636 2016. Dual permeability modeling of tile drain management influences on hydrologic and nutrient
637 transport characteristics in macroporous soil. *J. Hydrol.*, 535, 392–406.

638 Gärdenäs, A., Šimůnek, J., van Genuchten, M.T., 2006. Two-dimensional modelling of preferential
639 water flow and pesticide transport from a tile-drained field. *J. Hydrol.*, 329, pp. 647–660.

640 Gerke H.H., Van Genuchten M.T., 1993. A dual-porosity model for simulating the preferential
641 movement of water and solutes in structured porous media, *Water Resour. Res.* 29, pp. 305–319.

642 Hansen, A.L., Refsgaard, J.C., Christensen, B.S.B., Jensen, K.H., 2013. Importance of including
643 small-scale tile drain discharge in the calibration of a coupled groundwater-surface water catchment
644 model. *Water Resour. Res.* 49, 585–603.

645 Haws, N. W., Rao, P. S. C., Simunek, J., Poyer, I. C., 2005. Single-porosity and dual-porosity
646 modeling of water flow and solute transport in subsurface-drained fields using effective field-scale
647 parameters. *J. Hydrol.*, 313, 257–273.

648 Henine, H., Nédélec, Y., Ribstein, P., 2014. Coupled modelling of the effect of overpressure on
649 water discharge in a tile drainage system. *J. Hydrol.*, 511, 39–48.

650 Henine, H., Nédélec, Y., Augeard, B., Birgand, F., Chaumont, C., Ribstein, P., Kao, C., 2010.
651 Effect of pipe pressurization on the discharge of a tile drainage system. *Vadose Zone J.* 9, 36–42.

652 IUSS Working Group WRB, 2014. World Reference Base for Soil Resources 2014. International
 653 soil classification system for naming soils and creating legends for soil maps (PDF) (3rd ed.).
 654 Rome: FAO. ISBN 978-92-5-108370-3. Retrieved 29 August 2014.

655 Jansson, P. E., Karlberg, L., 2004. COUP manual: Coupled heat and mass transfer model for soil-
 656 plant-atmosphere systems. Technical manual for the CoupModel, 1–453.

657 Jarvis, N. J., 2007. A review of non-equilibrium water flow and solute transport in soil macropores:
 658 Principles, controlling factors and consequences for water quality. *Eur. J. Soil Sci*, 58, 523–546.

659 Jarvis, N., Larsbo, M., 2012. MACRO (v5. 2): Model use, calibration, and validation. *Transactions*
 660 *of the ASABE*, 55, 1413–1423.

661 Klaus, J., Zehe, E., 2010. Modelling rapid flow response of a tile-drained field site using a 2D
 662 physically based model: assessment of ‘equifinal’ model setups. *Hydrol. Process.*, 24, 1595–1609.

663 Köhne, J. M., Mohanty, B. P., 2006. Water flow processes in a soil column with a cylindrical
 664 macropore: Experiment and hierarchical modeling. *Water Resour. Res.*, 41.

665 Leij, F.J., Alves, W.J., van Genuchten, M.Th., Williams, J.R., 1996. Unsaturated Soil Hydraulic
 666 Database, UNSODA 1.0 User's Manual. Report EPA/600/R-96/095, US Environmental Protection
 667 Agency, Ada, Oklahoma, 103 pp.

668 Message P Forum, 1994. *Mpi: a Message-Passing Interface Standard*. Technical Report. University
 669 of Tennessee, Knoxville, TN, USA.

670 Messing, I., Wesström, I., 2006. Efficiency of old tile drain systems in soils with high clay content:
 671 Differences in the trench backfill zone versus the zone midway between trenches. *Irrigation and*
 672 *drainage*, 55, 523–531.

673

674 Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I — A
675 discussion of principles. *J. Hydrol.*, 10, 282–290.

676 Nielsen, M. H., Petersen, C. T., Hansen, S., 2015. Identification of efficient transport pathways
677 from the soil surface to field drains by smoke injection. *Eur. J. Soil Sci.*, 66, 516–524.

678 Nousiainen, R., Warsta, L., Turunen, M., Huitu, H. Koivusalo, H., Pesonen, L., 2015. Analyzing
679 subsurface drain network performance in an agricultural monitoring site with a three-dimensional
680 hydrological model. *J. Hydrol.*, 529, 82–93.

681 Nuutinen, V., Butt, K. R., 2003. Interaction of *Lumbricus terrestris* L. burrows with field
682 subdrains: The 7th international symposium on earthworm ecology· Cardiff· Wales· 2002.
683 *Pedobiologia*, 47, 578–581.

684 Petersen, C. T., Trautner, A., Hansen, S., 2007. Spatio-temporal variation of anisotropy of saturated
685 hydraulic conductivity in a tilled sandy loam soil. *Soil Till. Res.*, 100, 108–113.

686 Ritzema, H. P., Nijland, H. J., Croon, F. W., 2006. Subsurface drainage practices: From manual
687 installation to large-scale implementation. *Agric. Water Manage.*, 86, 60–71.

688 Rozemeijer, J.C., van der Velde, Y., McLaren, R.G., van Geer, F.C., Broers, H.P., Bierkens,
689 M.F.P., 2010. Integrated modeling of groundwater–surface water interactions in a tile-drained
690 agricultural field: The importance of directly measured flow route contributions. *Water Resour.*
691 *Res.*, 46, W11537, DOI: 10.1029/2010WR009155.

692 Salo, H., Warsta, L., Turunen, M., Paasonen-Kivekäs, M., Nurminen, J., Koivusalo, H., 2015.
693 Development and application of a solute transport model to describe field-scale nitrogen processes
694 during autumn rains. *Acta Agr Scand., Section B—Soil & Plant Science*, 65(sup1), 30–43.

695

696 Shipitalo, M. J., Nuutinen, V., Butt, K. R., 2004. Interaction of earthworm burrows and cracks in a
697 clayey, subsurface-drained, soil. *Applied Soil Ecology*, 26, 209–217.

698 Šimůnek, J., van Genuchten, M., 2008. Modeling nonequilibrium flow and transport processes
699 using HYDRUS, *Vadose Zone J.*, 7, 782–797.

700 Skaggs, R. W., 1980. DRAINMOD reference report. Washington, DC: USDA Soil Conservation
701 Service.

702 Stuyt, L.C.P.M., Dierickx, W., Martínez Beltrán, J., 2005. Materials for subsurface drainage
703 systems. FAO irrigation and drainage paper 60, rev. 1. FAO, Rome, Italy, 202 pp. Available at:
704 <ftp://ftp.fao.org/agl/aglw/docs/idp60.pdf>

705 Taskinen, A., Sirviö, H., Bruen, M., 2008. Generation of two-dimensionally variable saturated
706 hydraulic conductivity fields: model theory, verification and computer program. *Comput. Geosci.*,
707 34, 876–890.

708 Turtola, E., Paajanen, A., 1995. Influence of improved subsurface drainage on phosphorus losses
709 and nitrogen leaching from a heavy clay soil. *Agric. Water Manag.*, 28, 295–310.

710 Turtola, E., Alakukku, L., Uusitalo, R., 2007. Surface runoff, subsurface drainflow and soil erosion
711 as affected by tillage in a clayey Finnish soil, *Agric. and Food Sci.*, 16, 332–351.

712 Turunen, M., Warsta, L., Paasonen-Kivekäs, M., Nurminen, J., Myllys, M., Alakukku, L., Äijö, H.,
713 Puustinen, M., Koivusalo, H., 2013. Modeling water balance and effects of different subsurface
714 drainage methods on water outflow components in a clayey agricultural field in boreal conditions.
715 *Agric. Water Manage.*, 121, pp. 135–148.

716 Turunen, M., Warsta, L., Paasonen-Kivekäs, M., Nurminen, J., Alakukku, L., Myllys, M.,
717 Koivusalo, H., 2015a. Effects of terrain slope on long-term and seasonal water balances in clayey,

718 subsurface drained agricultural fields in high latitude conditions. *Agric. Water Manage.*, 150, 139–
719 151.

720 Turunen, M., Warsta, L., Paasonen-Kivekäs, M., Nurminen, J., Koivusalo, H., 2015b. Simulating
721 water balance and evapotranspiration in a subsurface drained clayey agricultural field in high-
722 latitude conditions. *Acta Agr Scand, Section B—Soil & Plant Science*, 65(sup1), 44–57.

723 Vakkilainen, P., Alakukku, L., Myllys, M., Nurminen, J., Paasonen-Kivekäs, M., Peltomaa, R.,
724 Puustinen, M., Äijö, H., 2008. Pellon vesitalouden optimointi – Väliraportti 2008. Salaojituksen
725 tutkimusyhdistys ry:n tiedote 29. Helsinki: Salaojituksen tutkimusyhdistys ry. 100 pp. ISBN 978-
726 952-5345-21-6.

727 Vakkilainen, P., Alakukku, L., Koskiaho, J., Myllys, M., Nurminen, J., Paasonen-Kivekäs, M.,
728 Peltomaa, R., Puustinen, M., Äijö, H., 2010. Pellon vesitalouden optimointi - Loppuraportti 2010.
729 Salaojituksen tutkimusyhdistys ry:n tiedote 30. Helsinki: Salaojituksen tutkimusyhdistys ry. 114 pp.
730 ISBN 978-952-5345-23-0.

731 van Dam, J.C., Groenendijk, P., Hendriks, R.F.A., Kroes, J.G., 2008. Advances of modeling water
732 flow in variably saturated soils with SWAP. *Vadose Zone J.*, 7, 640–653.

733 van Genuchten, M.T., 1980. A closed form equation for predicting the hydraulic conductivity of
734 unsaturated soils. *Soil Sci. Soc. Am. J.*, 44, 892–898.

735 Vogel, T., Gerke, H., Zhang, R., van Genuchten, M., 2000. Modeling flow and transport in a two-
736 dimensional dual-permeability system with spatially variable hydraulic properties, *J. Hydrol.*, 238,
737 78–89.

738 Warsta, L., Turunen, M., Koivusalo, H., Paasonen-Kivekäs, M., Karvonen, T., Taskinen, A., 2012.
739 Modelling heat transport and freezing and thawing processes in a clayey, subsurface drained

740 agricultural field. 11th ICID Int. Drainage Workshop on Agricultural Drainage Needs and Future
 741 Priorities. Cairo 23-27.9.2012, Egypt. Proceedings. 10 pp.

742 Warsta, L., Karvonen, T., Koivusalo, H., Paasonen-Kivekäs, M., Taskinen, A., 2013. Simulation of
 743 water balance in a clayey, subsurface drained agricultural field with three-dimensional FLUSH
 744 model. J. Hydrol., 476, pp. 395–409.

745 Williams, J., Shaykewich, C.F., 1969. An evaluation of polyethylene (P.E.G.) 6000 and 20000 in
 746 the osmotic control of soil water matric potential. Can. J. Soil Sci., 49: 397–401.

747 Young, D. M., 2014. Iterative solution of large linear systems. Elsevier.

748 Youngs, E.G., 1991. Hydraulic conductivity of saturated soils. In: Smith, K.A., Mullins, C.E. (Eds.).
 749 Soil analysis. Physical methods. 1991. 620 s.

750

751 Table 1. Soil hydraulic and structural properties for both model configurations (single pore system
752 and dual-permeability models). θ_s and θ_r are the saturated and residual water contents, w is the
753 macroporosity, K_{sat} is the saturated hydraulic conductivity, α and n are the van Genuchten water
754 retention curve parameters and $K_{FS,MUL}$ is the macropore saturated hydraulic conductivity multiplier.

755

756 Table 2. Nash-Sutcliffe efficiency numbers for single pore system and dual-permeability model
757 with homogeneous and randomized soil scenarios in 2008 autumn periods.

758

759 Table 3. Measured and simulated cumulative drain discharge results computed with the 16 m (2007)
760 and 8 m (2008, 2012) drain spacings. The cumulative drain discharge [mm] is presented in
761 parentheses and the percentage columns describe the drain discharge fraction of precipitation.
762 Simulated values are presented as median [%] and minimum and maximum values [mm] computed
763 with the five soil sets.

764 Figure 1. a) A map of Finland with the location of the Nummela field and b) detailed map of the C
765 section in the field (original and supplementary drains, soil sample locations and the locations of
766 groundwater observation wells, TDR sensors and measurement center).

767

768 Figure 2. Conceptual model setup of (a) a computational grid with original trench and surrounding
769 soil (Grid 1), (b) a grid with original and supplementary drain trenches (Grid 2) and (c) a
770 computational grid without trenches (Grid 3). The original tile drain trench is colored red (a and b)
771 and the supplementary trench is colored gray (b). The grid dimensions are shown in the upper left
772 corner of the figure.

773

774 Figure 3. Hourly measured and median of the simulated drain discharge results simulated with the
775 single pore (a–c) and dual-permeability models (d–f) during 2007 (a and d), 2008 (b and e) and
776 2012 periods (c and f). The Nash-Sutcliffe model efficiency coefficients (NS) are presented for each
777 event.

778

779

780 Figure 4. Hourly drain discharge with randomized soil hydraulic properties using a) single pore
781 system model and b) dual-permeability model for autumn 2008 period. The blue line is the average
782 of 5 randomization results and the black line is the measured hourly drain discharge.

783

784 Figure 5. Cumulative precipitation, measured cumulative drain discharge and simulated cumulative
785 drain discharge computed with the single pore system (a, c and e) and dual-permeability (b, d and f)
786 models during the 2007 (a and b), 2008 (c and d) and 2012 (e and f) periods. The simulated

787 cumulative discharge results computed with the five soil parameterizations are presented as range
788 graphs.

789

790 Figure 6. Water balance components for the 2008 period computed with a) grid 1 and single pore
791 system model, b) grid 1 and dual-permeability model, c) grid 2 and single pore system model, d)
792 grid 2 and dual-permeability model, e) grid 3 and single pore system model and f) grid 3 and dual-
793 permeability model.

Table 1. Soil hydraulic and structural properties for both model configurations (single pore system and dual-permeability models). θ_s and θ_r are the saturated and residual water contents, w is the macroporosity, K_{sat} is the saturated hydraulic conductivity, α and n are the van Genuchten water retention curve parameters and $K_{FS,MUL}$ is the macropore saturated hydraulic conductivity multiplier.

layer depth [m]	Soil set	Hydraulic parameters					Structure	
		α [1/m]	n [-]	K_{sat} [m/h]	θ_r [m ³ /m ³]	θ_s [m ³ /m ³]	w [-]	$K_{FS,MUL}$ [m/h]
0–0.25	C1	0.65	1.16	0.032	0.1	0.52	0.011	80
	C2	2.3	1.17	0.18	0.1	0.48	0.13	10
	C3	13.0	1.12	0.57	0.1	0.53	0.074	10
	C4	2.9	1.15	0.059	0.1	0.55	0.055	19
	C5	4.0	1.15	0.18	0.1	0.56	0.067	39
0.25–0.45	C1	0.12	1.30	0.0012	0.1	0.59	0.002	80
	C2	0.96	1.10	0.26	0.1	0.52	0.0057	80
	C3	0.54	1.13	0.19	0.1	0.51	0.003	80
	C4	0.45	1.16	0.004	0.1	0.54	0.0064	80
	C5	0.46	1.17	0.00004	0.1	0.53	0.002	9
0.45–1.0	C1	0.44	1.13	0.00005	0.1	0.55	0.0025	5
	C2	0.62	1.14	0.00005	0.1	0.55	0.0011	40
	C3	0.96	1.13	0.0004	0.1	0.54	0.0027	55
	C4	0.74	1.13	0.03	0.1	0.53	0.0084	80
	C5	0.66	1.12	0.0063	0.1	0.50	0.0079	80
1.0–1.5	Bottom soil	0.68	1.16	0.00008	0.1	0.53	0.0006	80
0.25–1.0	Gravel ^(a)	2.9	1.71	0.07	0.058	0.30	0.5	-
0–1.5	Macropores ^(b)	20	2	-	0.01	-	-	-

^{a)} Leij et al. (1996)

^{b)} Köhne and Mohanty (2006)

Table 2. Nash-Sutcliffe efficiency numbers for single pore system and dual-permeability model with homogeneous and randomized soil scenarios in 2008 autumn periods.

	Single pore system model		Dual-permeability model	
	Homogenous	Randomized	Homogenous	Randomized
16.–21.10.2008	0.44	0.00	0.55	0.53
21.–26.10.2008	0.72	0.75	-0.06	0.67
26.–30.10.2008	0.27	0.20	-0.33	0.28
30.10.–7.11.2008	0.76	0.75	0.46	0.78

Table 3. Measured and simulated cumulative drain discharge results computed with the 16 m (2007) and 8 m (2008, 2012) drain spacings. The cumulative drain discharge [mm] is presented in parenthesis and the percentage columns describe the drain discharge fraction of precipitation. Simulated values are presented as median [%] and minimum and maximum values [mm] computed with the five soil sets.

	Measured		Single pore system model		Dual-permeability model	
	[%]	[mm]	Median [%]	(min–max) [mm]	Median [%]	(min–max) [mm]
2007	40	(26)	69	(22–56)	54	(35–47)
2008	60	(57)	94	(46–82)	78	(60–67)
2012	71	(44)	89	(41–57)	70	(39–45)

Figure

(a)

© MML 2011

- Measurement center, outflow meters and rain gauge
- Location of soil samples in C section
- Original subsurface drains in C section
- Supplementary subsurface drains in C section
- Shallow drains for topsoil layer runoff measurements
- Subsurface drains (A, B, D and E)
- Groundwater observation wells (1.6 m depth) and TDR sensors (0-0.3 m)

(b)

Figure

Supplementary drain section (a)

(b)

(c)

Figure

Figure

Figure

Single pore model

Dual-permeability model

Cumulative drain discharge and precipitation [mm]

(a)

(b)

(c)

(d)

(e)

(f)

MIN-MAX Simulated Measured Precipitation

Figure

Single pore model

Dual-permeability model

(a)

(b)

16m drain spacing with orig.
trench segment (Fig. 2a)

(c)

(d)

8m drain spacing with orig. and
supp. trench segments (Fig. 2b)

(e)

(f)

8m drain spacing without trench
segments (Fig. 2c)

■ Tillage layer runoff
 ■ Drain discharge (Supp.)
 ■ Drain discharge (Orig.)
 ■ Groundwater outflow