Evaluation of DRAINMOD using saturated hydraulic conductivity estimated by a pedotransfer function model

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ABSTRACT

Direct measurement of soil saturated hydraulic conductivity (K_s) is time-consuming and therefore costly. The ROSETTA pedotransfer function model is able to estimate K_s from soil textural data, bulk density and one or two water retention points. This study evaluated the feasibility of running the DRAINMOD field-scale hydrological model with K_s input produced using ROSETTA. A hierarchical approach was adopted to estimate K_s using ROSETTA, with four limited-more extended sets of soil information used as inputs: USDA textural class (H1); texture (H2); texture and bulk density (H3); texture, bulk density, water retention at −33 kPa ($\theta_{33\ \mathrm{kPa}}$) and −1500 kPa ($\theta_{1500\ \mathrm{kPa}}$) (H4). ROSETTA-estimated K_s values from these four groups (H1–H4) were used in DRAINMOD to simulate drain outflows during a 4-year period from a conventional drainage plot (CD) and two controlled drainage plots (CWT1 and CWT2) located in south-east Sweden. The DRAINMOD results using ROSETTA-estimated K_s values were compared with observed values and with model results using laboratory-measured K_s values (H0). Deviations in simulated drainage outflow (*D*), infiltration (*F*) and evapotranspiration (ET) resulting from the use of ROSETTA-estimated rather than laboratory-measured K_s values were evaluated. During the study period, statistical comparisons showed good agreement on a monthly basis between observed and DRAINMOD-simulated drainage rates using five soil datasets (H0, H1, H2, H3 and H4). The monthly mean absolute error (MAE) ranged from 0.57 to 0.82 cm for CD, 0.38 to 0.41 cm for CWT1, and 0.15 to 0.22 cm for CWT2. On a monthly basis, the modified coefficient efficiency (E') values were in the range of 0.62 to 0.74 for CD, 0.72 to 0.74 for CWT1, and 0.79 to 0.86 for CWT2. The modified index of agreement (d') for monthly predictions ranged from 0.80 to 0.86 cm for CD, 0.87 to 0.88 cm for CWT1, and 0.89 to 0.93 cm for CWT2. The absolute values of the percent-normalised error (NE) on an overall basis when using ROSETTA-estimated rather than laboratory-measured K_s values were less than 3% in *E*, less than 1% in *F*, and less than 15% in *D*. The results suggest that ROSETTA-estimated K_s values can be used in DRAINMOD to simulate drainage outflows as accurately as laboratory-measured K_s values (H0) in coarse-textured soils.

Keywords:
Controlled drainage
Hydrologic model
ROSETTA
Subsurface drainage

1. Introduction

Models have been used to relate drainage system performance to design parameters such as drain spacing and depth, which span the wide spectrum from very approximate guidelines to computer models that simulate the performance of multi-component systems (Skaggs, 1999). However, one limitation of some hydrological models is the large amount of input

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variables and parameters necessary. In particular, the use of such models to date has been limited by the lack of site-specific input parameters, such as vertical saturated hydraulic conductivity (K_s) (Lilly et al., 2008). Alternate methods for input derivation are needed. Pedotransfer functions (PTFs) have been proposed to estimate K_s indirectly from surrogate data (Bouma, 1989; Wösten et al., 2001). PTFs have been used to estimate K_s from more easily measured soil properties usually available from soil surveys, such as particle size distribution, bulk density and organic matter content (Wösten et al., 1995; Rawls et al., 1998; Nemes et al., 2005; Mermoud and Xu, 2006). Recently, neural network analysis was used to establish empirical PTFs (Pachepsky et al., 1996; Schaap and Leij, 1998). The advantage of neural networks is their ability to simulate the behaviour of complex systems. Neural networks vary the strength of influence of network components on each other, as well as the range of choices for structures of interconnections among components (Wösten et al., 2001). To help application of the neural network PTFs, Schaap et al. (2001) developed the ROSETTA model, which is able to estimate K_s from soil textural data, bulk density and one or two water retention points.

The Swedish soil survey database offers an attractive option for estimating K_s from PTFs, although it is necessary to determine the soil information that would be sufficient for use with PTFs to extend the applicability of hydrological models. One of the most widely applied hydrological models is DRAINMOD (Skaggs, 1978, 1991). However, few studies to date have been done on comparing DRAINMOD-simulated results against observed data with varying levels of soil information (Workman and Skaggs, 1994; Borin et al., 2000; Öztekin, 2002; Singh et al., 2006; Yang, 2008). The purpose of this study was to evaluate the feasibility of running the DRAINMOD hydrological model with ROSETTA-estimated K_s using different complexity levels of soil information. This research was done for a coarse-textured soil with low water-holding capacity and high K_s, a type frequently found in leaching-prone coastal areas of southern Sweden. The results from 4 years of field experiments on subsurface drainage outflows were used to compare the model outputs. Differences in simulated drainage outflow (D), infiltration (F) and evapotranspiration (ET) were compared for datasets containing laboratory-measured K_s values and ROSETTA-estimated K_s values.

2. Model description

2.1. DRAINMOD

DRAINMOD (Skaggs, 1978, 1991) is a field-scale computer simulation model that characterises the response of the soil water regime to various combinations of surface and subsurface water management, such as surface drainage, subsurface drainage, controlled drainage and sub-irrigation. Although the model does not explicitly use the K_s relationship to predict soil water movement, it is needed to obtain the drained volume–watertable depth curve and the maximum upward flux–watertable depth relationship (Workman and Skaggs, 1994).

DRAINMOD uses approximate relationships developed from soil water characteristics [$\theta(h)$] and unsaturated hydraulic conductivity [$k(h)$] relationships to simulate storage and redistribution of water in the profile. The model simulates the effects of various water management on the watertable by performing a one-dimensional water balance at the midpoint between adjacent drains, by means of the equation:

$$\partial V_a = D + ET + DS - F \tag{1}$$

where ∂V_a is the drained volume (cm), D is the lateral drainage (cm) from the section, ET is evapotranspiration (cm), DS is the deep (vertical) seepage (cm), and F is infiltration (cm) entering the section in time increment ∂t.

DRAINMOD numerically solves the heat flow equation and predicts soil temperature to simulate processes controlling field hydrology under cold conditions, such as freezing, thawing and snowmelt (Luo et al., 2000). The model has been tested under cold climates in the USA (Jin and Sands, 2003), Canada (Wang et al., 2006a), Turkey (Luo et al., 2001) and Sweden (Wesström, 2002), and predicted values were generally found to agree well with field data.

Sensitivity analysis conducted on DRAINMOD showed that it is very sensitive to change in soil hydraulic properties (Anderson et al., 1987; Workman and Skaggs, 1994; Haan and Skaggs, 2003; Wang et al., 2006b), in particular, lateral saturated hydraulic conductivity (LK_s) in the soil layer where the drains are located (Haan and Skaggs, 2003). DRAINMOD calculates drainage rates assuming that lateral water movement occurs mainly in the saturated region, which usually contains the drains, where LK_s significantly affects all the functions under conventional and controlled drainage. For instance, Wang et al. (2006b) found that the model was most sensitive to LK_s in this layer.

2.1.1. *Subsurface drainage*

Subsurface drainage (D) is computed using the Hooghoudt steady state equation, as used by Bouwer and van Schilfgaarde (1963). This equation can be written as:

$$q = \frac{8K_e d_e m + 4K_e m^2}{L^2} \tag{2}$$

where q is the flux (cm h^{-1}), d_e is the equivalent depth of the impermeable layer below the drain (cm), m is the midpoint watertable height above the drain (cm), K_e is the effective lateral hydraulic conductivity (cm h^{-1}), and L is the distance between drains (cm). This approach assumes an elliptical watertable shape and is based on the Dupuit–Forchheimer assumptions with corrections for convergence near the drain lines. The change in watertable depth is based on the assumption that the soil water profile above the watertable is drained to equilibrium with the watertable. The amount of drainage determines a new drained-to-equilibrium profile. The amount of drainage from lowering the watertable is determined as the difference in soil water between the new and the original drained-to-equilibrium profiles.

2.1.2. *Infiltration*

For days with rainfall, hourly rainfall is used to compute infiltration rate using an approximate equation of the type presented by Green and Amp (1911). This equation can be written as:

$$f = \frac{K_s MSav}{F} + K_s \quad (3)$$

where f is the infiltration rate (cm h^{-1}), K_s is the vertical saturated hydraulic conductivity (cm h^{-1}), M is the initial soil water deficit (difference between final and initial volumetric water contents in $cm^3\ cm^{-3}$), Sav is the suction at the wetting front (cm), and F is the cumulative infiltration (cm).

2.1.3. *Evapotranspiration*

The amount of evapotranspiration (ET) is computed from potential evapotranspiration (PET) as limited by soil water availability. Actual ET is the amount that can be supplied from the watertable plus the amount available from the unsaturated zone. The PET represents the maximum amount of water that will leave the soil system by ET when there is a sufficient supply of soil water.

2.2. ROSETTA

ROSETTA (Schaap et al., 2001) implements five hierarchical pedotransfer functions (PTFs) to estimate vertical saturated hydraulic conductivity (K_s) using limited (textural classes only) to more extended (texture, bulk density, and one or two water retention points) input data. Schaap et al. (2001) obtained K_s values and corresponding predictive soil properties from databases of North America and Europe, which included 1306 soil samples. ROSETTA predicts saturated hydraulic conductivity (K_s) based on Mualem (1976) pore-size model. The retention function is given by:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha h)^n]^{1-1/n}} \quad (4)$$

where $\theta(h)$ is the measured volumetric water content ($cm^3\ cm^{-3}$) at the pressure head h (cm, taken as positive for increasing suction). The parameters θ_r and θ_s are residual and saturated volumetric water contents, respectively ($cm^3\ cm^{-3}$); α (>0, in cm^{-1}) is related to the inverse of the air entry pressure head, and n (>1) is a measure of pore-size distribution (van Genuchten, 1980). This equation can be rewritten to yield the relative saturation (S_e)

$$S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = [1 + (\alpha h)^n]^{1/n-1} \quad (5)$$

Eq. (5) can then be used in conjunction with the pore-size distribution model by Mualem (1976) to yield the van Genuchten–Mualem unsaturated hydraulic conductivity equation (van Genuchten, 1980):

$$K(S_e) = K_o S_e^L \{1 - [1 - S_e^{n/(n-1)}]^{1-1/n}\}^2 \quad (6)$$

where K is the unsaturated hydraulic conductivity (cm day^{-1}), K_o is the hydraulic conductivity (cm day^{-1}) acting as a matching point, and L (–) is an empirical pore tortuosity/connectivity parameter. The parameter K_o is a fitted matching point at saturation that resembles, but is not necessarily equal, to the parameter K_s, and the parameter L is normally assumed to be 0.5 (Mualem, 1976). Eq. (6) can also be expressed by h with the help of Eq. (4). Schaap and Leij (2000) found that K_o was almost 10 times smaller than K_s while L often was negative, having an optimal value of −1. Although these findings suggest an increased level of empiricism in the Mualem model, they provide a better description of K data than the common practice of using $K_o = K_s$ and $L = 0.5$ (Schaap et al., 2001). Therefore, the ROSETTA model that predicts both K_o and L from fitted retention parameters (θ_r, θ_s, α and n) was a substantial improvement over the traditional Mualem–van Genuchten model (Schaap and Leij, 2000).

In DRAINMOD, the routine for creating a soil file requires the following inputs: θ_r, θ_s, α, n, L, K_o and K_s, which can be obtained from the output of ROSSETA model.

3. Materials and methods

3.1. *Site description and measurements*

The experimental site is located at Gärds Köpinge, a coastal area of Skania, in south-east Sweden (55°56′N, 14°10′E). The climate in the region is classified as semi-humid, with mean annual precipitation of 562 mm and mean air temperature of 7.6 °C (Alexandersson et al., 1991). Three drainage plots were installed in 2000 with a plot size of 36 m × 40 m (Wesström, 2006). One plot was drained with conventional drainage (CD) at a drain depth of 1.0 m and two duplicate plots were drained with controlled watertable drainage (CWT1 and CWT2) with the watertable maintained at 0.5 m. The plots were drained separately and the drain outflow from each plot was measured by tipping buckets. The plots were incorporated into an ordinary Swedish crop rotation with winter wheat (*Triticum aestivum* L.), sugar beet (*Beta vulgaris* L. ssp. *vulgaris*) and spring barley (*Hordeum vulgare* L.).

The soil at the site is characterised by distinct textural horizons: a loamy sand topsoil (0–40 cm), weakly structured with an organic matter content of 5%, overlies a sand layer (40–100 cm) with low organic matter content. Below 1 m depth there is a clay layer, which effectively restricts downward seepage.

Soil bulk density (ρ_b), vertical saturated hydraulic conductivity (K_s) and soil water retention were determined using standard laboratory procedures on undisturbed soil cores in steel cylinders (7.2 cm in diameter, 10 cm in height) taken at 10 cm intervals down to 100 cm depth (Andersson, 1955). Soil water retention was measured at the pressure heads −0.5, −1.5, −3, −5, −10, −33, −60 and −1500 kPa. K_s was measured 1 and 24 h after saturated water flow at a constant head gradient. In addition, soil texture was determined for 10-cm layers down to 100 cm using the method of sieving and pipetting (Ljung, 1987). A summary of these soil parameters is presented in Table 1.

Climatological parameters (air temperature, soil temperature and precipitation) were measured hourly at the research site during 2001 and 2004. The potential evapotranspiration (PET) was calculated using the FAO Penman–Monteith

Table 1 – Soil parameters at the Gärds Köpinge experimental site in south-east Sweden

Soil parameters	Soil depth (cm)		
	0–40	40–100	100–130
Texture class	Loamy sand	Sand	Clay
Clay	0.09	0.02	0.56
Silt	0.10	0.03	0.36
Sand	0.81	0.95	0.08
ρ_b (g cm^{-3})	1.25	1.55	1.49
$\theta_{0.5\ \text{kPa}}$ (cm^3 cm^{-3})	0.46	0.36	0.46
$\theta_{1.5\ \text{kPa}}$ (cm^3 cm^{-3})	0.43	0.35	0.46
$\theta_{3\ \text{kPa}}$ (cm^3 cm^{-3})	0.39	0.30	0.45
$\theta_{10\ \text{kPa}}$ (cm^3 cm^{-3})	0.27	0.12	0.45
$\theta_{33\ \text{kPa}}$ (cm^3 cm^{-3})	0.22	0.10	0.44
$\theta_{60\ \text{kPa}}$ (cm^3 cm^{-3})	0.20	0.09	0.43
$\theta_{1500\ \text{kPa}}$ (cm^3 cm^{-3})	0.09	0.02	0.31
K_s (cm h^{-1})	9.70	14.10	0.00

Table 2 – Annual cumulative measured precipitation (*P*) and calculated potential evapotranspiration (PET) for 2001–2004

Year	*P* (mm)	PET (mm)
2001	636	585
2002	721	658
2003	454	583
2004	579	583

combination equation (Allen et al., 1998). Snow depth and missing data were obtained from the Swedish Meteorological and Hydrological Institute (SMHI) network stations. Table 2 shows an annual summary of rainfall and potential evapotranspiration for the study period.

3.2. *Hydraulic conductivity*

Measured soil parameters at three soil depths (0–40, 40–100 and 100–130 cm) were used as inputs in ROSETTA to estimate K_s. These parameters were assembled into four input datasets for ROSETTA through a hierarchical approach from limited (USDA textural class) to more extended sets of soil information, which included texture, bulk density (ρ_b), water retention at -33 kPa ($\theta_{33\ \text{kPa}}$) and -1500 kPa ($\theta_{1500\ \text{kPa}}$) (Table 3).

3.3. *Model evaluation*

In this study simulations were conducted using a 4-year (2001–2004) dataset from the field plots described above. DRAINMOD inputs include climatological data, soil properties, crop parameters and drainage parameters. Soil temperature parameters are required if the model is run under cold conditions. Table 4 lists some selected input data required from drainage system design, crop production and soil temperature. The lateral saturated hydraulic conductivity (LK_s) between 0–40 and 40–100 cm used in our DRAINMOD simulations were obtained through model calibration, which assumed LK_s values were in the range of 1–4 times K_s values. A pareto preference ordering procedure was applied to identify pareto-optimal solutions for LK_s values during calibration (Khu and Madsen, 2005). Mean absolute error (MAE), modified coefficient efficiency (E') and modified index of agreement (d') were used as objective functions during calibration, which are described in detail later. For calibration processes, data from conventional drainage (CD) for the period 2001–2004 were used, while datasets from the other two plots with controlled drainage (CWT1 and CWT2) were used for model validation for the period 2002–2004. During hydrological calibration/validation, laboratory-measured K_s values (H0) were considered for adjusting the subsurface drainage flow.

Table 3 – Combinations of soil parameter data used as input in DRAINMOD

Dataset	Description of data
H0	Laboratory-measured K_s
H1	ROSETTA-estimated K_s from texture class
H2	ROSETTA-estimated K_s from soil texture
H3	ROSETTA-estimated K_s from soil texture and ρ_b
H4	ROSETTA-estimated K_s from soil texture, ρ_b, $\theta_{33\ \text{kPa}}$ and $\theta_{1500\ \text{kPa}}$

Once the hydrological calibration and validation processes had been completed, a set of DRAINMOD simulations was conducted using ROSETTA-estimated K_s values (H1, H2, H3 and H4), which used the same parameters characterising the crop, drainage system parameters and climatological data. The laboratory-measured K_s values and four ROSETTA-estimated datasets were assembled into five input datasets for DRAINMOD (Table 3). These five datasets were used to develop drained volume–watertable depth–upward flux relationships and Green–Amp parameters using the SOILPREP programme in DRAINMOD.

3.4. *Statistical analysis*

Model outputs of DRAINMOD using ROSETTA-estimated K_s values (H1, H2, H3 and H4) were compared with observed values and with model results using laboratory-measured K_s values (H0). In model calibration/validation, monthly observed and simulated drainage outflows were compared by calculating three statistical measures: mean absolute error MAE, modified coefficient efficiency E' and modified index of agreement d' (Legates and McCabe, 1999):

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}|O_i - S_i| \tag{7}$$

$$E' = 1.0 - \frac{\sum_{i=1}^{n}|O_i - S_i|}{\sum_{i=1}^{n}|O_i - O'|} \tag{8}$$

$$d' = 1.0 - \frac{\sum_{i=1}^{n}|O_i - S_i|}{\sum_{i=1}^{n}(|S_i - O'| + |O_i - O'|)} \tag{9}$$

where O_i is the individual observed value at time i, S_i is the individual simulated value at time i, O' is the mean observed

Table 4 – DRAINMOD input parameters for conventional drainage (CD) and controlled drainage (CWT1 and CWT2)

Parameter	Value		
	CD	CWT1	CWT2
Drainage system design			
Drain spacing (m)	9.0	9.0	9.0
Drain depth (m)	0.99	0.83	0.96
Effective radius (mm)	3.5	3.5	3.5
Depth to impermeable layer (m)	1.0	1.3	1.4
Drainage coefficient (cm day^{-1})	1.0	1.0	1.0
Kirkham's coefficient, G	3.1	11.4	11.2
Initial depth to watertable (cm)	50	65	70
Weir setting (m)	1.0	0.5	0.5
Crop production			
Wheat			
Desired planting date			10 October 2000
Length of growing season (day)			329
Maximum effective root depth (cm)			45
Sugar beet			
Desired planting date			8 April 2002
Length of growing season (day)			185
Maximum effective root depth (cm)			45
Barley			
Desired planting date			31 March 2003
Length of growing season (day)			129
Maximum effective root depth (cm)			45
Barley			
Desired planting date			3 April 2004
Length of growing season (day)			132
Maximum effective root depth (cm)			45
Soil temperature			
Thermal conductivity function coefficients (W m^{-1} °C)			a = 0.552, b = 2.372
Diurnal phase lag of air temperature (h)			8.0
Base temperature as the lower boundary (°C)			7.6
Rain/snow dividing temperature (°C)			0.0
Snowmelt base temperature (°C)			2.0
Day-degree coefficient (mm day^{-1})			4.0
Critical ice content (cm^3 cm^{-3})			0.2

value and n is the number of paired observed–simulated values. MAE describes the difference between the model simulations and observations in the units of the variable. The value of MAE should be equal to zero for a model showing a perfect fit between the observed and predicted data. The value of E' ranges from minus infinity to 1.0, where an E' of 1.0 represents a perfect prediction and lower values indicate less accurate agreement between the model and observations. Thus a value of zero for E' indicates that O' is as good a predictor as the model, whereas negative values indicate that the observed mean is a better predictor than the model. The value of d' varies from 0.0 to 1.0, with higher values indicating better agreement with the field observations. The interpretation of d' closely follows the interpretation of R^2 for the range of most values encountered (Legates and McCabe, 1999).

In ROSETTA, the standard deviation (S_x) characterises the uncertainty in the K_s predictions. The deviation in DRAINMOD model outputs caused by using estimated rather than measured K_s values was evaluated by determining the percent-normalised error (NE) in simulated drainage outflows (D), infiltration (F) and evapotranspiration (ET) (Janssen and Heuberger, 1995).

4. Results and discussion

4.1. *Hydraulic conductivity measurements versus estimates*

Table 5 presents laboratory-measured K_s values (H0) and ROSETTA-estimated K_s values (H1, H2, H3 and H4). The results show that compared with measurements, ROSETTA underestimated K_s values between 0 and 40 cm; overestimated K_s values between 40 and 100 cm, except in H4 where estimated K_s was lower than measured; and overestimated K_s values between 100 and 130 cm. The uncertainty in ROSETTA prediction was highest in H1, which used a more limited set of soil information. Similarly, Schaap et al. (2001) found that ROSETTA-estimated K_s values were less accurate when fewer predictors were used during ROSETTA calibration. In this study, LK_s values were set

Table 5 – Vertical saturated hydraulic conductivity (K_s) values ± standard deviation (S_x) in ROSETTA predictions

Dataset	K_s (cm h^{-1})		
	0–40	40–100	100–130
H0	9.70	14.07	0.00
H1	4.38 ± 0.18	26.79 ± 0.16	0.61 ± 0.35
H2	3.64 ± 0.05	31.80 ± 0.05	1.13 ± 0.08
H3	8.48 ± 0.05	31.02 ± 0.05	0.22 ± 0.07
H4	7.15 ± 0.06	9.85 ± 0.06	0.10 ± 0.08

equal to laboratory-measured K_s values during model calibration.

4.2. *Model simulations*

4.2.1. *Drainage outflows*

Results for the days when drainage was measured in the conventional drainage plot (CD) during the period 1 July 2001–31 August 2004 (29 months) and in the controlled drainage plots (CWT1 and CWT2) during the period 1 March 2002–31 August 2004 (23 months) are shown in Table 6. Both visual and statistical comparisons showed good agreement between predicted and measured drainage rates (Fig. 1 and Table 7). The MAE comparing simulated and observed monthly drainage outflows was less than 1 cm in all the datasets. The E' values also indicated agreement between simulated and observed monthly drainage outflows, where E' values were higher than 0.60 in CD and 0.70 in both CWT1 and CWT2. During the study period the monthly d' values were $\geq$0.80, which confirmed that DRAINMOD performed well in predicting drain outflow during the study period. The H0 dataset produced the highest E' and d' in CD, while H4 produced the highest E' and d' in CWT1 and CWT2. Similarly, Singh et al. (2006) reported the index of agreement and model efficiency to be higher than 0.85 when comparing DRAINMOD-simulated and observed overall drainage outflows in conventional drainage plots in Iowa, where ROSETTA was used to estimate K_s values in two clay loam soils.

Differences in simulated drainage outflow (D) for conventional drainage (CD) and controlled drainage (CWT1 and CWT2) are compared for datasets containing laboratory-measured K_s values and ROSETTA-estimated K_s values in Fig. 2. The ROSETTA-estimated K_s values caused the greatest deviation in simulated D for the three plots studied. In the CD plot, D values simulated with the H1–H4 datasets were higher than those simulated with the laboratory-measured K_s value (H0), with NE ranging from 11 to 12%. In CWT1 and CWT2, errors in predicted D were less than 2% with the one exception of the H3 dataset simulating D in CWT2 (NE = 15%). In 3 out of 4 data sets the differences in D were higher in CD than in CWT1 and CWT2. Observed and DRAINMOD-predicted watertable levels showed that in CWT1 and CWT2 the watertable resided in the sandy layer (40–100 cm) for longer periods than in CD (data are not shown). Therefore, compared with CD, the sandy layer was saturated longer periods in CWT1 and CWT2. These results suggest that when the sandy layer with high K_s value (14 cm h^{-1}) is saturated during long periods, such as in controlled drainage, variations in K_s values (ranging from 10 to 32 cm h^{-1}) would not significantly affect the predicted D rates. This agrees with the uncertainty analysis in DRAINMOD developed by Haan and Skaggs (2003), who reported that D rates were more sensitive under conventional than controlled drainage to changes in LK_s values.

4.2.2. *Infiltration*

The absolute values of the percent-normalised error (NE) on an overall basis when using ROSETTA-estimated rather than laboratory-measured K_s values were less than 1% in F (Fig. 2). Most of the rainfall was predicted to infiltrate for all datasets due to the high K_s values in the coarse-textured soil profile (>80% sand), which offset the differences between predicted

Table 6 – Observed and simulated yearly drainage outflows for conventional drainage (CD) and controlled drainage (CWT1 and CWT2) using five soil datasets (H0, H1, H2, H3 and H4)

Year	N[a]	Observed (cm)	Simulated (cm)				
			H0	H1	H2	H3	H4
CD							
2001	6	9.74	11.20	13.91	13.78	13.87	14.50
2002	9	30.50	22.12	22.02	22.03	22.02	21.92
2003	6	8.70	7.86	7.46	7.62	7.52	6.46
2004	8	3.32	3.17	5.94	5.79	5.87	6.84
Overall	29	52.26	44.35	49.33	49.22	49.28	49.72
CWT1							
2002	9	17.65	18.63	18.64	18.68	18.56	18.32
2003	6	0.64	0.22	0.32	0.35	0.33	0.22
2004	8	5.09	6.68	6.95	6.97	6.97	6.86
Overall	23	23.37	25.53	25.91	26.00	25.86	25.4
CWT2							
2002	9	13.55	12.56	12.24	12.71	10.08	12.63
2003	6	0.09	0.00	0.00	0.00	0.00	0.00
2004	8	1.96	2.79	2.81	2.80	2.80	2.94
Overall	23	15.59	15.35	15.05	15.51	12.88	15.57

[a] N is the number of months.

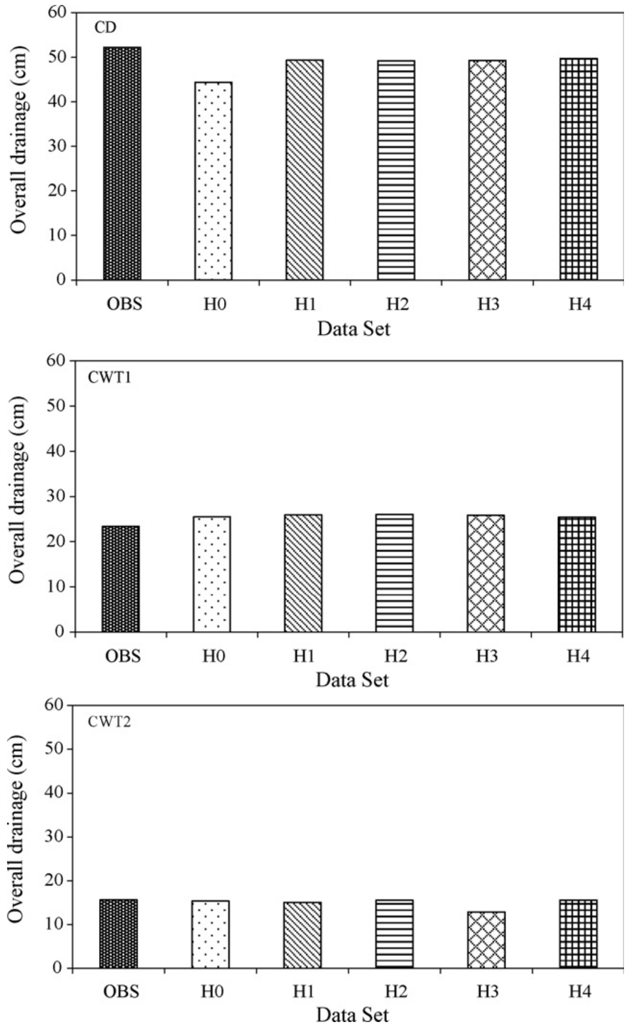

Fig. 1 – Observed (OBS) and simulated overall drainage outflows with five levels of soil information (H0, H1, H2, H3 and H4) in the conventional drainage plot (CD) (2001–2004) and controlled drainage plots (CWT1 and CWT2) (2002–2004).

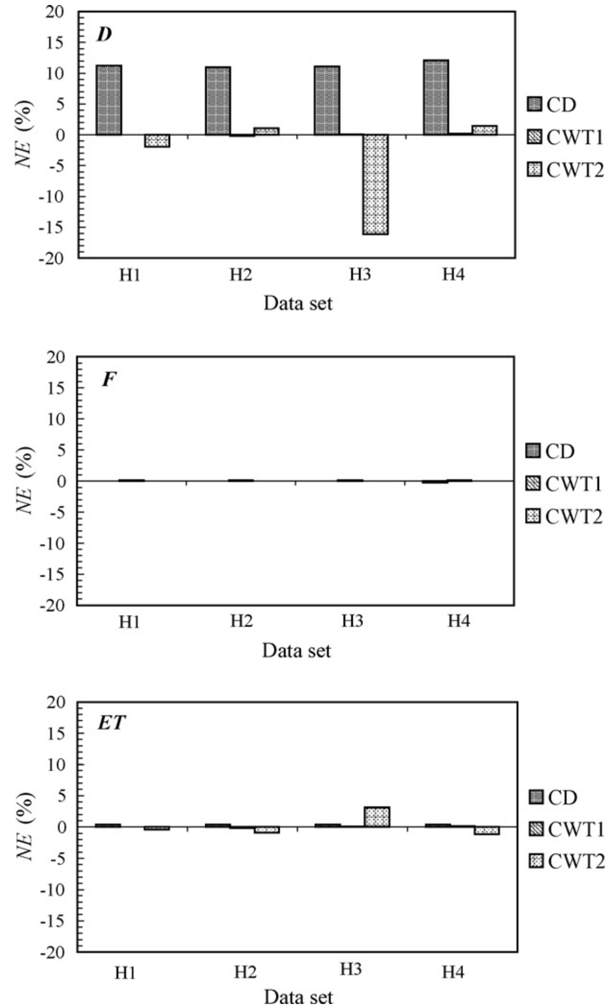

Fig. 2 – Percent-normalised error (NE) in simulated drainage outflow (D), infiltration (F) and evapotranspiration (ET) between laboratory-measured K_s value (H0) and four ROSETTA-estimated K_s values (H1, H2, H3 and H4) in conventional drainage (CD) and controlled drainage (CWT1 and CWT2).

or measured K_s values. Workman and Skaggs (1994) reported similar results when comparing measured versus estimated hydraulic properties to simulate F with DRAINMOD in a sandy soil (>89% sand) with high K_s.

4.2.3. *Evapotranspiration*

In most cases, ET values predicted with the ROSETTA-estimated K_s for the Gärds Köpinge soil (Fig. 2) were similar to those

Table 7 – Statistical comparison between observed and simulated monthly drainage outflows using five soil datasets (H0, H1, H2, H3 and H4) for conventional drainage (CD) (2001–2004) and controlled drainage (CWT1 and CWT2) (2002–2004)

Dataset	CD (cm)			CWT1 (cm)			CWT2 (cm)		
	MAE[a]	E'[b]	d'[c]	MAE[a]	E'[b]	d'[c]	MAE[a]	E'[b]	d'[c]
H0	0.57	0.74	0.86	0.40	0.73	0.87	0.16	0.85	0.93
H1	0.67	0.69	0.84	0.41	0.72	0.87	0.18	0.83	0.92
H2	0.68	0.68	0.84	0.41	0.72	0.87	0.18	0.83	0.92
H3	0.67	0.69	0.84	0.40	0.73	0.87	0.22	0.79	0.89
H4	0.82	0.62	0.80	0.38	0.74	0.88	0.15	0.86	0.93

[a] MAE is the mean absolute error comparing observed and simulated monthly drainage outflows.
[b] E' is the modified coefficient efficiency comparing observed and simulated monthly drainage outflows.
[c] d' is the modified index of agreement comparing observed and simulated monthly drainage outflows.

simulated with laboratory-measured K_s values, which showed NE values lower than 3%. Larger differences were found with the H3 dataset simulating ET in CWT2 (NE = 3%), where errors in simulated ET caused subsequent errors in simulated *D*. The majority of these discrepancies occurred in 2002, when DRAINMOD simulated an increase in ET during spring–summer (March–August) and a corresponding decrease in *D* during October. Compared to H0 dataset, the SOILPREP programme in DRAINMOD calculated higher water movement upward from the watertable and as a result higher ET with the H3 dataset. These increases in upflux values were due to higher ROSETTA estimated K_s value with the H3 dataset in the sandy layer (Table 5). Although DRAINMOD simulated an increase in ET with the H3 dataset for all plots, the only large difference occurred in CWT2 which presented the greatest thickness of the sandy layer (40–140 cm). Compared to H2 dataset, the ROSETTA estimated K_s values with H3 dataset were similar in the sandy layer but increased by a factor of 2 in the loamy sand layer (0–40 cm), which may explain higher ET with the H3 dataset.

5. Conclusions

This evaluation, which used 4 years of data from field experiments in south-east Sweden, demonstrated the feasibility of running DRAINMOD with ROSETTA-estimated K_s. During the study period statistical comparisons showed good agreement between observed and DRAINMOD-simulated drainage rates using different datasets. Simulation results indicated excellent agreement between observed and simulated overall drainage outflows with laboratory-measured K_s values (H0) for conventional drainage and the more extended set of soil information (H4) for controlled drainage. ROSETTA-estimated K_s values caused the greatest deviation in simulated drainage outflows under conventional drainage. DRAINMOD showed a few errors in simulated infiltration and evapotranspiration when ROSETTA-estimated K_s values were used. The conclusion is that ROSETTA-estimated K_s values can be used in DRAINMOD to simulate drainage outflows as accurately as laboratory-measured K_s values (H0), at least in coarse-textured soils. Since this study involved only one soil type, tests on different soil types are needed before we can fully recommend running DRAINMOD simulation with saturated hydraulic conductivity (K_s) input estimated from ROSETTA.

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