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Modeling performance of a tile drainage system incorporating mole drainage

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ABSTRACT. *In fine textured low permeability soil profiles, mole drainage is used as a supplementary measure to subsurface tile drains. However, performance is known to vary temporally and spatially due to variations in soil properties, installation conditions, mole channel integrity and weather patterns. A model study is presented whereby a finite element software package, SEEP/W, has been calibrated and validated for a field site having (System 1) subsurface tile drains with gravel aggregate (0.9 m depth, 15 m spacing) and intersecting mole drains (0.6 m depth, 1.4 m spacing) on the west coast of Ireland. The calibrated model showed close agreement between modeled and observed subsurface drainage (index of agreement = 0.89) and predicted cumulative subsurface drainage volumes 12% higher than observed in the validation period. The model was then used to evaluate the impact of a range of alternative drainage designs namely; System 2: tile drains only; System 3: Similar to System 1 with k_s of the mole drained soil layer decreased to mimic a reduction in mole drain integrity/effectiveness and System 4: Similar to System 1 with k_s of the mole drained soil layer increased to mimic improved soil disturbance and fissuring during installation. These systems were analysed under the calibration (Event A) and validation (Event B) dataset rainfall scenarios as well as notional rainfall scenarios; the "fixed rainfall" scenario (Event C), a rainfall rate of 2 mm/h applied to all systems for 50 hours and the "historical rainfall" scenario (Event D), the annual average (30 year) daily values for the area (taken as the average monthly total divided by the number of days) applied over a year. The designs modeled exhibited similar relative behavior in all simulated rainfall scenarios. Systems 1 and 4 consistently outperformed Systems 2 and 3 in terms of average and peak discharge and watertable control capacity. System 2 (without mole drains) was the least effective and was seen to decrease drain discharge by an average of 54% and reduce mean watertable depth by an average of 62% relative to Systems 1 and 4 across rainfall events.*

Keywords. *Fine soils, high rainfall, mole drainage, SEEP/W, simulation*

Introduction

Mole drainage is used in fine, poorly permeable soils in conjunction with conventional PVC tile drains with stone aggregate envelope to improve hydraulic conductivity and thereby increase infiltration of rainwater to the tile drainage system. In such soils, the installation of tile drains alone does not offer sufficient discharge capacity. Upper soil horizons are heavy textured and structureless, which prevents rapid inflow of excess water to drains or rapid drawdown of the watertable. The addition of mole drains thereby provides an effective shallow drainage system at an economic cost (Galvin 1978; Maticic & Steinman 2007). Mole drains are formed with a tractor mounted mole plough consisting of a torpedo-like cylindrical foot, attached to a narrow leg, drawing a slightly larger cylindrical expander behind (Tuohy et al, 2016). During installation the mole plough forms cracks in the soil that radiate from the tip of the foot at shallow depths as the soil is displaced forwards, sideways and upwards, failing along well defined rupture plains which radiate from the mole tip at an angle of approximately 45° to the horizontal (Smedema & Rycroft 1983). Their functionality relies on this network of closely spaced channels and subsoil cracks, formed during installation, to rapidly discharge excess soil water during rainfall events (Childs, 1943; Spoor, 1982; Hallard and Armstrong, 1992; Tuohy et al., 2015, 2016). Stable mole channels can only be formed in fine, plastic, stone free horizons and their performance and lifespan will be largely dictated by soil type and installation conditions (particularly soil moisture content during installation). Seasonal differences in performance have also been documented due to the propagation and degeneration of shrinkage cracks in dry and wet periods respectively (Jarvis and Leeds-Harrison, 1987; Robinson et al., 1987). The lifespan of mole drains can vary from 1 to 5 years (Galvin, 1983, 1986; Harris, 1984; Cavelaars et al., 1994).

Finite element modelling (FEM) is an analysis method used to analyse any physical phenomenon of a solid body such as deformation due to applied stress and fluid flow through porous material. Finite element modelling is particularly suited to processes where the body under investigation has a complicated shape, complex boundary conditions and heterogeneous and anisotropic material properties; as such FEM is a perfect method for analysing field drainage systems. If the input parameters (soil physical/hydrological characteristics, boundary conditions and weather data), can be successfully obtained and/or measured then the model can be used to predict drainage system responses. The basis of the concept is that any soil body may be divided into smaller elements of finite dimensions and homogenous properties called "finite elements". The total soil body is then considered as a collection of these elements. Any change to the soil body is numerically analysed, element by element, to obtain the properties of the soil body as a whole. Numerical models, including MACRO, HYDRUS and DrainMod have been used widely in recent years to simulate water flow in tile drained fields (Larsbro and Jarvis, 2003; Šimůnek et al. 2008). Numerical models of drainage systems that include tile and mole drains are much less common, particularly in Irish specific soil and climactic conditions. The study of Rodgers et al. (2003) looked at mole drainage independently using Irish specific input data using the SEEP/W model, while other studies have looked at the drainage performance of both in tandem using SEEP/W, APSIM-SWIM and HYDRUS models (Madvar et al., 2007; Snow et al., 2007; Filipović et al., 2014). The assessment of the applicability of such a model to a combined mole/tile system under Irish conditions would have merit. The objectives of this study were: i) to model the observed performance of a real-life combined tile/mole drainage system during a short-term high intensity rainfall event using SEEP/W software; ii) to validate the model and assess the reliability of model outputs relative to observed tile drain discharge data collected over a 3 month period and iii) to model the installed system and a range of alternative system designs under a range of rainfall event scenarios to assess their performance. The FEM software package SEEP/W developed by GEO-SLOPE (2012a) was used in this study.

Materials and Methods

SEEP/W modelling software

The flow of water through a variably saturated soil into field drains is described by the two-dimensional Richards equations (Richards, 1931).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(x)\frac{\partial H}{\partial x}\right] + \frac{\partial}{\partial y}\left[K\,(y)\frac{\partial H}{\partial y}\right] + q \qquad (1)$$

Where θ is the volumetric moisture content (m^3/m^3), t the time (s), K(x) the hydraulic conductivity in the x-direction [horizontal direction] (m/s), K(y) the hydraulic conductivity in the y-direction [vertical direction] (m/s), H the total hydraulic head (m), q the applied boundary flux, e.g. rainfall (m/s). The FEM software package SEEP/W developed by GEO-SLOPE (2012a) can model flow into drains using Eq (1) (GEO-SLOPE, 2012b) and was used in this study. SEEP/W comprises three separate programs, namely Define, Solve and Contour which allow the soil element/drainage system to be defined, solved and viewed graphically. In the define programme the geometry of the system and soil elements are outlined, the material properties are defined, the finite element mesh is generated and the boundary conditions are assigned. The type of analysis is also defined and in the case of transient analyses, the duration and number of time steps used in the analysis are prescribed. The solve programme computes total hydraulic and pore-water pressure heads, flux quantities, velocities and hydraulic gradients at each node and time-point. The contour programme is used to graph computed results.

Input parameters

Drainage system

The model outlined is based on a system installed on a 2 ha permanent grassland field site used for livestock grazing and silage production in Doonbeg on the west coast of Ireland (52°44’N, 09°30’W). The site has a slope of <1%. An automated weather-station (Campbell Scientific Ltd. Loughborough, UK) is installed on site and records meteorological parameters at a 15-minute resolution. Average annual precipitation (30 year) in the vicinity is 1185 mm (Met Éireann).

Soil type on site has been classified as a Humic Groundwater Gley. Horizon specific soil physical and modelled hydraulic parameters (Rosetta, Schaap et al. 2001) for all horizons are presented in Table 1. In June 2013 a series of tile drains were installed at a depth of 0.9 m and spacing of 15 m comprising of 110 mm corrugated PVC pipe and stone aggregate (10-50 mm grade) envelope backfilled to within 0.2 m of the soil surface. Subsequently mole drains were installed perpendicular to these drains using a tractor drawn mole plough (R&M Buckets, Slane, Co. Meath, Ireland) at a depth of 0.6 m and spacing of 1.4 m. Tile drain discharge is monitored by end of pipe flow-meters (Water Technology Ltd., Togher, Cork, Ireland) at a 10 minute resolution.

Table 1. Soil profile classified as Humic Groundwater Gley with soil physical (Hydrometer Method; ASTM D422, 2002) and modelled (Schaap et al., 2001) hydraulic parameters.

Depth (cm)	Model Layer	Horizon	Sand (%)	Silt (%)	Clay (%)	Dry Density (g/cm^3)	Bulk Density (g/cm^3)	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	k_s (m/s)
0-26	1	Apg	59.24	31.42	9.34	1.11	1.61	0.036	0.343	2.67E-06
26-47	2	Btg	27.32	56.36	16.32	1.23	1.73	0.047	0.323	5.59E-07
47-75*	3	Cg1	31.58	50.68	17.74	1.65	2.04	0.035	0.260	1.51E-07
75-140	4	Cg2	43.81	40.85	15.34	-	-	0.053	0.397	1.59E-06

*Mole drain channels installed in this horizon

Drainage system model

The system was modelled in SEEP/W as a two dimensional domain, with a width of 230 m (two full drain spacings + 100 m each side to negate effects of extreme boundaries) and a soil profile depth of 1.4 m. The following boundary conditions were employed: a constant head (m) corresponding with a watertable maintained at 0.9 m depth (the invert level of tile drains) was applied to the left and right hand boundaries. The lower boundary at 1.4 m was assigned as a no flow boundary while an applied flux equivalent to rainfall rate could be applied on a central 15 m wide band on the upper boundary, to model rainfall input to the catchment of one tile drain. The soil profile was split into 4 horizons as in Table 1. The tile drain was centred in the model domain was assigned as a potential seepage face to allow water out of the domain under appropriate conditions. The modelled tile drain had a width of 0.1 m at 0.9 m depth increasing to a width of 0.2 m at 0.6 m depth and thereafter at a width of 0.2 m to 0.26 m depth. The mole drains were simulated as a 0.08 m thick horizontal band with invert 0.6 m below surface running perpendicular to the tile drain.

Model calibration

The model was calibrated by simulating an actual rainfall event (Event A) which occurred over a 112 hour (4.67 day) period spanning September 10th to 15th 2015. During this period 156.4 mm of rainfall was recorded being concentrated on the 11th and the night of the 13/14th.

The material properties of soils below the mole channel invert were defined using data from the site soil survey and hydraulic properties derived from them by pedotransfer function (Table 1). Soil regions above the mole channel invert were defined in the profile to allow the material properties of soil influenced by the action of the mole plough to be adapted. Here soil properties could be varied to model the improved hydraulic properties of the soil matrix brought about by the action of the mole plough during installation. The tile drain was assigned a high k_s material (k_s = 10 m/s) to simulate the hydraulic properties of gravel while mole drains were assigned a k_s of 0.001 m/s.

Initially a steady-state analysis of the domain, not subjected to rainfall was used to establish initial conditions for the transient-state analysis. In the transient state analysis, 448 (15 minute) time steps were used over the 122 hour period and rainfall was input to a central 15 m wide band on the upper boundary of the model as water unit flux versus time at a 15 minute resolution. Quarter-hourly rainfall rates (mm) were transformed into m/s rates. For example, 1.8 mm recorded from 15:15-15:30 on September 11th was input as 2 x 10^{-6} m/s over the time 76,500-77,400 s and so on. Analyses were run with a range of values assigned for k_s above the mole channel until the drain discharge results in the model output were close to the field results observed. The resulting modelled drainage system is referred to as System 1 with soil k_s above the mole channel of 1.53 x 10^{-5} m/s (Table 2).

Model validation and performance evaluation measures

A dataset spanning a 3 month period from October 1st to December 31st 2015 (Event B) was used to validate the model formulated. For the analysis, 92 (1 day) time steps were used over the 92 day period and daily rainfall was input to a central 15 m wide band on the upper boundary of the model as water unit flux versus time. Daily rainfall rates were transformed into m/s rates. Three statistical measures were used to calculate the differences between modelled and observed variables and evaluate the performance of the model (Singh et al. 2006):

$$\text{Coefficient of mass residual (CMR)} = \frac{\sum_{i=1}^{N} M_i - \sum_{i=1}^{N} O_i}{\sum_{i=1}^{N} O_i} \quad (2)$$

$$\text{Index of Agreement (IoA)} = 1 - \frac{\sum_{i=1}^{N} (M_i - O_i)^2}{\sum_{i=1}^{N} (|O_i - O| + |M_i - O|)^2} \quad (3)$$

$$\text{Model efficiency (ME)} = \frac{\sum_{i=1}^{N} (O_i - O)^2 - \sum_{i=1}^{N} (M_i - O)^2}{\sum_{i=1}^{N} (O_i - O)^2} \quad (4)$$

Where N is the total number of observations, O_i is the observed value of the ith observation, M_i the modelled value of the ith observation and O is the mean of the observed values (i = 1 to N). The reliability of model output was also judged through the graphical presentations of the modelled and observed subsurface drainage discharge. These measures were also applied to the calibration dataset to evaluate the relationship between modelled and observed values, in this case data was evaluated in 30 minute time steps.

Modelled alternative systems

Three alternative drainage systems were evaluated under the conditions of both rainfall events i.e. the calibration event (Event A: September 10-15th 2015) and the validation event (Event B: October 1st - December 31st 2015). System 2 (Table 2) consists of tile drains only with no mole drains, to assess the value of mole drains to the overall performance of the system. System 3 and 4 (Table 2) are similar to System 1 except soil k_s above the mole channel has been set at 1.53 x 10^{-6} and 1.53 x 10^{-4} m/s respectively, equivalent to the calibrated k_s above the mole channel value in System 1 divided or multiplied by a factor of 10. These systems mimic a reduction in effectiveness of mole drainage due to poor installation/installation conditions or deterioration over time and increased effectiveness due to increased initial disturbance and greater soil fissuring respectively.

Table 2. Profile depths in SEEP/W model and assigned saturated hydraulic conductivity values (ks) for modelled drainage systems. Values in bold text were derived by pedotransfer (Schaap et al. 2001) from measured soil physical data. The values of those elements influenced by the installation of mole channels (0-60 cm) was assigned during model calibration (System 1) or derived from System 1 values (System 3 and 4).

		k_s (m/s)			
Depth (cm)	Element	System 1	System 2	System 3	System 4
0-26	HZ 1	1.53E-05	**2.67E-06**	1.53E-06	1.53E-04
26-47	HZ 2	1.53E-05	**5.59E-07**	1.53E-06	1.53E-04
47-52	HZ 3	1.53E-05	**1.51E-07**	1.53E-06	1.53E-04
52-60	Mole drain/HZ 3	1.00E-03	**1.51E-07**	1.00E-04	1.00E-02
60-75	HZ 3	**1.51E-07**	**1.51E-07**	**1.51E-07**	**1.51E-07**
75-140	HZ 4	**1.57E-06**	**1.57E-06**	**1.57E-06**	**1.57E-06**
-	Tile Drain	10	10	10	10

Hypothetical rainfall events

Furthermore, simulations were carried out for two hypothetical rainfall event scenarios to establish the relative performance of each system. In Event C, the "fixed rainfall" scenario, a rainfall rate of 2 mm/h was applied to all systems for 50 hours. In Event D, the "historical rainfall" scenario, the 30 year average daily values (taken as the average monthly total divided by the number of days) was applied to all systems. Multiple comparisons between drainage systems in terms of drain discharge and watertable (WT) depth were made using the PROC GLM procedure in SAS version 9.1.3 (SAS Institute, 2006).

Results and Discussion

Model Calibration

The SEEP/W model was calibrated by comparing modelled discharge estimations with observed drain discharge data from the installed drainage system (System 1) during Event A and adjusting the effective soil k_s to obtain modelled results reflective of field observations. Modelled and observed drain discharges from System 1 during Event A are presented in Figure 1. Modelled peak and average drain discharges were 11% higher and 6% lower than observed discharges respectively with CMR, IoA and ME of -0.06, 0.89 and 0.53 respectively.

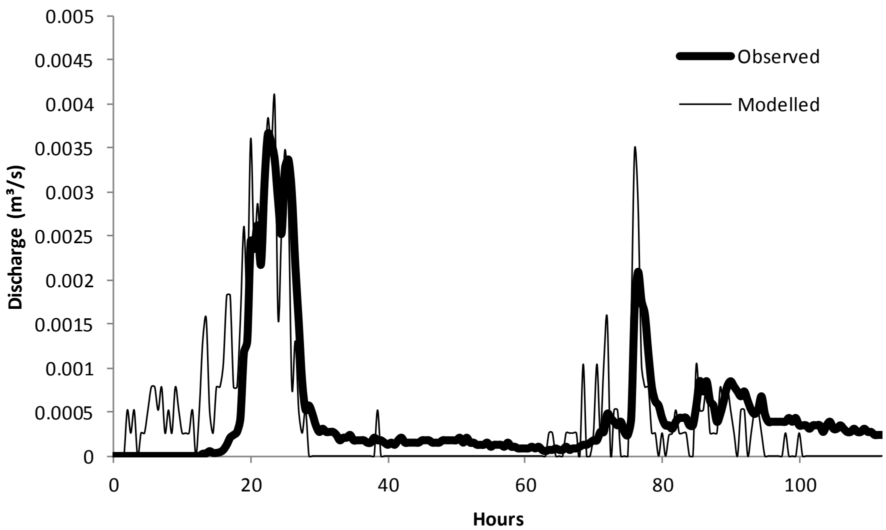

Figure 1. Comparison of tile drain discharge from modelled SEEP/W analysis and observed field measurements in System 1 during the calibration event (Event A)

Model Validation

The SEEP/W model would be expected to perform well in the calibration period as inputs were adjusted to obtain optimal agreement between the modelled and observed tile drain discharge during Event A. Therefore the model of System 1 was validated by comparing modelled and observed daily tile drain discharge data during the period from October 1st – December 31st 2015 (Event B). Modelled and observed drain discharges from System 1 during Event B are presented in Figure 2. Modelled peak and average drain discharges were 3% higher and 12% higher than observed discharges respectively with CMR, IoA and ME of 0.12, 0.94 and 0.74 respectively. The model is shown to offer valid predictions of tile drain discharge in this period. Modelled and observed daily tile drain discharge during Event B plotted against each other at 1:1 with a coefficient of correlation of 0.81. The SEEP/W model was seen to offer reliable predictions of drain discharge from the combined mole drain/tile drainage system. As such it offers a reliable methodology of assessing variations in system design on this, and similar sites.

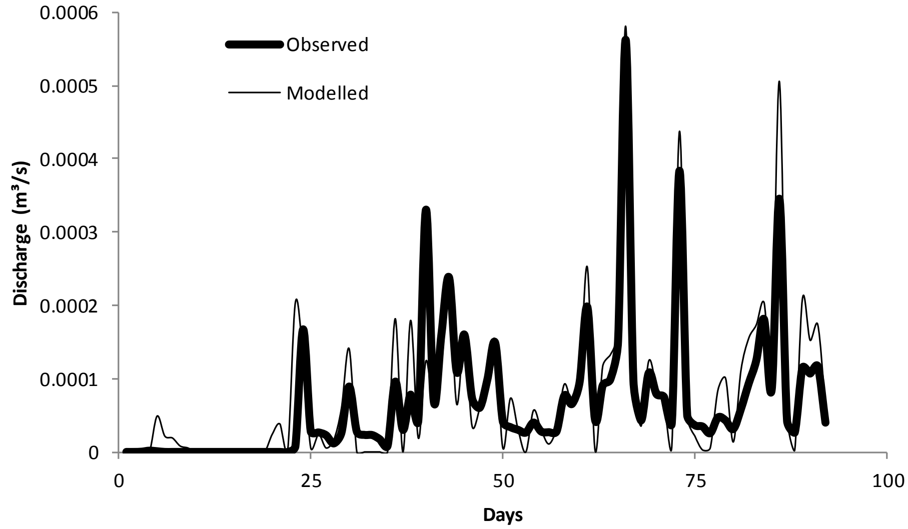

Figure 2. Comparison of daily tile drain discharge from modelled SEEP/W analysis and observed field measurements in System 1 during the validation event (Event B).

Alternative drainage system performance

Model estimates of the performance of alternative drainage systems was compared (Table 3). Sharp contrasts were evident between drainage systems. System 2 consistently had the lowest peak, average and total discharge, while Systems 1 and 4 were the best performing systems. The performance of System 3 was comparable to System 2 during high intensity rainfall Events A and C where its capacity was clearly exceeded but performed relatively well during lower intensity rainfall Events B and D (During Events A-D, the mean rainfall intensity was 1.40, 0.23, 2.00 and 0.14 mm/hr respectively). Watertable depth at 7.5 m from the tile drain centre (mid-way between adjacent drains) was also estimated by the SEEP/W model. While Systems 1 and 4 could control WT depth at approximately the tile drain invert level (0.90 m below ground level), Systems 2 and 3 did not (Table 3). During each event modelled, the depth to the WT varied widely between the ground surface and the tile invert level. A performance metric (T45) was applied to model output data to quantify WT control, with the proportion of time where the WT was within 0.45 m of the surface calculated (Table 3). This depth was selected as Brereton & Hope-Cawdery (1988) have shown that grass production on a poorly-drained soil will be limited until the WT depth reaches approximately 0.45 m. The T45 metric emphasises the poor performance of System 2 across events (Average T45 of 64.4 %) relative to 1.8, 37.7 and 0.0 % in Systems 1, 3 and 4 respectively.

Conclusions

The SEEP/W software was shown to offer reliable predictions of tile drain discharge of a combined tile/mole drainage system when compared with observed drain discharge during a short-term (5-day) rainfall event. The performance of the model was validated against a longer term (92 day event) and was shown to offer valid predictions of tile drain discharge in this period. The model therefore offers a reliable methodology of assessing design variations of such systems. The modelling of alternative system designs showed much variation in system performance. The poor performance of the tile only system showed the limitations of such systems in fine impermeable soils. Many farmers persist in installing tile only systems in inappropriate conditions. The tile only system fails to control the watertable as evidenced by its relatively high T45 value, in such conditions there will be a consequent loss in agricultural productivity and trafficability. The relative performance of such systems when compared to tile/mole drain combined systems in this study should provide further support for the use of mole drainage and similar supplementary measures in the drainage of poorly permeable soils. The performance of combined tile/mole drainage systems reflected the variations in k_s of that material above the mole drain channel. The greater the improvement in soil k_s brought about during mole channel installation the better the system capacity and performance will be. Optimum soil fissuring and cracking must be promoted during mole drain installation.

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Table 3. Modelled performance of drainage systems during rainfall events.

		System				
	Event	1	2	3	4	S.E.M.
Peak Discharge (m^3/s)	A	4.05×10^{-3}	4.53×10^{-4}	9.15×10^{-4}	4.95×10^{-3}	
	B	5.81×10^{-4}	1.86×10^{-4}	4.56×10^{-4}	5.81×10^{-4}	
	C	6.52×10^{-4}	1.96×10^{-4}	4.81×10^{-4}	6.52×10^{-4}	
	D	5.81×10^{-5}	5.75×10^{-5}	5.80×10^{-5}	5.81×10^{-4}	
Average Discharge (m^3/s)	A	$4.31 \times 10^{-4}{}_a$	$9.37 \times 10^{-5}{}_b$	$2.16 \times 10^{-4}{}_c$	$4.51 \times 10^{-4}{}_a$	1.49×10^{-5}
	B	$7.62 \times 10^{-5}{}_a$	$5.01 \times 10^{-5}{}_a$	$7.34 \times 10^{-5}{}_a$	$7.62 \times 10^{-5}{}_a$	4.73×10^{-6}
	C	$6.39 \times 10^{-4}{}_a$	$1.92 \times 10^{-4}{}_b$	$4.71 \times 10^{-4}{}_c$	$6.39 \times 10^{-4}{}_a$	1.38×10^{-5}
	D	$4.32 \times 10^{-5}{}_a$	$4.27 \times 10^{-5}{}_a$	$4.31 \times 10^{-5}{}_a$	$4.32 \times 10^{-5}{}_a$	2.76×10^{-7}
Total Discharge (m^3)	A	174.7	37.8	87.1	181.8	
	B	605.4	398.0	583.8	605.4	
	C	115.0	34.6	84.8	115.0	
	D	1357.7	1343.3	1356.2	1357.8	
Proportion of total Rainfall Discharged (%)	A	93.1%	20.1%	46.4%	96.9%	
	B	96.7%	63.6%	93.2%	96.7%	
	C	95.8%	28.8%	70.7%	95.8%	
	D	95.5%	94.5%	95.4%	95.5%	
Average watertable depth (m)	A	0.78_a	0.50_b	0.54_b	0.89_c	0.009
	B	0.88_a	0.43_b	0.73_c	0.90_a	0.015
	C	0.73_a	0.02_b	0.02_b	0.88_c	0.029
	D	0.89_a	0.36_b	0.79_c	0.90_a	0.006
T45: Proportion of Time period with $WT \leq 0.45$ m (%)	A	7.3%	44.1%	44.1%	0.0%	
	B	0.0%	49.5%	8.6%	0.0%	
	C	0.0%	98.0%	98.0%	0.0%	
	D	0.0%	66.1%	0.0%	0.0%	

Means having the same subscript letter are not significantly different. Comparisons significant at the 0.05 level.

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