MODELING PERFORMANCE OF A TILE DRAINAGE SYSTEM INCORPORATING MOLE DRAINAGE

P. Tuohy, J. O'Loughlin, O. Fenton

ABSTRACT. *Mole drain performance is known to vary temporally and spatially due to variations in soil properties, installation conditions, mole channel integrity, and weather patterns. In fine-textured, low-permeability soil profiles, moles can be installed to supplement an underlying tile drain system. However, moles are often not included in such designs. The objective of this modeling study was to investigate the performance impacts of variations in mole integrity and design in such a soil profile during a range of rainfall event scenarios. A finite element software package (SEEP/W) was used to model a field site having (system 1) subsurface tile drains (0.9 m depth, 15 m spacing) with gravel aggregate(10 to 50 mm) and intersecting mole drains (0.6 m depth, 1.4 m spacing). The field site was subjected to a pedological survey to characterize the soil profile, while an on-site weather station and end-of-pipe flowmeters provided rainfall and discharge data from which the model could be calibrated. The calibrated model showed close agreement between modeled and observed subsurface discharge in the validation period (coefficient of mass residual = 0.12, index of agreement = 0.94, model efficiency = 0.74). The model was then used to evaluate the impact of three alternative designs: tile drains only, a common practice in similar soils (system 2); a design similar to system 1 but with the saturated hydraulic conductivity (K_s) of the mole-drained layer decreased to mimic a reduction in mole drain integrity and effectiveness (system 3); and a design similar to system 1 but with K_s of the mole-drained layer increased to mimic improved soil disturbance and fissuring during installation (system 4). These systems were analyzed using the calibration (event A) and validation (event B) rainfall events as well as two notional rainfall scenarios: a "fixed rainfall" scenario (event C) with a rainfall rate of 2 mm h^{-1} applied to all systems for 50 h and a "historical rainfall" scenario (event D) with annual (30 year) average daily values for the area (taken as the average monthly totals divided by the number of days per month) applied over a year. Results showed that the modeled designs 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 water table control capacity. Across rainfall events, system 2 (without mole drains) was the least effective and was seen to decrease drain discharge by an average of 63% and reduce mean water table depth by an average of 72% relative to systems 1 and 4. Results showed the importance of mole channels in supplementing tile drainage on fine soils, as well as the importance of mole integrity for optimal performance. Such a tool could provide decision support in the drainage system design process and assess the implications of design variations on cost, expected performance, and likely returns to the landowner by estimating seasonal variations in drainage discharge and water table position. Identifying and characterizing the major soil types on a farm through soil profile pedological descriptions and collation of real soil physical and meteorological data is essential to prescribe appropriate drainage designs and prioritize areas for drainage installation in light of technical feasibility and cost estimates. With high-resolution data, the software can be calibrated for other drainage system and climate change scenarios.*

Keywords. *Mole drainage, Rainfall, SEEP/W, Simulation, Soil physical properties, Subsurface drainage.*

Mole drainage is used in fine, poorly permeable soils in conjunction with conventional PVC pipe drains to increase infiltration and downward movement of rainwater to the tile drainage system. Mole drains are formed with a tractor-mounted mole plow consisting of a torpedo-like cylindrical foot, attached to a narrow leg, drawing a slightly larger cylindrical expander behind (Tuohy et al., 2016; fig. 1). During installation, the mole plow forms cracks in the soil as the soil is displaced forward, sideways, and upward along well defined rupture plains (Smedema and Rycroft, 1983). Mole drainage relies on this network of closely spaced channels and subsoil cracks to rapidly convey excess soil water to the tile drainage system 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 are largely determined 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

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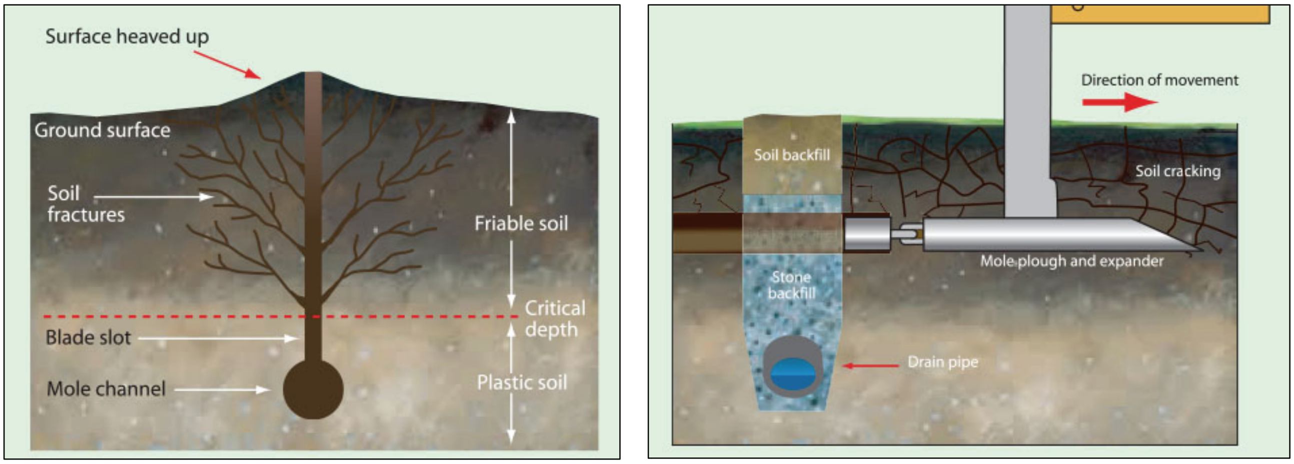
The authors are **Patrick Tuohy,** Research Officer, and **James O'Loughlin,** Heavy Soils Program Coordinator, Teagasc, Animal and Grassland Research and Innovation Centre, Fermoy, Ireland; **Owen Fenton,** Principal Research Officer, Teagasc, Environment Research Centre, Wexford, Ireland. **Corresponding author:** Patrick Tuohy, Teagasc, Fermoy, Co. Cork P61 C996, Ireland; phone: +353-25-42366; e-mail: patrick.tuohy@teagasc.ie.



(a) (b)

Figure 1. Cross-sections of (a) mole drain channel and (b) tile drain with stone aggregate backfill and intersecting mole drain.

and wet periods, respectively (Jarvis and Leeds-Harrison, 1987; Robinson et al., 1987; Tuohy et al., 2016). The lifespan of mole drains can vary from one to five years (Galvin, 1983, 1986; Harris, 1984; Cavelaars et al., 1994), with some systems showing a gradual decline in performance and others an abrupt failure, usually instigated by an extreme rainfall event or a series of events (Spoor et al., 1982; Mulqueen, 1998). The capacity of a combined tile/mole system at various stages in its lifespan is difficult to quantify empirically because the integrity of the system cannot be fully assessed without invasive investigations. Furthermore, variables such as weather, both current and antecedent, the intensity of agricultural production and traffic, and the interactions between these factors impact performance erratically. There is a tendency to install tile drainage systems independent of mole drainage or other supplementary measures in fine soils. The limitations of this practice need to be quantified. Numerical simulations of such systems would allow the effects on performance of variations in system design and variations in the integrity of the mole channel and related fissuring to be quantified in a controlled manner.

Finite element modeling (FEM) is a numerical method used to analyze any physical phenomenon of a solid body, such as deformation due to applied stress and fluid flow through porous material. Finite element modeling is particularly suited to processes in which the body under investigation has a complicated shape, complex boundary conditions, and heterogeneous material properties; as such, FEM is an extremely efficient method for analyzing field drainage systems. If the input parameters (i.e., soil physical/hydrological characteristics and boundary conditions) can be successfully obtained and/or measured, then the model can be used to predict drainage system responses to weather events. The concept is that any soil body can be divided into smaller elements (called finite elements) of finite dimensions and homogenous properties. The total soil body is then considered a collection of these elements. Any change to the soil body is numerically analyzed, element by element, to predict the response of the soil body as a whole. Simulation models, including MACRO, HYDRUS, and DRAINMOD, have been used in recent years to simulate water flow in tile-drained fields (Larsbro and Jarvis, 2003; Šimůnek et al., 2008; Skaggs et al., 2012). Numerical models of drainage systems that incorporate tile and mole drains are generally much less common, and they are non-existent for Irish soil and climatic conditions. Rodgers et al. (2003) used the SEEP/W model (GEO-SLOPE, 2012b) to assess mole drainage independently, using Irish-specific input data, to optimize mole drain spacing, compare model output with data measured in the field, and improve understanding of mole drain performance. They found the primary factors influencing the performance of mole drains to be (1) the spacing at which the mole drains are drawn, (2) the hydraulic conductivity of the loosened soil and topsoil, and (3) the intensity of rainfall. These factors can be presumed to apply universally. Other studies have looked at the performance of tile/mole drains in tandem using SEEP/W, APSIM-SWIM, and HYDRUS (Madvar et al., 2007; Snow et al., 2007; Filipović et al., 2014). Such models require high-resolution data relating to the modeled system in terms of soil characteristics, drainage system design (e.g., depth, layout, and material properties), and system performance (e.g., soil moisture status, drain discharge, and water table control). The availability of such data for this study allows detailed numerical models to be established.

The objectives of this study were to: (1) simulate an existing combined tile/mole drainage system using SEEP/W with data on system geometry, soil physical/hydrological characteristics, and assumed boundary conditions; (2) simulate the performance of this system during a short-term, high-intensity rainfall event and calibrate the model to allow observed performance in the field to be replicated by the model; (3) validate the model and assess the reliability of model outputs relative to observed tile drain discharge data collected over a three-month period; and (4) model the installed system and a range of alternative system designs, including a tile-only system and combined mole/tile systems of varying integrity, under a range of rainfall event scenarios to assess their performance.

Materials and Methods

SEEP/W Modeling Software

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

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

where θ is the volumetric moisture content (m^3 m^{-3}), t is the time (s), $K(x)$ is the hydraulic conductivity in the x-direction [horizontal direction] (m s^{-1}), $K(y)$ is the hydraulic conductivity in the y-direction [vertical direction] (m s^{-1}), H is the hydraulic head (m), and q is the applied boundary flux, e.g., rainfall (m s^{-1}). The FEM software package SEEP/W, developed by GEO-SLOPE (2012a), can model flow into drains using equation 1 (GEO-SLOPE, 2012b) and was used in this study. SEEP/W comprises three separate modules (DEFINE, SOLVE, and CONTOUR) that allow the soil elements and drainage system to be defined, solved, and viewed graphically. In the DEFINE module, the geometry of the system and soil elements is 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 module computes hydraulic and pore-water pressure heads, flux quantities, and hydraulic gradients at each node and time point. The CONTOUR module is used to graph the computed results.

Drainage System Input Parameters

The modeled site is a 2 ha permanent grassland field used for livestock grazing and silage production in Doonbeg on the west coast of Ireland (52° 44′ N, 9° 30′ W). The site has a slope of <1%. Soil type at the site has been classified as a Humic Groundwater Gley following a full pedological description of the soil profile (to below the depth of tile drain installation). Horizon-specific soil physical and corresponding modeled hydraulic parameters (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 110 mm corrugated PVC pipe and stone aggregate (10 to 50 mm grade) backfilled to within 0.2 m of the soil surface. Subsequently, mole drains were installed perpendicular to these drains using a tractor-drawn mole plow (R&M Buckets, Slane, Ireland) at a depth of 0.6 m and spacing of 1.4 m. An automated weather station (Campbell Scientific, Ltd., Loughborough, U.K.) was installed on site and recorded rainfall at 15 min resolution. Average annual (30 year) precipitation in the vicinity is 1185 mm (from Met Éireann, the Irish National Meteorological Service). Tile drain discharge was monitored by end-of-pipe flowmeters (Water Technology, Ltd., Togher, Ireland) recording at 10 min resolution.

Drainage System Model

The system was modeled in SEEP/W as a two-dimensional domain, with a width of 230 m (two full drain spacings + 100 m on each side) and a soil profile depth of 1.4 m (fig. 2). The subsoil is practically impervious below this depth, as observed during a pedological survey of the site. The following boundary conditions were employed: a constant head (m) corresponding with a 0.9 m water table depth (the invert level of tile drains) was applied to the left and right boundaries. The lower boundary at 1.4 m was assigned as a no-flow boundary, while an applied flux equivalent to the 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 tile drain centered in the model domain was assigned as a potential seepage face to allow water out of the domain under appropriate conditions. The soil profile was split into four horizons (table 1). The mod-

Table 1. Soil profile, classified as a Humic Groundwater Gley following pedological survey, with soil texture (by sieving and pipette sedimentation method), density, and modeled hydraulic parameters (Schaap et al., 2001).[a]

Depth (cm)	Soil Layer	Horizon Description	Sand (%)	Silt (%)	Clay (%)	Dry Density (g cm^{-3})	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	K_s (m s^{-1})
0-26	1	Apg	21	45	34	1.11	0.078	0.390	3.52E-07
26-47	2	Btg	13	49	38	1.23	0.077	0.370	1.75E-07
47-75[b]	3	Cg1	12	59	29	1.65	0.053	0.288	6.73E-08
75-140	4	Cg2	23	50	27	-	0.078	0.441	1.47E-06

[a] θ_r = residual water content, θ_s = saturated water content, and K_s = saturated hydraulic conductivity.
[b] Mole drain channels were installed in this horizon.

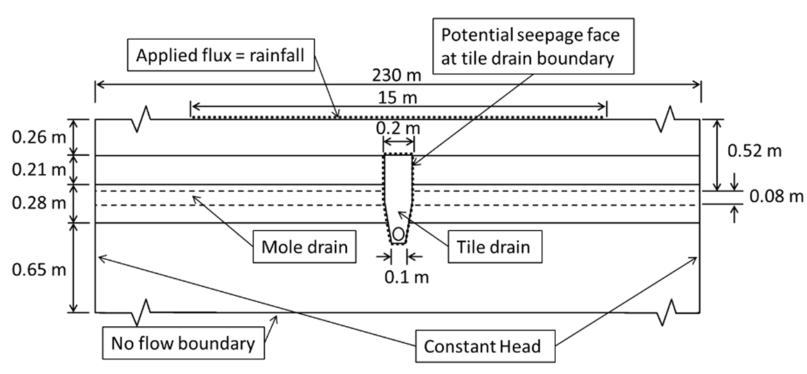


Figure 2. Cross-section of modeled system showing system geometry and boundary conditions (not to scale).

eled tile drain had a width of 0.1 m at 0.9 m depth, increasing to 0.2 m at 0.6 m depth (as dictated by the excavator bucket used during tile drain installation) and thereafter to 0.26 m depth (the invert level of the topsoil (Apg) layer). The mole drain was 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) that occurred over a 112 h (4.67 day) period spanning 10 to 15 September 2015. During this period, 156.4 mm of rainfall was recorded, concentrated on 11 September and the night of 13 September to the morning of 14 September.

In the model, properties of the soil layers below the mole channel invert were defined using actual soil horizon data and thereafter using hydraulic properties derived from pedotransfer functions (table 1). Soil regions above the mole channel invert were defined in the profile to allow the material properties of the soil, as influenced by the action of the mole plow, to be adapted. The soil properties could be varied to model the improved hydraulic properties of the soil matrix brought about by the action of the mole plow during installation. The tile drain was assigned a high saturated hydraulic conductivity value (K_s = 10 m s^{-1}) to simulate the hydraulic properties of gravel, while the mole drain was assigned a K_s of 0.001 m s^{-1}.

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 min) time steps were used over the 112 h 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 min resolution. Quarter-hourly rainfall rates (mm) were transformed into m s^{-1} rates. For example, 1.8 mm recorded from 15:15 to 15:30 on September 11 was input as 2×10^{-6} m s^{-1} over the time 76,500 to 77,400 s. 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 observed field results. The resulting modeled drainage system is referred to as system 1, with soil K_s above the mole channel of 1.54×10^{-5} m s^{-1} (table 2).

Model Validation and Performance

A dataset spanning a three-month period from 1 October to 31 December 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^{-1} rates. Three statistical measures were used to calculate the differences between modeled and observed variables and evaluate the performance of the model (Nash and Sutcliffe, 1970; Willmott, 1982; Helweig et al., 2002; Wang et al., 2006; Moriasi et al., 2015):

Coefficient of mass residual (CRM):

$$\text{CRM} = \frac{\sum_{i=1}^{N} M_i - \sum_{i=1}^{N} O_i}{\sum_{i=1}^{N} O_i} \tag{2}$$

Index of agreement (IoA):

$$\text{IoA} = 1 - \frac{\sum_{i=1}^{N} (M_i - O_i)^2}{\sum_{i=1}^{N} \left(|O_i - O| + |M_i - O| \right)^2} \tag{3}$$

Model efficiency (ME):

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

where N is the total number of observations, O_i is the ith observed value, M_i is the ith modeled value, and O is the mean of the observed values (i = 1 to N). A negative value of CRM (eq. 2) shows the model's tendency for under-prediction, while a positive value shows over-prediction. The IoA (eq. 3) measures the agreement between the modeled and observed daily subsurface drainage (Willmott, 1982): the closer IoA is to 1.00, the better the agreement between modeled and observed subsurface drainage. The ME (Nash and Sutcliffe, 1970) evaluates the error relative to the natural variation of the observed values and varies from $-\infty$ to 1.00 (eq. 4). Values of $0.50 \leq \text{ME} \leq 1.00$ are considered acceptable (Helweig et al., 2002; Wang et al., 2006).

The reliability of model output was also judged through graphical presentations of the modeled and observed subsurface drainage discharge. These measures were also applied to the calibration dataset to evaluate the relationship between modeled and observed values; in this case, the data were evaluated in 30 min time steps.

Modeled Alternative Systems

Three alternative drainage systems were evaluated under the conditions of both rainfall events, i.e., the calibration event (event A, 10-15 September 2015) and the validation

Table 2. Profile depths in SEEP/W model and assigned saturated hydraulic conductivity values (K_s) for modeled drainage systems.[a]

Depth		K_s (m s^{-1})			
(cm)	Element	System 1	System 2	System 3	System 4
0-26	Horizon 1	1.54E-05	**3.52E-07**	1.54E-06	1.54E-04
26-47	Horizon 2	1.54E-05	**1.75E-07**	1.54E-06	1.54E-04
47-52	Horizon 3	1.54E-05	**6.73E-08**	1.54E-06	1.54E-04
52-60	Mole channel/Horizon 3	1.00E-03	**6.73E-08**	1.00E-04	1.00E-02
60-75	Horizon 3	**6.73E-08**	**6.73E-08**	**6.73E-08**	**6.73E-08**
75-140	Horizon 4	**1.47E-06**	**1.47E-06**	**1.47E-06**	**1.47E-06**
-	Tile drain	10	10	10	10

[a] Values in bold text were derived by pedotransfer (Schaap et al., 2001) from measured soil physical data. The values of elements influenced by the installation of mole channels (0-60 cm) were assigned during model calibration (system 1) or derived from system 1 values (systems 3 and 4).

event (event B, 1 October to 31 December 2015). System 2 (table 2) consists of tile drains only, with no mole drains, to assess the value of mole drains in the overall performance of the system. Systems 3 and 4 (table 2) are similar to system 1 except soil K_s above the mole channel has been set at 1.54×10^{-6} and 1.54×10^{-4} m s^{-1}, 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 the effectiveness of mole drainage due to poor installation/installation conditions, or deterioration over time (system 3) and increased effectiveness due to increased initial disturbance and greater soil fissuring (system 4).

Hypothetical Rainfall Events

Furthermore, simulations were carried out for two hypothetical rainfall event scenarios to establish the relative performance of each system. In the "fixed rainfall" scenario (event C), a rainfall rate of 2 mm h^{-1} was applied to all systems for 50 h. In the "historical rainfall" scenario (event D), the annual (30 year) average daily values (taken as the average monthly totals divided by the number of days per month) was applied to all systems.

Statistical Analysis

Multiple comparisons between drainage systems in terms of drain discharge and water table (WT) depth were made using the PROC GLM procedure in SAS version 9.1.3 (SAS, 2006).

Results and Discussion

Model Calibration

The SEEP/W model was calibrated by comparing modeled discharge estimations with observed discharge data from the installed drainage system (system 1) during event A and adjusting the effective soil K_s to obtain modeled results reflective of the field observations. Modeled and observed drain discharges from system 1 during event A are presented in figure 3. The major discrepancies between observed and modeled discharge during the calibration event occurred during approximately the first 18 h of the event. The model reacted to the initial rainfall during this period, while in reality there was a delayed response to the start of rainfall. The event was preceded by nine rain-free days, which would have impacted the soil moisture such that a certain level of wetting would be likely before a significant discharge response. The model did not reflect this reality. Modeled peak and average drain discharges were, respectively, 12% higher and 6% lower than observed discharges, with CRM, IoA, and ME of -0.06, 0.89, and 0.54, respectively (table 3). In appraising these model performance evaluations, note that there is an inherent potential for discrepancies between observed and modeled discharges due to *in situ* variations between soil horizons, which may vary spatially in their physical parameters, and the assumed homogeneity of the modeled soil horizons due to their systematic formulation.

Table 3. Comparison of observed and modeled tile drain discharge performance parameters and statistical performance indicators for system 1 during events A and B.

	Discharge					
	Peak (m³ s^{-1})	Average (m³ s^{-1})	Total (m³)	CRM	IoA	ME
Event A (calibration)						
Observed	3.66E-03	4.59E-04	186.08			
Modeled	4.05E-03	4.31E-04	174.67			
			Performance:	-0.06	0.89	0.54
Event B (validation)						
Observed	5.62E-04	6.79E-05	539.81			
Modeled	5.81E-04	7.62E-05	605.36			
			Performance:	0.12	0.94	0.74

Model Validation

The SEEP/W model would be expected to perform well in the calibration period because the inputs were adjusted to obtain optimal agreement between the modeled and ob-

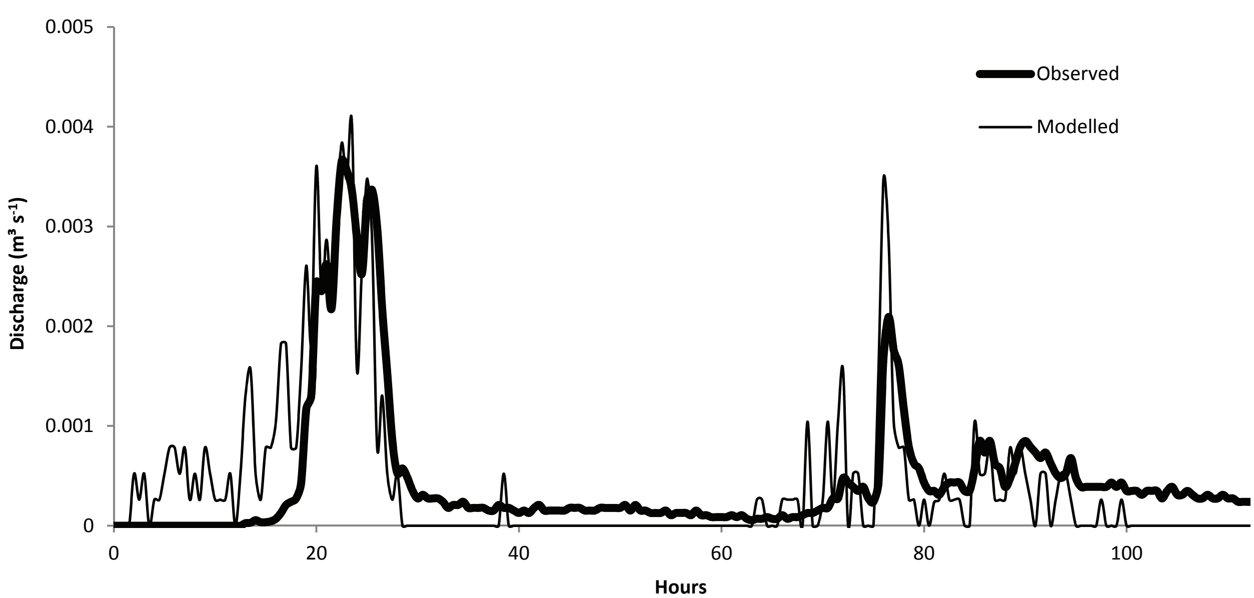


Figure 3. Tile drain discharge from SEEP/W analysis and observed field measurements in system 1 during event A (calibration).

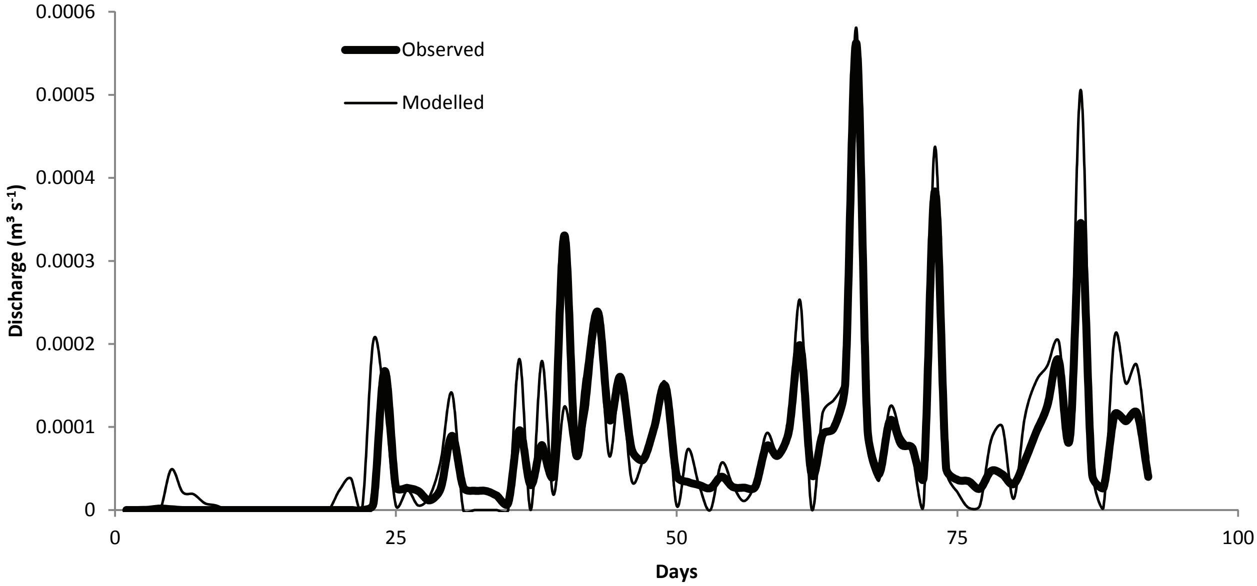


Figure 4. Daily tile drain discharge from SEEP/W analysis and observed field measurements in system 1 during event B (validation).

served tile drain discharge during event A. Therefore, the model of system 1 was validated by comparing the modeled and observed daily tile drain discharge data during the period from 1 October to 31 December 2015 (event B). The modeled and observed tile drain discharges from system 1 during event B are presented in figure 4.

Table 3 presents performance parameters of the modeled and observed discharges for system 1 during events A and B along with statistical performance parameters. For the validation period (event B), the CRM was 0.12, the IoA was 0.94, and the ME was 0.74, showing good agreement between the modeled and observed daily subsurface drainage from the combined tile/mole system. The model offered valid predictions of tile drain discharge for this period. Modeled and observed daily tile drain discharges during event B are plotted against each other in figure 5. The data are plotted at 1:1, with a correlation coefficient (R^2) of 0.811. The SEEP/W model offered reliable predictions of drain discharge from the combined mole drain/tile drainage system. As such, it offers a reliable method for assessing variations in system design on this site and similar sites.

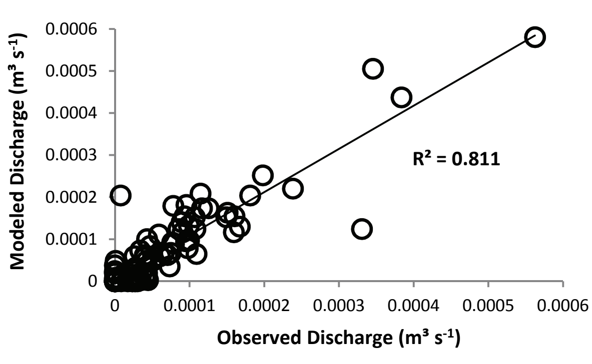


Figure 5. Modeled versus observed daily tile drain discharge ($m^3\ s^{-1}$) from system 1 during event B (validation).

ALTERNATIVE DRAINAGE SYSTEM PERFORMANCE

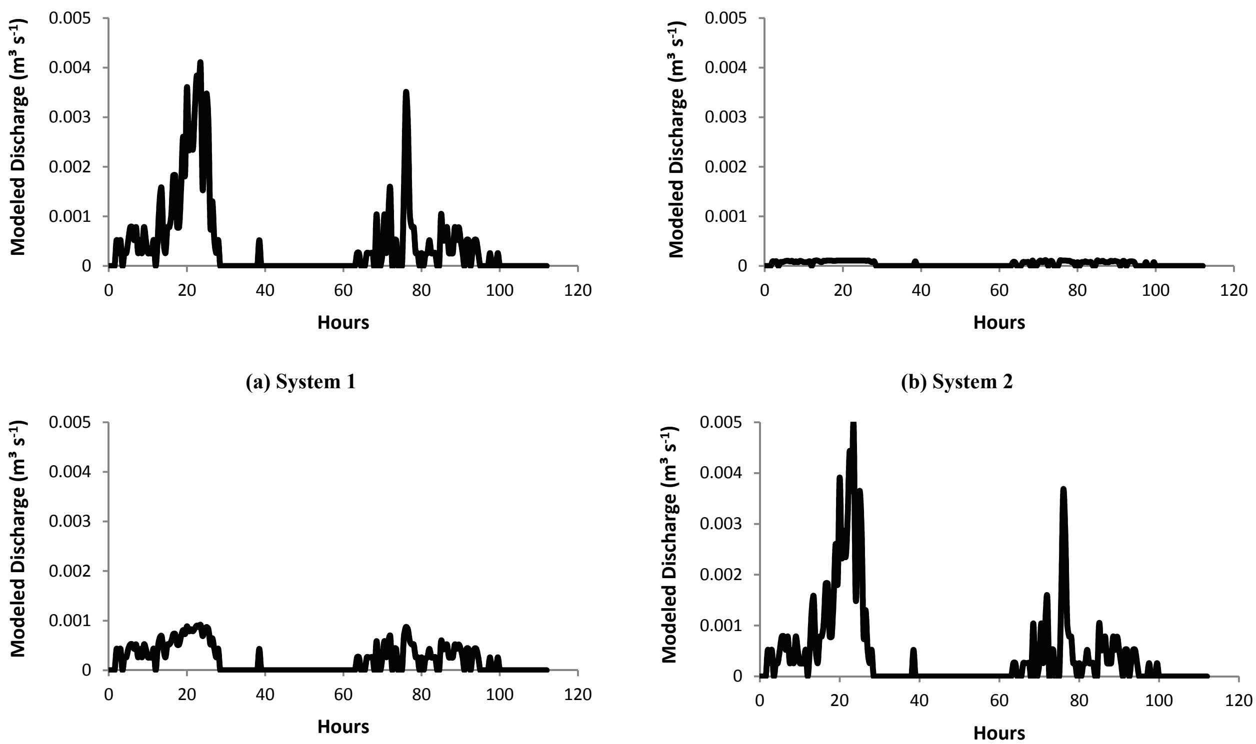
Model estimates of the performance of alternative drainage systems were compared (table 4). Sharp contrasts were evident between drainage systems. System 2 consistently had the lowest peak, average, and total discharge, while systems 1 and 4 were the best performing systems. The performance of system 3 was comparable to that of 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 through D, the mean rainfall intensity was 1.40, 0.23, 2.00, and 0.14 mm h^{-1}, respectively, while peak rainfall intensity was 15.20, 1.78, 2.00, and 0.18 mm h^{-1}, respectively). Discharge hydrographs and cumulative discharge plots during event A are presented in figures 6 and 7. Water table depth at 7.5 m from the tile drain center (midway 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 (fig. 8). During each event modeled, 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 when the WT was within 0.45 m of the surface calculated (table 4). This depth was selected because Brereton and Hope-Cawdery (1988) showed that grass production on a poorly drained soil is limited until the WT depth reaches approximately 0.45 m. The T45 metric emphasizes the poor performance of system 2 across events (average T45 of 75.2%) relative to 1.8%, 38.0%, and 0.0% for systems 1, 3, and 4, respectively. The installation of tile drains alone at such spacings does not offer sufficient discharge capacity. If the spacing were reduced beyond this level, the installation of tile drains would become uneconomical for grassland production (Teagasc, 2013). Shallow soil horizons are heavy textured and structureless, which prevents rapid inflow of

Table 4. Modeled performance of drainage systems during rainfall events.[a]

	Event	System 1	System 2	System 3	System 4	SEM
Peak discharge ($m^3 s^{-1}$)	A	4.05E-03	1.10E-04	9.13E-04	4.95E-03	
	B	5.81E-04	9.60E-05	4.54E-04	5.81E-04	
	C	6.52E-04	9.96E-05	4.78E-04	6.52E-04	
	D	5.81E-05	4.52E-05	5.81E-05	5.81E-05	
Average discharge ($m^3 s^{-1}$)	A	4.31×10^{-4} a	4.18×10^{-5} c	2.15×10^{-4} b	4.51×10^{-4} a	1.49×10^{-5}
	B	7.62×10^{-5} a	3.41×10^{-5} b	7.34×10^{-5} a	7.62×10^{-5} a	4.68×10^{-6}
	C	6.39×10^{-4} a	9.77×10^{-5} c	4.69×10^{-4} b	6.39×10^{-4} a	1.63×10^{-5}
	D	5.71×10^{-5} a	4.49×10^{-5} b	5.70×10^{-5} a	5.71×10^{-5} a	2.58×10^{-7}
Total discharge (m^3)	A	174.7	16.9	86.8	181.8	
	B	605.4	271.0	583.4	605.4	
	C	115.0	17.6	84.4	115.0	
	D	1794.3	1410.9	1792.5	1794.5	
Average water table depth (m)	A	0.78 b	0.50 c	0.54 c	0.89 a	0.009
	B	0.88 a	0.36 c	0.73 b	0.90 a	0.016
	C	0.73 b	0.02 c	0.02 c	0.88 a	0.029
	D	0.89 b	0.07 d	0.79 c	0.90 a	0.009
T45 (Proportion of time with water table depth ≤ 0.45 m)	A	7.3%	44.1%	44.1%	0.0%	
	B	0.0%	59.1%	9.7%	0.0%	
	C	0.0%	98.0%	98.0%	0.0%	
	D	0.0%	99.5%	0.0%	0.0%	

[a] Means followed by the same letters are not significantly different at the 0.05 level.



(a) System 1

(b) System 2

(c) System 3

(d) System 4

Figure 6. Modeled tile drain discharge for systems 1 through 4 during event A.

excess water to drains or rapid drawdown of the water table. The addition of mole drains thereby provides an effective shallow drainage system at an economic cost (Galvin, 1978; Maticic and Steinman, 2007). The performance of the combined tile/mole drainage systems reflected the variations in K_s of the material above the mole drain channel. The greater the improvement in soil K_s, brought about during mole channel installation, the better the long-term system capacity and performance will be.

Implications

The SEEP/W software offers reasonable predictions of the behavior of combined tile/mole drainage systems. Further work will be required to assess the applicability of the software to a wider range of the drainage systems and soil types prevalent in Ireland. It is anticipated that the software can be calibrated for these variations and used for other drainage system scenarios. Such a tool could provide decision support in the drainage system design process and assess the implications of design variations on cost, expected

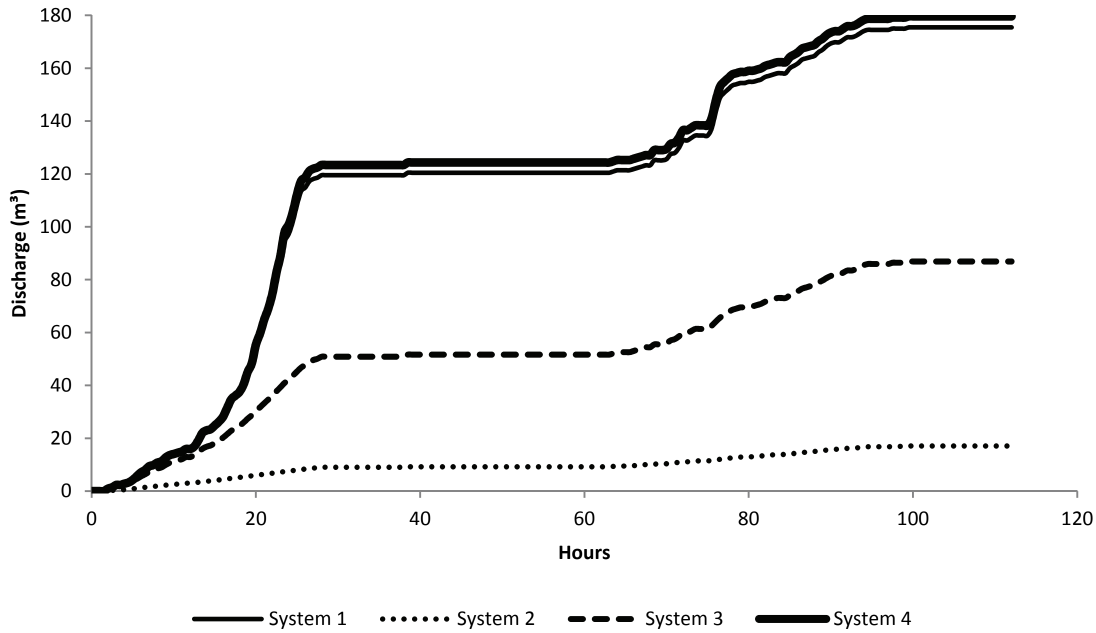


Figure 7. Modeled cumulative tile drain discharge during event A.

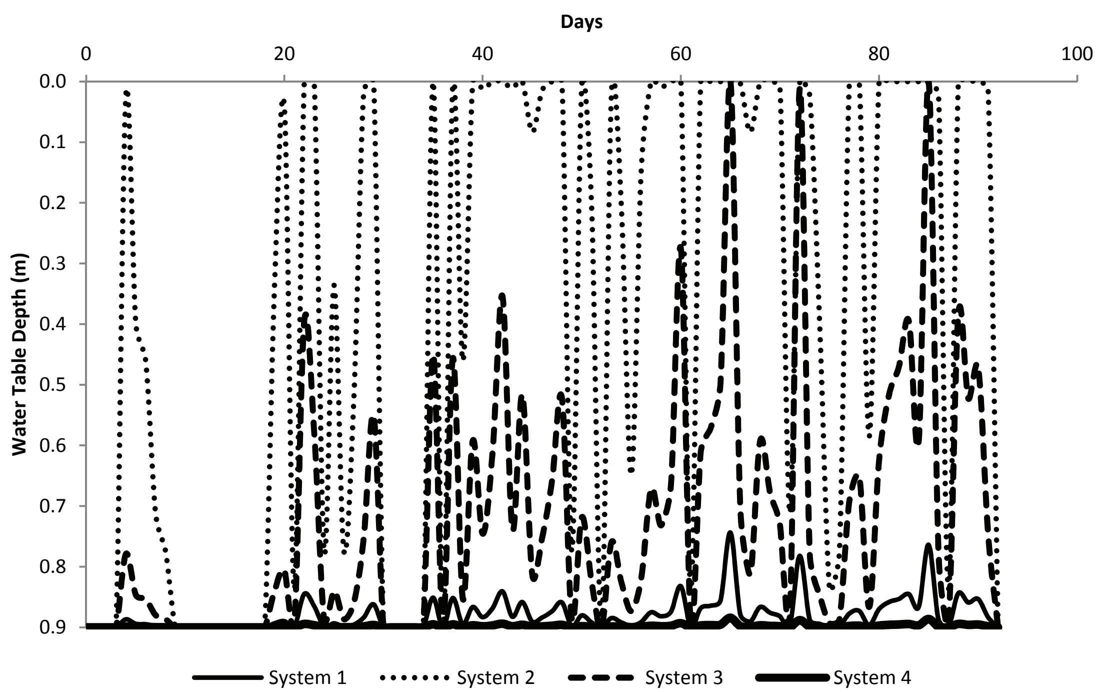


Figure 8. Modeled water table depth 7.5 m from tile drain center (mid-drain spacing) for systems 1 through 4 during event B.

performance, and likely returns to the landowner by estimating seasonal variation in drainage discharge and water table position. With appropriate soil profile characterization and suitable field data, whole-farm appraisals could be carried out to prescribe appropriate drainage designs and priority areas for drainage installation in light of the technical feasibility and cost estimations provided by an appropriately calibrated model. Future work should also quantify the implications of drainage efficiency on grassland productivity and trafficability to allow effects of alterations in drainage design to be estimated in terms of potential benefits and return on investments.

Once established, such models may also be used to assess the implications of climate change on drainage system design and performance. In recent years, analyses have shown a clear trend toward increased precipitation in Ireland (Walsh, 2012a, 2012b). Furthermore, it is predicted that a substantial increase in short-term extreme rainfall events and much seasonal variability in rainfall is likely (Nolan et al., 2013). Therefore, the design of drainage systems will need to be adapted for these climate changes. Software models could be used to assess the magnitude of these adaptations and the implications of these changes from an economic standpoint.

Conclusions

The SEEP/W software was shown to allow the formulation of an appropriate model of the drainage system in question and offer reliable predictions of tile drain discharge of the 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 for this period. The model therefore offers a reliable method for assessing the design variations of such systems. The modeling 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-textured, impermeable soils. Many farmers persist in installing tile-only systems in inappropriate conditions. The tile-only system failed to control the water table, 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 the combined tile/mole drainage 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 the material above the mole drain channel. The greater the improvement in soil K_s brought about during mole channel installation, the better the long-term system capacity and performance will be. As the installation cost of mole drainage is low (€125 to €300 ha^{-1}; Tuohy et al., 2016), the process should be repeated regularly (at 2 to 5 year intervals) to maintain channel integrity and optimize overall system performance. Maximum soil fissuring and cracking must be promoted during mole drain installation.

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