2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

An ASABE Meeting Presentation
DOI: 10.13031/ids.20162487014
Paper Number: 162487014

Runoff and subsurface drain response from mole and gravel mole drainage across episodic rainfall events in Ireland

Tuohy, P.[1], Humphreys, J.[1], Holden, N.[2], Fenton, O.[3]
[1]Animal and Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland,
[2] UCD School of Biosystems Engineering, University College Dublin, Belfield, Dublin 4, Ireland,
[3] Environment Research Centre, Teagasc, Johnstown Castle, Wexford, Co. Wexford, Ireland.

Written for presentation at the
10th International Drainage Symposium

Partners
University of Minnesota Water Resources Center
American Society of Agricultural and Biological Engineers

Minneapolis, Minnesota
September 7 – 9, 2016

ABSTRACT. *Shallow drainage techniques such as mole and gravel mole drainage are used in low permeability soils to siphon off infiltrating rainwater and mitigate the associated rise in watertable. Their purpose is to improve trafficability and agricultural production. In Ireland, long-term climate predictions envisage an increased level of short-term extreme rainfall events. Therefore, a key question is how these drainage techniques perform during episodic, high intensity rainfall events, specifically in terms of discharge hydrographs and associated parameters (principally flow start time, flow peak time, lag time, peak flow rate and flashiness index). We examined 12 rainfall events over a 1 year period on a clay-loam dominated grassland site of 1.4% slope in the south of Ireland. Four drainage treatments, namely; (A) an un-drained control, (B) Mole drainage installed in January 2011 (sub-optimal installation conditions), (C) Mole drainage installed in July 2011 (optimal installation conditions) and (D) Gravel mole drainage installed in July 2011 were examined. Results showed that gravel mole drainage exhibited shorter response times to rainfall events and ultimately drained greater volumes. Drain flow from mole drainage treatments B and C produced longer start, peak and lag times and lower peak and total flows relative to the other flow discharges. Variations in discharges from all treatments were closely correlated to soil moisture status, 30 day antecedent rainfall and rainfall event intensity. Drain flow response in all treatments was seen to deteriorate in time with the strongest responses evident in early events. Flow hydrographs showed strong variation in flow characteristics, within and across treatments and across events. If the predicted increase in short-term extreme rainfall events materializes then such systems will have to operate in increasingly adverse conditions. This will require changes in system design to improve the effectiveness of mole and gravel mole drainage.*

Keywords. *Drainage systems, flashiness index, flow response, Hydrograph*

Introduction

Many farms in Ireland suffer from the dual handicap of poorly drained soils and high precipitation levels. Precipitation ranges from approximately 750 to 3000 mm year^{-1} while evapotranspiration ranges from 390 to 570 mm (Mills, 2000). Updated 30-year rainfall averages show a clear trend towards increased precipitation in recent years (Walsh, 2012a, 2012b). Under climate change predictions the total annual rainfall will not vary substantially but significant changes in seasonal patterns will be evident with a likelihood for drier summers and wetter winters and a substantial increase in the number of short period extreme rainfall events (Nolan et al., 2013).

Mole drainage (€125–300 ha^{-1}, Crosson et al., 2013) is a shallow drainage technique comprising a series of closely spaced (1.0-2.5 m apart) unlined channels at approximately 0.4-0.6 m depth in cohesive soils. They increase the infiltration capacity of the soil by cracking, fracturing and loosening the heavy structureless layers close to the soil surface (Hallard and Armstrong, 1992). This allows excess water to be drained more quickly from the upper layers of the soil after rainfall events.

Mole drains are formed with a tractor mounted mole plough consisting of a chisel nosed torpedo-like cylindrical foot, attached to a narrow leg, and drawing a slightly larger cylindrical expander behind. Gravel mole drainage provides an alternative to mole drainage in those soils which cannot sustain a stable mole channel (Mulqueen, 1985). It was developed to overcome the limitations associated with less cohesive soils and offers a more robust system with a much longer lifespan than traditional mole drainage, but at a much higher cost (€1500–2800 ha^{-1}, Crosson et al., 2013). Mole drains rely on a network of subsoil cracks and closely spaced channels to rapidly carry away excess soil water during rainfall events (Spoor, 1982; Hallard and Armstrong, 1992). However, the nature of such soil disturbance features dictates that the response to rainfall events will vary temporally due to a number of inter-related variables related mostly to antecedent soil and rainfall event conditions (Robinson et al., 1987). The understanding of the hydrological response of these drainage systems is largely unknown. The efficiency and resilience of mole drainage is largely dependent on soil type and installation conditions (specifically soil moisture content during installation). They are known to have a limited lifespan before re-installation is required (Mulqueen, 1985). It has also been found that seasonal differences are evident in flow responses due to the instigation/propagation of shrinkage cracks in prolonged dry periods and their subsequent degeneration in wet periods (Jarvis and Leeds-Harrison, 1987; Robinson et al., 1987). Therefore the capacity of these systems is hugely variable both in terms of initial conditions (soil type/installation) and subsequent weather patterns. The addition of gravel to the mole channel also alters its hydrologic capacity and affects flow response from the drained land (Mulqueen, 1985).

The objective of this study was to compare the effectiveness of mole and gravel mole drainage by investigating surface runoff and subsurface drain discharge over 12 intense episodic rainfall events during one year. Flows were investigated in terms of discharge hydrographs and response parameters (principally flow start time (relative to event start time), flow peak time (relative to event start time), lag time (peak flow time relative to peak rainfall time), peak flow rate and flashiness index) from the following treatments; (A) un-drained control, (B) Mole drainage installed in January 2011 (sub-optimal installation conditions), (C) Mole drainage installed in July 2011 (optimal installation conditions) and (D) Gravel mole drainage installed in July 2011.

Materials and Methods

Site Details

The study site (2.5 ha) was located at the Solohead Research Farm (52 ha) in the south of Ireland (52°30'N, 08°12'W) and slopes gently (1.4%) with a southerly aspect (Figure 1). Average annual rainfall (10 years) on site is 1070 mm, with potential evapotranspiration of approximately 510 mm annually. Disturbed soil samples from soil test pits, representative of distinct soil horizons were bulked for each horizon and analysed for sand, silt and clay % (laser diffraction method with correction for clay fraction underestimation (Konert and Vandenberghe, 1997)). Indicative k_s was inferred for each sample using Saxton and Rawls (2006) assuming a soil organic matter content of 2.5 % (by weight). These samples and previous analyses (Jahangir et al., 2013) show the soil profile to be poorly permeable with little potential for efficient drainage using conventional drain spacings (10-50 m). Therefore, the site required the closely spaced drainage channels and soil loosening effects provided by mole and gravel mole drainage. Soil type was not ideal with regard to the formation of a stable mole channel (Burke, 1978), but occupied a zone of uncertainty where it is unknown whether mole drainage or gravel mole drainage is most appropriate. Many more soils would fit into this category than those with the "ideal" soil type for mole drainage. A direct comparison of mole and gravel mole drainage on such a site therefore has much practical value. The site was an ideal staging ground for assessing and comparing such drainage treatments.

Experimental setup

In January 2011, the study area was divided into four blocks (60 m-wide, 100 m-long). Each block was sub-divided into four 15 m wide plots. One of four treatments was imposed in each plot in a randomised complete block design with four replicates. The four treatments were (A) un-drained control, (B) mole drainage installed in January 2011, (C) mole drainage installed in July 2011 and (D) gravel mole drainage installed in July 2011. Mole drains were installed at 1.2 m spacing and 0.55 m depth, Gravel mole drains were installed at 1.2 m spacing and 0.40 m depth (Figure 1). Further detail is available in Tuohy et al. (2015, 2016).

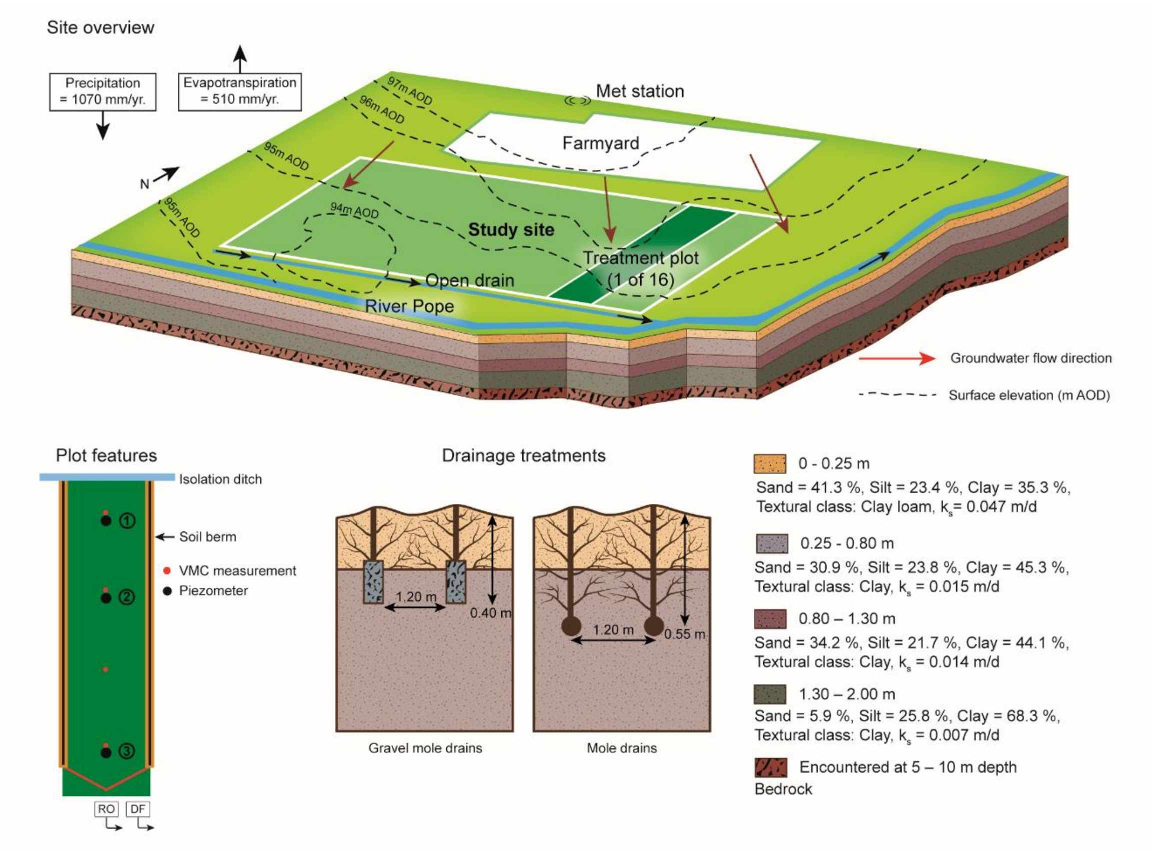

Figure 1. Site overview including typical soil profile, treatment plot features and mole/gravel mole drainage treatment detail. AOD = above ordnance datum, VMC = volumetric moisture content, RO = Runoff, DF = sub-surface drain flow.

Experimental measurements

All runoff (RO) from each plot was channeled towards an outlet point from which the RO was piped to a measurement tank. In each drained plot, there were eleven mole or gravel mole channels; the five central channels were connected to a pipe, which directed their flow to a measurement tank. The RO and drain flow (DF) passed through a v-notch weir constructed within their respective 1.0 x 0.6 x 0.6 m measurement tank (Carbery Plastics, Clonakilty, Co. Cork, Ireland). In three plots from each treatment, the tanks were fitted with a Sigma area/velocity probe connected to a Sigma 920 flowmeter (HACH Company, Maryland, USA) to monitor flow. Flow rate from each system was measured continuously, with the average rate logged every 15 minutes. Flow via DF was weighted by total plot area to account for flow from unmeasured channels.

Flow hydrographs were examined for particular rainfall events. A period of 12 hours without rainfall was used to separate one rainfall event from another (Ibrahim et al., 2013). A "perceptible rise in discharge" signalled the start of the flow event, while the end of the event was defined as flow returning to pre-event flow levels (Vidon and Cuadra, 2010). Base-flow from the treatments was non-existent such that the start and end of flow events was clearly defined. Start time, peak time and lag time were calculated. Variations in discharge are described using a flashiness index (Eq. 1). The flashiness index is calculated for the event as the total path length of flow divided by the sum of the average quarter-hourly discharge, the flow path in this case being equal to the sum of the difference between the quarter-hourly discharge values as:

$$FI = \frac{\sum_{i=1}^{n} |q_i - q_{i-1}|}{\sum_{i=1}^{n} q_i} \qquad (1)$$

Where q_i and q_{i-1} are the average quarter-hourly discharge values at consecutive time points (Deelstra, 2015). Quarter hourly values are used as mole drainage tends to exhibit short time-span flows.

All data (RO, DF, WT depth and VMC) were analysed by analysis of variance with treatment as a factor. Multiple comparisons between treatments and event response times and response parameters were made using the PROC GLM procedure in SAS version 9.1.3 (SAS, 2006). Regression analysis was carried out to establish the principle factors affecting (i) response times and (ii) the cumulative rainfall at response times. The independent variables assessed were VMC, 7 and 30 day antecedent precipitation and mean and maximum rainfall intensity using the PROC REG procedure in SAS version 9.1.3 (SAS, 2006).

Results

On-site annual rainfall was 1131 mm and 953 mm in 2012 and 2013, respectively. The 12 rainfall events in this study were selected from within the year beginning 1 April 2012 from an initial list of 32 rainfall events. These 32 events had high levels (> 5 mm) of effective drainage (ED; the difference between rainfall and estimated evapotranspiration using the hybrid grassland model of Schulte et al. (2005) assuming poorly drained soil criterion) and were chosen as such conditions were most likely to induce a widespread flow response from the drainage treatments. The selection of the 12 events reported herein was based on a need for full and legitimate flow data from all instrumented plots during high intensity events. Events with missing data were removed from the analysis. Total rainfall for the year beginning 1 April 2012 was 1242 mm. Total event precipitation was highest for Event 1 (63.8 mm) and lowest for Event 9 (10.4 mm).

Significantly more water was removed from drained treatments B, C and D relative to control treatment A ($P < 0.05$, s.e. 1.05 mm). Mean total RO and mean ratio of RO to ED were not significantly affected by treatment. Mean total DF was greater in treatment D than either treatment B or C which were not significantly different from each other (Tuohy et al., 2015, 2016). Cumulative RO and DF discharge relative to effective drainage from each treatment during the study period is presented in Figure 2. Generally RO was greater than DF in mole drainage treatments B and C, while in treatment D, DF was consistently higher than RO and ultimately yielded a higher total discharge. During this period total mean (S.D.) RO from treatments A, B, C and D was 149 (84.5), 166 (27.8), 154 (37.2) and 160 (56.9) mm respectively, total DF from treatments B, C and D was 106 (14.0), 130 (66.1) and 188 (68.9) mm respectively.

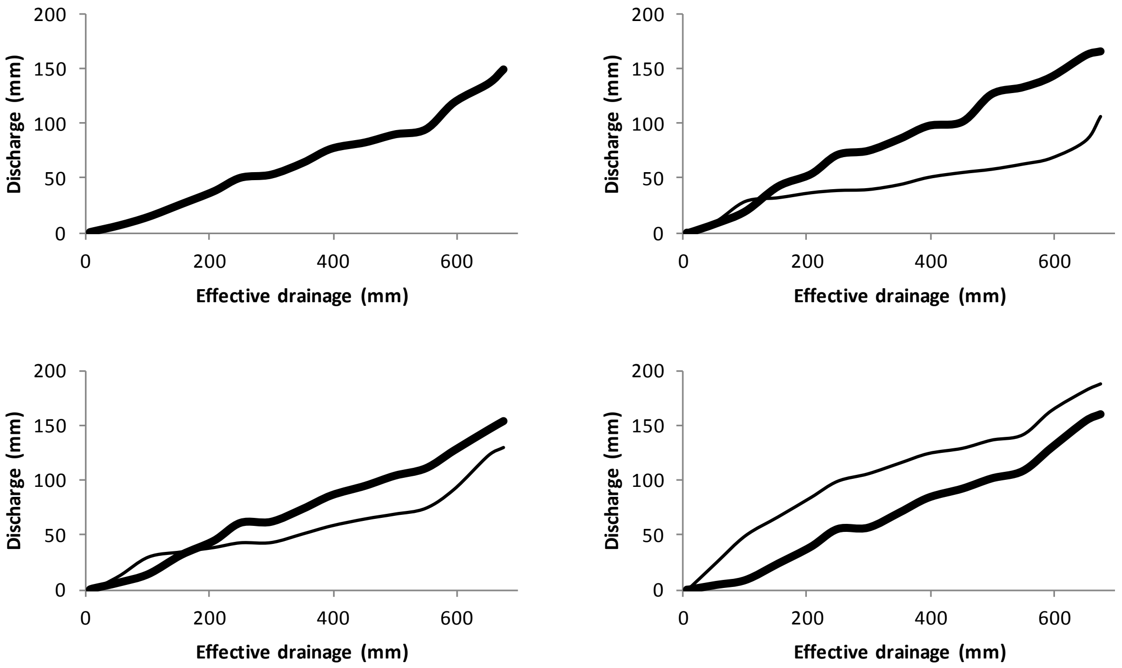

Figure 2. Cumulative runoff (━) and subsurface drain flow (─) discharge relative to cumulative effective drainage in the year beginning 01/04/2012 for (a.) Treatment A (un-drained control), (b.) Treatment B (mole drains installed in January 2011), (c.) Treatment C (mole drains installed in July 2011) and (d.) treatment D (gravel mole drains installed in July 2011).

Start, peak and lag times, cumulative rainfall at start and peak times, peak flow rate and total volume drained were affected by treatment (Table 1). Start time, cumulative rainfall at start time and cumulative rainfall at peak time were significantly lower in RO when compared to DF. Peak flow rate and total volume drained were significantly higher in RO relative to DF. Mean RO start times ranged from 9.1 to 10.1 h., while mean DF start times ranged from 9.2 to 13.5 h. Mean RO peak times ranged from 19.7 to 21.0 h., while mean DF peak times ranged from 17.9 to 22.7 h. and mean RO lag times ranged from 9.8 to 11.1 h., while mean DF lag times ranged from 7.8 to 12.2 h.. Start, peak and lag times were also affected by event. The principal factors affecting response times were shown, by regression, to be pre-event VMC, 30-day antecedent precipitation, and maximum and mean rainfall intensity during the event. Generally the higher the pre-event VMC, antecedent precipitation and maximum and mean rainfall intensity the shorter the start, peak and lag times became.

Table 1. Mean response times, rainfall at response times, peak flow rate and total volume drained from treatments A, un-drained control, B, mole drainage installed in January 2011, C, mole drainage installed in July 2011 and D, gravel mole drainage installed in July 2011.

	Runoff				Drain flow			
Treatment	A	B	C	D	B	C	D	S.E.M.
Start time (h)	9.1^{a}	10.0^{ab}	9.9^{ab}	10.1^{ab}	12.3^{ab}	13.5^{b}	9.2^{a}	0.65
Peak time (h)	20.5^{ab}	19.7^{ab}	19.9^{ab}	21.0^{ab}	21.8^{a}	22.7^{a}	17.9^{b}	1.14
Lag time (h)	10.5^{ab}	9.8^{ab}	10.0^{ab}	11.1^{ab}	12.2^{a}	12.0^{a}	7.8^{b}	0.93
Cumulative rain at start time (mm)	7.7^{a}	7.0^{a}	7.3^{a}	6.7^{a}	11.3^{ab}	13.5^{b}	8.3^{ab}	0.63
Cumulative rain at peak time (mm)	18.8	18.8	19.0	19.3	21.6	21.2	19.6	0.86
Peak flow rate (mm/h)	1.28^{abc}	3.01^{d}	1.80^{abcd}	2.17^{abd}	0.64^{c}	0.92^{bc}	2.74^{ad}	0.156
Flashiness index	0.20^{a}	0.34^{a}	0.24^{a}	0.25^{a}	0.20^{a}	0.37^{a}	0.60^{b}	0.021
Total drained (mm)	5.50^{ab}	6.47^{ab}	6.34^{ab}	6.69^{ab}	3.75^{a}	4.15^{ab}	7.43^{b}	0.378

	Runoff	Drain flow	S.E.M.
Start time (h)	9.8^{a}	11.6^{b}	0.65
Peak time (h)	20.3	20.9	1.14
Lag time (h)	10.4	10.7	0.93
Cumulative rain at start time (mm)	7.2^{a}	11.0^{b}	0.63
Cumulative rain at peak time (mm)	19.0^{a}	20.8^{b}	0.86
Peak flow rate (mm/h)	2.07^{a}	1.43^{b}	0.156
Flashiness index	0.26^{a}	0.38^{b}	0.021
Total drained (mm)	6.25^{a}	5.11^{b}	0.378

Means having the same superscript letter are not significantly different at the 0.05 level.

Flashiness index indicates that the largest variations in flow conditions occurred in DF from the gravel mole drains. The mean flashiness index across events for DF in treatment D was 0.60 and was significantly higher than the mean flashiness of all other flow discharges (Table 1). A closer inspection of the data reveals that there was a range of responses to rainfall evident. The response to rainfall varied between and within treatments (due to heterogeneity of soil physical parameters, micro-topography and the depth of the WT across the site) and across rainfall events. As examples, RO and DF hydrographs for Event 1 are presented in Figure 3.

Discussion

Flow responses in terms of start, peak and lag times were shown to be dependent largely on pre-event and event hydro-meteorological conditions, particularly pre-event volumetric moisture content at the soil surface (<5 cm), 30-day antecedent precipitation and maximum and mean rainfall intensity during the event. These parameters affect the soil moisture status before and during the event and its capacity to store and transmit water (Spoor et al., 2003; Deasy et al., 2014). The long-term performance of mole and gravel mole drainage are particularly reactive to changes in soil moisture status due to the influence soil moisture status has on soil cracking (Galvin, 1983). Flow from mole/gravel mole drains is reliant on the network of cracks and fissures created during the installation process, which provide an avenue for water flow (Spoor and Ford, 1987; Rodgers et al., 2003). However the long-term integrity of the cracks themselves is subject to the shrink/swell properties of the soil and their ability to carry water will vary with the natural wetting/drying cycles of the soil (Jarvis and Leeds-Harrison, 1987; Robinson et al., 1987).

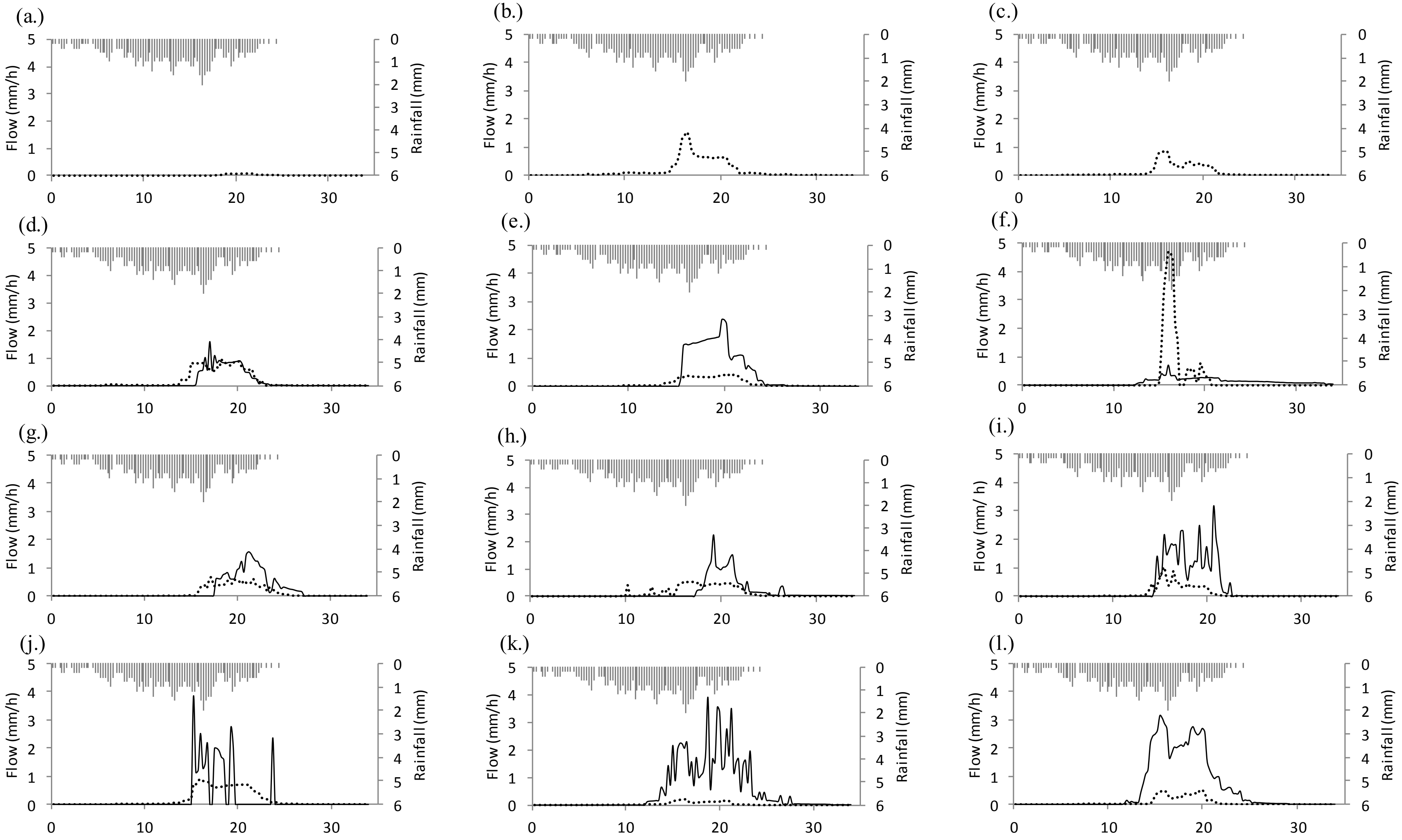

Figure 3. Runoff (••••) and subsurface drain flow (─) response to rainfall (│) versus time in hours during Event 1 for treatment A (un-drained control) replicates (a) A-1, (b) A-2 and (c) A-3, treatment B (mole drains installed in January 2011) replicates (d) B-1, (e) B-2 and (f) B-3, treatment C (mole drains installed in July 2011) replicates (g) C-1, (h) C-2 and (i) C-3 and treatment D (gravel mole drains installed in July 2011) replicates (j) D-1, (k) D-2 and (l) D-3.

Runoff and DF response did adhere to certain behavioral trends. The stronger DF in treatment D relative to treatment B and C indicates that gravel mole drainage was more effective than mole drainage in this soil type. Flow hydrographs (Figure 3) show that this is due to strong and sustained drain flow during events in treatment D relative to that from treatments B or C. The flow through gravel mole drains was more intense, with shorter start and peak times, higher peak flow rates and greater total flows than other treatments. The high flashiness index related to DF from treatment D indicates that the subsurface drainage system reacted faster to input precipitation than the other treatments. The range of implement designs available commercially does not cater for much variation in terms of design, which could increase the intensity of soil disturbance (Galvin, 1983) and ultimately system performance. As such the installation of such treatments tends to be standardized with little room for adjustment to soil conditions. Potential adjustments could include alterations to mole foot and expander diameter, leg width, spacing and working depth, multiple depths of mole channels and staged approaches to incrementally achieve effective drainage (if full mole drainage installation is not viable initially).

Conclusions

- Cumulative discharge plots show a variation in performance between drainage techniques and in time. The temporal changes in flow response were due to the loss of functional mole channels, in some cases, and the reduced effectiveness of the disruption techniques in persistent wet weather due to the natural shrink/swell properties of the high clay content soil. Gravel mole drainage consistently removed a greater volume of water in this soil type than mole drainage.
- Flow response times (start, peak and lag) show RO was more responsive to rainfall than DF in mole drainage treatments B and C. The relatively short mean start, peak and lag times from DF in the gravel mole drainage treatment show it to be the most responsive of all measured flows to rainfall events.
- Flow hydrographs show that the strong performance of gravel mole drains was due to strong and sustained drain flow during events. The flow through gravel mole drains was more intense, with shorter start and peak times, higher peak flow rates and greater total flows than other treatments. Gravel mole drainage offers greater potential to cater for the predicted increased level of short-term extreme rainfall events than mole drainage in this soil type.
- The response times from mole and gravel mole drainage were particularly reactive to changes in soil moisture status. Generally the higher the pre-event VMC, antecedent precipitation and maximum and mean rainfall intensity the shorter the start, peak and lag times became.
- Research in this area needs to closely examine the mole drainage failure mechanisms in such soils to establish the main factors affecting channel breakdown and investigate means to manipulate installation conditions and implement design to better cater for natural variations in soil conditions.

Acknowledgements

We would like to acknowledge the technical assistance of D. Barrett and the staff at the Teagasc Solohead Research Farm. This research was conducted with the financial support of Interreg IVB NWE Project No. 096D (Dairyman) and the Teagasc Walsh Fellowship Scheme.

References

Burke, W. (1978). The phyiscal basis of soil/water relationships. In: W. Burke (Ed.), Proc. Seminar on Land Reclamation. pp 1-16. Leitrim, Ireland: An Foras Taluntais.

Crosson, P., Shalloo, L. & Thorne, F. (2013). The economics of land drainage. In M. Moore, O. Fenton, P. Tuohy & T. Ibrahim (Eds.), Teagasc Manual on Drainage – and soil management; A best practice manual for Ireland’s Farmers (pp. 113-119). Carlow, Ireland: Teagasc

Deasy, C., Titman, A., Quinton, J.N. (2014). Measurement of flood peak effects as a result of soil and land management, with focus on experimental issues and scale. J. Env. Manage. 132, 304-312.

Deelstra, J. (2015). Subsurface drainage runoff behaviour in Norway. In Zeverte-Rivza, S. (Ed.)., Proc. 25th NJF congress: Nordic view to sustainable rural development. pp 186-191. Riga, Latvia: NJF.

Galvin, L.F. (1983). The Drainage of Impermeable Soils in High Rainfall Areas. Irish J. Ag. Res. 22, 161-187.

Hallard, M., Armstrong, A.C. (1992). Observations of water movement to and within mole drainage channels. J. Ag. Eng. Res. 52, 309-315.

Ibrahim, T.G., Fenton, O., Richards, K.G., Fealy, R.M., Healy, M.G. (2013). Spatial and temporal variations of nutrient loads in overland flow and subsurface drainage from a marginal land site in south-east Ireland. Biol. Environ. 113, 1-18.

Jahangir, M.M.R., Johnston, P., Barrett, M., Khalil, M.I., Groffman, P.M., Boeckx, P., Fenton, O., Murphy, J., Richards, K.G. (2013). Denitrification and indirect N2O emissions in groundwater: Hydrologic and biogeochemical influences. J. Contam. Hydrol. 152, 70-81.

Jarvis, N.J., Leeds-Harrison, P.B. (1987). Modelling water movement in drained clay soil. I. Description of the model, sample output and sensitivity analysis. J. Soil Sci. 38, 487-498.

Konert, M., Vandenberghe, J. (1997). Comparison of laser grain size analysis with pipette and sieve analysis: a solution for the underestimation of the clay fraction. Sedimentology. 44, 523-535.

Mills, G. (2000). Modelling the water budget of Ireland-evapotranspiration and soil moisture. Irish Geog. 33, 99-116.

Mulqueen, J. (1985). The development of gravel mole drainage. J. Ag. Eng. Res. 32, 143-151.

Nolan, P., McGrath, R., Gleeson, E., Sweeney, C. (2013). Impacts of climate change on Irish precipitation. In E. Gleeson, R. Mcgrath, M. Treanor (Eds.), Ireland's climate: the road ahead. pp 57-61. Dublin, Ireland: Met Eireann,.

Robinson, M., Mulqueen, J., Burke, W. (1987). On flows from a clay soil-Seasonal changes and the effect of mole drainage. J Hydrol. 91, 339-350.

Rodgers, M., Mulqueen, J., McHale, J. (2003). A model study of mole drain spacing and performance. Agr. Water Manage. 60, 33-42.

SAS (2006). SAS User Guide: Statistics. Ver. 9.1. Cary, NC: SAS Institute.

Saxton, K.E., Rawls, W.J. (2006). Soil water characteristics estimates by texture and organic matter for hydrologic solutions, Soil Sci. Soc. Am. J. 70, 1569-1578.

Schulte, R.P.O., Diamond, J., Finkele, K., Holden, N.M., Brereton, A.J. (2005). Predicting the Soil Moisture Conditions of Irish Grasslands. Irish J. Agr. Food Res. 44, 95-110.

Spoor, G., Ford, R.A. (1987). Mechanics of mole drainage channel deterioration. J. Soil Sci. 38, 369-382.

Spoor, G., Tijink, F.G.J., Weisskopf, P. (2003). Subsoil compaction: risk, avoidance, identification and alleviation. Soil Till. Res. 73, 175-182.

Tuohy, P., Humphreys, J., Holden, N.M., Fenton, O. (2015). Mole drain performance in a clay loam soil in Ireland. Acta Agr. Scand. B-S. P. 65(sup1), 2-13.

Tuohy, P., Humphreys, J., Holden, N.M., Fenton, O. (2016). Runoff and subsurface drain response from mole and gravel mole drainage across episodic rainfall events. Agric. Water Manag. 169, 129-139.

Vidon, P., Cuadra, P.E. (2010). Impact of precipitation characteristics on soil hydrology in tile-drained landscapes. Hydrol. Process. 24, 1821-1833.

Walsh, S. (2012a). A Summary of Climate Averages for Ireland. Met Eireann, Dublin.

Walsh, S. (2012b). New long term rainfall averages for Ireland. Proc. of the National Hydrology Conference. pp. 3-12. Tullamore, Ireland: Office of Public Work