Agricultural Water Management 210 (2018) 96–107

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

The performance and behavior of land drainage systems and their impact on field scale hydrology in an increasingly volatile climate

P. Tuohy[a,*], J. O' Loughlin[a], D. Peyton[a], O. Fenton[b]

[a] Animal and Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co., Cork, Ireland
[b] Environment Research Centre, Teagasc, Johnstown Castle, Wexford, Co., Wexford, Ireland

ARTICLE INFO

Keywords:
Flow response
Drain discharge
Hydrograph
Groundwater
Climate change

ABSTRACT

Escalations in rainfall intensity, both in terms of volume and frequency are increasing the volatility associated with grassland agriculture on poorly drained soils. The principal mechanism of reducing this volatility is by means of land drainage; however the efficacy of drainage systems is widely variable and has not been fully quantified. The excavation of soil test pits and a corresponding examination of the soil profile enables bespoke land drainage system design. Across heterogeneous soil-scapes this leads to variations to both groundwater and shallow drainage designs. In the present study we examine the performances of 9 site-specific drainage systems (5 groundwater and 4 shallow drainage designs), during a high rainfall period (01/10/2015–31/05/2016) in terms of response times (start, peak and lag times), discharge characteristics (peak flow rate, total discharge, flashiness index, discharge hydrographs) and water table control capacity. Response times were not affected by drainage system or drainage design type, showing similar responses despite variation in soil types where appropriate drainage systems are installed. Total discharge (1098.4 vs. 189.6 m^3/ha) and peak flow rate (51.0 vs. 16.8 m^3/ha/h) were significantly higher in groundwater designs relative to shallow alternatives. Groundwater drainage designs generally maintained a deeper mean water table depth (0.82 m) than shallow designs (0.53 m) during the study period. The functional capacity of each land drainage system was inherently different. The comparison of such systems highlights contrasting behaviors of individual drainage systems and drainage design types, which is dictated largely by the hydraulic capacity of the soil within their catchment and their connectivity to different water bodies (groundwater versus perched water). All systems reduced the overall period of waterlogging and improved the conditions for both the production and utilization of the grasslands they drain, although temporal variations in agronomic parameters are likely to be more pronounced in shallow designs.

1. Introduction

In poorly drained grassland soils, both production and potential for grazing (utilization) are restricted due to surface water logging, reduced yields and low soil bearing capacity (Bell et al., 2011; Patton et al., 2012; Kandel et al., 2013). Generally, grassland productivity is positively correlated with annual precipitation (Smit et al., 2008) but in the case of poorly drained soils in temperate regions, excess rainfall can result in a saturated root-zone which inhibits production (Fitzgerald et al., 2008). Furthermore, these soils become impassable to both machinery and livestock traffic for extended periods (Keane, 1992). This introduces significant costs to the farm system as normal farming practices are curtailed (Brereton and Hope-Cawdery, 1988; Shalloo et al., 2004).

Clearly observable escalations in rainfall intensity, both in terms of volume and frequency are increasing the volatility associated with grassland agriculture on poorly drained soils. The impacts of climate change in Ireland (Kiely, 1999) are being felt most keenly by those farms where trafficability is marginal during periods of high rainfall. Increasing likelihood of adverse weather, principally high rainfall, is forcing landowners to invest significantly in mechanisms to increase the resilience of their grazing systems by reducing the impact of excessive rainfall.

Effective land drainage systems provide relief of excess water and control the water table thereby improving yields and grazing conditions and reducing the volatility associated with periods of adverse weather (Armstrong, 1985; Nijland et al., 2005; Ibrahim et al., 2013). The design of land drainage entails the specification and installation of drains in the soil at such a depth and spacing to control the water table at a predetermined depth below ground level under a particular intensity of

* Corresponding author.
E-mail address: patrick.tuohy@teagasc.ie (P. Tuohy).

https://doi.org/10.1016/j.agwat.2018.07.033
Received 14 December 2017; Received in revised form 20 July 2018; Accepted 29 July 2018
0378-3774/

rainfall (Mulqueen, 1998). Effective design requires that soil physical properties are fully characterized with regard to their drainage capacity, and that the drainage system is tailored to optimize discharge levels from a particular soil (Galvin, 1986; Schultz et al., 2007; Skaggs et al., 2012). A number of drainage systems and techniques have been developed to suit different soil types and conditions with associated drainage characteristics, with this end in mind (Smedema et al., 2004; Tuohy et al., 2016b). These range from groundwater drainage designs, (1.0–2.0 m deep) which interact directly with groundwater by virtue of their position in a high permeability soil layer (Smedema and Rycroft, 1983; Teagasc, 2013) to shallow drainage designs, comprised of shallow (< 1.0 m) tile drains supplemented by mole drainage, gravel mole drainage or sub-soiling at spacings of 1–2 m, (Spoor, 1982; Mulqueen, 1985; Robinson et al., 1987; Tuohy et al., 2016a,b).

Consistent increases in rainfall levels in the south-west, and indeed nationally, are creating a renewed enthusiasm for land drainage works, particularly where grazing potential is impacted consistently in the main grazing season (March–November). Significant investments in land drainage systems are being undertaken at farm scale with little guidance on the performance capacity and potential returns achievable in a wide range of drainage design/soil type dynamics. The return on such investments is dependent on an increase in grass production and utilization (number of grazings/silage harvests) and these are both factors of the hydrologic changes brought about by the installation of the drainage systems. Therefore to understand the agronomic and economic impacts of site-specific drainage systems in a wetter climate, we must examine the hydrologic impact and responses of such systems during periods of high rainfall.

The efficiency of a drainage system is a measure of its ability to respond to rainfall events and discharge appropriate volumes of water. In a changing climate, a trend towards more rainfall and/or a greater number of high intensity rainfall events (Kiely, 1999; Walsh, 2012a,b; Nolan et al., 2013) is putting increasing pressure on land drainage systems (Sloan et al., 2016) and altering the dynamics with relation to efficiency. The performance of drainage systems installed is hugely variable and for the most part, poorly understood. A review of the performance of a range of recently installed land drainage systems in terms of their response to rainfall events, water table control and flow discharge behavior in a high rainfall period would add to the understanding of the capabilities and limitations of such systems and generate new knowledge with respect to the efficiency of various drainage designs, and their potential usefulness in improving the agronomic value of poorly drained soils in an increasingly wet climate.

The objectives of this study were to a) quantify the general performance and effectiveness of 9 site-specific drainage systems over a number of rainfall events of varying magnitude during an extended high rainfall period, b) compare system responses and performance across drainage systems and drainage design types during rainfall events of like magnitude, c) quantify behavior characteristics of drainage systems and drainage design types and d) determine the principal factors which dictate their behavior. Performance was measured in terms of water table control, response and discharge parameters (namely flow start, peak and lag times, peak flow rate, flashiness index and total discharge) and discharge hydrographs.

2. Materials and methods

2.1. Site details

The study involved 9 drainage systems across 7 farms in southwest Ireland (Table 1; Fig. 1). The farms are all participants in the Teagasc 'Heavy Soils Program', which aims to demonstrate methods to improve grassland productivity and utilization, decrease volatility and sustain viable farm enterprises on poorly drained soils. They were selected from within regions where poor soil drainage coupled with climate (principally precipitation less evapotranspiration) inhibits potential for production and on-farm profitability. In conjunction with each farmer an area of the farm with a history of impeded drainage was selected and a new drainage system was installed (Table 2). The drainage systems were designed to optimize system performance using the methods outlined in Tuohy et al. (2016b) by tailoring design to the intrinsic soil properties. In the case of both site 1 and site 7, adjustments to the site-specific designs led to the installation of alternative drainage systems on equivalent areas, as a result a total of 9 distinct drainage systems were installed (Table 2).

Drainage systems 1.1, 1.2, 2, 3 and 4 are classified as groundwater drainage designs (GW), which interact directly with groundwater by virtue of their position in a high permeability soil layer, where percolation to the water table is uninhibited (Smedema and Rycroft, 1983; Teagasc, 2013), while drainage systems 5, 6, 7.1 and 7.2 are shallow drainage designs (SH), installed where all layers in a soil profile are fine, heavy and poorly permeable and efforts are focused on improving

Table 1
Site Details.

Site	Location			Average annual precipitation (1981-2010)[a]		
	Northing (degree)	Westing (degree)	Elevation ASL (m)	Precipitation (mm)	Station distance from site (km)	Slope (%)
1	52°36'	08°01'	105	982	6.5	1–2%
2	52°28'	09°33'	8	1095	1.0	1–2%
3	51°59'	08°56'	231	1757	5.5	7–9%
4	51°12'	09°08'	233	1622	7.8	6–7%
5	52°44'	09°30'	9	1185	2.0	< 1%
6	52°27'	09°19'	139	1320	4.3	4–6%
7	52°13'	09°28'	36	1298	2.5	4–6%

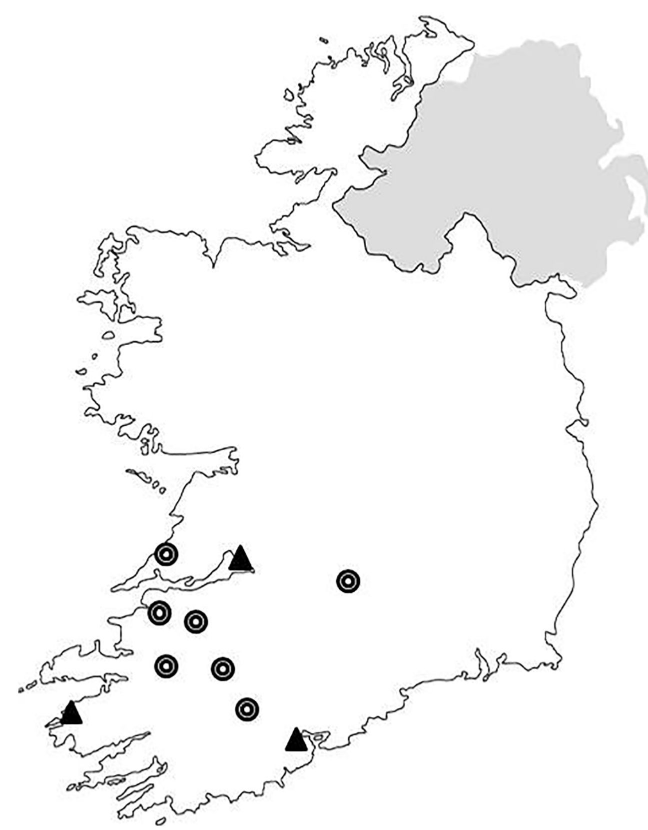

Fig. 1. Location of drainage sites (◎) and meteorological stations (▲) in the south-west of Ireland.

Table 2
Soil types, horizon descriptions, organic and mineral fraction composition and drainage system design details.

Site	Soil type	Horizon	Depth (cm)	OM (%)	Mineral Fraction			Textural Class	Drainage System (Design type: GW or SH)
					Sand (%)	Silt (%)	Clay (%)		
1	Surface Water Gley	Apg	0–28	5.6	69	16	15	Sandy Loam	1.1: Field drains at 1.6 m depth, 30 m spacing (GW)
		Eg	29–50	0.4	88	8	4	Loamy Sand	
		C	51–90	0.8	59	27	14	Sandy Loam	1.2: Field drains at 1.6 m depth, 15 m spacing (GW)
		Cr	91–140	0.6	69	17	14	Sandy Loam	
2	Ombrotrophic Peat	OA	0–40	68.8	–	–	–	–	2: Field drains at 1.7 m depth, 15 m spacing (GW)
		Of	41–85	89.5	–	–	–	–	
		Om	86–116	3.3	11	61	28	Silty Clay Loam	
		C1	117–141	–	–	–	–	–	
		C2	142–180	–	–	–	–	–	
3	Humic Surface Water Gley	AC	0–30	7.5	51	34	15	Loam	3: Field drains at 1.7 m depth, 20 m spacing (GW)
		BC	31–80	0.7	60	31	9	Sandy Loam	
		Cr	81–116	0.6	48	41	11	Loam	
4	Humic Brown Podzolic	Ap	0–25	11	15	49	36	Silty Clay Loam	4: Field drains at 1.1 m depth, 15 m spacing supplemented by sub-soiling at 0.6 m depth, 1.5 m spacing (GW)
		Bt	26–65	4.4	21	54	25	Silt Loam	
		Cr	66–110	2.3	39	40	21	Loam	
		R	111–220	–	–	–	–	–	
5	Groundwater Gley	Apg	0–26	6.3	21	45	34	Clay Loam	5: Field drains at 0.9 m depth, 15 m spacing supplemented by mole drains at 0.6 m depth, 1.4 m spacing (SH)
		Btg	27–48	2.2	13	49	38	Silty Clay Loam	
		Cg1	49–75	1	12	59	29	Silty Clay Loam	
		Cg2	76–140	0.9	23	50	27	Silt Loam	
6	Humic Surface Water Gley	Ap/O	0–40	59.6	40	26	34	Clay Loam	6: Field drains at 0.9 m depth, 20 m spacing supplemented by gravel mole drains at 0.45 m depth, 1.5 m spacing (SH)
		Btg	41–62	4.5	7	51	42	Silty Clay	
		Cg1	63–140	1.7	13	54	33	Silty Clay Loam	
		Cg2	141–170	0.9	22	55	23	Silt Loam	
7	Stagnic Luvisol	Ap	0–36	8.5	20	45	35	Silty Clay Loam	7.1: Field drains at 0.9 m depth, 20 m spacing supplemented by sub-soiling at 0.5 m depth, 0.6 m spacing (SH)
		BCtg	37–100	1.1	20	50	30	Silty Clay Loam	7.2: Field drains at 0.9 m depth, 20 m spacing supplemented by sub-soiling at 0.5 m depth, 0.6 m spacing and gravel mole drains at 0.45 m depth, 1.5 m spacing (SH)
		Cr	101–190	1.4	34	41	25	Loam	

Note: OM = organic matter; GW = Groundwater Drainage Design; SH = Shallow Drainage Design.

the hydraulic conductivity close to the surface by cracking and fissuring the soil using disruption techniques such as mole drainage (Rodgers et al., 2003), gravel mole drainage and sub-soiling at spacings of 1–2 m and being supplemented by a complimentary set of field drains at wider spacings, (Spoor, 1982; Mulqueen, 1985; Robinson et al., 1987; Tuohy et al., 2016a,b). All drainage systems were installed in the June–August period of 2013.

A detailed soil survey was undertaken to classify and characterize soil type in the drained area of each farm. Soil profile pits were delineated into horizons and described as per Simo et al. (2014). Disturbed soil samples, representative of distinct soil horizons were analyzed for organic matter content (loss on ignition method, Brookside Laboratories, Ohio, USA) and sand, silt and clay content (sieving and pipette sedimentation method, NRM Laboratories, Berkshire, UK) where appropriate samples could be collected (Table 2). Soil types at the 7 sites include gleys (surface and groundwater), luvisols and peats and all are characterized as poorly drained (B. Reidy, unpublished).

2.2. Climate change and increasing rainfall

There has been a marked increase in rainfall intensity in recent years throughout Ireland. An analysis of prevailing conditions in the south-west of the country was carried out to illustrate this phenomenon. Data from three long-term meteorological stations (Met Eireann) in the southwest, in the vicinity of study sites, were used, namely Cork Airport (CA), Shannon Airport (SA) and Valentia (VA) (Fig. 1). Annual total precipitation and its moving averages (10 year) at the three sites are shown in Fig. 2. A trend towards increasing precipitation is seen at each site in this period, in agreement with the trends observed by Kiely, 1999. A ranking of the 30 years from 1988 to 2017 in terms of total annual rain hours ($\geq$2.0 mm) and total annual rain days ($\geq$2.0 mm) is presented in Table 3. A clear trend is again evident. At each of the 3 sites, years in the decade from 2008 to 2017 are disproportionately represented in the highest ranking years for both annual rain hours and annual rain days. Taking rain day data from the 60 year period from 1958 to 2017 it is clear that this is a long term trend. The increases in rainfall seem to be particularly focused in 2 three month periods, namely June-August and October-December (Fig. 3). By subdividing the data into 20 year time blocks and focusing on the 2 periods above a trend for increasing incidents of rainfall at each site is again evident (Table 4).

2.3. Experimental measurements

2.3.1. Meteorological data

An automated weather station (Campbell Scientific Ltd., Leicestershire, UK) was installed adjacent to each drainage site. These recorded rainfall, among other parameters, at a 15 min resolution and allowed for event rainfall and 7-day and 30-antecendent rainfall to be calculated.

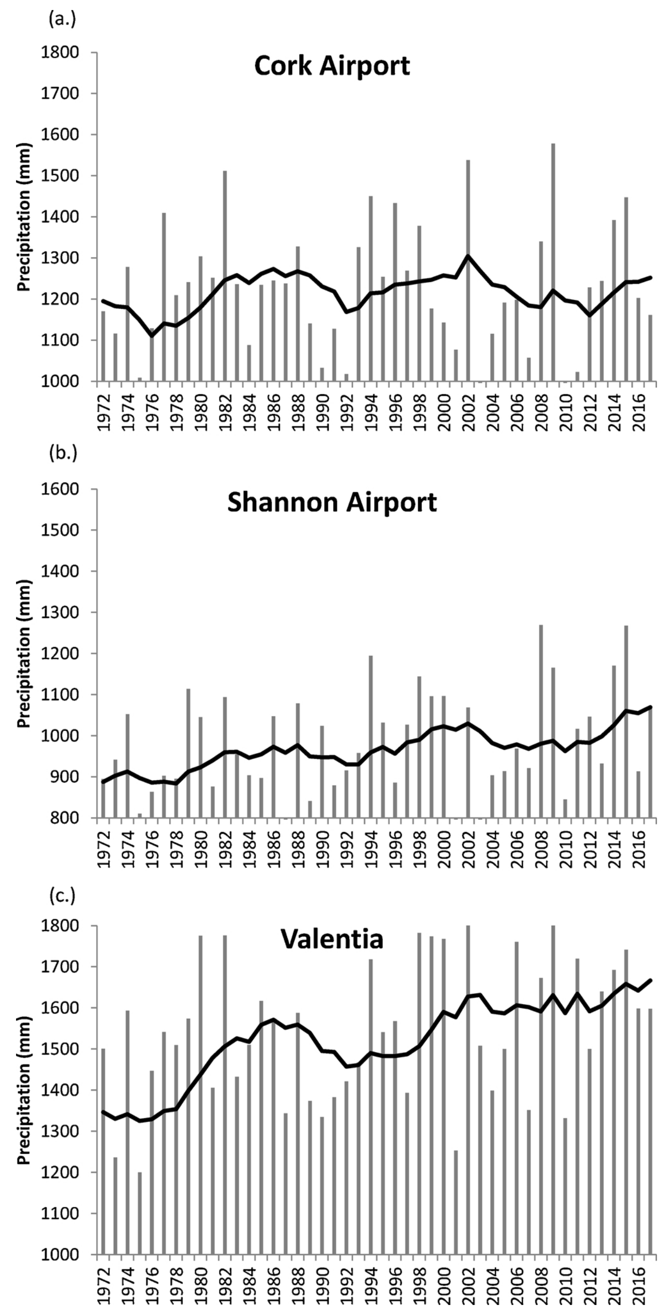

Fig. 2. Annual precipitation (1972–2017) and 10 year moving average at three sites in the southwest of Ireland, Cork Airport, Shannon Airport and Valentia.

2.3.2. Water table depth

Fully screened observation wells (Eijkelkamp, Giesbeek, The Netherlands) were installed at each site in the drained area(s) midway between adjacent drains to 2 m depth, unless impeded by stones/bedrock. A mini-diver® (Van Essen Instruments, Delft, The Netherlands) was installed in each well and, in tandem with a baro-diver® measuring barometric pressure installed on site, measured position of the water table every 15 min.

2.3.3. Subsurface drain flow

Flow discharge data was measured either by end-of-pipe flowmeters (Water Technology Limited, Cork, Ireland) or by calibrated in-stream flumes (Corbett Concrete, Tipperary, Ireland) in tandem with mini-divers® (Van Essen Instruments, Delft, The Netherlands) which monitored water-head passing through the flume, which was then converted to an open channel flow rate. The flow measuring system selected for each site was dependent on the practicalities of equipment installation particularly in relation to relative invert levels of subsurface and open drains and the geometry of the open drain. Flow rate was recorded automatically every 15 min.

2.3.4. Rainfall event delineation and event selection

At each site rainfall events, having at least 5.0 mm rainfall, occurring between 01/10/2015 and 31/05/2016 were selected for use in this study. Rainfall events were defined and separated by periods of at least 12 h without rainfall (Ibrahim et al., 2013; Tuohy et al., 2016a). Events with less than 5.0 mm total rainfall were excluded as such conditions would not consistently induce a flow response from the installed drainage systems. Rainfall events were categorized into Event types (A–D) depending on total rainfall amount (A = 5.0–9.9 mm, B = 10.0–19.9 mm, C = 20.0–39.9 mm, D = > 40.0 mm). At each site, two rainfall events from within each category were randomly selected for detailed analyses of drainage system response.

2.3.5. Flow event delineation and response parameters

The drainage system response was quantified by assessing the flow events related to the rainfall events outlined above. The start of flow events was signaled by a perceptible rise in discharge, while the end of an event was signaled by flow returning to pre-event levels (Vidon and Cuadra, 2010). Response was quantified according to a number of parameters such as start, peak and lag times, cumulative rain at start and peak times, flashiness index peak flow rate and total discharge (Tuohy et al., 2016a). Start time was defined as the time between the start of the rainfall event and the start of the related flow event. Peak time was defined as the time between the start of the rainfall event and the time of peak discharge. Lag time was defined as the time between peak rainfall and peak discharge from the drainage systems. Cumulative rain at start and peak times was calculated as the cumulative rainfall during the event at start and peak time respectively. Variations in discharge are described using a flashiness index (Eq. (1)). The flashiness index is calculated for the event as the sum of the difference between the quarter-hourly discharge values divided by the sum of the average quarter-hourly discharge, as

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

Where q_i and q_{i-1} are the average quarter-hourly discharge values at consecutive time points (Deelstra, 2015).

2.3.6. Statistical analysis

Rainfall events were analyzed by analysis of variance with site as a factor. Response parameters (start, peak and lag times, cumulative rain at start and peak times, peak flow rate, total discharge and flashiness index) were analyzed by analysis of variance with drainage system, drainage design type and rainfall Event type as factors respectively. Regression analysis was carried out to establish the principle factors affecting response times, the cumulative rainfall at response times, peak flow rate, total discharge and flashiness index. The independent variables assessed were total rainfall, 7 and 30 day antecedent precipitation, mean and maximum rainfall intensity and water table depth at the start of the rainfall event, using the PROC REG procedure in SAS version 9.1.3 (SAS Institute, 2006).

3. Results

3.1. Meteorological data and selected events

The period from 01/10/2015–31/05/2016 was characterized by relatively high rainfall levels at all sites ranging from 965.7 mm (Site 1) to 1520.8 (Site 4) (Table 5). Across the sites rainfall was on average

Table 3
Annual rain hours (≥2.0 mm) and Annual rain days (≥2.0 mm) ranked by year for the 30 year period from 1988 to 2017 at 3 meteorological stations in southwest Ireland. Years in the decade from 2008 to 2017 are in bold font.

	Annual rain hours (≥2.0 mm) ranked by year						Annual rain days (≥2.0 mm) ranked by year					
	Cork		Shannon		Valentia		Cork		Shannon		Valentia	
30 yr. average		1110		1117		1466		216		222		251
10 yr. average		1166		1194		1615		229		234		264
Rank:												
1	2002	1397	***2015***	1388	***2017***	1865	1994	246	***2017***	256	***2012***	296
2	***2009***	1353	1994	1358	***2015***	1775	***2012***	244	***2012***	247	***2017***	289
3	1994	1301	***2009***	1302	***2009***	1726	***2015***	241	***2014***	247	2000	276
4	***2015***	1299	***2008***	1295	***2014***	1708	2002	239	***2008***	242	1994	273
5	***2014***	1222	***2012***	1265	***2012***	1696	***2014***	239	1999	240	***2009***	272
6	***2008***	1216	***2014***	1250	1994	1627	***2008***	237	1998	238	1998	271
7	***2012***	1213	***2017***	1224	2000	1624	***2009***	237	***2011***	238	1999	271
8	1996	1185	1998	1222	2002	1609	***2011***	235	***2015***	238	***2011***	271
9	1988	1173	1990	1210	***2016***	1589	***2017***	226	2000	237	***2014***	266
10	***2013***	1173	1988	1207	***2013***	1575	1998	224	1994	236	***2015***	263
11	1998	1142	**2011**	1192	**2008**	1565	2000	217	**2009**	236	2002	261
12	**2016**	1138	2000	1178	1999	1526	2004	217	**2016**	231	**2008**	259
13	1993	1111	1999	1159	1998	1525	1999	215	2002	227	2004	257
14	**2017**	1103	2002	1153	**2011**	1483	**2013**	214	1988	226	1992	255
15	**2011**	1095	**2016**	1123	2006	1458	**2016**	212	1992	219	**2016**	250
16	1999	1087	1992	1093	1988	1408	1996	211	1993	219	**2013**	247
17	2005	1083	1993	1082	1990	1404	1993	210	2004	219	1993	241
18	1997	1074	2006	1061	1992	1394	1988	209	2005	219	2001	241
19	2006	1064	1995	1056	2003	1366	2005	208	1990	217	2003	241
20	2000	1063	**2013**	1047	2005	1355	1992	204	2006	211	2006	240
21	2007	1040	1996	1043	1996	1339	1995	204	1991	209	1988	238
22	1995	1037	2007	1042	1995	1334	1990	202	**2013**	209	1990	235
23	1989	1021	2005	1027	2004	1322	2006	202	2007	207	2005	235
24	2004	1017	1991	1012	1993	1296	1989	201	1989	204	2007	233
25	1990	993	2004	997	1997	1280	2003	200	1995	204	1989	231
26	1991	979	1989	994	1989	1262	2007	200	2001	204	1995	231
27	2001	969	1997	916	2007	1241	**2010**	200	**2010**	199	**2010**	230
28	2003	968	2001	889	1991	1231	2001	199	1996	193	1997	226
29	1992	930	2003	862	2001	1230	1997	196	1997	192	1991	220
30	**2010**	851	**2010**	851	**2010**	1168	1991	193	2003	187	1996	217

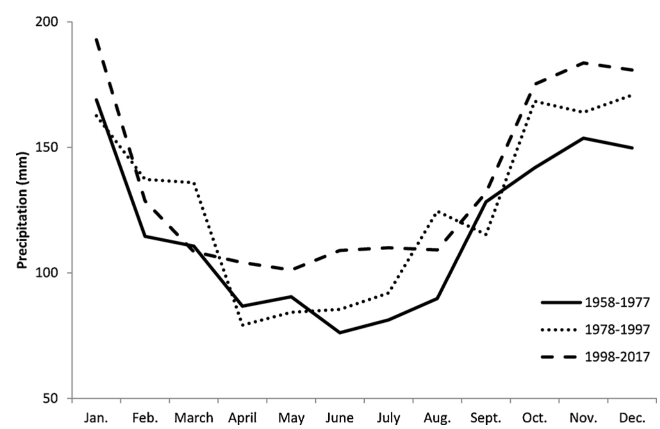

Fig. 3. Mean monthly precipitation at Valentia for three separate 20 year periods, (i) 1958–1977, (ii) 1978–1997 and (iii) 1998–2017.

27% higher than the long-term average during the same period. An average of 63.4 rainfall events (range: 52–72) of all depths > 1.0 mm, were recorded across the sites (Table 5), having an average rainfall amount of 18.6 mm (1.0–180.4 mm), duration of 41.2 h (0.50–392.00 h) and mean intensity of 0.54 mm/hr (0.05–3.10 mm/hr). The random subset of rainfall events, > 5.0 mm depth, selected for more in-depth analysis yielded a total of 56 rainfall events across the 7 farms (Table 6). These events had an average rainfall amount of 28.1 mm (6.0–93.4 mm), duration of 58.4 h (3.75–174.25 h) and mean intensity of 0.66 mm/hr (0.15–2.63 mm/hr). Mean rainfall increased with Event type magnitude (Table 7) as did mean event duration being 17.4, 35.2, 71.0 and 110.9 mm for Event types A, B, C and D

Table 4
Mean number of rain days (≥2.0 mm) for two three month periods; June–August and October–December in 20 year time blocks at 3 meteorological stations in southwest Ireland.

	June–August			October–December		
	Cork	Shannon	Valentia	Cork	Shannon	Valentia
1958–1977	42.2[a]	49.1	53.4[a]	57.4	59.8	68.6
1978–1997	44.7[ab]	50.2	55.6[ab]	59.8	59.1	68.4
1998–2017	51.0[b]	54.4	62.0[b]	62.2	63.9	71.4
S.E.M.	1.28	1.25	1.17	1.06	1.06	1.05

Means having the same superscript letter are not significantly different. Comparisons significant at the 0.05 level. S.E.M. = standard error of the mean.

respectively ($P < 0.05$, s.e. 5.51 h).

3.2. Water table depth

Average water table position midway between drains during the study period at each site ranged from 0.34 m below ground level (bgl, Site 5) to 1.37 m bgl (Site 4) with a mean of 0.69 m bgl across the 9 sites. The drainage systems were seen to control the water table below the surface during the study period (Fig. 4). The water table was controlled below 0.30 m bgl for the entire study period at sites 1.1, 2, 4 and 7.2 while at site 5, the water table was controlled below 0.30 m bgl for 36% of the study period. Groundwater drainage designs generally maintained a deeper water table (Average = 0.82 m) than shallow designs (0.53 m bgl), (Fig. 4). The average water table depth across drainage systems immediately prior to the subset of rainfall events studied was 0.52 m bgl and 0.44 m bgl immediately after these rainfall

Table 5
Details of rainfall and rainfall events (≥1.0 mm and separated by at least 12 h without rainfall) in the 01/10/2015 to 31/05/2016 period at each site.

Site	Total Rainfall (mm)	Long term average rainfall during this period (mm)	No. Events	Mean Rainfall (mm)	Mean Duration (h)	Mean Intensity (mm/h)
1	965.7	686.2	66	12.7[a]	31.8[a]	0.45
2	1041.4	780.8	67	15.4[a]	36.6[ab]	0.49
3	1503.0	1299.7	62	24.5[ab]	49.4[ab]	0.49
4	1520.8	1191.3	52	29.5[b]	59.9[b]	0.59
5	998.8	830.6	72	14.0[a]	32.7[a]	0.54
6	1182.4	933.3	64	18.4[ab]	43.3[ab]	0.53
7	1245.5	936.4	61	18.6[ab]	39.5[ab]	0.69
S.E.M.	–	–	–	1.12	2.2	0.021

Means having the same superscript letter are not significantly different. Comparisons significant at the 0.05 level. S.E.M. = standard error of the mean.

events. The largest average decrease in water table depth during events was 0.29 m (System 3) while in System 2 water table depth increased during events by 0.02 m on average. The water table rose by an average of 0.108 m during events in GW designs and 0.052 m in SH designs.

3.3. Subsurface drainage discharge and response times

Start time, peak time, lag time and cumulative rain at start time were not significantly affected by drainage system or drainage design type while cumulative rain at peak time was not affected by drainage system. Peak flow rate ranged from 5.5 (System 6) to 90.2 (System 3) m^3/ha/h and was significantly affected by drainage system and drainage design type (Table 8). The average total discharge during rainfall events was significantly higher in drainage system 2 (1666.3 m^3/ha) and 3 (1722.4 m^3/ha) than all other drainage systems with the exception of system 4 ($P < 0.05$, s.e. 114.32 m^3/ha), (Table 8). The lowest average discharge was from drainage system 6 (100.1 m^3/ha).

Groundwater drainage designs (1098.4 m^3/ha) discharged significantly more ($P < 0.05$, s.e. 114.32 m^3/ha) than shallow drainage designs (189.6 m^3/ha). Start time was affected by Event type ($P < 0.05$, s.e. 0.92 h) and ranged from 3.5 h (A Events) to 10.8 h (C Events). Peak and lag times were also affected by Event type (Table 8). Peak flow rate and total discharge were seen to increase with increasing magnitude of rainfall. D Events had significantly higher peak and total flows than all other Event types (Table 8). The principal factors affecting response times and drain discharge were shown, by regression, to be 30-day antecedent rainfall, event rainfall, and mean rainfall intensity (Table 9). Higher 30-day antecedent rainfall prior to event start resulted in shorter peak times and increased peak flow rates. Higher rainfalls lead to increased peak and lag times as well as higher peak flow rates and total discharges. Greater mean rainfall intensity resulted in shorter start and peak times and higher peak flow rates.

3.3.1. Cumulative discharge

The contrasting discharge characteristics of Groundwater and Shallow drainage designs is highlighted in Fig. 5, which presents cumulative discharge relative to rainfall from systems 1.1 (GW) and 5 (SH) during the period from 01/10/2015 to 31/05/2016. Total discharge as a proportion of total rainfall was 56.1% for system 5 and 291.5% for system 1.1.

3.3.2. Discharge hydrographs

Mean flashiness index ranged from 0.07 (System 4) to 0.23 (System 1.1) and was significantly affected by drainage system and drainage design type (Table 8). These mean values obscure the true variability observed from drainage systems during individual events where a range of responses to rainfall events was apparent. Discharge hydrographs from drainage systems 4 (GW) and 7.1 (SH) during the 8 rainfall events selected for analysis at each site are presented in Figs. 6 and 7 respectively to illustrate detailed flow responses from these systems. Contrasts between typical behavior of GW and SH designs are again clearly observed. The GW design exhibits higher average discharge rates and peak flows. Discharge from GW designs is comprised of a much higher element of base-flow than that from SH designs.

4. Discussion

Recent evidence and future predictions are indicating an increase in the frequency and intensity of rainfall (Kiely, 1999; Walsh, 2012a,b) and significant changes in seasonal rainfall patterns with a substantial increase in short term extreme rainfall events (Nolan et al., 2013; Barker et al., 2016). Increasingly volatile weather conditions, principally high rainfall during the main grazing season (March-November) is generating a greater appetite for the installation of land drainage systems on Irish grassland farms. The economic justification for such works is based on an adequate reduction in surface waterlogging and a corresponding increase in both grass production and utilization during adverse weather. Given the wide variety of land drainage problems, drainage design types and specifications installed, a review of drainage system performance across a number of contrasting sites is warranted. This will highlight the adequacy of current land drainage techniques in reducing the volatility associated with excessive rainfall. Such information is likely to have greater value in an increasingly wet climate where adaption to climate change will be fundamental to farm scale sustainability.

4.1. Water table depth

The desirable or appropriate water table depth at any time will depend on the crop grown, the period of the year in relation to crop growth stage and the method of harvesting (Williamson and Kriz, 1970; Allen et al., 1998; Kahlown et al., 2005). For poorly-drained Irish grasslands it has been shown that trafficability is compromised when water table depth is less than 0.32 m, while herbage production is restricted when water table depth is less than 0.45 m (Brereton and Hope-Cawdery, 1988). The mean water table depth over the study period across the drainage systems was 0.69 m and ranged from 0.34 m (System 5) to 1.37 m (System 4). The percentage of time each system was maintained at or above this level varied greatly resulting in some systems being hardly affected by precipitation, while others were severely affected before recovering to some extent after precipitation ceased. The water table depth was at least 0.45 m for an average of 65% of the study period across the drainage systems. For drainage systems 2, 4 and 7.2 this criteria was achieved for the entire study period while drainage systems 5, 6 and 7.1 showed the poorest performance in this regard with values of 30%, 23% and 39%, respectively.

Overall farms with GW designs maintained water table at a suitable depth more consistently, while SH designs struggled at some times to drain both infiltrating water and perched groundwater. The deeper average depth of the GW drainage systems (1.54 m) versus the SH drainage systems (0.90 m) in the study resulted in differing capacities for water table control. Furthermore shallow designs are installed in finer soil textures and as such the response of the water table to rainfall events is more subtle than those soils having higher infiltration rates. It is likely that in some cases the response of the water table to a particular rainfall event in SH drainage systems would not be fully apparent immediately as it would take time for equilibrium to be reached.

4.2. Subsurface drainage discharge and response times

All drainage systems were responsive to rainfall events with a mean (s.d.) start time of 6.1 (7.8) h and a mean (s.d.) lag time of 10.4 (18.0) h

Table 6
Pre-event and event characteristics of the 8 selected rainfall events at each site.

Site	Event type	Event	Event Duration (h)	7-days antecedent precipitation (mm)	30-days antecedent precipitation (mm)	Rainfall (mm)	Maximum Intensity (mm/h)	Mean Intensity (mm/h)
1	A	1A1	6.50	26.8	170.8	6.2	2.4	1.0
		1A2	19.75	25.8	213.8	7.4	4.0	0.4
	B	1B1	24.50	32.2	214.4	11.0	3.2	0.4
		1B2	25.50	21.6	156.0	16.2	1.6	0.6
	C	1C1	86.75	12.0	135.6	22.6	8.0	0.3
		1C2	92.25	43.6	82.6	31.6	8.0	0.3
	D	1D1	59.00	16.2	158.2	44.6	5.6	0.8
		1D2	152.25	28.8	100.0	56.6	5.6	0.4
2	A	2A1	41.00	32.4	229.0	6.2	4.0	0.2
		2A2	26.50	50.0	235.2	6.6	6.4	0.2
	B	2B1	47.50	51.8	156.4	11.8	3.2	0.2
		2B2	21.25	60.4	247.4	14.8	3.2	0.7
	C	2C1	133.50	40.0	236.4	31.0	4.8	0.2
		2C2	99.50	16.6	183.6	38.4	12.0	0.4
	D	2D1	83.25	62.8	235.8	49.8	12.0	0.6
		2D2	125.75	17.2	135.8	62.0	8.8	0.5
3	A	3A1	5.50	47.8	193.4	9.2	4.8	1.7
		3A2	31.50	45.4	387.4	9.4	4.8	0.3
	B	3B1	27.25	69.8	264.4	12.2	4.0	0.4
		3B2	44.00	39.8	353.6	13.4	5.6	0.3
	C	3C1	68.25	31.8	92.2	25.2	7.2	0.4
		3C2	23.00	27.2	330.6	30.8	7.2	1.3
	D	3D1	134.75	20.6	184.8	46.0	8.0	0.3
		3D2	27.00	113.2	402.4	46.4	7.2	1.7
4	A	4A1	30.25	44.0	353.0	7.6	2.4	0.3
		4A2	28.75	88.6	265.8	9.4	4.8	0.3
	B	4B1	34.50	39.2	52.8	11.0	3.2	0.3
		4B2	27.25	63.6	392.8	18.6	11.2	0.7
	C	4C1	40.50	90.6	255.2	24.8	4.0	0.6
		4C2	26.50	37.0	257.2	30.0	7.2	1.1
	D	4D1	174.25	92.6	383.2	60.8	8.8	0.3
		4D2	135.00	28.0	190.6	92.6	10.4	0.7
5	A	5A1	14.50	46.4	217.4	6.4	3.2	0.4
		5A2	5.50	40.4	163.6	8.6	4.8	1.6
	B	5B1	13.25	10.6	51.6	13.4	6.4	1.0
		5B2	48.00	22.2	228.8	19.6	2.4	0.4
	C	5C1	75.00	47.2	212.6	25.8	6.4	0.3
		5C2	12.25	71.6	216.2	32.2	9.6	2.6
	D	5D1	121.25	37.2	98.4	46.6	16.8	0.4
		5D2	35.25	50.0	182.4	59.4	4.8	1.7
6	A	6A1	21.50	36.6	65.0	6.0	3.2	0.3
		6A2	30.75	42.2	257.2	8.8	4.0	0.3
	B	6B1	30.25	13.6	79.2	14.4	7.2	0.5
		6B2	55.50	29.2	248.8	17.8	4.0	0.3
	C	6C1	131.25	39.8	261.0	29.2	6.4	0.2
		6C2	83.25	24.6	77.0	35.0	8.8	0.4
	D	6D1	71.50	74.0	228.4	65.0	4.8	0.9
		6D2	132.75	29.0	163.4	69.2	8.0	0.5
7	A	7A1	3.75	76.8	227.0	8.0	4.0	2.1
		7A2	8.25	69.4	202.0	8.4	6.4	1.0
	B	7B1	12.50	54.0	152.2	16.6	14.4	1.3
		7B2	80.00	64.8	303.4	18.2	6.4	0.2
	C	7C1	77.50	53.0	285.2	23.4	4.8	0.3
		7C2	36.25	78.8	281.6	34.4	6.4	0.9
	D	7D1	122.25	46.2	103.4	48.8	8.0	0.4
		7D2	143.75	23.4	164.3	93.4	9.4	0.6

with no significant effect of drainage system or drainage design type on these parameters, showing similar responses despite variation in soil types where appropriate drainage systems are installed. While no significant difference in rainfall or peak time is evident between drainage design types, a higher cumulative rain at peak time ($P < 0.05$, S.E.M = 1.64 mm) was recorded for shallow drainage designs (19.6 mm) versus groundwater drainage designs (15.2 mm). This indicates more rainfall is required to produce peak flow rates in SH designs. The intensity of discharge was greater in GW designs as evidenced by higher peak flow rates and total discharge relative to SH designs. This is largely due to the contribution of groundwater which combines with infiltrating water to increase discharge levels. The location of GW designs in a permeable horizon (Mulqueen and Hendriks, 1986; Tuohy et al., 2016b), relatively deep in the profile allows for direct interaction with groundwater and a larger zone of influence, therefore base-flow is a major component of flow due to the nature of these designs, while for SH designs flow events are almost entirely derived from the influx of surface water such that base-flow is non-existent (Mulqueen, 1998). This is evidenced in the cumulative discharges from contrasting drainage design types, presented in Fig. 5 where the GW design yields much higher discharges than the SH design and indeed total discharges amount to multiples of what is contributed

Table 7
Mean responses parameters of event types.

Rainfall event type	A	B	C	D	S.E.M.
Rainfall (mm)	7.8[a]	15.5[a]	29.2[b]	60.3[c]	2.60
Start time (h)	3.5[a]	4.3[ab]	10.8[b]	5.7[ab]	0.92
Peak time (h)	8.5[a]	20.4[ab]	36.4[bc]	54.5[c]	3.62
Lag time (h)	2.6[a]	8.9[a]	5.9[a]	28.3[b]	2.33
Cumulative rain at start time (mm)	1.6	2.6	3.2	2.5	0.23
Cumulative rain at peak time (mm)	6.0[a]	11.0[ab]	18.2[b]	33.4[c]	1.64
Peak flow rate (m^3/ha/h)	23.0[a]	22.1[a]	35.6[a]	62.5[b]	4.44
Flashiness index	0.13	0.14	0.14	0.13	0.008
Total discharge (m^3/ha)	270.5[a]	299.8[a]	630.0[a]	1577.6[b]	114.32

Means having the same superscript letter are not significantly different. Comparisons significant at the 0.05 level. S.E.M. = standard error of the mean.

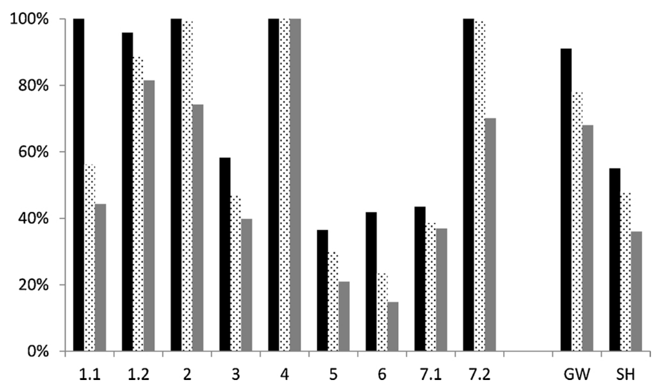

Fig. 4. Number of days, as a percentage of total days during the study period, at which water table was below 0.30 m (solid black), 0.45 m (dotted) and 0.60 m (solid grey) depth for drainage systems 1.1–7.2 and mean values for groundwater drainage designs (GW; 1.1–4) and shallow drainage designs (SH; 5–7.2).

directly to a given site in terms of rainfall.

Discharges from SH designs may also have been compromised in this period due to a reduction in the level of structural fissures and macropores established during installation, particularly for those systems reliant on mole drainage or sub-soiling. The high relative levels of rainfall during the study period would have resulted in persistently wet conditions which would have inhibited the effectiveness of shallow drainage techniques (Jarvis and Leeds-Harrison, 1987; Tuohy et al., 2016a). The integrity of cracks and fissures created when these system are installed is known to reduce in time and vary with the natural wetting/drying cycles of the soil (Jarvis and Leeds-Harrison, 1987; Hallard and Armstrong, 1992; Tuohy et al., 2016a). Such systems are at their most effective when the soil is at its driest; with a reduction in effectiveness in persistently wet conditions when connectivity between the soil surface and drainage channels becomes reduced (Youngs, 1985; Robinson et al., 1987; Tuohy et al., 2015, 2017). An increase in the efficiency of these techniques is required to maximize their performance and lifespan, and improve their potential usefulness in a more intense rainfall regime. The design of the implements used should be assessed to investigate whether adjustments to geometry or adaptability would allow for greater intensity of soil disturbance and system performance. Mean flashiness index was also greater for GW designs relative to SH designs, however a consistent trend is not apparent when mean values for individual systems are considered.

The effect of Event type on start times did not follow a specific trend. For peak and lag times the trend was for increasing response times with increasing event magnitude. Start time was longest for C Events while peak and lag times were longest for D events. Mean event duration was greater for higher magnitude Event types as higher magnitude events tended to be the amalgamation of a series of events with short (< 12 h) intervals rather than a single standalone episode. Therefore, increasing peak time is related to greater accumulations of rainfall developing latterly in a longer duration event. Drain discharge response times and rates were shown to be dictated largely by antecedent rainfall and event rainfall magnitude and conditions. These parameters impact directly on the soil moisture regime before and during the event and its capacity to store or discharge water (Deasy et al., 2014; Tuohy et al., 2016a). As water storage is increased, the level of saturation in the vadose zone is also increased which induces more rapid movement of water to the drainage systems. This is manifested in shorter response times and greater discharges where pre-event and/or event rainfall is of greater magnitude and intensity.

4.3. Discharge hydrographs

The form of discharge hydrographs is dictated largely by rainfall distribution during the particular event. Event types are notable by differences in rainfall magnitude and intensity of discharge response. A Events are generally comprised of single rainfall episodes and muted discharge responses while D Events are characterized by higher intensity of rainfall with a series of individual rainfall peaks being grouped together by virtue of the short interludes between them. This in-turn produces a series of discharge hydrographs with each receding limb being superseded by the rising limb of a subsequent flow surge. Contrasts in behavior of drainage design types are also evident in terms of the much greater base-flow contribution in a typical GW designs (Fig. 6) relative to a typical SH designs (Fig. 7) and the higher peaks and greater volumes discharged by GW designs. Discharge from groundwater designs was consistently of much greater magnitude than that from shallow drainage designs.

5. Conclusions

- All systems were capable of discharging excess water and controlling the water table to a certain extent but effectiveness was seen to vary. Response times were not affected by drainage system or

Table 8
Mean response parameters of drainage systems and drainage design types during the events analyzed.

	Groundwater Drainage Designs (GW)					Shallow Drainage Designs (SH)					System Type		
Drainage system	1.1	1.2	2	3	4	5	6	7.1	7.2	S.E.M.	GW	SH	S.E.M.
Rainfall (mm)	24.5	24.5	27.6	24.1	31.9	26.5	30.7	31.4	31.4	2.60	26.6	30.0	2.60
Start time (h)	5.8	6.9	5.8	8.3	9.5	3.0	7.9	2.5	5.2	0.92	7.3	4.6	0.92
Peak time (h)	36.7	34.3	29.8	25.3	19.6	16.6	36.0	31.6	39.8	3.62	29.1	31.0	3.62
Lag time (h)	12.4	14.4	6.5	2.5	4.5	10.3	8.3	11.6	21.0	2.33	8.1	12.8	2.33
Cumulative rain at start time (mm)	3.1	2.6	1.4	3.5	2.7	1.5	2.1	1.8	3.7	0.23	2.7	2.3	0.23
Cumulative rain at peak time (mm)	18.1	17.6	13.8	14.3	12.1	15.7	18.2	19.9	24.7	1.64	15.2[a]	19.6[b]	1.64
Peak flow rate (m^3/ha/h)	30.2[ab]	40.3[ab]	55.7[bc]	90.2[c]	38.8[ab]	25.2[ab]	5.5[a]	13.6[ab]	22.9[ab]	4.44	51.0[a]	16.8[b]	4.44
Flashiness index	0.23[a]	0.21[ab]	0.09[de]	0.15[bcd]	0.07[e]	0.17[bc]	0.08[e]	0.10[cde]	0.13[cde]	0.008	0.15[a]	0.12[b]	0.008
Total discharge (m^3/ha)	513.6[a]	649.5[a]	1666.3[b]	1722.4[b]	940.1[ab]	172.7[a]	100.1[a]	186.7[a]	299.1[a]	114.32	1098.4[a]	189.6[b]	114.32

Means having the same superscript letter are not significantly different. Comparisons significant at the 0.05 level. S.E.M. = standard error of the mean.

Table 9
Multivariate regression coefficients for flow response times, cumulative rain at response times, peak flow rate, total discharge and flashiness index.

Independent variables	Dependent variables							
	Start Time	Peak Time	Lag Time	Cumulative rain at start time	Cumulative rain at peak time	Peak flow rate	Total drained	Flashiness Index
Intercept	6.31 (3.532)	43.97*** (10.512)	12.45 (7.370)	2.22* (0.917)	10.58** (3.646)	−28.48 (15.583)	−764.04 (400.494)	0.21*** (0.029)
7-day antecedent precipitation (mm)	−0.03 (0.051)	0.17 (0.153)	0.03 (0.106)	0.00 (0.013)	0.00 (0.053)	−0.41 (0.227)	−0.44 (5.829)	−0.00** (0.000)
30-day antecedent precipitation (mm)	0.00 (0.013)	−0.10** (0.039)	−0.03 (0.027)	0.00 (0.003)	−0.03* (0.013)	0.15** (0.057)	2.61 (1.471)	−0.00 (0.000)
Rainfall (mm)	0.04 (0.046)	0.81*** (0.138)	0.63*** (0.100)	0.01 (0.012)	0.51*** (0.048)	0.45* (0.204)	19.00** (5.247)	−0.00 (0.000)
Maximum intensity (mm/h)	0.09 (0.336)	−0.96 (1.001)	−1.79** (0.639)	0.00 (0.087)	−0.13 (0.347)	2.04 (1.483)	32.23 (38.129)	−0.00 (0.003)
Mean intensity (mm/h)	−3.70* (1.876)	−23.58*** (5.583)	−4.63 (3.609)	0.31 (0.487)	0.96 (1.936)	23.72** (8.276)	−29.46 (212.702)	0.01 (0.015)
Water table depth at rainfall event start (m)	0.04 (0.023)	−0.04 (0.070)	0.00 (0.050)	0.01 (0.006)	−0.01 (0.024)	0.20* (0.102)	4.37 (2.631)	−0.00 (0.000)
R-squared	0.15	0.52	0.49	0.06	0.72	0.29	0.30	0.20
No. Observations	72	72	60	72	72	72	72	72

Standard errors are reported in parentheses, *, **, *** indicate *P* values below 0.05, 0.01 and 0.001, respectively.

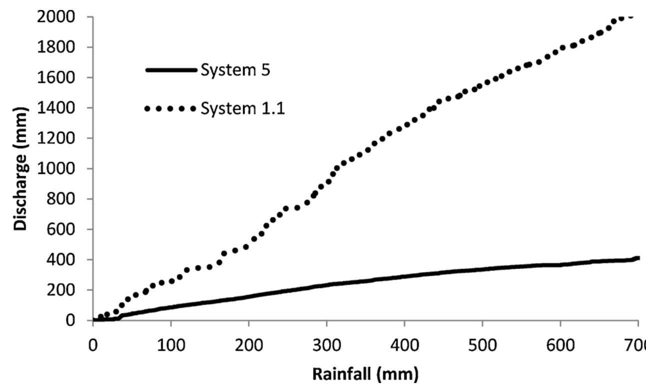

Fig. 5. Cumulative drain discharge relative to cumulative rainfall in the period from 01/10/2015 to 31/05/2016 for a groundwater drainage system (1.1) and a shallow drainage system (5).

drainage design type, showing similar responses despite variation in soil types where appropriate drainage systems are installed. Groundwater drainage designs were seen to discharge greater volumes of water and maintain a deeper water table relative to shallow drainage designs. The direct interaction of GW designs with the groundwater table was noted both in the level of base-flow apparent during flow events and the reactivity of the water table position to rain events.

- Overall GW designs performed better when compared against SH designs across the same time period. Future work would need to consider how agronomic performance, grass yield and trafficability are affected by the imposed drainage design as direct comparison is difficult based merely on volumes of water discharged.
- The comparison of such systems highlights the contrasting behaviors of individual drainage systems and drainage design types, which is dictated largely by the hydraulic capacity of the soil within their catchment and their connectivity to different water bodies (groundwater versus perched water). Classification of the performance of drainage systems must take account of their inherent differences. Performance metrics will need to allow for the contrasting responses of different drainage design types.
- The functional capacity of each specific land drainage system was inherently different. Groundwater drainage designs exploit natural conditions to discharge large volumes of water and can control water table directly by means of their interaction with layers and zones of high permeability. Shallow drainage designs are combatting the natural state of their host soils by relying on shallow disruption techniques which are ultimately destined to revert to their original state, particularly in the case of mole drainage and subsoiling techniques. They have a smaller zone of influence, no direct connectivity to the water table and displace lower volumes of water which is collected directly from the surface.
- Drain discharge response times and rates were shown to be dictated largely by antecedent rainfall and event rainfall magnitude and conditions. As water storage is increased, the level of saturation in the vadose zone is also increased which induces more rapid movement of water to the drainage systems. This is manifested in shorter response times and greater discharges where pre-event and/or event rainfall is of greater magnitude and intensity.
- As the study was carried out during the winter period of 2015 and early spring of 2016, when rainfall levels were well above normal, performance of the SH designs may have been and inhibited due to the natural shrink/swell properties of the high clay content soil in persistent wet conditions which has been shown elsewhere to drastically reduce the efficiency of such systems. These systems would likely perform better during lower intensity rainfall. Given the extreme levels of rainfall recorded during the study period on all sites, the study presents a view of these systems under exceptional

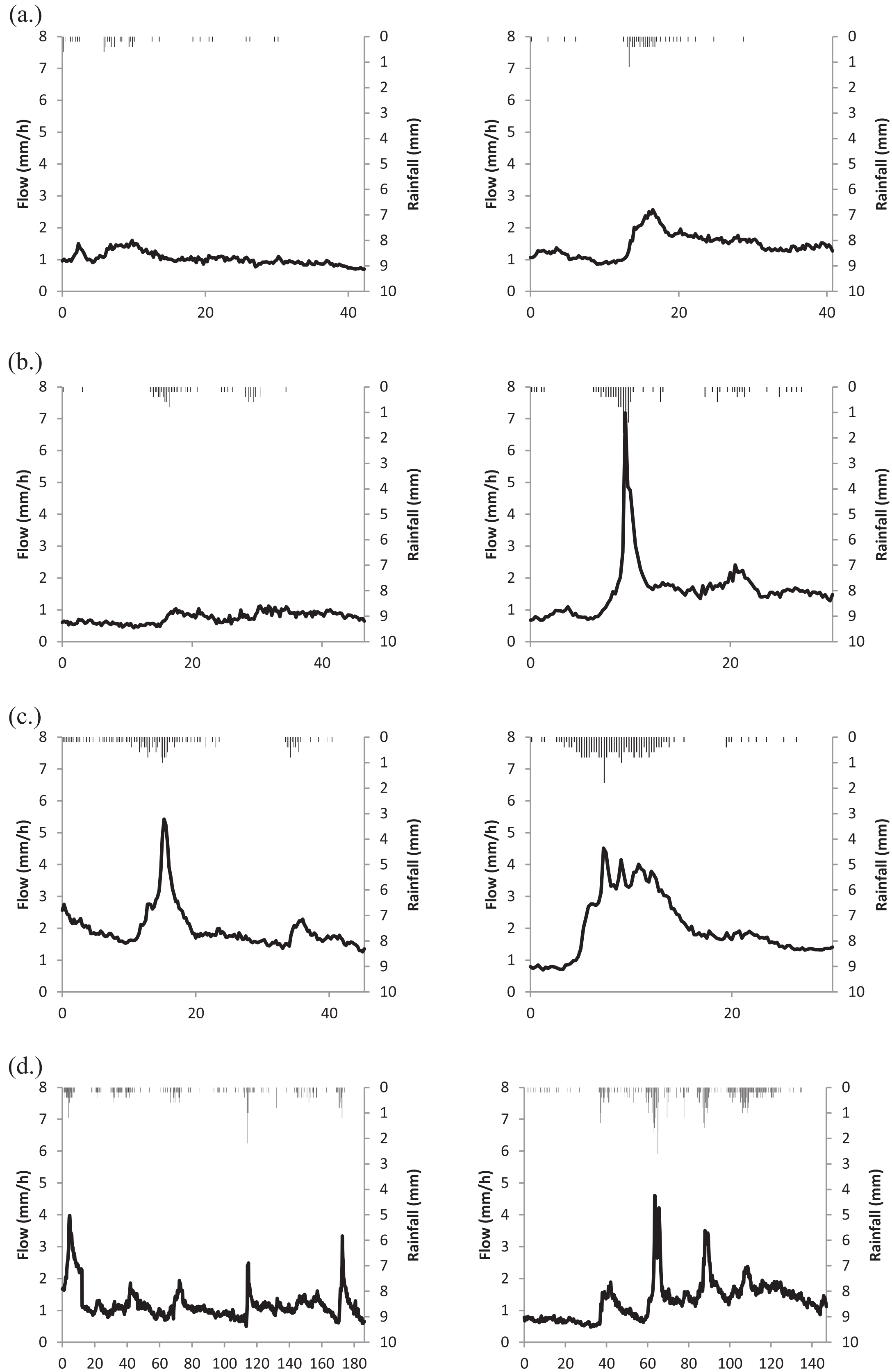

Fig. 6. Drain discharge response to rainfall versus time in hours from a groundwater drainage system (System 4) during 2 (a) A Events (5.0–9.9 mm), (b) B Events (10.0–19.9 mm), (c) C Events (20.0–39.9 mm) and (d) D Events (40.0 mm).

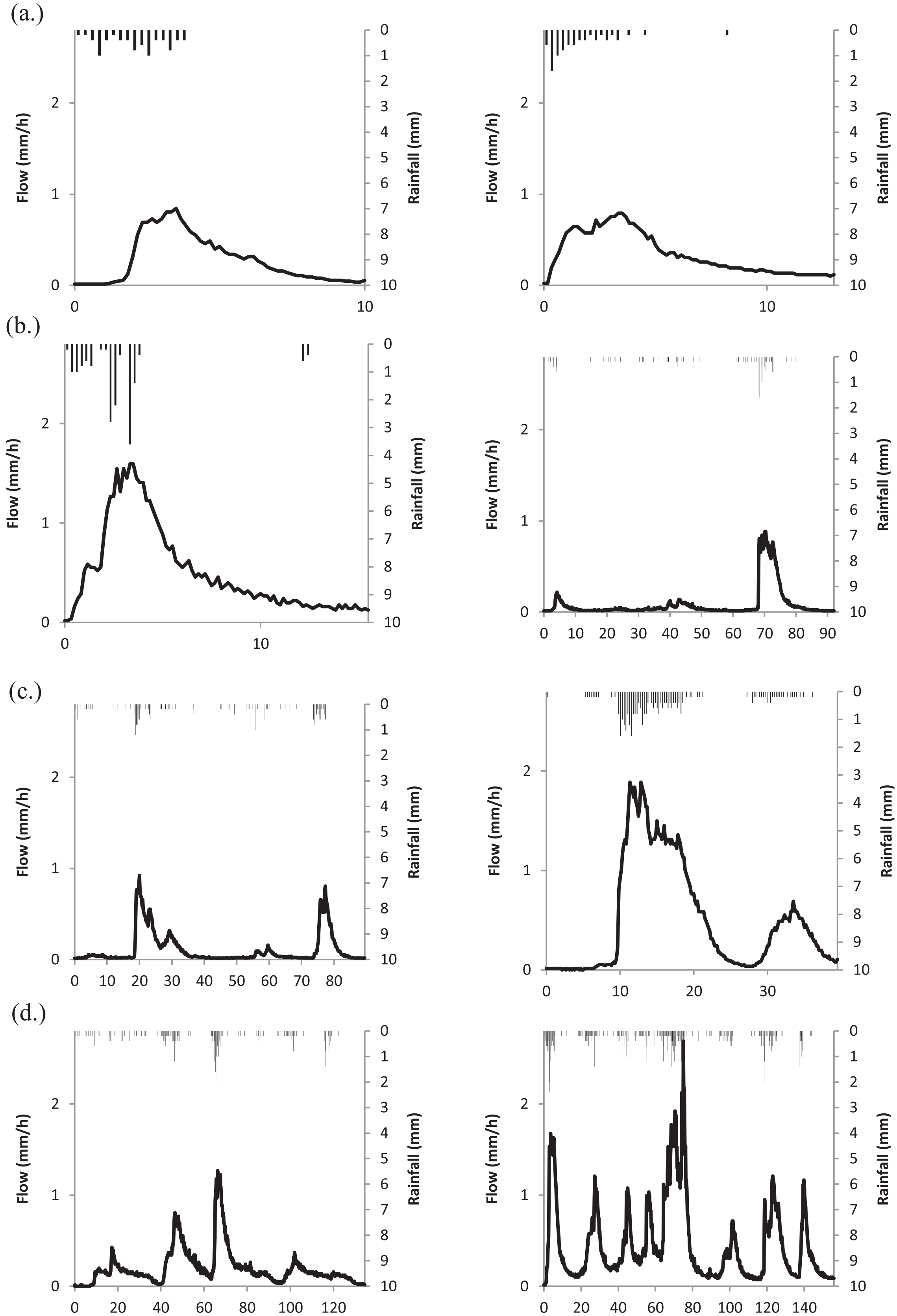

Fig. 7. Drain discharge response to rainfall versus time in hours from a shallow drainage system (System 7.1) during 2 (a) A Events (5.0–9.9 mm), (b) B Events (10.0–19.9 mm), (c) C Events (20.0–39.9 mm) and (d) D Events (40.0 mm)).

conditions. However, given climate trends and predictions, land drainage systems are increasingly likely to be subject to such extremes. New technologies and strategies to increase efficiency of such systems are warranted. These will be required to overcome the limitations of shallow drainage designs under current and potential future conditions.

- All systems were shown to reduce the overall period of waterlogging and thereby improve the conditions for both the production and utilization of the grasslands they drain. Further work is required to quantify system integrity and performance over extended timescales and a full range of rainfall intensities.

Acknowledgement

We would like to acknowledge the farmers of the Teagasc Heavy Soils Program who have contributed time and resources to the study.

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration: Guidelines for Computing Crop Requirements. Irrigation and Drainage Paper No. 56. FAO, Rome.
Armstrong, A.C., 1985. Drainage of clay lands for grassland production: problems, effects, benefits. Proceedings of C.E.C Symposium: Agricultural Water Management.
Barker, L., Hannaford, J., Muchan, K., Turner, S., Parry, S., 2016. The winter 2015/2016 floods in the UK: a hydrological appraisal. Weather 71, 324–333.
Bell, L.W., Kirkegaard, J.A., Swan, A., Hunt, J.R., Huth, N.I., Fettell, N.A., 2011. Impacts of soil damage by grazing livestock on crop productivity. Soil Till. Res. 113, 19–29.
Brereton, A.J., Hope-Cawdery, M., 1988. Drumlin soils: the depression of herbage yield by shallow water table depth. Irish J. Agric. Res. 27, 167–178.
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. Environ. Manage. 132, 304–312.
Deelstra, J., 2015. Subsurface drainage runoff behavior in Norway. Zeverte-Rivza, S. (Ed.), Proceedings of the 25th NJF Congress: Nordic View to Sustainable Rural Development 186–191.
Fitzgerald, J.B., Brereton, A.J., Holden, N.M., 2008. Simulation of the influence of poor soil drainage on grass-based dairy production systems in Ireland. Grass Forage Sci. 63, 380–389.
Galvin, L.F., 1986. Aspects of land drainage development in Ireland in the last twenty-five years. Vos, J. (Ed.), Symposium 25th International Course on Land Drainage, Twenty-Five Years of Drainage Experience 131–140.
Hallard, M., Armstrong, A.C., 1992. Observations of water movement to and within mole drainage channels. J. Agric. 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.
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.
Kahlown, M.A., Ashraf, M., Zia ul, H., 2005. Effect of shallow groundwater table on crop water requirements and crop yields. Agric. Water Manage 76, 24–35.
Kandel, H.J., Brodshaug, J.A., Steele, D.D., Ransom, J.K., DeSutter, T.M., Sands, G.R., 2013. Subsurface drainage effects on soil penetration resistance and water table depth on a clay soil in the Red River of the North Valley, USA. Agric. Eng. 15, 1–10.
Keane, T., 1992. Impact of weather on grassland farming. In: Keane, T. (Ed.), Irish Farming, Weather and Environment. AGMET, Dublin, pp. 125–135.
Kiely, G., 1999. Climate change in Ireland from precipitation and streamflow observations. Adv. Water Resour. 23, 141–151.
Mulqueen, J., 1985. The development of gravel mole drainage. J. Agric. Eng. Res. 32, 143–151.
Mulqueen, J., 1998. Depth, spacing and length of mole drains with applications to afforestation. Irish J. Agric. Food Res. 37, 39–49.
Mulqueen, J., Hendriks, R., 1986. The use of groundwater surveys in the diagnosis and solution of a drainage problem. Irish J. Agric. Res. 25, 285–298.
Nijland, H.J., Croon, F.W., Ritzema, H.P., 2005. Subsurface Drainage Practices: Guidelines for the Implementation, Operation and Maintenance of Subsurface Pipe Drainage Systems. International Institute for Land Reclamation & Improvement, Wageningen, Netherlands.
Nolan, P., McGrath, R., Gleeson, E., Sweeney, C., 2013. Impacts of climate change on Irish precipitation. In: Gleeson, E., Mcgrath, R., Treanor, M. (Eds.), IrEland'S Climate: the Road Ahead. Met Eireann, Dublin, pp. 57–61.
Patton, D., Shalloo, L., Pierce, K.M., Horan, B., 2012. A biological and economic comparison of 2 pasture-based production systems on a wetland drumlin soil in the northern region of Ireland. J. Dairy Sci. 95, 484–495.
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. Agric. Water Manage. 60, 33–42.
SAS Institute, 2006. SAS User Guide. Version 9.1. SAS Institute Inc., Cary, NC, USA.
Schultz, B., Zimmer, D., Vlotman, W.F., 2007. Drainage under increasing and changing requirements. Irrig. Drain. 56, S3–S22.
Shalloo, L., Dillon, P., O'Loughlin, J., Rath, M., Wallace, M., 2004. Comparison of a pasture-based system of milk production on a high rainfall, heavy-clay soil with that on a lower rainfall, free-draining soil. Grass Forage Sci. 59, 157–168.
Simo, I., Creamer, R.E., Reidy, B., Hannam, J.A., Fealy, R., Hamilton, B., Jahns, G., Massey, P., McDonald, E., Schulte, R.P.O., Sills, P., Spaargaren, O., 2014. Irish SIS final technical report 10: soil profile handbook. Associated Datasets and Digital Information Objects Connected to This Resource Are Available at: Secure Archive for Environmental Research Data (SAFER) Managed by Environmental Protection Agency Ireland. . http://erc.epa.ie/safer/resource?id=a1b872a2-3b8c-11e4-b233-005056ae0019.
Skaggs, R.W., Youssef, M.A., Chescheir, G.M., 2012. DRAINMOD: model use, calibration, and validation. Trans. ASABE 55, 1509–1522.
Sloan, B.P., Basu, N.B., Mantilla, R., 2016. Hydrologic impacts of subsurface drainage at the field scale: climate, landscape and anthropogenic controls. Agric. Water Manage. 165 (Supplement C), 1–10.
Smedema, L.K., Rycroft, D.W., 1983. Land Drainage: Planning and Design of Agricultural Drainage Systems. Cornell University Press, Ithaca, New York.
Smedema, L.K., Vlotman, W.F., Rycroft, D.W., 2004. Modern Land Drainage: Planning, Design and Management of Agricultural Drainage Systems. A.A. Balkema, Rotterdam.
Smit, H.J., Metzger, M.J., Ewert, F., 2008. Spatial distribution of grassland productivity and land use in Europe. Agric. Syst. 98, 208–219.
Spoor, G., 1982. Potential for mole drainage as drainage technique on heavy soils. In: Gardiner, M.J. (Ed.), Proceedings of C.E.C Seminar: Land Drainage. A.A. Balkema, Rotterdam, The Netherlands, pp. 249–251.
Teagasc, 2013. In: Moore, M., Fenton, O., Tuohy, P., Ibrahim, T. (Eds.), Teagasc Manual on Drainage – and Soil Management: A Best Practice Manual for Ireland'S Farmers. Teagasc, Carlow.
Tuohy, P., Humphreys, J., Holden, N.M., Fenton, O., 2015. Mole drain performance in a clay loam soil in Ireland. Acta Agric. Scand. B-S. P. 65 (sup1), 2–13.
Tuohy, P., Humphreys, J., Holden, N.M., Fenton, O., 2016a. Runoff and subsurface drain response from mole and gravel mole drainage across episodic rainfall events. Agric. Water Manage. 169, 129–139.
Tuohy, P., Humphreys, J., Holden, N.M., O' Loughlin, J., Reidy, B., Fenton, O., 2016b. Visual drainage assessment: a standardised visual soil assessment method for use in land drainage design in Ireland. Irish J. Agric. Food Res. 55, 24–35.
Tuohy, P., O' Loughlin, J., Fenton, O., 2017. Modelling performance of a tile drainage system incorporating mole drainage. Trans. ASABE In Press.
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. Proceedings of the National Hydrology Conference. pp. 3–12.
Williamson, R.E., Kriz, G.J., 1970. Response of agricultural crops to flooding depth of water table and soil gaseous composition. Trans. ASAE 13, 216–220.
Youngs, E.G., 1985. An analysis of the effect of the vertical fissuring in mole-drained soils on drain performances. Agric. Water Manage. 9, 301–311.