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How does drainage alter the hydrology of shallow degraded peatlands across multiple spatial scales?

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ABSTRACT

Shallow, degraded peatlands differ in both their structure and function from deeper, peatland ecosystems. Previous work has shown that shallow, drained peatlands demonstrate rapid storm runoff that is only minimally controlled by antecedent hydrological conditions. However, such peatlands are also known to exhibit significant variation in ecohydrological organisation and structure across different spatial scales. In addition, predictions of hydrological response using spatially distributed numerical models of rainfall-runoff may be flawed unless they are evaluated with datasets describing the spatial variability of hydrological responses. This paper evaluates to what extent, flow generation and water storage within shallow, degraded peatland catchments may be controlled by the spatial attributes of the contributing area of the peatland, the drainage ditch size, morphology and geometry.

Results from an experiment conducted over multiple spatial scales and multi-annual timescales highlights that subtle variations in the local slope and topography account for the long-term spatial patterns of water table depth. Neither the local scale of the drainage feature or the topographic contributing area is shown to be a definitive predictor of runoff in the studied catchments. Results also highlight the importance of using spatially distributed observations to ensure that estimates of water storage and runoff are representative of the fine scale spatial variability that occurs in such damaged and shallow peatlands.

1. Introduction

Shallow upland peatlands, containing soils between 0.1 and 1 m depth (Grand-Clement et al., 2015; JNCC, 2011) differ in both their structure and function from deeper peatland ecosystems (Grand-Clement et al., 2013; Dixon et al., 2013). In north-west Europe these shallower peatlands are also often influenced by maritime climates (in South West Ireland, West Wales, South West England) and are therefore more sensitive to climate change than their more northerly counterparts (Gallego-Sala et al., 2010; Clark et al., 2010). Indeed, it could be argued that such peatlands, located in climatically marginal positions, may be useful analogues for the effects of climate change on colder, wetter peatlands in the future. Previous work (Luscombe, 2014) has established that these ecosystems demonstrate rapid storm runoff that is primarily controlled by the total rainfall amount and is not significantly linked to the rainfall intensity or any antecedent hydrological conditions, which demonstrate minimal, secondary controls on runoff responses. Consequently, unlike deeper peatlands, where the longer term antecedent conditions have a greater potential to affect water tables and storm flow generation (Daniels et al., 2008; Holden, 2005), in these shallow peatlands, flow is generated quickly following rapid and short-lived, wet-up of the thinner, heavily drained peat soils (Bowes, 2006; Luscombe, 2014).

Understanding the temporal dynamics which govern hydrological processes in shallow, marginal and damaged peatlands is important as a baseline from which restoration interventions may be evaluated (Schumann and Joosten, 2008; Luscombe, 2014). However, these peatlands are also known to exhibit significant variability in ecohydrological organisation and structure across multiple scales (Luscombe et al., 2015b, 2015a). Given the uncertainty in the spatial understanding of peatlands more widely (Morris et al., 2011; Lindsay, 2010, 1995; Holden, 2005), it is suggested that fully spatially integrated monitoring of hydrological processes can improve understanding of these complex landscapes (Bragg and Tallis, 2001). A lack of monitoring programs able to capture the full spatial heterogeneity of hydrological behaviour in

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peatlands, is acknowledged by several authors (Holden et al., 2011, 2004; Parry et al., 2014; Harris and Bryant, 2009). This deficiency greatly limits the potential for extrapolation of processed-based understanding of rainfall and runoff response over larger landscape extents (Ballard et al., 2011). Thus, it is proposed that a detailed, spatially explicit and fine spatial resolution monitoring program may overcome these problems.

Predictions of hydrological response using spatially distributed, numerical models of rainfall-runoff will be flawed unless they are evaluated with datasets describing the spatial variability of hydrological response (Lamb et al., 1998; Beven, 2012). Indeed, the problem of spatial equifinality, where multiple expressions of a catchment response to rainfall might result in the same catchment outlet hydrograph, is a problem that is widespread throughout the hydro-geomorphological literature (Lamb, 1996; Beven and Brazier, 2011; Beven, 2006). Thus, spatially explicit datasets that may help to constrain model predictive uncertainty, by eliminating inappropriate representations of contributing source areas or ground water storage, are needed (Blöschl and Sivapalan, 1995).

This paper argues that the number, spatial distribution and range of drainage scales monitored is critical to build a dataset appropriately representative of the wider landscape extent and its intrinsic variability (Luscombe, 2014). In addition, the duration of monitoring, ideally over multiple years, may improve the likelihood that temporal variability of hydrological processes is sufficiently represented throughout all monitoring locations. In this paper the dataset reported by Luscombe (2014) is spatially interrogated to derive metrics describing the spatial distribution and variability of processes governing flow generation and water storage in a shallow, bioclimatically marginal peatland that has been extensively modified by anthropogenic drainage.

Specifically, this paper analyses multiple water table and discharge time series collected from eight scales subject to different anthropogenic drainage in terms of drainage depths, widths, densities and contributing areas (Luscombe, 2014). The data are used in combination with rainfall and LiDAR based digital surface models (DSM), to quantify hydrological variability. Data are also analysed to establish whether flow generation and water storage characteristics are controlled by attributes of the contributing catchment area or the local drainage patterns. The following hypotheses are tested:

1.1. Hypothesis A

Depth to water table is controlled by the size (width, depth) and position (local slope gradient and form) of anthropogenic drainage in the hillslope.

Given that drainage ditches were established to lower the water table in the adjacent peat mass, establishing the lateral extent of water table variability will allow an assessment of the distance over which the drainage channel impacts the hydrology. Examining variability in the water tables at any given distance from the drainage channels will improve understanding of the spatial impact of drainage on hydrological processes.

Variance in the observed water table depths across all monitored locations may also be affected by local heterogeneity in soil properties (e.g. bulk density, humification and hydraulic conductivity), soil depth and the hydraulic gradient of the groundwater with respect to localised topography (Allott et al., 2009; Evans et al., 2014; Holden, 2005; Morris et al., 2011; Wilson et al., 2010). Disaggregating water table measurements across the locations monitored may explain which variables control variation in water table in shallow peatlands. These data will therefore enhance the spatial understanding of how drainage affects water tables across larger spatial extents.

1.2. Hypothesis B

Spatial variability of rainfall-runoff response is proportional to the size of the drainage channel (width, depth) and the spatial attributes of its topographic contributing area (stream order, drainage density, contributing area).

It may be expected that analogous drainage channels on similar hillslope positions will exhibit similar runoff responses that vary proportionally to their contributing area or drainage network (Pilgrim et al., 1982). Accordingly, drainage structures of larger cross-sectional area or higher stream order may respond more to rainfall inputs. However, the hydrological connectivity of these peatlands is poorly understood (Goulsbra et al., 2014). It is not known whether complex microtopography, diplotelmic characteristics or high drainage densities control runoff dynamics. Therefore, examining drainage scale/size as a factor which may regulate discharge will inform conceptual understanding of flow generation and storage across these drained landscapes.

2. Methods

Two headwater catchments were selected within drained upland peatland areas in Exmoor National Park located in Devon/Somerset, England, which were representative of the regional shallow blanket mire complexes (Bowes, 2006; Mills et al., 2010; Grand-Clement et al., 2013; Luscombe, 2014; Luscombe et al., 2015a, 2015b). The sites were established to monitor a range of drainage ditch morphology, drainage density, peat depth, slope morphology, aspect and vegetation composition. Average peat depths are as shallow as 33 cm across both catchments but can increase to ca. 1 m at some locations (Bowes, 2006). Drainage ditches up to 0.5 m wide and 0.5 m deep were hand dug from the 1830s. Between the 1960s and 1980s, larger ditches (>1.5 m wide) were dug at targeted locations, for example, spring lines (Hegarty and Toms, 2009). The location of the studied catchments (known locally as Aclands and Spooners is shown in Fig. 1. The Aclands catchment is situated at 51°7′53.55″N, 3°48′39.58″W and has an area of 19.5 ha. Spooners catchment is situated at 51°7′26.77″N, 3°44′55.96″W and has an area of 46.5 ha.

A detailed description of site selection, monitoring design, analytical design and data acquisition methods are detailed in Luscombe (2014). To summarise briefly, the experimental design comprises monitoring of depth to water table (DWT) at 96 locations (dipwells) and discharge in 8 open channels, across two headwater sub-catchments and at multiple drainage scales (Fig. 1c). The monitoring period analysed here, runs from January 2011 to October 2013. Dipwells were constructed from 40 mm plastic tubing, drilled with 8 mm holes and inserted to the full depth of the peat (up to 1 m). Vented pressure transducers (Impress IMSL) with a precision of 1% across their range (0–1 m) were deployed at the dipwell base and fixed with a steel rod. They returned depth data ±1 mm accuracy. The stage, rainfall and DWT measurements were logged continuously every 15 min in the field using a telemetry system, which also returned data continuously via VHF and GPRS connectivity (Adcon remote telemetry system). Flow was modelled from stage data at three drainage channels, called ‘experimental pools’ (EP), of differing sizes within each of the two catchments and also monitored at each of the two catchment outlets using rated flume structures and stage/velocity monitoring equipment (Luscombe, 2014). Each monitored drainage channel was labelled relative to its size (width and depth) at installation (from one, small, to three, large) and was also identified with its overall catchment (S = Spooners, A = Aclands). Data for the overall catchment outlet is also included and denoted as f (flume site), giving rise to 8 scales of hydrological monitoring over 2

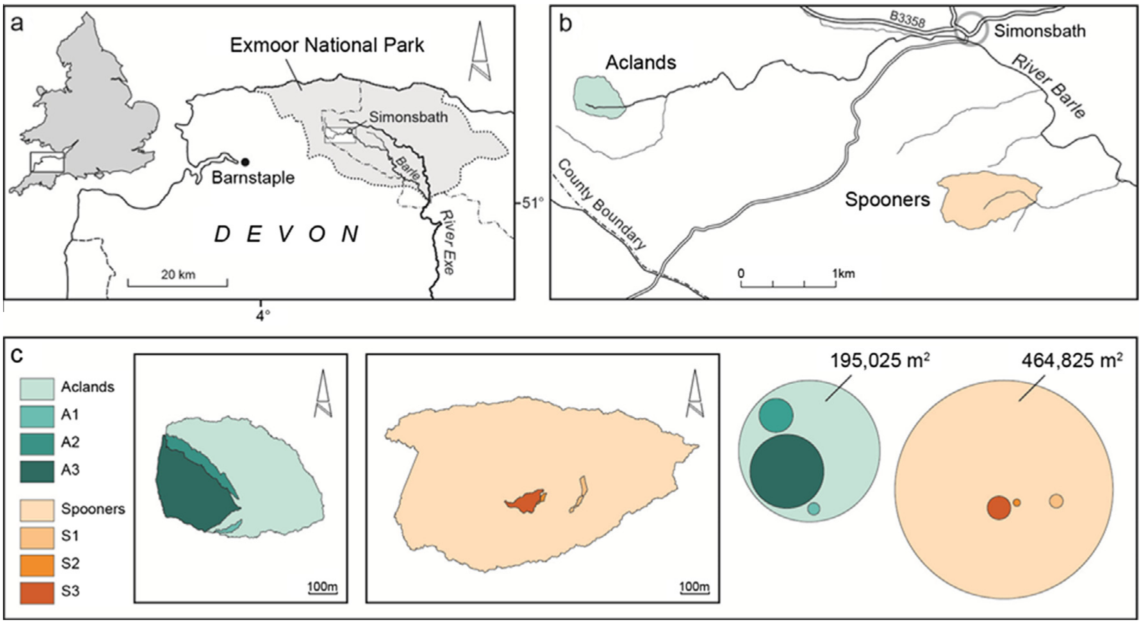

Fig. 1. (a) and (b) Location of study catchments in the south west of England (c) relative size of LiDAR delineated sub-catchments as both geographically correct and proportional contributing areas. Aclands catchment is situated at 51°7′53.55″N, 3°48′39.58″W and has an area of 19.5 ha. Spooners catchment is situated at 51°7′26.77″N, 3°44′55.96″W and has an area of 46.5 ha.

catchments (i.e. A1, A2, A3, Af, S1, S2, S3, Sf). The geographical position of the monitored drainage channels within the studied catchments (Fig. 1) is described in detail in Luscombe (2014). DWT measurements were taken at 16 locations around each monitored drainage channel, as detailed in Fig. 2.

2.1. Delineation of contributing areas

Topographic contributing areas for each EP and the wider catchment, were calculated using a LiDAR derived DSM and a basic flow accumulation modelling algorithm based on the methods described in Jenson and Domingue (1988). This technique models topographic contributing areas by calculating the accumulated weight of all cells "flowing" into each downslope cell in a given DSM. This Jenson and Domingue (1988) model provides a simple estimation of the topographic contributing area for any given point as all precipitation is assumed to become runoff and not lost to interception or groundwater (Beven, 2012). Although this approach is hydrologically simplified, previous work on these catchments suggests that runoff is generated quickly following rapid and short lived wet-up of the thinner, drained peat soils (Luscombe et al., 2015b, 2015a; Luscombe, 2014). As such, it was hypothesised that the Jenson and Domingue (1988) technique may be useful to delineate the topographic contributing areas for the monitored catchments (Vaze et al., 2010; Jarihani et al., 2015; Goulsbra et al., 2014; Wilson and Gallant, 2000).

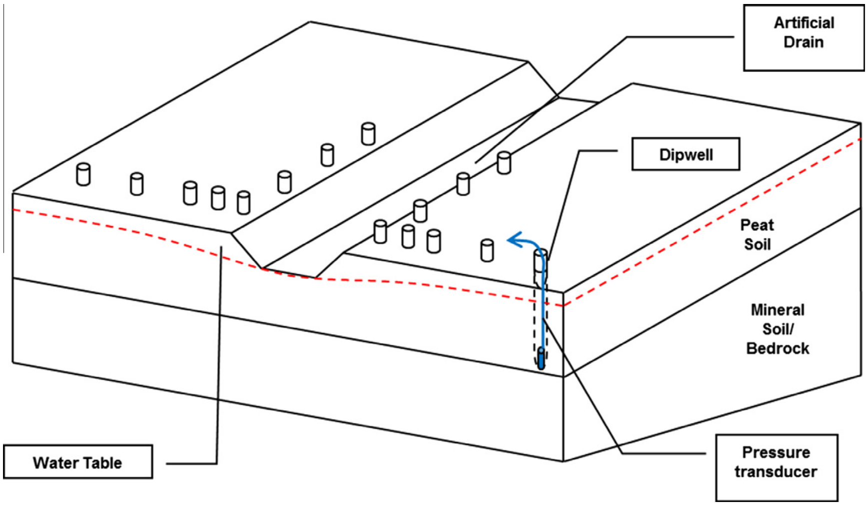

Fig. 2. Design of experimental pools and dipwell arrays. Conceptual design locating mini piezometers (dipwells) distributed along two axes adjacent to an anthropogenic drainage feature.

This approach was implemented using the spatial analyst extension in ArcGIS 10.0. Airborne LiDAR data were collected by the UK Environment Agency Geomatics Group (EAGG) in May 2009 and provided as a 0.5 m spatial resolution DSM product (first return). LiDAR data were checked for accuracy at five separate locations by the EAGG, using a differential Global Positioning System (DGPS) survey. These ground truth data indicated an average systematic error of +0.0004 m and an average random bias of ±0.047 m in elevation. The combined root-mean-square error (RMSE) for these data was 0.029 m i.e. within the product specification of 0.15 m (Luscombe et al., 2015b; EAGG, pers. comm., 2012).

To optimise the topographic representation of the contributing area, the LiDAR DSM was modified in two ways (Jarihani et al., 2015; Evans and Lindsay, 2010). First, as the surface drainage network is known to be under-represented in the LiDAR DSM due to the cover effect of short-sward vegetation, (Luscombe et al., 2015b), a manual GPS survey of the depth of the drainage channels, was undertaken to improve the representation of the ditch network in the DSM. A hand held GPS unit with a spatial accuracy of <1 m (Thales Navigation, MobileMapper CE) was used to record the position of these channels which were then rasterised in Arc GIS (version 10.0) with a constant depth value of 0.5 m (representing the average ditch depth) lower than the surrounding cells. Second, the DSM surface was optimised to remove spurious topographic sinks that actually reflect complex vegetation structure rather than isolated topographic depressions (Luscombe et al., 2015b). As vegetation sinks in the DSM relate to areas of higher connectivity in the landscape, the method employed a combined "cut and fill" algorithm to remove sink pixels without degrading the underlying surface complexity and connectivity. Using the methods from Soille (2004), sinks were removed by calculating the optimum minimum cost of vertical transformation to achieve connectivity with neighbouring non-sink areas. The resulting dataset comprised a modified DSM in which surface connectivity was maintained without significant degradation of the topographic complexity. The resultant DSM also enhanced representation of the surface drainage, without introducing any further topographic sinks. The planar area of the derived contributing areas was then calculated and used to derive summary statistics and frequency distributions for indices of surface roughness (Jenness, 2004), Strahler stream order delineation (Strahler, 1957) and drainage density (m/m). The spatial extent and lateral geometry of these contributing areas is illustrated in Fig. 1c.

2.2. Data and statistical analysis

Metrics describing discharge were extracted automatically for every rainfall/runoff event that occurred during the monitoring period (January 2011 to October 2013) (Luscombe, 2014). Rainfall/runoff metrics used in this analysis are defined as Q_t (total discharge) and Q_p (peak discharge). Long term averages of these data are also used for each location to quantify differences excluding inter-event discharge variability (i.e. baseflow and drought periods). To address hypothesis A, fourth order polynomial regression was used to explore the form and strength of the relationship between DWT and distance from drainage channels. At each location mean values (n = 63) were regressed from a total sample size of n = 5.94 × 10^6. Two further, second order, regressions were used to establish the strength of the relationship between DWT and distance from drainage following disaggregation of those data into individual upslope and downslope locations. R^2 statistics were also calculated for each regression. To address hypothesis B, following appropriate transformation (log 10) of Q_t and Q_p, the distribution of flow data for each monitoring scale was extracted and tested using a parametric analysis of variance (one way ANOVA and "least significant difference" *post hoc* testing). This analysis enabled the significance of the difference between any given pair of data (Q_t or Q_p distributions) to be established.

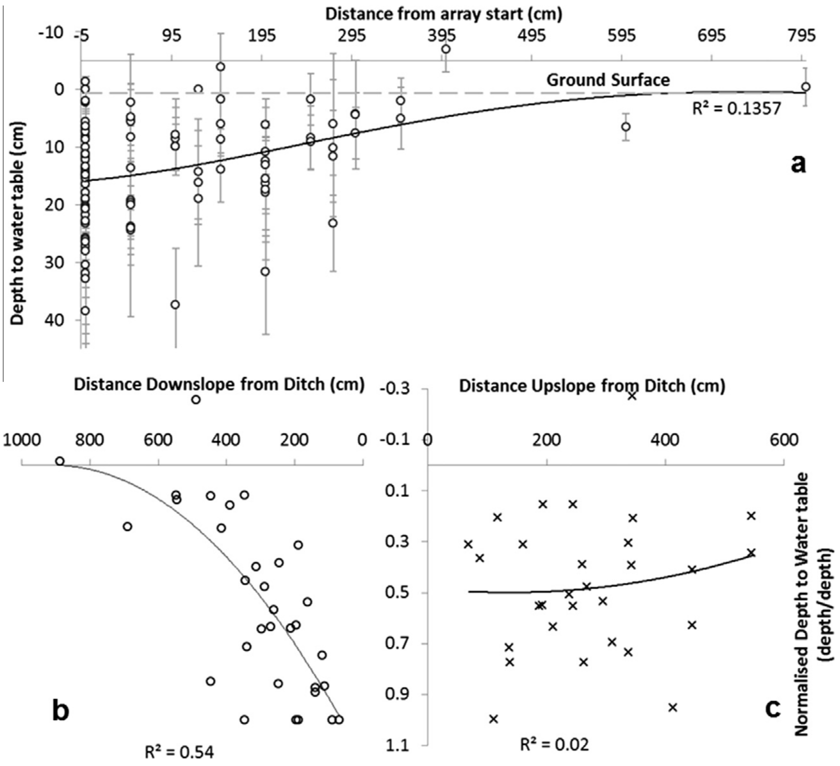

Fig. 3. Mean (±standard deviation) DWT for each of the 96 dipwells across both monitored catchments (March 2011–December 2013). (a) Regression of mean (standard deviation error bars) DWT for all 96 monitored locations. (b) Regression of mean DWT for all locations downslope of drainage features, depth is normalised by maximum recorded DWT at that experimental pool. (c) Regression of mean DWT for all locations upslope of drainage features, depth is normalised by maximum recorded DWT at that experimental pool.

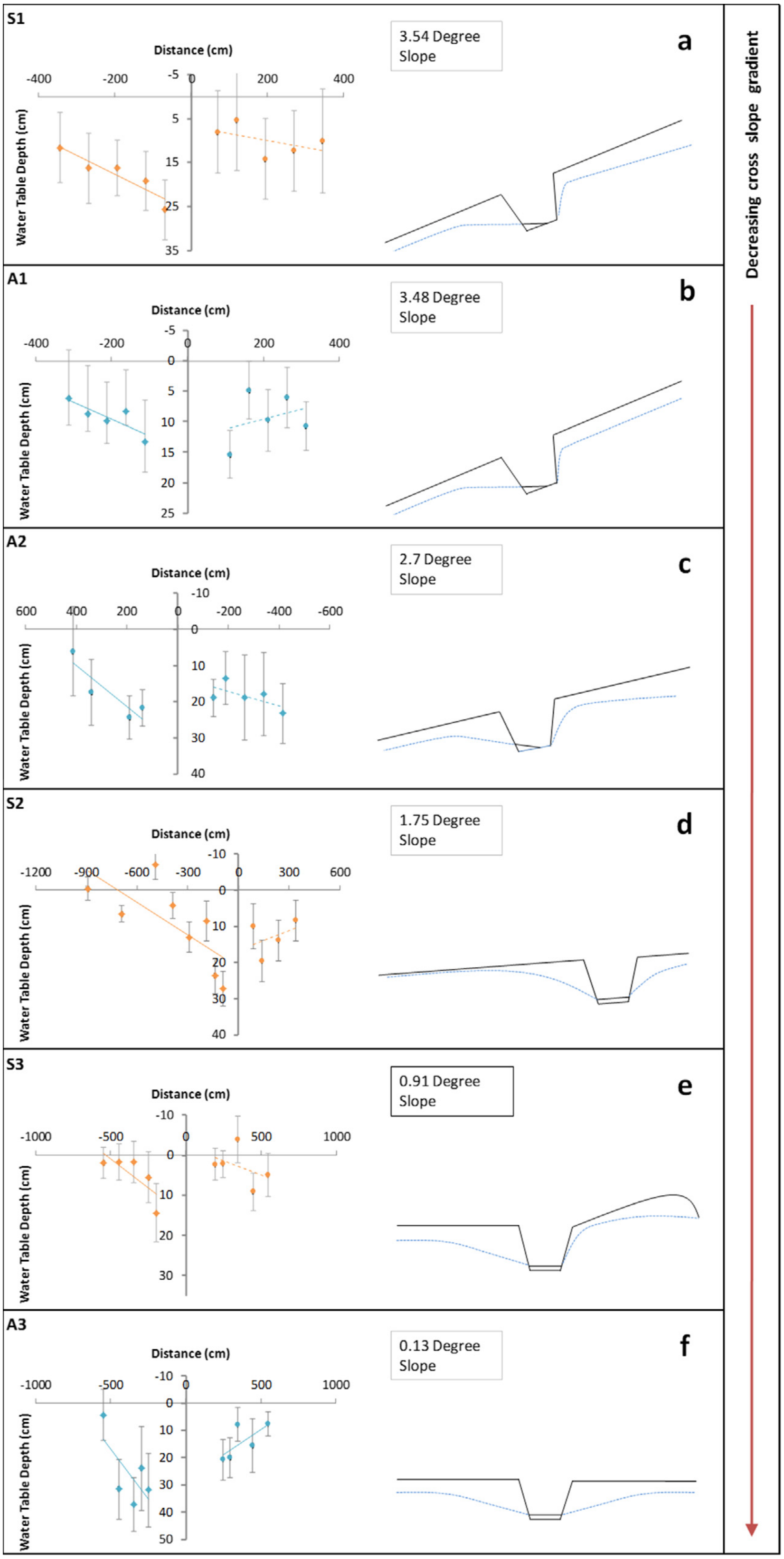

Fig. 4. Mean DWT data disaggregated for each drainage feature monitored (n = 6). Here, data are shown for each DWT dataset (n = 69,500 for each location at Spooners and 54,500 at Aclands) collected at each of the monitoring locations perpendicular to a drainage feature, alongside the relative cross slope angle and a conceptual model for the measured slope (black line) and water table (blue dashed line) at each location. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Results

3.1. Hypothesis A

Depth to water table is controlled by the size (width, depth) and position (local slope gradient and form) of anthropogenic drainage in the hillslope.

Regression of the average (±standard deviation) DWT for each of the 96 dipwells across all monitoring locations (Fig. 3a) demonstrates a large degree of spatial variability in the potential DWT at any given distance from a drainage feature when all monitoring locations are aggregated together (n = 54,500–69,500 measurements for each location). The distribution of DWT at locations close to drainage channels (0–1 m) indicates an increased likelihood of low or drawn-down water tables. Third order polynomial regression of these data (n = 96 locations) reveals that distance from the edge of a drainage feature explains only 13.6% of the observed variance, with DWT decreasing (i.e. water tables rising) with distance away from the ditch. Normalising these data by the maximum measured DWT within the EP array, in order to compare across EPs with different characteristics, improves the explanatory power of drain-edge distance as a control on DWT to 22%.

As many ditches are cut across slope, in order to explore possible controls that ditch position might exert on water tables, the data are disaggregated to those dipwells on the up and downslope side of drainage channels and normalised by maximum DWT, (Fig. 3b). For dipwells located on the downslope side of drains, >50% of the variance in DWT is explained by the distance to the drainage feature. Conversely, almost all upslope variation in DWT appears to be independent of the influence of distance to the drainage feature (Fig. 3c).

To explore how depth to water table is affected by *both* the size and position of anthropogenic drainage, data were disaggregated for each drainage feature monitored (n = 6) (Fig. 4). Here, data are shown for each DWT dataset (again, n = 69,500 for each location at Spooners and 54,500 at Aclands) at each of the monitoring locations perpendicular to a drainage feature, alongside the relative cross-slope angle and a conceptual model of the measured slope and water table at each location. Again, it is evident that the DWT measured downslope of drainage channels, or where little cross-slope gradient is present, is often strongly related to the distance away from these drainage channels (e.g. S1 and S2 in Fig. 4). Although the numbers of points in each location are too few to facilitate quantitative regression, the mean DWT values exhibit less variability compared to the simple linear fits included. Conversely, upslope of these areas, far less observed variation in DWT is explained by the distance from the drainage channels. A conceptual model of the relative position of the mean water table is also included highlighting that the monitoring locations with greater cross slope gradient exhibit stronger downslope control on DWT, despite all measured slopes being relatively subtle (i.e. a maximum of 6% gradient).

3.2. Hypothesis B

Spatial variability of rainfall-runoff response is proportional to the size of the drainage channel (width, depth) and the spatial attributes of its topographic contributing area (stream order, drainage density, contributing area).

Fig. 5 illustrates the proportion of total flow observed at each of the 8 scales that is created by (a) storm flow and (b) base flow. The data illustrate all scales are storm flow dominated with storm flow contributing between 52% and 68% of total flow regardless of either contributing area or ditch size.

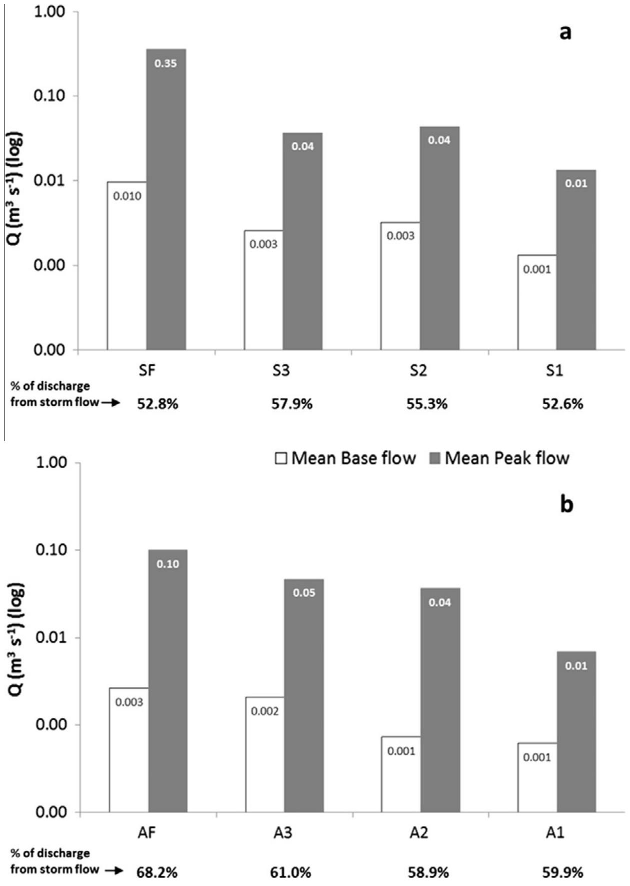

Fig. 5. Illustrates the proportion of total flow from storm and base flow contributions at a. Spooners and b. Aclands. Grey bars represent mean peak flow across all events observed at each scale ($m^3\ s^{-1}$). n = 89,984 for SF, 83,803 for S1, 93,159 for S2 and 87,358 for S3; n = 89,985 for AF, 48,573 for A1, 64,411 for A2 and 90,064 for A3; White bars represent mean base flow between all storm events observed at each scale ($m^3\ s^{-1}$). NB. Log scale used. Discharge metrics are reported without any contributing area assumption.

Fig. 5 also illustrates that the proportion of total flow varies across the scales monitored. To explore additional factors hypothesised to control spatial variability of hydrological processes, (contributing area, channel depth/width, stream order and drainage density) these independent variables were calculated for each monitoring scale alongside the absolute flow parameters (Table 1).

As both long-term and event-based hydrological metrics exhibit scale-related variation between monitoring locations (Fig. 5 and Table 1), Fig. 6 plots the distributions (including the 25th and 75th percentiles) of (a) total event flow from each observation scale and (b) peak event flow (n = 38–93 events). Event flow at each scale is highly variable, though substantial differences between Q_t and Q_p at each scale are rare. For example, the difference in observed Q_t between S3, A3 and A2 is not significant (Table 2, Fig. 6), whereas drainage depth and topographic contributing areas vary notably (0.34 m and 0.86 m deep and 53,161 m^2 and 5335 m^2 respectively, Table 1). Similarly, S2 demonstrates no significant difference in Q_t or Q_p with S3 and Af, despite a very small theoretical contributing area (499 m^2). Such a result suggests that although runoff is spatially variable, surface contributing area (scale) is not a good predictor of flow response at any given scale in these shallow, drained peatlands.

Using the topographic contributing areas for the Spooners (Sf) and Aclands (Af) parent catchments, to normalise event Q_t (Fig. 6c) derives distributions of event Q_t and Q_p that are not significantly different at $p < 0.05$. The production of runoff (mm) per unit

Table 1
Hydrological responses and landscape characteristics for each of the monitoring scales.

Sites	Hydrological response					Landscape characteristics				
	Average flow $(\mathrm{Q\,m^3\,s^{-1}})$	Max flow $(\mathrm{Q\,m^3\,s^{-1}})$	Mean base flow $(\mathrm{Q\,m^3\,s^{-1}})$	Mean peak flow $(\mathrm{Q\,m^3\,s^{-1}})$	Average daily flow $(\mathrm{m^3})$	Topographic cont. area $(\mathrm{m^2})$	Channel depth (m)	Channel width (m)	Strahler stream order (ND)	Drainage density $(\mathrm{m\,m^2})$
SF	0.035	3.117	0.010	0.355	3064	464,825	0.86	1.7	8	0.02
S3	0.006	0.157	0.003	0.037	504	5335	0.86	2.7	4	0.01
S2	0.007	0.164	0.003	0.044	594	499	0.49	1.6	3	0.05
S1	0.003	0.062	0.001	0.013	223	1770	0.31	1.4	3	0.03
AF	0.008	0.842	0.003	0.101	664	195,025	0.61	0.43	7	0.04
A3	0.005	0.192	0.002	0.047	396	53,161	0.55	5.6	6	0.06
A2	0.002	0.097	0.001	0.037	192	11,220	0.34	2.1	4	0.02
A1	0.001	0.029	0.001	0.007	105	1428	0.145	1	3	0.07

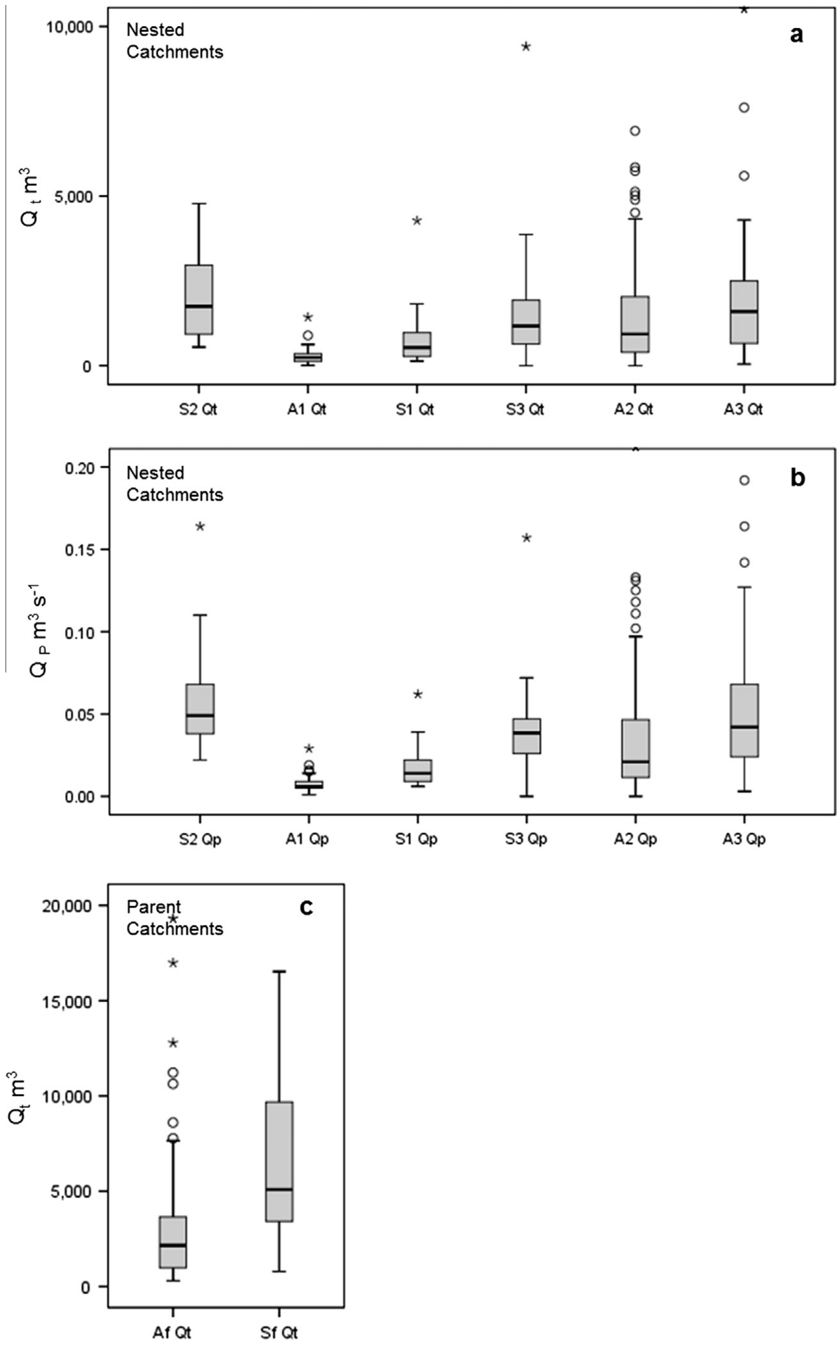

Fig. 6. Distributions of Q_p and Q_t for nested scales of monitoring and Q_t for both parent catchments, ranked by the relative topographically delineated contributing area, (Table 1), derived from LiDAR data. This ranges from 499 $\mathrm{m^2}$ at S2 to 464,825 $\mathrm{m^2}$ at Sf.

Table 2
Summary statistics (significance) for one way ANOVA and “least significant difference” *post hoc* testing of event Q_r and Q_p for each paired combination of the monitored drainage scales. Data were previously log10 transformed. Combinations with least significant difference ($p > 0.05$) are in bold, difference at $p > 0.01$ (black) and most significant difference in italic, at $p < 0.01$. All other combinations (not shown in Table 2) are significantly different at $p < 0.01$.

Combination		Q_r Sig.	Q_p Sig.
A3	S3	**0.92**	**0.59**
Af	S2	**0.46**	**0.28**
S2	S3	**0.13**	**0.15**
A2	S3	**0.09**	0.00
A3	S2	**0.05**	0.02
A2	A3	0.04	*0.00*
A2	S1	0.02	*0.00*
Af	S3	0.01	0.01

rainfall (mm) i.e. the runoff coefficient, at each catchment following normalisation is also comparable at 69.8% at Aclands and 79.4% at Spooners. However, the total discharge during storm flow events, is significantly higher at Spooners ($p < 0.01$), despite occasional large events at Aclands.

4. Discussion

The exploitation of peatland ecosystems to for agriculture (e.g. grazing) or resources (e.g. fuel), is common throughout the world (Grand-Clement et al., 2015). The effect of the drainage and damage of such systems has been studied internationally and in varying peatland ecosystems (i.e. bogs, fens, forests) (Page et al., 2009; Kløve and Bengtsson, 1999; Shantz and Price, 2006). Such studies provide important evidence and wider context for the

Table 3
Key studies monitoring the effect of peatland drainage and degradation on DWT and runoff. DWT = Depth to water table, NI = no information.

Monitoring undertaken	Context	Type of damage	Experimental design	Monitoring duration	Effect of damage/ degradation	Effect of restoration	Location	Peat depth (m)	Reference
DWT	Blanket Peat	Drained	Paired intact/ drained	18 months, 20 min interval, 27 locations	DWT most variable in the drained peatland	Recovery from drainage is slow	UK	>0.5 m	Holden et al. (2011)
DWT	Blanket peat	Bare Eroding	Paired intact/ Eroding sites	5 years, monthly interval, 48 locations	Lowest water table in bare peat areas	Increase in DWT	UK	0.7–0.9 m	Dixon et al. (2013)
DWT, Runoff	Blanket bog	Drained	Paired restored/ unrestored drains	1 year, 15 min interval, 10 locations	Rapid runoff in unrestored drains. Low but stable DWT	Runoff attenuated by blocking	UK	NI	Jonczyk et al. (2009)
DWT, Runoff (lag)	Blanket peat	Drained and cut	Before and after and restored/ unrestored drains	3 year, DWT: Fortnightly, 142 locations and 3 locations at 15 min interval Flow: 15 min, 10 locations	“Dry zones” within 2 m of drains. Lowest are downslope of drains. Low residency times	Increased water storage and lower peak flows	UK	NI	Wilson et al. (2010)
DWT	High elevation peat	Drained and cut	Before and after restoration	9 months, monthly interval, 30 locations	Lower water table. proximal to drainage canals	Water table near to or at the surface	China	NI	Zhang et al. (2012)
DWT	Minerotrophic fen and ombrotrophic bog	Drained and afforested	Before and after restoration	3 years, Weekly interval (summer), 23 locations	Water tables at least 20 cm below the surface	Higher water tables often reaching the surface	Finland	NI	Komulainen et al. (1999)
Runoff	Minerotrophic fen peatland	Drained and cutover	Monitoring degraded catchments only	May to October in 2 years, continuous and fortnightly interval (DWT), 3 locations	Little storm runoff is produced from newly drained cutover fen. Rapid groundwater response	NI	Finland	2–6 m	Kløve and Bengtsson (1999)
DWT	Minerotrophic fen and ombrotrophic bog	Drained and afforested	Before and after restoration	5 years, Weekly interval (summer), 23 locations	Average monthly DWT Ca. 40 cm	Average monthly DWT Ca. 15 cm	Finland	NI	Haapalehto et al. (2011)
DWT, Runoff	Ombrotrophic peat	Cutaway peat (not revegetated)	Paired restored/ unrestored sites	3 years, daily interval (summer), 2 locations	DWT > 40 cm at unrestored site	Higher mean water table	Canada	1.5-3 m	Shantz and Price (2006)
DWT	Tropical peat swamp forest	Drainage and logging	Paired intact/ degraded. Mixed monitoring and modelling approach used	1 year, NI	Increased water table fluctuations in drained and deforested areas	Increased annual minimum DWT, higher mean DWT	Indonesia	Mean 4.4–7.8 m m (mean)	Page et al. (2009)
DWT, Runoff	Blanket peatland	Drainage	Before restoration characterisation	3 Years, 15 min interval, 104 locations	DWT drawdown proximal to drainage. DWT sensitive to local topography. Highly spatially variable runoff	Forthcoming	UK	Mean < 0.5 m	This Study

effect of anthropogenic disturbance in the shallow, drained peatlands studied here. Table 3 provides summaries of studies describing the effect of anthropogenic drainage/damage in both the UK and globally, results from this study are also included for comparison. Critically, the shallow and more marginal peatlands studied here, are very poorly represented in the literature. Therefore characterising shallow peatland behaviour within the context of the wider scientific understanding, is useful both to understand the implications relative to deeper peatlands and the role of appropriate future management or restoration of these ecosystems.

From the data collated in Table 3 it is evident that the effects of land drainage on peatland hydrology is profound in both temperate and tropical peatlands throughout the globe (Jonczyk et al., 2009; Page et al., 2009). Indeed, the increased water table drawdown and its variability are common effects of peatland damage across different ecosystems including fen, bog and forested ecosystems (Page et al., 2009; Kløve and Bengtsson, 1999; Shantz and Price, 2006). However, Table 3 also highlights that the literature examining the effect of drainage and peatland degradation on hydrological behaviour is largely limited to deeper peatland systems, even within the UK (Daniels et al., 2008; Holden et al., 2006). The findings presented here are therefore important in confirming aspects of such hydrological behaviour in these shallower, degraded and more marginal peatland ecosystems.

4.1. Hypothesis A

Depth to water table is controlled by the size (width, depth) and position (local slope gradient and form) of anthropogenic drainage in the hillslope.

Data presented in Fig. 3 broadly agree with the findings of other studies, from deeper UK peatlands, where the presence of anthropogenic drainage is shown to increase the depth and variability of the DWT in the adjacent peat mass (Daniels et al., 2008; Wilson et al., 2010, 2011; Worrall et al., 2007; Boelter, 1972; Burke, 1963). However, this analysis has also highlighted that once DWT observations are compiled across all monitored locations within both headwater catchments, the overall trend for lower observed DWT distributions at locations closer to the edge of drainage channels can only explain 13.6% of the observed variance. When these data are normalised by maximum water table depth the distance to the ditch explains only a further 8.4% of the observed variation. However, classifying these data with respect to hillslope position indicates that downslope of the drainage ditch, notably more of the variability is explained by the distance from the drainage feature (54%). This finding indicates that fine-scale processes regulating DWT such as lateral flow, require analysis that considers more localised controls on DWT. Holden et al. (2006) showed in their study of land drainage in deep peatland systems that average DWT measurements, taken at a low temporal frequency (bi-weekly) also produce notable heterogeneity in DWT distributions. It is argued that the impact of drainage ditches is difficult to understand well, without high-resolution spatial data, describing the full range of DWT variability.

Analysis of data in Fig. 4 illustrate that subtle variations in the local topography (local cross slope gradient) are able to account for some of the observed variation in DWT and confirm enhanced water table drawdown downslope of these channels. However, at locations adjacent to these relatively subtle drainage channels (particularly upslope), the water table is able to persist at higher levels, although generally still below the peatland surface. On the upslope side of these channels only the highest vertical extent of the water table is close to the surface (i.e. during rainfall events) and the mean DWT measured is often significantly below the surface (up to 20 cm drawn-down). This finding agrees with other studies (Holden et al., 2006), albeit on deeper peatlands, demonstrating that local topography (and subsurface heterogeneity e.g. stratigraphy and macropore occurrence) are a key control on drainage function in a comparative study of hydrological behaviour in four drained and undrained peatland catchments.

Although the gradient of the slopes measured in this study are relatively subtle (<6.2% slope), the shallow nature of the peat deposits on Exmoor (Merryfield and Moore, 1974; Chambers et al., 1999) is likely to exaggerate the effect of a cross-slope gradient on the relative drawdown of water table adjacent to such drainage channels. Understanding these fine-scale influences on DWT is the first step towards more comprehensive estimates of how DWT is affected by drainage across larger spatial extents. A simple extrapolation of DWT data relative to distance from ditch will not necessarily provide an accurate picture of the spatial effect of ditches on water tables across such a heterogeneous landscape.

These data demonstrate the need for a spatially distributed understanding of DWT characteristics across the catchment extent. Horizontal heterogeneity in the ecohydrological structure and function of such systems is well evidenced in the literature. Notably, Morris et al. (2011) discuss the importance of understanding the spatial heterogeneity of peatland structure and function in the context of conventional diplotelmic models of peatlands. Herein, the unique way in which dipwells were distributed across the catchment allowed, for the first time, monitoring of DWT with regard to multiple and specific localised topographic controls. The use of distributed spatio-temporal monitoring networks is therefore advisable, to improve understanding of the hydrological processes regulating DWT in these peatland landscapes as argued by Holden (2005) and Holden et al. (2011) in deeper peatlands.

4.2. Hypothesis B

Spatial variability of rainfall-runoff response is proportional to the size of the drainage channel (width, depth) and the spatial attributes of its topographic contributing area (stream order, drainage density, contributing area).

Results show how drainage channel geometry/size or topographic contributing area can be used as a proxy to estimate runoff from anthropogenic drainage channels in shallow blanket peatlands. The presence of anthropogenic drainage is known to modify runoff generation across peatland ecosystems (Ramchunder et al., 2009). However, the nature of the change in the hydrological regime remains relatively poorly understood (Ballard et al., 2011), especially so in shallow peatlands. Here, the magnitude of discharge observed from nested drainage scales demonstrates, for the first time, how profoundly these features alter the runoff behaviour of shallow peatlands, modified by drainage ditches.

In this study, the variation in the (multi-annual) hydrological characteristics is significant across the spatial scales monitored (Figs. 5 and 6). These findings agree with studies elsewhere (Allott et al., 2014; Holden et al., 2006) and illustrate that highly spatially variable hydrological responses are a common characteristic of peatlands with very different structures. Event based analysis shows that the spatial variation in total and peak runoff (Fig. 6) is often significantly different between drainage channels within close proximity, despite storm flow uniformly dominating flow regimes and rainfall inputs being the same (Fig. 5). However, these data indicate that the discharge variability is often invariant with drainage scale and topographic contributing area (Table 1). Within the nested monitoring scales, statistically similar responses to rainfall are observed between drainage of strikingly different topographic contributing areas (Table 2).

Although, Q_t and Q_p are sometimes shown to scale in relation to the drainage size (Fig. 6 and Table 1), a lack of significant variation between key locations (e.g. Af and S2) (Table 2, Fig. 6) suggests that the processes governing the production of flow are related to factors other than the surface contributing area or drainage scale, in these peatlands (Holden and Burt, 2003, 2002; Evans et al., 1999). In agreement with other studies in deeper peatlands (Holden and Burt, 2003; Daniels et al., 2008), the findings of this paper may indicate that additional near surface (<10 cm) or subsurface inputs account for a significant proportion of the flow generated during the rapid wet-up of the peat matrix. Accordingly, the topographic watershed delineation for a location (e.g. S2) may account for only a small fraction of the hydrological source area during a rainfall event, or that topographic contributing areas are subject to step-changes in surface connectivity during rainfall events, as found by Goulsbra et al. (2014) in a study of severely eroded peatlands in Upper Derwent Valley, South Pennines, UK. Using surface topography to delineate contributing areas in this study is excessively simplistic despite the low depths (<1 m) of peat, confounding our ability to quantify potential source areas for a given drainage channel, as shown by Holden (2005) and Goulsbra et al. (2014). In the case of S2, for example, field visits confirm that the immediate upslope contributing area is within an area of historic peat cuttings. Similar to erosion features studied in deeper peat systems by Daniels et al. (2008), these features may accumulate flow as a consequence of preferential lateral subsurface/near surface flow from the surrounding, deeper peat mass, leading to elevated flow responses per catchment area.

At the scale of the parent catchment, flow is statistically similar in terms of rainfall:runoff coefficients (69.8% at Aclands and 79.4% at Spooners), broadly in line with other studies. For example, Holden and Burt (2003) record comparable coefficients of 72–82% in a blanket peatland with peat deposits up to 3 m, in the North Pennines UK. This finding demonstrates that at higher stream orders (Strahler >7) sufficient spatial and topographical complexity is incorporated (averaged) to describe similar relationships between rainfall and contributing area. Whilst the finer scale variation in hydrological behaviour may provide important insight into ecological organisation, these catchment-scale runoff coefficients are therefore, more useful as a baseline to understand the effects of future restoration work on the hydrology of these peatlands and to compare to other landscapes.

Finally, this research, has important implications for the spatially distributed modelling of runoff production over catchment scales in peatlands, and is of particular importance to research that quantifies associated ecosystem services that these uplands may offer. Spatially distributed modelling approaches that aim to predict runoff from such landscapes must apply appropriate methods to suitably high-resolution topographic data, such as those described in Lane et al. (2004) and Soille (2004). Moreover, researchers looking to apply rainfall-runoff models based on surface topography to peatlands should look not only to spatially distributed monitoring of this type (Lamb et al., 1998), but also to remotely sensed data able to constrain predictive uncertainty spatially and more accurately validate the hydrological connectivity and complexity of the peatland system (Luscombe et al., 2015a; Evans et al., 2014). The dataset presented here could provide strong spatial validation for model predictions of catchment hydrographs, that are also internally consistent with the distribution of water tables within a catchment and confronting the problem of spatial equifinality of rainfall-runoff predictions.

5. Conclusion

For the first time, evidence is provided on the effect of anthropogenic drainage networks on the spatial distribution of water tables and runoff within shallow and marginal peatlands. The principle conclusions are summarised as:

- Anthropogenic drainage increases the depth and variability of the water table in the adjacent peat soil and variations in the local slope and topography explain important variance in DWT upslope and downslope of drainage channels.
- At a fine spatial scale (i.e. individual drains) neither the size of the drainage feature (depth and width), or the topographic contributing area is an indicator of peak or total storm flow. Indeed, channels of varying size and topographic area exhibit statistically similar discharge.

Whilst the use of topographic contributing area is common to many spatially distributed models of rainfall-runoff processes; results presented here suggest that such an approach would be inappropriate in these shallow peatlands at scales smaller than the headwater catchment.

Data generated in this study are important as no previous studies describe the dominant hydrological processes in these types of shallow and maritime peatlands. They also provide a baseline to gauge the effectiveness of future drain blocking and the spatial extent of peat rewetting across these landscapes. The spatially explicit understanding of water table variability that this research provides could also be used to improve the parameterisation of spatially distributed models of water table depth used by those managing and studying such ecosystems.

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