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The impact of ditch blocking on the hydrological functioning of blanket peatlands

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Abstract

Ditch blocking in blanket peatlands is common as part of peatland restoration. The effects of ditch-blocking on flow regimes and nearby water tables were examined in a field trial. After an initial six month monitoring period, eight ditches had peat dams installed 10 m apart along their entire length (dammed), four of these ditches were also partially infilled through bank reprofiling (reprofiled). Four ditches were left open with no dams or reprofiling (open). These 12 ditches and the surrounding peat were monitored for a further 4 years. An initial five-fold reduction in discharge occurred in the dammed and the reprofiled ditches with the displaced water being diverted to overland flow and pathways away from the ditches. However, there was a gradual change over time in ditch flow regime in subsequent years, with the overall volume of water leaving the dammed and the reprofiled ditches increasing per unit of rainfall to around twice that which occurred in the first year after blocking. Hence monitoring for greater than one year is important for understanding hydrological impacts of peatland restoration. Overland flow and flow in the upper ~4 cm of peat was common and occurred in the inter-ditch areas for over half of the time after ditch blocking. There was strong evidence that topographic boundaries of small ditch catchments, despite being defined using a high-resolution LiDAR-based terrain model, were not always equivalent to actual catchment areas. Hence caution is needed when upscaling area-based fluxes, such as aquatic carbon fluxes, from smaller scale studies including those using ditches and small streams. The effect of ditch blocking on local water tables was spatially highly variable but small overall (time-weighted mean effect < 2 cm). Practitioners seeking to raise water tables through peatland restoration should first be informed either by prior measurement of water tables or by spatial modelling to show whether the peatland already has shallow water tables or whether there are locations which could potentially undergo large water-table recoveries.

Keywords: peat, drainage, ditches, wetland, restoration, water tables, discharge

Introduction

Peatlands are an important form of wetland where net litter formation has exceeded decomposition, enabling the build-up of organic matter as peat. Blanket peatlands are a type of rainwater-fed peatland which can occur even on sloping ground as long as there is sufficient rainfall and impeded subsurface drainage. Blanket peatlands typically occur in hyper-oceanic regions of the world (Charman, 2002; Gallego-Sala and Prentice, 2012). The hydrological regime of blanket peatlands tends to be dominated by water movement at or close to the surface due to saturation of the peat and a low hydraulic conductivity throughout most of the peat profile (Price, 1992; Evans *et al.*, 1999; Holden and Burt, 2003; Holden and Burt, 2003).

In the UK, blanket peat accounts for 87 % of peatland cover (Baird *et al.*, 2009), equivalent to 6.5 % of the land area, and exists primarily in the uplands, covering mostly gently rolling terrain. Blanket peat depths are typically 1-3 m but can be in excess of 6 m in places. Many UK peatlands were artificially drained between the 1940s and 1980s to support agricultural demand in areas of marginal productivity (Green, 1974; Baldock *et al.*, 1984), for commercial forestry (Holden *et al.*, 2007), to aid peat extraction for horticulture and energy production, and because of the perception that peatland drainage could alleviate flood risk (Newson, 1992; Holden *et al.*, 2006; Acreman and Holden, 2013). Drainage of UK blanket peatland has been relatively widespread, most commonly through ditch cutting. Cross-slope ditches have been shown to alter water-table depths and dynamics, typically resulting in deeper and more highly fluctuating water tables immediately downslope of each ditch (compared with intact slopes) because ditches effectively shorten the upslope contributing area (Holden and Burt, 2003; Holden *et al.*, 2006; Holden *et al.*, 2011). The ratio of subsurface flow to overland flow has been shown to be greater in ditched peatland slopes than for undrained systems nearby (Holden *et al.*, 2006). Even when ditches are orientated in a downslope direction in blanket peatlands there could be local effects on peatland water tables and therefore on the propensity to saturation and the amount of overland flow. This is because water levels in the ditch will tend to be lower (relative to a datum) than water tables within the surrounding peat and hence there will be a hydraulic gradient towards the ditch. However, while hydraulic conductivity can be high very near the peat surface and above pipes in blanket peatlands (Cunliffe *et al.*, 2013), for most of the peat profile hydraulic conductivity appears to be very low, albeit highly variable (Holden and Burt, 2003; Lewis *et al.*, 2011). Therefore, it may be that hydraulic gradient effects on water flow into ditches running downslope may be minor.

In response to concerns about biodiversity, erosion, carbon storage and potentially exacerbated flood risk, many UK peatland ditch networks are being blocked as part of peatland restoration schemes (Armstrong *et al.*, 2009; Parry *et al.*, 2014). Many different techniques are used for ditch blocking; particularly common is the installation of peat dams at intervals of several metres along the course of the ditch (Armstrong *et al.*, 2009). Sometimes ditches are ‘reprofiled’ by moving peat from ditch sides into ditch channels to reduce the sidewall gradient, the result being a much shallower channel on which a vegetation cover develops (Parry *et al.*, 2014).

Ditch blocking and reprofiling are likely to alter hydrological flowpaths in blanket peatlands. Depending on dam success, water can pond to create pools (Peacock *et al.*, 2013; Beadle *et al.*, 2015) and excess water can be forced out of the ditch channel across the surrounding peat surface to follow topographic drainage routes (Holden, 2006). These routes may differ from the routes that existed before blocking (Lane and Milledge, 2012). The effects of drainage on peatland hydrological processes have been shown to change over long time periods (years and decades) as the peat system adjusts in response to management interventions (Holden *et al.*, 2006). In the same way, there may also be lag effects in response to peatland restoration measures such as ditch blocking. These apparent lag effects have been observed in water-table response time series (Wilson et al., 2010) and in drained, blocked and control comparison studies of water-table dynamics (Holden *et al.*, 2011). However, following ditch blocking, it has not been established whether the flow regime from blanket peat hillslopes progressively changes over time in the months and years after ditches have been blocked.

There have been few studies of the hydrological impact of ditch blocking in situations where peatland ditches run predominately downslope. Most studies have examined water-table behaviour in and around ditches and blocked blanket peat ditches where the ditches are orientated across the slope (e.g. Worrall *et al.*, 2007; Gibson *et al.*, 2009; Wilson *et al.*, 2010; Holden *et al.*, 2011) or where the site is virtually flat (e.g. Haapalehto *et al.*, 2011; McCarter and Price, 2013). However, there are large areas of blanket peatland with both downslope and cross-slope ditch layouts in the UK.

There is an assumption for blanket peatlands that the surface topography draining into a point in a ditch or stream is equivalent to the water source area for that point. This assumption seems reasonable given the dominance of near-surface flow within blanket peat systems. However, it has not been tested. In particular, given that drains or drain blocking may alter hydraulic gradients on site, it is important to establish whether surface topography can be used as a reasonable guide to determining the water source area. A key variable which relies on good quality area-averaged (areal) water flow information is the peatland aquatic carbon flux. These fluxes (and those of other parameters) are often expressed as mass per unit area per unit time so that they can be directly compared to free-phase carbon gas fluxes which are typically reported in the same format (e.g. Gibson *et al.*, 2009; Billett *et al.*, 2010). Many aquatic carbon sampling points have been located in small catchments including peatland ditch systems (Gibson *et al.*, 2009; Turner *et al.*, 2013). Areal flux values are often upscaled in modelling studies or applied to larger catchments (e.g. Worrall *et al.*, 2007). However, at smaller scales in blanket peatlands there is greater risk that the surface catchment area may not represent the actual catchment area of the channel. Differences between the hydraulic gradient and the surface slope are more likely to affect catchment water budget calculations at the scale of small catchments around ditches. In addition, radiocarbon data have shown that the sensitivity of different peatlands to carbon loss following drainage is highly variable due to large differences in their hydraulic properties (Evans *et al.*, 2014). Therefore, considerable caution is required when translating understanding from studies undertaken in one peat type (e.g. continental raised bog) to another (e.g. blanket bogs), or even from one blanket bog to another where the drainage characteristics vary.

This study aims to: i) determine the effects of typical ditch blocking methods on flow regimes for ditches that are predominantly downslope; ii) determine whether the surface topographic catchment area is suitable for water budget calculations at the drainage ditch scale in blanket peatlands; iii) determine whether there is evidence for a lagged response to ditch blocking in the discharge regime from the peat system and iv) test whether ditch blocking significantly affects water tables in the nearby peat in situations where drains run in a predominantly downslope direction.

2. Methods

2.1 Study site

The study was carried out at the Migneint blanket peatland in the upper Conwy catchment in North Wales (52.97°N, 3.84°W) on an area of hillslope located at approximately 500 m altitude, with a across an area of *c*. 2 ha, drained by a set of 12 parallel ditches running in a roughly downslope direction (Figure 1). The ditches had a mean spacing of 16 m (range 11 to 26 m), mean slope of 4.5° (range 3.9 to 5.1°), and a mean length of 99 m (range 84 to 107 m). The ditches were mostly shallow with a mean depth of 0.58 m (range 0.1 m to 1.53 m) and in some cases overgrown by vegetation, although all were hydrologically functional at the start of the experiment. Peat depths in the study area range from around 0.5 to 2.5 m, and the vegetation comprises a typical blanket peatland assemblage including *Calluna vulgaris* (L.) Hull. (common heather), *Eriophorum* *vaginatum* L. (hare's tail cotton grass) and various species of *Sphagnum* (bog mosses). The peat in this area overlies Cambrian mudstones and siltstones (Lynas, 1973).

In February 2011, eight of the ditches were blocked using two common methods widely used in blanket bogs (Parry *et al.*, 2014), and four open ditches were retained as controls (Figure 1). The two ditch-blocking methods used were damming and reprofiling plus damming (henceforth referred to as reprofiling). The ditches chosen to receive each treatment were assigned by a statistician, taking into account measured flow rates from the ditches. Those ditches with similar flow rates were grouped together and then treatments randomly assigned within groups. Within this random approach, reprofiled ditches were not adjacent to one another as it was felt that this method was most likely to impact on adjacent ditches through generating dispersed surface flow. Following typical UK practice, peat dams were constructed at regular intervals (~10 m) along the ditch using peat taken from ‘borrow pits’ next to the ditch immediately upslope of each dam. Pools formed behind the dams and extended into the adjacent borrow pits forming water bodies of approximately 2-3m width, but with their lengths extending into the original ditch channel upslope by a distance that was dependent upon the gradient of the hillslope. For ditches in the reprofiling treatment, ditch vegetation was removed, the base of the ditch compressed and the ditch partially infilled with peat scraped from ditch walls to reduce the steepness of the sidewall slope, and the vegetation replaced. This treatment also involved the construction of peat dams at regular intervals. Given that the ditches were orientated in a predominantly downslope direction it is probable that some pool overspill could re-enter the same ditch channel downslope depending on hydrological flowpaths.

2.2 Measurements

Discharge and water-table equipment was installed in June 2010 and monitoring commenced in August 2010. All monitoring equipment was removed in early February 2011 to allow for the eight ditches to be blocked, and equipment reinstalled by the end of the month. Monitoring resumed for a period of four years, until the end of February 2015. Rainfall was recorded using an automated tipping bucket raingauge logged hourly which was located within the 2 ha study site. As the area of study was relatively small and ditches closely spaced, rainfall variability between ditches should not be a major factor affecting differences in ditch flow. All raingauges may be prone to error in catch, particularly when there are strong winds. Therefore the gauge was placed in small hollow to minimise these effects.

2.2.1 Discharge

Discharge from each ditch was measured using a 22.5° v-notch weir and a WT-HR 1000 water-height logger (TruTrack Ltd, Christchurch, New Zealand) recording at 15-minute intervals, with logged values being an average (over 15 minutes) of readings taken every minute. The logger was calibrated, so logged water heights were known to be accurate and the v-notch weir was calibrated by collecting manual discharge data to create a stage-discharge relationship. The ditch flow weirs measured both overland flow and lateral subsurface flow that entered and flowed along the ditches.

Discharge of overland flow on the areas between the ditches was monitored from July 2011 until February 2015 to determine whether the volume of overland flow changed over time since ditch blocking. Overland flow generated from the peat on both sides of each study ditch (Figure 1) was channelled into one overland flow weir box per ditch using ultraviolet-stable polyvinyl chloride (PVCu) soffit boards pushed into the peat to a depth of 3-5 cm. Microtopographic variation meant it was impossible for the boards to remain at one depth across their length. The soffit boards varied in length running from the approximate mid-point between ditches towards the ditch. Overland flow channelled from one side of the ditch crossed over the ditch via a PVC pipe before entering the overland flow weir box near the ditch. Overland flow weir boxes were gauged at 15-minute intervals (averaged as for ditch discharge above) using TruTrack WT-HR 500 loggers and calibrated with manual stage-discharge readings. The outflow from the overland flow weir boxes occurred downslope of the main ditch weir to ensure that the monitored overland flow did not affect water flow in the gauged ditch. The downslope location of the soffit boards also meant that they had no impact on the measurement of ditch flow because any flow that they captured would not have otherwise flowed into the ditch weirs had the soffit boards not been present. Because the soffit boards were inserted to a depth of 3-5 cm, overland flow in this study refers to all water flow at the surface and, on average, the flow in the upper 4 cm of the peat profile.

Over the study period there were occasional logger failures. Unreasonable values from the ditch flow and overland flow records caused by, for example, icing up, or occasional one-off erroneous readings from the pressure sensor were removed before data analysis. Where a data gap of two points or fewer (2 × 15-min intervals) occurred in the automated record the values were infilled using linear interpolation. Otherwise, data gaps were retained and reported as missing values to be taken into account when interpreting the total water flux.

2.2.2 Water-table depths

Eighty-three dipwells were installed (Figure 1), of which 24 were fitted with automatic water-level recorders. At the other dipwells, manual readings were taken approximately every three weeks in summer and every six weeks in winter. The automated dipwells comprised high-density polyethylene (HDPE) pipes, with an outside diameter (o.d.) of 32 mm, a length of 1000 mm and 3.5 mm wall thickness. These pipes were perforated with numerous 2 cm horizontal, 0.3 mm wide slits spaced at intervals of 5 mm. The automated wells were located midway between each ditch and also within each ditch to measure water level within the ditch (or water-table depth below the ditch floor when the ditch was dry). They were fitted with either WT-HR 1000 water-height data loggers, or Divers (DI240, 5 m, Schlumberger Water Services, Delft, The Netherlands), which measured and recorded water tables at 2-hr intervals. Each data logger was manually calibrated, and thereafter checked and cleaned throughout the project at regular intervals. Manually gauged dipwells were made from 32 mm o.d. × 1000 mm (PVC) pipe with a 3.5 mm wall thickness. The tubes were perforated with 8-mm diameter holes drilled at 100 mm intervals along four lines running lengthwise along the pipe, with holes in each line offset from those in neighbouring lines by 50 mm. One set of manually recorded dipwells were located at 2 m from each ditch both on the eastern and western sides (coded x.2E or x.2W, where x is the ditch number) in line with an automated dipwell within the ditch (coded x.0) and an automated dipwell installed half way between ditches (coded x.mid). The installation of this set of dipwells was completed in August 2010. In June 2011, the remaining manually-recorded dipwells were installed adjacent to 35 gas flux collars (our gas flux data are not reported herein). These were located within the ditch channel and 1 m and 3 m west of each ditch (coded Cx.0, Cx.1W or Cx.3W where x is the ditch number). In Ditch 5 the gas flux collar was coincident with dipwell 5.0; hence, no additional manual dipwell was installed at that point. All dipwells were surveyed for their altitudinal position using the x.mid dipwell as a local transect datum in each case so that absolute water-table heights could be plotted relative to one another across each dipwell transect. All dipwells were tested for their response time by measuring the recovery of well water levels in response to a sudden withdrawal of water. The time for 90% recovery ranged from a few seconds to 120 minutes. Hence our water-table data are deemed to be very reliable as all our dipwells functioned well with rapid response times.

2.3 Calculations

Total discharges were calculated for each weir in m^3 (total volume over a given time period) and mm (areal discharge over a given time period). Areal discharge was calculated by determining the surface topographic catchment area of each weir. If areal discharge > rainfall this indicates that the topographically-defined catchment area must be under-estimating the true area contributing flow to the gauging point, and therefore suggests that water budget calculations at the ditch scale are unreliable. Figure 1 shows the surface-derived catchment area for each ditch weir, calculated from LiDAR digital elevation model (DEM) data provided by the National Trust using 50 cm grid cells.

However, damming of ditches may lead to changes in catchment areas for adjacent ditches, notably if water is shed from a dammed ditch into an adjacent undammed ditch. While attempts were made to minimise this effect in the current study by selecting a site in which the ditches follow an approximately downslope direction, there may still be some spillage from pools in ditches where the ditches do not run exactly downslope. To examine the *maximum* theoretical effect of such changes in surface flowpaths, a DEM was created where it was assumed that all of the dammed or reprofiled ditches had been completely infilled with peat. The four open control ditches were, however, left in place in the DEM. The catchment area for each ditch weir under this infilling scenario is shown in Figure 1. There would also be some modifications to the surface catchment areas for overland flow collectors under such a scenario. The catchment areas for both scenarios (scenario 1: pre-blocking catchment areas; scenario 2: catchment areas assuming complete infilling of dammed and reprofiled ditches) for the ditch and overland flow weirs are shown in Table 1 and both are used when calculating the areal discharge from each weir. Note the infilling scenario is an extreme one and unlikely to be fully met during the initial years after ditch blocking. However, by calculating total areal discharge it will be possible to check whether any such water redistribution effects have been occurring.

Scenario 2 results in very small catchment areas for the weirs in Ditches 3, 4, 5, 11 and 12 (Table 1, Figure 1). In the case of Ditches 3, 4 and 5, however, there is a large theoretical rise in catchment areas for overland flow weirs. For Ditches 10, 11 and 12 the overall catchment areas for both overland flow and ditch flow weirs are substantially reduced in scenario 2 largely due to downslope flow towards the west away from the weirs. The overall area of the monitored hillslope that captures *both* overland flow and subsurface flow (i.e., the ditch weirs) is 24 % smaller in the infilled scenario. Hence, if ditch blocking was fully effective we would expect to capture less total flow because ~24 % of the water should be diverted away from blocked ditches to follow the topographic gradient of the site in a direction that partly by-passes the weirs. The catchment area supplying overland flow weirs in scenario 2 is about three times greater than that for scenario 1 (Table 1).

Importantly, Figure 1 and Table 1 highlights that Ditches 6 and 7, which were open ditches, appear to act as effective controls because their theoretical catchment areas are hardly affected under the maximum infilling scenario for the surrounding ditches. In this paper, calculations to compare blocked ditch flow and associated overland flow and water-tables to the open control treatments are typically made with reference to Catchment 6. If the particular dataset being analysed from Catchment 6 had any major problems (such as missing data due to data logger malfunction) then comparisons were made to the matching dataset from Catchment 7.

When data have been evaluated on an annual basis, the data are treated in full years from 1st March (2011/12, 2012/13, 2013/14, 2014/15) because ditch blocking took place in February 2011. Data from before March 2011 are included, where relevant and available, and tend to run for the 6 months from August 2010 to January 2011 inclusive, covering both summer and winter periods.

For some of the dipwell and ditch flow data, calculations were performed to determine relative impacts of ditch blocking compared to control ditches using *both* before and after blocking datasets (hereafter referred to as the BACI approach). The BACI approach helps deal with problems around differences in water-table depth between treatments resulting solely from wetter or drier weather conditions experienced in a given year. For example, for each particular dipwell location (e.g., 2 m west of the ditch) the mean difference between water-table depth was determined relative to the control at open Ditch 6 ((control water-table depth) minus (study ditch water-table depth)). This mean ‘offset’ was calculated for the period before ditch blocking. The calculation was repeated for each of four study year periods (see above). The former offset value was subtracted from the latter offset values. If the resulting annual number was >0 this suggested a relatively ‘positive’ change in the treatment water-table depth compared to the control (i.e., the water tables had become shallower (closer to the surface) relative to the control).

For some water-table comparisons we calculated time-weighted means to account for variations in the intervals between water-table measurements, thus removing biases that may be caused by a higher frequency of readings at one time of year compared to another. The measured water-table depth for a dipwell was assigned to represent a proportion of the year calculated as half the number of days between the previous reading and the current reading plus half the number of days between the current reading and the next reading. The water-table depth was multiplied by that proportion of the year and this value was then summed across the year to provide a time-weighted annual mean water-table depth.

3. Results

3.1 Ditch flow

For ditches that were dammed or reprofiled in February 2011 there was, as expected, an immediate effect on the discharge regime (Figure 2), with flow considerably reduced. Ditch 3 appears, from Figure 2, to be an exception but 30 % of the datalogger record for Ditch 3 was lost during the August 2010 to January 2011 (inclusive) pre-blocking phase. As a consequence many of the higher peaks in flow for the earlier part of the record that were observed in other ditches are missing from the Ditch 3 record. Ditches that were left open (2, 6, 7, and 9) show larger peak flows compared to the other ditches for the period from March 2011. There were very large differences in total flows between ditches, with the largest total flows after February 2011 occurring in the open ditches (2, 6, 7, and 9) (Table S1). The logger for Ditch 2 suffered regular failures and was out of action for a large proportion of the time and so we treated those records with more caution. Runoff efficiency (areal discharge expressed as a percentage of precipitation) for the study area as a whole was 82 % before ditch blocking. However, during this first period of the study two ditches (4 and 9) appeared to produce more areal discharge than rainfall (Figure 3). During later periods of the study several ditches appeared to produce more areal discharge than rainfall under both catchment area scenarios (Figure 3). When using scenario 1 catchment areas for the period after ditch blocking, the runoff efficiencies for the whole site were 32 % (2011/12), 56 % (2012/13), 89 % (2013/14) and 71 % (2014/15). For the scenario 2 catchment areas, the runoff efficiencies for the whole site were 122% (before), 47 % (2011/12), 83% (2012/13), 132 % (2013/14) and 106 % (2014/15) (Table S1).

The proportion of time when flow was occurring in the ditches varied markedly between ditches, with Ditches 1, 9, 11 and 12 having the longest dry periods (Table 2). The proportion of time flow occurred increased for each full year of the study from 2011/12 to 2013/14 in all ditches except the open ones and Ditch 10 (Table 2). Further increases in flow time (i.e. with the greatest values since the ditch blocking took place) were found for Ditches 1, 8, 10 and 12 for the final year of the study, although flow periods were longer in 2014/15 for control ditches 7 and 9 compared to the other years since ditch blocking took place. Overall, flows were more continuous from ditches in later years of the study. There appeared to be a large increase in flow periods at the Ditch 10 (dammed) weir after ditch blocking compared to the period before blocking suggesting that pooled water (water in pools behind dams) upslope was able to slowly seep out of this drain system for long periods after rainfall. This hydrological behaviour is confirmed by less steep flow duration curves for Ditch 10 in the years after ditch blocking (Figure 4).

At the high flow end of the flow duration curves (Figure 4) in particular, but for most of the dataset, open control Ditches 6 and 7 have very similar curves between each year. The curves only deviate between years for Ditch 6 during low flow conditions. The open Ditches 2 and 9 have similarly-shaped curves across the years. The other ditches, however, show large differences in the slopes of the curves between years, with more separation at the high end of the curves between years and in particular between the pre- (black symbols) and post-blocking periods. The very gentle gradient curves for Ditch 5 (dammed) after blocking indicate a change to more continuous flow all year as also outlined in Table 2 with a less ‘flashy’ regime year on year as indicted by the progressively less steep curves for each year in the record (Figure 4). The weir at Ditch 5 may also have a very large increase in catchment area (and consequent discharge totals) associated with spillage of water from other blocked drains (Table 1).

The total flow passing the ditch weirs declined from 14.96 m^3 per mm of rainfall to only 5.80 m^3 per mm in the first year after blocking compared to the period before blocking. When only ditches that were blocked are considered that figure was 9.39 m^3 mm^{-1} dropping to 2.30 m^3 mm^{-1}. Considering only the period after ditch blocking, most of the ditches experienced a significant increase ($p < 0.05$) over time (using month since blocking as the sequential time unit in a linear regression) in the volume of water produced per mm of rainfall (Table 3). At control Ditch 6 there was no significant increase in runoff volume per mm of rainfall over the same period. Open Ditch 9 did show a significant trend of increasing discharge per unit of rainfall but this is in line with expectations that water from adjacent blocked ditches would flow into that ditch which may have experienced an increase in catchment area of ~20 % after ditch blocking operations compared to the situation before February 2011.

3.2 Overland flow

Overland flow regularly occurred on the site (Table 4) and all weir boxes recorded overland flow showing that it was spatially widespread. Most weir boxes recorded flow for extended periods after rainfall, suggesting that saturation-excess overland flow was the dominant surface flow mechanism. Unfortunately overland flow data are unavailable for weir box 6 from July 2014 onwards due to logger failure so we therefore used weir box 7 as a comparative control. For the eight blocked or reprofiled ditches there were three full years of overland flow data. When each of these 24 possible ditch-years was compared to control weir box 7 it was found that 19 had more frequent overland flow than recorded at weir box 7 (Table 4). Overland flow occurred less frequently at weir box 12 in all study years compared to control weir box 7. Weir box 12 is the only one which theoretically would have a reduced catchment area due to drain infilling and this weir box did experience much less frequent overland flow than any other site. The duration of overland flow increased each year relative to control weir box 7 for weir boxes 1-5 (Table 4).

The volume of overland flow almost tripled between the first year after blocking and the final year of the study despite similar rainfall totals (Table S2). The large values of overland flow in catchments 6 and 7 combined suggest that even where the ditches are open, overland flow (and shallow throughflow to ~4 cm depth) may be the dominant flow path for water at the study site. Note that the catchment areas for the ditch weirs and the overland flow weir boxes are different and so it is not possible to simply partition the total ditch flow recorded in a ditch weir into overland flow and subsurface flow based on the overland flow recorded at the overland flow weir box.

The relationship between overland flow and ditch flow was fairly stable during the study period for control catchments 6 and 7 (Figure 5; only data for Ditch 7 are shown - patterns were similar at Ditch 6) suggesting that the relative importance of overland flow and subsurface flow remained stable in these control ditches. The relationship was also stable for most other ditches suggesting that the balance of overland flow and lateral subsurface flow partitioning did not change in the years after blocking. However, for Ditch 4 there was a tendency towards higher overland flow rates in 2014/15 compared to earlier years for comparable ditch flows. The opposite was the case for Ditch 8 (reprofiled). For Ditch 5 (dammed) the relationship between overland flow and ditch flow was similar between years but there was a tendency for higher rates of both in 2013/14 and 2014/15 (note data only available to May 2014), compared with 2012/13 (Figure 5).

3.3 Water tables

Water tables at the study site tended to be very shallow (Table S3). Some of the dipwells located within ditches (x.0 and Cx.0) were clearly located where ponding above the surface was common while others were not, including for dipwells in the same ditch, highlighting the spatially variable nature of water level conditions on the floor of both blocked and unblocked drains (Table S3). At a distance of only 2 m from open ditches, before blocking occurred, the mean time weighted water-table depth for each dipwell ranged from 1.7 cm to 20.2 cm. Of the 24 dipwells located 2 m from ditch edges, eight had mean time weighted water-table depths within 5 cm of the surface for the 6 month period before ditch blocking.

Using time-weighted annual means for each dipwell, a repeated measures one-way analysis of variance (ANOVA) was used to test for treatment and time (year) effects for the 2 m dipwells (east and west combined, n=8 per year per treatment). This indicated no significant effect of drainage treatment (open, dammed, reprofiled) ($p = 0.197$), but a significant effect of year on water-table depths ($p < 0.001$), with 2013/14 having significantly deeper water tables (by *c*. 1.3 cm) than 2012/13. The dipwells to the west of the ditches are where effects of treatment are likely to be greatest due to the site’s gradient. However, a repeated measures one-way ANOVA for these dipwells alone (n= 4 per year per treatment) indicated no significant effect of drainage treatment, but a significant effect of year on water-table depths, with 2013/14 having significantly deeper water tables (by *c*. 1.7 cm) than 2012/13. A separate repeated-measures ANOVA was used to compare the Cx.1 and Cx.3 dipwells and there was no significant effect of treatment ($p = 0.067$)

from open (average depth: 10.0 cm), dammed (7.2 cm) or reprofiled (5.9 cm) ditches. The results also showed that there was a significant effect of the year after blocking (p= 0.001), with 2011/12 (9.2 cm) > 2014/15 (8.3 cm) > 2013/14 (7.1 cm) > 2012/13 (6.1 cm). There was no effect of distance from the ditch or an interaction effect between year after blocking, treatment and distance. However, the above strict ANOVA analysis masks some of the spatial variability across the site. Using time weighted means, 11 of the 16 dipwells either side of dammed or reprofiled ditches indicated shallower water tables after blocking of ditches compared with the relative conditions 2 m either side of control Ditch 6. Using the BACI approach, at some locations the apparent mean net water-table rewetting effect was around 10 cm (e.g., 1.2W (reprofiled), 3.2E (reprofiled), 5.2W (dammed), 10.2W (dammed)). However, the average time-weighted relative rewetting effect (compared to the period before site interventions) across all of the 2 m dipwells when comparing all blocked and reprofiled ditches with control Ditch 6 was only 0.4 cm, 1.4 cm, 1.8 cm and 1.5 cm in the four study periods (2011/12, 2012/13, 2013/14, 2014/15) after blocking respectively.

By taking an annual mean approach the above BACI and ANOVA analyses remove some of the temporal variability which may be important on site. Therefore as a further check ordinary least squares regression was performed on the 2 m water-table records using day since blocking as a predictor. Five dipwells out of 24 tested showed a trend towards a wetter condition (Figure S1, S2) (reprofiled: 1.2W, 3.2E, 11.2W; control: 7.2E; dammed: 5.2W and 10.2W). However, these trends were weak with $r^2 < 0.1$ in all but one case (3.2E). Thus the three analytical techniques for dealing with the water-table data adjacent to ditches described above suggest that ditch blocking has had a limited impact on water tables except in a few locations.

Examination of dipwell transects relative to a local datum (separate datum for each dipwell transect) showed that in all cases water-table heights above datum, for mid-points between ditches, were much greater than those around the ditches (two examples shown in Figure 6). Such an effect is most likely due to the peat surface being typically higher at the mid-points than adjacent to or within each ditch (e.g., the median peat surface height difference was 28 cm between mid-point dipwells and the dipwells 2 m east of the ditch). The absolute water-table height for the 2 m dipwells east and west of each ditch were very similar except for around Ditch 9 – open.

For the automated dipwells located midway between ditches the records showed a relatively small range in means between dipwells for any given year (e.g., for 2011/12 4.0 cm (Ditch 2) to 12.7 cm (Ditch 7)). Dipwell 7 was used as a control as it was midway between two open ditches (control ditches 6 and 7). During the second half of the study period there was a relative deepening of water-tables at the mid-point between ditches towards that found at the control (7.mid) for dipwells 4.mid, 5.mid, 10.mid, 11.mid, and 12.mid (all dammed or reprofiled) (Figure 7).

4. Discussion

4.1 Catchment area assessment

The 82 % runoff efficiency for the 2 ha hillslope before ditch blocking took place is in line with previous water budgets for headwater blanket peatlands (Evans *et al.*, 1999; Holden, 2006; Holden *et al.*, 2012), and almost identical to the 81% runoff efficiency measured during more than 30 years of water balance monitoring at the Plynlimon (Pumlumon) moorland research catchment in mid-Wales (Marc and Robinson, 2007). For the period before ditch blocking we can be most confident about the cumulative surface catchment area for the twelve ditch weirs. However, even during this first period of the study there are two ditches (4 and 9) that produced far more areal discharge than rainfall. Such data provide clear evidence that the water (and carbon) source areas for these ditches are different from those defined by the surface topography alone. It may be that subsurface springs, pipes and other throughflow pathways result in source areas for those ditches which stretch beyond the topographically-defined catchment; water chemistry data (not shown - see Evans *et al.*, 2016) show unusually high pH and inorganic carbon concentrations in Ditch 4, suggesting groundwater influence. Hence, at scales of around 1000 to 3000 m^2 which are typical surface catchment areas for the outlets of first order ditches, caution must be taken when calculating water budgets and it may be necessary to reconsider the findings from earlier studies that have looked at areal flow rates and aquatic carbon fluxes at such scales, including those from ditch and ditch-blocking studies. Fortunately, at a one order of magnitude greater scale (20000 m^2), such effects appear to become less important. However, it is still possible that subsurface sources for the monitored part of the hillslope occur outside this cumulative topographic area, but logically such effects should decrease as catchment area increases.

4.2 Flow regimes and lag effects

There is strong evidence, at the study site, of both a step change in flow as a result of ditch blocking and a gradual change over time after ditch blocking. The ditch blocking had the expected immediate effect on ditch flows with a ~ five-fold reduction in flow down the ditches that were blocked. This should not be interpreted as an overall reduction in water loss from the site: in upland UK catchments with high rainfall and low mean temperatures, there is very limited capacity for even quite drastic changes in land use, such as afforestation of grassland, to change runoff efficiencies by more than a few percent (Marc and Robinson, 2007). Thus water leaving the hillslope must have been transported away from the ditch gauging points, following the pre-drainage topography, or been transported down the hillslope as inter-ditch flow.

After ditch blocking there was a gradual overall increase in ditch discharge from the site so that for each unit of rainfall the site exported a greater volume of water via the ditch network. Such a change was related to an increase in baseflow from the ditches, with more prolonged flow periods (shorter dry periods) and more gently sloping flow duration curves. The gradual changes over time that were observed indicate a lagged hydrological response to ditch-blocking. Such lagged responses have been shown for water-table records before (slow recovery in water-table depths and slow reduction in water-table variability (Wilson *et al.*, 2010; Holden *et al.*, 2011)) but never for water flows in a blanket peatland channel system.

It is not clear why the ditch flows should increase over time in the years after ditch blocking, compared to the year immediately after blocking, but it is possible that the enhanced baseflow was related to increased lateral subsurface flow on site caused by slightly shallower mean water-table depths at some locations across the site. However, it may also be that leaks slowly developed in the dam network. The re-packed peat that formed the dams may not be stable and could be prone to piping and cracking caused by subsidence or the high seepage force associated with the large hydraulic gradient between the upper and lower part of the dam. It may also be that adjustments to surface and subsurface flowpaths occurred such as new routes for water to bypass dams and flow back into ditches around vegetation on the peat surface, or changes in subsurface pipe connectivity associated with ponding in ditches. These possible processes require further research and in most cases (e.g. studies of piping, pipeflow and macropore flow) would require new studies to investigate how these peat physical properties and rates of flow through different pore structures change after ditch blocking. As vegetation re-establishes within the system of pools and dams it is possible that some of the breaches in the system could gradually become blocked, reversing this initial response; however, we did not observe this in the four years post blocking.

When using areal discharge based on the original topographically-derived catchment areas for each ditch, the total discharge efficiency was found to be greater than 100% for several drains. Thus their real catchment areas must have increased over time due to the ditch blocking activity and to spillage of water from one ditch to another. However, the whole system had not shifted to behave as if the blocked drains had completely infilled because, when the cumulative catchment area for the weirs was used in the infilling scenario for the overall study site, runoff efficiency was > 100%. The figure is so high because the catchment area in the infilling scenario is much smaller than for the open ditch scenario. The system therefore appeared to be operating in the latter part of the study, in terms of catchment source areas, somewhere in between that of scenario 1 and scenario 2.

Overland flow was only monitored for the period after blocking. There were very long periods of saturation-excess overland flow production on the site, particularly around blocked drains. Overland flow continued to occur on the slopes near all blocked drains for more than 50 % of the time after blocking. It is possible that changes may have happened below the soffit boards over time that caused more overland flow to be produced in later years such as pore clogging due to disturbance and accumulation of debris around the boards. However, we saw little evidence of surface debris build up and so it is unlikely that deep subsurface pore blocking due to debris accumulation occurred. The relationship between overland flow and ditch flow was stable from year to year for the open control ditches. However for some (but not all) of the blocked ditches the relationship shifted from year to year suggesting that long-term changes to the hydrological system as a result of ditch blocking were spatially variable, with lagged effects in some areas and for some processes.

Evidence from some of the water-table records also suggests lag effects such as water-tables becoming deeper at the mid-point between ditches in comparison to the mid-point control in the latter part of the record. This may either be a recovery effect from site disturbance operations and machinery, or it may be further evidence to suggest that the site became ‘leaky’ and that initial successful rewetting of inter-ditch areas was reduced as ditch dams (and the ditch-flow weirs) started to release more water in the latter half of the study. Haapalehto *et al.* (2014) found, in a regional survey in Finland, that even after restoration, water tables tended to be to be deeper in old ditch lines, indicating the leakiness of filled ditches. The ‘leaky’ site hypotheses is more likely for our site given the strength of evidence from our ditch discharge data, but further research is required to understand what effects restoration machinery may have on long-term ecohydrological functioning of peatlands.

4.3 Water-table change

Overall, water-table depths on site were relatively shallow, similar to what one would expect to see on an intact and fully functioning blanket bog (Gilman, 1994; Evans *et al.*, 1999; Lindsay, 2010). On first inspection these data suggest that ditch drainage was not very effective at the site. This is potentially due to high rainfall at the site, low hydraulic conductivity of the peat and the fact that ditches were orientated in an almost downslope direction. Ditch blocking and reprofiling had no significant overall effect on water-table depths relative to the peat surface when taking a strict statistical approach for treatments as a whole. This is unlike findings for fens and raised bog peatlands on more gently sloping terrain (e.g. Menberu *et al.*, 2016).

We found evidence of an important topographic effect whereby the peat surface at mid-points between ditches was at a higher elevation than the peat adjacent to ditches. Absolute water-table elevations were therefore also higher in mid-point regions compared to the locations 1-3 m from the ditches. This peat surface elevation difference is likely to be due to long-term subsidence of the peat near to the ditches. Such subsidence effects around peatland drains have been observed in many types of peatland over the past few decades including raised bogs (e.g. Haapalehto *et al.*, 2014), fens (e.g. Leifeld *et al.*, 2011) and tropical peat swamps (e.g. Wöstena *et al.*, 1997). However, these effects have not, until now, been reported on steeply sloping blanket peatlands.

Long-term consolidation or wastage of the peat near to ditches at our study site may have taken place thereby reducing pore space and, through a negative feedback, generated shallow water tables near to ditches. Such an effect may have caused steepened hydraulic gradients on site in the years after ditch creation thereby potentially forcing more surface and subsurface flow into the ditches (depending on the hydraulic conductivity – which was not measured on site). These topographic effects may not be reversed in the short-term (decades) after ditch blocking as peat growth rates tend to be very slow, although where ditches are reprofiled or ponded with water behind dams there may be a reduced hydraulic gradient from mid-way between ditches towards the ditch channel. Such effects could be localised around individual pools and therefore water-table effects of restoration on sloping blanket bogs, particularly where drains run predominately downslope, may be very localised. The legacy of such spatially-structured topographic responses to drainage may have implications for carbon fluxes. As there were only modest effects on water-table regime, some ditch blocking may have little impact on key parts of the peatland carbon cycle including decomposition, except for local effects focussed on pools formed behind dams. Due to sideways shedding of water into the ditches, downslope inter-ditch areas may still be deprived of water even after damming of ditches, particularly if there has been near-ditch subsidence. In some places, however, as would be expected, blocked ditch water levels were higher in absolute terms than in the surrounding peat and so water would tend to flow from the ditch into the peat at those points. Our data suggest that water may be drawn into the ditch from the peat at some points and then from the ditch back into the peat at other points along the ditch course.

5. Conclusions

The hydrological analysis at the study site has shown that the site is a typical flashy blanket peatland system, dominated by overland flow, but with evidence of subsurface flow connectivity that extends beyond the topographic boundaries of small ditch catchments. There was extremely high variability in flow rates between ditches which had similar surface catchment areas. Hence caution is needed when upscaling from studies that may have only collected evidence on hydrological flows and aquatic carbon fluxes from one or two ditches (or blocked ditches) (e.g. Gibson *et al.*, 2009; e.g. Armstrong *et al.*, 2010). At small individual ditch catchment scales, care must also be taken when calculating water and carbon budgets based on surface topographic area. The evidence suggests that it may be necessary to reconsider the findings from earlier studies that have looked at areal discharge and aquatic carbon fluxes at such scales, including those from ditch and ditch-blocking studies. We also recommend that aquatic flux measurements at small scales should always be reported alongside water balance data to give confidence in the extrapolation.

While ditch blocking had an immediate effect on ditch flows, the analysis shows that there has also been long-term change in the hydrology of the system in the years following ditch blocking. There was some evidence (ditch, overland flow and water-table data) to suggest that the system has become more ‘leaky’ since the initial restoration works were carried out with a greater volume of water per mm of rainfall flowing down the ditch or former ditch channels (but in the form of slow seepage and baseflow, rather than high flow peaks). It is not clear why this has occurred and several lines of investigation should be explored including the possibility that the dams are leaking at an increasing rate, that new flow routes have formed allowing water to enter back into ditches that was previously distributed away from ditches, and that subsurface connectivity of bypassing flow (e.g., pipeflow) may be important on site. Our analysis has shown the need for long-term monitoring studies to test whether findings in the initial post-restoration phase still apply several years later and also as part of testing the robustness of management intervention measures in later years after ditch blocking. It may be that, because the predominant orientation of the ditches in our study was downslope, leakiness changes over time were more likely than at sites where ditches run in a more cross-slope direction.

The surface topography at the site suggested that subsidence of the peat had occurred close to the drains. While this has been commonly reported for peatlands, it has not, until now, been reported for steeply sloping blanket peatlands. More research is required to determine whether this subsidence effect is widespread across sloping blanket peatlands, but if it is then it makes water-table restoration even more challenging for blanket peatlands, particularly for cases where drains are orientated predominantly downslope. There was relatively little impact of ditch blocking or reprofiling on site water tables. Practitioners seeking to raise water tables more widely across blanket peatland sites should be informed either by prior measurement of water tables or by topographic modelling to highlight where surface flows might be redirected after management interventions on site. This information may help prioritise resource use by showing whether the peatland already has shallow water tables or whether there are locations which could potentially undergo larger water-table recoveries through ditch blocking than were observed at our study site.

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Table I. Surface topographically-derived catchment areas (m^2) of the study weirs for two scenarios.

Ditch	Ditch flow		Overland flow	
	Scenario 1: Assuming all open ditches	Scenario 2: Assuming treatment ditches act as if they are infilled	Scenario 1: Assuming all open ditches	Scenario 2: Assuming treatment ditches act as if they are infilled
1	2942	2499	100	69
2	1950	2537	229	322
3	2426	105	291	777
4	1350	19	61	527
5	969	38	43	1639
6	1462	1494	79	117
7	1227	1340	45	54
8	1195	823	280	50
9	1642	1997	55	25
10	2142	1329	161	103
11	1541	4	63	713
12	1311	40	108	37
Total	20157	12225	1515	4433

Table II. Proportion of time (%) when flows < 0.1 mL s^{-1} occurred at the ditch weir.

Ditch	Before	2011/12	2012/13	2013/14	2014/15
1 (reprofiled)	50.9	80.0	63.2	33.9	22.2
2 (control – open)	13.1	25.4	1.2	5.2	5.9
3 (reprofiled)	7.2	30.1	17.6	10.1	15.1
4 (dammed)	0.0	8.4	0.5	0.0	0.0
5 (dammed)	15.2	0.2	0.0	0.0	0.0
6 (control – open)	0.0	19.8	1.1	8.7	1.9
7 (control – open)	29.3	24.5	9.1	6.7	6.4
8 (reprofiled)	0.4	36.5	15.1	7.4	6.0
9 (control –open)	33.4	69.7	44.9	32.9	31.6
10 (dammed)	49.6	11.1	1.4	7.0	0.8
11 (reprofiled)	49.6	52.4	35.0	18.1	24.3
12 (dammed)	1.4	99.6	98.1	97.6	97.1

Table III. Correlation coefficients and the gradient of change over time since March 2011 in monthly discharge per unit rainfall (m^3 mm^{-1}). Coefficient and gradient values only shown where $p < 0.05$.

Ditch	Correlation coefficient	Gradient of change	p value
1 (reprofiled)	0.45	0.0081	0.001
2 (control – open)			0.087
3 (reprofiled)	0.40	0.0087	0.007
4 (dammed)			0.190
5 (dammed)	0.66	0.0690	<0.001
6 (control – open)			0.747
7 (control – open)	0.51	0.0571	0.001
8 (reprofiled)	0.71	0.0153	<0.001
9 (control –open)	0.44	0.0227	0.002
10 (dammed)	0.47	0.0193	0.001
11 (reprofiled)	0.29	0.0143	0.048
12 (dammed)	0.47	0.0002	0.001

Table IV. Proportion of time overland flow (OLF) was recorded at the weir boxes (flow ≥ 0.1 mL s^{-1}) and the difference in proportion of time OLF occurred compared to weir box 7.

Ditch	% time OLF recorded			% difference to control weir box 7		
	2012/13	2013/14	2014/15	2012/13	2013/14	2014/15
1 (reprofiled)	66	77	79	4	23	23
2 (control – open)	80	78	83	18	24	27
3 (reprofiled)	40	51	61	-22	-3	5
4 (dammed)	44	71	86	-18	17	30
5 (dammed)	69	94	100*	7	40	44
6 (control – open)	72	56	56*	10	2	0
7 (control – open)	62	54	56			
8 (reprofiled)	73	53	72	11	-1	16
9 (control –open)	72	30	32	10	-24	-24
10 (dammed)	98	63	61	36	9	5
11 (reprofiled)	76	63	48	14	9	-8
12 (control – open)	24	25	9*	-38	-29	-47

*Data available for weir box 5 until May 2014 only, weir box 6 until July 2014 only and weir box 12 until September 2014 only

References

Acreman M, Holden J. 2013. How wetlands affect floods. *Wetlands*, **33**: 773-786, doi: 710.1007/s13157-13013-10473-13152.

Armstrong A, Holden J, Kay P, Foulger M, Gledhill S, McDonald AT, Walker A. 2009. Drain-blocking techniques on blanket peat: a framework for best practice. *Journal of Environmental Management*, **90**: 3512-2519, doi:3510.1016/j.jenvman.2009.3506.3003

Armstrong A, Holden J, Kay P, McDonald AT, Gledhill S, Foulger M, Walker A. 2010. The impact of peatland drain-blocking on dissolved organic carbon loss and discolouration of water; results from a national survey. *Journal of Hydrology*, **381**.

Baird AJ, Holden J, Chapman PJ. 2009. A literature review of evidence on emissions of methane in peatlands, Defra project SP0574.; 54.

Baldock D, Hermans B, Kelly P, Mermet L. 1984. *Wetland drainage in Europe: the effects of agricultural policy in four EEC countries*. International Institute for Environmental and Development and the Institute for European and Environmental Policy: Nottingham; pp 166.

Beadle J, Brown LE, Holden J. 2015. Biodiversity and ecosystem functioning in natural peat pools and those created by rewetting schemes. *Wiley Interdisciplinary Reviews: Water*, **2**: 65-84. DOI: 10.1002/wat1002.1063.

Billett MF, Charman DJ, Clark JM, Evans CD, Evans MG, Ostle NJ, Worrall F, Burden A, Dinsmore KJ, Jones T, McNamara NP, Parry L, Rowson JG, Rose R. 2010. Carbon balance of UK peatlands: current state of knowledge and future research challenges. *Climate Research*, **45**: 13-29, doi: 10.3354/cr00903.

Charman D. 2002. *Peatlands and environmental change*. John Wiley: Chichester; pp 312.

Cunliffe A, Baird AJ, Holden J. 2013. Hydrological hotspots in peatlands: spatial variability in hydraulic conductivity around natural soil pipes. . *Water Resources Research*, **49**: 5342-5354.

Evans CD, Chapman PJ, Green S, Baird AJ, Holden J, Cooper D, Peacock M, Callaghan N, Robinson I. 2016. Fluvial carbon flux and water quality responses to ditch blocking of a blanket peatland. In Green, S. *et al.,* Investigation of peatland restoration (grip blocking) techniques to acheive best outcomes for methane and greenhouse gas emissions. Department for Environment Food and Rural Affairs, Project SP1202.

Evans CD, Page SE, Jones T, Moore S, Gauci V, Laiho R, Hruška J, Allott TEH, Billett MF, Tipping E, Freeman C, Garnett MH. 2014. Contrasting vulnerability of drained tropical and high-latitude peatlands to fluvial loss of stored carbon. *Global Biogeochemical Cycles*, **28**: 1215-1234.

Evans MG, Burt TP, Holden J, Adamson JK. 1999. Runoff generation and water table fluctuations in blanket peat: evidence from UK data spanning the dry summer of 1995. *Journal of Hydrology*, **221**: 141-160.

Gallego-Sala AV, Prentice IC. 2012. Blanket peat biome endangered by climate change. *Nature Climate Change*, **3**: 152-155, doi: 110.1038/NCLIMATE1672.

Gibson HS, Worrall F, T.P. B, J.K. A. 2009. DOC budgets of drained peat catchments: implications for DOC production in peat soils. *Hydrological Processes*, **23**: 1901-1911.

Gilman K. 1994. *Hydrology and wetland conservation*. John Wiley: Chichester; pp 101.

Green FHW. 1974. Changes in Artificial Drainage, Fertilizers, and Climate in Scotland. *Journal of Environmental Management*, **2**: 107-&.

Haapalehto T, Kotiaho JS, Matilainen R, Tahvanainen T. 2014. The effects of long-term drainage and subsequent restoration on water table level and pore water chemistry in boreal peatlands. *Journal of Hydrology*, **519**: 1493-1505.

Haapalehto TO, Vasander H, Jauhiainen S, Tahvanainen T, Kotiaho JS. 2011. The effects of peatland restoration on water-table depth, elemental concentrations, and vegetation: 10 years of changes. *Restoration Ecology*, **19**: 587-598, doi: 510.1111/j.1526-1100X.2010.00704.x.

Holden J. 2006. Peat hydrology. In: *Peatlands: basin evolution and depository of records of global environmental and climatic changes*, Martini IP, Cortizas AM, Chesworth W (eds.) Elsevier: Amsterdam; 319-346.

Holden J, Burt TP. 2003. Hydraulic conductivity in upland blanket peat: measurement and variability. *Hydrological Processes*, **17**: 1227-1237.

Holden J, Burt TP. 2003. Hydrological studies on blanket peat: the significance of the acrotelm-catotelm model. *Journal of Ecology*, **91**: 86-102.

Holden J, Chapman PJ, Lane SN, Brookes CJ. 2006. Impacts of artificial drainage of peatlands on runoff production and water quality. In: *Peatlands: evolution and records of environmental and climate changes*, Martini IP, Cortizas AM, Chesworth W (eds.) Elsevier: Amsterdam; 501-528.

Holden J, Evans MG, Burt TP, Horton M. 2006. Impact of land drainage on peatland hydrology. *Journal of Environmental Quality*, **35**: 1764-1778, doi:1710.2134/jeq2005.0477.

Holden J, Shotbolt L, Bonn A, Burt TP, Chapman PJ, Dougill AJ, Fraser EDG, Hubacek K, Irvine B, Kirkby MJ, Reed MS, Prell C, Stagl S, Stringer LC, Turner A, Worrall F. 2007. Environmental change in moorland landscapes. *Earth-Science Reviews*, **82**: 75-100.

Holden J, Smart RP, Dinsmore KJ, Baird AJ, Billett MF, Chapman PJ. 2012. Natural pipes in blanket peatlands: major point sources for the release of carbon to the aquatic system. *Global Change Biology*, **18**: 3568-3580.

Holden J, Wallage ZE, Lane SN, McDonald AT. 2011. Water table dynamics in drained and restored blanket peat. *Journal of Hydrology*, **402**: 103-114.

Lane SN, Milledge DG. 2012. Impacts of upland open drains upon runoff generation: a numerical assessment of catchment-scale impacts. *Hydrological Processes*, **27**: 1701-1726.

Leifeld J, Muller M, Fuhrer J. 2011. Peatland subsidence and carbon loss from drained temperate fens. *Soil Use and Management*, **27**: 170-176.

Lewis C, Albertson J, Xu X, Kiely G. 2011. Spatial variability of hydraulic conductivity and bulk density along a blanket peatland hillslope. *Hydrological Processes*, **26**: 1527-1537, doi:1510.1002/hyp.8252.

Lindsay R. 2010. *Peat bogs and carbon: a critical synthesis*. Royal Society for the Protection of Birds: Edinburgh; pp 315.

Lynas BDT. 1973. The Cambrian and Ordovician rocks of the Migneint area, north Wales. *Journal of the Geological Society of London*, **129**: 481-503.

Marc V, Robinson M. 2007. The long-term water balance of (1972-2004) of upland forestry and grassland at Plynlimon, mid-Wales. . *Hydrology and Earth Systems Sciences*, **11**: 44-60.

McCarter CPR, Price JS. 2013. The hydrology of the Bois-des-Bel bog peatland restoration: 10 years post-restoration. *Ecological Engineering*, **55**: 73-81, doi:10.1016/j.ecoleng.2013.1002.1003.

Menberu M, Tahvanainen T, Marttila H, Irannezhad M, Ronkanen A-K, Penttinen J, Kløve B. 2016. Water-table dependent hydrological changes following peatland forestry drainage and restoration: Analysis of restoration success. *Water Resources Research*, **52**: doi:10.1002/2015WR018578.

Newson MD. 1992. Conservation management of peatlands and the drainage threat: hydrology, politics and the ecologist in the UK. In: Peatland ecosystems and man: an impact assessment, Bragg OM (ed.) University of Dundee, Dundee; 94-103.

Parry LE, Holden J, Chapman PJ. 2014. Restoration of blanket peatlands. *Journal of Environmental Management*, **133**: 193-205.

Peacock M, Evans CD, Fenner N, Freeman C. 2013. Natural revegetation of bog pools after peatland restoration involving ditch blocking -The influence of pool depth and implications for carbon cycling. *Ecological Engineering*, **57**: 297-301.

Price JS. 1992. Blanket Bog in Newfoundland 2. Hydrological Processes. *Journal of Hydrology*, **135**: 103-119.

Turner EK, Worrall F, Burt TP. 2013. The effect of drain blocking on the dissolved organic carbon (DOC) budget of an upland peat catchment in the UK. *Journal of Hydrology*, **479**: 169-179. DOI: 110.1016/j.jhydrol.2012.1011.1059.

Wilson L, Wilson J, Holden J, Johnstone I, Morris M. 2010. Recovery of water tables in Welsh blanket bog after drain-blocking: discharge rates, timescales and the influence of local conditions. *Journal of Hydrology*, **391**: 377-386.

Worrall F, Armstrong A, Holden J. 2007. Short-term impact of peat drain-blocking on water colour, dissolved organic carbon concentration, and water table depth. *Journal of Hydrology*, **337**: 315-325.

Worrall F, Gibson HS, Burt TP. 2007. Modelling the impact of drainage and drain-blocking on dissolved organic carbon release from peatlands. *Journal of Hydrology*, **338**: 15-27.

Wöstena JHM, Ismailb AB, van Wijka ALM. 1997. Peat subsidence and its practical implications: a case study in Malaysia. *Geoderma*, **78**: 27-36.

Figure captions

Figure 1. Map of the study site showing the 12 ditches and their catchment areas for Scenario 1 and Scenario 2, the treatments (O = open, D = dammed, R = reprofiled), location of each ditch weir and overland flow soffit boards, and the location of the dipwells.

Figure 2. Discharge record for the study ditches from 1 August 2010. Management interventions on the ditches took place in February 2011 and hence there is a gap in all ditch flow records for that month – dashed lines indicate the timing of the interventions for affected ditches.

Figure 3. Annual discharge for each ditch using the two catchment area scenarios. Horizontal bars indicate annual precipitation total, highlighting cases where areal discharge exceeds precipitation.

Figure 4. Flow duration curves for all ditch weirs by year

Figure 5. Scatterplots of overland flow and ditch flow for Ditches 4, 5, 7 and 8. Data shown are square root discharges.

Figure 6. Water-table height above local datum for two example ditch transects. 2E, 0 and 2W indicate dipwells 2 m east of the ditch, in the ditch and 2 m west of the ditch respectively.

Figure 7. Monthly mean offset (based on 2-hourly data time series) between x.mid dipwell and 7.mid dipwell (the control). A positive value indicates shallower water-table conditions compared to the control dipwell 7. A negative value indicates deeper water-table conditions compared to control dipwell 7. For example, the mid-point dipwell for Ditch 8 became deeper over time compared to the ditch 7 control dipwell.

Supporting Information

Table S1. Total annual water fluxes from the ditch weirs

	m^3 of water					mm of runoff assuming original catchment area					mm of runoff assuming infilled ditch catchment area					% missing data in time series				
Year	Before	2011/12	2012/13	2013/14	2014/15	Before	2011/12	2012/13	2013/14	2014/15	Before	2011/12	2012/13	2013/14	2014/15	Before	2011/12	2012/13	2013/14	2014/15
Rainfall						1238	2255	2409	1786	1888	1238	2255	2409	1786	1888	0.0	0.0	0.0	0.0	0.0
Ditch 1 (reprofiled)	1747	391	534	659	847	594	133	181	224	288	717	160	219	270	348	0.0	4.5	0.6	0.2	0.2
Ditch 2^ (control – open)	2251	2167	14066	3448	2690	1154	1111	7213	1768	1379	930	895	5812	1425	1111	1.6	49.5	12.4	6.2	18.0
Ditch 3 (reprofiled)	580	575	1015	1167	1090	239	237	419	481	449	10945	10840	19158	22022	20568	31.3	19.3	0.6	0.3	0.2
Ditch 4 (dammed)	4328	2571	4266	8662	1985	3206	1904	3160	6416	1470	10183	6049	10038	20381	4670	0.2	0.0	0.6	0.3	0.2
Ditch 5 (dammed)	1090	458	1855	2606	4117	1125	473	1914	2689	4249	677	285	1151	1617	2556	0.0	0.0	0.6	6.2	0.2
Ditch 6 (control – open)	1631	3864	7053	4692	3978	1115	2643	4824	3209	2721	1091	2587	4721	3141	2663	11.4	0.0	0.6	6.2	0.2
Ditch 7 (control – open)	1065	2554	3618	4413	5570	868	2081	2949	3596	4539	796	1907	2702	3295	4160	6.9	0.0	28.1	13.8	0.2
Ditch 8 (reprofiled)	1360	184	492	720	995	1138	154	412	603	833	1878	253	680	995	1375	0.0	0.0	0.6	6.2	0.2
Ditch 9 (control –open)	3164	1087	2102	2575	2583	1927	662	1280	1568	1573	1457	501	968	1186	1189	8.7	0.0	0.6	0.3	0.2
Ditch 10 (dammed)	1218	558	1171	1013	1529	568	260	546	473	714	980	449	942	815	1230	0.0	0.0	0.6	6.4	12.8
Ditch 11 (reprofiled)	1116	447	249	1257	809	724	290	162	816	525	1827	731	408	2057	1323	0.0	9.7	51.6	0.3	0.2
Ditch 12 (dammed)	182	2	5	10	28	139	1	4	7	21	1431	15	40	77	219	6.9	0.0	15.3	3.4	0.2
Total	19731	14857	36426	31222	26220	979	737	1807	1549	1301	1346	1014	2486	2130	1789	5.6	6.9	9.3	4.1	2.8
Total (not including Ditch 2)	17480	12690	22360	27773	23530	960	697	1228	1525	1292	1429	1037	1828	2270	1923	5.9	3.0	9.1	4.0	1.4
Adjustment for missing data*	18518	13076	24507	28873	23853	1017	718	1340	1586	1344	1513	1068	1994	2361	2000					
Overall runoff coefficient, %						82	32	56	89	71	122	47	83	132	106					

‘Before’ data available 1st Aug 2010 to 31st Jan 2011

^Ditch 2 flow data less reliable

*There was a tendency for missing data to be distributed throughout the year and there was no fixed seasonal pattern in rainfall. Therefore the uplift was calculated by multiplying the existing value by $(1 + \beta)$ where β is the proportion of missing data for that weir.

Table S2. Total annual water fluxes from the overland flow (OLF) weir boxes.

	m^3 of water				mm of runoff assuming original catchment area				mm of runoff assuming modified catchment area				% missing data in time series			
Year	2011/12*	2012/13	2013/14	2014/15	2011/12*	2012/13	2013/14	2014/15	2011/12*	2012/13	2013/14	2014/15	2011/12*	2012/13	2013/14	2014/15
Rainfall					1716	2409	1786	1888	1716	2409	1786	1888	0.0	0.0	0.0	0.0
Ditch 1 (reprofiled)	0	141	567	708	0	1406	5671	7075	0	204	822	10254	0.0	2.1	0.2	1.4
Ditch 2 (control – open)	455	504	1260	3213	1987	2200	5504	14030	141	156	391	44	0.0	0.0	0.2	0.5
Ditch 3 (reprofiled)	53	170	336	559	181	585	1153	1921	7	22	43	2	0.0	0.0	0.2	2.0
Ditch 4 (dammed)	2	9	10	51	33	146	172	830	0	2	2	2	0.0	0.0	0.2	0.5
Ditch 5 (dammed)	0	102	504	225	0	2363	11718	5235	0	6	31	3	54.2	0.1	0.2	75.6
Ditch 6 (control – open)	88	433	467	202	1119	5475	5914	2557	76	370	399	22	0.0	2.1	10.5	58.7
Ditch 7 (control – open)	1	13	93	91	11	293	2061	2016	1	24	172	37	0.0	0.0	5.9	1.0
Ditch 8 (reprofiled)	693	349	67	50	2476	1245	238	180	1387	697	133	4	0.0	0.0	0.3	1.1
Ditch 9 (control –open)	1	46	40	23	23	839	727	421	5	185	160	17	43.0	0.0	5.9	1.2
Ditch 10 (dammed)	146	618	57	25	908	3840	355	156	14	600	55	2	69.7	0.0	0.1	1.2
Ditch 11 (reprofiled)	158	417	362	115	2510	6613	5741	1820	22	58	51	3	43.0	19.4	0.1	0.0
Ditch 12 (dammed)	52	19	14	7	485	179	126	67	142	52	37	2	43.0	44.0	0.3	46.8
Total	1650	2820	3776	5269	1089[a]	1862[a]	2493[a]	3478[a]	372[a]	636[a]	852[a]	1188[a]	21.1	5.6	2.0	15.8
Uplift for missing data[b]	1841	2922	3840	5600	1215	1929	2535	3696	415	659	866	1263				
Overall OLF capture, % of rainfall					71	80	142	196	24	27	48	67				

*2011/12 from 1st July 2011 to end of February 2012

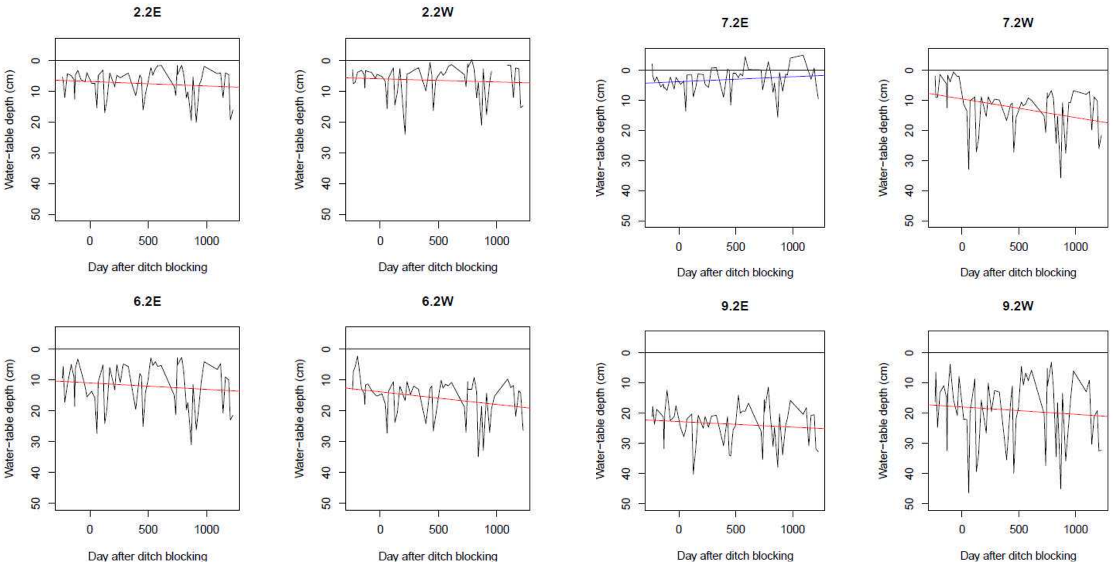
[a] Total area weighted OLF across the site (i.e., not a sum of the values in the column above)

[b] There was a tendency for missing data to be distributed throughout the year and there was no fixed seasonal pattern in rainfall. Therefore the uplift was calculated using $1 + \beta$ for each weir box where β is the proportion of missing data for that weir box.

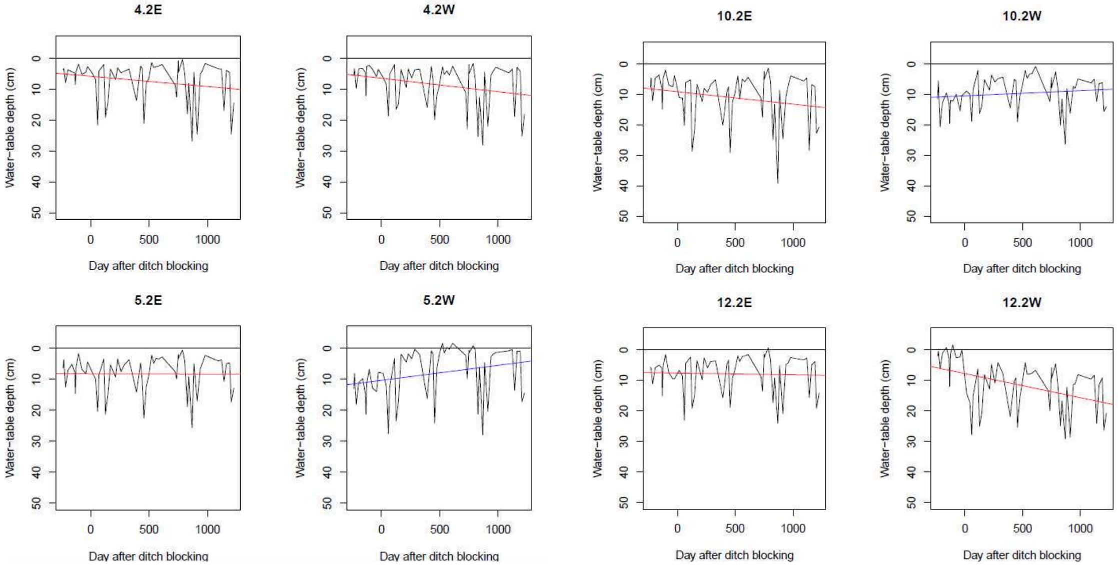
Table S3. Time-weighted mean water-table depth (cm) for each dipwell based on data from manual sampling visits (or extracted for the same time as the manual sampling from automatic records for x.mid and x.0). Negative values indicate water height above the peat surface. Empty cells indicate no data. Coding: mid = midpoint between ditches, 2E = 2 m east of the ditch, 2W = 2 m west of the ditch, 0 = within the ditch, C=located at gas flux chamber collar, 0 m, 1 m west or 3 m west of the ditch.

Ditch	Period	x.mid	x.2E	x.0	x.2W	Cx.0	Cx.1W	Cx.3W
1 reprofiled	before		4.4		15.7			
	2011/12	9.0	8.9	2.2	7.0	5.1	5.4	2.9
	2012/13	2.2	8.8	0.2	7.3	6.3	5.3	3.5
	2013/14	5.9	8.5	2.4	7.8	7.2	6.0	3.6
	2014/15	2.2	8.1	-0.1	8.8	6.7	6.7	4.8
2 open	before		5.6		4.0			
	2011/12	5.0	6.7	2.3	6.8	-3.5	1.4	5.2
	2012/13	4.6	6.2	-1.0	4.8	-3.5	2.4	5.2
	2013/14	6.9	7.0	-1.8	5.6	-3.9	2.5	5.3
	2014/15	4.1	7.6	-5.2	5.8	-3.0	3.1	5.2
3 reprofiled	before		10.8		5.1			
	2011/12	10.2	2.3	-2.6	6.1	6.0	4.5	4.5
	2012/13	7.4	1.8	-4.6	5.6	9.0	5.4	4.5
	2013/14	7.4	1.7	-3.9	7.1	11.9	6.1	5.5
	2014/15	15.2	2.5	-6.9	6.6	13.7	6.7	6.2
4 dammed	before		4.1		4.8			
	2011/12	6.8	6.3	10.6	6.6	4.5	4.8	1.1
	2012/13	6.2	6.3	9.6	8.0	5.1	7.6	2.1
	2013/14	8.0	7.4	9.8	9.0	5.7	9.5	2.8
	2014/15	9.0	7.7	5.6	8.6	4.3	11.7	3.7
5 dammed	before		6.4		12.0			
	2011/12	12.4	8.0	4.1	7.0	1.7	6.3	14.1
	2012/13	10.9	7.5	3.3	3.8	2.1	7.6	7.0
	2013/14	12.2	7.1	5.0	5.9	4.7	8.4	10.3
	2014/15	13.8	8.2	1.3	5.2	1.0	9.4	12.4
6 open	before		9.6		12.0			
	2011/12	8.9	10.7	-15.6	14.9	-0.6	21.7	17.8
	2012/13	0.9	10.6	-15.3	15.9	-1.1	7.6	8.6
	2013/14	9.9	11.5	-14.6	17.2	-2.7	9.8	9.1
	2014/15	7.2	11.6	-15.0	16.6	-4.6	12.1	10.4
7 open	before		1.9		2.8			
	2011/12	13.4	2.9	6.8	13.0	-7.1	15.7	20.7
	2012/13	12.4	1.7	1.6	13.3	-9.6	5.0	10.1
	2013/14	12.6	1.0	4.1	13.1	-8.8	5.2	12.1
	2014/15	12.5	2.3	5.1	12.5	-9.4	6.4	12.1
8 reprofiled	before		3.4		8.7			
	2011/12	11.2	7.8	21.0	14.0	16.9	6.6	5.4
	2012/13	9.4	7.7	18.3	13.1	14.8	7.1	5.7
	2013/14	13.2	8.7	20.7	13.6	19.1	8.9	7.0
	2014/15	19.4	8.3	18.7	13.3	20.0	9.4	7.7
9 open	before		20.2		14.5			
	2011/12	5.9	24.0		19.8	2.4	21.6	19.7
	2012/13	7.1	23.1		16.6	4.0	9.2	7.9
	2013/14	6.8	22.4		17.1	7.0	10.2	8.7
	2014/15	5.8	23.0		19.9	3.7	12.2	14.2
10 dammed	before		6.5		12.0			
	2011/12	11.1	10.1	10.5	7.4	3.6	12.5	6.9
	2012/13	8.9	10.3	10.3	7.1	3.5	8.9	7.4
	2013/14	15.5	10.7	13.4	9.2	4.8	9.6	8.7
	2014/15	15.5	10.2	15.7	7.8	2.0	10.4	9.7
11 reprofiled	before		7.3		8.3			
	2011/12	7.2	13.7	-4.0	5.6	2.9	8.2	2.9
	2012/13	-1.6	14.3	-6.9	5.0	2.9	6.9	3.9
	2013/14	6.5	14.6	-8.1	6.3	3.2	8.2	4.2
	2014/15	6.9	15.0	-9.5	5.0	5.4	9.6	5.8
12 dammed	before		6.6		1.7			
	2011/12	2.3	6.9	-9.9	11.8	3.4	6.8	4.4
	2012/13	1.1	6.6	-10.3	11.7	5.8	6.6	2.0
	2013/14	4.4	7.0	-7.5	13.4	3.6	8.3	0.3
	2014/15	2.2	6.2	-8.1	12.7	3.9	9.2	1.3

Control - Open



Dammed



Reprofiled

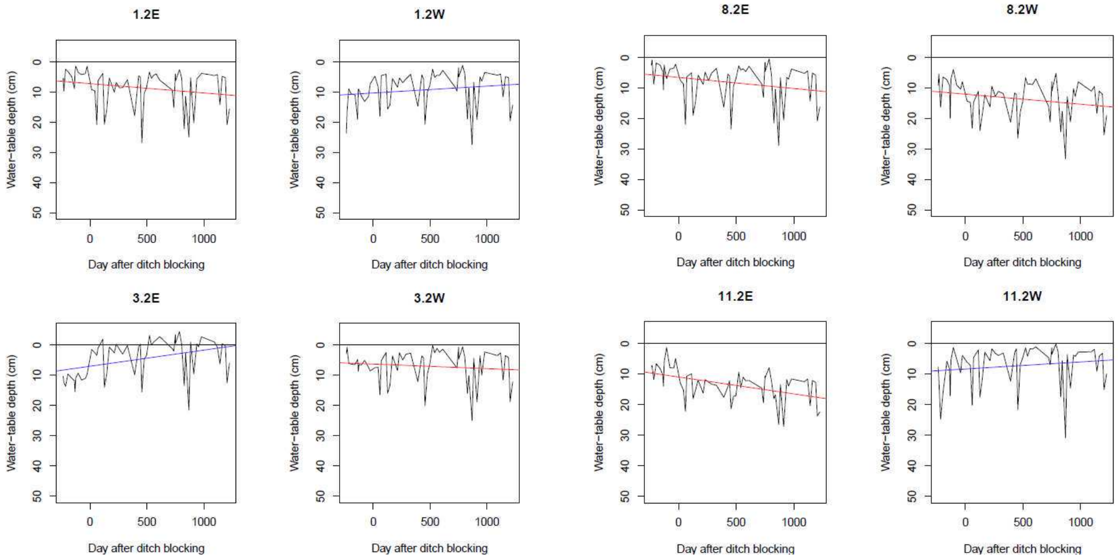


Figure S1. Water-table time series for dipwells located 2 m from each ditch with ordinary least squares regression trend lines.

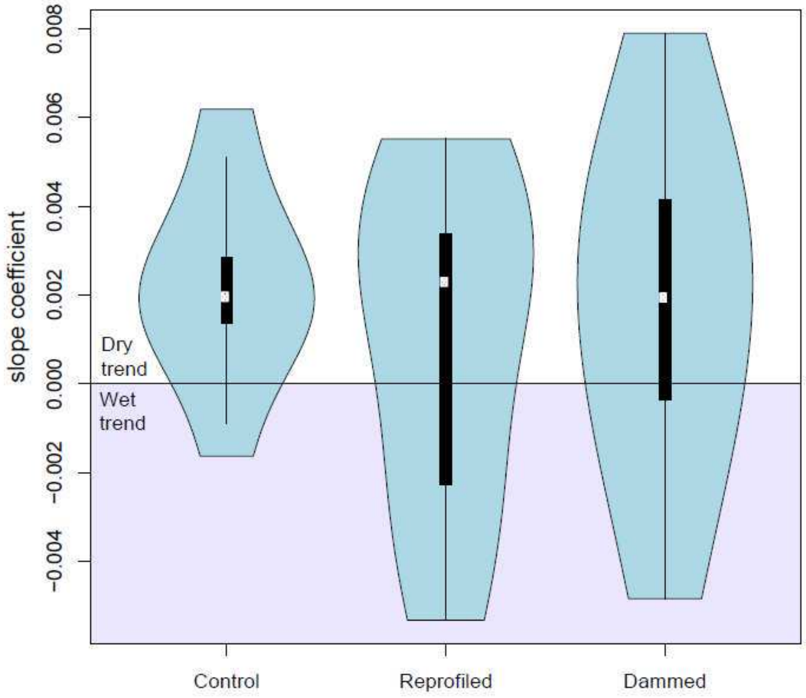
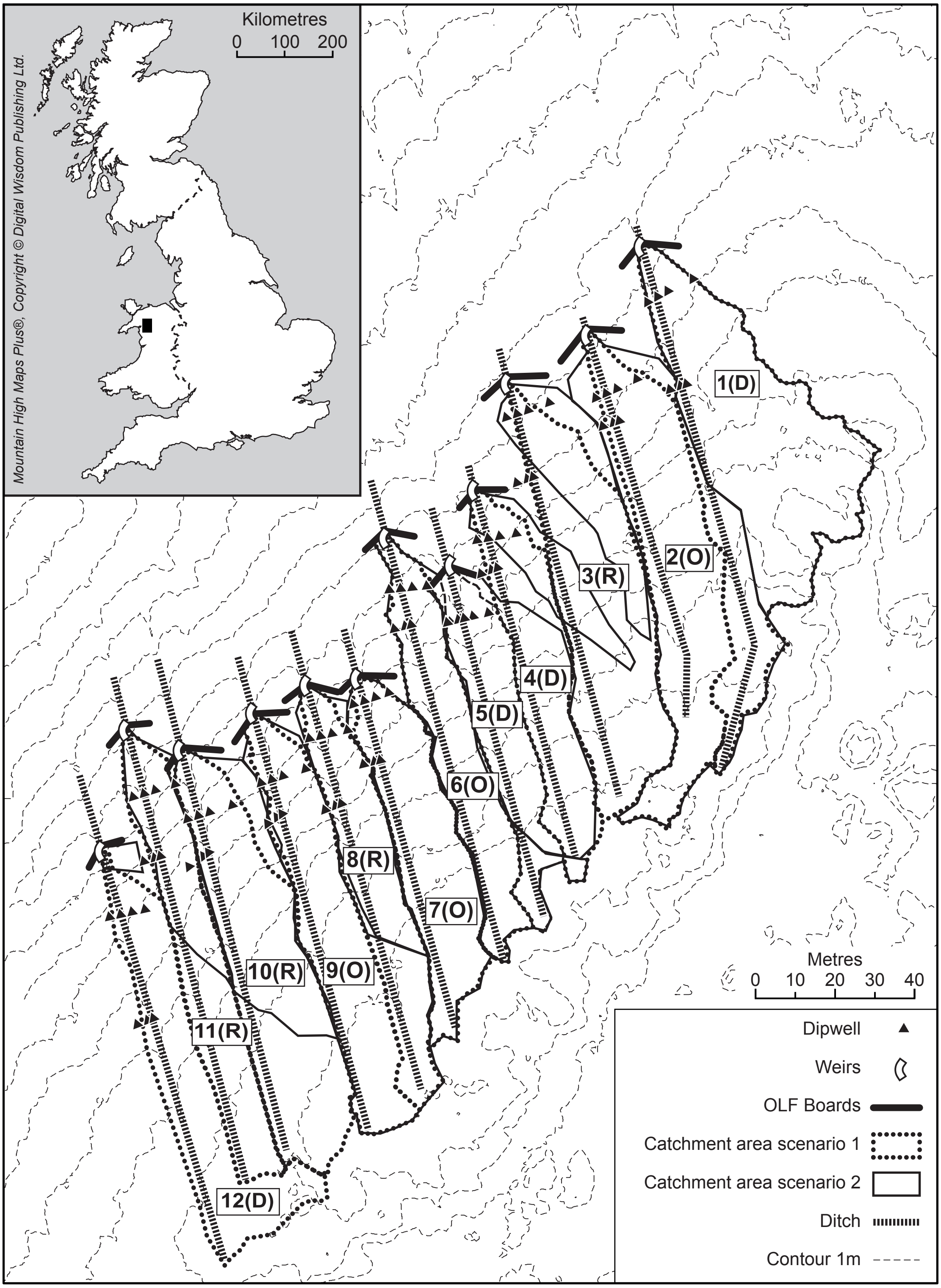
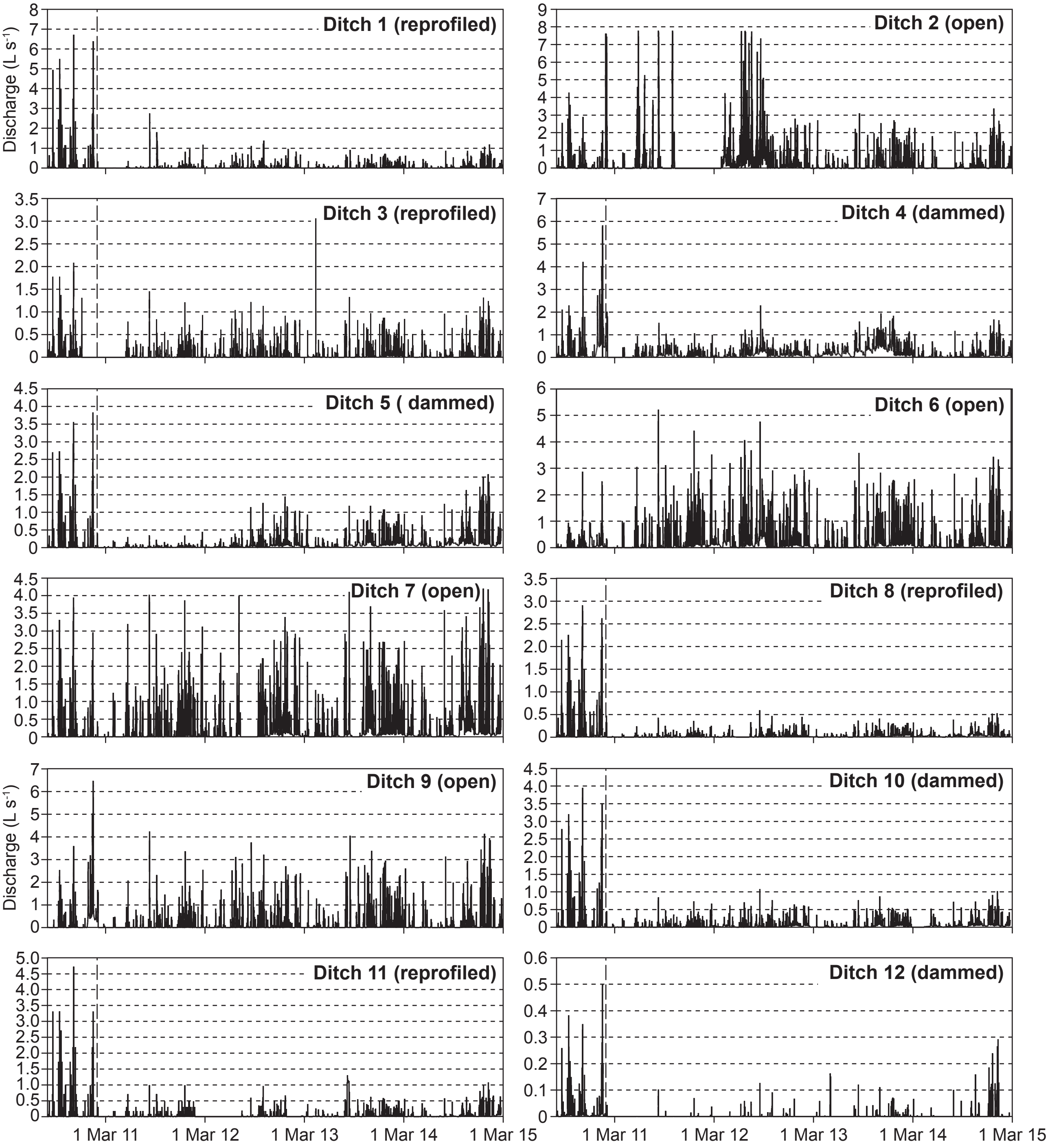


Figure S2. Violin plot (boxplot with kernel density) of least squares regression slope coefficients illustrating the greater number of trends towards increased wetness in the re-profiled and dammed treatments.


Kilometres
0 100 200
Mountain High Maps Plus®, Copyright © Digital Wisdom Publishing Ltd.
1(D)
2(O)
3(R)
4(D)
5(D)
6(O)
7(O)
8(R)
9(O)
10(R)
11(R)
12(D)
Metres
0 10 20 30 40
Dipwell
Weirs
OLF Boards
Catchment area scenario 1
Catchment area scenario 2
Ditch
Contour 1m


Ditch 1 (reprofiled)
Ditch 2 (open)
Ditch 3 (reprofiled)
Ditch 4 (dammed)
Ditch 5 (dammed)
Ditch 6 (open)
Ditch 7 (open)
Ditch 8 (reprofiled)
Ditch 9 (open)
Ditch 10 (dammed)
Ditch 11 (reprofiled)
Ditch 12 (dammed)
Discharge (L s^{-1})
Discharge (L s^{-1})
0
1
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1.0
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1 Mar 11
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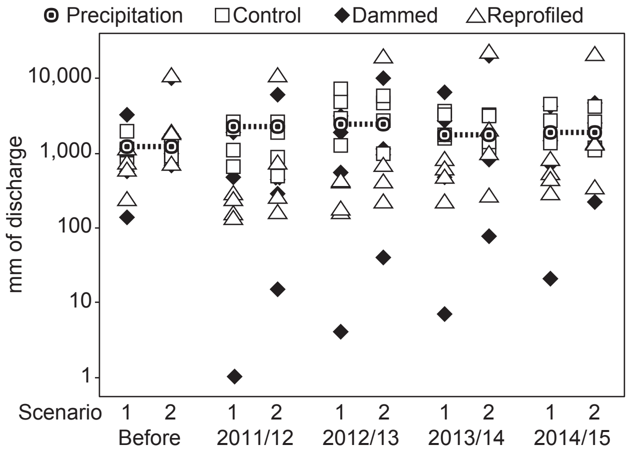
1 Mar 15


Precipitation
Control
Dammed
Reprofiled
mm of discharge
10,000
1,000
100
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1
Scenario
1
2
1
2
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1
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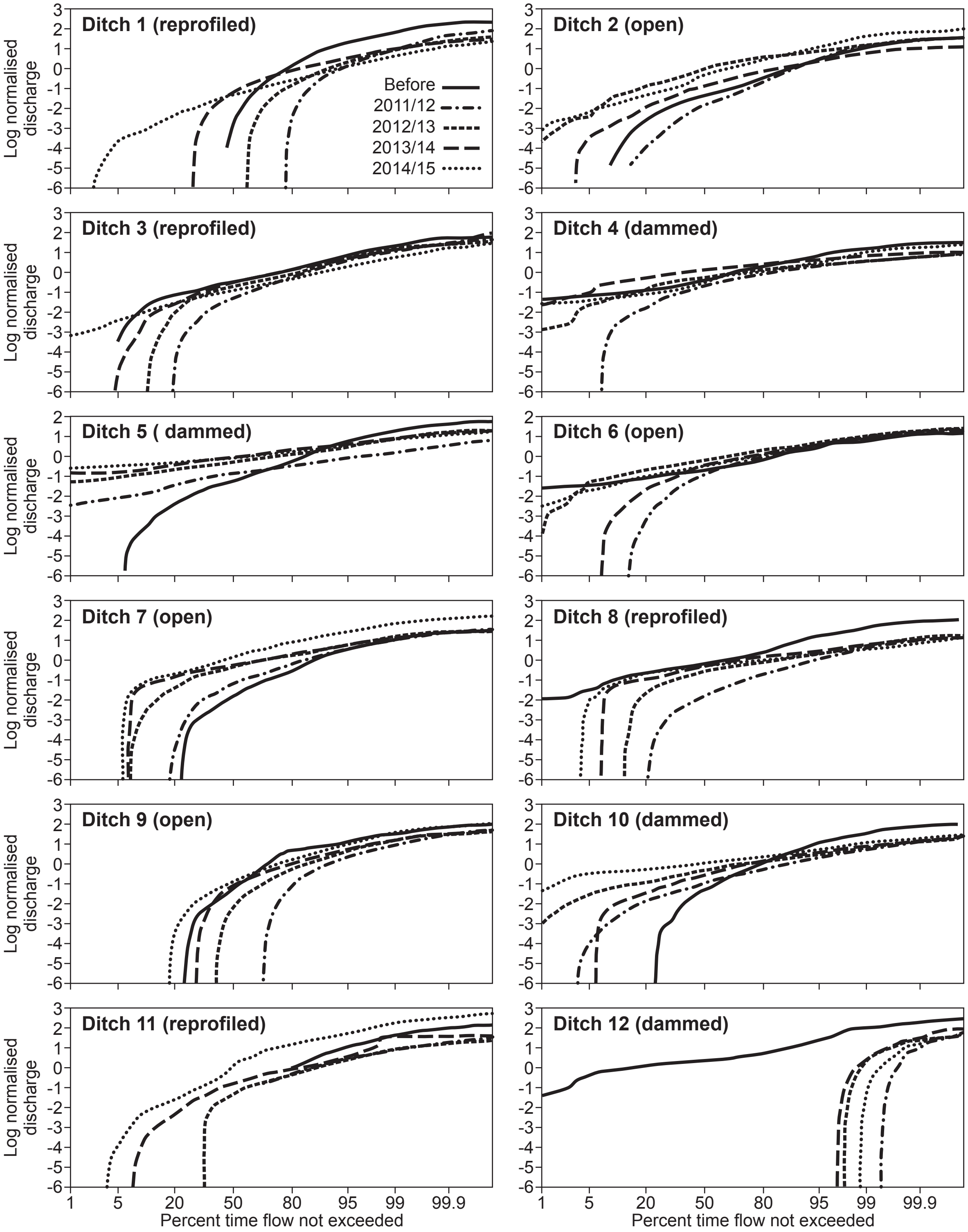
Before
2011/12
2012/13
2013/14
2014/15

Ditch 1 (reprofiled)
Ditch 2 (open)
Ditch 3 (reprofiled)
Ditch 4 (dammed)
Ditch 5 (dammed)
Ditch 6 (open)
Ditch 7 (open)
Ditch 8 (reprofiled)
Ditch 9 (open)
Ditch 10 (dammed)
Ditch 11 (reprofiled)
Ditch 12 (dammed)
Before
2011/12
2012/13
2013/14
2014/15
Log normalised discharge
3
2
1
0
-1
-2
-3
-4
-5
-6
1
5
20
50
80
95
99
99.9
Percent time flow not exceeded

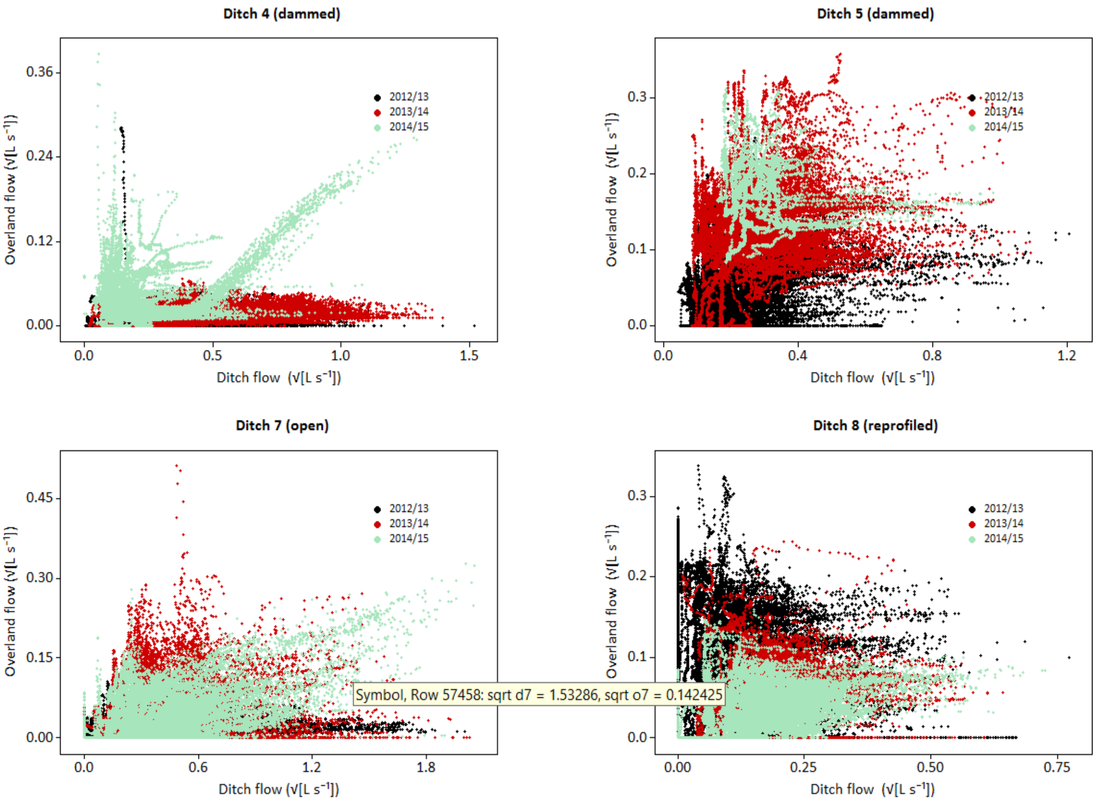


Figure 5. Scatterplots of overland flow and ditch flow for Ditches 4, 5, 7 and 8. Data shown are square root discharges.

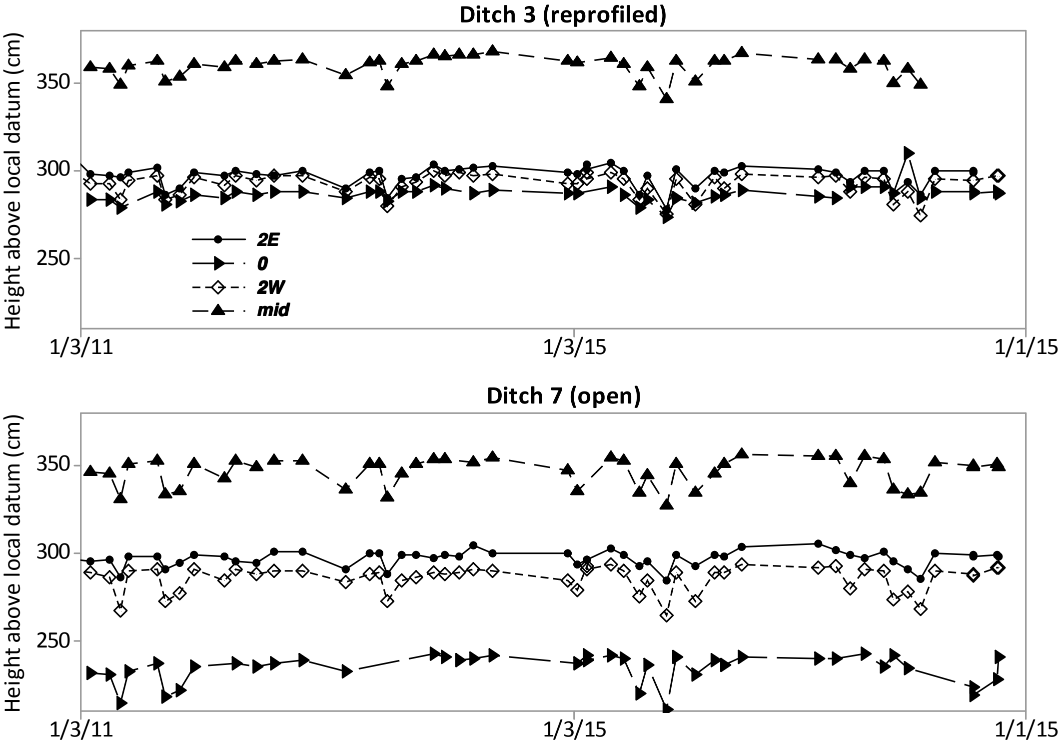
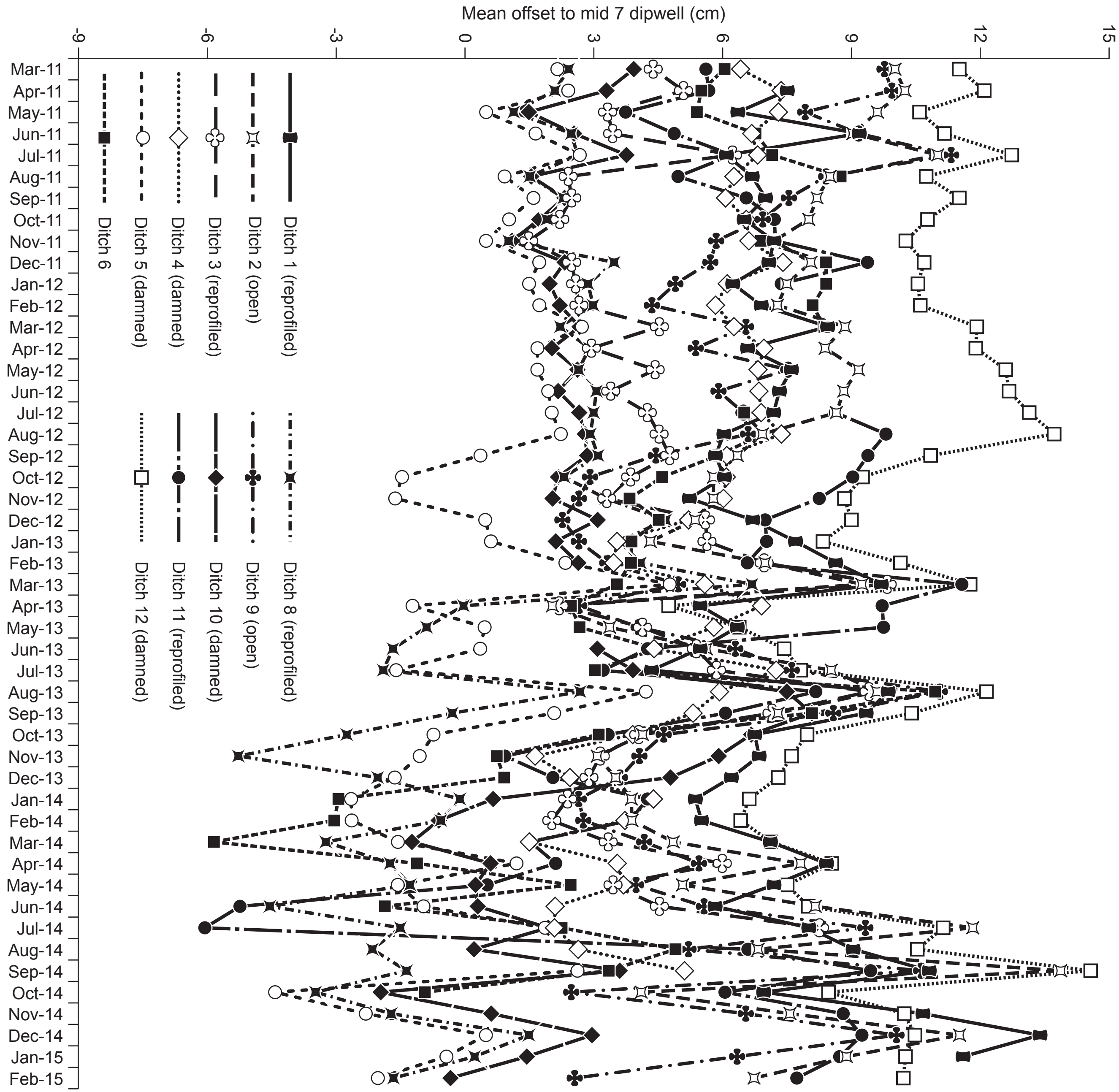


Figure 6. Water-table height above local datum for two example ditch transects


Mean offset to mid 7 dipwell (cm)
-9
-6
-3
0
3
6
9
12
15
Mar-11
Apr-11
May-11
Jun-11
Jul-11
Aug-11
Sep-11
Oct-11
Nov-11
Dec-11
Jan-12
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Feb-15
Ditch 1 (reprofiled)
Ditch 2 (open)
Ditch 3 (reprofiled)
Ditch 4 (damned)
Ditch 5 (damned)
Ditch 6
Ditch 8 (reprofiled)
Ditch 9 (open)
Ditch 10 (damned)
Ditch 11 (reprofiled)
Ditch 12 (damned)