Paper:
Wilson, L, Wilson, J, Holden, J, Johnstone, I, Armstrong, A and Morris, M (2011) *The impact of drain blocking on an upland blanket bog during storm and drought events, and the importance of sampling-scale.* Journal of Hydrology, 404 (3-4). 198 - 208. ISSN 0022-1694

http://dx.doi.org/10.1016/j.jhydrol.2011.04.030

Title: The impact of drain blocking on an upland blanket bog during storm and drought events, and the importance of sampling-scale.

Authors: Lorraine Wilson[1,6], Jared Wilson[1,4], Joseph Holden[2], Ian Johnstone[3], Alona Armstrong[2,5] & Michael Morris[1].

Affiliations at time of study:

[1] LIFE ABBW Project, Severn Trent Water Office, Llanwddyn, Oswestry, Powys, UK.

[2] School of Geography, University of Leeds, Leeds, UK.

[3] RSPB, North Wales Office, Uned 14, Llys Castan, Fford y Parc, Parc Menai, Bangor, Gwynedd, UK.

Contact details for corresponding author (Lorraine Wilson):

[6]SOI Ltd, New Technology Centre, North Haugh, St. Andrews, Fife, KY16 9SR.

Email: Lorraine_mb@hotmail.com

Tel: 01333 311746

Current Address (where different from above):

[4] SOI Ltd, New Technology Centre, North Haugh, St. Andrews, Fife.

[5] Department of Geographical and Earth Sciences, University of Glasgow, Glasgow.

Abstract:

Organic carbon solution and transport processes which occur during periods of heavy rainfall and periods or little or no rainfall, can exert a significant control over a systems' annual organic carbon budget. In addition, either or both extremes can be key contributors to contaminant release, water discolouration, flood risk or vegetation growth. Although there is an increasing body of work studying hydrological responses to peatland restoration, there are very little available data on the performance of restored peatlands during these key periods. This study builds on previous work from an upland peatland in Wales that has been restored through drain-blocking, and presents evidence from a landscape scale experimental study at the site. A comparison of sampling scales within the study demonstrates the necessity of larger spatial scales, in combination with high resolution datasets, in assessing catchment level responses. Our results suggest that drain blocking leads to higher and more stable water tables that are able to better resist drought periods, and thus lead to more stable discharge from the system. The shallower water tables and pooling in drains also appear to reduce the production and transport of fluvial organic carbon, and thus less organic material is available to be released as during peak flow or dry periods. Despite restoration apparently reducing the available water storage within the peat, the increase in overland flow and in pooling within blocked drains appears to have led to a less flashy system. Peak flow responses in both drains and upland streams are less severe, with more rainfall being retained within the bog. We suggest that restoration leads to a more buffered system, with more moderate responses to extreme events, and reduced release of both dissolved and particulate organic carbon. We discuss the implications of this for fluxes of fluvial organic carbon and sediment loss.

Keywords: blanket bog, DOC, POC, water colour, water table depth, flood risk, ecosystem services, water quality, climate change mitigation.

Introduction:

The increase in peatland restoration work seen in recent years has largely been driven by legislative protection (EU Habitats Directive, 92/43/EEC) and attempts to protect and restore peatland biodiversity (Holden et al., 2007). This is generally based upon the creation of shallower and more stable water tables (Holden et al., 2004), under the premise that this will promote the recovery of specialist vegetation communities (Komulainen et al., 1999; Tuittila et al., 2000). Despite the singularity of its principle aim, there is an increasing focus on such restoration as a tool for delivering a wider set of ecosystem service benefits. These include improving water quality, both for drinking water and to meet environmental standards (such as those in the EU Water Framework Directive, 2000/60/EC), reducing soil erosion (Evans et al., 2006; Holden, 2006b), improving the carbon storage potential of the peatland itself (Lindsay, 2010; Worrall et al., 2009), and acting to stabilise water discharge (Lane et al., 2003). This last function encompasses both reducing the severity of flood responses (peak timing and size) and increasing the stability of water tables during drought events. As both of these extremes are predicted to become more likely in the changing global climate, understanding the role of land management and restoration on water supplies is likely to become increasingly important (Delpla et al., 2009).

Improving the stability of water tables during periods of low or no rainfall is an important part of peatland recovery (Money and Wheeler, 1999). As already mentioned, the recovery of peatland vegetation can be largely dependent on water tables (Cooper et al., 2005; Girard et al., 2002), and maintenance of near-surface water during drought periods is thought to be particularly important (Breeuwer et al., 2009). However, drought periods also tend to see very high fluvial concentrations of dissolved organic carbon (DOC), with autochthonous material becoming more important (Glatzel et al., 2006; Jager et al., 2009). But, considering the low flows associated with droughts, perhaps of more importance are reported large flushes of organic carbon when dried peat is re-wetted (Francis, 1990; Jager et al., 2009). Although collectively these two scenarios do not necessarily lead to greater overall DOC fluxes (Jager et al., 2009; Worrall and Burt, 2008), it does have implications for drinking water treatment through both increased costs, and the difficulty of treating "spikes" of colour entering a treatment works which can lead to a reduced flow through the works which in turn can cause drinking water supply issues. If there are significant levels of DOC in the treated water when finally chlorinated there is a risk of exceeding safe limits for carcinogenic trihalomethanes (Pereira et al., 1982; Watts et al., 2001). With rainwater and throughflow penetrating into deeper soil layers during dry periods (Worrall et al., 2007b), several studies have demonstrated concurrent increases in the release of heavy metals and other nutrients (Eimers et al., 2007; Tipping et al., 2003), along with both positive and negative links between these and the production of DOC within the peat (Clark et al., 2005; Tipping et al., 2003). If peatland restoration is capable of reducing the exposure of deeper peat layers during dry periods, then the levels of metals and nutrients within the peat and in discharge waters under these regimes needs further study.

Higher water tables during summer periods may also alter the supply of water from peat catchments. However, the flashy nature of peatland discharge, and a paucity of available data, makes it difficult to predict whether successful restoration would lead to more stable summer discharge or the complete cessation of summer baseflow (Evans et al., 1999; Holden and Burt, 2003a). Interestingly, some studies have suggested a degree of feedback between vegetation growth and water table stability, with increasing vegetation cover improving the self-regulating abilities of the peat acrotelm, probably by retaining higher moisture levels beneath plant canopies, and thus reducing surface evaporation (Petrone et al., 2004; Smolders et al., 2003). With little data available to enable comparison of the behaviour of water tables or stream discharge during drought events before and after peatland restoration, there is a need for further study of this area to permit better prediction of the wider implications of restoration.

In common with drought periods, the hydrological performance of peatlands during periods of peak flow is of particular interest, for a wide range of reasons. Perhaps the most significant is that of sediment (or particulate organic carbon, POC) and DOC release, with the vast majority of sediment transport thought to occur during peak flow events (Evans et al., 2006). In contrast to the changes in DOC release during drought events, concentrations of both DOC and POC may show an initial rise during peak flow events followed by greater declines, but with the higher discharge, overall loads are generally greater (Clark et al., 2007; Holden and Burt, 2002a). There is also strong evidence that peatland drainage has led to increased yields of both DOC and POC (Evans and Warburton, 2005; Holden, 2006b; Worrall and Burt, 2007), and thus peatland restoration, if it can reduce the severity of peak flow events, or alter the flowpaths used, has the potential to reduce overall fluxes of fluvial organic carbon (Holden et al., 2004; Wallage et al., 2006; Worrall et al., 2007c). There is some evidence that rewetted peatlands show an increased importance of saturation-excess overland flow relative to flow through the peat (Wilson et al., 2010). While overland flow is often considered a fast route for water escape across catchments, if the peatland has a good, thick vegetation cover with high roughness then water will be slowed compared to more rapid pathways along open drains or eroding, less well-vegetated peat (Holden et al., 2008). This attenuated route for rainfall leaving the system along with pooling behind dams, has the potential to provide a buffer during peak flow events, slowing water release and reducing the flashiness of the discharge response (Holden, 2006b; Holden and Burt, 2002a). Few studies have directly investigated the impact of drain blocking on peak flow hydrographs, although this is often cited as a potential benefit to restoration (reducing down-stream flood surges, Beven et al., 2004; Lane et al., 2003). Thus, while some evidence suggests that raised water tables will increase flashiness or that rapid pipeflow will maintain rapid flood responses (Daniels et al., 2008; Holden and Burt, 2002c; Holden et al., 2004), others demonstrate a general decline in discharge and DOC yields after restoration (Armstrong et al., 2010; Wilson et al., 2010). These apparent conflicting results may stem simply from the considerable variation observed between different study sites (see Armstrong et al., 2010), but they only highlight the need for further study of the impact of drain blocking on peak flow events if we are to better understand this issue.

In this study we aim to test whether drain-blocking alters the performance of a blanket peat system during extreme events; in particular, whether both water tables and discharge become more stable during short-term drought periods, whether peak flow events become less severe and whether any changes are apparent in streams as well as drains. An additional aim is to explore the response of organic carbon release during storm events, and during and just after drought events to test whether drain-blocking has the potential to reduce release during these key periods.

1.1 Study site

This study was based within the Lake Vyrnwy catchment (mid-Wales, OS Grid Reference SJ016192), which covers approximately 10,000 ha, and contains 4743 ha of upland blanket bog as part of an extensive upland mire mosaic. The blanket bog here and on surrounding land is the qualifying feature for the Berwyn & South Clwyd Mountains Special Area of Conservation (SAC, EC Habitats Directive, 92/43/EEC). Assessed as being in unfavourable ecological condition (CCW, 2008) due to historic burning and overgrazing, and extensive drainage, the site has been managed through a program of drain-blocking, with heather bale dams at approximately 5m intervals, as part of the LIFE-Nature Active Blanket Bogs in Wales Project (LIFE ABBW project, www.blanketbogswales.co.uk). Four sub-catchments within the site (Eiddew, Eunant, Hirddu and Nadroedd, see Fig. 1) were restored sequentially in each winter period of the project (starting winter 2006/07, finishing winter 2009/10). This allowed the collection of both longitudinal before/after data within sub-catchments, and experimental/control data across sub-catchments thus providing the unusual combination of a landscape scale and experimental study. Data collection commenced in November 2007 and continues, although this paper presents data from November 2007 to August 2010. Previously we have presented evidence that the restoration programme has lead to raised and more stable water tables, with more surface flow and lower overall discharge (Wilson et al., 2010). We have also suggested that these changes have led to observed declines in water colour, and overall yields of dissolved and particulate organic carbon leaving the system (Wilson et al., 2011).

Methods:

2.1: Data collection

To obtain flow rate data, automatic pressure transducers (Trafag Series 64) were installed in stilling wells (to prevent sediment build up) in 1 drain and 1 stream in each of Eiddew, Eunant, and Hirddu, and in 1 drain in Nadroedd. All except the Hirddu stream transducer were installed directly upstream of a V-notch weir to allow accurate gauging. As a weir could not be installed in the Hirddu stream, the stilling well was situated within a rated section (Gibb, 2009). An additional 3 transducers were installed in 1m plastic pipe dipwells located at 0.5m, 1m and 5m downslope from a drain (which followed the slope contour) within the Nadroedd catchment to provide high temporal resolution water table depth records. All transducers were set to record pressure readings at 15 minute intervals and data were downloaded regularly. Pressure readings were converted to water depth via calibration against regular manual samples, and stream and drain datasets were further converted to flow rates using a standard V-notch weir equation (www.lmnoeng.com).

An automated sampler (Teledyne Isco 6712) was installed in a drain in Hirddu to allow collection of water samples at 15 minute intervals during peak flow events. These samples were tested to determine water colour as measured by absorbance at 254nm, 400nm, 450nm and 650nm (using Thermo Scientific Genesys 10uv), and dissolved and particulate organic carbon levels (DOC using thermal oxidation with an Analytical Sciences Elemental Analyser, and POC using methods modified from Ball, 1964).

Catchment size for each flow gauge was estimated using Ordinance Survey and mapped drain layers in MapInfo (v. 6.2). High resolution rainfall data were provided by the Environment Agency Wales, from a gauge at Lake Vyrnwy (OS Grid Reference: 301540 318810, lying between 3-10km from the study areas). Rainfall in 2007-2009 fell within the 1971-2000 regional mean, but 2010 represented a slightly drier and sunnier year compared to the 30 year means (www.metoffice.gov.uk). To identify discrete storm event hydrographs (with few peaks and low antecedent flow), dates were chosen which had more than 10mm of rainfall, and little rainfall (less than 1mm) on preceding or following days. Drought events were identified as any period of five days or more where there was no rainfall. This duration was selected as preliminary analyses suggested that streamflow recession following rainfall events never exceeded 2-3 days, and evidence of peat drying was apparent within 5 days. This drought length also ensured that sufficient discrete events were available to permit robust analyses.

Additional data on water table depth, water colour and levels of DOC and POC in discharge waters during and just after drought periods, were obtained from fortnightly surveys in all four sub-catchments where survey dates fell within the identified drought periods, or within 10 days of the end of the drought. These survey data are described fully in Wilson et al. (2010) and Wilson et al. (subm.), but briefly they include water table depth measurements from all four sub-catchments, with 78 dipwells on 13 transects spanning drains (dipwells were located at 0.5, 1 and 5m from drains; the drains themselves typically ran parallel to slope contours). Water colour data as measured by absorbance at the wavelengths listed above, were obtained from 38 sample points located across all sub-catchments (22 in drains and 16 in small streams), and these data were later converted to estimated DOC and POC concentrations (mg l^{-1}) and loads (mg s^{-1}) using calibration datasets and standard regression models (see Wilson et al., 2011 for full methods).

2.2 Data analysis: Drought events

Periods of at least 5 days without rainfall were identified as droughts, with 17 in total occurring during the study period (4 of which were in the winter half year: October to March, and 13 in the summer half year: April to September). Drought length ranged from 5 to 18 days, averaging 9.33

days, and with data being collected from each flow gauge this gave a total of 98 discharge hydrographs (35 pre-blocking, 63 post-blocking), and 54 water table traces (27 pre-blocking, 27 post-blocking). Drought timeseries were plotted against rainfall for each of the three dipwell gauges, and for the seven flow gauges. As antecedent levels (when rainfall ceased) of both water tables and flow rates were likely to largely determine levels during subsequent drought periods, all data were converted to change relative to antecedent level ('adjusted' data). Additional variables were created that gave the change in water table depth or flow rate over each 12 hr period. These 'rate of change' variables were intended to give a measure of the rate of water table or discharge decline occurring during the droughts.

Adjusted water table data were entered into simple Generalised Linear Models (GLM, each dipwell analysed separately) with antecedent depth, and day since last rainfall ('drought day', testing whether rates changed over the course of a drought) as explanatory variables, alongside the experimental factor of whether the drain was blocked (unblocked/blocked), and an interaction term of unblocked/blocked * drought day. GLMs for rates of change of water tables were as above, but included the additional factor of whether it was day or night. These GLMs were also repeated using only the six summer events (within June to August). This was to test, and control for, a prediction that summer evapotranspiration would cause drawdown of water tables to follow a diurnal pattern (Evans et al., 1999). Flow rate data from drains and streams were analysed separately, with simple GLMs modelling both adjusted flow and rate of change data against site, antecedent flow, drought day, and the experimental factor of unblocked/blocked. In these GLMs, two interaction terms were included: site * unblocked/blocked and unblocked/blocked * drought day.

Water table depth and estimated DOC and POC levels taken from the wider fortnightly surveys covered 14 of the 18 droughts, and 12 post-drought periods (only post-drought surveys days with >0.4mm rainfall were used). Four basic dependent variables: water table depth, water colour (absorbance at 400nm), DOC and POC concentrations; plus three flow-weighted measures of 'total' colour, DOC and POC loads were used, with all except water table depth being split into drain and stream samples. These were then entered into simple GLMs against site, date and unblocked/blocked. The water table depth models included a distance to grip parameter. Larger sample sizes within the drought analyses, allowed the inclusion of an interaction term of site * unblocked/blocked in the water table and drain GLMs. Small sample sizes in the post-drought stream analyses necessitated the exclusion of the date variable. As multiple variables were being entered into the drain and stream models, a reduced p_{crit} of 0.01 was applied.

2.3 Data analysis: Storm events

31 different storm events were identified from rainfall datasets where the data fitted two basic criteria: these events needed to be isolated from previous and subsequent persistent rainfall by at least 48 hours, and had to consist of a relatively concentrated period of rainfall. These two criteria allowed an assessment of change from, and return to, an approximate baseflow; and provided a simple hydrograph response allowing more accurate data extraction. Storm hydrographs for each flow gauge and dipwell were plotted against rainfall, and standard parameters were measured either from the hydrograph, or calculated from the timeseries data. From the water table datasets, the following parameters were measured: peak depth (shallowest water table depth), water table difference (difference between antecedent and shallowest levels), and recession duration (time taken to return to antecedent level). Parameters measured from drain and stream flow rate datasets include: antecedent flow, start lag (time from rainfall start to start of hydrograph rise), peak lag (time from rainfall peak to hydrograph peak), peak flow rate, time to peak (from start of hydrograph rise to its peak), recession duration (from hydrograph peak to point of levelling off), and total storm flow. Using antecedent flow as an estimate of baseflow throughout the event, total baseflow, and therefore total runoff and the runoff/baseflow ratio were calculated. Using total storm rainfall, and estimated catchment size, total runoff could be converted to a runoff efficiency factor representing the amount of rainfall falling on the catchment that was released during the event. The ratio of peak

flow rate to total storm flow was used as an index of 'flashiness'. Each of these parameters was entered into a simple GLM with the catchment, total storm rainfall, and whether the catchment was blocked as explanatory variables. Data from drains and streams, and from each dipwell were analysed in separate GLMs. Larger sample sizes within drain GLMs permitted the inclusion of the interaction term catchment * unblocked/blocked. As multiple dependent variables were being entered into the same GLMs a reduced p_{crit} of 0.005 was applied.

Equipment problems meant that the automatic storm sampler only collected samples from six of the events identified above prior to drain blocking, and none after. The collected samples also failed to cover the entire peak flow event in all but one case. Thus it was only possible to provide simple regression analyses of peak flow rates (which were covered for each event) and maximum observed DOC and POC concentrations or loads. While this did not provide a solid assessment of fluvial organic carbon release during peak flow events, it provides basic information on the link between release and a reliable measure of event severity. Unlike for the drought analyses, the short duration of storm events prevented the wider routine DOC and POC survey data being used.

Results:

3.1 Drought events

Adjusted water table depth GLMs all showed good model fit (R^2 = 0.89, 0.87 and 0.93 for 0.5m, 1m and 5m dipwells respectively), and all showed highly significant responses to all of the GLM factors including the interaction terms of unblocked/blocked * drought day (Table 1). These results suggest that water table depths drop more rapidly and to a greater depth from their antecedent starting point after blocking, at both 0.5 and 5m from the drain, with the dipwell at 1m being more variable and showing no overall trend. Rate of change GLMs generally showed less consistent results, with only the 1m dipwell showing a marginally significant response to drain blocking (Table 1). However, data from each dipwell were so variable that no overall trend is apparent. It is worth noting that none of the models showed a significant effect of day/night periods, and when models were repeated with only the summer events, this pattern remained ($p > 0.1$) .

GLMs analysing wider survey data showed a contrasting result to the three Nadroedd dipwell transducers analysed above. In these analyses, drain blocking had a significant effect on water table depth during drought periods (Unblocked/blocked: $F_{1,694}$=7.72, p=0.006; Site * Unblocked/blocked: $F_{2,694}$=5.75, p=0.003), with water tables being slightly higher after blocking (unblocked: -9.27 ± 0.99cm, blocked: -7.81±0.47cm). The degree of change depended on the distance from the drain with water tables being less responsive to blocking at 5m from drains (Fig. 2).

Adjusted drain discharge rates, and rates of change in drain discharge (model fits: R^2=0.55, R^2=0.90) showed highly significant responses to drain blocking when looking within sites (adj. flow: $F_{2,38355}$=1444.2, p<0.0001; rate of change: $F_{2,800}$=7.95, p=0.0004). Drain blocking appears to have led to more stable, higher flow rates throughout droughts, and slower declines in flow rate during the first 5 days of a drought (Fig. 3).

Stream discharge GLMs followed the same pattern as drain discharge data (models fits: adj. flow R^2= 0.77; rate of change R^2= 0.98), with flow rates across all catchments being higher and hydrograph recession rates generally slower after blocking (adj. flow: $F_{2,25987}$=1200.1, p<0.0001; rate of change: $F_{2,538}$=18.08, p<0.0001). The importance of the unblocked/blocked *drought day interaction term shows that while post-blocking flow rates remained higher throughout droughts, hydrograph recession rates were lower only during the first 3 days (Fig. 4).

During drought periods, Abs^{400} measured as part of wider, fortnightly surveys appeared to increase slightly in drains (Table 2). However accounting for flow rates, ‘total’ colour released showed a slight decline in drains after blocking (Fig. 5). In streams, neither absorbance measure varied during droughts in responses to blocking, although there was a slight trend towards lower flow weighted Abs^{400} after blocking (Table 2). In drains, DOC concentration during droughts increased significantly after blocking, but as with colour, flow weighted loads showed slight declines (Fig. 5). This variation was not apparent in streams, with neither concentration nor loads changing after blocking. Neither POC concentrations nor POC loads released during drought periods changed in response to blocking, although in streams, there was a non-significant trend towards lower POC loads after blocking (Table 2).

Prior to drain blocking, there was evidence of a re-wetting 'flush', with higher absorbance and dissolved organic carbon values during post-drought periods (Figs 5 and 6). Within drains, blocking led to marked declines in post-drought flow weighted Abs^{400} (although simple Abs^{400} showed a marginal increase, see Table 3), and declines in loads of both DOC and POC, while concentrations of both showed little change after blocking (Table 3 and Fig. 5). Although matching post-blocking changes within streams were suggested by the data within streams (Fig. 6), these were statistically non-significant, possibly due to a combination of lower sample sizes and greater inter-stream variability (Table 3).

3.2: Storm events

The peak water table depth reached during storm events increased in response to drain blocking at both 0.5 and 5m from the drain but not at 1m (Table 4), although the data suggest that this dipwell shows a matching trend. The difference between antecedent and peak levels did not change at any distance, probably due to higher antecedent levels after blocking, however, the recession duration of water tables showed some evidence of increasing at all distances.

Peak flow events in drains (see Fig. 7) showed significantly lower peak flow rates, baseflow rates remained stable but declines in total runoff led to strong declines in the runoff:baseflow ratio. Both indices of efficiency and flashiness showed significant declines after blocking, however lag times, despite being potentially vulnerable to error due to the distance from rain gauge to weir, did not change.

Peak flow events in streams showed generally less response to drain blocking than drains, however peak flow rates showed a non-significant matching decline (Fig. 8). Again, although runoff did not show any overall trend, the runoff:baseflow ratio in streams showed significant declines after blocking, as did the flashiness of the hydrograph (Fig. 8). As observed in drains, lag times did not change, and at the stream scale, no change in system efficiency was observed.

Simple regression analyses for peak flow rate versus maximum DOC and POC concentrations and loads showed only one relationship that approached significance, with DOC load showing some signs of increasing with higher peak flow rates ($R=0.76$, $n=6$, $p=0.08$), all other regressions had p-values > 0.3.

Discussion:

Previous studies have suggested that the drawdown in water tables during dry periods can lead to considerable changes in peat structure, with increased occurrence of macropores and recession of the peat surface (Francis, 1990; Holden and Burt, 2002b). However, the persistence of such changes, and their impact on flowpaths and nutrient release after the drought is less clear (Holden and Burt, 2002b; Worrall and Burt, 2008; Worrall et al., 2007b), although the occurrence of a major flush of both sediment and dissolved nutrients on re-wetting of the peat has been widely reported (Clark et al., 2005; Francis, 1990; Holden and Burt, 2003a; Holden and Burt, 2002a; Mitchell and McDonald, 1992). Very little is known about the role of peatland restoration in influencing drought hydrology, although it has the potential to mitigate against many of the negative effects of droughts such as organic carbon release or vegetation change (Breeuwer et al., 2009; Wilson et al., 2011). In this study, we focussed on short term dry spells to allow both a high resolution study of water table and discharge responses, and also an experimental test of the impact of peatland restoration on such responses. We analysed water table depth in three dipwells at high temporal resolution, and at low temporal resolution over a much wider area and larger sample size. Although both datasets showed the expected water table drawdown during drought periods, they showed conflicting responses to drain-blocking with two of the three high resolution dipwells showing water tables falling to deeper levels after blocking than before, whereas the larger study showed generally shallower water tables during post-restoration droughts. These results suggest that at least two of the water table loggers were installed at points with non-standard local hydrology, perhaps due to the presence of a peat pipe linking that point directly with the stream system (Daniels et al., 2008; Holden, 2005a), or localised variation in peat saturation (Holden and Burt, 2003b). The wider datasets, although without the fine temporal resolution, were inherently robust against such small scale variations and thus whilst representing a more reliable indicator of the impact of drain-blocking, also serve to highlight the importance of larger scale studies in overcoming potential biases. The atypical nature of the high resolution dipwells prevents a robust assessment of the role of evapotranspiration in water table drawdown during summer droughts, with the absence of a diurnal pattern possibly being unrepresentative of the wider system. Although the observed increase in drought water tables after restoration was slight, this matches results from a previous study that drain-blocking at this site had resulted in much more stable water tables during the summer period (Wilson et al., 2010).

This study demonstrates that discharge from both drains and streams remained higher during droughts after blocking. Prior to blocking, flow rates in both drains and streams declined rapidly during the first few days without rainfall. However after restoration, this rapid drop was almost completely removed, with flow rates declining much less and remaining more stable throughout the drought period. Previous work at this site has shown that average flow rates from both drains and streams decline after drain-blocking, largely due to a reduction in the time spent at peak flows (Wilson et al., 2010), however this study demonstrates that a generally lower flow rate does not necessarily translate into lower flows or cessation of flows during drought periods. In fact the more stable water tables appear to be permitting a more stable, sustained release of discharge waters, which may have implications for summer domestic water supplies (Delpla et al., 2009). These changes are relative within a blanket peat context since these types of peatlands tend to have a flashy regime with low baseflows even when in pristine condition (Bay, 1969; Holden, 2006a; Price, 1992).

With higher and more stable water tables after restoration, it is perhaps not surprising that our results suggest a decline in the amounts of colour and fluvial organic carbon leaving the system during droughts. While changes were less marked in streams than in drains, drain blocking still appeared to lead to less colour and less POC release. These changes during the drought periods appear likely to stem from a reduction in the amount of humification of the aerobic peat layer, and thus both less production of 'fresh' organic carbon, and maintenance of shallower flow paths (Holden and Burt, 2002a; Holden and Burt, 2002b). There was also possibly a contrasting process occurring, with increasing acidity during drought periods suppressing the solubility of DOC (Clark et al., 2005), and therefore with the more stable post-restoration conditions incurring less suppression of DOC release. This might explain the slight increases in Abs^{400} and DOC concentrations observed in blocked drains in this study, as might the flushing of DOC produced and stored prior to drain blocking. However, any such effects appear to be outweighed by the decline in production of organic carbon. This reduced production during droughts also explains the almost complete removal of the re-wetting flush of colour and organic carbon that was evident in both drains and streams prior to restoration in this study. Before drain blocking, lower water tables during droughts appears to have led to an accumulation of available sediment and organic matter, which was then transported as rain recommenced and water tables and drain flow rose (Francis, 1990; Holden and Burt, 2002a; Mitchell and McDonald, 1992; Watts et al., 2001). This study, however, shows that drain blocking restoration considerably reduces the scale of this re-wetting flush of colour, DOC and POC from the system. Previous work at this site suggested that drain blocking restoration had led to a lower overall fluvial organic carbon flux, as well as lower colour exports in discharge waters (Wilson et al., 2011); and the current study suggests that an important contribution to these trends is the increased drought-resistance of the system.

As well as having implications for carbon fluxes (Evans et al., 2006; Strack et al., 2009) and contaminant release (Tipping et al., 2003), more stable and higher summer water tables are a key factor in restoring conditions for specialist peatland vegetation (Breeuwer et al., 2009; Gerdol et al., 2008; Money and Wheeler, 1999), and potentially for promoting key invertebrate groups and the bird species that depend on them (Buchanan et al., 2006). While previous studies have demonstrated that drain blocking can restore shallower water tables (Ramchunder et al., 2009; Wilson et al., 2010; Worrall et al., 2007a), this study is the first to show that these restored water tables can persist during the crucial dry summer periods.

At the other end of the spectrum, the hydrological response of peatlands to storm events has perhaps received more attention, and is again a key factor in determining organic carbon fluxes, as well as shaping flood risk and providing vital information on processes within the system (Clark et al., 2007; Daniels et al., 2008; Rothwell et al., 2007). The standard model of peatlands is of a flashy system, where rainfall events trigger rapid and concentrated runoff and discharge (Holden and Burt, 2003a; Holden and Burt, 2002a), and predicting the impact of restoration has proven difficult as it has the conflicting effects of reducing available storage and promoting slower flow paths (Holden, 2005b; Holden et al., 2004). This study has demonstrated that water table response to storm events changes after drain blocking, with levels rising higher and taking longer to recede to antecedent levels. Likewise, peak flow hydrographs from drains show considerable change after restoration, with lower peak flow rates, less runoff and less of the rainwater being released during the event. Changes in streams were less marked, as would be expected (Stutter et al., 2008), but matching trends were still apparent. No change in lag times was apparent in this study, although any response to blocking may have been masked by the error incurred from the wind-dependent lag or lead times between rainfall being recorded at the rain gauge, and arriving at each weir catchment. These results concur with previous work at this site, which suggested that the proportion of time at high stream flows reduced after drain-blocking (Wilson et al., 2010). While this previous work also showed a rise in water tables after blocking (Wilson et al., 2010), the current study demonstrates that even with a reduced potential storage, restored peatlands can demonstrate less flashy flood responses and provide better retention of rainfall even during peak events. However, the most severe events covered in our study had return periods of 2 years, thus very extreme events were not observed during our study, and may show different flood responses. During such events the peat will become fully saturated and all surface pool spaces taken up so that the buffering effect will then be minimal and dependent only on how well surface roughness effects are maintained as the depth of overland flow increases over the land surface (Holden et al., 2008).

As equipment failure prevented the collection of full datasets on water colour and organic carbon levels during storm events, this study was unable to test the hypothesis that the generally shallower water tables, and the reduced severity of peak flow events should lead to reduced water colour and organic carbon flushes during peak flows (Clark et al., 2010; Clark et al., 2007). The only prediction possible from the very limited data collected is that as DOC loads appeared to be linked to peak flow rates, the observed reduction in peak flows following restoration should lead to lower DOC loads and thus lower DOC fluxes. Although there is considerable variation between sites, DOC release generally appears to decline in response to drain-blocking restoration (Armstrong et al., 2010; Höll et al., 2009; Wallage et al., 2006). Previous work at this site has likewise shown declines in both DOC and POC yields following restoration, and has further suggested that mechanisms behind organic carbon production are altered by drain blocking, with younger, less humified carbon from shallower peat dominating (Wilson et al., 2011). As peak flow events are thought to contribute a major part of organic carbon fluxes (Clark et al., 2007; Jager et al., 2009), understanding changes in the peak flow responses after restoration are likely to be key to accurately modelling organic carbon flux. This study in combination with previous findings, suggests that restored, shallower water tables lead to reduced production of dissolved organic carbon, thus during storm events, as was apparent after drought events, there may be less material available to be flushed into drains and streams (Holden, 2005b; Höll et al., 2009). The reduced release of particulate matter may be more directly linked to drain-blocking itself rather than to changes in the main peat mass, with drain dams and slower flow rates cutting off sediment transport and reducing channel erosion .

With warmer, drier summers and stormier winters being likely with continuing climate change, the impact of drought periods and storm events on fluvial organic carbon release from peatlands could become an increasingly important factor in determining sediment loss and carbon fluxes (Clark et al., 2007; Evans et al., 2006; Strack et al., 2009). Likewise understanding the potential of restoration in reducing erosion and fluvial carbon yields during these key periods is vital given the importance given to these issues in recommending peatland restoration (Holden et al., 2004). This study presents evidence that drain blocking restoration can create higher and more stable water tables and discharge during drought periods and that this more resistant system appears to reduce the production and release of water colour and fluvial organic carbon, most noticeably during the post-drought re-wetting period. We also present evidence that drain blocking reduces the flashiness of storm discharge, a change apparent in streams as well as drains; and we predict that this change has contributed to the observed declines in annual fluvial organic carbon fluxes at the study site.

Acknowledgements

This study was funded by the EU LIFE-Nature scheme with additional support from the project partners, the Royal Society for the Protection of Birds, Countryside Council for Wales, Environment Agency and Forestry Commission Wales. The study site is owned by Severn Trent Water and managed by the RSPB. The contribution of a Philip Leverhulme Prize awarded to JH which provided time for him to contribute to this paper is gratefully acknowledged. We thank Fiona Walker and Jude Lane for assistance with field data collection, and Rachel Glasior and staff at the School of

Geography, University of Leeds for carrying out laboratory analyses on organic carbon samples. LW thanks Phil Tavener at the EA for his help with rainfall datasets.

References:

Armstrong, A. et al., 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(1-2): 112-120.

Ball, D.F., 1964. Loss on ignition as an estimate of organic matter and organic carbon in non-calcareous soils. Journal of Soil Science, 15: 84-86.

Bay, R.R., 1969. Runoff from small peatland watersheds. Journal of Hydrology, 9: 90-102.

Beven, K.J., O'Connell, P.E., Harris, G. and Clements, R.O., 2004. Review of impacts of rural land use and management on flood generation. Impact study report., Defra/Environment Agency, London.

Breeuwer, A. et al., 2009. Decreased summer water table depth affects peatland vegetation. Basic and Applied Ecology, 10(4): 330-339.

Buchanan, G.M., Grant, M.C., Sanderson, R.A. and Pearce-Higgins, J.W., 2006. The contribution of invertebrate taxa to moorland bird diets and the potential implications of land-use manegement. Ibis, 148: 615-628.

CCW, 2008. Berwyn & South Clywd Mountains ACA & Berwyn AGA.

Clark, J.M. et al., 2010. The importance of the relationship between scale and process in understanding long-term DOC dynamics. The Science of the Total Environment, In press. .

Clark, J.M., Chapman, P.J., Adamson, J.K. and Lane, S.N., 2005. Influence of drought-induced acidification on the mobility of dissolved organic carbon in peat soils. Global Change Biology, 11: 791-809.

Clark, J.M., Lane, S.N., Chapman, P.J. and Adamson, J.K., 2007. Export of dissolved organic carbon from an upland peatland during storm events: Implications for flux estimates. Journal of Hydrology, 347(3-4): 438-447.

Cooper, A., McCann, T., Davidson, R. and Foster, G.N., 2005. Vegetation, water beetles and habitat isolation in abandoned lowland bog drains and peat pits. Aquatic Conservation-Marine and Freshwater Ecosystems, 15(2): 175-188.

Daniels, S.M., Agnew, C.T., Allott, T.E.H. and Evans, M.G., 2008. Water table variability and runoff generation in an eroded peatland, South Pennines, UK. Journal of Hydrology, 361(1-2): 214-226.

Delpla, I., Jung, A.V., Baures, E., Clement, M. and Thomas, O., 2009. Impacts of climate change on surface water quality in relation to drinking water production. Environment International, 35(8): 1225-1233.

Eimers, M., Watmough, S., Buttle, J. and Dillon, P., 2007. Drought-induced sulphate release from a wetland in south-central Ontario. Environmental Monitoring and Assessment, 127: 399-407.

Evans, M. and Warburton, J., 2005. Sediment budget for an eroding peat-moorland catchment in Northern England. Earth Surface Processes and Landforms, 30: 557-577.

Evans, M., Warburton, J. and Yang, J., 2006. Eroding blanket peat catchments: Global and local implications of upland organic sediment budgets. Geomorphology, 79(1-2): 45-57.

Evans, M.G., Burt, T.P., Holden, J. and Adamson, J.K., 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.

Francis, I.S., 1990. Blanket peat erosion in a mid-wales catchment during two drought years. Earth Surface Processes and Landforms, 15(5): 445-456.

Gerdol, R., Bragazza, L. and Brancaleoni, L., 2008. Heatwave 2003: high summer temperature, rather than experimental fertilization, affects vegetation and CO2 exchange in an alpine bog. New Phytologist, 179: 142-154.

Gibb, J.C., 2009. DOC flux in an upland blanket peat catchment in the Berwyn and South Clwyd mountains, Northeast Wales., University of Leeds, Leeds, UK.

Girard, M., Lavoie, C. and Theriault, M., 2002. The regeneration of a highly disturbed ecosystem: A mined peatland in southern Quebec. Ecosystems, 5(3): 274-288.

Glatzel, S., Lemke, S. and Gerold, G., 2006. Short-term effects of an exceptionally hot and dry summer on decomposition of surface peat in a restored temperate bog. European Journal of Soil Biology, 42(4): 219-229.

Holden, J., 2005a. Controls of soil pipe density in blanket peat uplands. Journal of Geophysical Research, 110: F010002.

Holden, J., 2005b. Peatland hydrology and carbon cycling: why small scale process matters. Philosophical Transactions of the Royal Society. Series A, 363: 2891-2913.

Holden, J., 2006a. Peat hydrology. In: I.P. Martini, A.M. Cortizas and W. Chesworth (Editors), Peatlands: basin evolution and depository of records of global environmental and climatic changes, . Elsevier, Amsterdam, pp. 319-346.

Holden, J., 2006b. Sediment and particulate carbon removal by pipe erosion increase over time in blanket peatlands as a consequence of land drainage. Journal of Geophysical Research, 111: F02010.

Holden, J. and Burt, T., 2003a. Runoff production in blanket peat covered catchments. Water Resources Research, 39(7): 1191-1200.

Holden, J. and Burt, T.P., 2002a. Infiltration, runoff and sediment production in blanket peat catchments: implications of field rainfall simulation experiments. Hydrological Processes, 16(13): 2537-2557.

Holden, J. and Burt, T.P., 2002b. Laboratory experiments on drought and runoff in blanket peat. European Journal of Soil Science, 53: 675-690.

Holden, J. and Burt, T.P., 2002c. Piping and pipeflow in a deep peat catchment. Catena, 48: 163-199.

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

Holden, J., Chapman, P.J. and Labadz, J.C., 2004. Artificial drainage of peatlands: hydrological and hydrochemical process and wetland restoration. Processes in Physical Geography, 28(1): 95-123.

Holden, J. et al., 2008. Factors affecting overland flow velocity in peatlands. Water Resources Research, 44: W06415.

Holden, J. et al., 2007. Environmental change in moorland landscapes. Earth-Science Reviews, 82: 75-100.

Höll, B.S. et al., 2009. Characteristics of dissolved organic matter following 20 years of peatland restoration. Science of The Total Environment, 408(1): 78-83.

Jager, D.F., Wilmking, M. and Kukkonen, J.V.K., 2009. The influence of summer seasonal extremes on dissolved organic carbon export from a boreal peatland catchment: Evidence from one dry and one wet growing season. Science of The Total Environment, 407(4): 1373-1382.

Komulainen, V.-M., Tuittila, E.-S., Vasander, H. and Laine, J., 1999. Restoration of Drained Peatlands in Southern Finland: Initial Effects on Vegetation Change and CO2 Balance. Journal of Applied Ecology, 36(5): 634-648.

Lane, S.N. et al., 2003. Land management, flooding and environmental risk: new approaches to a very old question., CIWEM National Conference, Harrogate, UK.

Lindsay, R., 2010. Peatbogs and carbon: A criticial synthesis to inform policy development in oceanic peatbog conservation and restoration in the context of climate change, University of East London, London.

Mitchell, G. and McDonald, A.T., 1992. Discolouration of water by peat following induced drought and rainfall simulation. Water Research, 26: 321-326.

Money, R.P. and Wheeler, B.D., 1999. Some critical questions concerning the restorability of damaged raised bogs. Applied Vegetation Science, 2: 107-116.

Pereira, M.A., Lin, L.H., Lippitt, J.M. and Herren, S.L., 1982. Trihalomethanes as initiators and promotors of carcinogenesis. Environmental Health Perspectives, 46: 151-156.

Petrone, R.M., Price, J.S., Waddington, J.M. and von Waldow, H., 2004. Surface moisture and energy exchange from a restored peatland, Québec, Canada. Journal of Hydrology, 295(1-4): 198-210.

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

Ramchunder, S.J., Brown, L.E. and Holden, J., 2009. Environmental effects of drainage, drain-blocking and prescribed vegetation burning in UK upland peatlands. Processes in Physical Geography, 33: 49-79.

Rothwell, J.J., Evans, M.G., Daniels, S.M. and Allott, T.E.H., 2007. Baseflow and stormflow metal concentrations in streams draining contaminated peat moorlands in the Peak District National Park (UK). Journal of Hydrology, 341(1-2): 90-104.

Smolders, A.J.P., Tomassen, H.B.M., van Mullekom, M., Lamers, L.P.M. and Roelofs, J.G.M., 2003. Mechanisms involved in the re-establishment of Sphagnum-dominated vegetation in rewetted bog remnants. Wetlands Ecology and Management, 11: 403-418.

Strack, M., Waddington, J.M., Lucchese, M.C. and Cagampan, J.P., 2009. Moisture controls on CO2 exchange in a Sphagnum-dominated peatland: results from an extreme drought field experiment. Ecohydrology, 2(4): 454-461.

Stutter, M.I., Langan, S.J. and Cooper, R.J., 2008. Spatial and temporal dynamics of stream water particulate and dissolved N, P and C forms along a catchment transect, NE Scotland. Journal of Hydrology, 350(3-4): 187-202.

Tipping, E., Smith, E.J., Lawlor, A.J., Hughes, S. and Stevens, P.A., 2003. Predicting the release of metals from ombrotrophic peat due to drought-induced acidification. Environmental Pollution, 123(2): 239-253.

Tuittila, E.-S., Vasander, H. and Laine, J., 2000. Impact of Rewetting on the Vegetation of a Cut-Away Peatland. Applied Vegetation Science, 3(2): 205-212.

Wallage, Z.E., Holden, J. and McDonald, A.T., 2006. Drain blocking: An effective treatment for reducing dissolved organic carbon loss and water discolouration in a drained peatland. Science of The Total Environment, 367(2-3): 811-821.

Watts, C.D., Naden, P.S., Machell, J. and Banks, J., 2001. Long term variation in water colour from Yorkshire catchments. . The Science of the Total Environment, 278: 57-72.

Wilson, L. et al., 2011. Ditch blocking, water chemistry and organic carbon flux: evidence that blanket bog restoration reduces erosion and fluvial carbon loss. Science of The Total Environment, 409: 2010-2018.

Wilson, L. et al., 2010. Recovery of water tables in Welsh blanket bog after drain-blocking: Discharge rates, time scales and the influence of local conditions. Journal of Hydrology, 391: 377-386.

Worrall, F., Armstrong, A. and Holden, J., 2007a. Short-term impact of peat drain-blocking on water colour, dissolved organic carbon concentration, and water table depth. Journal of Hydrology, 337: 115-125.

Worrall, F. and Burt, T.P., 2007. Trends in DOC concentration in Great Britain. Journal of Hydrology, 346(3-4): 81-92.

Worrall, F. and Burt, T.P., 2008. The effect of severe drought on the dissolved organic carbon (DOC) concentration and flux from British rivers. Journal of Hydrology, 361(3-4): 262-274.

Worrall, F., Burt, T.P. and Adamson, J.K., 2007b. Change in runoff initiation probability over a severe drought in a peat soil - Implications for flowpaths. Journal of Hydrology, 345(1-2): 16-26.

Worrall, F., Burt, T.P., Rowson, J.G., Warburton, J. and Adamson, J.K., 2009. The multi-annual carbon budget of a peat-covered catchment. Science of The Total Environment, 407(13): 4084-4094.

Worrall, F., Gibson, H.S. and Burt, T.P., 2007c. Modelling the impact of drainage and drain-blocking on dissolved organic carbon release from peatlands. Journal of Hydrology, 338(1-2): 15-27.

Table 1: GLM results and parameter estimates for adjusted water table depth and rate of change of water table depth measured in three dipwells located at 0.5, 1 and 5m from a drain in Nadroedd. Results are for the interaction term unblocked/blocked * drought day, parameter estimates are for the interaction Blocked * drought day, against the baseline of Unblocked * drought day.

Dependent	Distance from drain	F	df	p	Blocked parameter estimate	SE
Adjusted water table depth	0.5m	87.74	10366	<0.0001	0.041	0.005
	1m	2932.2	10366	<0.0001	-0.401	0.007
	5m	2995.4	9310	<0.0001	-0.372	0.007
Rate of change of water table	0.5m	0.31	212	0.58	0.002	0.004
	1m	4.62	212	0.03	-0.007	0.004
	5m	2.30	191	0.13	-0.008	0.005

Table 2: GLM results for manual sample data collected during drought events from all sub-catchments. For water table depth and drain models, the results given are for the unblocked/blocked * site interaction term, for stream models, results are for the unblocked/blocked term. $P_{crit} = 0.01$.

Dependent		F	df	p
Water table depth		5.75	694	0.003
Drains	Abs^{400}	23.42	205	<0.0001
	Flow weighted Abs^{400}	4.03	149	0.051
	DOC concentration	12.27	151	0.0006
	DOC load	1.36	151	0.246
	POC concentration	1.79	141	0.183
	POC load	1.92	141	0.168
Streams	Abs^{400}	4.63	68	0.035
	Flow weighted Abs^{400}	4.61	24	0.042
	DOC concentration	0.35	28	0.560
	DOC load	3.33	24	0.080
	POC concentration	0.28	24	0.601
	POC load	3.59	20	0.072

Table 3: GLM results for manual sample data collected during post-drought re-wetting periods in all sub-catchments. Results given are for the unblocked/blocked term, $P_{crit} = 0.01$.

Dependent		F	df	p
Drains	Abs^{400}	3.04	125	0.084
	Flow weighted Abs^{400}	5.45	120	0.021
	DOC concentration	0.61	120	0.437
	DOC load	15.09	120	0.0002
	POC concentration	0.15	120	0.696
	POC load	8.14	120	0.005
Streams	Abs^{400}	2.22	42	0.144
	Flow weighted Abs^{400}	0.41	27	0.526
	DOC concentration	0.19	25	0.664
	DOC load	0.09	25	0.764
	POC concentration	0.01	17	0.987
	POC load	0.01	17	0.913

Table 4: GLM results and mean values for peak levels and recession duration for water tables during storm events measured from three dipwells in Nadroedd before and after drain-blocking.

Dependent	Dist. to drain	F	df	p	Unblocked	SE	Blocked	SE
Peak water	0.5m	3.05	17	0.099	-1.36	1.09	0.25	0.46
table depth	1m	0.04	15	0.841	-4.45	2.50	-0.87	2.90
(cm)	5m	5.95	17	0.026	-0.69	1.05	1.78	0.95
Recession	0.5m	3.83	14	0.071	22.32	4.92	68.50	15.82
duration	1m	4.02	15	0.063	18.33	1.65	44.83	11.58
(hrs)	5m	19.7	16	0.0004	17.36	3.75	55.64	9.52

Figure 1: Study site, showing the sub-catchments covered by the study, locations of sampling equipment, and inset, the study site location within Wales.

Figure 2: Mean ± SE water table depths measured across 4 sub-catchments during drought periods, from dipwells located at 0.5, 1 and 5m from drains, and measured before and after drain-blocking.

Figure 3: Mean ± SE adjusted (relative to antecedent levels) daily mean flow rates in drains before and after drain-blocking, per day during drought periods.

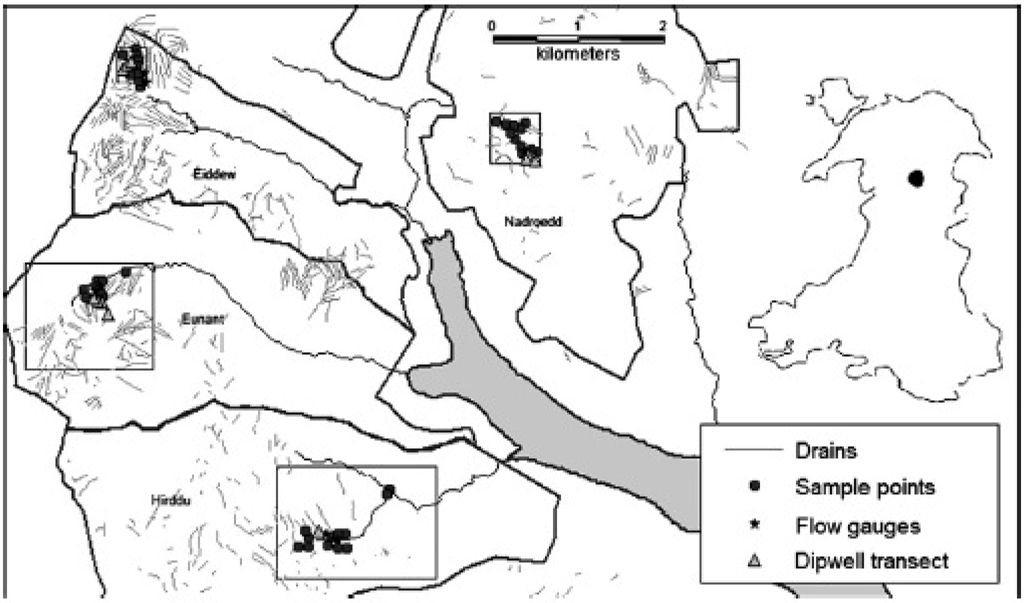
Figure 4: Mean ± SE adjusted (relative to antecedent levels) daily mean flow rates in streams before and after drain-blocking, per day during drought periods.

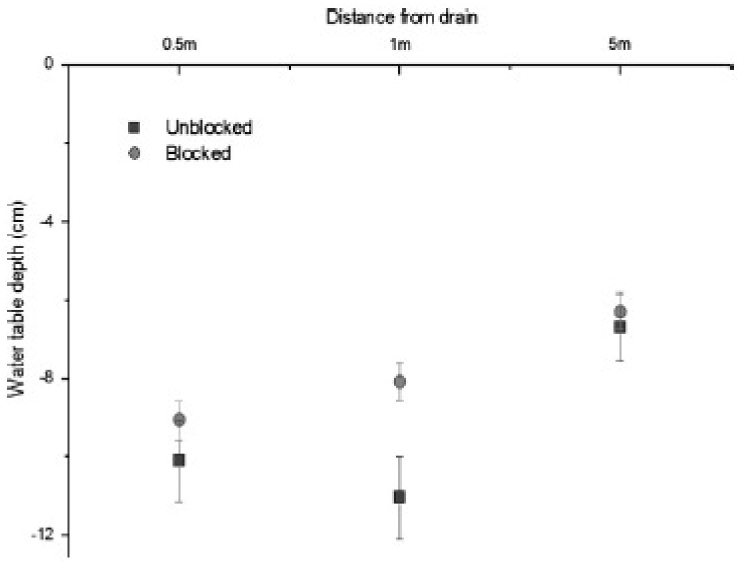
Figure 5: Mean ± SE values for flow weighted Abs^{400}, DOC loads and POC loads, measured in drains during drought periods, and during post-drought wet periods, before and after drain-blocking.

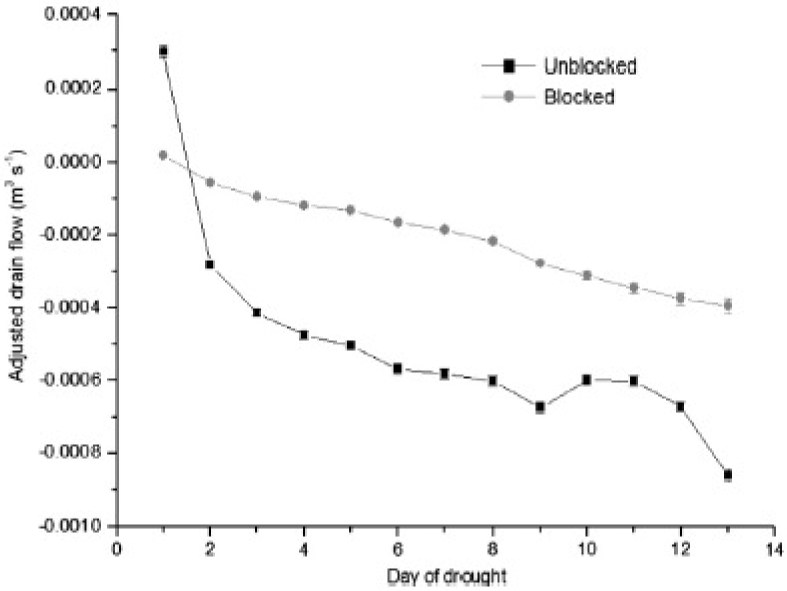
Figure 6: Mean ± SE values for flow weighted Abs^{400}, DOC loads and POC loads, measured in streams during drought periods, and during post-drought wet periods, before and after drain-blocking.

Figure 7: Mean ± SE values for storm hydrograph parameters measured from drains, prior to and after drain-blocking. Peak flow rate $F_{1,75}$=43.00, p<0.0001; Total baseflow $F_{1,75}$=0.14, 0.709; Total runoff $F_{1,75}$=50.33, p<0.0001; Runoff:baseflow ratio $F_{1,75}$=35.97, p<0.0001; Efficiency $F_{1,75}$=46.46, p<0.0001; Flashiness $F_{1,75}$=13.24, p=0.0005.

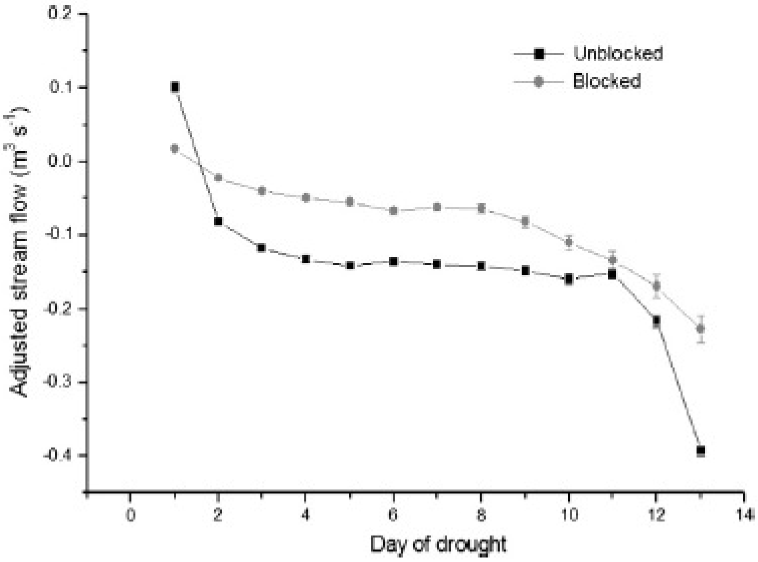
Figure 8: Mean ± SE values for storm hydrograph parameters measured from streams, prior to and after drain-blocking. Peak flow rate $F_{1,52}$=3.51, p=0.067; Runoff:baseflow ratio $F_{1,48}$=4.48, p=0.039; Flashiness $F_{1,52}$=20.89, p<0.0001.


0 1 2
kilometers
Eiddew
Nadroedd
Eunant
Hirddu
Drains
Sample points
Flow gauges
Dipwell transect

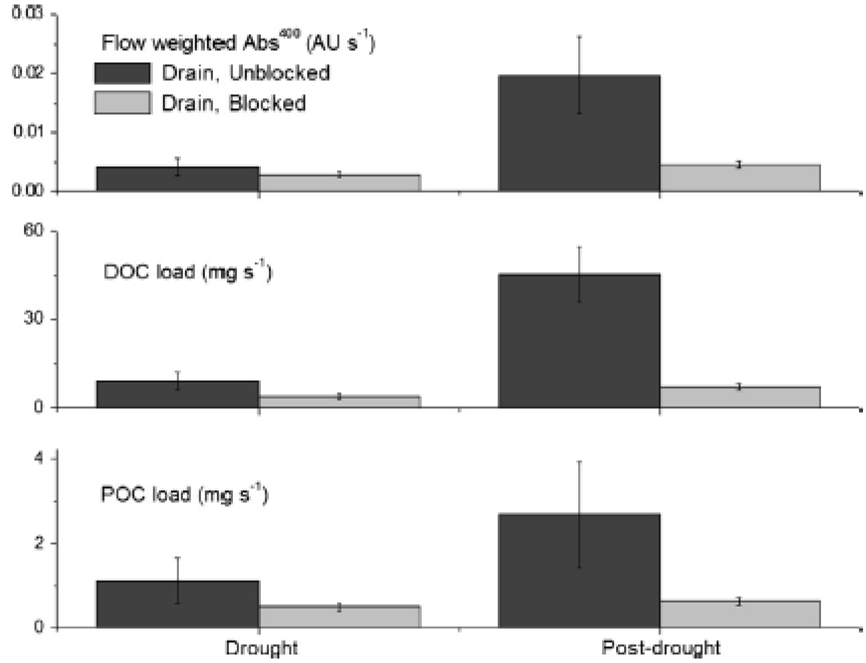

Distance from drain
0.5m
1m
5m
0
-4
-8
-12
Water table depth (cm)
Unblocked
Blocked

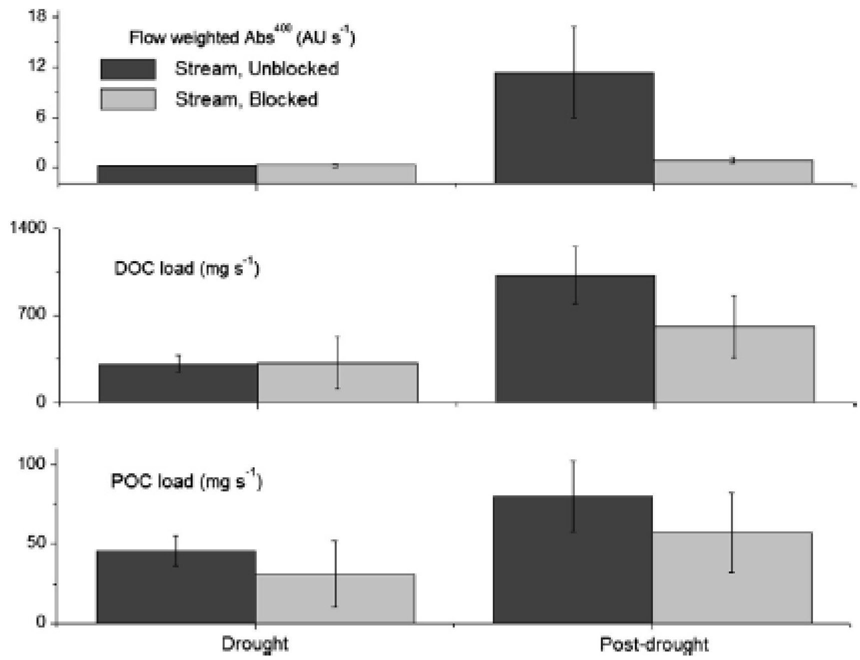


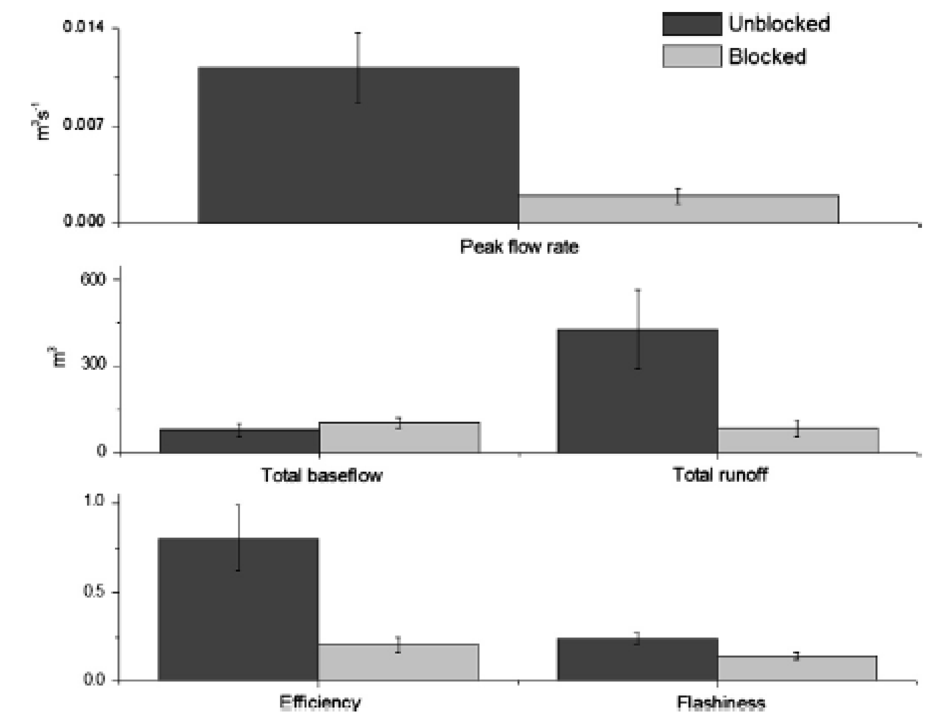
Unblocked
Blocked
Adjusted drain flow ($m^3 s^{-1}$)
Day of drought
0.0004
0.0002
0.0000
-0.0002
-0.0004
-0.0006
-0.0008
-0.0010
0
2
4
6
8
10
12
14

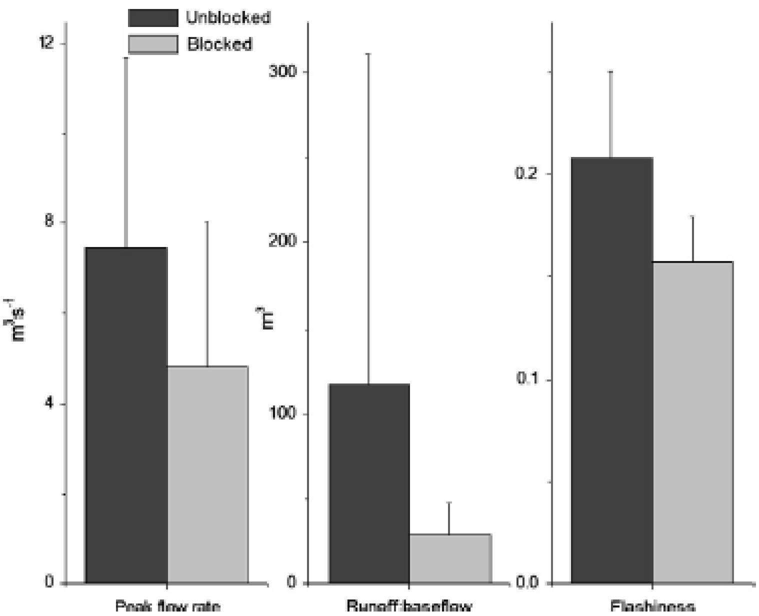


Unblocked
Blocked
Adjusted stream flow ($m^3 s^{-1}$)
Day of drought
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
0
2
4
6
8
10
12
14


Flow weighted Abs400 (AU s-1)
Drain, Unblocked
Drain, Blocked
0.03
0.02
0.01
0.00
DOC load (mg s-1)
60
30
0
POC load (mg s-1)
4
2
0
Drought
Post-drought


Flow weighted Abs400 (AU s-1)
Stream, Unblocked
Stream, Blocked
18
12
6
0
DOC load (mg s-1)
1400
700
0
POC load (mg s-1)
100
50
0
Drought
Post-drought


Unblocked
Blocked
0.014
0.007
0.000
m^3s^{-1}
Peak flow rate
600
300
0
m^3
Total baseflow
Total runoff
1.0
0.5
0.0
Efficiency
Flashiness


Unblocked
Blocked
12
8
4
0
m^3s^{-1}
Peak flow rate
300
200
100
0
m^3
Runoff:baseflow
0.2
0.1
0.0
Flashiness