A grip-blocking overview

Joseph Holden
water@leeds, School of Geography, University of Leeds, Leeds, LS2 9JT
December 2009

1. Introduction

This document serves as a short briefing to provide information on the impacts of drain-blocking (also known as grip-blocking) in upland blanket peat. While there are drains in other types of peat (e.g. lowland fen), 87 % of the UK's peat is blanket peat and most resources are being targeted at upland blanket peat drain-blocking and hence this briefing will focus on upland blanket peat. The report focuses on:

i) What we know about the hydrology and carbon cycle of UK upland blanket peat
ii) What we know about impacts of blanket peat drainage
iii) What we know about the impacts of blanket peat drain-blocking on hydrology and carbon cycling

In England, to date, the drains in around 3200 ha of upland blanket peat have been blocked. However, this only represents 4 to 5 % of the area of drained blanket peat in England. It is vital to understand what we have learned from the first 5 % of drain-blocking work before we embark on the remaining 95 %. It should be noted that the purpose of this report is to provide a summary overview. As such it is not meant to be comprehensive in the depth of material it covers but, nevertheless, it will attempt to capture most areas of published work on UK grip-blocking as well as some of the grey literature.

2. An overview of the hydrology and carbon cycle of UK upland blanket peat

2.1 River flow

Upland blanket peat acts a source of 'quickflow'. In other words, the river levels rise and fall very quickly in response to rainfall in blanket peat systems. The river discharge response of a typical blanket peat catchment is shown in Figure 1. The hydrographs for individual rainfall events are very spiky, very quickly rising to high levels (often within an hour or two of the rainfall starting) and then within a few hours falling back to low flow again. During dry spells of no more than a week many peatland streams can have virtually no flow in them at all (Bragg, 2002; Holden and Burt, 2003b). Bullock and Acreman (2003) produced a database of research on the role of wetland soils in the hydrological cycle and found no support for the idea that upland peatlands acted to buffer floods. This is because peat retains large quantities of water within it, even during dry periods, leaving little room for storage of fresh rainfall. Saturated peat tends to be 90-98 % water by mass. Even above the water table (maximum height of the saturated zone), peat can still hold large volumes of water (approximately 90-95 % water by mass). In many peatlands, the water table is within just 40 cm of the surface for 80 % of the year at least (Holden and Burt, 2003a). Hence when it rains there is little space for water storage and so most of the rainfall will flow over the peat surface (or close to the surface) and quickly enter the river network.

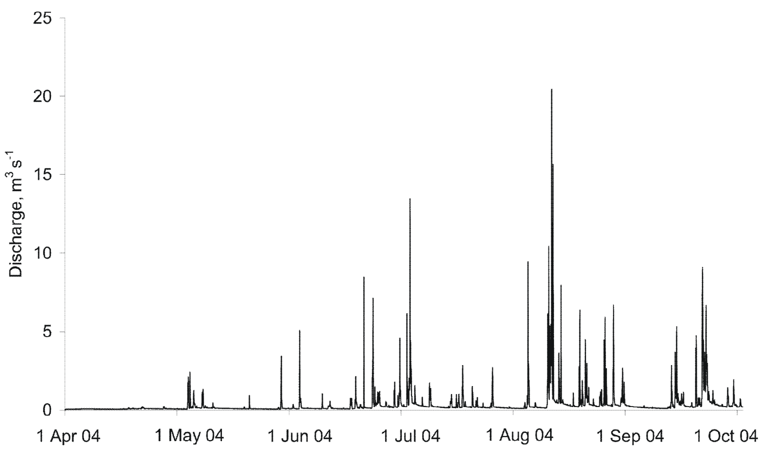


Figure 1. Discharge from Oughtershaw Moss, a peatland catchment in the Yorkshire Dales, over a six month period. Data from Environment Agency gauge L1990.

2.2 Hillslope hydrology

The movement of water across and through any landscape occurs in a number of ways (Figure 2). These include infiltration-excess overland flow (where inputs of water are in excess of the rate at which water can infiltrate into the surface), saturation-excess overland flow (where the soil is saturated and water ponds up and flows back out onto the surface), and throughflow (where water flows through the soil or rock substrate). Throughflow can occur through the tiny pores of soils or rocks (matrix flow), or through larger cavities and pores (macropore flow or pipeflow). All of these processes operate in blanket peatlands.

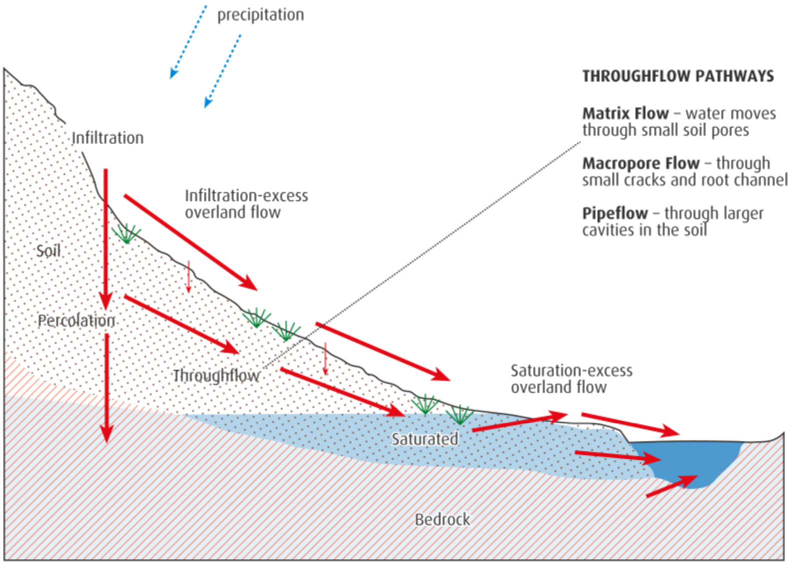


Figure 2. The main water flow pathways across landscapes

Intact blanket peatlands are dominated either by saturation-excess overland flow or by throughflow in the upper few centimetres of the peat. In essence the saturated zone follows the slope so that saturation-excess overland flow can occur across most of the peatland landscape when it rains (Figure 3). This leads to rapid movement of water from the hillslope to the stream. The properties of the peat mean that at depths greater than just a few centimetres, the rate of lateral water movement through the small pores of the peat is virtually zero. Therefore, the peat retains its water except in summer dry periods when evapotranspiration causes water table lowering which only occurs during daytime and stops over night (Gilman, 1994).

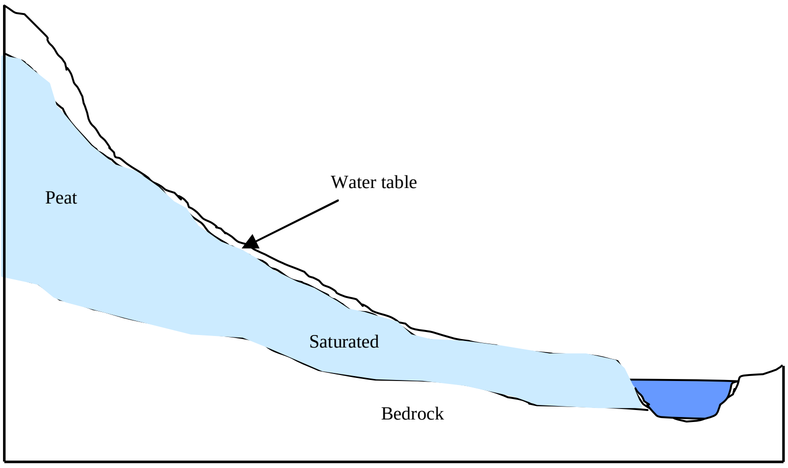


Figure 3. Typical zone of saturation in blanket peat showing how the water table is close to the surface across the slope even when it is not raining

Figure 4. Natural pipe outlet in peat

However, water flow in blanket peat does occur at depth through larger holes called 'soil pipes' (Figure 4). These are natural cavities which are connected over long distances and they can form labyrinthine networks that are longer than 100 m in length (Holden, 2004). They have been written about in peatlands for over 100 years. Cavers in the English Peak District often explore the larger of these pipes which are known as 'slutch caves' (Chapman, 1993). Pipes have been well researched on the stagnopodzols and shallow peats of the Maesnant catchment of mid-Wales by Tony Jones and colleagues (e.g. Jones, 1997; Jones, 2004; Jones and Crane, 1984). Here, pipeflows contribute 50 % to streamflow and the areas of the catchment with more piping yield more sediment to the stream system than other parts of the catchment.

However, there have only been two detailed studies on blanket peat. Holden and Burt (2002c) identified 10 % of streamflow being delivered by the pipe network while Holden et al. (2009) have found around 20 % of the flow is produced by these pipes. Some of the pipes can produce discharges as high as 14 litres per second. The existence of peatland pipes therefore opens the way for the fluxes of water, sediment and nutrient contributions from deep within and below the peat rather than simply by rapid transfer through the upper peat layers.

2.3 Carbon cycle

The dominant controls on the peatland carbon cycle are often stated as plant community, temperature, water table position, and the chemistry of the peat. Peatlands take up carbon via the uptake of atmospheric carbon dioxide (CO_2) during the growth of peatland plants. This is known as photosynthesis. When the plants die their carbon matter becomes part of the peat itself. Waterlogging and cold temperatures mean that the rate of decomposition of the dead plant material is very slow and hence the peatland can accumulate in mass over time (Limpens et al., 2008). Some additional carbon may be added to the peatland from dissolved carbon in rainfall (although this is usually a very small contribution), from weathering of the underlying strata, and from a small amount of methane taken into the peat. However, carbon does not just accumulate on the land surface in peatlands. It is lost from peatlands via a number of pathways (Figure 5). CO_2 is produced in peatlands from respiration (breathing) of the plants and also from the slow decay of plant litter and peat. This release of CO_2 is much faster where air can get into the peat, and slower when it is waterlogged. The balance between the uptake and the release of CO_2 is called the 'net ecosystem exchange' and for most pristine peatlands this is a 'negative' balance so that more CO_2 is taken up by the peatland than is released. Carbon is also released in the form of methane which is produced under waterlogged conditions. Methane is a much more powerful greenhouse gas than CO_2 and because of this it is possible for a peatland to be a net sink for carbon but at the same time to have a warming effect on climate (Baird et al., 2009).

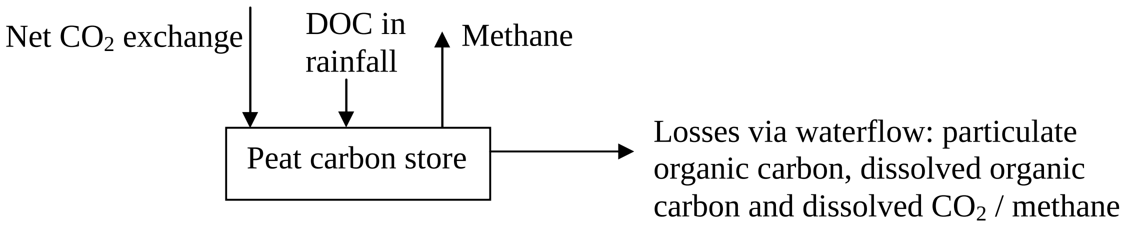


Figure 5. A simplified version of the carbon cycle in peatlands

In addition, carbon may be lost from peatlands via the flow of water into streams. This can take place in the form of particulate organic carbon (i.e. erosion of the peatland sediment), dissolved organic carbon and also dissolved CO_2 and dissolved methane. Despite all these potential loss pathways for carbon, undamaged peatlands are usually net accumulators of carbon so that more is taken up from photosynthesis than is lost via all these pathways. However, the situation may be quite different in damaged peatlands.

Most movements of carbon are considered to occur close to the peat surface (e.g. overland flow transporting sediment, or flow through the upper peat layers transporting dissolved organic carbon). However, because methane is produced under waterlogged conditions, bubbles of methane can be produced deep within the peat and then move up through the peat to be released (Baird et al., 2004). Additionally, pipes (described above) can also move carbon from the deeper layers of peat. Recent work measuring carbon losses from blanket peat pipes in the UK (which is the first time this process has been measured in any type of peatland) has shown that the pipes produce around 50 % of the dissolved organic carbon entering the stream, a significant amount of the sediment, and are also hotspots for rapid degassing of methane and CO_2 (imagine opening a lemonade bottle - all the gas suddenly fizzes out).

There are relatively few studies that have measured all of the components (net ecosystem exchange of CO_2, methane, particulate and dissolved organic carbon, dissolved CO_2 and dissolved methane) of the peatland carbon cycle. For Auchencorth in central Scotland the system has a negative global warming potential (-352 tonnes CO_2-equivalents per km^2 per year) and is a net sink for carbon (-69.5 tonnes carbon per km^2 per year) (Dinsmore et al., in press) which is similar to the 13 year average of -59 tonnes carbon per km^2 per year estimated by Worrall et al. (2009) for Moor House in the north Pennines. Dinsmore et al (in press) showed that the aquatic fluxes of carbon were very important, representing 41 % of net ecosystem exchange CO_2. Other studies outside of the UK include a six year study by Roulet et al. (2007) who found that the peat acted as net carbon sink of -21 tonnes carbon per km^2 per year, although this varied significantly between years, and a two year study of a Swedish peat bog by Nilsson et al. (2008) who found that the peatlands acted as a net carbon sink of between -20 and – 27 tonnes carbon per km^2 per year. However, despite the claims of these papers to have measured all of the components of the peatland carbon cycle we have to remember that sampling is done at certain spatial locations and certain points in time and yet the movement of gaseous carbon can be very variable across a peatland surface (Holden, 2005c). Also, the fluxes of carbon in rivers very greatly over time (e.g. most movement of carbon is likely to happen at high flows even though the concentrations might be low). Therefore, we need to take note of the way in which the components of the carbon cycle have been measured to interpret the findings.

A final issue to consider is what happens to the particulate and dissolved organic carbon, and dissolved CO_2 and methane downstream. It is all well and good to have measured these types of carbon at a point in the river network within the peatland and then to use these data to determine the carbon budget. However, if we are interested in the global warming potential of the carbon release then we need to know what happens to the different forms of carbon downstream. For example, it may be that particulate organic carbon decomposes in the river / reservoir / estuary system into CO_2 or even methane which would have greater global warming impacts. However, some dissolved and particulate carbon almost certainly will end up in long-term sedimentary storage where it may reside for decades or centuries. However, there is a lack of research in this area.

3. Overview of impacts of blanket peat drainage

3.1 Hydrology

Upland drainage has resulted in changes in water flow paths through and over blanket peatlands (Holden et al., 2006b) and has been reported to both increase and decrease flood peaks (Holden et al., 2004). Given that both increases and decreases in flood risk have been reported as a potential result of drainage it is important to be able to understand the conditions under which such effects occur and the magnitude of such effects. While lowering the water table buffers (slightly) the impacts of a rainfall event by providing extra soil storage capacity for rainwater and reducing saturation-excess overland flow, the ditches themselves speed up the removal of water from the land into streams. Therefore, the local impacts on flooding might depend on factors such as ditch network design, slope and local vegetation (e.g. Gilman, 2002 at Cors y Llyn). Moreover, the position of the drainage within the catchment as a whole is important because even if drainage slowed and decreased the flood peak from a tributary, it may cause this peak to be delayed, to the extent that it occurs at the same time as the main channel flood peak (Holden et al., 2004). This could therefore cause flood peaks to increase overall. Therefore, unless the large majority of the catchment is covered by one type of land management a spatial approach which takes account of the nature of the drainage network and the timing of flows from each part of the drainage network and how they are influenced by specific management practices in their area is essential to understand the impacts of management activity on flood hydrology.

Many drained peatland catchments exhibit increases in low flows (Baden and Eggelsmann, 1970; Robinson, 1985). This has often been attributed to catchment ‘dewatering’ following drainage (Burke, 1975) and changes to soil structure (Holden, 2005b) and is often only a temporary response. Peats shrink, crack (Holden and Burt, 2002a; Holden and Burt, 2002b) and decompose when dried. This change in peat structure is important for hydrology, water quality and ecology. Furthermore, Holden (2005b) found that peats that had been drained had significantly greater amounts of soil piping than other undrained peats. This finding was assisted by the use of ground-penetrating radar to find the underground pipes across 320 peat catchments in the UK. In a follow-up study to this work, Holden (2006) showed that as the drain networks get older, the density of piping increases. This long-term increase in piping over time in drained peat catchments has been shown to have an influence on riverflow at least at the small catchment scale (Holden et al., 2006b).

The creation of drain channels interferes with the natural pattern of water flow across hillslopes (Figure 6) and this can cause drying of the peat and a lowering of the water table more than any ‘drawdown’ of water table surrounding each drain. Figure 7 shows the average water table depth and the frequency of occurrence of overland flow between bi-weekly visits over a two year period for two similar plots. For the intact plot, overland flow and high water tables are to be expected. However, for the plot with drains crossing it, the downslope area below each drain tends to be driest. This is simply because that part of the slope no longer receives water from upslope. Effectively, the drains have shortened the slope length. This means that anywhere downslope of a land drain will be drier than it would otherwise have been and will have less overland flow. It is possible to predict which drains will have the biggest impact on downslope saturation and therefore on peatland ecology or carbon cycling, simply by mapping the topography of the landscape and the location of the drains. In other words, Figure 7 is based on real data, but we have simple tools that can predict these maps for large areas without having to go through the time-consuming and laborious process of collecting new water table data for each area we are interested in restoring (Figure 8). Such information can be useful to land managers who are considering blocking land drains because it can guide them to target particular drains and use their resources more effectively (Holden et al., 2006a).

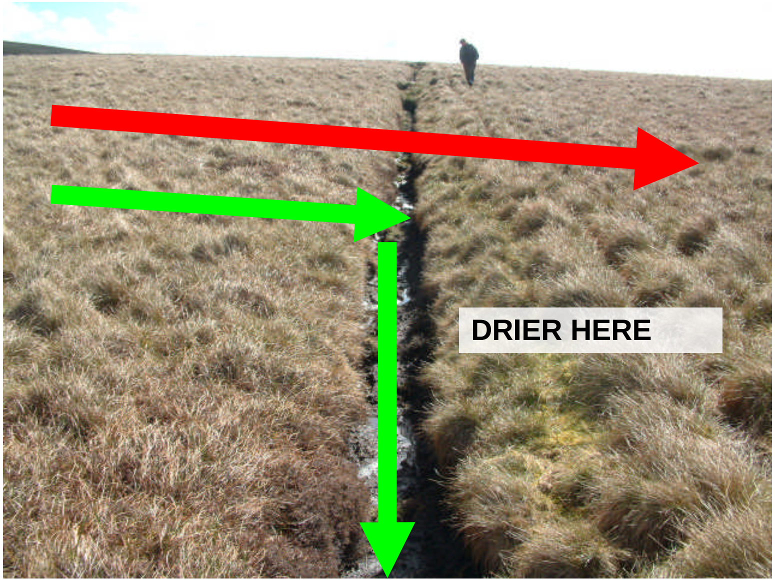


Figure 6. Ditches interfere with the natural flow of water and hence immediately downslope from a drain the peat is driest because there is no area upslope providing water flow.

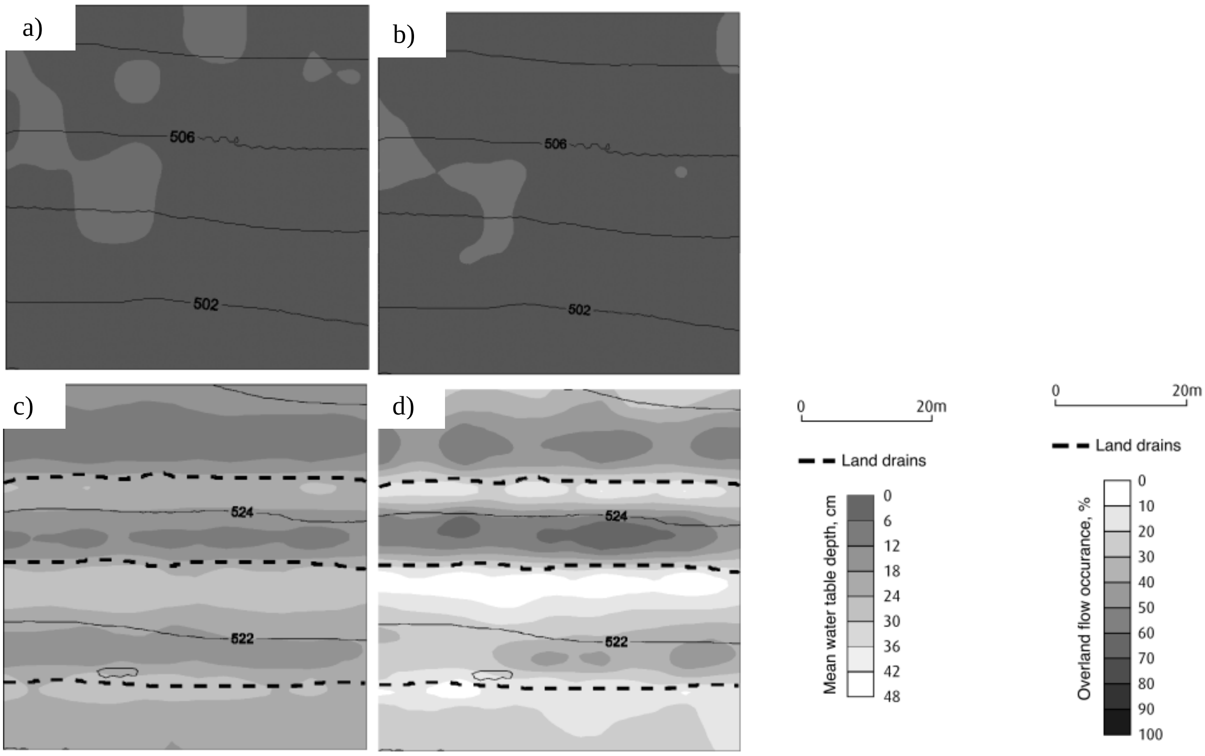


Figure 7. Mean water table depth (a, c) and percent occurrence of overland flow (b, d) on bi-weekly monitored plots October 2002 to October 2004 for an intact slope (a, b) and a drained slope (c, d). Contour lines are heights at 2 m intervals, right hand diagrams are overland flow and left hand diagrams are water table. Flow is down screen.

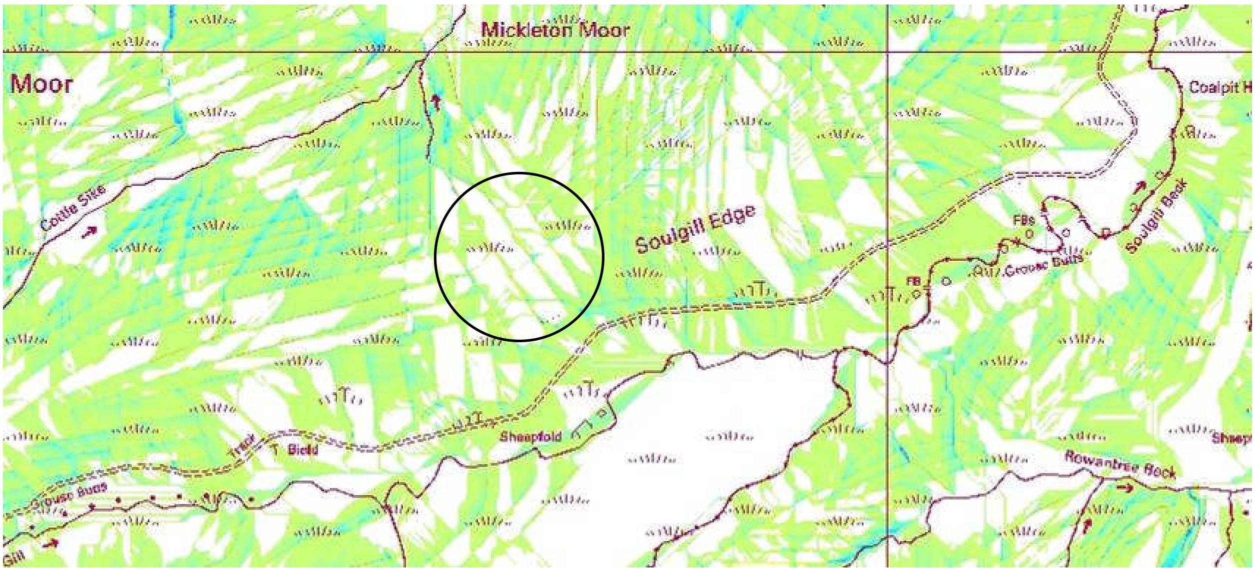


Figure 8. Predicted drier areas (green) due to gripping using topographic data for a site in the north Pennines. The area within the black circle shows a location where grips have a relatively small influence on the surrounding hillslope hydrology (i.e. not much green around the drains) compared to other grips shown on the map. This sort of tool can be used to guide restoration agencies towards target areas for drain-blocking if hydrological recovery on hillslopes is a key aim.

3.2 Carbon cycling

Rates of litter and peat decay in blanket peat may increase because of a thickening or deepening of the aerated zone caused by drainage (lowering of the water table). Decay rates in the aerated (oxic) zone are thousands of times greater than those in the absence of oxygen (e.g. Clymo, 1983; Frolking et al., 2002).Therefore, a deepening of the oxic zone caused by drops in the water table can cause large increases in rates of CO_2 emissions from peatlands and a loss of carbon sink function (Dirks et al., 2000). However, a lowering of the water table may result in less methane emissions.

Studies that have investigated the impact of drainage on dissolved organic carbon concentration have observed contradictory results. Clausen (1980), Edwards et al. (1987) and Mitchell and McDonald (1995) found that drained catchments produced much more discoloured (dissolved organic carbon-rich) water than undrained catchments. In contrast, Moore (1987) in southern Quebec, observed only minor changes in stream dissolved organic carbon concentrations in drained peat extraction sites, compared to undisturbed peatlands. Results from studies investigating the role of deeper water tables on dissolved organic production and export are also contradictory, with some studies observing an increase (Tipping et al., 1999) while others observed a decrease (Freeman et al., 2004) or no significant changes (Blodau et al., 2004). However, in the UK, the most widely held view is that drainage of blanket peat leads to enhanced dissolved organic carbon production and the studies on drainage (rather than experimental water table lowering) from the UK are in agreement here. Indeed a large amount of unpublished data collected as part of water colour projects for water companies in the 1980s demonstrates this very clearly and more recent work by Wallage et al (2006) showed that dissolved organic carbon concentrations within the peat were significantly greater within drained peat than there were in nearby undrained peat. Chapman and McDonald (in review) have shown for a blanket peatland, where measurements were taken in 1986, that water colour (a surrogate for dissolved organic carbon) was greater in drained subcatchments than in undrained peat. However, when the measurements were repeated in 2006/7 the difference in water colour between drained and undrained sites was much smaller. The colour had increased in all subcatchments over time, but had increased at a faster rate in the undrained catchments. In other words the undrained catchments had ‘caught up’ with the drained catchments in terms of colour production. There may, therefore, be some important long-term changes in dissolved organic carbon production with time since drainage which means that the findings might vary between sites depending on how long it has been since those sites were drained.

The production of particulate organic carbon has been found to be significantly greater from drained peats than in undrained peats at many sites and this appears to impact invertebrate communities in peatland streams (Ramchunder et al., 2009). In many places, the ditches themselves can be subject to severe scouring, widening and deepening often by several metres (Mayfield and Pearson, 1972). At other sites there is a more gradual erosion of drains but there is often no stabilisation (Carling and Newborn, 2007 - who found drain sediment yields between 10 and 10,000 times greater over a five year period to that in natural streams) suggesting that only direct intervention can reduce particulate carbon loss. Site characteristics (e.g. steep slopes) often mean that even relatively recently drained catchments may be significant sources of sediment and carbon. Holden et al. (2007a) showed that for Oughtershaw Moss (Upper Wharfedale) peat drains were major sources of suspended sediment with 18.3 % of the sediment originating from drains which drained 7.3 % of the area. Enhanced piping in drained peatlands (see above) may also exacerbate sediment losses and other forms of carbon loss. If there are more pipes there should, theoretically, be more carbon being produced by pipes, although no measurements of pipe carbon losses have been made in drained catchments.

3.3 Other water quality issues

Sometimes where peatland drainage appears to have little effect on the hydrological regime of the catchment, it can have significant effects on soil and drainage water quality (Ministry of Agriculture Food and Fisheries, 1980). Many studies have observed that installation of drainage ditches usually increases the leaching of nutrients. For example, in blanket peat, large increases in ammonium concentrations have been observed following drainage (Lundin, 1999; Miller et al., 2001; Sallantaus, 1995) and drought (Adamson et al., 2000). In Canada, Prevost et al.(1999)observed that solute content was enhanced by drainage and this was associated with slight decreases in pH and coincided with an increase in soil temperature, a decrease in moisture content and accelerated decomposition rates observed within the top 30 cm of the peat. Additionally where drainage ditches penetrate the mineral soil beneath the peat there may be other effects such as aluminium and manganese release (Astrom et al., 2001) or an increase in pH of drainage waters.

Most studies that have investigated the impact of peatland drainage on water chemistry have observed changes in concentrations and fluxes of solutes in the short-term. However, the duration of the drainage effects on water chemistry is not known because few studies have continued monitoring for more than five years. In addition, most studies have monitored the chemistry of drainage water rather than the soil solution, and few studies have linked these measurements to soil processes. Therefore, it is not known in detail to what extent and by which mechanisms various solutes are released and leached in artificially drained catchments. Compared to forested peatlands, there is little information on the impacts of drainage on water chemistry in unforested blanket peatlands.

4. Overview of impacts of blanket peat drain-blocking

There is relatively little published research on the impacts of blanket peat drain-blocking in the UK. There are a number of overseas studies on restoration including drain-blocking of a number of other types of peat, although again relatively little on blanket peat. As this report is meant to be a summary overview it will focus on UK blanket peat research. For reference purposes some of the recent research on drain-blocking includes:

- Armstrong, A., Holden, J., Kay, P. McDonald A.T., Gledhill S., Foulger, M. and Walker, A. (in press) Peatland drain blocking reduces dissolved organic carbon loss and discolouration of water; results from a national survey. *Journal of Hydrology.*
- Armstrong, A., Holden, J., Kay, P. McDonald A.T., Gledhill S., Foulger, M. and Walker, A. (2009) Drain blocking techniques on blanket peat: a framework for best practice. *Journal of Environmental Management,* 90, 3512-2519.
- Armstrong, A., Holden, J. and Stevens, C. (2008) The differential response of vegetation to grip-blocking. Peatscapes project report, 29pp.
- Baird, A.J., Holden, J. and Chapman, P.J., 2009. A literature review of evidence on emissions of methane in peatlands, Defra project SP0574.
- Chapman, P.J., Robroek, BJM., Holden, J., Ashley, D. Irvine, B. (in review) Spatial variability in water chemistry related to catchment characteristics and land management in the Nidderdale Area of Outstanding Beauty, North Yorkshire. Submitted to *Science of the Total Environment.*
- Gibson, H. S., Worrall, F., Burt T. P., Adamson J. K. (2009) DOC budgets of drained peat catchments: implications for DOC production in peat soils. *Hydrological Processes*, 23, 1901–1911
- Holden, J, Wallage, Z.E., Lane, S.N and McDonald, A.T. Water table dynamics in drained and restored blanket peat. Submitted to *Journal of Hydrology*
- Holden, J., Gascoign, M. and Bosanko, N.R. (2007) Erosion and natural revegetation associated with surface land drains in upland peatlands. *Earth Surface Processes and Landforms,* 32, 1547-1557
- Holden, J. Walker, J., Evans, M.G., Worrall, F., Bonn, A. (2008a) A compendium of peat restoration and management projects. Defra report SP0556.
- Holden, J., Kirkby, M.J., Lane, S.N., Milledge, D.J., Brookes, C.J., Holden, V. and McDonald, A.T. (2008b) Factors affecting overland flow velocity in peatlands. *Water Resources Research*, 44, W06415, doi: 10.1029/2007WR006052.

- Holden, J. (2005) Analysis of Geltsdale hydrological data from grip blocking sites. English Nature report.
- Jonczyk, J. Rimmer, D. and Quinn, P. (2009) Geltsdale grip block monitoring report, Peatscapes.
- Ramchunder, S., Brown, L.E. and Holden, J. (2009) Environmental effects of drainage, drain-blocking and prescribed vegetation burning in UK upland peatlands. *Progress in Physical Geography,* 33, 49-79.
- Wallage, Z.E., Holden, J. and McDonald, A.T. (2006) Drain blocking is an effective treatment for reducing dissolved organic carbon loss and water colour in peatlands. *The Science of the Total Environment* 367, 811-821.
- Wallage, Z.E., Holden, J., Jones, T. and McDonald, A.T. (in review) Microbial activity and dissolved organic carbon production potential in drained and restored blanket peat. *Journal of Hydrology*
- Worrall, F., Armstrong, A. and 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 H.S. and Burt T.P. (2007). Modelling the impact of drainage and drain-blocking on dissolved organic carbon release from peatlands. *Journal of Hydrology* 338(1-2): 15-27.

The Defra peat restoration compendium (Holden et al., 2008b) showed that there are many projects where monitoring work is taking place (see below) but the monitoring is often different between projects and tends to focus on biodiversity indicators rather than hydrological or carbon ones. In addition to the monitoring projects listed in the compendium, there are also a number of other ongoing research projects which have not yet published. These include (among others):

- Impact of drain-blocking on cranefly populations (York University PhD project, Matthew Carroll)
- The Vrynwy UKPopNet research project (www.ukpopnet.org)
- Small UKPopNet project "How does hydrologically induced environmental change mobilise soil carbon? Use of lead isotopes as a marker for organic matter mobilisation" University of Aberdeen (Julian Dawson is the contact).
- The Vrynwy RSPB EU LIFE research on water tables, grip flow, overland flow, water colour, dissolved organic carbon and sediment production before and after grip-blocking (http://www.blanketbogswales.org/news--events/progress-to-date_238.html). Data analysis is currently being performed by Lorraine Wilson.
- SCAMP project results from United Utilities/Penny Anderson Consultants (focus mainly on water colour).
- SCAMP flow modelling by Newcastle University for the Environment Agency (focus mainly on flooding).
- FRMRC peatland drainage and drain-blocking modelling study (using field data to support the modelling) led by Howard Wheater and Caroline Ballard (Imperial College London).
- PhD project by Sorain Ramchunder who is investigating stream invertebrate communities in drained, drain-blocked, intact and burnt peatlands.

The above work has shown a number of things as indicated below. The main points are in bold while additional detail (where deemed important) is provided in normal font below each bold section:

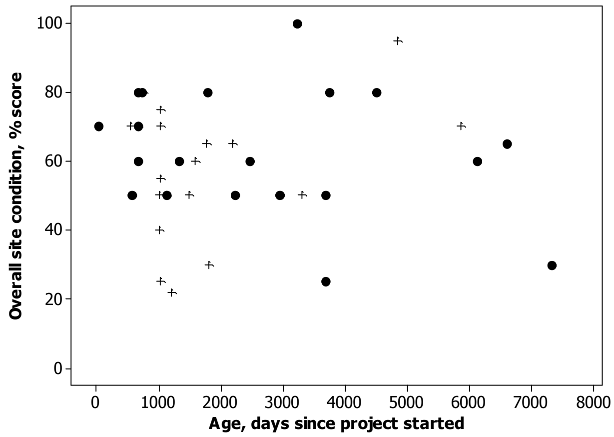
1. **There are over 150 peat restoration projects occurring in the UK covering more than 1000 sites; many of these involve drain-blocking on blanket peat. The largest area under restoration lies on blanket peat (Holden et al., 2008b).**

A detailed survey of project staff undertaken for the Defra peat restoration compendium demonstrated a number of features of peatland restoration projects as well as providing information on the types of restoration methods being adopted including those used for drain-blocking. Most projects reported that one of their main challenges was physical access for machinery to develop practical works on site. Health and safety considerations were found to be another key challenge, particularly where land was accessible by the public.

Most projects focussed on restoring ecological and hydrological function, or whole ecosystem function. In terms of project justification, biodiversity came across overwhelmingly strongly and was used as a justification for all projects. Hydrological function was the second most important justification factor. Carbon was used as a justification for 62% of the projects, but was only considered extremely important in three cases. There have been changes recently in that less of the newer projects claim that carbon is of no importance or of very low importance when justifying the need for restoration or management.

There was a significant difference in how staff graded the site conditions at the start of their project compared to 'present' conditions (i.e. at the time of the survey). The average score of site condition (100% is excellent state, 0% is totally destroyed) rose from 46% to 61%. However, the dataset suggested that overall while there were thought to be significant improvements in hydrological condition and some improvement in carbon sequestering potential, there were no significant improvements in biodiversity. The average overall project success score provided by project staff was 67%. Examination of the success scores by length of project (Figure 9) showed that perceived success increased rapidly through the first three years of a project before levelling off at 80-100% thereafter. In contrast, the estimated site condition data showed relatively little pattern in time and much greater variation. There is a natural desire to claim project success within a typical three year funding window but there was a disparity between success scores and reported site condition improvements with time. Therefore, the nature of self-reported success needs to be carefully evaluated in the light of supporting measurable data. Projects can succeed in many ways and this success may not map directly onto restoration of biodiversity, water table or peatland condition.

a) b)



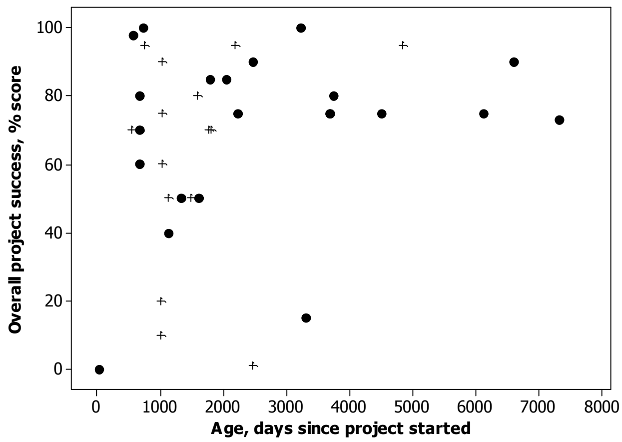


Figure 9. Plots showing (a) site condition and (b) project success scores with age of project for upland and lowland peatland projects (circles = lowland, crosses = upland).

Almost all projects were found to be monitoring vegetation, mainly through ground survey but assisted in about half of the cases by air photos and other remote sensing techniques. Indeed there is widespread use of GIS and remote sensing (air photos and LiDAR) among peat restoration and management projects. Many have noted that these tools were invaluable for the project. Hydrology is being monitored by ground survey in 70% of projects. Invertebrate and bird monitoring are also common occurring in more than 50% of projects while carbon, peat erosion, climate and pollution are being monitored in few cases. Monitoring was delivered by a variety of personnel ranging from academic collaborators to volunteers and private contractors. Most vegetation monitoring was delivered in-house while most monitoring for other variables was delivered by others. Academic collaborators dominated the delivery of carbon and climate monitoring.

Monitoring is expensive and should be properly costed, planned and implemented early in the life of a project. There is a lack of pre-restoration monitoring of long time series (i.e. years) to generate baseline conditions on functions such as hydrology. More focussed monitoring work is required to examine hydrological and carbon cycle changes following peat drain-blocking using careful protocols. Work is also required using an ergodic method (space for time substitution) to establish patterns of change where drain-blocking has taken place.

2. **Techniques for peatland ditch blocking have evolved over time; but the most cost-effective on blanket peat are carefully installed peat dams, but this depends on slope and other local factors and sometimes requires careful reprofiling of the drain edges (Armstrong et al., 2009).**

The first upland peat drain dams in the UK were installed in Caithness, Scotland, in the late 1980s and there has been a dramatic increase in blocking since then. Complete infilling of peat drains is rare and more commonly drain-blocking occurs through the installation of dams at intervals along the length of each drain. A number of different techniques have been adopted to block drains including use of plastic piling, straw or heather bales, wool in Hessian sacks (now prohibited) and wooden dams (Figure 10). The favoured technique is now carefully cut and packed peat dams where the peat is taken from adjacent to the drain at the dam location creating a gentle exit route for water from the blocked drain. This is the most cost-effective method and is favoured by most land owners (Armstrong et al., 2009). It has to be done with care in order to create a seal and to minimise damage to the surrounding peat. Furthermore, pools created cannot be too deep otherwise they will be unlikely to colonise with vegetation (Armstrong et al., 2008; Middelboe and Markager, 2003). However, it may not be possible to use this method on steep slopes, where the drain has eroded significantly or where the drain spacing is very short. It is fair to say that contractors have refined their methods over time and that there are a limited number of contractors able to perform the drain-blocking work in blanket peat to a high standard.

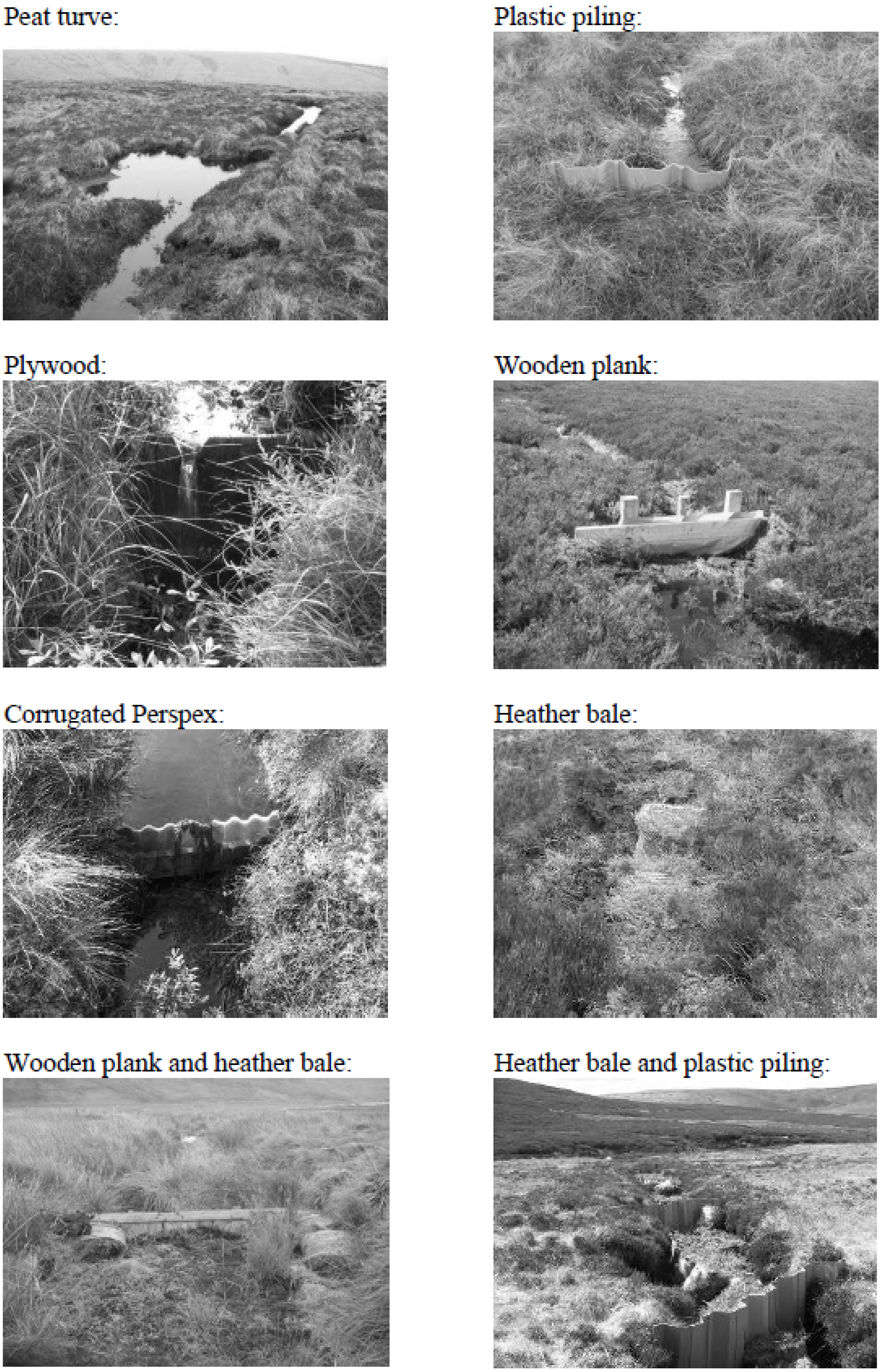


Figure 10. Some of the major drain-blocking methods found across the UK.

3. **Flow velocities across the surface of restored / drain-blocked peatlands are slower than in drained peatlands. Often this is due to the greater *Sphagnum* cover around blocked drains which is excellent at slowing the flow. Flow velocity is slower within vegetated drains (even ones without dams and pools) compared to bare peat drains by at least 10-fold (Holden et al., 2008a).**

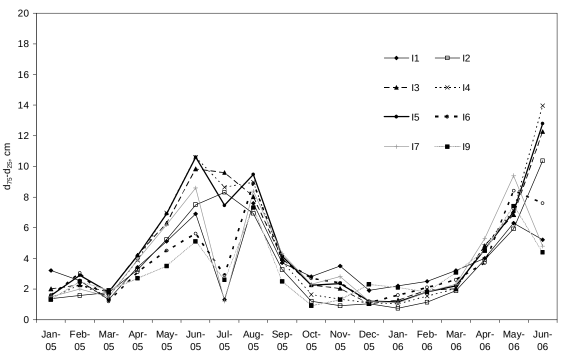
4. **The volume of water flowing along drain channel outlets is significantly reduced by drain-blocking (Holden, 2005a).**

The above is true especially when escape routes for water have been created to allow the water to flow along the natural slope. However, when the drain is aligned in the same direction as the slope or there have been no attempts to enable water to be redistributed from the dammed drain then water can often just flow around the dams and back into the drain again. Under these conditions flow volumes at drain outlets are not reduced.

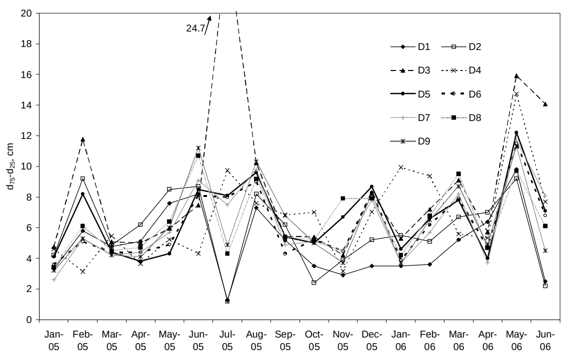
5. **While mean water table recovery can be fast, the water table dynamics remain very different in drain-blocked sites compared to intact peats several years after blocking and so hydrological recovery is actually much slower than a simple mean water table measurement would suggest (Holden et al., in review). The hydrology of peat systems is more than just a water table measure and a stream runoff measure.**

Transects of automated water table recorders have been deployed at a number of drain-blocking sites and at other sites water tables have been monitored manually. One of the most important findings has been that while average water tables do seem to recover fairly well after drain-blocking and can be quite quick to repsond (e.g. Worrall et al., 2007a) at most sites there is a long lag time before the peatland water table behaves in a similar way to that of an intact peat site. The study of Jonczyk et al (2009), for example, monitored for 17 months and did not find that blocking had a major influence on water tables across the peatland slopes as a whole. Thus longer-term monitoring is needed to establish the full effects. In the studies at Vyrnwy, there seems to be an almost two year lag time before water tables recover. At a site in Upper Wharfedale, Holden et al. (in review) have found using high resolution transects of data loggers that even six years after blocking, the water tables do not behave like those in a nearby intact peat and they have a greater range of depths and fluctuate more frequently. They showed that in intact peat the dominant control on water table drawdown was evapotranspiration (low variability in winter and high variability in summer; Figure 11a) while in the drained peat it was free movement of water through the deeper peat layers (high variability all year round with no difference between summer and winter; Figure 11b). The drain-blocked site was somewhere in between (Figure 11c).

a)



b)



c)

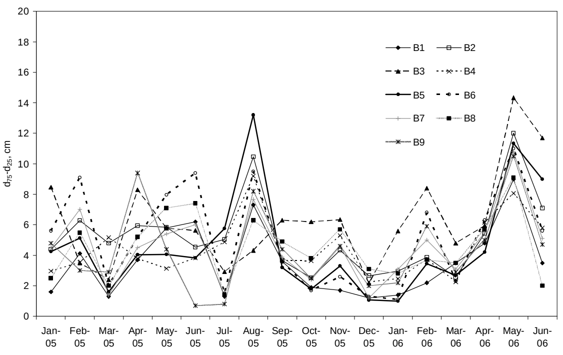


Figure 11. Seasonal variation in interquartile range for water tables for each dipwell: a) intact site; b) drained site; c) blocked site

6. **Drain-blocking in blanket peat, in general, results in a significant decrease in water colour and dissolved organic carbon concentrations in peat (Wallage et al., 2006) and stream waters (Armstrong et al., in press), but these patterns are not found at all sites (Gibson et al., 2009; Jonczyk et al., 2009; Worrall et al., 2007a); in many places there is no significant difference between drained and blocked systems.**

Given drainage lowers the water table by restricting upslope flow of water, drained blanket peats have a higher dissolved organic carbon release potential than undrained peats. Conversely, drain-blocking (normally) raises the water table (Worrall et al., 2007a) and therefore, should consequently decrease water discolouration and dissolved organic carbon concentrations and flux. However, there is some concern that blocking drains may not be an effective strategy for reducing dissolved organic carbon loss. This is because in peatlands, decomposition, and therefore dissolved organic carbon production, is restricted by suppression of major organisms that decompose the peat (Kang and Freeman, 1999). However, Freeman et al. (2001) demonstrated that this suppression is destroyed (i.e. the organisms are activated) when water table in peat is lowered, and may not recover upon rewetting and thus decomposition may continue even when the water table rises again (the organisms stay activated).

Furthermore, local surface topography affects water table depth with areas at the foot of slopes tending to have shallower water tables for longer durations than areas upslope, particularly if there is a steeper gradient upslope (Holden et al., 2006b). Therefore, dissolved organic carbon production potential is influenced by topography and the relative success of drain-blocking will be dependent on slope position (e.g. Figure 8).

Some short-term studies have been undertaken to examine the effects of drain-blocking on dissolved organic carbon *at individual sites*. Three studies show limited impacts of drain-blocking on water colour or DOC concentrations:

- Gibson et al (2009)
- Worrall et al (2007)
- Jonczyk et al (2009)

Gibson et al., (2009) monitored four drains: three parallel drains at one site in northern England, two of which were blocked in 2003 and one of which was left unblocked, as well as another at a different site, also in northern England, which was blocked in 1995. Samples of water from the drains were analysed for water colour (absorbance at 400 nm) and dissolved organic carbon and it was shown that both fluxes were less in the three blocked drains than in the unblocked one. However, this was mainly explained by the reduction in water discharge from the drains rather than by decreases in concentrations. Worrall *et al.* (2007) found water colour to be slightly higher in blocked drains when compared to unblocked drains. However, the work here was limited in that monitoring only began one month prior to blocking and ceased eight months after. Similarly, Jonczyk et al. (2009) performed a study in the immediate aftermath of blocking and found little effect of blocking on colour and dissolved organic carbon. This latter study has not yet been published after peer review.

Three studies have shown blocking to be an effective method for reducing dissolved organic carbon concentrations and fluxes.

- Wallage et al (2006)
- RSPB Vrynwy study (paper in progress)
- Armstrong et al (2009)

Wallage et al. (2006) demonstrated that drain-blocking decreased water colour (absorbance at 254, 465, 665 nm) and dissolved organic carbon concentration (by 65 % on average) in soil water sampled in the vicinity of blocked and unblocked drains at one site in northern England. In fact concentrations were lower than in the nearby intact (undrained) peat. It is noteable here that the drains were blocked six years prior to sampling and that sampling took place over an 18 month period. However, no water samples from runoff were measured. At Vrynwy, samples have been taken (every two weeks) from both drains and streams for dissolved organic carbon and colour. Here blocking does significantly reduce the concentrations of dissolved organic carbon and colour in the stream and drain waters. Armstrong et al (2009) performed a sample survey of drain-blocking sites across the UK and found that in general, although not everywhere, colour and dissolved organic carbon concentrations were lower in flowing water in blocked compared to unblocked drains. In their same study they found that at one site where they monitored more intensively there was no significant difference between blocked and unblocked drains in dissolved carbon concentrations. The results may depend on peat type, position within the landscape and other environmental parameters. A modelling study by Worrall et al (2007b) predicted that drain-blocking should reduce dissolved organic carbon concentrations and fluxes but found that the magnitude of the decrease is critically dependent upon the drain-spacing and for the larger drain-spacings no decrease may be observed.

7. **Drain-blocking appears to change the constituents of dissolved organic carbon being produced by the peat system (Gibson et al., 2009; Jonczyk et al., 2009; Wallage et al., in review; Wallage et al., 2006).**

All of the dissolved organic carbon / water colour studies seem to agree that blocking changes the composition of the discoloured water, even in cases when the discolouration of dissolved organic carbon concentrations themselves are not shown to be different between blocked and unblocked This makes the water easier (cheaper) to treat by water companies.

8. **Vegetation change (driven by management practice, including drain-blocking) may have a strong impact on dissolved organic carbon production**

Evidence is building from a number of sources that vegetation cover is a key driver of dissolved organic carbon concentrations. Much of this evidence has been compiled into one document by Armstrong et al (in review). *Sphagnum* and *Molinia* seem to be associated with low concentrations while heather is associated with higher concentrations of dissolved organic carbon. Note that the latter finding is not related to burning. Thus if drain-blocking alters the vegetation cover of sites then this might reduce dissolved organic carbon concentration in the long term.

9. **In Upper Wharfedale drain-blocking significantly reduced fine sediment (and POC) yield by over 50 fold (Holden et al., 2007b).**

10. **Methane flux is likely to increase from peatlands with lots of drain-blocking pools; the evidence points in this direction although there is a lack of data from blanket peat (Baird et al., 2009).**

The Defra review used published and grey literature from around the world, a questionnaire to international scientists and a workshop with UK scientists. Across all peatland types, very little work has been done on restoration impacts on methane emissions and how such emissions affect the carbon sink function. Work has started but more work is needed especially in blanket bogs and fens. Despite the lack of work, it is possible to make the following tentative general conclusions based on the evidence compiled:

- Restoration does not necessarily lead to a peatland becoming a carbon sink (either in terms of a simple carbon balance or in terms of its effect on global warming potential): it should not be assumed that all restored peatlands are carbon sinks.

- Methane is often an important component of the carbon balance of restored peatlands when considered in terms of global warming potential even when, in terms of mass, methane losses are only a few percent (3-5%) of the net exchange of CO_2 between the peatland and the atmosphere.

- Restored peatlands have less of an impact on global warming than unrestored peatlands. Thus, although they may not be carbon sinks, they have a smaller global warming potential than damaged peatlands. Restoration is therefore generally beneficial from a global warming point of view. However, we did find examples of restored peatlands that had higher global warming potentials than unrestored peatlands; much seems to depend on the nature of damage and the type of restoration.

- In raised bogs blocked ditches have been found to be hotspots of methane emissions. Bunded areas with open water and sedges may also be important hotspots. Where possible areas of open water on restored raised bogs should be minimised.

- There are too little data to know whether the same is true for blanket peat drain-blocking pools. However, those methods of ditch blocking that do not create additional areas of open water are preferred over those that do (methane emissions tend to be higher from areas of standing water).

11. **Stream ecology (e.g. invertebrate communities) is significantly impacted by drainage and drain-blocking (Ramchunder's PhD in progress, University of Leeds).**

12. **Terrestrial ecological recovery on peatlands is generally slow and lags hydrological recovery (Holden et al., 2008b).**

No work has been published on:

- The effects of drain-blocking on flooding (modelling work here is ongoing at Newcastle and Imperial)
- The effects of blanket peat drain blocking on pipeflows and associated carbon release.
- Methane loss from drain-blocked pools in blanket peat.
- Other water quality variables (although Armstrong et al., 2008 did produce a short pilot study for Peatscapes with some water quality data).

References

Adamson, J.K., Scott, W.A., Rowland, A.P. and Beard, G.R., 2000. Ionic concentrations in a blanket peat bog in northern England and correlations with deposition and climatic variables. European Journal of Soil Science, 51, 1-15.

Armstrong, A., Holden, J., Kay, P., Foulger, M., Gledhill, S., McDonald, A.T. and Walker, A., 2009. Drain-blocking techniques on blanket peat: a framework for best practice. Journal of Environmental Management, doi:10.1016/j.jenvman.2009.06.003

Armstrong, A., Holden, J., Kay, P., McDonald, A.T., Gledhill, S., Foulger, M. and Walker, A., in press. Peatland drain blocking reduces dissolved organic carbon loss and discolouration of water; results from a national survey. Journal of Hydrology.

Armstrong, A., Holden, J., Luxton, K. and Quinton, J.N., in review. Peatland vegetation type - a key driver of DOC? Science of the Total Environment.

Armstrong, A., Holden, J. and Stevens, C., 2008. The differential response of vegetation to grip-blocking. Report for Peatscapes, North Pennine AONB, 29pp.

Astrom, M., Aaltonen, E.K. and Koivusaari, J., 2001. Impact of ditching in a small forested catchment on concentrations of suspended material, organic carbon, hydrogen ions and metals in stream water. Aquatic Geochemistry, 7, 57-73.

Baden, W. and Eggelsmann, R., 1970. Hydrological budget of high peat bogs in the Atlantic region, Proceedings of the third international peat congress, 1968. Department of Energy, Mines and Resources, Ottawa, Quebec, pp. 260-311.

Baird, A.J., Beckwith, C.W., Waldron, S. and Waddington, J.M., 2004. Ebullition of methane-containing gas bubbles from near-surface Sphagnum peat. Geophysical Research Letters, 31, art. no.-L21505.

Baird, A.J., Holden, J. and Chapman, P.J., 2009. A literature review of evidence on emissions of methane in peatlands, Defra project SP0574.

Blodau, C., Basiliko, N. and Moore, T.R., 2004. Carbon turnover in peatland mesocosms exposed to different water table levels. Biogeochemistry, 67, 331-351.

Bragg, O.M., 2002. Hydrology of peat-forming wetlands in Scotland. The Science of the Total Environment, 294, 111-129.

Bullock, A. and Acreman, M., 2003. The role of wetlands in the hydrological cycle. Hydrology and Earth System Sciences, 7, 358-389.

Burke, W., 1975. Effect of Drainage on Hydrology of Blanket Bog. Irish Journal of Agricultural Research, 14, 145-162.

Carling, P. and Newborn, D., 2007. Erosion and moorland drainage - lessons from a past experiment. Review of 2006; research section I - Uplands.

Chapman, P., 1993. Caves and cave life. Harper Collins.

Clausen, J.C., 1980. The quality of runoff from natural and disturbed Minnesota peatlands, Proceedings 6th International Peat Congress, Duluth, Minnesota, 1976, Minnesota, pp. 523-532.

Clymo, R.S., 1983. Peat. In: A.J.P. Gore (Editor), Ecosystems of the World 4A, Mires: swamp, bog, fen and moor. Elsevier, Oxford, pp. 159-224.

Dinsmore, K.J., Billett, M.F., Skiba, U.M., Rees, R.M., Drewer, J. and Helfter, C., in press. Role of the aquatic pathway in the carbon and greenhouse gas budgets of a peatland catchment. Global Change Biology.

Dirks, B.O.M., Hensen, A. and Goudriaan, J., 2000. Effect of drainage on CO2 exchange patterns in an intensively managed peat pasture. Climate Research, 14, 57-63.

Edwards, A., Martin, D. and Mitchell, G., 1987. Colour in upland waters. Proceedings of Yorkshire Water/Water Research Centre Workshop, Leeds, 29 September 1987.

Freeman, C., Fenner, N. and Ostle, N.J., 2004. Export of dissolved organic carbon from peatlands under elevated carbon dioxide levels. Nature, 430, 195-198.

Freeman, C., Ostle, N. and Kang, H., 2001. An enzymic 'latch' on a global carbon store – a shortage of oxygen locks up carbon in peatlands by restraining a single enzyme. Nature, 409, 149.

Frolking, S., Roulet, N.T., Moore, T.R., Lafleur, P.M., Bubier, J.L. and Crill, P.M., 2002. Modeling seasonal to annual carbon balance of Mer Bleue Bog, Ontario, Canada. Global Biogeochemical Cycles, 16, 10.1029/2001GB001457.

Gibson, H.S., Worrall, F., T.P., B. and 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, 101 pp.

Gilman, K., 2002. A review of evapotranspiration rates from wetland and wetland catchment plant communities, with particular reference to Cors y Llyn NNR, Powys, Wales, CCW Science Report; 504, Countryside Council for Wales, Bangor.

Holden, J., 2004. Hydrological connectivity of soil pipes determined by ground-penetrating radar tracer detection. Earth Surface Processes and Landforms, 29, 437-442.

Holden, J., 2005a. Analysis of Environment Agency hydrological monitoring data collected at Geltsdale in conjunction with grip blocking works at Halton Lea Fell, Report for English Nature.

Holden, J., 2005b. Controls of soil pipe frequency in upland blanket peat. Journal of Geophysical Research, 110, F01002, doi:10.1029/2004JF000143.

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

Holden, J., 2006. 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.P., 2002a. Infiltration, runoff and sediment production in blanket peat catchments: implications of field rainfall simulation experiments. Hydrological Processes, 16, 2537-2557.

Holden, J. and Burt, T.P., 2002b. Laboratory experiments on drought and runoff in blanket peat. European Journal of Soil Science, 53, 675-689.

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., 2003a. Hydrological studies on blanket peat: the significance of the acrotelm-catotelm model. Journal of Ecology, 91, 86-102.

Holden, J. and Burt, T.P., 2003b. Runoff production in blanket peat covered catchments. Water Resources Research, 39, 1191, doi:10.1029/2003WR002067.

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

Holden, J., Chapman, P.J., Lane, S.N. and Brookes, C.J., 2006a. Impacts of artificial drainage of peatlands on runoff production and water quality. In: I.P. Martini, A.M. Cortizas and W. Chesworth (Editors), Peatlands: evolution and records of environmental and climate changes. Elsevier, Amsterdam, pp. 501-528.

Holden, J., Evans, M.G., Burt, T.P. and Horton, M., 2006b. Impact of land drainage on peatland hydrology. Journal of Environmental Quality, 35, 1764-1778, doi:10.2134/jeq2005.0477.

Holden, J., Gascoign, M. and Bosanko, N., 2007a. Erosion and natural revegetation associated with surface land drains in upland peatlands. Earth Surface Processes and Landforms, in press.

Holden, J., Gascoign, M. and Bosanko, N.R., 2007b. Erosion and natural revegetation associated with surface land drains in upland peatlands. Earth Surface Processes and Landforms, 32, 1547-1557.

Holden, J., Kirkby, M.J., Lane, S.N., Milledge, D.G., Brookes, C.J., Holden, V. and McDonald, A.T., 2008a. Factors affecting overland flow velocity in peatlands. Water Resources Research, 44, W06415, doi: 10.1029/2007WR006052.

Holden, J., Smart, R., Chapman, P.J., Baird, A.J. and Billett, M., 2009. The role of natural soil pipes in water and carbon transfer in and from peatlands. In: A.J. Baird, L. Belyea, X. Comas, A.S. Reeve and L. Slater (Editors), Northern Peatlands and Carbon Cycling. American Geophysical Union Monograph., Washington DC.

Holden, J., Walker, J., Evans, M.G., Worrall, F. and Bonn, A., 2008b. A compendium of peat restoration and management projects. Defra report SP0556.

Holden, J., Wallage, Z.E., Lane, S.N. and McDonald, A.T., in review. Water table dynamics in drained and restored blanket peat. Journal of Hydrology.

Jonczyk, J., Rimmer, D. and Quinn, P., 2009. Geltsdale grip block monitoring report, Peatscapes project final report.

Jones, J.A.A., 1997. Pipeflow contributing areas and runoff response. Hydrological Processes, 11, 35-41.

Jones, J.A.A., 2004. Implications of natural soil piping for basin management in upland Britain. Land Degradation & Development, 15, 325-349.

Jones, J.A.A. and Crane, F.G., 1984. Pipeflow and pipe erosion in the Maesnant experimental catchment. In: T.P. Burt and D.E. Walling (Editors), Catchment experiments in fluvial geomorphology. Geo Books, Norwich, pp. 55-72.

Kang, H. and Freeman, C., 1999. Phosphatase and arylsulphatase activities in wetland soils - annual variation and controlling factors. Soil Biology and Biochemistry, 31., 449-454.

Limpens, J., Berendse, F., Blodau, C., Canadell, J., Freeman, C., Holden, J., Roulet, N., Rydin, H. and Schaepman-Strub, G., 2008. Peatlands and the carbon cycle: from local processes to global implications - a synthesis. Biogeosciences, 5, 1475-1491.

Lundin, L., 1999. Effects on hydrology and surface water chemistry of regeneration cuttings in peatland forests. International Peat Journal, 9, 118-126.

Mayfield, B. and Pearson, M.C., 1972. Human interference with the north Derbyshire blanket peat. East Midland Geographer, 12, 245-251.

Middelboe, A.L. and Markager, S., 2003. Depth limits and minimum light requirements of freshwater macrophytes. Freshwater Biology, 37, 553-568.

Miller, J.D., Adamson, J.K. and Hirst, D., 2001. Trends in stream water quality in Environmental Change Network upland catchments: the first 5 years. The Science of the Total Environment, 265, 27-38.

Ministry of Agriculture Food and Fisheries, 1980. Land drainage service research and development. Field Drainage Experimental Unit Technical Report 3, MAFF, Trumpington.

Mitchell, G. and McDonald, A.T., 1995. Catchment Characterization as a Tool for Upland Water-Quality Management. Journal of Environmental Management, 44, 83-95.

Moore, T.R., 1987. A preliminary study of the effects of drainage and harvesting on water quality in an ombrotrophic bogs near Sept-Iles, Quebec. Water Resources Bulletin 23, 785-791.

Nilsson, M., Sagerfors, J., Buffam, I., Laudon, H., Eriksson, T., Grelle, A., Klemedtsson, L., Weslien, P. and Lindroth, A., 2008. Contemporary carbon accumulation in a boreal oligotrophic minerogenic mire - a significant sink after accounting for all C-fluxes. Global Change Biology, 14, 2317-2332.

Prevost, M., Plamondon, A.P. and Belleau, P., 1999. Effects of drainage of a forested peatland on water quality and quantity. Journal of Hydrology, 214, 130-143.

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

Robinson, M., 1985. The Hydrological Effects of Moorland Gripping - a Reappraisal of the Moor House Research. Journal of Environmental Management, 21, 205-211.

Roulet, N.T., Lafleur, P.M., Richard, P.J.H., Moore, T.R., Humphreys, E.R. and Bubier, J., 2007. Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland. Global Change Biology, 13, 397-411.

Sallantaus, T., 1995. Leaching in the material balance of peatlands - preliminary results. Suo, 43, 253-258.

Tipping, E., Woof, C. and Rigg, E., 1999. Climatic influences on the leaching of dissolved organic matter from upland UK moorland soils, investigated by a field manipulation experiment. Environment International,, 25, 83-95.

Wallage, Z.E., Holden, J., Jones, T. and McDonald, A.T., in review. Microbial activity and dissolved organic carbon production potential in drained and restored blanket peat. Journal of Hydrology.

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, 811-821.

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, 315-325.

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. The Science of the Total Environment, 407, 4084-4094.

Worrall, F., H.S., G. and T.P., B., 2007b. Modelling the impact of drainage and drain-blocking on dissolved organic carbon release from peatlands. Journal of Hydrology, 338, 15-27.