Peatland Hydrology

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Summary

The nature of a peatland is controlled by hydrological processes. Its existence depends upon retaining water and its characteristics depend upon the origin, volume, chemical quality and variability of water supply.

The often-repeated description of peat as a “sponge” slowly releasing large amounts of water to a stream is erroneous; a wet sponge cannot hold much additional water. Even intact blanket peat is highly productive of storm runoff very soon after rainfall, and generates little baseflow in out-flowing streams during times of low rainfall. Rainfall input is rapidly followed by a response of rising flow (discharge) in the stream, then an almost equally rapid fall back to a very low base flow level.

The dominant flow processes in rain-fed peatlands are over or close to the surface. Water moves fastest over a bare peat surface and is slowed by friction over cottongrass and even more so when the peat surface is covered by rough Sphagnum moss. The depth of water also influences the speed of flow because deeper water moves faster.

The velocity water flow though peat is determined by its hydraulic conductivity, which is typically in the range of mm or cm per day but can vary widely depending on the physical properties of the peat (including vegetation composition, compaction, decomposition and the presence of macropores (pipes) and entrapped gas bubbles. These will all affect the rate of runoff from a peatland. The layer of peat at the surface is typically the least decomposed and the most permeable, sometimes termed the “acrotelm” or active layer where the water table fluctuates. Beneath this the peat remains saturated, so oxygen cannot penetrate. Here in the “catotelm” the plant material decomposes slowly and becomes more compact and less permeable to water. Large pores and pipes (sometimes many centimetres in diameter) and common in upland blanket peats and provide a pathway for the rapid transport of water. Pipes have been associated with drying and erosion of peat, sometimes exacerbated by artificial drainage undertaken to lower the water table for agriculture or forestry.

Water table depth is critical for plant growth and whilst water tables are typically 5cm below the surface of a pristine bog we know that different plant species have root systems that can utilise water at varying depths. This illustrates how a changing rainfall/hydrological regime can lead to a different bog character and may help us understand the impact of future climate change.

Heavily eroded peatlands are characterised by predominantly low water table conditions with very rapid ‘wet-up’ responses to rainfall followed immediately by rapid drain-down after the cessation of rainfall. Intact peatlands have generally high water tables except during very dry periods after which water tables generally recover rapidly. Peat forming processes are thus maintained for longer periods in intact peatlands. Gully-edge peats provide a key linkage between hillslope and channel flow, so their influence on peatland hydrological function is disproportionate to their limited spatial extent.

Monitoring water table fluctuations is key to characterising the hydrology of a peatland. Manual dipwell systems are inexpensive, simple to install and read, but expensive in labour costs over long periods. Their fundamental advantage is that, as they are so inexpensive, large numbers may be installed to characterise spatial hydraulic gradients as well as at-a-point measures of water table depth. Allott *et al* (2009) have suggested that 15 dipwells is the minimum required for adequate representation of water table fluctuations at a site. Where more temporal detail is required, automatic data loggers based on capacitance

probes have proved reliable and cost-effective compared to the more traditional pressure transducers or shaft encoders.

Key drivers of change in peatland hydrology are climate, land use and inputs of nutrients and pollutants from the atmosphere or external water sources. Although the Environment Agency and Natural England have published hydro ecological guidelines for several other vegetation communities, they have not done so for bogs.

Water quality in a peatland depends upon the way the water moves and how it interacts with the peat itself, the underlying substrate, the vegetation and the atmosphere. Bogs depend on rainfall and have low nutrient status and low pH (acid waters) whereas in a fen the water quality is determined primarily by the characteristics of the underlying substrate, and concentrations of nutrients and minerals are generally higher. Bogs and fens thus tend to have very different vegetation assemblages. In an intact bog, the near-surface “acrotelm” is the layer in which concentration of rainfall by evaporation and dilution of soil water is most immediately and directly experienced.

Peatlands form major catchments for surface water supply reservoirs across the uplands of the UK. A major issue for many water companies in recent years has been the rising trend in dissolved organic carbon (DOC) from peatland catchments. The doubling of levels of DOC (and associated discolouration of water) has been identified as the largest change in upland water quality over the last 30 years. Impacts on water treatment costs have been significant, with new treatment works required, in addition to implications for carbon export from the peatland system and for aquatic flora and fauna.

Afforestation of peatlands may lead to a slight decrease in the frequency but increase in duration of flow pulses above selected thresholds over decadal timescales. However the extent of afforestation, amount of drainage and proportion of the catchment affected appear to lead to significant variation in impact and nested scale studies may be needed to understand the full extent of the impact.

It seems likely that ditches running up and down slope will produce more rapid flow velocities and so are likely to lead to increased peat erosion compared to ditches excavated along the contours, but little direct evidence for this has been found in the literature. Grips cut following slope contours have been shown to dry the ground on the downslope side by intercepting overland flow. Blocking of grips can reduce runoff from peatlands but careful targeting is required to locate grips with large upslope contributing areas. Use of Geographical Information Systems (GIS) allows calculation of topographic indices to assist in this process.

Ramchunder *et al* (2009) noted that, although hundreds of millions of pounds are being invested in peatland restoration schemes in the UK uplands, including drain blocking, such investment is not being matched by appropriate monitoring programmes. Simply rewetting and/or revegetating degraded peats will not necessarily reverse the process response and they appealed for improved knowledge in order to aid practical solutions. The same issue applies to the very many windfarm developments on peat across the UK: claims of minimal impact are not supported by consistent, long-term monitoring of hydrological impacts and there is an urgent need for the renewable energy sector to address this. There is still significant uncertainty associated with trackway impacts on blanket peat hydrology, and a need for some well-monitored examples across the UK. Guidelines on best practice are being prepared by the Scottish Natural Heritage and Countryside Council for Wales.

The Defra funded Peatland Compendium (Holden *et al,* 2008) found that 70% of peatland restoration projects included some monitoring of hydrology (the second most popular monitoring after vegetation) but its precise nature varied; furthermore, conservation agencies have noted that the list of restoration projects included was very incomplete, with some substantial geographical gaps.

Baird *et al* (2003) acknowledged that the annual volume of peat extraction was only a small fraction of the net global peat accumulation, but noted that on a regional and local scale peat cutting profoundly alters hydrological and ecological conditions and cannot be considered sustainable.

Most traditional classifications of peatlands emphasise the origin and flow pathway of the water supply in controlling the nature of the wetland, but few have noted the variability of supply as being particularly important. This may be a result of an assumption of static climatic conditions but may also represent a significant gap in our understanding of how climate change could lead to changes in peatlands and how much a change in water supply (rainfall change) could alter a peatland state. There have been relatively few direct studies of the effects of varying water supply on peatlands, either in the short term of rainfall events and seasons or the longer term over years or centuries. Prediction of the impacts upon a peatland of changing water supply and climate remains a significant gap.

1. Introduction

Hydrology is the science of the occurrence, distribution, and movement of water, including both its quantity (flows and resting water levels whether over the surface, within the soil and deeper in the ground) and its quality (including acid/base status and concentrations of nutrients and toxins). Peatlands here are defined as areas of deep peat soils with an organic layer deeper than 40 cm depth, which coincides with the definition used within the Soil Survey of England and Wales, or 50 cm deep in Scotland. These may or may not be currently active in forming peat. The term "mire" is normally used for wet terrain dominated by living peat-forming plants (Rydin and Jeglum, 2006). Whilst the high organic content of the peat soil is its primary defining characteristic, it is the water-retention and thus the hydrological properties of peat which allow its continued existence and produce its distinctive suite of habitats. Understanding the hydrology of peatlands is fundamental to such habitats, as "*it is probably the single most important condition influencing peatland ecology, development, functions and processes*"(Rydin and Jeglum, 2006,p138). Bragg and Tallis (2001) also stressed the sensitivity of peatlands, especially the ombrogenous (rain-fed) peatlands known commonly bogs, to any change in their hydrology. Figure 1 illustrates how both the peat itself and the plant assemblages it supports are intimately connected with the water (hydrological conditions) in a mire.

The current state of peatlands in the UK has been reviewed by Shepherd *et al* (2010). Both raised and blanket bogs (explained further in section 2) are priority habitats under the UK Biodiversity Action Plan and securing favourable conditions for the long-term maintenance or re-establishment of regenerating and self-sustaining bog ecosystems is a target of the UK Biodiversity Action Plan (1999). The estimate in the National Peatland Resource Inventory (quoted in JNCC, 1994) was that of 37,413 ha of land in England with raised bog soils, only 493 ha (1% of the area, in 15 sites) retained near-natural bog vegetation. Tallis (1998) suggested that of 22500km^2 of blanket bog in Britain, only 4000km^2 remained in a near-natural state, with 3500 km^2 afforested and another 3500km^2 eroded. JNCC (1994) guidelines for the selection of bog SSSIs state that "*site boundaries must be chosen to include all land judged necessary to provide and maintain the hydrological functions needed to conserve the special features of the site*", recognising the fundamental importance of hydrology for continued existence.

Figure 1 Interrelations in a mire (from Schumman and Joosten, 2008)

This review concentrates upon peatland systems that are currently functioning or capable of being restored so that they are not losing peat, including both upland and lowland habitats. These include some areas that are currently bare of vegetation, either because of erosion by wind and water or because of deliberate peat extraction for horticulture or fuel (sometimes termed “cutover” peatlands). We present evidence and present scientific consensus on water retention and water movement in peatlands, together with related aspects of water quality, and highlight gaps in understanding. We summarise current understanding of the role of peatlands in affecting river flows, flooding and its management, and quality of water (including dissolved organic carbon, acidification and transport of suspended sediment).

2. Controls on Peatland Hydrology

The nature of a peatland is controlled by hydrological processes. Its existence depends upon retaining water and its characteristics depend upon the origin, volume, chemical quality and variability of water supply. Wetlands include, but are not restricted to, peatlands. Researchers have classified wetlands using various criteria, but Hughes and Heathwaite (1995) identified the source of the water as a fundamental control as shown in table 1.

Some workers have included the topography (the shape of the land or of sub-peat strata) as a characteristic feature important in the classification of peatlands (Wheeler, 1995). Mires have often been subdivided on this basis into three main types:

- **ombrogenous** mires are those under the exclusive influence of water from rainfall;
- **topogenous** mires are controlled by horizontal flows of ‘mineral soil water’ confined by topography;
- **soligenous** mires are developed on sloping sites where laterally mobile ‘mineral soil water’ maintained wet conditions.

This review mainly considers rainfall-fed peatlands (raised and blanket bogs) because these form the majority of the peatland resource in the UK. Blanket bogs are found in the uplands and the peat “drapes” over the gently sloping ground. A raised bog ecosystem develops when a body of topogenous peat grows beyond the influence of groundwater, in the form of a mound or dome, meaning that direct precipitation (in the UK this is almost all rainfall) falling onto the surface of the mire is now the only source of water available.

Table 1. A hydrologically based classification of wetlands (adapted from Hughes and Heathwaite, 1995, p14)

	Extent		
Source of water	**Small (<50 ha)**	**Medium (50-1000 ha)**	**Large (>1000 ha)**
Rainfall	Part of some basin mires	Raised bogs	Blanket bogs
Springs	Flushes: acid valley and basin mires	Fen basins: acid valley and basin mires	Fen massif
Floods	Narrow floodplains	Valley floodplains	Floodplain massif

The vegetation community that characterises a peatland is dependent not only on the source of its water but also on the degree of waterlogging and variability of water supply, and this may be altered where peatlands are damaged by drainage, extraction or other human activity. Wheeler *et al* (2009, p56) suggested that the water source is important because it determines both the wetness and hydro chemical environment of the main plant rooting zone. They said that characteristics for assessing wetland sites of conservation importance include the landscape type (e.g. hillslope, valley head or basin), base richness (acidity), fertility (nutrient status) and management activity. They identified 20 different “water supply mechanisms”, ranging from domed ombrogenous bog surfaces through surface-water percolation floodplains to groundwater-fed valley bottoms and said that assessment of the water supply should be done for stands of relatively uniform vegetation, rather than attempting to define a single hydrological mechanism for a whole site within the boundary designated for nature conservation. Existing classifications emphasise the origin and flow pathway of the water supply in controlling the nature of the wetland, but few have noted the variability of supply as being particularly important. There have been relatively few direct studies of the effects of varying water supply on peatlands, either in the short term of rainfall events and seasons or the longer term over years or centuries. Our understanding of the impact of changing water supply and the impact of climate on a peatland remains a significant gap. However, several palaeoecological studies use the nature of peat to infer past climate changes and these could be a helpful route towards predicting future change.

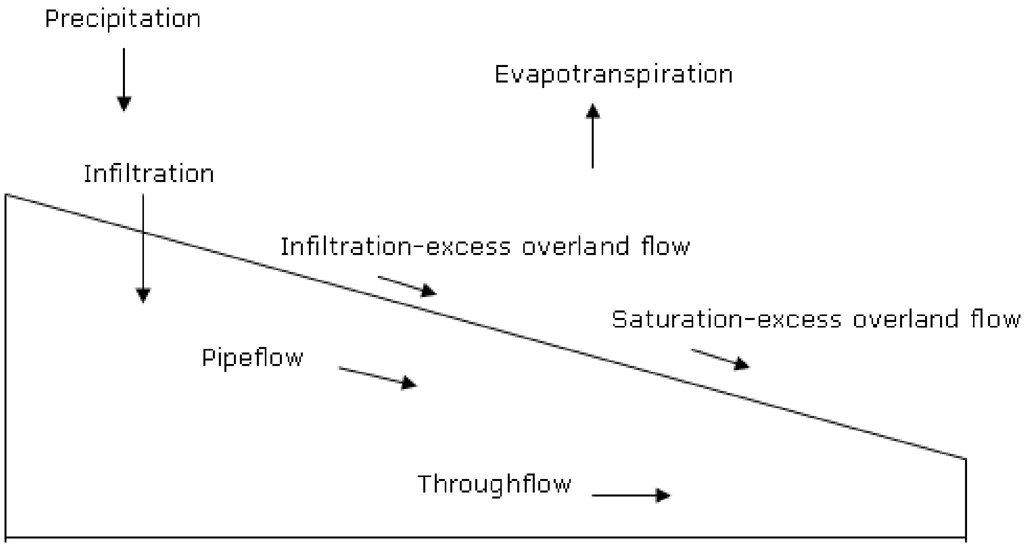

Figure 2: Schematic diagram to illustrate water pathways in a bog

Although large amounts of water are held within the peat of a blanket bog, it is important to understand that little of the water received as rainfall is retained. Peat has extremely high water content and, in an intact peatland, most of the water storage capacity is already full. Figure 2 is a schematic diagram illustrating the main water pathways. Even intact blanket peat is highly productive of rapid (rainfall event) runoff and, by contrast, generates little long-term “baseflow” during dry periods. For example, in the Feshie catchment in the Cairngorms (Scotland), Soulsby *et a*l (2006) showed that peat areas had the smallest groundwater contributions compared to areas on other soil types, and that streams draining blanket bog are often ephemeral in their flow regime, ceasing to flow in driest periods. Riparian wetlands (those on river floodplains and at the side of streams) may act as good flood attenuators, acting as shallow reservoirs to delay flow as it passes downstream, but many bogs do not act to delay flow into streams (Rydin and Jeglum, 2006, p152). The often–quoted idea of a peatland as a “sponge” that soaks up rainfall and then releases it slowly into rivers is erroneous.

2.1 Water retention and subsurface flows in peatlands

Peatland development depends on a relatively impermeable underlying geology to ensure sufficient water retention on the land surface (Charman, 2002). In more freely draining contexts, peat development relies on a consistent water supply, such as from springs. Peat soils typically contain very high moisture contents, usually in the range 600-1800% compared to the mass of dry material in the same volume (Hobbs, 1986). Darcy's law suggests that water flows through a unit area of wet peat will be determined primarily by the combination of hydraulic conductivity of the material (K, expressed as a speed of transmission of water through the material) and the hydraulic gradient (fall in height over horizontal distance travelled). Bogs remain wet because peat generally has low hydraulic conductivities, retaining water even when there is a relatively high hydraulic gradient.

Velocity of flow of water though peat is determined by its hydraulic conductivity, which is typically in the range of mm or cm per day but can vary widely depending on the physical properties of the peat (including vegetation composition, compaction, decomposition and presence of macropores (pipes) and entrapped gas bubbles) . These will all affect the rate of runoff from a peatland.

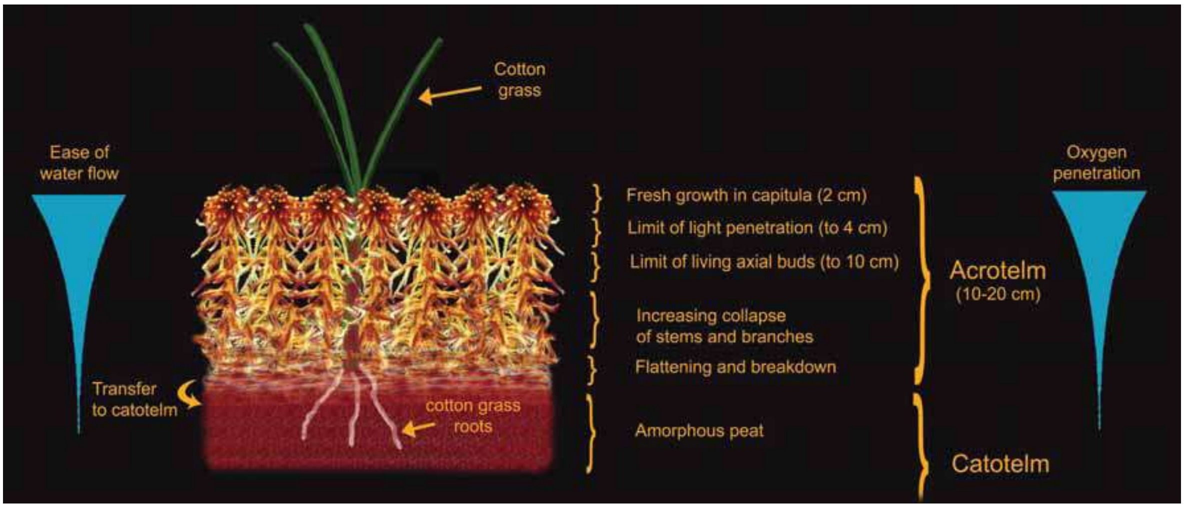

Figure 3 Acrotelm structure and properties. From Lindsay (2010), based on Clymo (1983, 1992)

A peat bog is often described as being "diplotelmic", meaning that it has two layers of soil with distinct characteristics: an upper active layer of roots and recently decomposing plant material termed the "acrotelm", above a lower layer of denser and more decomposed (humified) peat called the "catotelm" (Ivanov, 1981). In this idealised situation (see Figure 3), the hydraulic conductivity of the acrotelm is very much higher than that of the catotelm, and this together with its relative thinness results in a limited storage capacity for water within it. Unlike the acrotelm, the catotelm remains permanently saturated because rates of water movement within it are very low. Material is added annually to the catotelm by decomposition of plant material from the acrotelm, so that it becomes deeper and denser over time, with smaller pores, reducing the hydraulic conductivity of the peat and enabling maintenance of a high water table despite the continually deepening catotelm. This ensures that, despite storing large amounts of water, peat-covered catchments are poor suppliers of baseflow to streams and rivers (Burt *et al.*, 1990). The low hydraulic conductivities within the catotelm help to maintain a water table close to the ground surface, a condition which is essential to the continuing functioning of surface vegetation and any disturbance of the catotelm or acrotelm hydrology has a consequent impact on surface vegetation.

Water movement in reality can be more complex than is suggested by the idealised diplotelmic model. Rates of hydraulic conductivity were measured at around 0.003 $m.day^{-1}$

for peat at 1m depth in a large raised bog at Wedholme flow in Cumbria by Bragg (1991) and on the same bog Labadz *et al* (2001) found many values of a similar order, but also some locations where hydraulic conductivity reached up to almost 1m.day^{-1}. A summary of permeability values drawn from the literature by Wheeler *et al* (2009) indicates that whilst rates of cm or mm per day are probably typical of peatlands, in some circumstances acrotelm bog peat may experience water transport at rates up to the order of hundreds of m.day^{-1}. This may be in part due to the method of measurement, with larger scale experiments leading to higher values by up to three orders of magnitude (Bromley, Robinson and Barker, 2004).

The dual acrotelm/catotelm division, used in most conceptual models, is a simplification of a much more complex variation in peat properties with depth, as several highly humified bands of peat may be separated by more fibrous ones. The peat stratigraphy at Walton Moss, a raised mire complex in Cumbria which is notable for being "almost completely intact" and having suffered only relatively minor damage from human activity, was described by Dumayne-Peaty and Barber (1998) and by Hughes *et al* (2000). They noted that the maximum peat depth of 10m began with fen or fen carr deposits (relatively thin), overlain by highly humified (decomposed) peat dominated by remains of cotton grass and heather, and topped by fresh peat with *Sphagnum* mosses dominant but some local tussocks of cotton grass. This clearly fits the catotelm-acrotelm model but in detail they noted many changes in the main peat-forming species, resulting in a layering or "stratigraphy" suggesting seven different shifts to wetter conditions, which in turn will affect the physical properties of the peat. They stated (p473) that the leaf and rhizome fibres of cottongrass (*Eriophorum vaginatum*) are resistant to decay, often being the last surviving macrofossils in highly degraded peat, and much more efficient than *Sphagnum* peat at retaining water during phases of desiccation. They did not, however, present any measurements of hydraulic conductivity variations through the peat depth.

Hobbs (1986) indicated the variability of saturated hydraulic conductivity at a single location, ranging over as much as eight orders of magnitude in a single peat profile. Baird *et al* (1997) also pointed out that the hydraulic conductivity of a given volume of peat is unlikely to be uniform in all directions, which will affect the direction and quantity of flow, and that entrapped gas bubbles may retard flow in peat pores even below the water table. Surridge and Baird (2005) worked on peat at Strumpshaw fen, Norfolk, and concluded that although the peat was indeed very variable spatially, but said that with care it was possible to obtain good estimates of hydraulic conductivity. Baird *et al* (2008) undertook a study at Cors Fochno, an estuarine raised bog in west Wales. They used 107 measurements of hydraulic conductivity to show that, although there was an increase in K with depth, the lower peat layers in this case were still quite permeable, and there was marginal peat with low conductivity. They suggested that this low-permeability margin may have been important in allowing deep peat to develop and maintaining wet conditions in the centre of the bog. This suggestion was supported by Hughes *et al* (2000) at Walton Moss, stating that a period of humification under conditions marginal for peat formation leads to slow water movement and may be a precursor for the development of the permanently high water tables that allow the development of the domed *Sphagnum*-dominated bog.

2.2 Water tables

Water table is the level at which water pressure in the soil is equal to atmospheric pressure, at which water will stand in a well that is hydraulically connected with the groundwater body (Gilman, 1994). Broadly speaking, material below the water table is saturated. In "healthy" peatlands this level is very close to the ground surface for most of the year and depth to water table in a peatland is one of the most important influences on plant occurrence and growth (Rydin and Jeglum, 2006, p139). Figure 4 illustrates the variations in water table at

Walton Moss, an almost-intact raised bog in Cumbria which is amongst the least disturbed in England (Hughes *et al*, 2000, Labadz *et al*, 2007).

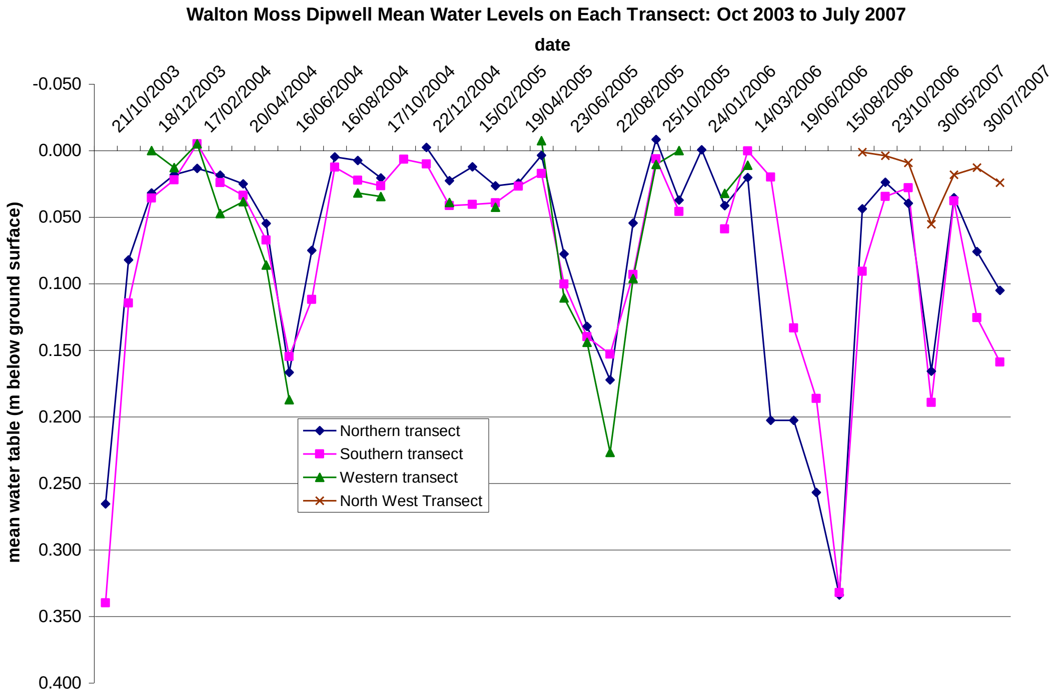

Figure 4 Average water levels at Walton Moss, Cumbria, 2003-7 (Labadz et al, 2007)

The water table is critical for peatland development because it controls species composition through anoxia (lack of oxygen) at depth, which retards decomposers and so enables peat accumulation. Price *et al* (2003) reported that a summer water table 40cm below ground is commonly accepted as a critical level for growth of raised bog plant communities, and noted that at Thorne moors, a cutover raised bog in eastern England, it was 70cm below the winter level. Evans *et al* (1999) reported the impact of the dry summer of 1995 on the water tables in a relatively intact blanket bog at Moor House, with water tables there falling to more than 40cm below the ground surface for a short time, compared to 20-25cm in more typical summers of 1996 and 1997. This is a blanket bog where most peat is intact but around 18% of the area is classified as eroded. They found that the water table stayed within 5cm of the ground surface for 83% of the time, with the fall in summer being explained by evaporation losses. They discussed historic studies which suggested that *Eriophorum* (cotton grass) roots my be able to draw water from depths up to 50cm, whereas *Calluna* (heather) may only recover nutrients efficiently from depths of less than 15cm. Rainfall events led to rapid recharge of the water table, typically rising at 5mm.hr^{-1} but in 3 events reaching as much as 20mm.hr^{-1}. The stream flow response over time is termed a hydrograph. Figure 5 shows the response of water table and stream discharge to a rainfall event in July 1995.

Working on a more severely eroded blanket bog in the southern Pennines, Daniels *et al* (2008) showed that persistent and frequent water table draw-downs occur at gully edge locations, defining a deeper and thicker acrotelm than would be the case in intact peatlands. Typical water table fluctuations ranged over 800mm at the gully edge dipwell tube, compared to 300mm at a dipwell located in more intact peat. Allott *et al (*2009) reported results of a much wider survey of over 500 dipwells in blanket peat in the Peak District during 2008 and found significant between-site variation related to erosional status. Intact sites typically had median water tables less than 100mm below ground, compared to more than 300mm in areas of dense erosion gullies. Although the Environment Agency and Natural England have published hydro ecological guidelines for several other vegetation communities, they have not done so for bogs.

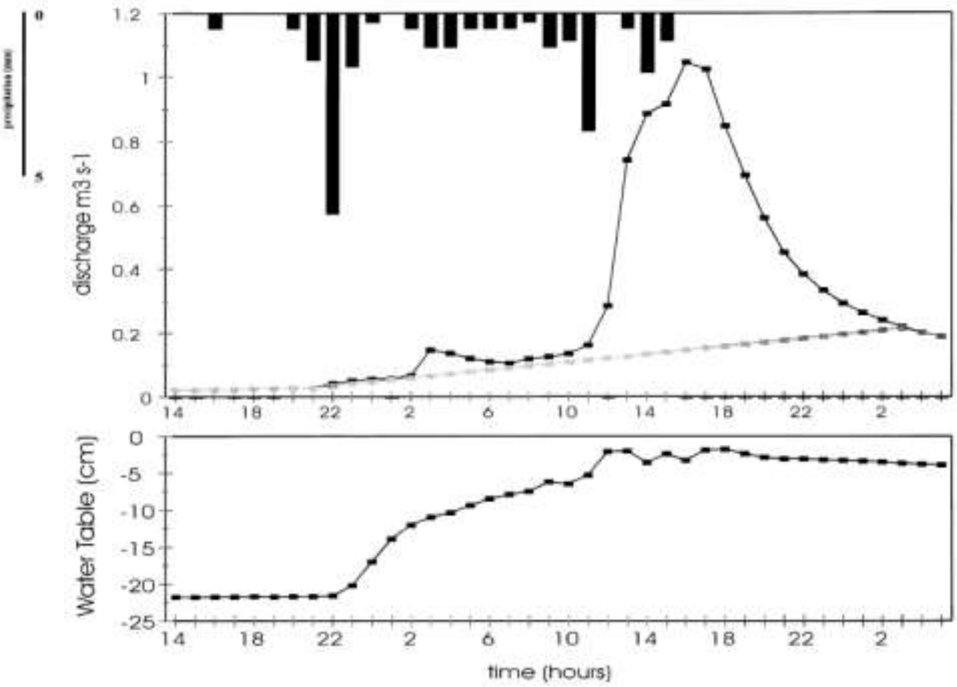

Figure 5 Hydrograph and water table response for the event of 6 July 1995, showing the importance of near surface water tables in generating stream runoff (discharge). After Evans et al (1999)

2.3 Generation of surface water runoff in peatlands

2.3.1 Measurements of surface runoff

The response of an out-flowing stream to rainfall received over a peatland depends upon the path taken by the water and the velocity of the flow it achieves. In a pristine peatland, the water table is likely to be close to the surface almost all the year and rainfall will quickly lead to saturation of the peat which in turn leads to overland flow and in some cases to flow concentrated in channels. Surface runoff is important because it can affect the nature of the peat itself (for example if artificial drainage leads to desiccation, see section 3.1) but also because stream runoff in response to rainfall events has implications for “ecosystem services” including water supply and for risks such as flooding downstream.

Early studies of blanket peat hydrology gave little consideration to the hydrological processes generating storm runoff. A lack of sophisticated monitoring equipment meant that the drainage basin was viewed as a simple input-output system with little understanding of internal process mechanisms being sought. This has changed more recently. Holden and Burt (2002) performed rainfall simulation experiments on blanket peat and showed that 30-40% of rainfall could appear as surface runoff and another 20-35% would runoff rapidly at a depth of only 5cm, but under vegetation the flow at 10cm depth was much less than 10% of rainfall. Holden *et al* (2008) investigated the velocity of flow over bare peat and different types of vegetation on slopes with blanket peat 2m deep in the Upper Wharfe catchment. *Sphagnum* cover showed significantly greater hydraulic roughness, with the increased friction slowing flow to an average velocity of around 0.015m.s^{-1} compared to the much faster 0.034 $m.s^{-1}$ over *Eriophorum* and 0.05 $m.s^{-1}$ over bare peat (but also showing variation depending on the depth of the water flowing).

Grayson *et al* (2010) investigated the role of changing vegetation in shaping the nature of the storm event hydrograph response, doing further work on Trout Beck, an upland stream of $11km^2$ catchment with 90% blanket peat cover. They mapped the extent of bare peat using aerial photographs and found that around 5% was bare in 1950, rising to 9% in 1975 but reduced again to less than 5% in the more recent images (1995 and 2000).They then selected as many single-peaked storm event hydrographs as possible, to make comparisons over time. Several adjustments were required to account for different methods of data collection over time, and there may be some questions about missing baseflow records and relatively few events captured in the 1970s, but their results showed that whilst rainfall and mean discharge had not changed significantly over time, the typical peak discharge (PeakQ) showed a decline over time since 1974 and importantly this remained true when peak discharge is calculated in relation to each $mm.hr^{-1}$ of peak rainfall received. The reduction was from 1.5 m^3mm^{-1} in 1974-1980 down to 1.1 m^3mm^{-1} in 2000-2007. The hydrographs had also become less flashy (measured by total storm discharge divided by the duration of the event) and the lag time from peak rainfall to peak discharge had decreased, although the latter was not statistically significant. Grayson *et al* concluded that this was evidence of the impact of revegetation, slowing down the passage of overland flow, but making little impact on the total discharge in the stream. They suggested that this may be in part because most of the discharge occurs in only a small fraction of the time on peatland catchments, and in part because bare peat has two separate effects on evapotranspiration, which is reduced because there is no vegetation but increased because the dark surface has a high albedo and will warm up more than a vegetated surface. They noted that practitioners involved in revegetation of peatland may be able to demonstrate river flow benefits from their work, and that the real effect may be greater than demonstrated because the hourly flow records available are not sufficiently detailed to capture all the detail of quickflow responses in blanket peatland catchments. Impacts on total discharge, however, were stated to be likely to be small and difficult to detect at a catchment scale.

The flashy nature of stream flows from blanket peat, shown in Figure 5, has been recognised in the literature for over 40 years (see Labadz *et al*, 1991, Holden and Burt, 2003, O'Brien, 2009). Conway and Millar (1960), working at Moor House in the north Pennines is probably the most notable early study. They showed conclusively that, in this semi-intact blanket bog, rainfall input produces a rapid stream runoff response, especially where the catchment has a dense gully network or where the peat has been burnt. Water balance calculations showed that a relatively uneroded *Sphagnum*-covered drainage basin retained significantly more water than another basin which had been both drained and burnt (for grouse management). Paradoxically, this result may have revived a traditional view that peat-covered catchments act like aquifers (or a "sponge"), storing rainfall up and releasing it gradually during dry periods. However, as will be demonstrated below, this is incorrect: even intact blanket peat is highly productive of storm runoff and, by contrast, generates little baseflow in outflowing streams during times of low rainfall.

Evans *et al* (1999) undertook further work at Trout Beck in the Moor House NNR and found that blanket bog water tables remained within 5cm of the ground surface (i.e. within the acrotelm) for over 90% of the time, and that high stream flows always occurred at times of high water table. They concluded that there are 2 important mechanisms for generating rapid flow from blanket peat catchments:

- saturation-excess overland flow (in areas such as hollows or close to the stream channel, where already saturated peat cannot accept any further input of water from the surface);

- rapid acrotelm flow over a saturated catotelm (a lateral flow, often within 5cm of the ground surface, generated by the lower hydraulic conductivity of the deeper peat).

Evans *et a*l (1999, p148) reported that stream runoff measured during a flow event was typically more than 40% of the input from rainfall, which is consistent with the rapid and efficient transfer of water from the catchment to the channel. They showed that in Trout Beck, a blanket bog catchment with 18% of the area classified as eroded, the stream responded very rapidly to rainfall. Low flows (less than $0.5m^3.s^{-1}$) occurred for 71% of the time but accounted for only 22% of the total stream water leaving the catchment, indicating that there is minimal contribution from groundwater flow. They also noted that, despite a wet winter in the preceding months, baseflow during the dry summer of 1995 was virtually non-existent. Again this suggests that groundwater input is minimal. Rainfall input was rapidly followed by a response of rising flow (discharge) in the stream, then an almost equally rapid fall back to a very low base flow level (see Figures 5 and 6).

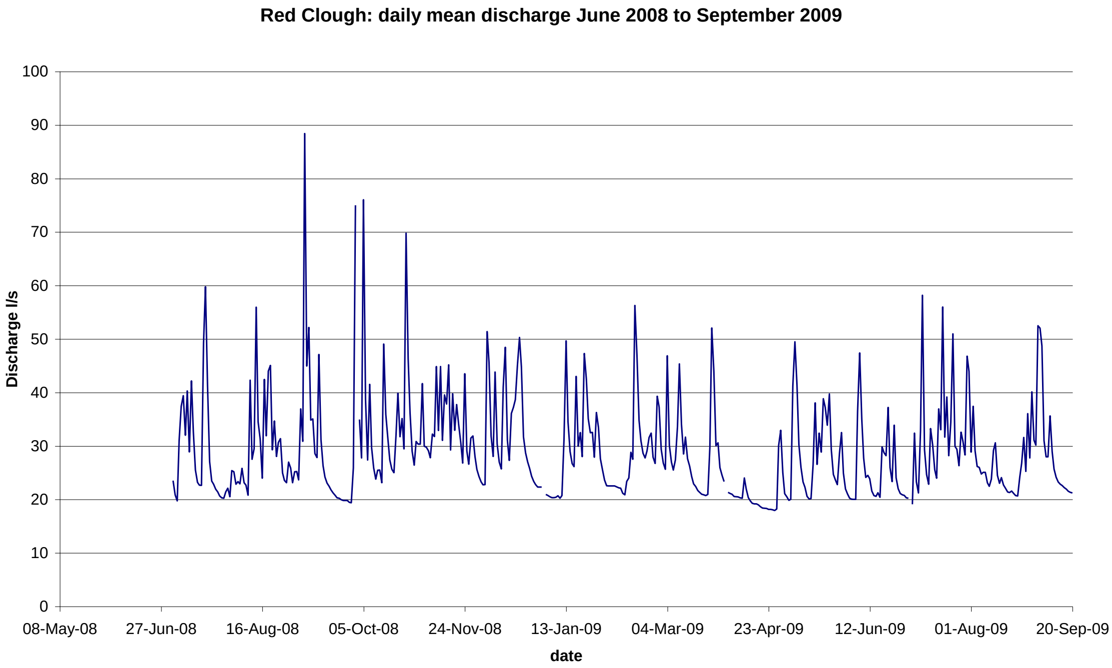

Figure 6 Variations in daily mean discharge at Red Clough, a blanket bog catchment in the Peak District (Cork et al, 2009)

Daniels *et al* (2008 JoH), working on an eroded blanket bog in the Peak District, showed that when event precipitation (rainfall) is high and intense, so are the total storm runoff and peak discharge in the stream. They investigated timing of stream discharge response to rainfall events and compared this to the nature and timing of water table rise. They found that greatest stream flows were observed when water tables were within 100mm of the ground surface near the gully edge, but that stream discharge could rise even when the water table in the gully side was 500-800mm below the ground surface. They concluded that this was due to the influence of macropores and/or pipes (cavities and pores which are larger than the multitude of small ones generally found in the peat “matrix”). These deliver water to the stream channels, and they drew parallels with the work of Holden *et al* (2006) in the vicinity of artificial drains (grips). In the current review, the influence of land management and other drivers of change in peat hydrology are covered in section 4. Daniels *et al* also noted the importance of the deeper water tables and thus a thicker erosional acrotelm alongside the gullies (stream channels) and suggested that gully-edge peats provide a key linkage between hillslope and channel flow, so their influence on peatland hydrological function is disproportionate to their limited spatial extent. Figure 7 summarises the development of flow pathways in eroded blanket peat during a rainfall event.

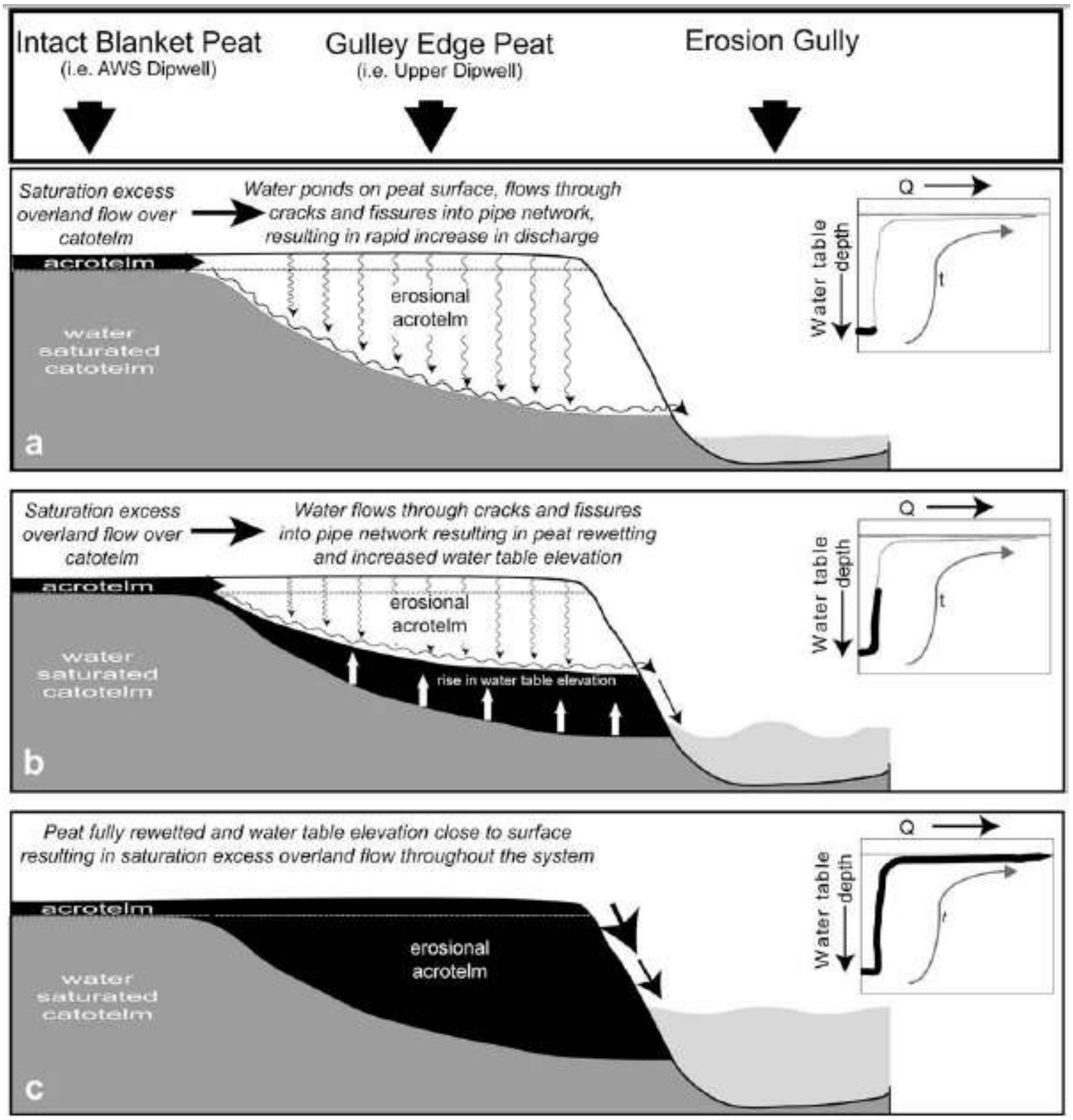

Figure 7 Development of flow pathways in an eroded peatland during a rainfall event, with plots of stream discharge against water table elevation in the gully-edge peat (after Daniels et al, 2008). At peak discharge during the largest events or those with wet antecedent conditions (illustrated schematically in Figure 6c), the eroded peatland starts to behave in a similar manner to an intact peatland (whether raised or blanket bog) with shallow subsurface flow through the acrotelm and eventually saturation-excess overland flow. Many smaller rainfall events on eroded peat will not reach this condition

Holden and Burt (2002 Catena) noted around 10% of flow being accounted for by pipe flow. Jones (2004) reviewed evidence for the contribution of natural soil piping in upland Britain and concluded that, in catchments where pipes have been reported, average contributions were often in excess of 40% of total stream flow, with timings being slower than overland flow but quicker than through the soil matrix. Some pipes experience only intermittent (ephemeral) flow during or immediately after a rainfall event, whereas some larger pipes deeper in the peat experience perennial flow. In some cases, as at the Maesnant blanket peat catchment in mid-Wales, the pipes had mostly formed from desiccation cracks allowing water to enter the peat from the surface, and piping has been linked with development of gullies and with river bank failure. Jones noted that 30% of the UK is covered by soils susceptible to natural piping (including peat), so this important flow path should not be ignored.

2.3.2. Modelling of surface runoff

There is growing interest in the prediction of flow paths and quantities in peatlands through topographic index models, which use the slope of the ground surface together with upstream contributing area to predict areas of saturation. Lane *et al* (2004) described such a model for Oughtershaw Beck, a shallow blanket peat subcatchment of the River Wharfe in North Yorkshire, and commented that it is important to consider whether areas of saturation are connected to the stream channel by other areas that are also saturated. If not, water which has begun to flow over the ground surface may go back into storage or flow in the sub-surface layers.

2.4 Water quality

Water quality includes the various dissolved substances and suspended particles that are derived from the soil, air and organisms and it has a profound influence on the type of plants and animals that can occur in a peatland (Rydin and Jeglum, 2006, p154).

2.4.1 Water quality in different types of peatland

Water quality in a peatland depends upon the way the water moves and how it interacts with the peat itself. Influencing factors include the underlying geology, the number and nature of water sources and of chemical deposition from the atmosphere as well as the characteristics of the vegetation and the peat itself (permeability, presence of pipes etc). Rydin and Jeglum (2006, p160) stated that the strongest link between water chemistry and vegetation in peatlands is seen along the environmental gradient from bog to rich fen, with pH for ombrotrophic bogs usually being below 4.2 and calcium concentration usually $2 mg.l^{-1}$ or less. In a fen the water quality is determined primarily by the characteristics of the underlying substrate, and concentrations of nutrients and minerals are higher. Bogs and fens thus tend to have very different vegetation assemblages. In an intact bog, the acrotelm is the upper layer in which concentration of rainfall by evaporation and dilution of soil water is most immediately and directly experienced, but Proctor (1995) said that even here the chemical processes were still far from fully understood. It is clear that most variation within mire vegetation is explained by three ecological gradients: the composition of base chemistry; the gradient in fertility related to availability of the limiting nutrient elements N and P; and the water level gradient (Wheeler and Proctor, 2000). The effects of salinity and spring–flush–fen gradients are of more local significance but land use is an important additional factor (Wheeler and Proctor, 2000).

Controls on surface water chemistry in fens in boreal forest in Canada were investigated by Whitfield *et al* (2010), who noted that it was very variable but found that evaporative concentration was a significant driver, with concentrations of most elements increasing in summer. Local groundwater was an important contributor of base cations (especially calcium and magnesium) whilst the organic peat soils acted as “sinks” for sodium, nitrogen and chloride from the atmosphere.

Proctor (1994) investigated water quality in a number of raised bogs and noted that they were extremely good sinks for ammonium (NH_4) and for nitrate (NO_3), with trace or undetectable levels in bog water even where rainfall concentrations were elevated. His earlier work (Proctor, 1992) had shown that, for 39 ombrogenous bogs and 10 basin/valley mires in Britain and Ireland, the influence of sea spray was marked in coastal locations and there was a gradient of sulphate from west to higher values in the east (associated with historic atmospheric emissions). Comparison with published rainfall quality data was difficult because of lack of comparable sites, but Proctor suggested that average concentration factors were of the order of 2 (range 1.25 to 2.5) for calcium, magnesium, sodium and chloride. Valley mires tended to show higher concentrations and different proportions from rain water, but there was no absolute divide in water quality from ombrogenous bogs.

Adamson *et al* (2001) studied water quality variations in soil water from a blanket bog at Moor House, in the north Pennines, and found that dissolved organic carbon (DOC) at 10cm depth peaked each summer and was related to temperature. Concentrations of principal anions and cations varied little except in the autumns of 1994 and 1995, following unusually dry summers, when sulphate increased markedly and there were smaller increases in sodium, magnesium, calcium and hydrogen ions. The latter represents a fall in pH from the usual value of around 4.2 to a very acid 3.5.

Jones (2004) reviewed evidence for the impact of natural soil piping on water quality in blanket bogs and suggested that it can be an important source of “dirty water”, with very marked brown colour especially during the first rains of autumn following a dry summer. It can lead to increased acidity (low pH) of surface water streams because it contributes water that has had only a short residence time and has been in contact with the upper organic soil horizons (peat) rather than weathered mineral surfaces. He also noted that by draining and aerating peaty horizons, piping may encourage release of sulphates and organic acids from the peat. In the Maesnant catchment, a headwater stream in mid-Wales, he reported spatial and temporal variation but average pH was 4.58 in pipeflow compared to 5.16 for the stream overall, and average concentration of dissolved organic carbon was 3.81mg.l^{-1} in pipeflow compared to 2.69mg.l^{-1} overall.   Levels of aluminium in the perennially flowing pipes frequently exceeded the toxic threshold for fish (around 0.12mg.l^{-1} in a peaty, low calcium environment). Evidence suggested that some water flowing from pipes may be relatively “old”, having spent time residing in the peat matrix, whereas some water also flows very rapidly through the pipes with little time for chemical interaction with the peat. In the Maesnant the combination of drainage/aeration and water quality led to increased decomposition of the peat and an association between the location of the pipes and major plant associations, with the pipes themselves surrounded by and area of dry grassland but with areas of rushes and *Sphagnum* bog/flush found immediately downstream.

2.4.2 Dissolved organic carbon

An increasing concern for water companies with gathering grounds located in the Pennines and Wales has been rising levels of water colour, caused by dissolved organic carbon (DOC) associated with blanket peat catchments since at least the mid 1970s and leading to increasing difficulty and costs of water treatment (Watts *et al* , 2001). For example, O’Brien *et al* (2008) reported daily mean true colour routinely above 100 hazen units and reaching over 200 hazen during late summer/autumn for 6 small blanket peat catchments in the Peak District. This meant that the stream water was visibly brown, even after filtering, and corresponded to daily mean DOC concentrations of 8-16mg.l^{-1} and export of between 5 and 18 tonnes C.km^{-2}.$year^{-1}$. Daniels *et al* (2008) worked on one of the same catchments (Upper North Grain) and reported that, for detailed temporal sampling of 5 storm events, DOC typically averaged 24-26mg.l^{-1} and peaked at over 36mg.l^{-1}.

The mechanisms responsible for rising levels of water colour and DOC from peat catchments have been the subject of much study and debate. Dawson *et al* (2002) investigated DOC in two contrasting upland peat catchments, the Brocky Burn in Scotland and the Upper Hafren in mid-Wales. At both sites they reported DOC concentrations positively correlated with stream discharge. The Hafren has much shallower peats (1-2m rather than 5m) and it was suggested that this may help to explain lower DOC concentrations there, although land use and climate were also noted as possible influences. Billett *et al* (2006) further investigated spatial changes in DOC downstream on the Brocky Burn and said that it was related to the soil carbon pool (peat cover), whilst temporal changes were related to temperature, discharge and soil solution DOC.

Clark *et al* (2007 a, b) stated that peatlands are the greatest source of DOC to natural waters and that most of it is transported during storm (rainfall) events. They discussed hydrologic transport of DOC and suggested that its concentration may increase with flow in organo-mineral soils because the flow moves from the lower mineral layers to the upper organic layers where more DOC is produced, but said that in deep peat soils there is no comparable switch in flow path and so although flux increases a dilution effect may be evident in the concentrations of DOC observed. They illustrated this with results from blanket peat at Moor House. In previous work Clark *et al* (2005) found a strong relationship between DOC and sulphate dynamics, and suggested that lowering the water table allows oxygenation of sulphides to sulphate, which is acid and so reduces the solubility and mobility of the carbon, thus DOC concentrations will be lower during droughts and rise again afterwards. This effect has also been noted on lowland raised bogs, especially in the north of England. Proctor (1994, p608) stated that under reducing conditions, when water levels are high, bogs can act as substantial sinks for sulphate. This is incorporated in part into the organic matter, and in part into inorganic sulphides, probably mainly ferric sulphide (FeS). These are readily oxidised when the water level falls and the peat is aerated, forming sulphuric acid which lowers the pH of the bog and, when flushed out by rain into streams and rivers, has been known to cause mass kills of fish. To some extent, Proctor noted, the acidification of ombrotrophic peats is moderated by reduction of some of the sulphate to insoluble sulphides, but this acidity maybe released again under oxidising conditions if water levels fall.

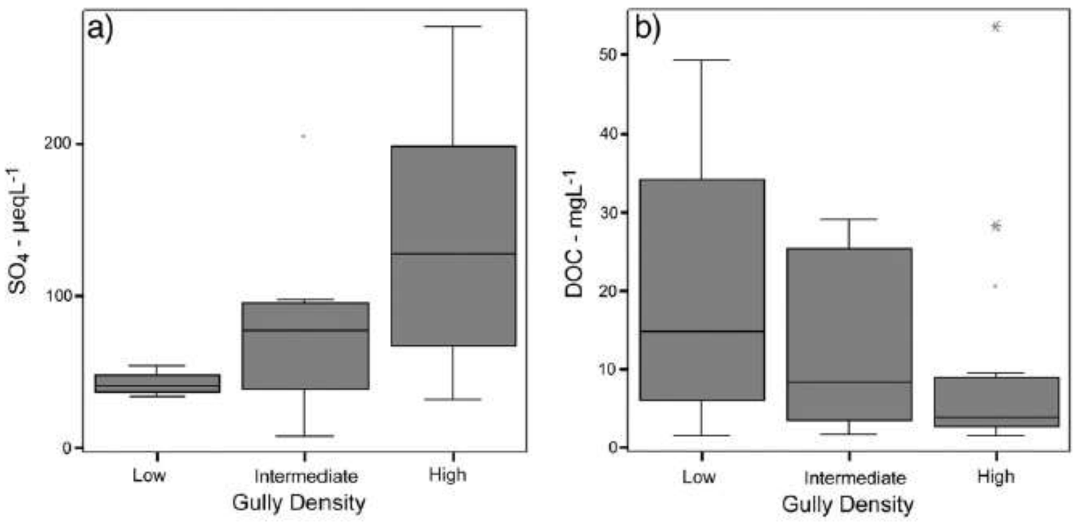

Figure 8 Box and whisker plots showing density of erosion gullies with range and median (line in the centre of the box) for sulphate and DOC concentrations in 27 small catchments in Peak District blanket peat (Daniels et al, 2008)

Sulphur leaching from blanket peat in the Peak District was also the subject of a study by Daniels *et al* (2008 SoTE), who noted that it remains a key acidifier despite falling atmospheric emissions over the last 20 years. They studied 27 small streams on blanket peat and stated that hydro chemical behaviour of eroded catchments is different from more intact bogs, because persistently lower water tables at the gully edges allow aeration, oxidation and flushing throughout the year. In each case pre-event water, rich in DOC and sulphate, was diluted by event water (from rain) flowing quickly through macrospores or overland. Catchments with very dense networks of erosion gullies showed high sulphate but low DOC concentrations in baseflow (Figure 8). Catchments with fewer gullies had lower sulphate and higher DOC in baseflow. They concluded that this is consistent with the idea that high concentrations of sulphate can suppress the solubility of DOC, and said that continued gully erosion will enhance sulphur leaching and should be included in models trying to predict recovery of upland systems from acidification.

A different mechanism for production of high levels of DOC from peat catchments after drought was suggested by Freeman *et al* (2001), related to the activity of enzymes. They showed that phenolic compounds can build up in peat in the absence of oxygen, because phenol oxidase enzymes are restricted in such circumstances. The phenolic compounds in turn restrict activity of hydrolase enzymes which are responsible for decomposition of the peat. A fall in the water table allows oxygen ingress and so the phenolic compounds can be destroyed, meaning that hydrolase enzyme activity can increase and peat decomposition can continue even after the water table has risen again.

Evans *et al* (2005) investigated trends in dissolved organic carbon (DOC) at 22 upland lakes and streams in the UK, with peat and peaty soils dominated by grazed moorland but with no indications of extensive draining or burning at most sites. Over 15 years all 22 sites showed significant increasing trends in DOC, whist 17 showed decreases in non-marine derived sulphate and 8 showed increases in pH. Monteith *et al* (2007) reported that the phenomenon of rising DOC has been found across eastern North America as well as northern and central Europe, and suggested that it was due to changes in atmospheric deposition chemistry (specifically a decline in anthropogenic sulphur deposition) and to catchment acid-sensitivity. Worrall and Burt (2007) undertook a wider analysis of monthly samples of dissolved organic carbon records at 315 sites in the UK from 1977 to 2002, using a calibration with water colour where DOC measurements were not available directly. 216 sites showed a significant increasing trend, but 44 showed no change and 55 showed a significant decrease (the first time this had been reported at sites in the UK). The largest decreases were found in the south, and particularly the southwest, as well as some lowland peat catchments in eastern England, but no clear mechanism for this was proposed.

Evans and Monteith (2004) concluded that “Regardless of mechanism, it is clear that DOC levels in UK upland waters have almost doubled since the late 1980s, representing perhaps the largest change in upland water quality over this period. The full consequences of this change have yet to be determined, but impacts are likely to be significant, including changes in aquatic flora and fauna in response to changing light, nutrient, energy and acidity levels; increased water treatment costs in peaty areas; and increased carbon (and associated metal) export from terrestrial stores to freshwater and marine systems.”

A spatial aspect of DOC transport was investigated by Billett *et al* (2006) in Brocky Burn, a small (1.3km^2) catchment in north-east Scotland with 59% peat soils (histisols). They found that concentrations of DOC increased downstream towards the centre of the catchment and then decreased again, linked to changes in the soil carbon pool and the percentage of peat cover in the headwaters but with this linkage much weaker downstream where mineral soils become more important. They said that stream water DOC was related to that in shallow peats, but that the deeper peat horizons did not seem to be hydrologically connected to the streams. This fits with notions of the acrotelm (near-surface peat) supplying most runoff during and after rainfall events. They also noted that stream DOC was positively related to temperature and that this appeared to be a more important than hydrology as a control on DOC concentration.

Evidence of any link of DOC to a drought effect was sought by Worrall *et al* (2008) who analysed records of dissolved organic carbon flux from two catchments with peat-covered headwaters. They noted that both increasing temperature and nitrogen deposition have been proposed as possible causes but that these cannot explain the magnitude of observed rises in DOC. They did not find any significant correlations with drought variables, but rather that runoff and a seasonal cycle were the most important explanatory variables. They suggested that DOC loss from peat is limited by its solubility and that production is fast (on the time-scale of runoff events).

Toberman *et al* (2008) did experiments manipulating summer drought conditions in shallow peaty upland soils (4-10cm of soil at around 90% organic matter) and found that DOC and dissolved phenolics were lower in the droughted plots in summer, but in non-drought months the droughted plots actually had higher concentrations than were found in the control plots. They suggest that low moisture levels may restrict contact between enzyme and substrate (soil) molecules and so inhibit the activity of phenol oxidase enzyme activity during drought, but also mention that drought may reduce photosynthesis and flow of carbon from plant roots to the soil. They noted that in deeper, wetland or riparian peats, with restricted drainage and higher water inputs, drought effects may instead be associated with changes in oxygenation and soil chemistry. They suggested that soluble phenolics may be an important part of DOC released and that extracellular phenol oxidase activity may have an optimal moisture level, above which low oxygen inhibits activity and below which the moisture level limits activity. They also suggested that different hydrological regimes may lead to differing effects of drought upon soluble phenol dynamics and thus DOC production, and concluded that further work is required to assess whether drought effects on DOC generation has contributed to the long-term concentration increases observed in upland waters.

High levels of DOC in water from peaty catchments come primarily from humic substances, which although not directly harmful are removed from drinking water for aesthetic purposes and to prevent formation of disinfection by-products. With regard to treatment of water for public supply, Fearing *et al* (2004) have shown that it is not only the DOC concentration but also its exact composition that governs the amount of coagulant required at a water treatment works. Having analysed long term water colour records obtained from the Broken Scar water treatment works, Worrall and Burt (2009) showed that the water treatment ratio (i.e. the amount of coagulant required per unit of colour measured in Hazen units) rose by 6.5% from March 1999 to November 2006. They concluded that the changing composition of DOC entering the treatments works was responsible for changes in water treatability, with a greater proportion of soluble, hydrophilic fractions present that are increasingly difficult to remove by coagulation. If this trend continues it may have implications for the cost of water treatment in future.

In addition to high levels of DOC and water colour, water flowing from blanket peat has been associated with a number of other water quality issues. Heal (2001) summarised evidence about the micronutrient manganese (Mn), which in high concentrations can be toxic to fish, in upland catchments in Scotland. She noted that the acid, organic nature of peat soils favours manganese mobilisation and that relationships with percentage of peat cover have been noted in Wales and England also. She also discussed the role of land-use, which will be discussed further in section 4. Abesser *et al* (2006) investigated both manganese and iron (Fe) in three streams within a major water supply catchment in the Southern Uplands of Scotland. Soils in two (the Peaty Muckle and Shielhope Burn) are approximately half blanket peat and half peaty podsols/gleys, whilst the Winterhope Burn has 38% blanket peat plus 31% peaty podsols and some non-peat soils. Based on two weeks of intensive sampling, they suggested that the organic-rich upper soil horizons are a source of Fe and Mn during rainfall events, but that a deeper soil/groundwater source becomes important just before peak flow as riparian (bank-side) groundwater is displaced into the stream. They noted that better understanding and prediction were still required to assist in managing water quality for reservoirs.

Rothwell *et al* (2008) investigated heavy metal mobilization resulting from peatland degradation in atmospherically-contaminated blanket peat in the Peak District. Seven catchments were sampled in baseflow conditions and one (Upper North Grain, 0.38km^2) during rain storm events. They found that there was a great deal of temporal and spatial variability but previously deposited (industry-derived) copper, nickel, lead, vanadium and zinc were all being leached from the blanket peat into the fluvial system. The export of lead (Pb), titanium (Ti) and vanadium (V) were all closely related to DOC concentration during stormflow and they attributed this to the metals complexing with the dissolved carbon.

2.5 Peat gully erosion and hydrology

Figure 9 Gully formation in deep peat, southern Pennines, UK, showing channel eroded down to mineral substrate (O'Brien et al, 2007)

Gully erosion (Figure 9) is widespread across the blanket peatlands of the UK and is most severely developed in the southern Pennines (Daniels *et al*, 2008, O'Brien *et al*, 2007, Labadz *et al*, 1991). Allott *et al* (2009) undertook a wide survey of over 500 dipwells and stated that distinct patterns of temporal water table behaviour are apparent between intact and heavily eroded locations. At intact locations, water levels were predominantly close to the ground surface except during periods of dry weather when a gradual water table drawdown occurs. Water tables rose rapidly following rainfall. At heavily eroded locations behaviour was very different, characterised by predominantly low water table conditions with very rapid 'wet-up' responses to rainfall followed immediately by rapid drain-down after the cessation of rainfall. They concluded that these patterns demonstrate the very different hydrological behaviours of eroded and intact peats, with clear implications for the hydrological functioning of the peatland.

Effects of revegetation on water tables in eroded blanket peat restoration were also discussed by Allott *et al* (2009), who noted that two restored sites (revegetated with heather brash, grass seed, lime and fertiliser) had higher water tables, but the number of sites was too small to be statistically significant and so further work is required to confirm this.

An important aspect of peat erosion is the export of particulate matter (sediment) from the system. Evans and Warburton (2005; 2007) attempted to construct a sediment budget for Rough Sike, a stream at Moor House in the northern Pennines with a blanket peat moorland catchment where 17% of the area has suffered gully erosion. They concluded that the flux of suspended sediment in controlled largely by channel processes, with only poor connectivity between the hillslopes and the channels. They noted that a 60% reduction in suspended sediment yield (since early studies by Crisp) matched well with photographic evidence of significant revegetation of gullies over this time. This has not been noted to such an extent in the southern Pennine blanket peats, which tend to experience lower rainfall, higher grazing pressures and greater impact of historic air pollution. Evans *et al* (2006) presented a detailed organic sediment budget which gave a yield for Rough Sike of

31t.km^{-2}.a^{-1}, and comparative data for the more actively eroding Upper North Grain in the southern Pennines which yielded 195t.km^{-2}.a^{-1} of organic (peat) sediment. The latter site is thus a major carbon source and there is a possibility raised that physical degradation of peatlands could become a significant positive feedback on global warming.

Another potentially important impact of peat erosion is that, since blanket peat moorlands form the gathering grounds for many important water supply catchments, it may eventually reduce available water storage capacity in reservoirs. Labadz *et al (*1991) presented some early results and Halcrow (2001) summarised available data on reservoir sedimentation in the UK, which showed that reservoirs in peat catchments exhibited an average sedimentation rate approaching 150 t.km^{-2}.a^{-1}, very much higher than was found on non-peat catchments.

Other issues associated with peat erosion include transport of pollutants such as lead. Rothwell *et al* (2010) noted that lead concentrations in sediment derived from shallow headward-eroding gullies in the Peak District were higher than those found in the base of deep gullies, and said that if the aim is to limit the export of stored contaminants, then the focus of future gully restoration should be on stabilisation of the shallow headcutting gully systems.

Evans and Warburton (2007) noted how the hydrology and geomorphology are related by a number of feedback mechanisms, with erosional gullying leading to lower water tables which may in turn promote the importance of macropore flow with implications for both stream flow and water quality. Gullying will lead to more rapid runoff and typically has a positive feedback leading to increased erosion and export of particulate and dissolved organic carbon,

3. Drivers of Change in Peatland Hydrology

Currently, most human-induced drivers of change in peatlands lead to drying out of the upper peat layers. Peatlands are sensitive to changes in hydrology, including both water level and water chemistry. The underlying peat is likely to undergo degradation by decomposition of plant material (sometimes termed humification) when it experiences dewatering (Bragg and Tallis, 2001). A bog in “favourable condition” will have a water table permanently close to the ground surface, and most losses of water will occur either as evaporation or as diffuse overland or near-surface flow, radiating outwards from the centre of the bog towards the peripheral areas. However, some form of human intervention has damaged most, if not all, existing raised bog sites in the UK and many of the blanket bogs. This is primarily a result of the historical threats of drainage for agriculture, forestation and commercial peat extraction. The recent “National Ecosystem Assessment” for mountains, moorlands and heathlands (de Wal *et al*, 2010 in press) noted that substantial changes have taken place since the mid 20th Century, with greatest losses in extent reported for bog, and upland and lowland heathland. There is widespread evidence increased levels of peat erosion, general decrease in species richness and expansion of grasses at the expense of moss and dwarf shrub-dominated communities. They said that attributing causes to observed major changes in habitat extent and quality was difficult because large-scale changes may be due to a plethora of factors including changes in land management, atmospheric pollution, climate, or more likely, a combination of such factors. O’Brien *et al* (2007) reviewed the main causes of blanket bog degradation and found that burning, grazing and drainage practices can change the species composition as a result of changes in peat hydrology. Drivers of change in peatland hydrology were also reviewed by Holden (2009) who highlighted the important role of climate change (both natural, long-term change and more recent anthropogenic change) but also discussed the impact of land use and management changes. These include drainage, grazing, burning, afforestation, peat cutting and construction (including roads, railways and more recently windfarms). Each of these is discussed in more detail in subsections 3.1- 3.5. The role of future climate change is discussed in section 5.

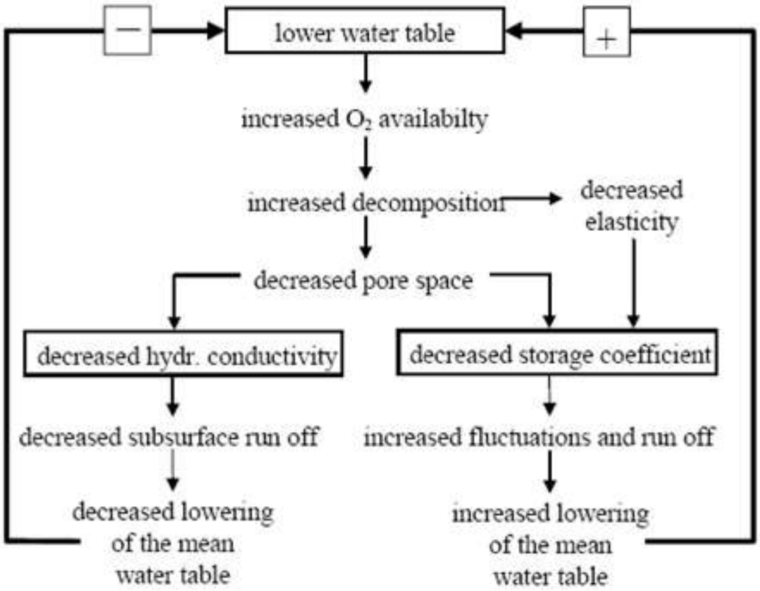

Figure 10 Feedback mechanisms between water levels and hydraulic peat properties (after Schumann and Joosten 2008)

Figure 10 shows the main processes and the feedback effects that occur associated with lower water tables in peatlands. Money and Wheeler (1999) noted that water table instability is a feature of many damaged raised bogs, with a drop to 50-100cm below the surface not uncommon in summer months which generates adversely dry conditions for *Sphagnum* establishment. Evans *et al* (1999) noted that prolonged desiccation of surface peat layers may lead to development of a hydrophobic layer which would reduce infiltration capacity of the acrotelm peat and so generate increased occurrence of infiltration-excess overland flow. Since peat is typically 90% water by mass (i.e. 900% moisture content compared to dry mass of material), such desiccation may well lead to shrinkage and cracking, and may lead to increased flow in macropores. They identified this as an area requiring further study, especially in the light of predicted changes in UK climate. They also highlighted the potential impact of shrinkage and cracking on carbon balance of blanket bog peatlands, both increasing water colour (dissolved organic carbon) and triggering erosion (particulate organic carbon transport). They suggested that these possibilities emphasize the importance of continuing long-term monitoring at sites such as Moor House, one of the few upland blanket bog sites where response of peatland ecosystems to climatic forcing can be identified.

Grayson *et al* (2010) investigated whether “natural” revegetation of previously bare blanket peat at Moor House resulted in observable change in the river flow hydrograph at the catchment scale ($11.4km^2$). They related measurements of the shape of the hydrograph during different time periods to areas of bare peat from aerial photographs at corresponding dates, and found that larger extents of bare peat were associated with flashier, narrower hydrographs with higher peaks. The difference in peak flows averaged $0.8\text{-}1m^3.s^{-1}$, which is a reduction of around 20% on the typical peak flow, but they noted that the total volume of runoff did not show any significant change.

Beven *et al* (2004) reviewed the literature on data sources and related studies of the impacts of land use change on flood runoff generation in rural catchments, including the effects of peat drainage and moorland gripping. They said that distinguishing the effects of change is made difficult by scale effects, data uncertainties and the effects of piecemeal and gradual change at the scale of larger catchments, and noted that there was much less information available about the response of peat catchments than other agricultural catchments.

3.1 Impacts of drainage on peatland hydrology

A significant threat to the sustainability of both upland and lowland peatlands in the UK has been the degradation associated with the installation of open-cut drainage ditches, also known as grips (Holden *et al* 2004). Armstrong *et al* (2009) noted that grips are typically 50cm deep and 50-70cm wide, and have been installed in a large proportion of UK peatlands. Their work was on upland blanket peats, and it should be noted that drainage of lowland raised bogs has included drains both significantly smaller and larger. Drainage has been shown to influence both the properties of the peat and the runoff characteristics of outflowing streams. Ramchunder e*t al* (2009) noted impacts on peat shrinkage and consolidation, microbial activity and decomposition, all influencing hydraulic conductivity and water storage capacity as well as flow rates and processes and susceptibility of the peat to erosion.

Price *et al* (2003) reviewed evidence on efficacy of drainage and noted that it will depend on the depth of the ditch, the distance between ditches and the hydraulic conductivity of the peat. They quoted several studies suggesting that water tables might be drawn down up to 50m from the ditch in fibrous peat, but hardly affected at all in very decomposed fen peat. Any slope will also have an effect (Darcy's law). On gentle slopes, closer drain spacing increases the likelihood that water tables will be depressed over large areas of the landscape. In addition to drawing down the water table by their effect on subsurface flows, ditches can have a significant effect on peatland by interrupting water which would naturally flow over or near the surface of the peat. Ramchunder *et al* (2009, p58) noted that many blanket peatland drains were excavated so that they run across the slope, typically following contours and so interrupting natural flow routes.

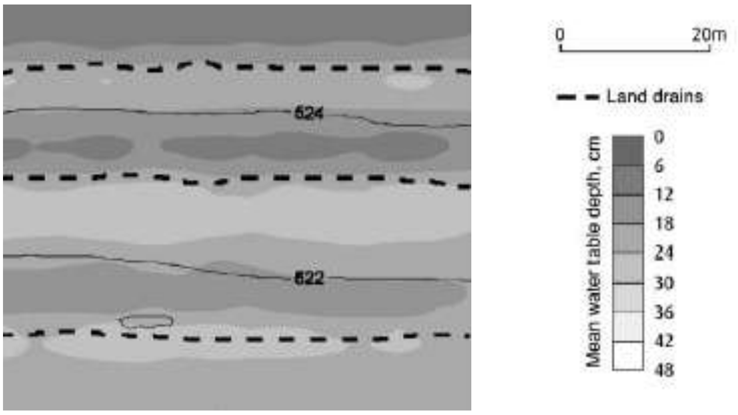

Figure 11 Mean depth to water table 2002-2004 on an artificially drained plot, showing ground contours (mAOD) and location of land drains (grips). After Holden et al (2006)

In other cases, however, grips are often channelled directly into an adjacent watercourse and in some cases 'herringbone' patterns either side of watercourses have been created. Ditches running up and down slope are typically thought to produce rapid flow velocities and have a very different effect on water tables from ditches following the contours, which have been shown to produce the asymmetric patterns of water table upslope and downslope of the drain (Figure 11). Holden *et al* (2004) also noted the importance of the position of grips in the catchment, because ditches serve to lower the water table (and so may increase storage and reduce flow peaks in the stream) but they also increase the velocity of flow once it reaches the drain, and may thus increase the peak flow by speeding water from one point to another.

Robinson *et al* (1998) worked on the Coalburn catchment (upland peat soils) and showed how moorland gripping and drainage for forestry planting can increase the runoff response of peat areas under wet conditions, but can also induce increased storage between storms leading to larger antecedent soil moisture deficits. Some drained blanket peatland catchments have been found to exhibit an increase in low flows and this may be associated with the 'de-watering' of the catchment through the slow drainage and drying out of the normally saturated catotelm (Holden and Burt 2003, Holden 2006). Although it is accepted that the lowering of the water table may cause an increase in available storage of water during rainfall events, making the stream runoff response less sensitive in the short-term, this is not sustainable and, in the medium term, water will continue to leave the catchment (Holden *et al* 2004). In the long-term, continuous dewatering of peat potentially creates desiccation and soil instability resulting in an increase in subsidence and decomposition, a widening of surface drainage and subsequently an increase in runoff and the return of a flashy response to rainfall events and flood-risk once more (Holden *et al* 2004, Holden *et al* 2006).

Holden *et al* (2006) studied five locations in two blanket peat catchments that had been drained with open ditches in the 1950s and found that on the drained catchments the overland flow response was short and sharp, as the ditches efficiently removed runoff and produced an even narrower, more peaked hydrograph than on the intact catchments. Over time, however, this effect had decreased and by 2002-4 the role of overland flow was significantly less in the drained catchments whereas throughflow in deeper peat layers was providing a greater proportion of total flow (average 23% on gauged plots). The drained catchments showed overland flow and high water tables upslope of the drains, but lower water tables downslope (Figure 11). The two artificially drained catchments also had contrasting behaviour over time, with one showing high and increasing runoff-rainfall efficiency (over 81% in 2003 and 2004) whereas the other showed efficiency of 58-65% with some evidence that this has decreased since the 1950s.

The loss of water from the drained catchments may also change the importance of flow processes and quickflow may be exacerbated by increased macropore flow through the soils and drainage underground in the form of soil pipes developing in deep peat (Holden *et al* 2006). Holden (2006) found that macropore flow and the number of soil pipes on the drained catchments at Moor House NNR were significantly higher than those on the intact catchments. The study indicated that not only did the density, but also the size of the pipes increase over time caused by the movement and scouring effect of water below the surface (Holden and Burt 2002, Holden 2005, 2006, Holden *et al* 2006), creating wider and deeper ditches on the peat surface. This suggests that peat properties and bypassing flow may alter over time, changing the structural properties of the peat caused by enhanced desiccation which may not always be reversible simply by a process of ditch blocking (Holden *et al* 2006).

Lane (2008, see also Lane *et al* 2004) reviewed evidence for the hypothesis that rural land management might change flooding in the Pennine uplands and noted how more than 50% of the Swale and Nidd catchments were subject to moorland gripping in the period 1940-1965, generally to improve grazing quality and grouse shooting. He noted evidence from the literature that grips could have two contradictory effects, potentially hindering the generation of rapid runoff by enhancing soil storage, but also increasing flood risk by allowing more rapid connection of rainfall to the river network (i.e. increasing connectivity). Lane suggested that at the catchment scale, the location of the drainage activity is a crucial variable, since grips will act to change which parts of the catchment deliver flow to the river at which time. Depending on location it may either flatten or increase the peak discharge experienced at a point on the river. Gripping in the headwaters may deliver water more quickly to the drainage network and be a cause of additional flood risk, whereas gripping closer to the catchment outlet may actually reduce the flood peak. The effect of a single grip may therefore be different from the effect of gripping a wide area, and as the spatial scale of the enquiry is increased so other factors will become more important. Lane ended by noting a concern that use of rural land management as a flood mitigation strategy is fraught with difficulties, partly because of the social uncertainty inherent in management by multiple individuals but also because the link between rural land management and flood risk is a generalisation whose details vary in time and space. Whilst the descriptive association of rural land management with flood risk may be perfectly legitimate, Lane suggested that it is not possible to assign explanation because the same land management cannot always be taken as having the same flood impact.

Ramchunder *et al* (2009) reviewed evidence for impacts of peat drainage on water chemistry, including studies both in the UK and overseas, and noted multiple and sometimes contradictory findings on carbon, pH, nutrients and metals. In summary, however, Ramchunder *et al* state (p58) that other environmental degradation associated with drainage of peatlands includes the mobilization of metals and pollutants and reduction of in-stream light penetration (linked to higher turbidity and water colour).

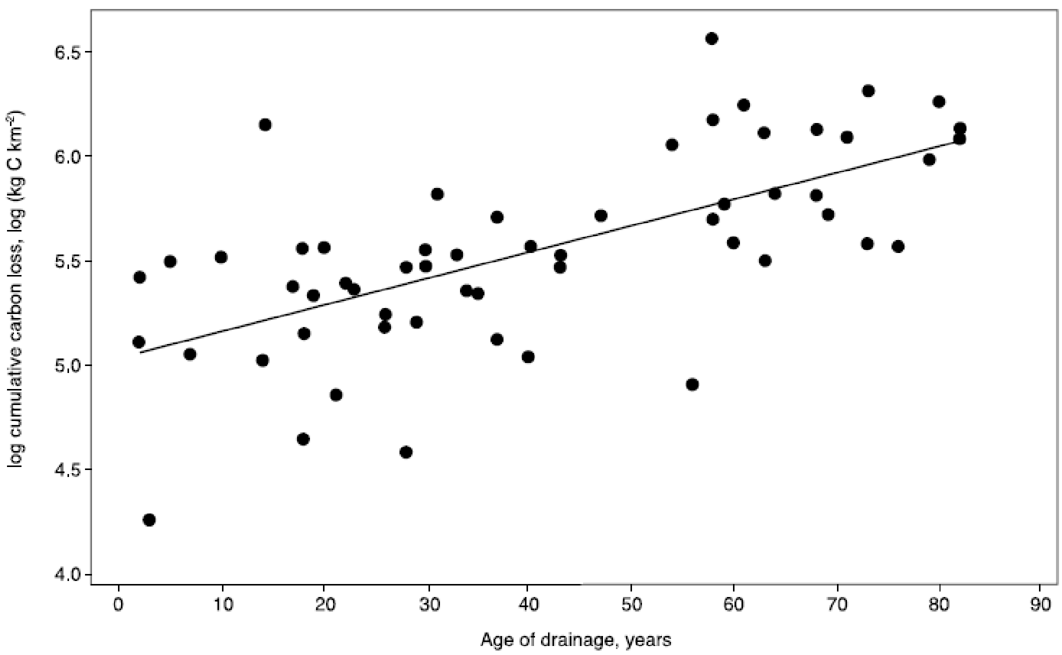

Figure 12 Scatterplot of estimated cumulative particulate carbon loss against the age of drainage (after Holden 2006).

The loss of vegetation and subsequent increase in bare areas of peat and acceleration of peat desiccation along the sides of a ditch can lead to hydrophobicity which may exacerbate the erosion rate and increase the volume of sediments by producing more sheet flow (Holden and Burt 2002). This, together with the underground erosion of soil pipes can cause an exponential rise in the erosion rate of sediment and carbon release from drained catchments (Holden 2005). Figure 12 shows a linear relationship between the age of the peat drain and the cumulative carbon loss from peat caused by piping (Holden 2006). Holden (2005, 2006) therefore suggests that those areas subject to a greater discharge of sediments and carbon, that is, areas with an ageing system of drains on steeper slopes, should be targeted for ditch blocking to reduce these losses. Holden (2006) noted a concern that the existence of pipes and macropores is encouraged by artificial drainage of peatlands, and may open the way for water, sediment and nutrients to be transferred from deep within and below the peat rather than just simply transferred rapidly through the aerobic acrotelm (upper peat layer).

Gibson *et al* (2009) investigated links between DOC export and drainage over a period of two years. They worked on two natural streams, at Moor House and Widdybank Fell, and four managed catchments in the north Pennines. One of the blocked drains (near Cow Green reservoir) was in peat only 50cm deep but the others were in deep blanket peat. They used automatic water samplers set on an 8-hourly interval and v-notch weirs recording every 15 minutes to measure flow. There was only very limited data (2 months) pre-blocking, so a paired catchment approach was not possible. Although they did find a decrease in water colour (absorbance) and DOC, it accounted for only 1% of the variation in the data. DOC production appeared to be fast on the timescale of a runoff event, and they found no evidence of exhaustion (supply-limitation) instead the transport capacity of the flow seemed to be most important. They concluded that the blocking of drains had decreased the export of DOC, but this was by decreasing water yield (flow) rather than reducing concentrations. They also noted a difference between response in first-order peat drains and those in higher order streams (with many tributaries), suggesting that there may be large in-stream losses of DOC and meaning that findings from a single drain cannot be simply transferred to a larger catchment.

It seems likely that ditches running up and down slope will produce more rapid flow velocities and so are likely to lead to increased peat erosion compared to ditches excavated along the contours, but little direct evidence for this has been found in the literature.

3.2 Impacts of grazing and burning on peatland hydrology

Burning is the subject of a separate peatland review (reference details) so this section contains only a very brief summary of some of the hydrological implications. Ramchunder *et al* (2009) stated that burned catchments have a greater proportion of land that is exposed to wind and water erosion, and may also suffer from induced hydrophobicity of the peat. This might be expected to give faster and flashier runoff, although little published evidence is available to date. They noted that a host of variables can influence post-fire runoff and erosion rates, including vegetation, topography, slope, aspect, fire severity, post-fire rainfall and the extent of changes induced in soil properties. They summarised impacts of rotational burning on upland blanket peat, noting that burning has occurred for over 5000 years and has been regulated since the medieval period. They said that there is evidence for reduced infiltration rates following burning, and some evidence of increasing rates of sediment transport, but conflicting results on whether or not runoff rates increase. They concluded that more work is required on the impacts of burning on hydraulic conductivity of peat, and on the physicochemical properties of stream water.

O'Brien *et al* (2008) investigated a small blanket peat catchment in the Peak District (Nether gate Clough, a tributary of the Ashop) where typical managed burning was suspended for a period of 4 years. By means of a paired catchment study they found that water tables rose after cessation of burning, but there was no significant recovery in monthly mean DOC concentrations over this time period.

Yallop and Clutterbuck (2009) examined relationships between dissolved organic carbon (DOC) and burning on 50 small blanket peat catchments across the southern Pennines and North York Moors, plus 7 larger catchments feeding water treatment works. They found that the proportion of exposed peat surface resulting from new heather burning was consistently the most significant predictor of variation in DOC (Figure 13), and proposed that burning favours aerobic microbial activity which leads to increased rates of peat decomposition (humification) and increased losses of carbon from these environments.

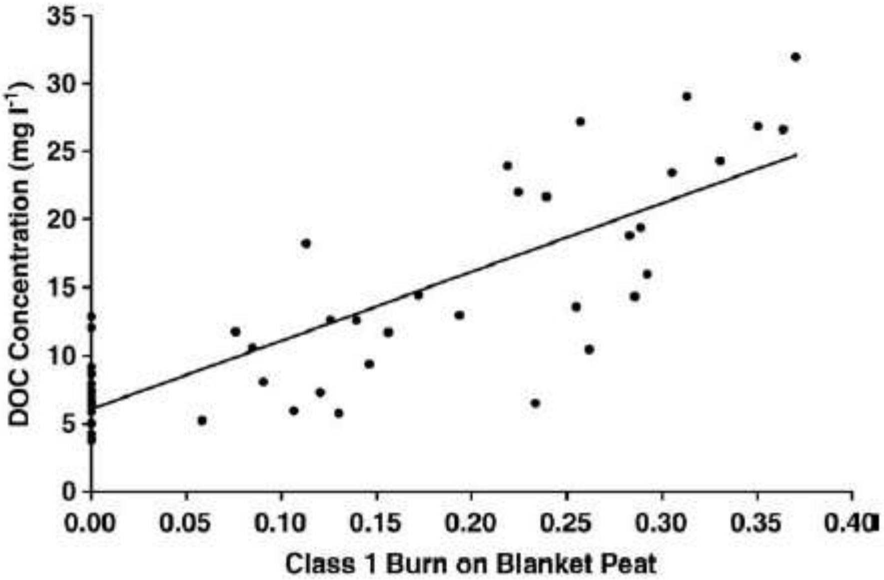

Figure 13 Recent burn (visible exposed peat surface, no Calluna regeneration) against bimonthly mean (November and December) DOC concentration in 2005 (r^2=0.69, p<0.001, n=50) (Yallop and Clutterbuck, 2009).

Worrall *et al* (2007) reported on long-term results from experimental plots on blanket peat at Hard Hill on the Moor House National Nature Reserve in the north Pennines. The plots were established in 1954, when all were burnt. Since then some have had no further burning, whilst others were burnt on 10 and 20 year rotation. Previous studies had shown that 10 year rotation burning led to the increased presence of cottongrass over heather (*Calluna*) whereas heather dominated in the 20 year rotation burn plots. Some plots were left open and others fenced to remove sheep grazing. They found greatest depth to water table on plots which were ungrazed and had not been burnt since 1954, with water tables closest to the surface on plots that did have grazing and were subject to a 10 year burn cycle, but the impact of burning was more important than that of grazing. Water quality (pH, conductivity and DOC concentrations in soil water extracted from dipwells) varied noticeably between different sampling days but grazing did not have a significant impact whereas repeated burning did, giving rise to lower pH, conductivity and DOC content. They suggested that this may be because burning can lead to the development of a hydrophobic surface which limits interaction of the peat with rain water, and that unburnt plots have some access to a deeper, near-neutral, water source. They concluded that land management influences the hydrology and water quality through its influence on vegetation, but acknowledge that increasing the number of sampling days, replicate plots and levels of grazing would be desirable. It is also worth noting that not of the plots had been burnt within the last 10 years, so this experiment does not necessarily contradict evidence of immediate post-burn impacts as suggested by Yallop and Clutterbuck (2009).

Worrall and Warburton (undated) carried out a spatial survey of water colour (absorbance) in 410 drains in the North Pennines AONB and concluded that burning was associated with an 18% increase in colour on average, and the presence of heather with a 22% increase, whereas blocked ditches showed a 14% decrease.

Clay *et al* (2009a, b) did a longer study which included effects of recent (2007) managed burns at Hard Hill (Moor House) and found that water tables afterwards were shallower than those before the burn, whilst runoff occurred more frequently. They compared similar months before and after the burn and found that the greatest difference was in July. Prior to the 2007 burn all the plots had shown similar runoff percentage, at about 50-60% of rainfall received. Post-burn this increased in all cases (including on plots not burnt) but the effect was most marked on the plots that had been burnt on a 10-year cycle and the result for those was statistically significant. They attributed the shallower water tables after the burn to removal of vegetation, which would be expected to decrease evapotranspiration, increase rainfall actually reaching the ground surface (by reducing interception) and perhaps lead to hydrophobic compounds or soil crusting. The plots previously had heather (Calluna) and cotton grass with a significant proportion of *Sphagnum* moss. It is interesting to note that, although on average the burned plots had shallower water tables than those which remained unburned, the range of water tables measured was down to 500mm below surface on the non-burnt plots compared to over 600mm on the 20-year burning cycle and a maximum of 671mm on the 10-year burning cycle. In terms of water quality, burning did significantly increase water colour (measured by absorbance at 400nm) but they did not find any evidence that the recent burn had affected the DOC concentration of either soil or runoff water (the former measured in dipwells and the latter in crest-stage tubes with holes at the ground surface to catch overland flow), but the latter had lower concentrations. There were peaks in DOC and water colour in the weeks following the burn, and the elevated values did persist one year later but this effect was not statistically significant. They concluded that managed burning can have important consequences on DOC export through changing the water table and the proportion of rainfall that becomes runoff, and noted that longer burning rotations may be beneficial but that burning in itself did not lead to dramatic increase in DOC in soil water. They did also note that their study was not at a catchment scale and that further work is required.

3.3 Impacts of afforestation on peatland hydrology

Many upland blanket peat catchments have been affected by afforestation, with associated drainage. An important impact on peat hydrology is the ploughed drainage channels cut as preparation for planting with conifers. Drains cut on 30% of the area (affecting 50% of the vegetation cover) on a deep peat catchment at Leadburn, in southern Scotland were shown to act as a major source of runoff, including the effect of direct rainfall into the channels themselves.

The hydrological effects of peat gripping and drainage for forestry planting can vary temporally. Robinson *et al* (1998) studied the Coalburn catchment, a headwater area with upland peat soils in Kielder Forest, which was more than 90% afforested and showed how drainage for forestry may increase the runoff response of peat areas under wet conditions, but can also induce increased storage between storms, leading to larger antecedent soil moisture deficits which would tend to reduce stream runoff.

Archer (2003) also investigated impacts of afforestation on the flow record at Coalburn (1.5km^2) and compared it to the much larger catchment of the River Irthing further downstream (over 300km^2). He used indices of flow variability to show that at Coalburn ditching was initially associated with an increase in stream flow “pulses” above a selected threshold and then over time there was a progressive decrease in the frequency of flow pulses and an increase in pulse duration, so that after 12 years the runoff response had become much less flashy. In the larger Irthing catchment, the impact of forestry was much less detectable. This was partly because a lower proportion of the wider catchment was affected by the afforestation (only 19%), but Archer concluded that climatic variation and channel processes were much more important than land use change in determining the runoff response of the larger catchment. The change that could be detected suggested a slight decrease in the frequency but increase in duration of pulses above selected thresholds since the late 1980s, which was in direct contrast with the stated opinions of surveyed river users. Archer concluded that a range of process studies was required at different spatial scales, and mentioned the CHASM initiative (O'Connell *et al*, at Newcastle University) as one such opportunity.

Robinson *et al* (2003) reported on impacts of forestry on flows at a number of sites across Europe, including blanket peat in northern England but also Ireland and Germany in addition to other sites not on peat. They noted the importance of comparing with a nearby "control" site, and reiterated that at Coalburn peak flows increased by about 15% in the short to medium term after drainage and afforestation, but this decreased over the years as a closed forest canopy developed. They suggested such effects could last 10 years or longer. In small upland catchments they also suggested that drainage for forestry could double the originally low base flows, but as the tree crop grows again this will decline, depending on the nature of weed growth and accumulation of leaf litter to block the drains. At Coalburn and elsewhere they indicated that mature forest has a drying effect, lowering the soil water table to beneath the artificial drains, so that the long term drying is "biological" rather than engineered. They concluded that peak flows from a mature forest cover on peaty soil in north-west Europe may be little different from on unforested land. Felling of trees on blanket peat at Glenturk (Ireland) increased moderate peak flows immediately downstream, making the runoff response more flashy than under 15 year-old forest but still not as peaked as it had been when the trees were 8 years old, and they suggested that this effect may be not detectable at larger catchment scales.

Anderson (2001) summarised the effect of damming plough furrows on an afforested blanket bog in Caithness, suggesting that the combination of felling trees and damming plough furrows was more successful at raising the water table than either of those actions alone. In a dry summer, the water table on the section with tree-felling and damming was 31cm below ground surface, compared to 47cm depth on the unchanged (control) area.

In terms of water quality effects of forestry, this land-use has been widely stated to exacerbate the acidification of streams attributed more widely to acid rain. Bradley and Ormerod (2002) reported on liming in afforested catchments to prevent further acidification, whilst Ormerod and Durance (2009) discussed recovery from acidification in the catchment of Llyn Brianne, Wales, where soils include podzols as well as blanket peat. They noted that although liming had increased pH initially, the differences had diminished over 12-18 years and conifer forest streams in this area were still too acid for sensitive invertebrates, whilst Welsh moorland streams were still at risk from acid events despite the general reduction in acid deposition across Europe.

3.4 Impacts of mechanised peat cutting on peatland hydrology

Price *et al* (2003) explained that commercial peat extraction removes the surface layer (acrotelm) to expose the more decomposed peat of the catotelm beneath. This has low hydraulic conductivity (K), which profoundly affects the way that water is stored and runoff is produced. In addition, peat cutting is usually associated with artificial drainage (typically 0.7-1m deep and spaced at 30m intervals, but with some more major drains, see Figures 14 and 15) designed to lower the water table and allow machinery to gain safe access to the site. Impacts on runoff production can be complex and sometimes contradictory, often increasing both peak and baseflow but sometimes reducing peaks because of an increase in available water storage. They noted that there can be significant shrinkage of peat above the water table (mostly because of oxidation) as well as some compaction below the water table. This may assist in producing an apparently near-surface water table once extraction has ceased, but not without cost in terms of ecology because capillary flow of water to non-vascular plants (such as *Sphagnum* mosses) will be reduced. Low and variable water tables, with low

Figure 14 Drain cut in raised bog, Cumbria, to enable commercial peat extraction

pore water pressures and enhanced microbial activity, also make for an environment hostile to recolonisation by *Sphagnum*. The change in topography at cut-over sites may in some cases be such that enriched water can enter, and conditions in a former bog can become more similar to those normally expected in a fen.

Cruickshank *et al* (1995) stated that in Northern Ireland there is a tradition of peat cutting, such that 78 per cent by area of remaining lowland hogs and 46 per cent of blanket bogs have been cut over. Baird *et a*l (2003) acknowledged that the annual volume of peat extraction was only a small fraction of the net global peat accumulation, but noted that on a regional and local scale peat cutting profoundly alters hydrological and ecological conditions and cannot be considered sustainable. Tomlinson (2010) noted that in Northern Ireland by 2007-8 the cutting of peat for fuel had declined to 10% of its previous value in 1990-1 (now 329 ha) but that the area cut for horticulture had increased to 689 ha, now accounting for 95% of the carbon lost through peat extraction there. Peat cutting had ceased at several sites now used as location for windfarms, and other possible causes include social changes that have reduced demand for peat fuel as well as designation of additional peatland conservation areas and restrictions associated with ESA and other agricultural schemes.

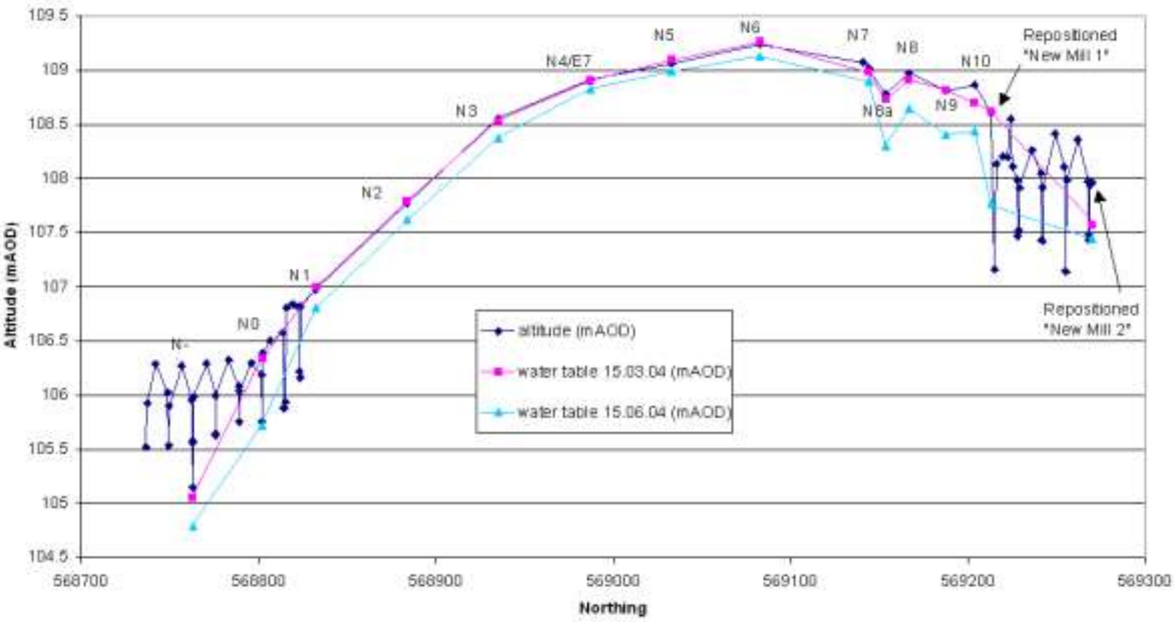

Figure 15 Impact of drainage ditches on water tables on a cut-over raised bog

3.5 Impacts of construction on peatland hydrology

Impacts of construction on peatland hydrology include the effects of roads, railways, grouse moor tracks and more recently access tracks for wind farm developments (Figure 16). Gunn *et al* (2001) summarized literature on these impacts for Countryside Council for Wales, and Stunnel (2009) has updated this in an extensive review for Natural England. Dargie (2007, 2008) has undertaken several studies on proposed wind farm developments in Scotland, as have Grieve and Gilvear (2008) whilst Lindsay and Bragg (2005) discussed the possible link between a wind farm and a bog burst at Derrybrien in Ireland.

Natural England staff have provided anecdotal evidence of moorland tracks sinking over time as the underlying peat compacts, so that they eventually act as a focus for water movement and require significant addition of aggregate to restore their initial surface levels. Gunn *et al* (2001) noted that construction and loading of access tracks could be expected to locally reduce the volume of the acrotelm, possibly by more than half, which would in turn reduce permeability, increase saturation and could potentially pond water on the upslope side. They also noted the need to avoid disruption of macropores and larger peat pipe networks. They noted that whilst hydrological impacts of the turbines themselves are likely to be very limited, the management and engineering of access roads does need clear specification to avoid the possibility of storm runoff generating erosion and possible undermining.

Figure 16 a and b Track across peat (cotton grass flush) to wind turbines at Ovenden Moor, West Yorkshire, showing use of sub-track drains and gravel to prevent erosion

Stunnel (2009) noted how roads for wind farm access may be either of a “floating” construction on cut and filled to the base of the peat. They can influence flow patterns, and can result in drainage and oxidation of peat. At some sites there may also be a risk of catastrophic peat failure (as at Derrybrien). Introduction of “exotic” material such as alkaline aggregate fill may also affect water quality if not carefully considered. In general she concluded that the risks associated with construction on deep peat are much greater than those on shallow peat, and that much can be done in the design and construction to reduce impact. She also stated that special consideration is given to bogs of highest conservation value, and although wind farm construction may have similar impacts on degraded bog, it may also bring opportunity for investment in restoration measures. CCW has produced detailed guidance on assessing windfarm impacts on peat but there is still significant uncertainty associated with trackway impacts on blanket peat hydrology, and a need for some well-monitored examples across the UK.

3.6 Impacts of grip-blocking on peatland hydrology

The restoration of peatlands is the subject of a separate IUCN review, but it is necessary here to discuss at least one aspect of restoration which has an overtly hydrological aim. Since the 1980s there has been a notable increase in the use of grip blocking (O'Brien *et al*, 2007, Armstrong *et al*, 2009), alongside some more recent efforts to block "natural" eroding peat gullies on blanket bogs.

Price *et al* (2003) reviewed evidence on drainage blocking following commercial peat cutting and said that, whilst it may be possible to restore the summer water budget of a site, changes to the nature of the peat that occurred during drainage are likely to mean that even when ditches are blocked it can hold less water and experiences pore-water pressures far below those necessary to ensure adequate supply of water for the growth of *Sphagnum* mosses. They therefore suggested that a more aggressive approach to restoration may be necessary on such sites, including the use of bunds or excavation of shallow basins to retain water.

3.6.1 Changes in water table and flows following grip blocking

Labadz *et al* (2001) reported their own and previous data collected by Mawby for Natural England at Wedholme Flow, a large cutover raised bog in Cumbria. Figure 17 shows the contrast in water tables between an intact area of bog (the northern half of the dipwell transect) and a cutover area, as well as the change produced by damming of ditches in the cut area in 1992. Variations in water table reflected changes in rainfall, with cut-over peat experiencing fluctuations of at least 500mm on an annual basis and in some cases 700mm during dry summers. In the first year following damming, the peat was shown to become saturated during the winter months, but water levels still dropped considerably during the summer. Monitoring of peat anchors by Mawby showed that the peat surface had risen following damming.

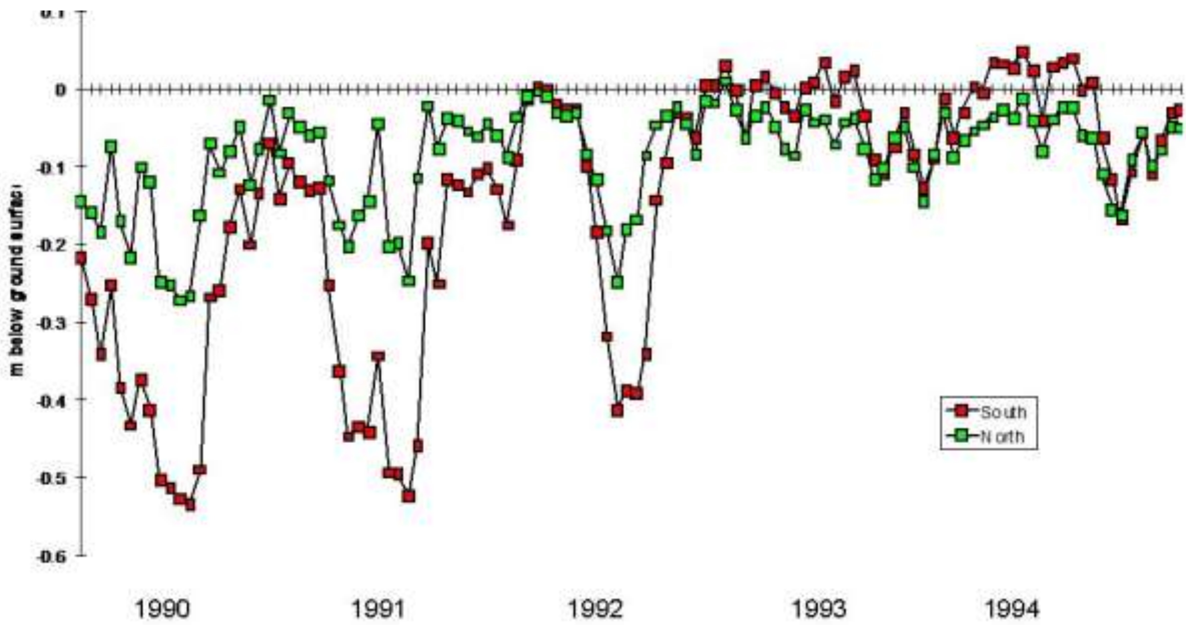

Figure 17 Wedholme Flow, Cumbria: mean water table relative to ground surface, transect 1 north (active raised bog) and south (abandoned cutover bog) 1990-1994, data collected by Frank Mawby. Damming of the drains in the south transect occurred in January 1992. (After Labadz et al 2001)

It is rare for peat grips on blanket peat to be in filled completely. Instead, most grip-blocking projects use small dams at very frequent intervals, in an effort to create shallow pools and slow the flow of water through the drainage network. Materials include wooden, heather bale and plastic piling dams, but the most favoured technique now seems to be carefully cut and packed peat dams (Armstrong *et al*, 2009, found these accounted for 74% of dams over 32 sites surveyed). This method has aesthetics in its favour as it does not introduce any foreign material onto a sensitive site and can be relatively cheap and effective provided that it is done carefully to create a seal, and that the ditches are not too steeply sloping or rapidly eroding. They found that dam spacing needs to be informed by local topography, but suggested that greater than 12m gaps were associated with less efficient systems. Grip blocking appears to be less successful where slopes are steep (>3 °), drains are large or the peat is very wet or very dry.

Worrall, Armstrong and Holden (2007) investigated short-term impacts of grip-blocking, on blanket peat in the Whitendale catchment (Forest of Bowland, northern England) used for water supply by United Utilities. They sampled at 54 stream and drain sites four times prior to drain blocking in Feb/March 2005, and then weekly until late October 2005. They also had automatic water samplers set every 8 hours on 10 drains including a number of different treatments: heather bales, turfs, plastic piles, combinations of these, and controls (no blockage). Discharge was not monitored directly but inferred by presence or absence of a sample, and showed that unblocked drains flowed 81% of the time compared to only 10% of the time where blockages had been installed. On each of the 10 monitored ditches a single piezometer was installed 3m upstream of the drain block and 1m away from the edge. They found that the water table was significantly higher in peat adjacent to the blocked drains, increasing by an average of 9cm, but could not detect differences due to the blockage type because of co-linearity in the data. Blockages had therefore affected both storage and flow of water.

Hydrological impacts of grip blocking in blanket peat at Geltsdale and Priorsdale in the north Pennines were reported by Jonczyk *et al* (2009). 4 grips were monitored at each site, using dipwells with pressure transducers to record changing water levels and water tables. At Geltsdale data commenced in September 2007, with blockages complete in February 2008. Data were reported for a 12 month period (7 months after blockage). Water level in the blocked grip rose by around 25cm. Unblocked grips at both sites showed a rapid runoff response to rainfall, whereas in the blocked grips water level responded more slowly. Nearby dipwells in the peat responded much less either to dry periods or rainfall. They suggested that the attenuation of water level fluctuations may indicate some additional storage but said that it may be small and not affect flood risk, because the acrotelm and subsurface pipes will still be delivering runoff to the main stream channels. It is certainly likely that the blockages are slowing the flow in the grip (discharge was not measured) but given that water levels in the blocked grips are initially higher than those in the unblocked grips, it is difficult to see how additional storage would be achieved.

Ramchunder *et al* (2009) noted that although drain blocking prevents efficient delivery of water through the artificial network, and alters hydrological routing to give non-continuous flow, there is little evidence as yet of larger scale impacts. Grayson *et al* (2010) have also noted that although carbon storage and flood mitigation are increasingly used to justify the expenditure on peatland restoration, there is a lack of reliable evidence of impacts on the flood peak downstream of grip blocking and revegetation of bare/eroded peat. Ballard *et al* (2010) have recently attempted to take a physically-based approach to predicting the effect of drain blocking on peak flows and found that it may depend on conditions, sometimes increasing and sometimes decreasing peak flows. They suggested that the greatest benefits for flood management would be achieved by blocking drains on steep slopes that are poorly vegetated, but acknowledged that there are many uncertainties and suggested that better characterisation of overland flow and drain roughness is required.

Lane *et al* (2003, 2004) stated that that the prime effect of blocking grips in a catchment was to change the way in which rainfall connects to the drainage network. They said that the effect of blocking a ditch depends on its location in the topography around it. They suggested that with a grip across a slope, the hydrological connectivity of the hillslope is broken and water is diverted into the drainage network instead of progressing downslope, meaning that for a given point on the lower part of the slope there is a smaller upslope contributing area and hence less surface wetness. Since water travels faster in the ditches than over the hillslope, it will also be delivered much more efficiently to the catchment outlet. When the ditch is blocked the expected result would be increased saturation of the lower parts of the slope. They indicated that blocking all grips may not be necessary and spatial optimisation of blocking activities may save significant amounts of time and money. The importance of prioritising amongst ditches for blockage in order to target resources effectively was also noted by Holden *et al* (2006), who explained that blocking many thousands of kilometres of grips would be very expensive. They suggested (p1771) that peatland topography and ditch location should be taken into account, since a dense ditch network on relatively flat terrain may be much less important to peat saturation and decomposition than a few ditches running across a steeper slope.

Ongoing work monitoring the restoration of blanket peat on Lake Vyrnwy and at other sites will hopefully give us new information of the impacts of grip blocking on the reduction in peak flows and changes in runoff volumes. However, assessments of how this impacts on flood risk requires scaling up these changes to assess their impact on flood risk communities that may be long distances downstream. Those charged with flood risk management also need to know how measures such as grip blocking may compare in effectiveness with alternative land management options such as planting trees and flood water storage.

3.6.2 Changes in water quality following grip blocking

Grip-blocking also has potential to influence water quality. Jonczyk *et al* (2009) did not find any clear effect on water colour or DOC on blanket peat in Geltsdale and Priorsdale (north Pennines), with any effect of grip blocking masked by strong seasonal effects (variability with high water colour in summer) although there was some indication of release of more highly humified organic material following grip blocking. At Geltsdale they had only 2 water sample dates before the blocks were installed, and these had very variable water colour making it difficult to draw conclusions.

A national survey on the impacts of drain-blocking on DOC and water discolouration was undertaken by Armstrong *et al* (2010). Results collated from 32 sites in northern England and NE Scotland suggested that mean DOC concentration with blocked drains was 28% less than for those with unblocked drains, but the pattern was not consistent at all sites. It should be noted that sites were sampled on different days, so antecedent conditions are not always comparable. Where samples were taken on the same day, blocked drains had lower DOC in 60% of cases. All these had been blocked at least 7 years previously. Sites were categorised by whether water was standing or flowing, by block effectiveness and by the type of block used (heather bales, peat turfs, plastic piles, plywood etc) but these did not have a significant effect. At a site in Upper Wharfedale with 2m deep blanket peat (also used by Wallage *et al*, 2006, in their investigation of DOC in soil water) automatic daily water samples and some more intensive storm samples were collected from both a blocked and an unblocked drain, alongside biweekly hand samples. The blocked drain showed a more gradual increase in water colour through storm events, with a peak on the rising limb. The unblocked drain was associated with lower and more variable water tables and a more marked difference between the water table on upstream and downstream sides. The blocked drain had water table within 10cm of the surface for 81% of the time, compared to 52% of the time at the unblocked drain.

The short-term effectiveness of drain blocking on DOC export was the aim of an investigation for Peatscapes by Bonnett *et al* (2008) using peat samples in the laboratory. Samples were obtained from different depths (to 90cm) and distances (to 20m) from a natural well-drained gully and a 12-year old grip on blanket peat at Langdon Moor in the Pennines. Depth to water table was not measured in the field and DOC was not measured in the laboratory. They concluded that grip blocking had a significant effect on the amount of water colour and phenolic compounds. Both sites showed greatest enzyme activity near the peat surface (top 5cm) but colour increasing with depth, presumably because the peat at depth is already more decomposed (the von Post scale uses the colour of extruded water as a measure of the degree of humification of the peat). The range of colour was also much greater from peat samples around the blocked grip than the natural gully, reaching a peak at 85cm below the surface where they also found high concentrations of phenolic compounds. The actual relationship between colour and phenolics was different at each site. They do not state how deep the grip was before blockage, and say that they can offer no clear explanation for this phenomenon, but it seems likely that the artificial drainage altered the peat properties and water chemistry in the immediate vicinity prior to the blockage. It would seem helpful to understanding of DOC export if any future study could include a greater number of sites and also include the hydrological and physical properties of the peat.

Wallage *et al* (2006) conducted a more detailed temporal study at a single blanket peat site, Oughtershaw Beck in Yorkshire, comparing water colour and DOC in water extracted from piezometers (narrow tubes in the peat) in a pristine area with that from a drain which was unblocked and from one that had been blocked several years previously. They found that DOC and water colour values were significantly greater at the drained site than the intact site, whilst those at the blocked site were significantly lower. Wallage *et al* concluded that there was a contrast in the quality of the carbon from the different areas, with the drained and blocked sites having more of the large molecules of highly coloured humic acids and the intact sites more of the fulvic acids that characterise newly decomposing plant litter Wallage *et al* (2006)also looked at the ratio between water colour and DOC and suggested that an elevated ratio at the blocked site indicated continued disturbance to DOC production and transportation, possibly by enhanced microbial activity, despite the lower concentrations found. It should be noted that the drainage and blockage had occurred prior to the start of this study so no direct “calibration period” was available for comparison, and the conclusions do depend upon finding situations which were truly comparable before the intervention took place.

Ramchunder *et al* (2009) reviewed evidence and noted that most restoration programmes of upland drain-blocking have been carried out on an ad hoc basis, reflecting the urgency of the need to protect important sites. They said that the effect of drain blocking on stream physico-chemistry remains poorly understood. In contrast to Wallage *et al* (2006), Worrall *et al* (2007) said that drain blocking was ineffective for reducing water discolouration and DOC, at least in the short term. Their work at Whitendale (blanket peat) showed that mean water colour and DOC were higher in the blocked drains than in unblocked drains or streams. Relative water colour was approximately twice as high in the blocked drains compared to unblocked ones. Streams tended to have higher specific absorbance (ratio of colour to DOC) than the drains, and showed a greater increase in water colour after the blockages were installed. However, seasonality effects still seemed to be more important than the effect of the blockage in explaining observed variations.

Evidence of impacts of drain blocking on particulate organic carbon (POC) was sought by Holden *et al* (2007) who surveyed drains at four upland blanket peat sites (two in northern England and two in Scotland). They found that drains on slopes gentler than 2° rarely eroded and natural infilling of drains often occurred on slopes less than 4°. A more detailed study at Oughtershaw Beck, in Upper Wharfedale, used turbidity probes and pump samplers to measure variations in suspended sediment. Sediment transport was most during winter, even though this was not the time of greatest rainfall, Active drains were a major source of sediment, giving sediment yields around 30-50 $t.km^{-2}$ during the 12 month study, and accounting for 18.3% of the sediment from only 7.3% of the catchment area. Drains that had been dammed along their length using peat blocks had very low sediment yields, and even poorly functioning dams were very effective at reducing suspended sediment. The overall sediment yield for the catchment was estimated as $17t.km^{-2}.a^{-1}$ compared to less than $4t.km^{-2}.a^{-1}$ for an undisturbed subcatchment. They concluded that drain blocking is an effective treatment for reducing sediment movement, and that natural revegetation is more common than many land mangers have assumed so effort should be concentrated in areas where this is unlikely, particularly where drains have steep slopes, or large catchments or are cut into the substrate beneath the peat.

Armstrong *et al* (2009) noted the contrast between conclusions applicable to blockage or artificial grips and those for blockage of erosional gullies, which are often deeper and larger. Work on gully blocking for *Moors for the Future* by Evans *et al* (2005) investigated gully blocking techniques and feasible locations. They found evidence of extensive natural re-vegetation in eroded peat gullies. Over 80% of existing blocks surveyed showed some sediment accumulation, and where this was relatively shallow the cotton grass had often started to colonise. They suggested 45cm as the target height for gully blocks, at maximum spacing 4m (depending on gully depth), ensuring that the pool from one dam reaches to the foot of the next upstream in order to reduce scour and aiming to encourage sedimentation and revegetation of the gully floor rather than to raise water tables across the entire peatland. They suggested that blockage efforts should concentrate on slopes less than 6°, and that "water holding" blockages such as plastic piling are really only suitable for relatively intact domes of peat with minimal gullying. Another part of their study used detailed topographic data obtained from LiDAR (Light Distance and Ranging) to produce an index (based on upslope area and slope) to show which areas are most likely to be saturated and experience overland flow. The idea is that ground at the base of a long, gentle hollow is more likely to be saturated than that at the base of a short, steeply sloping convex spur. This allows prediction of changes in flow patterns after gully blocks have been installed, and can help managers to obtain beneficial effects.

O'Brien *et al* (2008) monitored hydrology, water colour and DOC over one year preceding and three years following intensive gully blocking on blanket peat in the Ashop (Within Clough) catchment in the Peak District. They used a paired catchment approach to show a significant rise in water table and a fall in monthly average of daily mean stream flow, suggesting that the catchment was successfully rewetting, but they did not find any statistically significant changes in water colour over the 3 years since blocking which implies a longer timescale required for any beneficial effect. Further monitoring has since been funded by Severn Trent Water, following additionally gully blocks installed by National Trust in this catchment important for nature conservation and water supply as well as rural economic value, but by summer 2009 (almost 6 years after the original blockage) there was still no significant reduction in water colour.

With regard to attempts to reverse the effects of peat drainage, Schumann and Joosten (2008, p 22) stated that restoring peat hydraulic conditions is virtually impossible. They suggested that compacted peat prevents the water from entering the peat body and the decreased storage coefficient of the peat leads to larger water level fluctuations, which increases peat decomposition. This means that peatlands where the hydraulic peat properties have been changed often cannot be restored to their former hydrological functioning, but that alternative restoration aims have to be formulated.

3.7 Impact on peatland hydrology of scrub clearance

There appears to be little published evidence of the impact of scrub clearance on peatland hydrology, but Price *et al* (2003) reviewed evidence from the Somerset levels to suggest that birch may be associated with evapotranspiration losses up to 30% greater than nearby *Molinia* (purple moor grass), and that drained woodland may have evapotranspiration of the order of 50mm (more than 10%) greater than undrained *Sphagnum* bog.

4. Practical Tools for Monitoring and Assessment of Peatland Hydrology

Ramchunder *et al* (2009) noted that, although hundreds of millions of pounds are being invested in peatland restoration schemes in the UK uplands, including drain blocking, such investment is not being matched by appropriate monitoring programmes. Simply rewetting and/or revegetating degraded peats will not necessarily reverse the process response and they appealed for improved knowledge in order to aid practical solutions. The same issue applies to the very many windfarm developments on peat across the UK: claims of minimal impact are not supported by consistent, long-term monitoring of hydrological impacts and there is an urgent need for the renewable energy sector to address this.

Holden *et al* (2008) produced the Peatland Compendium for Defra and found that 70% of peatland restoration projects included some monitoring of hydrology (the second most popular monitoring after vegetation) but its precise nature varied; furthermore, conservation agencies have noted that the list of restoration projects included was very incomplete, with some substantial geographical gaps.

Basic monitoring of water table is straightforward using dipwells and manual measurement. However attention needs to be paid to the possibility that the bog surface may move in response to changing water table or the water table may be impacted by loading from the observer (Lindsay, 2010). These effects are not apparent on all bogs but should be assessed. Recent availability of low cost loggers for monitoring water table (e.g. Trutrak capacitance probes) allow for more detailed monitoring. This can be important as Allott *et al* (2009) have demonstrated variation in water table behaviour associated with lower mean water tables detectable only by higher resolution monitoring. Simple water table monitoring provides important information on the average water table condition which is a key control on biogeochemical processes and runoff generation. More comprehensive monitoring strategy is required to assess peatland water balance including measurement of runoff, rainfall and evaporation. This more intensive monitoring is at higher cost but necessary to demonstrate changes in water balance and runoff regime.

Holden (2009 review of grip blocking p9) said: “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.”

There are a number of projects that have used modelling and other approaches to target restoration and to plan monitoring to assess the effectiveness of this restoration at meeting wider objectives. There is clearly the potential to learn from these activities and to select elements of best practice from them. Workshop attendees have suggested the following projects:

- Vyrnwy rspb.org.uk/reserves – monitoring of grip blocking on hydrology
- Humberhead levels (Dargie *et al* 5 year monitoring)
- SCaMP – monitoring restoration for water quality improvements
- Exmoor blanket bog grips www.exmoor-nationalpark.gov.uk/mire
- Stuart Lane/Geoff Pacey Upper Ouse modelling
- Ashway Gap – restoration on carbon loss
- Geltsdale burning/grazing reduction (Jonczyk *et al* 2009)
- Flow country grip blocking
- Peatscapes See EA 2010 Working with natural processes
- Using Lidar and topographic indices (Allott et al, 2009)

A meta analysis of the results from the many small projects may be helpful to start addressing knowledge gaps. Practitioner focussed guidance on using the available tools such as how to make the best use of topography and GIS to map surface wet/dryness from drains. Many workshop attendees have suggested guidance outlining the minimum monitoring required to assess the hydrological characteristics of peatlands and what is required to assess runoff changes driven by restoration measures.

5. Future Impacts on UK Peatland Hydrology

Worrall *et al* (2008) noted that, with respect to climate change, the increase in DOC concentration observed in many rivers with extensive peat cover may be indicative of changes in terrestrial carbon reserves (see IUCN review on climate change and peat condition).

Wilby *et al* (2008) reviewed climate change and flood risk in the UK and noted the policy drivers including Defra's (2005) Making Space for Water. They concluded that both climate change and land management could either exacerbate or help mitigate local flooding, stating that to date most evidence was for very local scale effects and non-urban cases. They made no mention of peatlands directly.

Jones (2004) stated that future climate change may well enhance the role of pipe networks in (blanket peat) moorland catchments, since desiccation cracking is a major initiator of pipes and an increase in density of pipe networks was noted after the severe drought of 1976.

A predicted increase in winter rainfall could also increase flow in perennial pipes, with potential consequences of increased peat erosion, gullying and water discolouration as well as acidification and increased stream flows. However, Jones (2004) also pointed out that soil pipes are a 'natural' feature of the British landscape. He recognised the potential negative effects of flood-flow response and hydro chemical processes, but also emphasised the positive effects of piping contributing to landscape diversity by altering the 'stormflow contributing area' and said that this natural process should be integral in preserving and restoring a 'natural' landscape.

O'Connell *et al* (2004;2007) noted that runoff generation and routing (changes as the water transfers down the river system) that relate primarily to natural catchments may no longer apply to a large part of the UK because of changes in agricultural and other land use practices in both the uplands and the lowlands. They do not specifically mention peat in their review, but they stated that there is substantial evidence that modern land-use practices (over the last 50 years) have enhanced surface runoff generation at the local scale, creating "muddy floods" with high suspended sediment concentrations. However, they noted that there is little evidence that such local scale changes in runoff generation propagate downstream to create impacts at a larger catchment scale. They pointed to a need for multi-scale catchment experimentation, linked to modelling, in order to lead to better understanding. This need applies to peatland catchments as much as to the wider situation. Lane et al (2003) note that the debate over whether land management exacerbates flooding problems is a sectoral view, it is difficult to allow generic conclusions to be made: whether or not land use management matters depends upon the catchment that is under consideration. Even if land management might have some beneficial flood-reducing impact, a sectoral approach also overlooks other potential environmental benefits (and costs) that might derive from a more enlightened approach to land management (e.g. restoration of blanket peat bog if drains are blocked in an appropriate way). By taking a catchment-scale view, supported by an appropriate decision-making tool, it is possible to escape the limits of sectoral enquiry and produce land management decisions that address environmental risk as a whole rather than one narrowly defined sub-component of that risk (Lane et al, 2003 pg10).

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