# *Water tables in Peak District blanket peatlands*

Moors for the Future Report No 17

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## Moors for the Future Partnership

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## Summary


1. This report presents research carried out during the pilot project "*Hydrological Benefits of Moorland Restoration*" funded by the Environment Agency and the National Trust. The main objectives of the research were (i) to evaluate water table conditions and behaviour in blanket peat systems in the Peak District, (ii) to develop a model describing water table conditions at the landscape scale, and (iii) to provide a preliminary assessment of the impacts of moorland restoration on local peatland water tables.

2. A detailed programme of water table monitoring was undertaken during 2008, involving regular measurements of water table depth in over 530 dipwells at 19 sites across the 47 $km^2$ peatland landscape of the Kinder Scout / Bleaklow area. This included a campaign of regular, simultaneous water table measurements from clusters of dipwells at the main sites, supplemented by continuous (hourly) water table monitoring in selected dipwells. It also included studies to evaluate within-site variation in water table conditions and local water table drawdown effects associated with gully erosion.

3. Analysis of within-site variation in water table depths shows that multiple randomly located dipwells (preferably >15) are required for reliable quantification of water table conditions at the site scale, where site scale is 30m x 30m.

4. There is substantial between-site variation in average water table conditions across the blanket peat landscape, with median site water table depths varying from 26 to 451 mm. This variation is strongly associated with site erosion status. Water tables at intact sites with no erosion gullies at or proximate to the site are consistently close to the ground surface (median site water table depth typically < 100 mm). However, sites with dense erosion gullies are associated with lower water table conditions (median site water table depths > 300 mm).

5. Gully erosion causes water table drawdown through two distinct processes. The first is local water table drawdown immediately adjacent to erosion gullies. This effect is restricted to a zone within 2 m of gully edges, and water tables within the gully edge drawdown zone are approximately 200 mm lower than in the adjacent peatland. The second effect is a more general water table lowering at eroded sites, with median water table depths at heavily eroded sites up to 300 mm lower than intact sites. This site-scale effect is hypothesised to result from reduced hydrological contributing areas (drainage areas) at eroded sites, with hillslope drainage diverted into gully channels.

6. Distinct patterns of temporal water table behaviour are apparent between intact and heavily eroded locations. At intact locations water tables are predominantly close to the ground surface, except during periods of dry weather when a pattern of gradual water table drawdown occurs. Water tables rise rapidly following rainfall. This behaviour is characteristic of intact blanket peats in other regions. Water table behaviour at heavily eroded locations is very different, characterised by predominantly low water table conditions with 'wet-up' responses to rainfall, i.e. very rapid rises in water table followed immediately by rapid drain-down after the cessation of rainfall. These patterns demonstrate the very different hydrological behaviours of eroded and intact peats with clear implications for the hydrological functioning of the peatland.

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7. Evaluation of the topographic (wetness) index shows that it is a good predictor of water table conditions across the range of site types in the Peak District peatland landscape and a suitable basis for water table model development. However, the index does not effectively represent water table variation within the intact sites. In particular, it predicts much higher water table conditions at intact plateau/flat sites than at intact hillslope sites,

a pattern not observed in the measured data. This finding has important implications for the use of the topographic index to represent hydrological conditions in intact blanket peat systems.

8. A landscape-scale water table model has been developed based on high resolution topographic (LiDAR) data. This assumes that topography represents the key control on peat water tables at the landscape scale. The model is based on calibration of the topographic (wetness) index against measured site water table data, modified to account for the effect of local gully edge water table drawdown. It predicts median water table depth at the site scale. The model requires further development and validation, and is therefore described as ‘first-order’, but initial model application provides a prediction of water table conditions across the peatland landscape. This application identifies high water table conditions in the remaining intact areas of the peatland and demonstrates the extent of water table lowering associated with gully erosion in the Bleaklow and Kinder Scout areas.

9. Comparison of water tables at bare peat and restored (re-vegetated) sites indicate higher water tables at the restored sites. This suggests that water tables can be raised by re-vegetation of bare peat. If confirmed this has significant implications for moorland restoration strategies as well as for hydrological and runoff processes in bare and restored systems. However, the current analysis is based on too few sites to be statistically significant and further work is required to confirm the observations

10. The final section of the report makes recommendations of further work required to more fully evaluate the hydrological functioning of the peatlands and the hydrological effects of moorland restoration. In particular we recommend:
    - further model development and validation, including evaluation of model uncertainty to underpin future applications of the water table model, and terrain analysis to more fully establish the processes of water table lowering at eroded sites;
    - a field study to characterise drainage and water table behaviour on intact hillslopes, in order to improve hydrological modelling at intact sites;
    - a field study to confirm the observation that restoration by re-vegetation results in significant rises in peat water tables;
    - a more comprehensive research programme to evaluate the hydrological functioning of these peatlands, focusing on the impacts of restoration on runoff generation and downstream flow;
    - an assessment of the relationship between water table conditions and runoff water quality.

11. The research has provided important baseline data on water table variation and behaviour in the Peak District blanket peats and demonstrated the viability of water table modelling at the landscape scale. It has several immediate applications, including the provision of water table data for carbon models and for targeting *Sphagnum* propagation work. It will also underpin further research efforts, including comprehensive evaluation of the hydrological effects of moorland restoration and the implications of predicted climate change for water table conditions in these peatland systems.

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## 1. Introduction

The hydrological status of blanket peat influences a wide range of peatland functions. In particular, peatland water tables control factors such as runoff generation (e.g. Holden and Burt 2003, Daniels *et al.* 2008a), water quality (e.g. Clark *et al.* 2005, Daniels *et al.* 2008b), vegetation distribution (e.g. Grosvernier *et al*. 1997, Charman 2002) and rates of carbon sequestration (e.g. Moore and Dalva 1993, Worrall *et al.* 2003). Water table status is therefore a crucial attribute of blanket peat systems. Although there is a wide literature on blanket peat hydrology, including studies which specifically evaluate water table conditions (e.g. Evans *et al*. 1999, Holden *et al.* 2006), data on water table behaviour and variability at the landscape scale are sparse. This limits our capacity for modelling landscape responses to interventions such as moorland restoration and to future environmental trends such as climate change.

This report summarises work undertaken for the pilot research project '*Hydrological Benefits of Moorland Restoration'* funded by the Environment Agency and National Trust via the Moors for the Future Partnership. The project ran from February 2008 to January 2009.

The objectives of the research were as follows.

1. To establish a water table monitoring scheme for the blanket peats of the Bleaklow and Kinder Scout areas of the Peak District National Park, and to provide baseline water table data for these peatlands.

2. To develop a model for hillslope saturation and water table conditions for the Peak District peatland landscape.

3. To provide a preliminary evaluation of the impacts of moorland restoration on local peatland water tables.

4. To provide water table data for the Bleaklow and Kinder Scout areas to inform both ongoing research and restoration practice, including projects on *Sphagnum* propagation and reintroduction and on peatland carbon budgets.

Water tables in blanket peat environments are controlled by a variety of factors. Precipitation and evapotranspiration represent primary controls on peat saturation and associated water tables. At a landscape scale, however, topography exerts a key influence on drainage and associated hillslope saturation (Beven and Kirkby 1979) and at a local scale factors such as variations in the composition (hydraulic conductivity) of the peat (Beckwith *et al.* 2002) or the prevalence of pipes or macropores (Holden and Burt 2002) could influence the water table. In degraded peatlands, such as found on the Kinder Scout and Bleaklow plateaux, local water tables are also strongly influenced by the local drawdown effect caused by proximity to erosion gullies cut into the peat (Hill 2007, Daniels *et al*. 2008a). Peatland water tables are therefore highly variable in both time and space and require characterisation at a variety of scales. Although dipwells allow peatland water tables to be relatively easily and reliably monitored at any single location, the representation of water table variation across a whole peatland landscape is more complex and requires an appropriate strategy to integrate measured water table data with modelling approaches.

Hydrological models and/or indices that can capture the potential spatial variability of water table dynamics are required in order to evaluate the hydrological effects of moorland restoration. Significant resources have been invested in peatland restoration in the Peak District peatlands (see www.moorsforthefuture.org.uk). A key objective of moorland restoration is the raising of peat water tables, but there has been limited research on the effects of restoration on water table depth, runoff generation and associated hydrological characteristics. A first step in evaluating the potential hydrological benefits of moorland restoration is to evaluate the effect of current restoration practice on peat water tables. However, simple comparisons between water tables at bare peat and restored sites may be unreliable unless the effects of topographic setting and gully-edge water table drawdown are accounted for. The basic requirement of the current project was therefore to develop a model representing spatial variation in water table conditions at the landscape scale suitable for a range of applications. We base this model on the widely used topographic (wetness) index of Beven and Kirkby (1979).

This report therefore summarises a series of linked field studies undertaken to provide an extensive database of water table measurements at sites across the Peak District peatlands. We also present water table maps derived from a first-order empirical water table model calibrated against measured water tables for the Kinder Scout and Bleaklow areas. More specifically, the report includes:

- a description of the water table monitoring programme;
- an assessment of the number of dipwells required to reliably quantify water table conditions at the site scale;
- an evaluation of the effect of gully erosion on local water tables;
- a description of spatial variation in water table conditions across the peatland landscape;
- a description of the temporal behaviour of water table depth at sites with different erosion and wetness status;
- an assessment of the topographic (wetness) index as a model for peat water tables;
- the development of a simple empirical model of water table conditions for the Peak District peatlands;
- a preliminary analysis of the effect of moorland restoration on water table depth;
- recommendations for further research required to underpin hydrological understanding of moorland restoration practice.

Overall, we aim to provide a detailed description of water table conditions in the Peak District blanket peat system.

## 2. Water table monitoring in the Peak District peatlands

The project has monitored peatland water tables in 536 dipwells installed at sites across the Bleaklow, Kinder Scout and Upper Ashop areas of the Peak District (Table 1 and Figure 1). This is probably the most comprehensive and detailed monitoring program for water table dynamics in peatlands in the UK.

### Dipwell design and water table measurement

Peatland water tables were measured using dipwells. These were constructed from either 1 m or 1.2 m lengths of 34 mm diameter polypropylene waste pipe (internal diameter 30 mm). Perforation holes were drilled at 100 mm intervals, with the first perforation holes located 100 mm below the position of the ground surface after installation. The base of each dipwell was sealed with layers of gaffer tape. In the field the dipwells were installed by coring out peat, using a pipe of identical diameter to the dipwell, to the depth of the base of the dipwell. The dipwell was then installed into the hole with approximately 100 mm of pipe protruding above the ground surface. The top of the dipwell was sealed with gaffer tape to prevent direct precipitation, and a small (2 mm diameter) hole drilled in the dipwell 500 mm above ground level to allow air passage during water level changes. Manual measurements of water levels in the dipwells were made using purpose-constructed electronic dipmeters. All manual measurements of water table depths were made relative to the ground surface using a 150 mm long plastic collar which fitted closely over the protruding section of dipwell.

Continuous (i.e. hourly) water table logging was performed in a master dipwell located at each site. This is described in Section 5.

### Site types and sampling regimes

Four types of site were included in the monitoring programme: model calibration, bare peat, restored, and gully drawdown.

The main field study quantified water table conditions at a series of sites with varying topographic contexts. These sites were used for model calibration, and are referred to as calibration sites. Sites are represented by a 30 m by 30 m area of blanket peatland. Thirteen calibration sites were chosen covering a gradient of topographic conditions as represented by the topographic (wetness) index (Beven and Kirkby 1979) (see Table 1). All calibration sites had an original, extant vegetation cover. Erosion status varied across the calibration sites, from intact sites with no erosion features within or proximate to the site to sites containing high density erosion gullies. Site altitude varied between 510 – 623 m.

At all calibration sites except for NGV 21 dipwells were installed. A master dipwell was installed in the centre of the 30 x 30 m site. The remaining 20 dipwells were installed in a nested, random design, with 5 dipwells randomly located within a 2 x 2 m box centred on the master dipwell, and 15 dipwells randomly located within the whole 30 x 30 m site. Dipwells were only installed on the bog surface i.e. not on gully walls or in gullies themselves. This design allows mean site conditions to be inferred from 16 randomly located dipwells (15 within 30 x 30 m box plus one from the 2 x 2 m box). Mean site water table is the key water table measurement used in this report. The design also allows detailed evaluation of the spatial variability in water table conditions at a variety of scales including pixel (2 x 2 m), site (30 x 30 m) and landscape, although this comprehensive analysis is outside the scope of the current report. Sample design was different at site NGV, which was used for evaluating within-site variability in water table depths (see Section 4). Here 41 dipwells were randomly located across the 30 x 30 m site.

Four sites were chosen to evaluate the effects of restoration on water table conditions; two bare peat sites and two restored sites (see Table 1 and Figure 1). The restored sites had been re-vegetated using a combination of heather brash, grass seed, lime and fertilizer; B04 in 2003 and B05 in 2006. The bare peat and restoration sites were located in eroded areas at altitudes between 587 and 624 m (Table 1) and were set up in an identical fashion to the calibration sites (i.e. with 21 dipwells installed in a 30 x 30 m area).

Water tables depths were manually measured in dipwells at the calibration, bare peat and restored sites on ten separate occasions in 2008: 9th April, 16th July, 30th July, 13th August, 27th August, 10th September, 28/29th September, 1st October, 5th November and 4th December. Deep snow cover on 4th December resulted in incomplete records for many sites, and this sample run has therefore been excluded from the main analysis. Data for site NGV are available for 30th July, 13th August, 29th September, 1st October, and 5th November The water table depth measurements for each sample run were made within (at most) a six hour period, except for on 28th/29th September which followed a prolonged dry period and when measurements were undertaken over a 28 hour period. Inspection of continuous water table data from logged dipwells within each of the sampling runs showed no significant changes in water tables over the sample periods. The sample runs can therefore be considered simultaneous measurements of water table depth at all sites across the network.

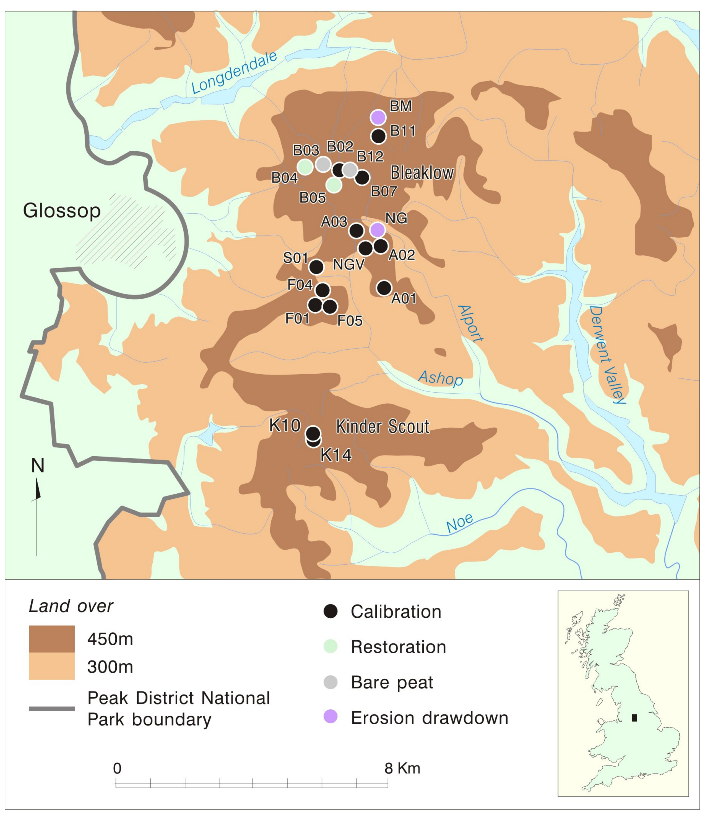


**Figure 1:** Location map for water table monitoring sites

Two further sites were selected for studies focusing on the effects of gully erosion on local water table drawdown; Bleaklow Meadows and North Grain (Table 1). These studies used different sample designs and frequencies to the main monitoring programme. Details of these are given in Section 3.

The location of all dipwells in the project were recorded using a Thales Mobile Mapper differential GPS to a precision of 0.1 m and a reported accuracy of less than 2 m.

**Table 1:** Water Table Monitoring Sites

| Site Code | Working Name | Site type | Easting | Northing | Altitude (m) | Site Wetness Index | Topographic setting |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| **A01** | Panorama | Calibration | 411100 | 392600 | 520 | 6.1 | Intact plateau |
| **A02** | Badlands | Calibration | 411017 | 393848 | 523 | 3.7 | Type I erosion |
| **A03** | Plover | Calibration | 410332 | 394300 | 540 | 6.0 | Intact footslope |
| **B02** | Hares | Calibration | 409763 | 396128 | 619 | 2.9 | Type I erosion |
| **B07** | Belle Vue | Calibration | 410429 | 395921 | 608 | 3.8 | Type II erosion (high density) |
| **B11** | Hareline | Calibration | 410973 | 397100 | 566 | 4.2 | Intact slope/footslope |
| **F01** | Mosstop | Calibration | 409053 | 392088 | 544 | 5.5 | Intact plateau |
| **F04** | Crusty | Calibration | 409277 | 392521 | 510 | 4.7 | Type II erosion (low density) |
| **F05** | Snakebed | Calibration | 409491 | 392031 | 530 | 3.9 | Type I erosion |
| **K10** | Gates View | Calibration | 408998 | 388205 | 618 | 4.1 | Intact slope |
| **K14** | Kaywhy | Calibration | 409001 | 388010 | 623 | 3.1 | Type II erosion (high density) |
| **S01** | Penguins | Calibration | 409100 | 393200 | 506 | 4.3 | Intact slope |
| | | | | | | | |
| **B03** | Trenches South | Bare peat | 409397 | 396384 | 612 | 2.7 | Type I erosion |
| **B04** | Joseph Patch | Restored | 408779 | 396216 | 587 | 3.9 | Type II erosion |
| **B05** | Tubby East | Restored | 409613 | 395695 | 618 | 2.7 | Type I erosion |
| **B12** | Sweaty Brow | Bare peat | 410099 | 396143 | 624 | 4.4 | Type I / II erosion |
| | | | | | | | |
| **NGV** | North Grain variability | Variability/ calibration | 410843 | 393907 | 520 | 4.4 | Type II erosion |
| | | | | | | | |
| **BM** | Bleaklow Meadows | Hagg study | 410840 | 397230 | 560-565 | - | Type I erosion |
| **NGB to NGM** | North Grain Transects | Transect study | 411000 | 393900 | 520-533 | - | Type II erosion |

## 3. Local water table drawdown associated with gully erosion

### Introduction

Gully erosion is widespread in the Peak District peatlands and typically takes one of two dominant forms (Bower 1960; Figure 2). Type I erosion is represented by frequently branching and dissecting channels, dendritic in form and with a high drainage density. This type of erosion occurs in areas with low slope angles (< 5 degrees) and in the Peak District is typically found on the top of the Bleaklow and Kinder Scout Plateaux. Type II erosion is represented by relatively straight un-branched or low density dendritic gullies which run down the slopes of steeper ground. In both cases the gullies cut into the peat, typically to depths of 1.5 – 3 m, with mature gullies reaching the mineral substrate.

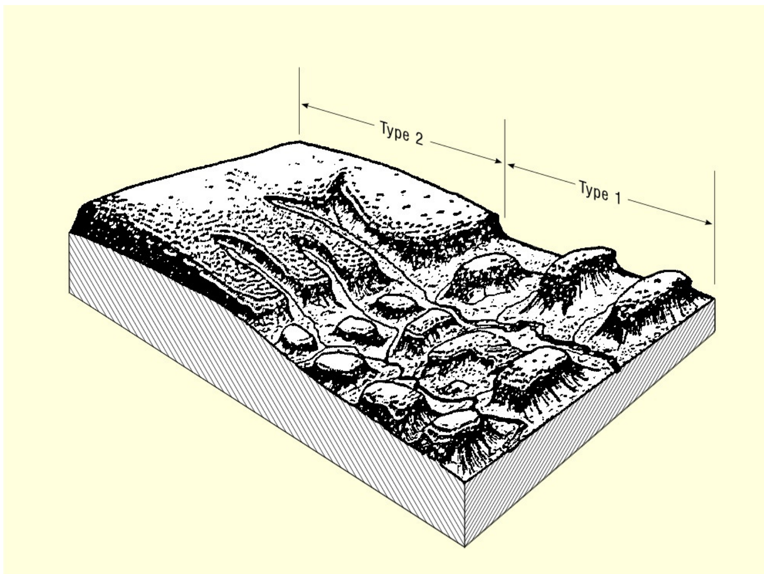


**Figure 2:** Type I and Type II gully erosion in blanket peat.
Redrawn from Evans and Warburton (2007) after Bower (1960)

It has long been recognised that the installation of ditches (grips) in peat catchments alters peat hydrology, in particular resulting in water table drawdown round each ditch (Boelter 1972, Stewart and Lance 1991). A similar effect has been associated with gully erosion (Tallis 1973; see Figure 3) and demonstrated by comparing water table behaviour in intact peat and gully edge locations (Daniels *et al.* 2008a). However, there has been limited evaluation of the magnitude or extent of this effect (i.e. the depth of drawdown or how far away from a gully it extends). This information is needed in order to model peatland water tables at a landscape scale. A preliminary study recently conducted on Bleaklow (Hill 2007) demonstrated the significance of the gully edge drawdown effect, confirming its strong influence on water tables adjacent to Bower Type II gullies during both high and low water table conditions. Hill (2007) also suggested that gully depth was a key parameter in the relationship between gullying and water table drawdown. Our working hypotheses are therefore that (i) the drawdown effect shows a distance-decay effect away from the gully edge (Figure 3) and (ii) the magnitude (depth) of drawdown is a function of the depth of the gully.

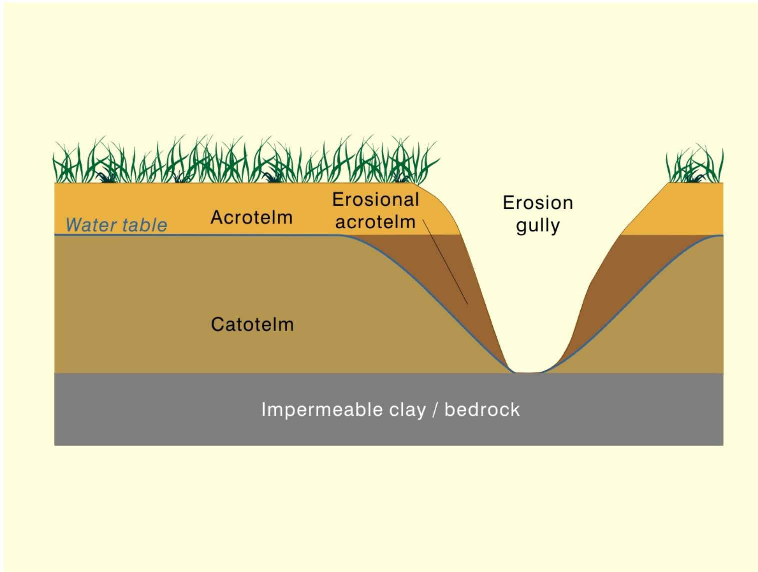


**Figure 3:** Conceptual model of local water table drawdown associated with gully erosion

This section of the report summarises two studies which directly measure the effect of gullying on local peat water table, first for an area of Type I (dissection) erosion and second for Type II (linear) erosion.

### Water table drawdown and Type I (dissection) erosion

Type I peat erosion typically occurs on flat and summit areas of blanket peats and is characterised by isolated haggs or 'islands' of peat. These haggs are irregular in shape and vary in size from less than a metre across to more than 10 metres. If the gully edge drawdown effect is restricted to a zone adjacent to the gully, then the effect on water table will be proportional to the size of the hagg (see Figure 4). In the centre of very large haggs there will be no drawdown effect whereas small haggs will be affected by drawdown from all sides. The extent and size of the drawdown effect can therefore be quantified by measurements of water table in the centre of haggs of different sizes.

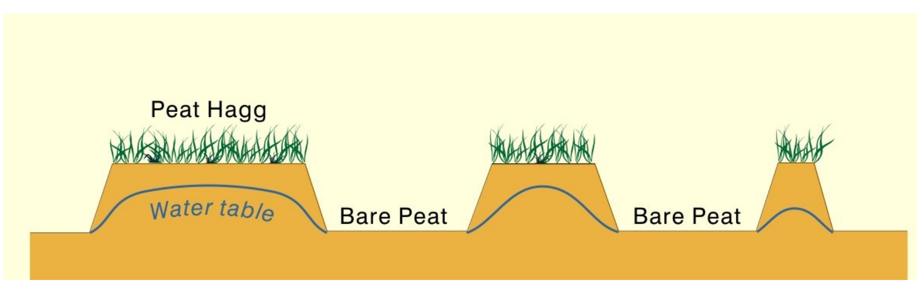


**Figure 4:** Conceptual model of the effect of Type I gully erosion on local water tables in peat haggs of different sizes

An area of Type I erosion at Bleaklow Meadows (NGR 410840 397230) was selected for study. Dipwells were installed into the centre of 23 haggs of different sizes, with the distance from the dipwells to the hagg edges (gullies) varying from 0.45 to 5.5 m. Water tables depth in each dipwell was measured manually on nine occasions between 30$^{th}$ July and 5$^{th}$ November 2008. For each hagg the maximum depth of the adjacent gully was measured by levelling. Gully depth varied between 0.75 m and 2.84 m.

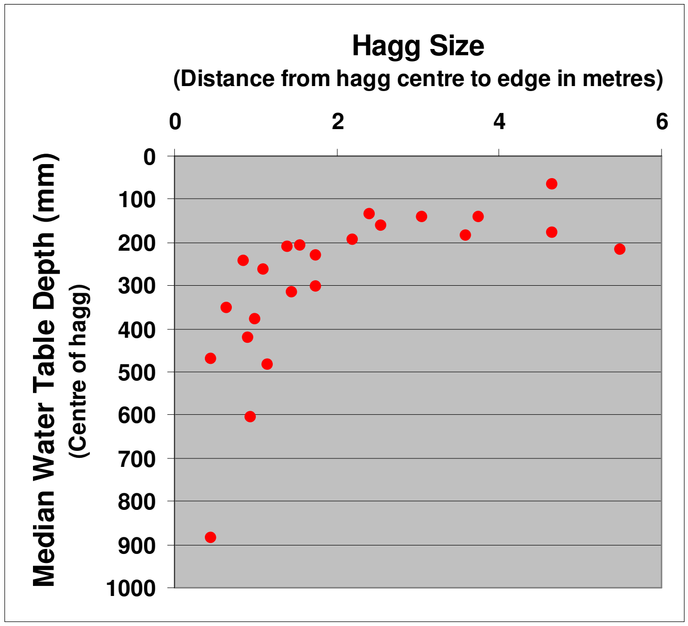


**Figure 5:** Median water table depths in the centres of 23 peat haggs of increasing size

There is a strong relationship between hagg size and water table depth, with water table depth in the centre of the haggs increasing as hagg size decreases (Spearman's rank correlation r = -0.825, $p < 0.001$, n = 23; see Figure 5). As haggs get smaller and the distance from the centre of the hagg to the gully declines there is a clear drawdown effect, and water tables in small haggs can be more than 400 mm below those observed in the larger haggs. Conversely median water table depths in the centre of the larger haggs are relatively high (< 200 mm). There is a marked threshold in the relationship at 2 m distance from the gully. Above this distance median water table depths vary between haggs but there is no significant trend. Below this threshold there is a systematic relationship between distance and water table, with hagg centre water tables clearly falling below the lowest median levels observed in the larger haggs.

There is no relationship between median water table in the centre of the haggs and the maximum depth of adjacent gully (Spearman's rank correlation r = 0.185, $p = 0.399$, n = 23; see Figure 6).

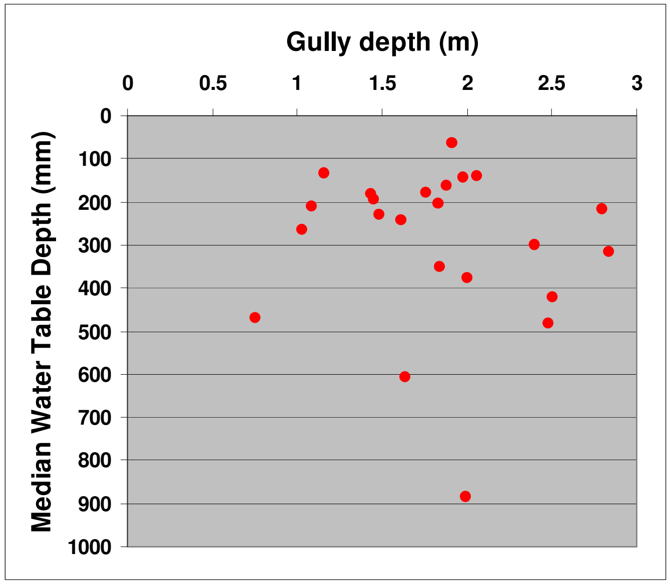


**Figure 6:** Median water table depth in 23 peat haggs against maximum depth of adjacent gully

These data suggest that the drawdown effect in this area of Type I gully erosion extends 2 m into the haggs. Drawdown is therefore restricted to a zone within 2 m of gully edges. The amount of drawdown is inversely proportional to the size of the hagg (i.e. with distance from the gully edge to the centre of the hagg). Although in very small haggs the amount of drawdown can exceed 400 mm, an estimate of the overall drawdown effect can be made by comparing means of the median water table conditions outside and within the 2 m drawdown zone. Mean water table depth is 157.4 mm for the larger haggs (distance > 2m) and 383.4 mm for the smaller haggs (distance < 2 m). Water tables in haggs affected by local gully edge drawdown are therefore 226 mm lower than in haggs unaffected by local gully edge drawdown. There is no clear evidence from the data that the amount of drawdown is also affected by gully depth, although gully depths in this dataset are relatively high (typically >1.5 m). A fuller range of gully depth conditions would be needed to properly evaluate the impact of gully depth on drawdown, including possible co-variance with hagg size.

## Water table drawdown and Type II (linear) erosion

Type II peat erosion is widespread in the Peak District on hillslopes and sloping ground, and is characterised by linear un-branched or low density dendritic gullies. The drawdown effect here can most effectively be measured using transects of dipwells running perpendicular to the gullies.

An area of peatland at Upper North Grain with extensive Type II erosion was chosen for study. Nine gully locations were selected to encompass a gradient in gully depth and dipwell transects installed across the bog surface at 90 degrees to each gully (see Table 2). Water table depth in each dipwell was measured manually on eight or nine occasions; except for transect NGN which was measured on four occasions. Gully depths were measured by levelling.

**Table 2:** Dipwell transects used in the study of water table drawdown and Type II erosion

| Transect | NGR | Gully Depth (m) | Dipwell positions relative to the gully edge (m) |
|---|---|---|---|
| **NGB** | 410817 393931 | 2.17 | 0 - 0.5 - 1 - 2 - 3 - 4 - 6 - 10 - 14 |
| **NGC** | 410829 393945 | 2.02 | 0 - 0.5 - 1 - 2 - 3 - 4 - 6 - 10 - 14 |
| **NGD** | 410843 393953 | 1.40 | 0 - 0.5 - 1 - 2 - 3 - 4 - 6 - 10 - 14 |
| **NGE** | 410961 394179 | 1.69 | 0 - 0.5 - 1 - 2 - 3 - 4 - 6 - 10 - 14 |
| **NGF** | 410949 394197 | 0.86 | 0 - 0.5 - 1 - 2 - 3 - 4 - 6 - 10 - 14 |
| **NGG** | 410949 394211 | 0.87 | 0 - 0.5 - 1 - 2 - 3 - 4 - 6 - 10 - 14 |
| **NGH** | 410942 394188 | 0.31 | 0 - 0.5 - 1 - 2 - 3 - 4 - 6 - 10 - 14 |
| **NGM** | 411025 393923 | 2.38 | 0 - 0.5 - 1 - 1.5 - 2 - 2.5 - 3 - 3.5 - 4 - 4.5 - 5 - 5.5 - 6 - 6.5 - 7 - 7.5 - 8 |
| **NGN** | 411149 394055 | 2.28 | 0 - 0.5 - 1 - 1.5 - 2 - 2.5 - 3 - 3.5 - 4 - 4.5 - 5 - 5.5 - 6 - 6.5 - 7 - 7.5 - 8 |

The water table data from the transects are summarised in Figure 7 which shows profiles of median water table depth along each transect. These data are noisy, demonstrating the high degree of variability inherent in water table depth at a site (see also Section 4). There are relatively few observations on each transect, which together with the high variability in the data makes detailed quantification of the drawdown function in each transect difficult. Nevertheless, there is a consistent pattern of drawdown close to the gully edges, with higher but variable water tables further from the gullies. Progressing along the transects towards the gully edge, a ‘break point’ can be identified in each profile where median water table depths in the dipwells fall *consistently* below the range of median water table depths observed away from the gully-edge zone. This drawdown ‘break point’ occurs at different positions in different transects (Figure 7 and Table 3) but is typically between 1.5 and 3.5 m from the gully edge. It represents the maximum extent of the drawdown zone that can be clearly identified from the transect data, and its mean position in the nine transects is at 2.05 m from the gully edge. This figure is almost identical to the 2 m drawdown zone identified in the Type I study, indicating that drawdown zones associated with both Type I and Type II erosion extend 2 m away from the gully edge.

The magnitude (depth) of water table drawdown in the Type II gully transects can be calculated by comparing means of the median water table conditions outside and within a 2 m drawdown zone for each of the transects (see Table 4). The mean size of this drawdown effect across the nine gully transects is 202 mm. There is no significant relationship in the data between the depth of water table drawdown in each transect and the depth of the adjacent gullies (Spearman’s rank correlation $r = 0.300$, $p = 0.433$, $n = 9$). This statistic is based on relatively few transects and a scatterplot suggests that the highest levels of drawdown occur in deep gullies (> 2 m) (Figure 8). Nevertheless, a larger number of transects would be needed for a more robust test of the effect of gully depth on drawdown.

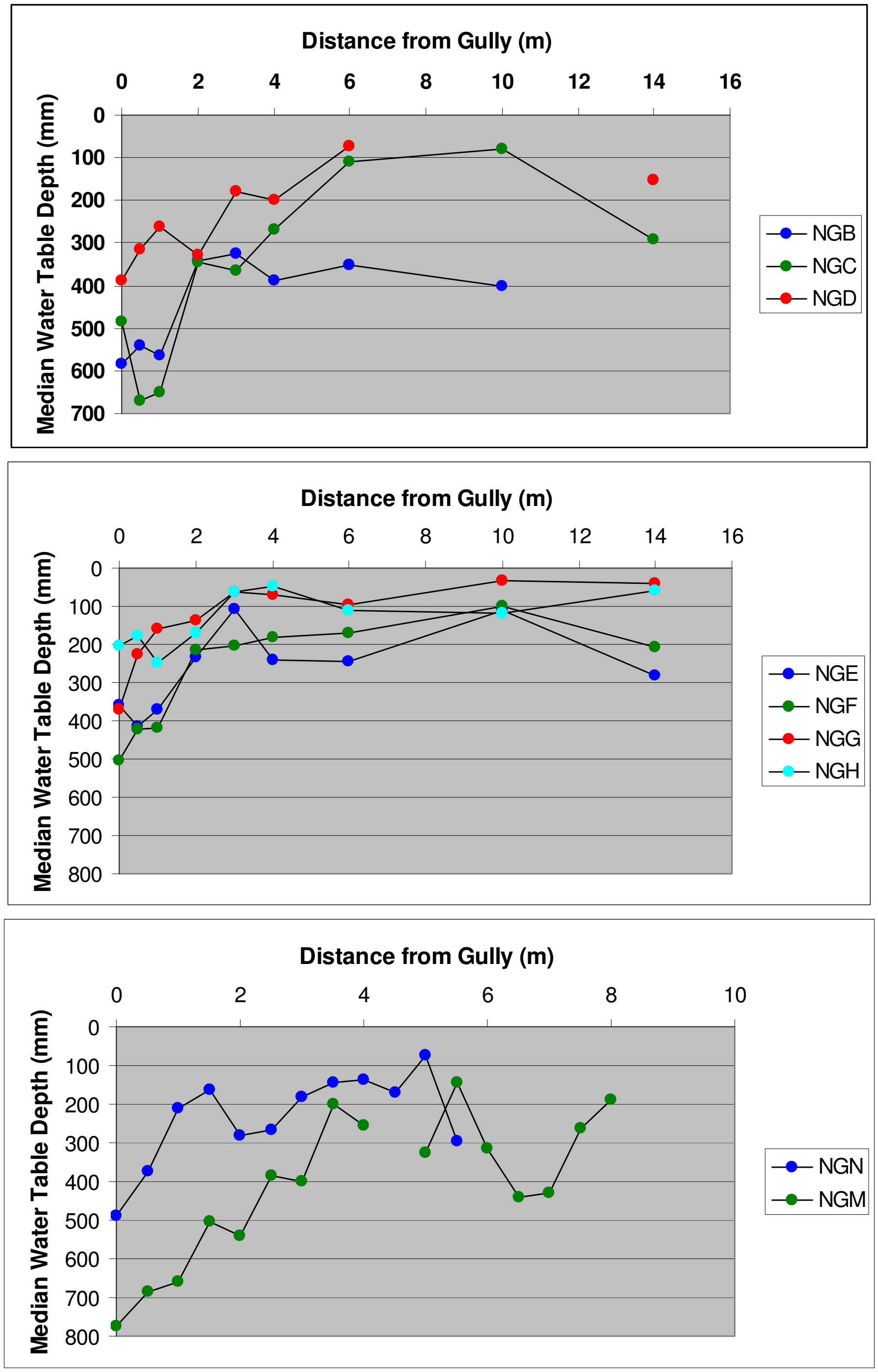


**Figure 7:** Median water table depth profiles from Type II erosion dipwell transects. Note different axes scales for NGN and NGM.

**Table 3:** Position of drawdown 'break point' in dipwell transects

| Transect | Break Point (m) | Notes |
|---|---|---|
| **NGB** | 1.50 | |
| **NGC** | 3.50 | Break point constrained by observation at 14 m |
| **NGD** | 2.50 | |
| **NGE** | 1.50 | Break point constrained by observation at 14 m |
| **NGF** | 1.50 | |
| **NGG** | 2.50 | |
| **NGH** | 2.50 | Break point constrained by observation at 10 m |
| **NGM** | 2.25 | Break point constrained by observation at 6.5 m |
| **NGN** | 0.75 | Break Point constrained by observation at 5.5 m |

**Table 4:** Magnitude of water table drawdown in each dipwell transect

| Transect | Mean water table in dipwells between 0 – 2 m from gully edge | Mean water table in dipwells > 2 m from gully edge | Drawdown (mm) |
|---|---|---|---|
| **NGB** | 507.8 | 366.0 | 141.7 |
| **NGC** | 537.5 | 223.6 | 313.9 |
| **NGD** | 323.3 | 186.8 | 136.4 |
| **NGE** | 345.0 | 197.0 | 148.0 |
| **NGF** | 389.5 | 172.4 | 217.1 |
| **NGG** | 224.0 | 61.2 | 162.8 |
| **NGH** | 200.5 | 80.8 | 119.7 |
| **NGM** | 633.5 | 318.8 | 456.7 |
| **NGN** | 304.0 | 179.7 | 124.3 |

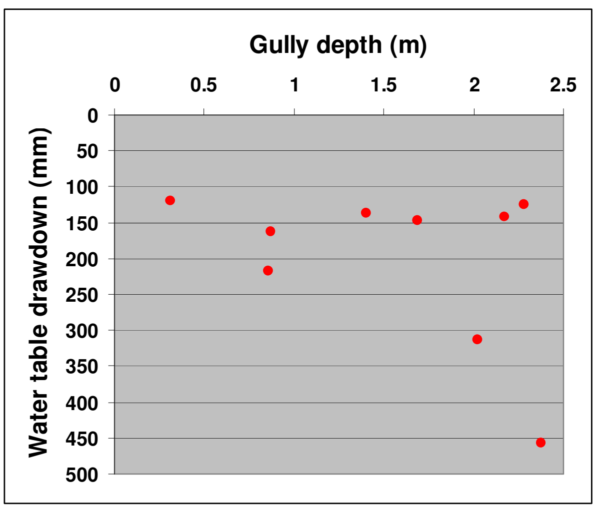


**Figure 8:** Water table drawdown and gully depth in Type II erosion dipwell transects

## Summary of results from gully edge drawdown studies

The studies of water tables adjacent to gullies reveal similar patterns of local water table drawdown associated with both Type I and Type II erosion. In particular:

1. Gully erosion is associated with local water table drawdown, with the highest amount of drawdown immediately adjacent to the gullies and a distance-decay effect in drawdown with distance from gully edge.
2. The zone of drawdown extends 2 m into the peatland from the edges of gullies.
3. Water tables within the drawdown zone are approximately 200 mm lower than in the adjacent peatland.

## 4. Spatial variation in peatland water tables

### Within-site variation in water table depth

Reliable measures of water table conditions are needed for the sites in this study, where site is defined as a 30 x 30 m area of blanket peatland. This requires an evaluation of within-site variability in water table depth and estimation of the number of samples (dipwells) needed to reliably establish water table depth and variation for a site. Here we use stochastic simulations to estimate uncertainty in the calculation of mean and standard deviation in site water table depth and to determine the number of dipwells required to reliably quantify water table conditions at the site scale.

Forty one dipwells were randomly located within a 30 x 30 m area at site NGV in the Upper North Grain catchment (NGR 410843 393907; see Table 1). This site is an interfluve on gently sloping ground between two Type II erosion gullies. It was selected for this study as preliminary observations suggested that sites in eroding areas show the highest levels of within-site variability in measured water table (see below). The intention was therefore to provide a conservative estimate of within-site variability in water table estimation (a 'worst case' exercise). Manual measurements of water table depth were made from the dipwells on five occasions; 30th July, 13th August, 29th September, 1 October and 5th November 2008. The measurements show high variability, with high standard deviations relative to the estimates of mean site water table depths (see Table 5). The measurements from 13th August were used for the analysis as the standard deviation of water table depth was highest for this sample run.

**Table 5:** Summary statistics of water table measurements from site NGV

| | 30/07/2008 | 13/08/2008 | 29/09/2008 | 01/10/2008 | 05/11/2008 |
|---|---|---|---|---|---|
| **Mean** | 387.7 | 270.4 | 330.2 | 244.6 | 246.5 |
| **Median** | 360.0 | 214.0 | 290.0 | 195.0 | 210.0 |
| **Max** | 845.0 | 865.0 | 880.0 | 864.0 | 730.0 |
| **Min** | 175.0 | 40.0 | 120.0 | 65.0 | 20.0 |
| **Range** | 670.0 | 825.0 | 760.0 | 799.0 | 710.0 |
| **SD** | 169.2 | 179.5 | 154.4 | 171.7 | 156.2 |

The stochastic simulations were used to determine the uncertainty in estimates of the mean and standard deviation in site water table depth for an increasing number of sub-samples (5, 10, 15, 20, 25, 30, 35 dipwells). 200,000 sub-samples of the specified size were selected randomly from the population of all possible sub-samples. The outcome of each simulation was converted into a cumulative probability distribution to allow comparison amongst simulations. The results show that estimates of both the mean and standard deviation of site water table are unstable when based on only a few dipwells (10 or less) (Figures 9 and 10). In these cases dipwells with anomalously high or low water table conditions can affect estimates of water table conditions at the site scale. The cumulative probability distributions start to converge when more than 15 dipwells are included in the simulations. With a sub-sample size of 15 dipwells 90% of the sample generated means lie between 210 – 331.5 mm (a range of 121.5 mm) whereas the mean estimated from all 41 dipwells is 270.4 mm.

These analyses suggest that at least 15 dipwells are required to obtain reliable estimates of site water table conditions at any given time.

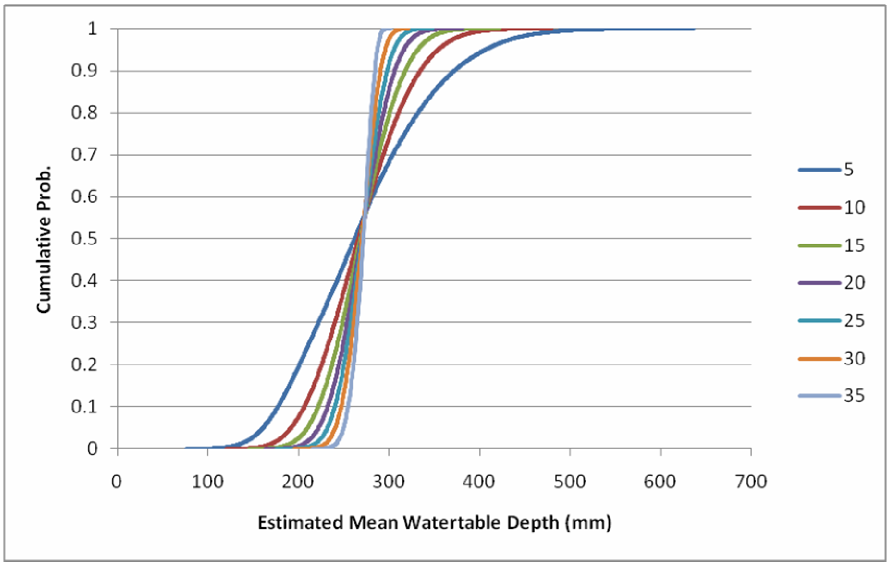


**Figure 9:** Cumulative probability plot of mean water table depth from the results of stochastic simulations for different numbers of sub-samples of water table measurements taken from site NGV on 13th August 2008

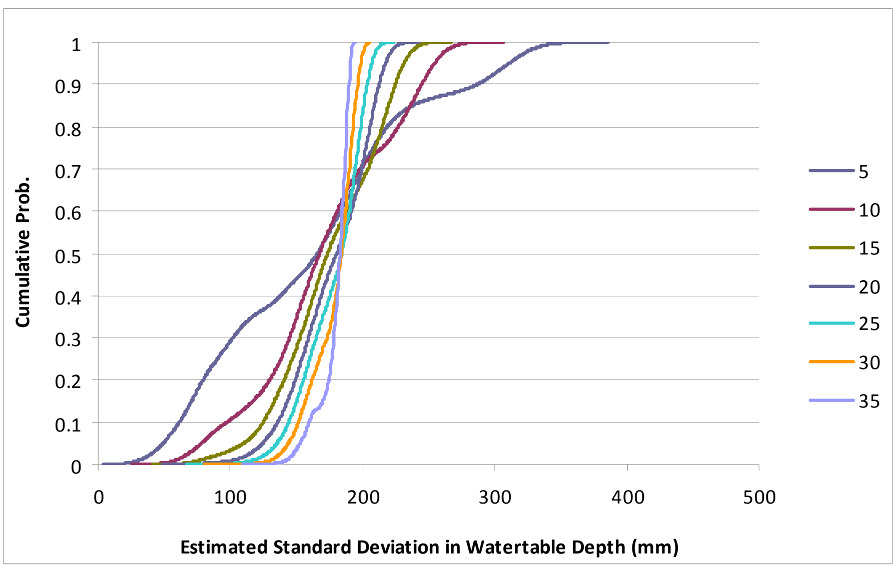


**Figure 10:** Cumulative probability plot of standard deviation in water table depth from the results of stochastic simulations for different numbers of sub-samples of water table measurements taken from site NGV on 13th August 2008

**Between-site variation in mean water table depth**

Variation in water tables across the Bleaklow and Kinder peatlands is examined here with reference to mean water table data for the 13 calibration sites (Table 1 and Figure 1). These data are available for nine different sample dates (see Section 2) and are shown in Table 6. There is significant variation in mean water table conditions both within and between sites.

**Table 6:** Mean water table depth data (mm) for the calibration sites from the nine sample runs

| Site | n Dipwells | 9/4/08 | 16/7/08 | 30/7/08 | 13/8/08 | 27/8/08 | 10/9/08 | 28/9/08 | 1/10/08 | 5/11/08 |
|---|---|---|---|---|---|---|---|---|---|---|
| **A01** | 16 | 72.0 | 87.6 | 102.1 | 56.1 | 89.3 | 71.2 | 198.9 | 63.9 | 54.6 |
| **A02** | 16 | 315.9 | 362.6 | 415.6 | 263.8 | 345.9 | 261.4 | 446.8 | 196.5 | 265.6 |
| **A03** | 16 | 40.7 | 99.8 | 180.6 | 82.1 | 127.5 | 84.9 | 278.4 | 70.6 | 65.9 |
| **B02** | 11 | 396.8 | 486.4 | 504.5 | 346.8 | 410.5 | 320.9 | 510.9 | 210.0 | 352.0 |
| **B07** | 15 | 340.0 | 380.7 | 447.3 | 308.3 | 374.3 | 294.7 | 456.5 | 246.0 | 315.4 |
| **B11** | 16 | 56.6 | 124.9 | 169.5 | 94.9 | 149.1 | 91.9 | 232.1 | 57.8 | 77.8 |
| **F01** | 16 | 141.8 | 98.4 | 107.8 | 197.9 | 179.3 | 134.8 | 221.6 | 127.8 | 89.7 |
| **F04** | 16 | 73.4 | 121.3 | 129.6 | 72.1 | 100.4 | 75.2 | 184.1 | 68.9 | 41.4 |
| **F05** | 16 | 252.5 | 272.6 | 290.6 | 199.7 | 259.6 | 220.1 | 345.3 | 138.0 | 227.3 |
| **K10** | 16 | 108.3 | 161.0 | 197.0 | 92.9 | 132.9 | 82.6 | 263.7 | 53.7 | 91.8 |
| **K14** | 16 | 481.4 | 493.1 | | 352.6 | 457.3 | 359.1 | 551.8 | 246.6 | 445.0 |
| **NGV** | 41 | | | 383.15 | 255.58 | | | 316.5 | 229.15 | 246.5 |
| **S01** | 16 | 13.3 | 32.6 | 75.7 | 19.0 | 42.8 | 26.1 | 186.6 | -12.2 | 9.6 |
| **Mean** | | 241.1 | 258.9 | 290.4 | 200.3 | 255.4 | 194.0 | 354.4 | 139.7 | 205.2 |

The highest water table conditions measured were at site S01 on 1 October 2008, when mean site water table was above the ground surface. Conversely the lowest water table conditions measured were at site K14 on 28 September 2008, when mean site water table depths exceeded 550 mm.

The data are summarised in Table 7. There is a pronounced gradient in average water table conditions between the sites, represented by both mean and median water tables. Although there is a very strong relationship between mean and median water table depths (Pearson product moment correlation $r = 0.996$, $p < 0.0001$, $n = 13$), median water tables are consistently higher than mean water tables at the wettest sites. These are also intact sites away from areas of gully erosion (Table 7 and Table 1). This asymmetry in the distribution of water table conditions is consistent with a pattern of predominantly high water tables with occasional periods of water table drawdown following dry weather (cf. Evans *et al.* 1999). For example, the sample run on 28 September 2008 occurred at the end of such a dry spell and the lowest water table conditions for all of the intact sites were recorded on this day. These observations suggest that median data provides the most robust estimate of average site water table conditions for comparative purposes.

Median water table depths at the sites vary between 26.1 and 451 mm. The wettest five sites show median depths less than 100 mm, but four of the sites have median depths greater than 300 mm. These latter sites have exceptionally low average water tables conditions in relation to both the wetter sites in the dataset and observations of peatland water tables from other regions (e.g. Evans *et al.* 1999, Holden and Burt 2003). There is evidence that within-site variation in water table conditions is more pronounced at the drier sites (Table 7) and higher ranges in site water table conditions are associated with the drier sites (Figure 11). However, a more detailed comparison of within-site variation is required before this effect can be fully evaluated.

**Table 7:** Summary statistics for mean site water table at the calibration sites from the nine sample runs, ordered by median and showing topographic setting and erosion status. The final column shows median data calculated after excluding dipwells located closer than 2 m to a gully edge.

| Site | Median | Mean | SD | Min | Max | Range | Topographic setting | Median excluding gully edge dipwells |
|---|---|---|---|---|---|---|---|---|
| **S01** | 26.1 | 43.7 | 58.8 | -12.2 | 186.6 | 198.8 | Intact slope | 26.1 |
| **A01** | 72.0 | 88.4 | 44.4 | 54.6 | 198.9 | 144.3 | Intact plateau | 72.0 |
| **F04** | 75.2 | 96.3 | 43.0 | 41.4 | 184.1 | 142.6 | Type II erosion (low density) | 76.8 |
| **A03** | 84.9 | 114.5 | 73.6 | 40.7 | 278.4 | 237.8 | Intact footslope | 84.9 |
| **B11** | 94.9 | 117.2 | 58.0 | 56.6 | 232.1 | 175.6 | Intact slope/footslope | 94.9 |
| **K10** | 108.3 | 131.5 | 65.8 | 53.7 | 263.7 | 210.0 | Intact slope | 108.3 |
| **F01** | 134.8 | 144.3 | 45.9 | 89.7 | 221.6 | 131.9 | Intact plateau | 134.8 |
| **F05** | 252.5 | 245.1 | 58.7 | 138.0 | 345.3 | 207.3 | Type I erosion | 200.0 |
| **NGV** | 255.6 | 186.2 | 63.4 | 229.2 | 383.2 | 154.0 | Type II erosion | 255.6 |
| **A02** | 315.9 | 319.3 | 81.0 | 196.5 | 446.8 | 250.3 | Type I erosion | 315.9 |
| **B07** | 340.0 | 351.5 | 70.0 | 246.0 | 456.5 | 210.5 | Type II erosion (high density) | 324.6 |
| **B02** | 396.8 | 393.2 | 98.7 | 210.0 | 510.9 | 300.9 | Type I erosion (high density) | 385.0 |
| **K14** | 451.1 | 423.4 | 97.6 | 246.6 | 551.8 | 305.3 | Type II erosion (high density) | 445.7 |

There is a very strong association between water table conditions and site erosion status (Table 7). Intact sites have relatively high average water tables. The lowest water table conditions are found at the most severely eroded sites i.e. those with high densities of Type I or Type II gully erosion. This demonstrates the very strong effect gully erosion has on peat water tables. Importantly, this is not simply a function of the gully edge drawdown effect. Relatively few of the site dipwells are located within the local gully edge drawdown zone (i.e. within 2 m of a gully edge): 3 at F04, 7 at F05, 2 at B07, 3 at B02 and 3 at K14. Exclusion of these dipwells makes little difference to median site water table depths (Table 7) or the association between erosion and water table conditions. A process of water table lowering is therefore occurring at eroded sites *in addition* to the gully edge drawdown effect established in Section 9. A crude estimate of the size of this effect can be inferred from comparisons of median water table conditions at intact and heavily eroded sites (Table 7), indicating water table lowering of up to 300 mm. This site-scale water table lowering at eroded sites is discussed further in Section 8.

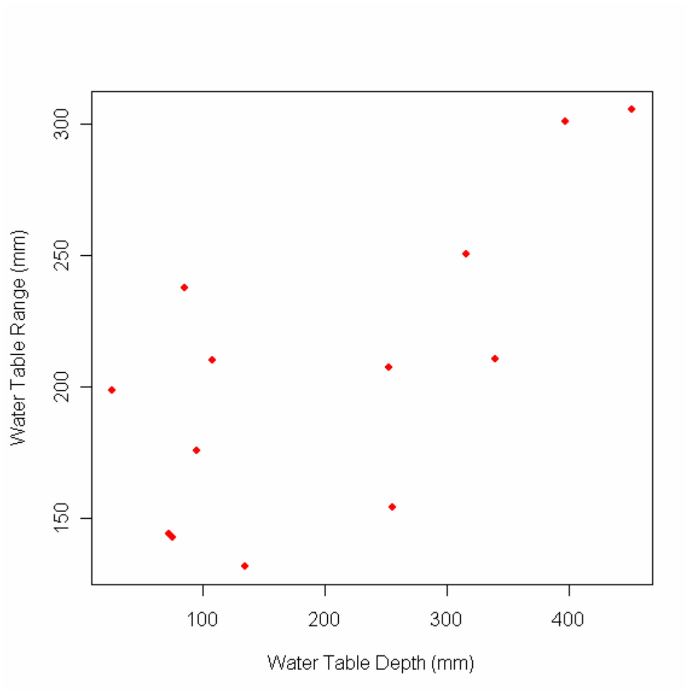


**Figure 11:** Range in mean site water table against median site water table depth for the 13 calibration sites

## 5. Temporal variation in peatland water tables

In order to evaluate temporal behaviour in water tables, loggers were installed in a central dipwell at 16 of the study sites. These sites included 12 of the calibration sites, both of the bare peat sites and both of the restored sites. The loggers were installed into a single dipwell in the centre of each 30 x 30 m site plot. Water table in the dipwells was recorded at hourly intervals using a 1 m capacitance probe and associated data logger (WR HR-1000 from www.trutrack.com). The capacitance probes were calibrated before installation, and the calibration checked approximately every three months by direct field measurement. Loggers were installed either in May or July 2008.

It is important to recognise that the data from these loggers represent water table fluctuations within an individual dipwell. Water tables can vary significantly between dipwells at the same site (see Section 4), and the water table depths recorded in the individual wells are not necessarily representative of water tables at the site scale. Although there is broad correlation between average water table depths in the continuously monitored dipwells and for the site as a whole (Table 8), data from some of the logging dipwells reflect either higher or lower water table conditions than observed across the site as a whole. In particular the continuous data from B11-01, B07-01 and K14-01 reflect lower water tables than the respective site averages, and data from F01-01 and A02-01 show higher water tables than the site averages.

**Table 8:** Details of dipwells used for continuous water table monitoring at the calibration sites. Median water table data calculated for the period 26 July 2008 – 22 January 2009. Note that loggers were also installed at sites A01 and F04; the former failed and the latter was stolen

| Dipwell code | Date Installed | Median Water Table (mm) Site | Median Water Table (mm) Logging Dipwell |
|---|---|---|---|
| **S01-01** | 16.5.08 | 26.1 | 79.9 |
| **A03-01** | 19.5.08 | 84.9 | 107.0 |
| **B11-01** | 19.5.08 | 94.9 | 174.1 |
| **K10-01** | 25.7.08 | 108.3 | 168.9 |
| **F01-01** | 16.5.08 | 134.8 | 33.0 |
| **F05-01** | 16.5.08 | 252.5 | 218.2 |
| **A02-01** | 15.5.08 | 315.9 | 192.4 |
| **B07-01** | 19.5.08 | 340.0 | 564.2 |
| **B02-01** | 19.5.08 | 396.8 | 478.2 |
| **K14-01** | 25.7.08 | 451.1 | 581.0 |

The data from the continuously monitored dipwells reveal very distinct differences in water table behaviour (Figures 12 and 13). Broadly speaking, three different types of behaviour can be observed in the dipwells:

1. *Water tables predominantly close to the ground surface (median water table < 150 mm) with occasional drawdown events during periods of dry weather.*

Drawdown events are represented by relatively slow falls in water table during dry weather. For example, there was a pronounced drawdown period in late September 2008 during dry weather between 7th and 29th September. On 7th September the water table in dipwell F01-01 was at the ground surface following wet weather (see Figure 12). By 29th September the water table depth had fallen to 220 mm. Rainfall on 29th September then raised the water table to above the ground surface in a matter of hours. In these dipwells water tables during drawdown events typically fall to between 200 and 300 mm from the ground surface. Following drawdown events water tables respond quickly (within hours) to rainfall events with rapid rises in water table. These dipwells (F01-01, S01-01 and A03-01) are located at sites with high median water tables.

2. *Water tables predominantly fluctuating between depths of 100 and 250 mm with occasional deeper drawdown events during periods of dry weather.*

This behaviour is seen in dipwells K10-01, B11-01, A02-01, and F05-01 (Figure 13). Water table fluctuations in these dipwells generally parallel those of the first set of wells, but at a lower depth. In drawdown events water tables fall below 300 mm and can fall below 400 mm. Following drawdown events water tables again respond quickly to rainfall events with rapid rises in water table. However, water tables rarely reach the ground surface.

3. *Water tables predominantly very low (median water table < 400 mm) with occasional 'wet-up' events during rainfall*

This behaviour is seen at dipwells B02-01, B07-01 and K14-01. These dipwells occur at the sites with the lowest median water tables conditions (see Table 7). They are affected by drawdown in dry weather, with water table conditions sometimes falling as low as 700 mm. However, a key feature of this group of dipwells is the distinct, short-lived 'wet-up' events that occur following rainfall, represented by very rapid rises in water table followed immediately by rapid drain-down to lower water table depths. For example, a typical 'wet-up' event is recorded in dipwell B02-01 on 8 December 2008 (see Figure 12). Data from the weather station at Upper North Grain show that 6.84 mm of rain fell between 12:00 and 17:00 following 10 days of dry weather. At the start of the event (12:00) the water table depth in B02-01 was 564 mm but four hours later the water table had risen to almost the ground surface (5 mm depth), a rise of 550 mm in 4 hours. After rainfall ceased the water table subsided rapidly, dropping by 450 mm in 24 hours. These 'wet-up' events during rainfall are common to the three dipwells with very low average water table conditions as indicated in the cumulative water table curves (Figure 13).

The continuous water table data have highlighted a number of important features of temporal water table behaviour in these systems. Dipwells at the wetter locations exhibit similar water table behaviour than observed in intact blanket peats in other regions such as the North Pennines (cf. Evans *et al.* 1999) with water tables predominantly close to the ground surface. During periods of prolonged dry weather water tables are gradually drawn down by up to approximately 300 mm. Rainfall following dry weather results in rapid water table rises and water table depth returning to close to the ground surface. Water table is therefore generally high with occasional periods of lower water table conditions. This behaviour has been modified at locations affected by erosion. At some locations this modification takes the form of a general lowering in water table, with similar temporal trends in water table position than observed at intact sites but at lower depths. However at the driest locations, which occur at the most severely eroded sites (see Table 7), the temporal trends in water table are very different. In particular such sites experience water table 'wet-up' events during rainfall, with water tables returning to low conditions rapidly after such events. Water table at these locations is therefore consistently low except during rainfall events.

The temporal data therefore reveal very different water table behaviours at intact and eroded sites. This has implications for hydrological functioning of the peats, including processes of runoff generation and water quality regulation, which are discussed in Section 9.

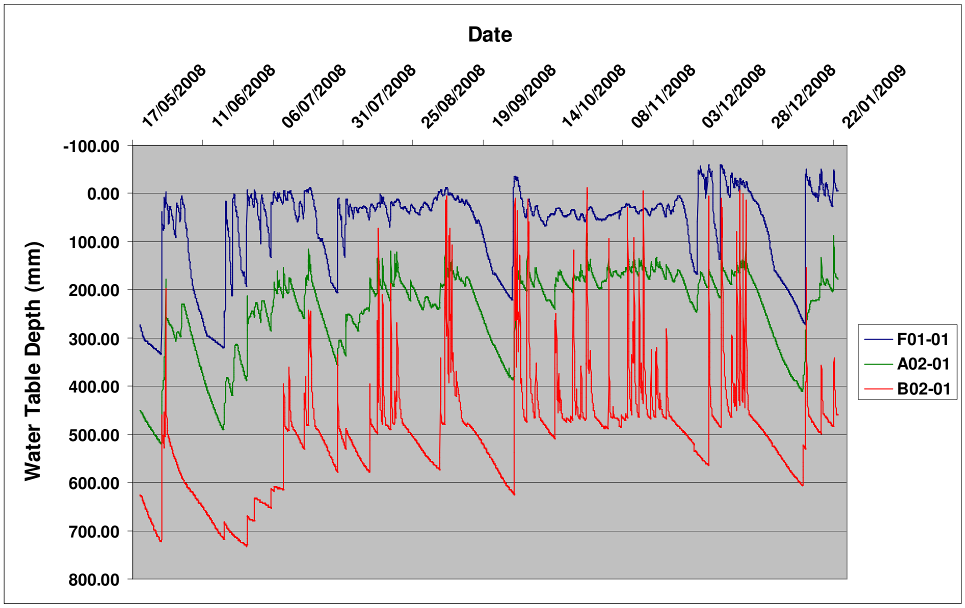


**Figure 12:** Continuous water table data for three of the monitored dipwells: F01-01, A02-01 and B02-01.

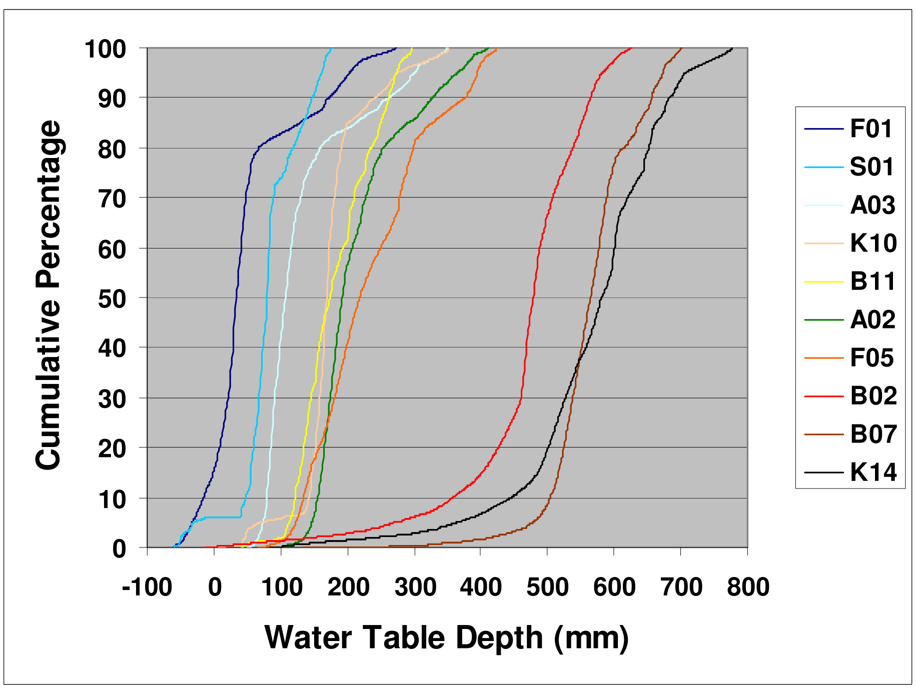


**Figure 13:** Cumulative water table depth data from the continuous loggers installed at the calibration sites for the period 26 July 2008 to 22 January 2009. The graphs indicate the proportion of time water tables are higher than each water table depth.

## 6. Modelling peatland water tables

This section uses the measured water table data from the calibration sites to model peatland water tables. First, we evaluate the topographic (wetness) index as a basis for water table modelling in these peatland environments; second, we develop a simple 'first-order' empirical water table model for the Peak District blanket peats.

We have adopted a parsimonious approach to the modelling, concentrating on key landscape controls on water table. We hypothesise that the two key controls of water table variation at the landscape scale are general topographic setting (e.g. hillslope hydrology) and the local gully edge drawdown effect. We acknowledge the potential importance of factors such as piping (Holden and Burt 2002) and variation in peat hydraulic conductivity (Beckwith *et al.* 2003) on local water table variability, but these effects are difficult to evaluate at the landscape scale. Therefore we treat these as underlying variation in the local signal (i.e. part of the error component in our model).

The importance of topographic setting to hillslope saturation is well established and the topographic (wetness) index provides a robust and widely used representation of topographic drainage (Beven 1997, Beven and Freer 2001). The index is a measure of the drainage area per unit contour length ($a$) divided by the local slope (tan $\beta$). The wetness index is high when slope is low (plateau and footslopes), predicting poor drainage and high water table conditions. Conversely, hillslopes (steeper slopes) are predicted to have relatively low water table conditions (see Figure 14). However, the index also takes into account the supply of water through upslope drainage, as characterised by the upslope contributing area (drainage area). Footslopes are therefore predicted to have higher water table conditions than plateau and head-slope locations for a similar slope gradient.

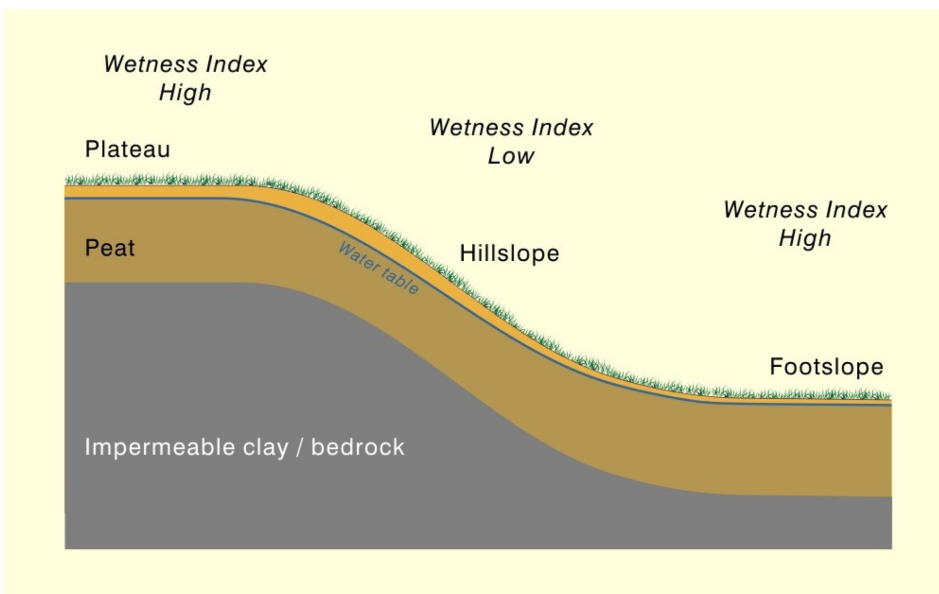


**Figure 14:** Hypothetical hillslope profile in a blanket peat system showing water table depth as predicted by the topographic (wetness) index

The wetness index formed the basis of the models of hillslope saturation developed by Holden *et al*. (2004) and applied to the LiDAR DEM (digital elevation model) available for the Peak District study region. It was also used by Lane *et al.* (2004) as the basis for a model of hillslope saturation in a blanket peat system in North Yorkshire. However, water table models for the Peak District peatland landscape also need to take into account local water table drawdown in areas adjacent to the erosion gullies prevalent on Bleaklow and Kinder (see Section 3). Our modelling approach is therefore based on the topographic (wetness) index modified to account for this gully edge drawdown effect.

**The wetness index as a predictor of peatland water table conditions**

There is a strong relationship between average water table conditions at the 13 calibration sites and the wetness index. There is a significant negative correlation between wetness index and median site mean water table depths (Spearman's rank correlation r = -0.791, $p = 0.0021$, n = 13); water tables are low when the wetness index is low and *vice versa*. However, this relationship is largely associated with increasingly low water water tables, and correspondingly low wetness index values, at sites with prevalent gully erosion (see Figure 15). There is no relationship between wetness index and water table depth within the seven sites which are intact or have only low density erosion (Table 9). Wetness index at these sites varies between 4.08 and 6.13, with the index making a clear distinction between intact sites with different slope conditions (i.e. hillslopes where slope > 4$^{o}$ against plateau/flat sites where slope < 3$^{o}$). This is not reflected in differences in water table depth, and all these sites are relatively wet with median water table depths < 150 mm. The wetness index is therefore a good predictor of site water table depths across the range of water table conditions represented at the calibration sites, and a good basis for modelling water tables across the Peak District landscape which encompasses a wide range of site conditions from intact to heavily eroded sites. However, the data suggest that the index is a poor predictor of differences in water table depth between intact sites, in particular over-predicting the measured differences in water table depth between intact hillslope and intact flat areas of the blanket peat landscape.

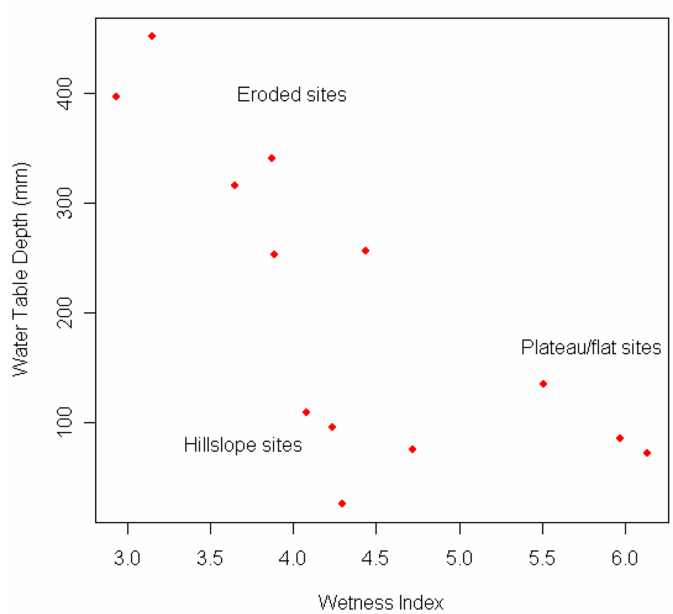


**Figure 15:** Median site water table depth against wetness index for the 13 calibration sites

**Table 9:** Topographic characteristics of the 13 calibration sites, ordered by median water table depth

| Site | Median Water Table (mm) | Wetness Index | Site Slope (degrees) | Specific Contributing Area | Topographic setting |
|---|---|---|---|---|---|
| **S01** | 26.06 | 4.30 | 4.12 | 11.26 | Intact slope |
| **A01** | 72.00 | 6.13 | 2.37 | 69.99 | Intact plateau |
| **F04** | 75.19 | 4.72 | 6.33 | 50.24 | Type II erosion (low density) |
| **A03** | 84.94 | 5.97 | 0.45 | 269.33 | Intact footslope |
| **B11** | 94.94 | 4.24 | 5.24 | 9.79 | Intact slope/footslope |
| **K10** | 108.25 | 4.08 | 4.43 | 9.22 | Intact slope |
| **F01** | 134.75 | 5.51 | 1.04 | 7.84 | Intact plateau |
| **F05** | 252.50 | 3.89 | 10.65 | 9.96 | Type I erosion |
| **NGV** | 255.58 | 4.44 | 3.04 | 12.00 | Type II erosion |
| **A02** | 315.88 | 3.65 | 8.16 | 15.41 | Type I erosion |
| **B07** | 340.00 | 3.87 | 8.47 | 15.02 | Type II erosion (high density) |
| **B02** | 396.82 | 2.94 | 12.97 | 4.17 | Type I erosion (high density) |
| **K14** | 451.13 | 3.15 | 8.15 | 20.58 | Type II erosion (high density) |

There is also a strong relationship between wetness index and the range in mean site water table depths (Spearman's rank correlation r = -0.632, p = 0.02, n = 13). The relationship is striking (see Figure 16) with water table range closely coupled to the wetness index apart from one clear outlier site (A03). Exclusion of this site results in a highly significant relationship (Spearman's rank correlation r = -0.958, $p < 0.0001$, n = 12). It is unclear why site A03 should be an outlier, although this is the only intact footslope site in the dataset. Nevertheless it is clear that wetness index is a very good predictor of within-site range in water table conditions, a key aspect of water variability.

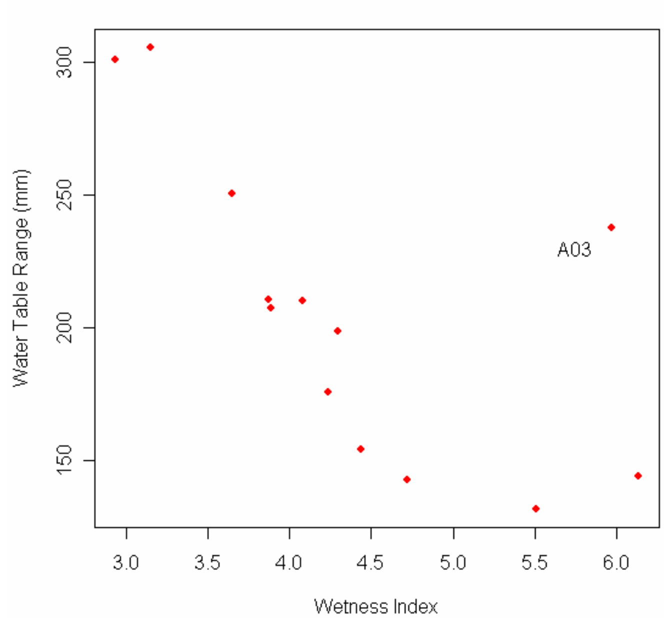


**Figure 16:** Range in mean site water table depth against wetness index for the 13 calibration sites

**A first-order water table model for the Peak District blanket peatlands**

The previous analysis has established the wetness index as a basis for the development of a water table model for the Peak District peatland landscape. We have therefore developed a simple 'first-order' model to predict median water table depth conditions. The approach we take is empirical and the model contains two steps:

1. Calibration of the wetness index against observed median site water table depths to allow water table depth to be predicted at the site scale;
2. Adjustment of the water table depth predictions at locations proximate to erosion gullies, where the local gully edge water table drawdown effect will occur.

The first step in model development is therefore to calibrate the wetness index against median site water table depths. The calibration uses a dataset from the calibration sites which excludes all dipwells within the gully edge drawdown zone (i.e. < 2 m from a gully, see Section 3). This is to avoid inclusion of the gully edge drawdown effect in both steps of the model. Relatively few of the site dipwells are located within 2 m of a gully edge: 3 at F04, 7 at F05, 2 at B07, 3 at B02 and 3 at K14. The relationship between wetness index and water table depth used for calibration is therefore very similar to that described above (see Figures 14 and 15).

$$WT = 634.76 - 100.67\ (WI) \qquad \textit{Equation 1}$$

$$WT = 1827.78 - 642.65(WI) + 58.78(WI^2) \qquad \textit{Equation 2}$$

The relationship can be described by a straight line regression (*Equation 1*; Residual standard error = 98.24, $R^2 = 0.53$, $p = 0.0049$, 11 df; Figure 17). However, there is systematic bias in the linear model. It results in under-estimates of median site water table depth at the heavily eroded sites (low wetness index values), over-estimates for intact hillslope sites and under-estimates for intact plateau/flat sites (high wetness index values).

Empirically, a better fit is provided by a curved (polynomial) relationship (*Equation 2*; Residual standard error = 81.77, $R^2 = 0.700$, $p= 0.0023$, 11 df; Figure 18). Model fit is significantly better than for the linear model (Anova $p = 0.03$), it has lower residual errors, much less bias and improved predictions for the sites with highest and lowest WI. The polynomial model still over-predicts water table depth at the intact hillslope sites, but not as badly as the linear model. This model has therefore been used to calibrate the wetness index.

The second step in model development is to adjust initial model estimates within the gully edge drawdown zone. Evaluation of the gully edge drawdown has shown that the effect is restricted to a zone extending 2 m from gully edge. The mean difference in water table depth between dipwells located within the drawdown zone and dipwells outside of the zone is approximately 200 mm in both Type I and Type II erosion gully systems (see Section 3).

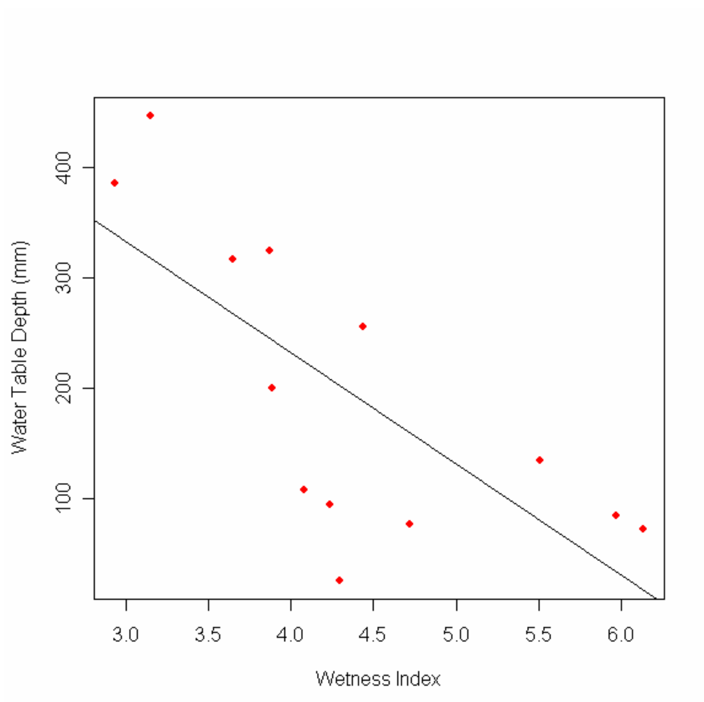


**Figure 17:** Median site water table against wetness. The line indicates the linear regression model (*Equation 1*).

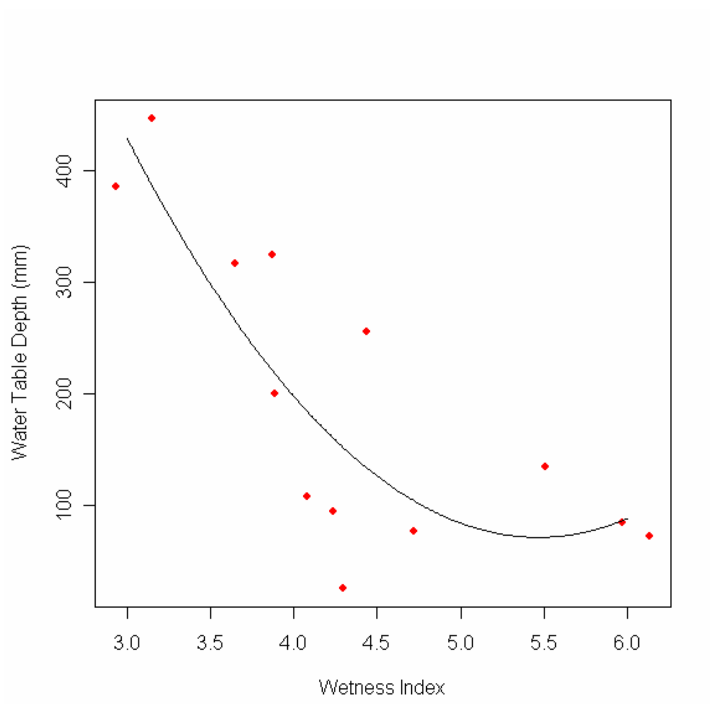


**Figure 18:** Relationship between median site water table and wetness index used for model calibration. The line indicates the polynomial regression model (*Equation 2*).

The water table model was implemented using TAS (Lindsay, 2005). The implementation had two stages. Initial estimates of water table depth were based on wetness index using the relation developed above. The index derived median water table was then modified for all locations within 2 m of an erosional gully. The modification was a 200 mm depression of water table as identified above.

The basic topographic input data for the modelling process were Lidar data for the Peak District moorlands (2 m ground resolution, 250 mm z resolution) supplied by Moors for the Future and a gully map derived from the Lidar model based on previous work by the Upland Environments Research Unit (Lindsay and Evans 2006, Evans and Lindsay in prep). The procedure was as follows (see Figure 19).

1) The DEM was filled and depressions were breached using the minimum impact approach within TAS.
2) Wetness index (WI) was calculated within TAS as ln ($a$ / tan $\beta$), where $a$ = specific contributing area and $\beta$ = slope.
3) Wetness index was filtered to site level using a circular 15 pixel (30 m) moving filter. The filtering algorithm was modified to include a mask so that masked values were not incorporated in the calculated mean value. The gully map was used as a mask to remove the effects of steep gully walls and high channel wetness index. Effectively the filter produced a site level map of interfluve (bog surface) wetness index.
4) The wetness index map was reclassified so that sites with WI in excess of 5.47 were defined as having a wetness of 5.47. This was necessary because the curve of the polynomial relation made extrapolation to WI values in excess of 5.47 physically unreasonable (see Figure 18).
5) An initial water table model was derived from the WI map using the polynomial WI-WT relation derived previously.
6) A gully edge image was derived by applying a 2 m buffer around a mask of the gully map.
7) The final gully model was produced by addition of the gully edge buffer (assigned a value of 200 mm) and the initial model.

This model has been applied to the Bleaklow and Kinder Scout areas (see Figures 20 - 23).

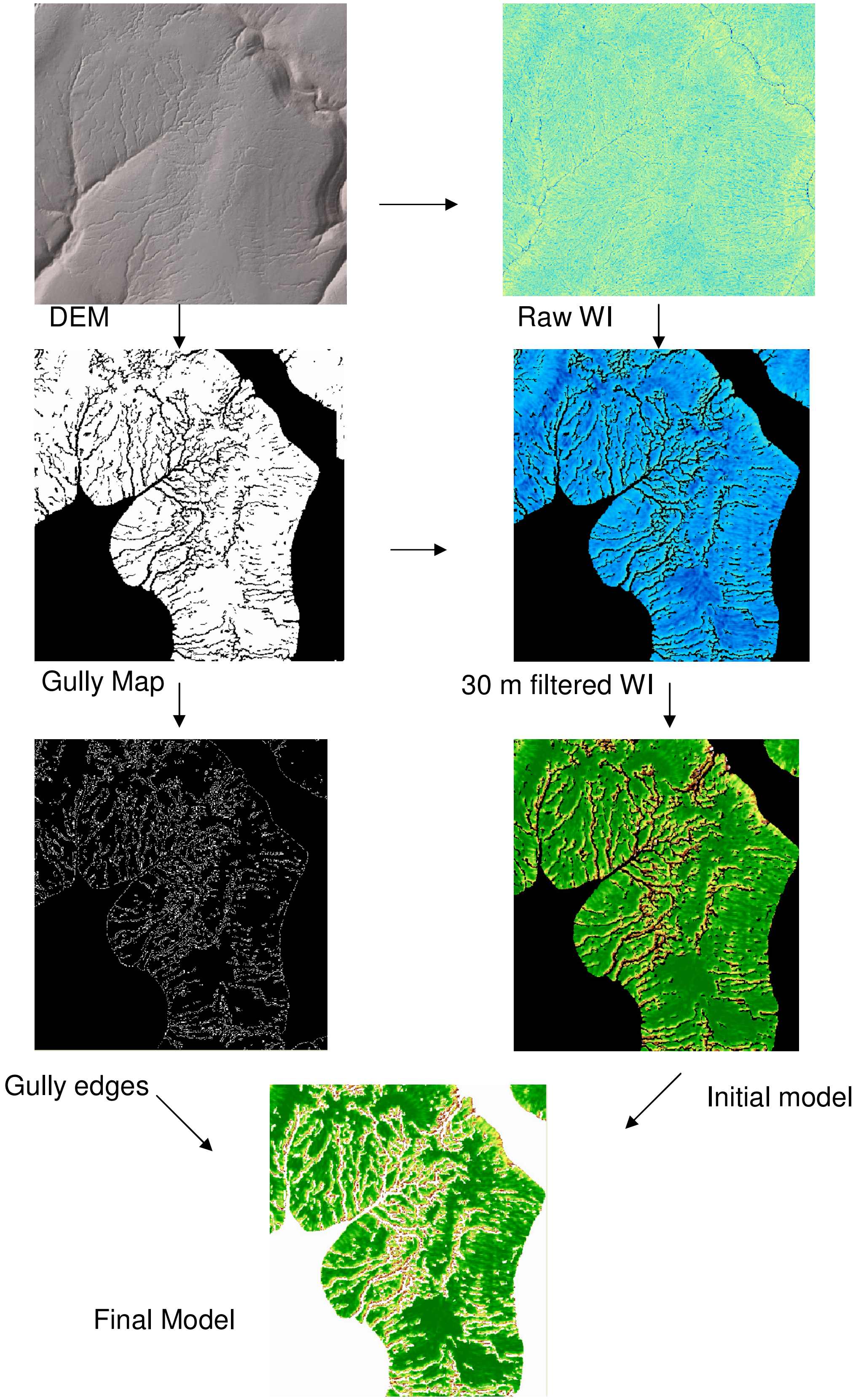


**Figure 19:** Implementation of the first-order water table model

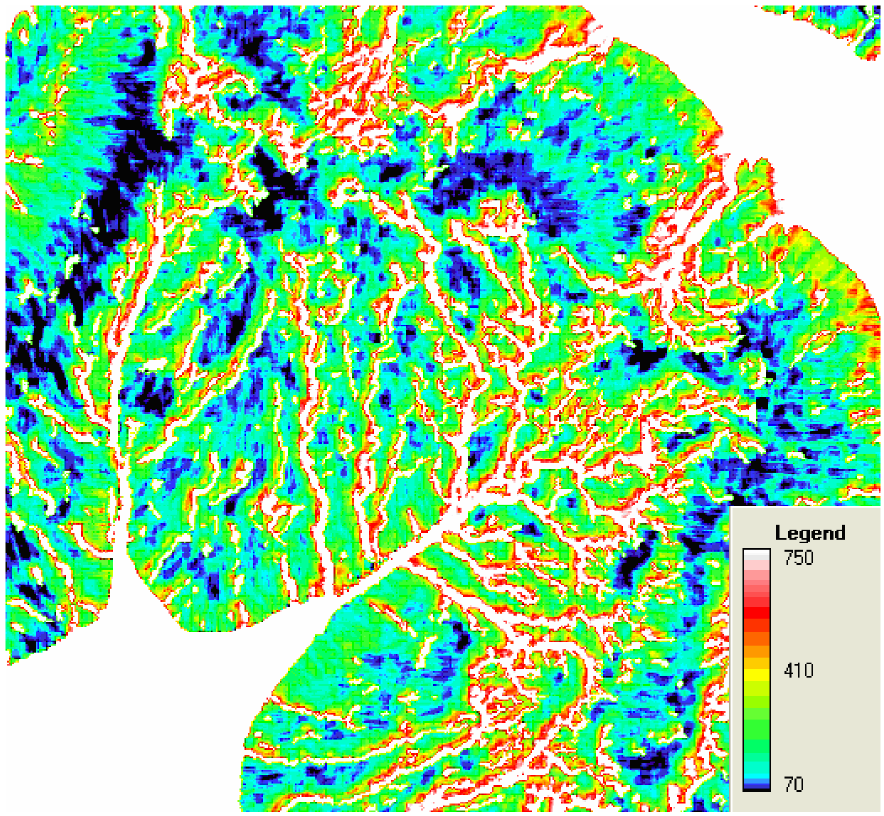


**Figure 20:** Median water table depth in millimetres for the Upper North Grain area (altitude > 500 m) predicted using the first-order water table model. Erosion gullies are masked out of this image. Note the pattern of pronounced water table drawdown at the edges of gullies. Predicted water tables are high (depth < 100 mm) at intact areas of the blanket peatland.

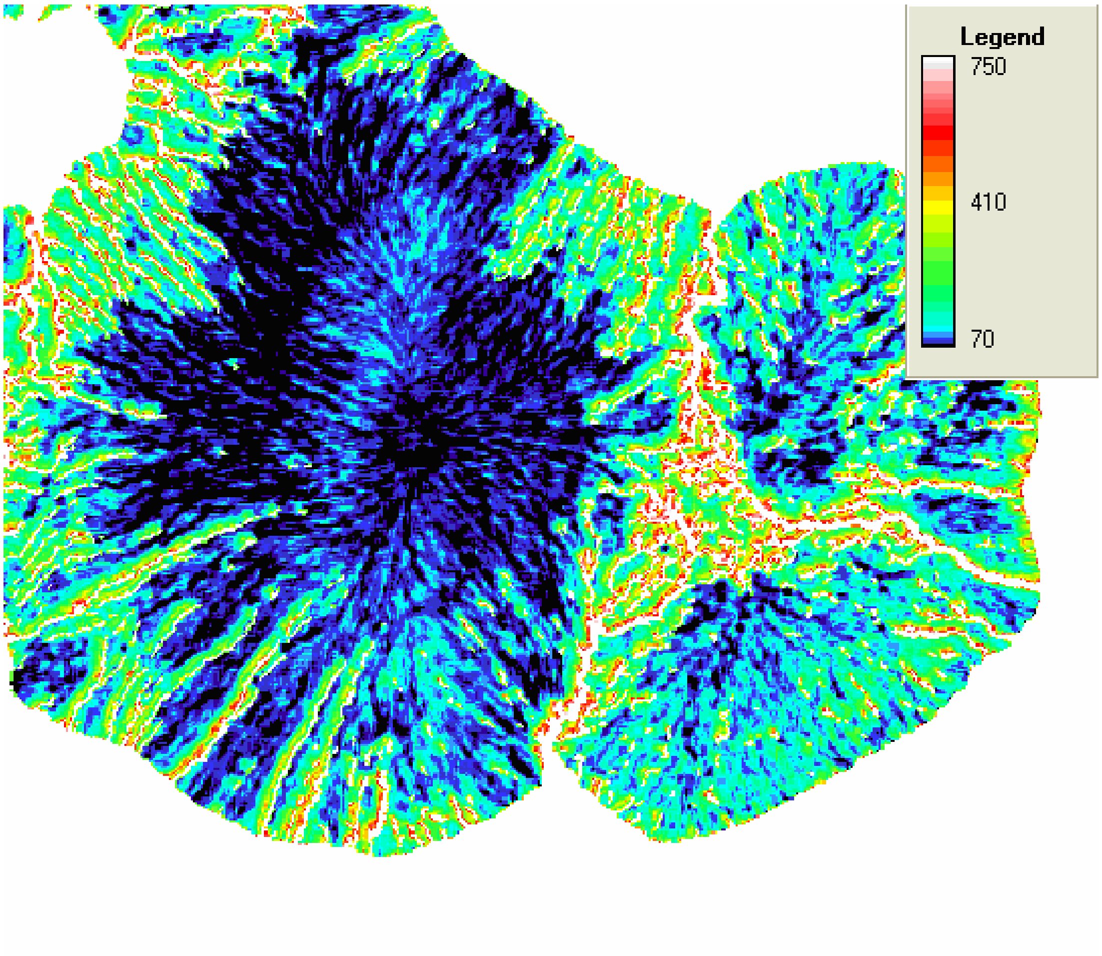


**Figure 21:** Median water table depth in millimetres for the Featherbed Moss area (altitude > 500 m) predicted using the first-order water table model. Erosion gullies are masked out of this image. Note the high predicted water table conditions on the intact peat dome of Featherbed Moss, the water table drawdown predicted around the linear Type II gullies which fringe the dome, and the low water tables predicted for the densely gullied Salvin Ridge / Thomason's Hollow area to the centre-right of the image.

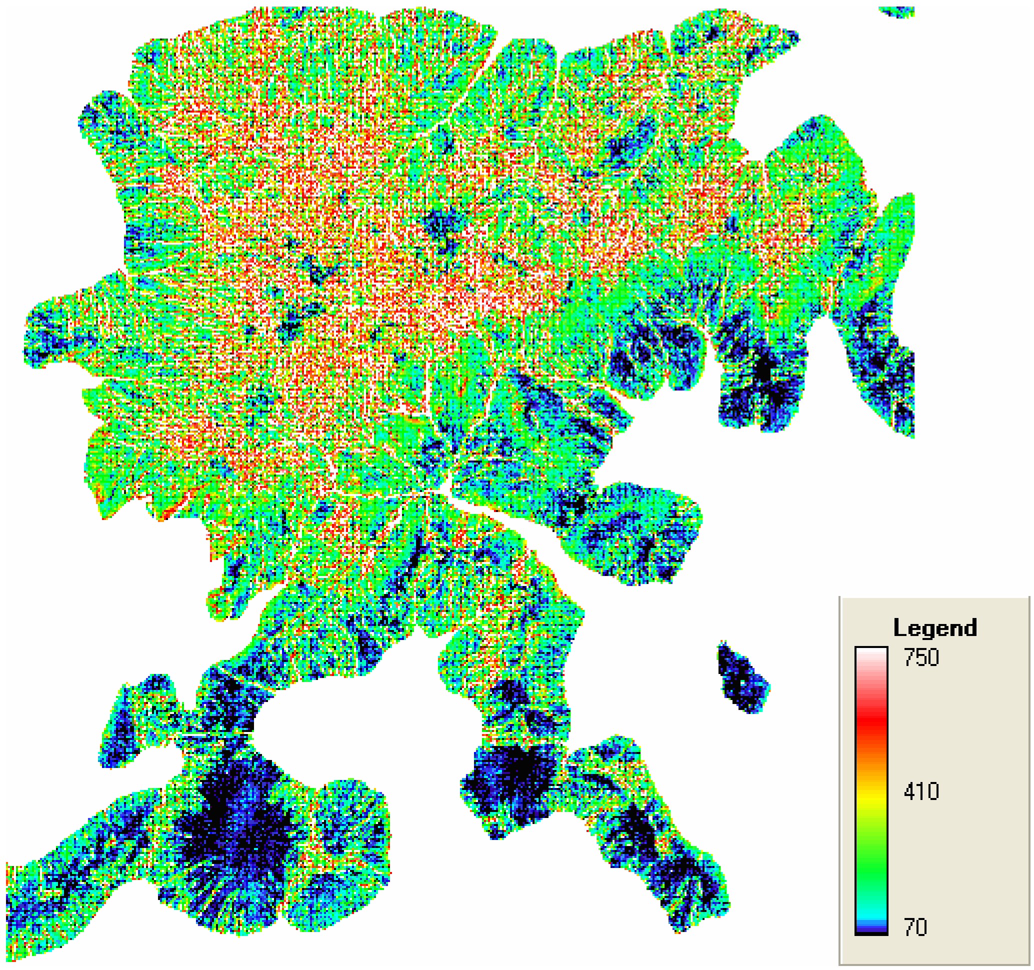


**Figure 22:** Median water table depth in millimetres for the Bleaklow plateau and Upper Ashop areas (altitude > 500m) ) predicted using the first-order water table model. Erosion gullies are masked out of this image. Note the relatively high water table conditions predicted for intact peatlands on the southern fringes of Bleaklow and in the Upper Ashop area. Note also the very low predicted water table conditions (> 400 mm depth, red colours) associated with the high density Type I erosion prevalent on the Bleaklow Plateau (centre-top of the image).

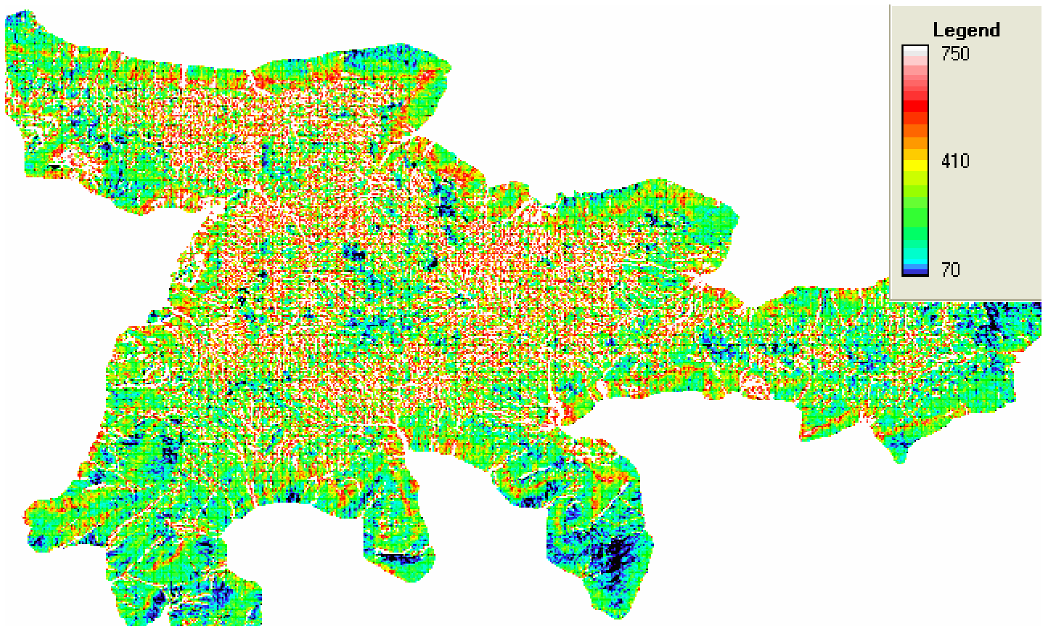


**Figure 23:** Median water table depth in millimetres for the Kinder Scout plateau (altitude > 500 m) ) predicted using the first-order water table model. Erosion gullies are masked out of this image. Note the very low predicted water table conditions (> 400 mm depth, red colours) associated with high density Type I erosion on the plateau. Nevertheless, there are some patches of high water table conditions (dark blue) predicted on the plateau. Some of these patches represent small areas of intact, vegetated peat, such as that found at the monitoring site K10 (see Section 4). Other patches with predicted high water table conditions represent areas of severe erosion, where peat haggs have been eroded down to peat or mineral flats. Water tables in peat / mineral flats are not adequately represented in the current model, and further work is required to develop a screening procedure for such areas.

## 7. The effect of moorland restoration on water table depth

The inclusion of both bare peat and restored (re-vegetated) sites into the regular water table monitoring programme allows an initial evaluation of the differences in water table conditions between these two site types, and by inference the impact of restoration on peat water tables. The two bare peat sites have consistently lower mean water table conditions than the two restored sites (Figure 24). However, water table depths are strongly influenced by local topography (see above) and this must be taken into account in any comparison between water table conditions. The four sites can be divided into two pairs on the basis of local topographic context, as represented by the wetness index.

Sites B03 and B05 have very low but almost identical wetness index values (Table 10), indicating similar topographic contexts, and can be considered representative of high density Type I erosion on the Bleaklow Plateau. There is no significant difference in the variances of mean site water table measurements at these sites ($F = 3.353$, $p = 0.124$, df = 7). Mean water tables at B05 (restored) are significantly higher than at B03 (bare peat) (paired $t$ test: $t = 2.158$, $p = 0.009$, df = 7, mean of the differences = 86.2 mm).

Site B12 and B04 have higher but relatively similar wetness index values (4.36 and 3.91 respectively). There is no significant difference in the variances of mean site water table measurements at these sites ($F = 0.353$, $p = 0.193$, df = 7). Mean water tables at B04 (restored) are significantly higher than at B12 (bare peat) (paired $t$ test: $t = -3.206$, $p = 0.015$, df = 7, mean of the difference = 75.7 mm). Although the wetness index values of the two sites are not identical, wetness index alone would predict that B12 has higher water table conditions than B04. This is the reverse of the observations, reinforcing the significance of the difference between water tables at the two sites.

The two pair of sites therefore show a consistent pattern in between-site water table depths, with higher water tables found at the restored sites.

Application of the first-order water table model to the sites predicts median water table depths of 518 and 508 mm at B03 and B05 respectively (Table 10). These predictions are lower than the observed values, but the difference between measured and modelled is more pronounced at the restored site. At the other pair of sites the model predicts median water table depths of 143 and 214 mm at B12 and B04 respectively. These predictions are higher than the observed values, with the difference being more pronounced at the bare peat site. There is therefore no consistent pattern in modelled against observed water table depths between the two pairs of sites.

The analyses presented here are limited as they are only based on four sites, and clearly more sites would be needed to make a robust, statistically significant evaluation of the effect of restoration practice on peatland water table depths. Nevertheless, the data are consistent with a pattern of higher water table conditions at restored sites compared to un-restored bare peat sites.

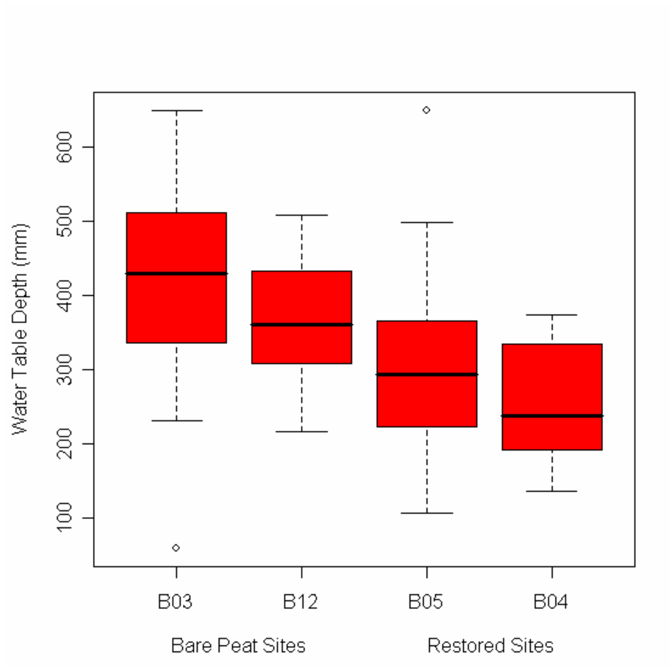


**Figure 24:** Boxplots of median water table data from the 16 randomly located dipwells in each of the bare peat and restored sites

**Table 10:** Measured and predicted water table conditions at the bare peat and restored sites

| Site | Status | Wetness Index | Measured mean site water table depth (mm) | | | Modelled median water table (mm) | Measured – modelled (mm) |
|---|---|---|---|---|---|---|---|
| | | | Median | Min | Max | | |
| **B03** | Bare peat | 2.71 | 423 | 142 | 573 | 518 | 95 |
| **B04** | Restored | 3.91 | 249 | 179 | 402 | 214 | -36 |
| **B05** | Restored | 2.74 | 308 | 191 | 399 | 508 | 200 |
| **B12** | Bare peat | 4.36 | 359 | 165 | 487 | 143 | -216 |

## 8. Discussion and recommendations

This report has described a series of inter-connected studies of water table conditions in the Peak District blanket peatlands and presented associated data and analyses. A number of the research findings are particularly significant. These are highlighted and discussed here and recommendations made for future research priorities.

***Multiple dipwells are required for reliable measurement of water table conditions at the site scale***

It is clear that even on small spatial scales (metres) there can be significant variability in measurements of water table depth. This has been evaluated in the study of within-site variability (Section 4) but is also apparent in the other datasets collected in this research (e.g. Figure 7). Such variability could be associated with a number of factors. Small scale variability in surface topography is a feature of peatland landscapes (Charman 2002, Evans and Warburton 2007), expressed for example in pool-hummock terrain. In many of the sites in the current study small scale topographic variability can be observed associated with hummocks of peat where tussocks of *Eriophorum vaginatum* (cotton grass) have formed. In such cases the absolute position of the water table might be relatively uniform across the site, but variability in surface topography will result in differences in measured water table depths, with dipwells located on raised areas having greater depths to the water table. Alternatively, there might be factors which influence the absolute position of the water table, leading to areas of lower water table conditions within the site. For example, pipes and macropores can be common in blanket peat systems (Holden and Burt 2002) and could result in local water table lowering. There have been suggestions that pipes and macropores are particularly prevalent in eroded peatland systems (see Evans and Warburton 2007) and in the site data reported in this study within-site variation in water table depth tends to be higher at the more eroded sites (see Table 7). Small-scale variation in the nature of the peat with depth, such as sub-surface layers of *Sphagnum* peat, may also lead to local variability in hydraulic conductivity (Beckwith *et al.* 2003) and associated water table conditions.

Regardless of the cause of this variability there is a clear implication. Reliable quantification of water table conditions at the site scale requires multiple, randomly located dipwells, and the stochastic simulations presented in Section 4 indicate that wherever possible at least 15 dipwells should be used. The use of fewer dipwells will increase the chances of anomalous conditions being used to represent site water table status.

***Gully erosion lowers water tables through both local gully edge drawdown and wider landscape effects***

The research has identified two distinct processes of water table lowering associated with gully erosion. The first was anticipated; the local water table drawdown adjacent to erosion gullies. This effect is spatially restricted to a zone within 2 m of gully edges, and this highly localised effect is consistent with a physical processes of drawdown associated with gravimetric pressure in a medium (peat) with very low hydraulic conductivity. The limited spatial extent of the drawdown effect is consistent with observations from ditch systems. For example, Stewart and Lance (1991) found that mean water tables close to drains were lower than at places further away, but that the lowering was confined to a zone within a few metres of the ditches. The lack of influence of gully depth on the drawdown effect is more surprising, but may be a function of the limited number of samples and transects included in this study.

It is also clear, however, that water tables are more generally lower at eroded sites than at intact sites, and that this water table lowering affects the whole site and not just the areas immediately adjacent to erosion gullies. Two possible mechanisms for this more general site-scale pattern of water table lowering at eroded sites can be hypothesised; reduced hydrological contributing area or increased site drainage through pipe and macropore networks. Eroded areas contain peat haggs and other more extensive areas of peat which are surrounded by gullies. Drainage densities are therefore higher in eroded areas than in intact peats, and this might result in reduced water supply from throughflow processes to eroded areas due to increased drainage through gully systems (i.e. reduced hydrological contributing areas). This reduction in contributing area could explain the water table lowering. Alternatively, if pipe and macropore networks are more prevalent in areas with gully erosion than in intact peats, then increased drainage and local drawdown associated with these systems might explain the observed site differences in water table conditions. These hypotheses could be tested by more detailed analysis of site topography and contributing areas, and by surveys of pipe and macropore densities (e.g. Holden and Burt 2002).

***Gully erosion significantly alters the temporal pattern of water table behaviour***

The data from the continuously logged dipwells (Section 5) show that intact sites in the Peak District peatlands show very similar temporal behaviour in water table conditions as observed in intact blanket peats in other regions, with water tables close to the ground surface except during periods of dry weather when gradual water table drawdown occurs. Rainfall results in rapid hydrological responses in these peats with water tables rising back to near the ground surface within a few hours. The pattern here is one of high water table conditions (typically < 100 mm depth) with occasional drawdown events. This is characteristic of blanket peat systems where specific yield (water storage) is low and even relatively small rainfall events can quickly re-charge water tables following prolonged dry weather (Evans *et al*. 1999). Water table behaviour in areas of heavily eroded peat is very different. Here water table conditions are generally very low (typically > 300 mm depth). Although dry weather leads to further water table drawdown, a key hydrological characteristic of these eroded peats is their ‘wet-up’ response to rainfall. Rainfall events result in rapid rises in water table, sometimes to the ground surface, followed by almost equally rapid declines in water tables after the cessation of rainfall. The pattern in these peats is therefore one of very low water table conditions with occasional ‘wet-up’ events which flush the upper (acrotelm) peat. The rapidity of the water table declines after rainfall suggests that these upper peat layers in eroded areas have much higher hydraulic conductivities than upper peats in intact areas, possibly due to the development of micro- or macro-pore networks following sustained water table drawdown.

Together with the observation of general water table lowering in eroded areas, the different temporal patterns in water table behaviour demonstrate the very different hydrological behaviours of eroded and intact peatland sites and have potential implications for the hydrological functioning of the peatland, including flow pathways and runoff generation from the peatland, and processes of water quality regulation including the production of acidity and colour / dissolved organic carbon (e.g. Clark *et al.* 2005, Daniels *et al.* 2008b).

***The topographic (wetness) index is a good predictor of water table conditions across the Peak District peatland landscape, but is a poor predictor of water table differences between the intact sites***

At the site scale there is a strong relationship between the wetness index and median water table depth (see Figure 15), confirming topography as a key control on water table variation across the peatland landscape. The strength of this relationship is due to the very long topographic gradient across sites in the calibration dataset, which includes a wide range of erosion and slope conditions. The index is clearly able to distinguish between sites with different erosion status, with the most heavily eroded sites having low water tables and wetness index values and intact sites having high water tables and wetness index values. Gully erosion has significant direct and indirect effects on local site topography. In particular it alters hydrological contributing area through diversion of flow into the gully systems, but it can also influence local site slope conditions. The correspondence between erosion, wetness index and water table conditions emphasises the distinct topographic conditions found at eroded sites, with corresponding effects on water tables.

Significantly, however, the index does not effectively represent water table variation between the intact sites (Figure 15). Water table variability between these sites is relatively low, with median site water tables consistently close to the ground surface (typically above 100 mm, see Table 7), but the index predicts significant differences in wetness conditions due to hillslope position. In particular, the index predicts much wetter conditions in the plateau / flat sites than at the hillslope sites. These patterns are not observed in the measured dataset. This suggests that the wetness index does not adequately represent the hydrology of intact areas of the peatland, and that topography is not the key control on water table conditions at these sites. The index was largely developed with reference to relatively large catchments with mineral soils (Beven & Kirkby 1979). Peat soils have low hydraulic conductivities, and the hillslope drainage characteristics of peat systems might therefore be expected to differ from large drainage basins dominated by mineral soils. In particular, if hillslope drainage in intact peatland areas is dominated by throughflow, and low hydraulic conductivities limit throughflow rates, hillslope drainage in intact areas of peatland would be impaired. Hydrological responses in such systems might not correspond to the model presented in Figure 14. Rather, hillslopes could be permanently saturated due to recharge from slow throughflow of water from upslope (hilltop and plateau locations). In this instance drawdown in dry weather would be more pronounced in water-shedding hilltop locations than on water-gathering slopes, and median water table conditions would be higher on hillslopes than at hilltop sites. The data presented in this report are consistent with this pattern, suggesting that slope is a less important control on water table conditions than hydrological contributing area.

These findings have very important implications. The topographic (wetness) index is increasingly being used to represent hydrological conditions in blanket peat systems and to help inform restoration practice (see Holden *et al.* 2004), and these applications assume the index adequately represents hydrological conditions at intact sites. Further work is needed to test this assumption before wider application of the index to blanket peat systems

***A simple empirical model can be developed to predict water table conditions in Peak District blanket peatlands***

We have developed and applied a simple, empirical model to predict spatial variation in median water table conditions for the Peak District peatlands. This model represents median water table depth at the site scale, and has been calibrated against sets of water table depth measurements collected during 2008. The model has relatively low residual standard errors in comparison to the between-site range of water table depth conditions, and we consider that it provides a realistic representation of variation in median water table depths across the peatland landscape. However, we describe it as a 'first-order' model to indicate that further model developments can be made and more comprehensive model validation is required, including the analysis of model uncertainty.

The model is based on a calibration of the wetness index against measured site water table data, modified to account for the effect of local gully edge water table drawdown. Evaluation of gully edge drawdown in different locations with different erosion types has shown a consistent pattern in terms of both spatial extent and magnitude of the drawdown effect (see Section 3). This provides confidence that the model contains a robust representation of this local effect of gully erosion on peatland water tables. In terms of the calibration of wetness index, as discussed in the previous paragraphs the index over-predicts water table depths at intact hillslope sites. This is turn leads to similar bias in the first-order model, although this has been reduced by the use of a polynomial relationship for model calibration. Nevertheless, further work is needed to refine the model calibration, in particular with reference to the distribution of uncertainty within the model and a comprehensive analysis of model performance across the full range of water table conditions (e.g. Freer *et al.* 2004).

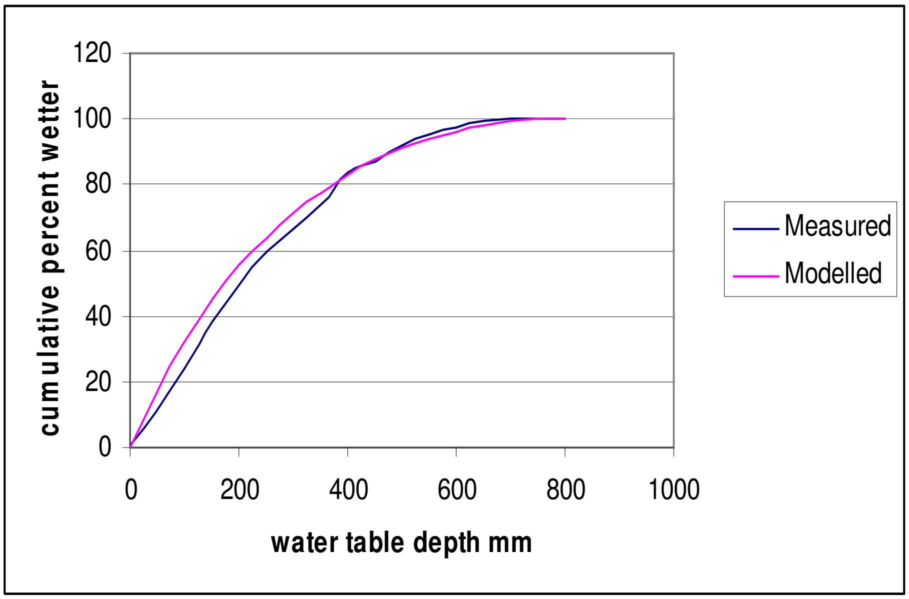


**Figure 25:** Distribution of modelled median water tables across the Peak District peatland landscape by pixel (n = 9,496,732) and measured median water table at the monitored dipwells (n = 536)

In terms of applying the model to the Peak District blanket peat landscape, a key potential weakness is that at the site scale it involves some extrapolation in water table prediction in the driest locations. The driest measured median water table for a calibration site is 451 mm at site K14 whereas the polynomial model predicts water tables deeper than 600 mm across significant areas of gullied peat. This difference is largely due to the addition of the gully edge drawdown effect to the wetness index calibration, but in order to assess the reasonableness of the extrapolation a cumulative frequency plot of modelled median water table for the whole study area (see Figures 22 and 23) was derived together with a similar plot derived from the median water table at each of the 536 individual dipwells measured during the monitoring period (Figure 25). The plot demonstrates that the distributions of the modelled and measured data are broadly comparable, although few measured dipwells are drier than 700 mm whereas 2% of modelled sites are in the range 700 - 800 mm. Nevertheless the cumulative frequency plots provide some confidence that the model is not grossly over- or under-predicting water tables, particularly as there are relatively few dipwells in gully edge locations and the measured dataset would be expected to under-represent extreme values at the landscape scale. Even in the relatively restricted gully transect data included in this study, several individual dipwells have mean water table depths below 600 mm and the lowest median water table measured for an entire gully edge zone (dipwells < 2 m from a gully) is

634 mm (transect NGM; see Figure 7). Consequently the model predictions at the driest sites are not considered unreasonable.

***Gully erosion has profoundly altered water table conditions across wide areas of the Peak District blanket peat landscape***

Application of the first-order model demonstrates the very significant effect of gully erosion on water tables on the Bleaklow and Kinder Scout Plateaux. Intact sites have median water tables higher than 150 mm (Table 7), and these conditions are consistent with observations of near surface water tables from intact blanket peats in other regions (e.g. Evans *et al.* 1999). Prior to erosion median water table depth might therefore have been expected to exceed 150 mm across the whole peatland landscape. Application of the model predicts that only 45% of the peatlands above 500 m altitude in the Kinder, the Upper Ashop and Bleaklow areas now have median water tables < 150 mm (see Figures 22, 23 and 25), and this figure excludes the area of gullies themselves, estimated as 25% of the 22.8 $km^2$ of the Bleaklow plateau (Evans and Lindsay in prep) and an even higher percentage of the Kinder plateau. Further, the model predicts median water table depths greater than 400 mm for 16% of the peatland area above 500 m (Figure 25), a figure which represents extremely low water table conditions with very significant changes to the peat hydrology (see Section 5).

These data emphasise the scale of water table lowering associated with gully erosion across the Peak District landscape. This will inevitably have resulted in profound changes to the functioning of the peatlands, including carbon sequestration, water quality regulation, runoff regulation and vegetation community composition.

***Preliminary data suggest that restoration of bare peat by re-vegetation raises water tables***

The comparisons of water table data from bare peat and restored sites indicate higher water table conditions at the restored sites, with mean site water table depths approximately 80 mm higher than at topographically comparable bare peat sites. The restored sites in this comparison have been re-vegetated using a combination of heather brash, grass seed, lime and fertilizer. These data therefore suggest that re-vegetation results in higher water table conditions, and contradict a commonly held assumption that vegetation will increase water loss through evapotranspiration. If the observations can be confirmed, they indicate a difference in the water balances of bare peat and re-vegetated sites. The most likely explanation would be an alteration in evapotranspiration rates i.e. that rates of evapotranspiration from re-vegetated peat are lower than rates of evaporation from bare peat. This is plausible given that the relatively low albedo (dark colour) of bare peat could enhance rates of evaporation. An alternative although more speculative explanation is that re-vegetation leads to physical changes in the upper layers of peat which alter hydrological conditions. For example, root penetration may lead to enhanced infiltration with corresponding increases in water tables.

Increasingly the raising of water tables is an explicit aim of peatland restoration projects, and in the Peak District considerable efforts have been made to evaluate gully blocking as a key strategy for raising peat water tables (Evans *et al.* 2004). The data presented here are therefore important, as they suggest that water tables can be raised by re-vegetation alone. This has significant implications for restoration strategy as well as for our understanding of hydrological and runoff generation processes in bare and restored systems. Crucially, however, the observations are based on data from only four sites and cannot be considered statistically significant. Further replication is required.

There is therefore a priority to (i) confirm the observations of higher water table conditions at restored sites and (ii) investigate the processes which result in this different hydrological behaviour at bare and re-vegetated sites.

## Further research priorities

Several important research questions follow from the pilot study work presented in this report.

*1. How reliable is the first-order water table model?*

Although this report has demonstrated that spatial variations in peatland water tables can be modelled at the landscape scale, further work is required to fully develop and validate the water table model. In particular, the measured dataset has not been fully exploited to address uncertainty in water table prediction. Water table measurements at the calibration sites included random replicate dipwells nested at two scales; site scale (30 x 30 m) and pixel scale (2 x 2 m). This design and the associated data provide a powerful opportunity to evaluate uncertainty in model predictions at a variety of scales; landscape, site and pixel. A model could also potentially be developed based on individual dipwell measurements rather than average site data to maximise the potential offered by the high resolution (2 x 2 m) Lidar data. Full model validation is also required using water table data which are independent from the calibration data. Such data are available both from within the current project and from other studies of the Peak District peatlands, such as the carbon (restoration) project funded by Natural England. These extensions of the modelling would require a further desk study.

*2. What are the causes of general water table lowering at eroded sites?*

A key finding has been the general water table lowering observed at eroded sites, an effect which is independent from the drawdown effect immediately adjacent to erosion gullies. The primary hypothesis for the site-scale effect is a reduction in hydrological contributing area. It is important to test this hypothesis, as this mechanism would result in significant differences in the processes of runoff generation at eroded and intact sites with further implications for water quality regulation (i.e. colour / DOC production). It would also mean that areas of eroded peatland potentially offer space-for-time analogies for water table lowering under scenarios of future climate change. The hypothesis can be relatively easily tested by a desk study based on further terrain analysis of the LiDAR dataset, in particular by focusing on the relationship between water table conditions and measures of hydrological contributing area at the study sites.

*3. What controls water table behaviour on peatland hillslopes?*

Another important finding has been the failure of the topographic (wetness) index to reliably predict water table conditions at intact hillslope sites. This has important implications for the use of topographically based models and terrain (LiDAR) analysis for water table prediction in blanket peat systems (see above). Further work is therefore needed to more fully characterise drainage and water table behaviour on intact hillslopes in order to refine the models. This would involve a field campaign to monitor water tables along a hillslope transect (catena) and associated desk analysis.

*4. Does restoration by re-vegetation really result in raised water tables?*

The observations of higher water tables conditions at restored (re-vegetated) sites compared to bare peat sites are potentially highly significant with implications for restoration strategy. However, they are based on comparisons from only four sites and therefore require replication before the effect can be confirmed. This would require a straightforward field campaign to measure water tables at a larger number of bare peat and re-vegetated sites, together with associated desk analysis.

5. *What effects does restoration have on run-off characteristics?*

In order to more fully understand the hydrological effects of restoration research on water table behaviour should be integrated with further hydrological monitoring, such as that associated with the Natural England carbon (restoration) project. This offers the possibility of a more comprehensive research programme to evaluate the hydrological functioning of these peatlands and the hydrological effects of restoration. This is important in order to establish the impact of restoration practice on flow generation and downstream runoff. The work would require a field programme to characterise water balances, including monitoring of water tables, flow generation and runoff. It would involve the evaluation of water table – runoff relationships and flow generation at different site types and characterisation of the hydrological behaviour of different peat systems (e.g. restored, bare, intact, managed), including water table drawdown and recharge characteristics and the relationships with runoff generation. Such work is a prerequisite for complete assessment of the hydrological benefits of moorland restoration.

*6. What are the impacts of water table drawdown on water quality?*

Water table conditions provide a key control on runoff water quality from peatlands, particularly dissolved organic carbon (colour) production and sulphate and nitrogen leaching (e.g. Daniels *et al.* 2008b). The range of water table conditions identified in this report allow evaluation of the relationship between water table lowering and water quality change through the use of isobasins (sub-catchments) with varying water table conditions. This would provide a space-for-time analogy for water quality change under future climate scenarios and restoration management. The research would involve a field campaign of water sampling at a range of flows with associated water quality determinations (colour / DOC, acidity, sulphate, nitrogen), together with desk analysis of the data.

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