THE ROLE OF MICROTOPOGRAPHY IN THE ASSESSMENT OF ECOLOGICAL CONDITION ON LOWLAND RAISED BOGS OF CONSERVATION IMPORTANCE

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Abstract

The principal aim of this thesis is to investigate relationships between the hydrology, ecology and vegetative microtopography of lowland raised mires, using data collected from two sites in Cumbria: Bolton Fell Moss and Walton Moss. The sites were chosen for study as they provided a contrast between the almost pristine condition of Walton Moss and the heavily modified Bolton Fell Moss, which has a long history of mechanised peat cutting. The study uses data collected from the two sites over a four year monitoring period between 2004 and 2007. Depth to water table data was obtained from five dipwell transects, complemented by seven automated loggers to provide temporal variation. A series of corresponding vegetation quadrats were established to inform ecological condition.

The applicability of using remotely sensed LiDAR data to determine bog hydro-ecological condition was considered. The variation in LiDAR spot heights in 20m^2 plots associated with the dipwells was used to provide an indicator of topographic variability at that location. Topographic variability was also directly measured by measuring spot heights across a corresponding 2m^2 plot using differential GPS surveying equipment.

It was established that although overall dGPS and LiDAR spot heights were very similar and that although in most cases there was a relationship between the two measures of microtopographic variation, the LiDAR data were more closely related to hydrological condition. An increase in microtopographic variation was, at the majority of quadrat locations, closely related to an increase in drier conditions, however this relationship was not consistent enough to provide a qualitative prediction of hydrological condition. This relationship was much clearer on Walton Moss, where the topography was not obscured by tree cover and had not been manipulated by management.

Canonical Correspondence Analysis was used to investigate if there were any specific vegetative components contributing to microtopographic change, but no strong associations emerged. It seems likely that

microtopographic variation within an area of raised bog is not principally dependent on NVC community, and that therefore drier conditions induce topographic change before the vegetation communities start to change. This has implications for the applicability of this methodology in preventing change in hydrological condition before ecological condition is damaged.

Only farmers and summer guests walk on the moss. What they don't know – and it cannot be repeated too often – is that moss is terribly frail. Step on it once and it rises the next time it rains. The second time, it doesn't rise back up. And the third time you step on moss, it dies.

Tove Jansson, The Summer Book

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My Wife, Kathryn

1 Introduction to the project

1.1 Principal objectives

This project investigates the relationships between hydrology, vegetation and surface micro-topography at two lowland raised bog sites in Northern England. In particular it investigates if changes in hydrological condition are reflected in changes to the surface micro-topography. If such change is detected, this project investigates whether this reflects a change in the nature of the vegetative communities or a change in the structure of otherwise similar communities.

This project also investigates the relationship between small scale surface micro-topographic variation measured directly using differential Global Positioning System surveying (dGPS) equipment over a $2m^2$ plot and the larger variation detected remotely, using Light Detection and Ranging (liDAR) data derived from an aerial survey, to determine if data from such remote sensing can be used to detect early change in the hydrological condition of these sites. It is intended that such methodologies will be used by site managers and statutory conservation agencies to help safeguard this fragile and internationally important habitat.

1.2 Aims of the investigation

- To investigate relationships between hydrology and vegetation in lowland raised bogs.
- To determine the effect of drainage on ecological condition.
- To determine how hydrology influences the development of such vegetation.
- To determine if hydrological change is a precursor to adverse change in ecological condition.
- To determine how vegetation relates to the topography of these areas.
- To develop a methodology for investigating whether LiDAR data obtained from aerial monitoring can be used to characterise small scale topographic variation on such sites.
- To obtain a representative ground truthed data set for comparison with the LiDAR data.
- To test the assertion that there are relationships between vegetation, hydrology and surface micro-topography.
- To determine if it is possible to use either LiDAR or ground based topographic data to predict early ecological change in lowland raised bogs before such change becomes a significant problem for site managers.

1.3 Introduction to bog hydrology

1.3.1 Ombrogenous mires

1.3.1.1 Origins and morphology

Ombrogenous mires are peat-forming wetlands where both water and nutrient supply are derived from atmospheric input alone (Lindsay, 1995). They form in regions of high rainfall and locally, in areas of impeded drainage. Mire development is dependent on conditions where precipitation, as the sole hydrological input, exceeds water losses through drainage or evapo-transpiration (Moore, 1995). Geographically, this limits mires to locations of high rainfall or humidity. Furthermore, it should be recognised that regularity of rainfall, as well as high annual total is an important requirement. As bogs are typically perched above the surrounding land forms (Hughes & Barber, 2004), water will be lost due to gravity, and high frequency of replenishment is necessary to maintain the saturated anaerobic conditions to promote the preservation and development of peat. In areas of high temperature such as the tropics, high humidity is also required to limit losses due to evaporation.

Ombrogenous mires are characterised by being both highly acidic and low in nutrients. This environment also reduces vegetation decay, which in turn leads to the accumulation of compressed, partly decomposed vegetation, or peat. In lowland raised mires, this process leads over time to the development of a characteristic shallow dome like topography. In upland blanket bogs, this development is not contained in a single basin, but overlies the features of the underlying geomorphology, as is implied by the terminology (Stoneman *et.al.*, 1997).

1.3.1.2 Geographical distribution

In practice, the factors producing peat limit mire locations globally (typically, but not exclusively) to some parts of the tropics, such as Kalimantan in Indonesia, and boreal regions of high rainfall, such as north western Europe and coastal areas of the northern USA and Canada (Lindsay, 1995), although Almquist-Jacobson & Foster (1995) suggest that low temperatures limit bog development and provide an effective northern limit to bog development.

In the United Kingdom, environmental conditions have limited bog development to the western areas of England and Wales, large areas of western and upland Scotland, and Northern Ireland, all areas of frequent and higher than average rainfall. Whickman (1951) suggested a minimum rainfall of 475mm is required for successful bog development, and whilst subsequent work by Backeus (1988) and Kirkby et. al. (1995) amongst others, indicate that this is an oversimplification, the fundamental requirement of high and frequent rainfall remains true.

1.4 Raised mires

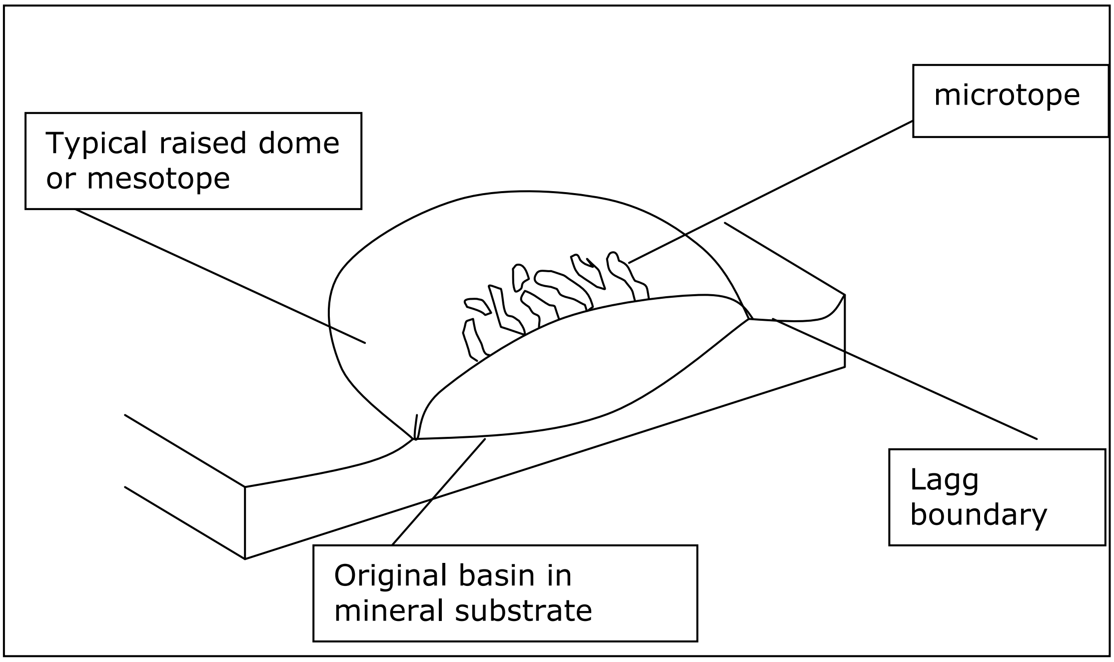
1.4.1 Conditions for raised mire development

Raised mires are formed exclusively from organic material, and in particular from the remains of S*phagnum spp. Sphagnum* is extremely tolerant of the acid conditions found in these sites, and is usually the most abundant genus found (Van Breeman, 1995). Typically mires form in impermeable basins in the British context, usually glacial till (Hughes and Barber, 2004). Because of the organic nature of the material, it is possible to date the origin of these sites very accurately using AMS carbon 14 dating (Yeloff *et.al.* 2006) and these indicate that most UK deposits began 3-5000 years ago.

Typically, raised bogs develop from the infilling of the lakes which form in depressions with emergent vegetation and the accumulation of fen peat. As this material rises above the level of the surrounding land, water supply becomes entirely ombrotrophic and a true raised bog begins to develop. In a true bog archetype, the bog will retain a mineratrophic lagg fen around the margin, but this is often incomplete or curtailed in reality by development or agricultural improvement (Hughes & Barber, 2004).

The typical raised mound profile shown in Figure 1.1 is a consequence of the deposition of recently dead plant material exceeding the decay of older matter. Charman (2002), based on work by Ivonov (1981) defines the bog mesotope as the distinct and separate raised bog mound isolated and surrounded by mineral soils, although it may be associated with other nearby raised bogs, such as is the case with the South Solway Mosses (JNCC,2008). Within the mesotope, Charman (2002) describes the microtope as an area of uniform plant cover and similar environmental features. The lagg boundary is the border between the raised bog mound, and the surrounding mineratrophic fen, referred to as the lagg fen (Lindsay, 1995).

Figure 1.1 Typical raised bog profile



Arrested decay also leads to very deep peat deposits, typically in excess of 10m (Hughes *et. al.*, 2000), depending on the length of deposition.

1.4.2 Hydrology

Ombrogeny is the underlying principle of raised bog ecology. All water inputs to a classical raised bog are derived from rainwater only, and this is the most significant factor in their low nutrient condition (Lindsay, 1995). The movement of water through a raised bog is governed by Darcy's Law, and is a function of the area of the bog, the hydraulic conductivity of the peat and the hydraulic gradient to the point where discharge is measured, and is usually expressed as:

Equation 1.1

$$Q=KIA$$

Where Q = discharge/ unit time, I = hydraulic gradient and K is a constant derived from the material water is moving through, in this instance, peat (Rycroft *et. al.*, 1975).

Rycroft *et. al.* note that this is a simplified situation, and that testing in the field and laboratory gives a range of values and may possibly indicate that some water movement through peat is non – Darcian. This has been explored further by others including Baird *et. al.* (2008) & Bromley *et. al.* (2004).

Given the high levels of water input, and that the peat matrix has very poor hydraulic conductivity (Ingram, 1982), this physical mound is mirrored by an equivalent water mound – in ideal conditions the peat is completely saturated, and the bog is composed primarily of rainwater, with only 2-5% peat solids. The groundwater mound theory proposed by Ingram (1982) suggests that the final form and height of this water mound (and therefore the physical form of the bog) is a function of the climatic conditions under which the bog exists and that any climatic changes will lead to a change in bog morphology.

Above the water mound, the peat is subject to wetting and drought, according to prevailing weather conditions. This material is aerated and biologically active, although the acidic conditions limit decomposition rates, and this upper zone is referred to as the acrotelm (Moore, 1989). It is typically less than 50cm in depth, although the boundary between what might be considered peat and what is still growing vegetation is blurred and impossible to identify accurately. The peat below this groundwater level is referred to as the catotelm and is permanently saturated, with low hydraulic conductivity and anaerobic conditions, although Baird *et. al.* (2008) note that there is still some water movement through this mass, which has implications when losses by throughflow are considered. The catotelm will slowly accrete over time as new material is deposited above, but there is little loss of water in favourable circumstances, maintaining anaerobic conditions. Drought or artificial drainage may, however, lead to oxidization rapid degradation of the upper layers of peat (Kechavarzi, 2007). Again, the boundary between the acrotelm and catotelm is not defined absolutely, rather there is a gradual increase in anaerobic condition, and biological activity decreases. At least in part, this is a consequence of the mobility of the water level, depending on drainage and meteorological conditions.

However, the notional raised water mound theory proposed by Ingram (1981) is still a useful, though simplified model. This concept suggests that the permanently saturated area within the peat mound or catotelm is determined by the equilibrium between discharge and seepage. Ingram suggested that the peat above the catotelm has a higher conductivity than the acrotelm and that lateral movement of rainwater occurred within this layer. In a healthy bog, the high water table means that majority of water lost from the site is via rapid overland or near surface flow (Bragg, 2002, Labadz *et. al.*, 2002).

Degraded bogs often have a higher conductivity rate due to degradation in the catotelm allowing open pores and piping to occur (Holden *et. al*., 2006). This is often enhanced artificially through drainage where the peat is being exploited commercially, both to improve the soil agriculturally, and to permit access by machinery. Conversely, where a bog is subject to ecological restoration, drains are usually blocked as a precursor to re-wetting (Schouten *et. al*, 2002). In addition compression of the perimeter has also been used to decrease conductivity of this peat and extend the time water is retained on site (van Seters & Price, 2002).

In addition to drainage of the bog, drainage of the adjacent land may also lead to degradation of the peat, as water levels in the peat are dragged down towards the lowered water tables in the adjacent drained land (Palejs, 2006). Where it is intended to protect or enhance the ecological condition of the bog, it may prove necessary to restrict drainage in adjacent land, in addition to the drainage of the bog proper. Work by the Environment Agency to determine the size of such Hydrological Protection Zones has cost implications for management as, unless the land is in the same or sympathetic ownership, it will be necessary to compensate adjacent landowners for income foregone (Morgan-Jones, 2005, Labadz *et. al*, 2006).

1.4.3 Ecology

The ecology of raised mires is one of extremes. Bogs are a habitat of extremely low nutrient levels, as all inputs are derived from rainwater, with no external mineratrophic input. A raised bog in good hydrological condition is an extremely wet habitat. As hydraulic conductivity is so low, the ground is subject to frequent inundation as rainwater cannot infiltrate the saturated ground and therefore runs off across the surface. These saturated anaerobic conditions give rise to very acidic soils, typically of pH 3.5-5.5 (Craft, 2001). Conversely, in times of drought, the surface may become extremely dry, although the water table may only be a few centimetres below ground surface (Worrall *et. al.*2007). The normal saturated conditions do not favour deep rooted plants and many of the plant species will not be able to access this lower groundwater and must therefore be able to accommodate such periods of drought. In addition, *Sphagnum* is better able to take advantage of limited nutrient availability than many of the vascular plants which are able to grow in these conditions, and therefore tends to dominate.(Malmer *et.al.*, 2003).

Conditions of saturated soils, periodic drought, low nutrient levels and low ph give rise to very specialised plant communities, which although limited in overall species diversity, are rare in both the UK and European contexts (Chapman *et.al* 2003, Charman, 2002). Such species tend to be specialists with specific adaptations to these conditions and therefore unable to adapt to changes in management such as drainage, agricultural improvement or peat extraction (Smith *et. al.*, 1995).

Typical communities of healthy raised bog comprise shallow rooted acid tolerant shrub species such as *Calluna vulgaris* and *Erica tetralix* co-dominant with bryophyte species, in particular *Spahgnum* species. The National Vegetation Classification recognises several such sub-communities within the overarching M18 *Erica tetralix- Sphagnum papillosum* raised and blanket mire community (Rodwell, 1991). By contrast fens, which are superficially similar, have a significant groundwater input and consequently usually have both a higher pH and greater nutrient inputs, leading to vegetation dominated by grasses, sedge and rush species, typically M23 *Juncus effusus / acutiflorus – Galium palustre* rush pasture community, rather than the *Calluna / Sphagnum* communities of raised bogs (Rodwell, 1991, Lindsay, 1995).

In ideal conditions, this will remain a relatively stable system, with peat gradually accreting and the profile of the bog slowly raising (Ingram, 1982). There may be occasional catastrophic bog bursts as a result of sudden water input from rainfall, resulting in the peat becoming unstable and liquefied peat flowing out from the bog, (Warburton *et. al*. , 2004) but these events are uncommon in healthy raised bogs. Unfavourable change is more likely to arise as a result of anthropogenic activity, primarily drainage for agricultural and peat extraction purposes (Holden *et. al*, 2004, Chapman *et.al* 2003). Such change can be slow and difficult to detect in early stages, but can in the longer term lead to dramatic changes in vegetation communities and a decline towards unfavourable ecological condition (wheeler and Shaw, 1995), although overall biodiversity may increase (Chapman *et. al*., 2003). "Unfavourable condition" is the term used by Natural England, the English statutory conservation agency, to classify sites which have deteriorated from the conditions likely to be encountered on an undamaged and undisturbed site (Natural England, 2008$_1$). As a consequence, most sites of recognised ecological importance, such as Sites of Special Scientific Interest (SSSIs) and Special Areas of Conservation (SACs) have regular and comprehensive monitoring programmes for hydrological and ecologicical condition. However such monitoring has been undertaken within the constraints of limited budgets. The historical context and purpose of such monitoring should also be considered, as priorities have changed as the science of bog ecology has become more completely understood.

1.4.4 Threats

Historically, raised mires have not been regarded as important, either scientifically, commercially or aesthetically, being land with no aesthetic landscape appeal and no obvious commercial potential. However this situation began to change in the latter eighteenth and early nineteenth centuries, when their commercial potential for agriculture and waste disposal was recognised (Joosten, 1985, Cruickshank *et.al*, 1995). As a resource in its own right, peat had been used a fuel in much of Ireland and upland Scotland, but in addition to this, the value of peat as a horticultural resource was also recognised, with peat production for this purpose becoming increasingly important in England in the twentieth century (SNH, 2003).

Peat extraction developed on an industrial scale as more effective drainage and engineering solutions became available. There was initially little consideration of ecological importance or preservation, and most subsequent ecological adverse change to these sites in much of the UK can be said to have its origin at this time (Cooper & McCann, 1995 Cruickshank *et. al.,* 1995). The degree of exploitation and agricultural improvement is, in part, related to accessibility to major population centres, and therefore sites in the midlands and the urban north of England, such as Thorne & Hadfield Moors or Fenns and Whixall Mosses (Smart *et. al.*,1986, Berry, 1997) initially underwent much more comprehensive degradation than similar sites in more remote areas, such as the Solway Mosses or Walton Moss in the north of Cumbria. However large scale industrial peat milling, together with improved national transport links meant these site were also subject to later exploitation, and it is these larger sites which were the subject of much domestic peat extraction in more recent times (Alexander *et. al.* 2008).

Ecological protection for such sites has often been made subject to existing mineral planning consents, which has resulted in peat extraction continuing, with the attendant consequential ecological degradation. In addition, until the middle part of the twentieth century, these sites were often still being improved through drainage and cultivation for productive agriculture.

In the later part of the twentieth century the rate of change of many of these sites was accelerated by use of peat in the new horticultural industries, which lead to a demand for peat extraction on a much greater scale than had happened previously (Stoneman *et.al.,* 1997). Technological innovations also led to new larger scale methods of peat extraction – in particular a change from hand cut ditches and baulks to mechanical surface milling. This increase in the rate of deterioration was, however coupled with an increased recognition of the ecological importance of these sites, leading in some cases to protective designation as SSSIs (Sites of Special Scientific Importance) or in exceptional cases, SACs (Special Areas for Conservation) (Natural England, 2001, 1986).

1.4.5 Conservation significance & legal protection

The ecological importance of raised mires can be seen in the context of several overarching conservation goals. Whilst historically, they have not been valued for aesthetic or ecological reasons, in more recent years, they have been recognised as important reserves of rare, primarily botanical, species (Lindsay, 1995). Statutory protection measures, principally designation as SSSIs, have been for their rare and distinctive botanical communities (for example, Natural England, 1985, 1986, 2001). In addition, they have been recognised as important for avian conservation with SPA (Special Protection Area) designation. Both SPA and SAC offer statutory protection derived from the UK's obligations to protect internationally important European species and habitats under the EC Directive on the Conservation of Wild Birds and the EC Habitats Directive, respectively (JNCC, 2009). In addition many such sites are recognised as being of global international importance and are protected under the Ramsar Convention on Wetlands of International Importance (Ramsar Convention Secretariat, 2009). Many of the individual plant and bird species are recognised as being vulnerable rarities in their own right and are listed in the JNCC red lists and have specific legislative protection through the Wildlife & Countryside Act 1983 and its successor legislation, the Countryside and Rights of Way Act 2000. Any changes of use, agricultural improvement or peat extraction is likely to require consent from both Defra and the relevant local planning authority. New activities which are likely to adversely affect intact sites are unlikely to be approved (Natural England 2008_2).

The situation pertaining to sites which have consents predating conservation designation, which is often the case with mineral rights, is less straightforward; regardless of the current protection, the right to exercise mineral extraction rights is preeminent. Historically, government conservation bodies (Natural England and its precursor bodies in the case of this study) have sought to mitigate works to protect remaining areas not subject to extraction or improvement, whilst not affecting current commercial activity (Cosgrove,2004). In recent times they have taken a more proactive approach, using public money to effectively buy out the mineral extraction rights before they are exhausted. This approach is expensive, and alternative benefits from spending elsewhere must be considered, however the EC directives place an additional obligation on the UK to protect these sites and habitats, with the possibility of punitive measures by the EU if the UK is found not to be taking reasonable steps (EU, 1992). Thus in the case of sites designated SACs or SPAs, financial intervention is considered appropriate. This has already happened at Wedholm Flow in Cumbria and the Humberhead Levels National Nature Reserve (NNR) in Lincolnshire (Natural England 2009). However, this is an inherently expensive option, with costs for Wedholme Flow and Thorne Moors given by Natural England at £17.3m and it is unlikely that this will be a widespread solution, and is unlikely to be applied to sites beyond those of the highest conservation importance (Natural England, 2009).

This distinction is important in the context of this research as one of the study areas at Bolton Fell Moss is about to be designated as an SAC as "a degraded raised bogs capable of natural regeneration" with the consequent requirement for proactive safeguarding through restriction or cessation of peat digging likely (William Sinclair Holdings, 2009).

Climate change studies have recognised the importance of peat in carbon storage and much recent research has been in the context of the role of both blanket and raised mires in carbon storage (Yu *et.al.*, 2001, Worrall *et.al*., 2007$_2$). In particular degraded bogs have been identified as a significant source of atmospheric carbon dioxide, and that, conversely, bogs in healthy condition act as carbon sinks, a fact indirectly recognised by previous generations in their use of peat as a fuel. This role in the wider global environmental context has the potential to make any research into the conservation of bogs even more important in an international context.

Bogs also contain an important paleo-climatic and paleo-ecological record. Peat cores have provided important information about pre-industrial climatic conditions, and also contain pollen records of plant species (Barber, 1993, McMullen *et.al.* 2004), not just those directly associated with the bog habitat itself, but also of windblown pollen from the surrounding region. The value of bogs for this purpose is also dependent on maintaining the saturated, anaerobic conditions of a healthy bog to prevent oxidation and decomposition of the peat and associated botanical material (Bragg, 2002).

1.5 Introduction to the Study sites

The criteria for the selection of these sites are discussed in detail in Chapter 4. The sites were selected for both pragmatic reasons and research necessity. The study required sites which were both in good ecological condition, but had a variety of management history. Walton Moss has suffered little historical damage beyond some minor agricultural management by grazing, whereas the area of Bolton Fell Moss used in this study has been highly impacted by human activity. The location of the study sites in the UK and their position relative to each other is shown in Figures 1.2 and 1.3. Because they were very close together, less than 2 kilometres at their closest point, they were subject to the same meteorological conditions. Both sites had pre-existing instrumentation and available data appropriate to this study, and Nottingham Trent University had an established working relationship with both English Nature and William Sinclair, the peat harvesting company. These combined factors made these sites an excellent pair for further investigation.

1.5.1 Walton Moss

Walton Moss is generally regarded as an excellent example of active raised bog (Natural England, 1985, Barber *et al.,* 2003). It is designated as a National Nature Reserve, (NNR), Site of Special Scientific Interest (SSSI) and Special Area for Conservation (SAC). The site is therefore of both national and international importance and has appropriate legal protection. The site has not undergone significant agricultural improvement or peat extraction and is considered to be amongst the best examples of this habitat in England (Natural England, 1985). Whilst the site does have evidence of both drainage and peat cutting, these have been, in the main, small scale and localised. It should be noted that there is a network of shallow herringbone pattern drains in the southern section, dug to improve the area for grazing (Natural England, 1985).

1.5.2 Bolton Fell Moss

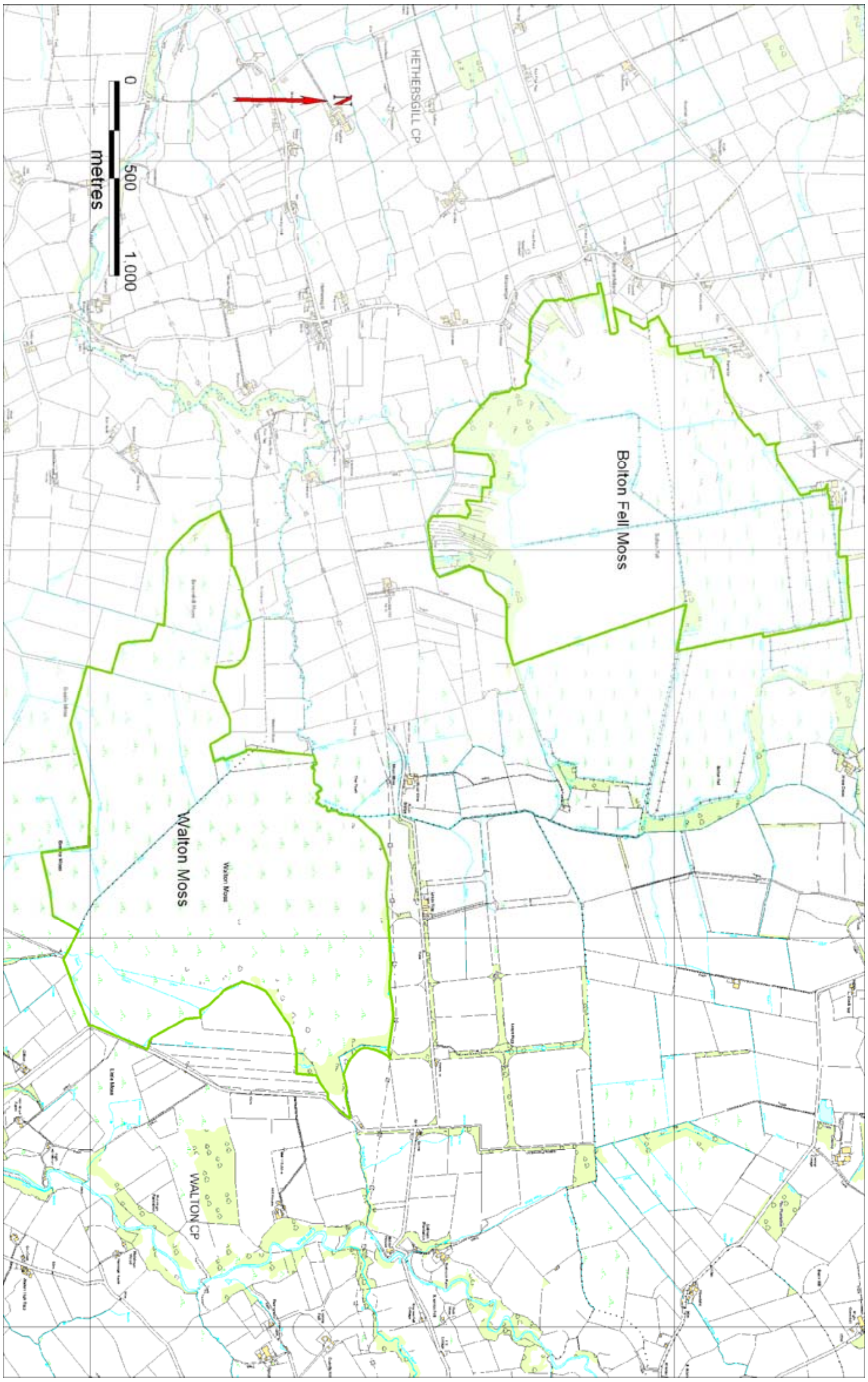
Bolton Fell Moss is also a SSSI. It is about to be designated as an SAC following a lengthy consultation (JNCC, 2009, William Sinclair Holdings, 2009). The site has an extensive depth of peat, although a significant proportion of this has been removed since 1959, when commercial scale peat extraction began (Labadz *et.al.*,2006).

The reserve area, which is part of this study, is a remnant of a much larger area of moss, probably continuous with Walton Moss. Extensive peat harvesting for the horticultural industry has reduced this area to a small island, surround on 3 sides by milled bare peat surfaces (Natural England, 2001). These areas are intensively drained to enable peat milling, and previous peat harvests have reduced the levels of these areas to well below the level of the reserve area, which has been retained as part of the peat extraction planning conditions and provides both an area of conservation importance, and a potential resource of appropriate habitat for restoring cut over areas when peat extraction has finished.

Both sites have a history of academic research, with work, notably by Barber *et.al.* (2003) on paleoclimate and paleoecology, Bragg (2001) on hydrological integrity and Labadz (2006) on hydrological conditions. The author has been collecting hydrological & ecological data on these sites from 2003 to 2008.

Figure 1.2 Location of Bolton and Walton Mosses in national context

Figure 1.3 Relative locations of Bolton Fell and Walton Mosses



2 Vegetation & ecology of raised bogs

2.1 Botanical communities of raised bogs

Raised Bogs are communities of limited diversity (Couwenberg and Joosten (2005). The species within the communities are defined by their ability to thrive in hostile conditions with extremes of moisture, high acidity and low nutrient levels (Lindsay, 1995). Such species are often unable to compete in more moderate environments and therefore are often limited to other habitats of similar conditions, such as blanket bog or mineratrophic fen. As these habitats have become increasingly uncommon, due to factors such as agriculture and peat extraction outlined in section 1.4.4, so the constituent species have become uncommon. Thus, whilst not a particularly biodiverse habitat, many of the species which are present are considered scarce and important in the context of UK conservation (JNCC, 1999).

Typically raised bogs are of the National Vegetation Classification (NVC) M18 *Erica tetralix- Sphagnum papillosum* raised mire group (Rodwell 1991). The dominant vascular plants of raised bog are typically *Erica tetralix, Calluna vulgaris and Eriophorum vaginatum* over a carpet of lower plants, principally *Sphagnum spp*, but also including other species such as *Cladonia* and *Hypnum spp.* In addition there are several notable grasses and sedges. Of particular interest in the context of this study are *Eriophorum Vaginitum* and *E. Angustifolium* (Phillips, 1953), together with *Mollinea Caerulea* as these are potentially important species in the development of vegetative topography (Malmer *et.al*. 1994).

Notable minor species include *Andromeda polifolia, Empetrum nigrum, Drosera rotundifolia, Narthecium ossifragum, Vaccinium oxycoccus* and *Vaccinium myrtillus* (Rodwell 1991). It is usual that 1m quadrats will only contain a handful of species; however it is likely that *all* of these species will be uncommon in the British context (Shaw and Wheeler, 1995). Therefore this habitat has become a priority for UK conservation authorities and good examples all benefit from legal protection as SSSIs (JNCC, 1999). It is an indication of the importance and rarity of the habitat that many damaged, degraded or partially destroyed sites are also given high levels of protection (McCloud *et. al.,* 2005), and that the management of such sites is intended to arrest such degradation and restore them where possible to their former condition. This is usually through a process of ending potentially damaging management, notably drainage and peat extraction together with improving the hydrological regime to restore the high ground water levels and predominantly wet conditions favoured by *Sphagnum spp.* and associated species (Shaw and Wheeler, 1995, Schouten *et.al.,* 2002). *Sphagnum* can be described as a bog building species, in that it contributes to the accretion of peat and therefore to the mass of the raised bog. Of the vascular plants *Eriophorum sp* also makes a similar contribution and both species are constant in the paleoecological record (Barber, 1993).

2.1.1 Importance of *Sphagnum* to bog ecology

Sphagnum has been identified as a key species in the ecology of raised bogs and will have been essential to the development of the bog historically (Barber, 1993), but it is not always abundant in the current vegetation communities, particularly where there has been significant change due to management or wider changes in the hydrological conditions (McMullen *et.al. 2004).* In many areas of upland blanket bog, live *Sphagnum* is an unusual occurrence away from bog pools, and similarly in raised bogs, *Sphagnum* is not always present in dryer or revegetating areas (Cooper *et.al*. 2001, JNCC,1999). The re-establishment of sphagnum communities has also been a particular concern of those investigating restoration of bogs as restoration of hydrological regime alone seems insufficient to ensure the development of typical sphagnum communities where they have been lost (Cooper *et.al*. 2001, Meade,1992, Chirino *et. al.* 2006). Where *Sphagnum* is present or has been re-established, the diversity of species is often much lower, and the different species are not as widespread across the whole area (Cooper *et. al.* 2001, Meade, 1992). This suggests that it is important to prevent loss of *Sphagnum* and *Sphagnum* species initially, rather than relying on the success of subsequent restoration projects.

The difficulties of re-establishing *Sphagnum* after drainage and peat cutting have implications for those working on conservation of raised bogs which are currently being exploited for horticultural peat, and supports Natural England's policy of stopping or limiting the extent of peat exploitation on those sites which still have typical *Sphagnum* communities, such as is the case at Bolton Fell Moss. William Sinclair Holdings announced in August 2008 that Bolton Fell Moss had been submitted to the EU for consideration as an SAC (Kee, 2008, William Sinclair Holdings, 2009). William Sinclair Holdings are currently negotiating with Natural England over compensation for production foregone as a consequence of this designation. The European Union requires the UK to take action to safeguard such sites under the Habitats Directive from further exploitation if they are still of sufficient quality to be designated as SACs, as is the case at Bolton Fell Moss (Brown *et. al.* 1997). In practice, this means Natural England are likely to compensate William Sinclair Holdings for loss of income from the site, effectively buying out the mineral rights, as was the case at Wedholme Flow and Thorne and Hadfield Moors (Natural England, 2004).

Superficially, bogs of differing ecological quality may appear very similar, as many of the key species, notably S*phagnum spp.*, tend to occur as a sub-layer to the vascular plants (Large, 2001), thus both sites in good and degraded condition might be expected to have a vascular plant community mainly comprising *Eriophorum sp*. with *Vaccinium myrtillus* and *Calluna vulgaris/ Erica tetralix* (Rodwell, 1991). The difference between a good example of healthy raised bog, and a site which is either degraded or which has been damaged in the past is that degraded communities are likely to have fewer of the minority species such as *Narthecium ossifragum*, *Vaccinum oxococcus* or *Scirpus cespitosa*. The mosses below these species are also likely to be less diverse, and may also have a higher proportion of non Sphagnum lower plants such as *Cladonia, Hypnum sp.* and especially *Polytrichum commune* (Money & Wheeler, 1999).

Nungesser (2003) observed that *Sphagnum* development is a key factor in bog microtopography, as it tends to develop a distinctive hummocked landscape. Under different hydrological conditions, vegetation communities can change, and even where there is no overall loss of *Sphagna* the species composition is likely to change, as different species favour different hydrological conditions (Weltzin *et. al.* 2001, Roebroek *et.al*. 2007), therefore it is possible that degraded bog vegetation may develop a different morphology (Roebroek *et.al*. 2007).

Polytrichum commune makes superficially similar large hummocks in the topography, but is a species which is less important in the development of bogs and is often an indicator of degrading bog (Laitinen *et. al.* 2008). It has a much more open habit (Watson,1981) and it is this insubstantial nature that makes it less significant to defining surface topography. It is therefore important to differentiate the more substantial topography related to Sphagnum from the apparent vegetation surface derived from *Polytrichum* and other loose structured vegetation surface, such as the canopy of woody shrubs like *Erica tetralix* or *Calluna vulgaris*. This is a straightforward operation to do on site as any physical measurement device, such as a ruler or survey staff passes easily through the open structure to the actual vegetation surface, but difficulty may arise when using any form of optic remote sensing, which does not easily differentiate the *density* of the vegetation (Hopkinson *et.al.* 2005). It is common to use vegetation stripping algorithms in conjunction with remote sensing methodologies, but this study investigates the topography resulting from the vegetation and therefore such techniques require consideration as to their appropriateness in this circumstance.

It should be remembered that subtle differences in bog microtopography may be obscured by larger scale changes as a consequence of topographic change due to peat extraction (Smart *et. al.*, 1986). It is also important to differentiate topographic change as a consequence of vegetation difference from topographic variation as a result of differential peat accumulation

(Belyea & Clymo, 2001). In particular, larger scale changes may be the result of the characteristic baulk and ditch method of peat cutting (Smart *et. al.* 1986). These works are in some cases quite old, dating from the early part of the 20th century and subsequent erosion and revegetation may obscure them from superficial inspection. It is therefore important to be aware of management history when considering any analysis of topographic variation, particularly if using data gathered using remote sensing technology, where there can be no first hand investigation of the landforms (Rockall *et. al.* 2008).

2.1.2 Other botanical communities associated with raised bog

Typical raised bog communities do not occur uniformly and in isolation (Rodwell, 1991). Vegetation community change can be observed along a notional transect from the centre of a typical raised bog to the perimeter of the site. Although no two bogs are identical, some general patterns can be observed.(Cowenberg & Joosten, 2005) The lower sections of the bog dome toward the perimeter may be drier, and the vegetation may include more grass species, such as *Molinea caerulia,* and the ratio of *Eriophorum vaginatum* and Eriophorum *angustifolium* may also differ as the two species have differing hydrological preferences (Gebauer *et.al.* 1995). Numbers of bog specialists in any one quadrat such as *Narthecium ossifragum* and *Vaccinium oxycoccus* may reduce and are likely to be replaced by *Vaccinium myrtillus*, although both species are found in a wide range of hydrological conditions (Smith *et.al.*, 1995).

In addition to change within the raised bog area, a lagg fen can normally be observed along the perimeter of the site where a more mineratrophic M23 community has developed. This is described in section 1.4 and illustrated in Figure 1.1. In part this is a consequence of mineral leaching from the raised bog element (Hughes, 2002, Barber, 1993). This fen may also include a lagg stream, a watercourse which may develops to drain runoff. The lagg fenn community differs in that it often has a higher pH and greater nutrient levels, compared to those found on the main part of the raised bog dome. This often leads to a more diverse community in the lagg fen area, typically including *Juncus* species, fewer *Sphagna* and a more diverse collection of higher plants (Lindsay, 1995). Although still a marsh community, it is likely to have a more variable hydrological regime and therefore greater aerobic activity in the soil micro-organisms, leading to more complete decomposition. As a consequence, peat does not form as readily from this material (Robichaud & Begin, 2009).

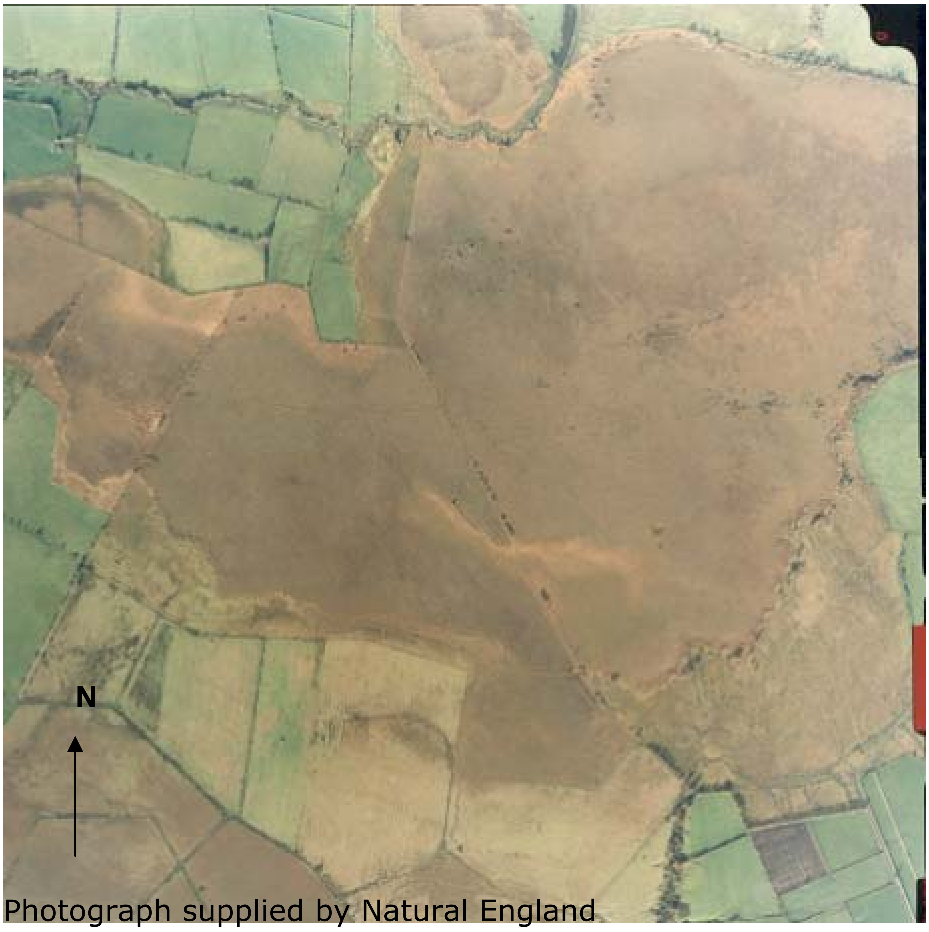
In an uninterrupted natural succession, the lagg fen might be expected to transition to a woodland or grassland habitat, still damp, but more freely draining, and this peripheral wetland would provide a buffer to maintain the saturated conditions required for continued bog development (Morgan-Jones *et.al.*, 2005). In contemporary conditions, it is likely that such land has now been developed for agriculture or other commercial activity, and that therefore the bog boundary is more abrupt (Cooper and McCann, 1995). It is also possible that any lagg fen has also been developed. In these circumstances, the perimeter of the bog itself may have become much drier and the typical mire communities will have changed to something more closely approximating M20b degraded mire or M23 rush pasture community (Rodwell, 1991). Given the importance of all mire communities in the UK national and international context, this degradation of the bog perimeter is of concern to ecologists, and various strategies have been developed to maintain sites' ecological integrity. These are primarily methods to manage the hydrological conditions of the perimeter and are discussed in chapter 3.

2.2 Site management

2.2.1 Agricultural management

Typically raised bogs have not been intensively managed for agriculture. Where they have, this has usually resulted in their destruction as mire communities, therefore, of necessity; remaining raised bogs in good condition have been subject to little or no management beyond small scale peat cutting and low levels of grazing. Agricultural management of raised bogs is inevitably concerned with drainage. In the English midlands, this has resulted in the complete destruction of some areas of raised bog as a viable ecosystem, leaving only damaged remnants (Lindsay & Immirizi, 1996). Most remaining areas of bog show some form of drainage history (Smith *et. al.* 1995), even if the bog has been used primarily as grazing land, as livestock will gain condition quicker on the grass species drainage will favour over the bog specialists. In addition, permanently saturated conditions can lead to health problems in livestock, such as foot rot and liver fluke (GAP, 2001). Therefore drainage is a precursor to any serious agricultural improvement. Although there has not been much attempt at improvement at Walton Moss, drainage grips dating from the 1980s are visible on the aerial photograph in Figure 2.2. The effectiveness of these grips was the primary focus of the Labadz and Butcher (2006) study for Natural England. Walton Moss is registered common land, with grazing rights assigned to local agricultural holdings (Defra, 2008). These rights are exercised, with year round low intensity grazing by cattle and sheep. In addition to agricultural livestock, the site is also grazed by small groups of roe deer (*Capreolus capreolus*) and brown hare (*Lepus europaeus*) which are also present at Bolton Fell Moss, but which has no agricultural grazing (Natural England, 1985, 2001).

Figure 2.1 Arial photograph of Walton moss



2.2.2 Grazing by domestic and wild animals

Grazing has not proved to be a major concern on sites with a history of extensive low input management (Smith, 1995, Segerstrom and Emanuelsson, 2002). There is a history of common grazing rights on such sites, and although there are difficulties in regulating the number of animals on site in such circumstances where there may be multiple graziers (Short and Winter, 1999), the low quality of the sward and the associated potential animal health issues make overgrazing and high livestock numbers unlikely, although undergrazing has also been identified as a potential problem for such sites (Williams, 2006)). Numbers of wild animals on the study sites described in section 1.5 currently appear to be low. Hostile conditions, and the relatively low nutritional value of the sward deter high numbers of animals, although its remoteness and inaccessibility to predators and disturbance do make the site more attractive to wild herbivores (Pellerin *et.al*, 2006). Often such sites are used for shooting, as is the case at Walton Moss, which may be a factor in reducing numbers of game species, but there are no records of the deer on Walton Fell Moss being managed in this way.

Such activity would now require the temporary closure of Walton Moss to public access. As registered common land, Walton Moss is designated as Access Land under the Countryside and Rights of Way Act, 2001 (Defra,2008). This potentially allows the public almost unrestricted access to the bog surface, which could have implications for the vegetation and erosion of the surface micro-topography. In practice, the remote location of the site, together with the absence of paths and the difficulty of the terrain, make the site very lightly used for recreational access. The only paths apparent are those of the land manager and field researchers for this project (Natural England, 2002).

In general, grazing tends to be heavier on drier areas, and increased attractiveness to grazing animals is another biological indicator of a lowered water table (Bragg & Tallis, 2001). Intensity of grazing may be monitored at the same time as other botanical recording and can be assessed using a subjective grazing index on a scale of 1-5 (Hill *et. al.*, 2005), with no grazing recorded as 1 and intensive grazing, leading to the loss of fruits and flower heads and a shortened sward recorded as 5. It is also prudent to record sward height, which may also give an indication of grazing intensity, although other environmental conditions may also contribute.

2.2.3 Peat Extraction

Vegetation can be destroyed by large scale peat milling, as is practiced at Bolton Fell Moss. By the nature of the operation, modern peat extraction completely removes the surface vegetation and subsequent re-vegetation and restoration of these areas has relied on translocation or re-colonisation from intact areas (Alexander *et. al*., 2008), as is being undertaken at Wedholme Flow (Natural England, 2009). Such re-vegetation is outside the scope of this study, however it is a pertinent point to consider as it is hoped that the intact area of Bolton Fell Moss which does comprise part of this study will be available as a donor site for the re-vegetation of the much larger cut over area of Bolton Fell. Similarly other areas of remnant bog may provide similar reservoirs for other restoration projects .

Many raised bogs have areas where historical peat cutting has occurred. Often these sites have a long history of peat digging, and this can result in a variety of different botanical and hydrological conditions (Wheeler & Shaw, 1995). Manual cutting often results in a distinctive baulk and ditch topography, both of which have distinctive vegetation communities, with dryer, *Eriophorum* dominated communities developing on the baulks, with the ditches developing a variety of communities, depending on wider hydrological conditions of the site (Smart *et.al*. 1986), ranging from open water & bog pool communities where the ambient water levels are sufficiently high, through to drier communities similar to those found on the baulks, where water levels have been drawn down across the whole site.

In the context of this study, which investigates surface microtopography and vegetation communities, areas of peat cutting present distinct problems for microtopographic assessment. In these instances any variation or subtle differences in topography which may occur due to change in vegetation species or habit will be lost in the coarser topographic changes as a consequence of the excavations. Whilst it is straightforward to determine these characteristics on the ground, the coarser resolution of remote sensing methods may not be able to differentiate such fine scale differences in topography due to natural condition from larger scale artificial changes. Detection of such gross changes from natural surface is more straightforward and has been used recently in assessing the conservation value of larger areas of habitat which may contain areas of uncut raised bog (Anderson *et. al.* 2009).

2.2.4 Conservation activities

As discussed in Section 1.4.3, raised bog is of the highest value in nature conservation terms and has a high level of statutory protection. The importance of degraded or destroyed sites is much less clear, although it often still has statutory protection reflecting the potential for recovery (JNCC, 2009). This is reflected in the fact that many ostensibly destroyed sites have SSSI designation, as is the case at Bolton Fell Moss. Such protection does not enhance site protection when planning consents predate the designation, meaning that many sites recognised for the importance of their botanical communities continue to be drained and such vegetation destroyed for peat extraction (Smart *et. al,* 1986). In some cases, this is recognised by government and the damage recognised as practically irreversible and the SSSI designation is subsequently removed (Tucker *et. al.*, 2004).

This situation is more complex where a site is proposed as a SAC. In the case of SAC designation, there is a requirement that the EU member government take steps to ensure the continued protection of such sites from further damage and to ensure their subsequent restoration (European Union, 1992). To date, this has resulted in the statutory conservation agencies (in the case of Bolton Fell Moss, Natural England and its predecessor bodies), buying out, or compensating the holders of mineral rights in order to cease mineral extraction (Alexander *et. al*. 2008). This has happened at several other such SACs, notably Wedholm Flow, Thorne and Hadfield Moors and Fenns & Whixall Mosses (Natural England, 2004).

Bolton Fell Moss was not originally intended for designation, but it seemed likely that unless it was, Britain would not fulfil its obligation under the Habitats Directive for the preservation of degraded raised bog and faced possible referral to the European Court of Justice and subsequent fines (Kee, 2008).

Such re-designation has potentialy serious economic repercussions as the value of unexploited peat may be high, and local communities may also suffer with the closure of a local employer, so the importance of ecological gain has to be considered against social and economic losses (Alexander *et. al.* 2008, Kee, 2008). However, such considerations are outwith the scope of this study. As Bolton Fell Moss has only recently been confirmed by the UK government as a candidate SAC for designation by the EU, it is yet to be seen how the protection of this site will be ensured, though it seems likely that some form of reduction or curtailment of peat production is inevitable (Kee, 2008).

Where ongoing extraction or agriculture continues adjacent to protected mire, this can have potential consequences for the eco-hydrology of the site. Work by Ingram (1967) and more recent work by Holden *et. al.* (2004, 2006), Bromley *et. al*. (2004), Baird *et. al*. (2008) and others has shown that groundwater levels peat can be significantly drawn down by drainage of adjacent land. For smaller fragments, such as the reserve area at Bolton Fell Moss, this may affect a significant proportion of the site. Therefore it is important to consider how to mitigate this effect.

Such mitigation concentrates on retaining water within the site, either by reducing drainage from the site, or reducing the hydraulic gradient by raising water levels in adjacent land (Lindsay, 1995). Reducing outflow is usually achieved by impeding drainage, usually by blocking drains on the perimeter or reducing hydraulic conductivity of the boundary through compaction. Natural England has commissioned work on the protection of sites through maintaining Hydrological Protection Zones of raised water levels and impeded land around sites perimeters (Morgan Jones *et. al*. 2005). These alternatives are discussed in more detail in Chapter 3.

2.3 Indicators of vegetation community change

2.3.1 Conditions for sphagnum development and relative species abundance

Several researchers, including Price & Whitehead (2004) & Weltzin *et.al*. (2001) have shown that although the gross cover of sphagnum may remain constant despite change in hydrological condition, the species composition within a study area is likely to change. Individual *Sphagnum* species show distinct preferences for different hydrological conditions, and also have different morphological characteristics (Nungesser, 2003), potentially contributing to change in the topography of the bog surface. Many of the species which prefer wetter conditions, such as *Sphagnum cuspidatum* do not demonstrate the hummock forming characteristics of other species. Conversely, the sphagna which prefer drier conditions, such as *Sphagnum capillifolium* are more likely to form hummocks, which themselves will provide drier conditions (Guinan *et. al.*, 1998 Roebroek, 2007).

In a typical healthy raised bog, an equilibrium is likely to occur with a relative balance of sphagnum species with differing hydrological requirements. If a change in hydrological conditions occurs, this proportion is likely to change (Tantram *et.al*., 1999). Typically such change is due to anthropogenic activity, such as drainage and results in drier conditions, and so favours the hummock forming species. Given that development of hummocks produces locally higher, and therefore drier, areas, such topography tends to remain extant, even if hydrological conditions revert to a wetter regime, as the hummocks will remain higher above the groundwater levels (Nungesser, 2003), although such conditions would not favour new hummock development. Therefore it is possible that such topography could be an indicator of past change, rather than current conditions.

2.3.2 Indications of community change from other species

It is also important to consider that such changes do not happen in isolation. Like any vegetation community, changes are not restricted to one or two species. In addition to changes in *Sphagnum* species abundance , communities of higher plants are also likely to change, with species such as *Vaccinium myrtillus* and *Calluna vulgaris* increasing at the expense of *Vaccinium oxycoccus* and *Erica tetralix* (Guinan *et. al.* 1998). Both *V. Myrtillus* and the ericaceous species are also likely to contribute to micro-topographic development. Change in proportion of species does not necessarily lead to micro-topographic change, either. The low and insubstantial habit of *V. oxycoccus* and the open nature of plants such as *Narthecium ossifragum* do not materially affect measured topography, so change in micro-topography is only one element of measurable change.

The effects of tree colonisation on bog vegetation communities are well known and recorded . In particular, *Betula pendula* is an early coloniser of bogs with a low water table, and once established its continued colonisation is hard to limit with increased wetness alone (Tomassen *et. al.* 2003). As birch produces a large volume of viable seed, once it has established under drier conditions, it is perhaps able to continue to propagate itself, even under wetter conditions. Mature birch are able to locally draw down the water table and areas of denser birch will have a significant contribution to the drying out of raised mires, particularly if they are combined with other existing drainage (Money and wheeler, 1999). In addition, leaf litter will contribute to localised nutrient enrichment, which benefits species such as *Betula* and *Molinea* over bryophytes(Thomasson *et.al*, 2003) and the root complex will further break down and assist with oxidization of the deeper peat catotelm (Lindsay, 1995). Removal of tree species can be undertaken by hand at an early stage of development, but is more difficult as the trees mature, due to the necessity of heavy equipment to remove the trunks. The presence of trees, particularly in number, also make any remote sensing of bog surface difficult, and whilst it is possible to counter these effects at a coarse scale using post measurement algorithms (Hill and Thomson, 2005), finer surface detail will be lost, together with any measurements or classification of sub arboreal surface vegetation dependant on direct surface measurements, such as determining vegetation cover using false colour satellite or aerial photography images (Mehner *et.al.*, 2005, Hopkinson *et. al.*, 2005).

2.3.3 Implications of species loss for restoration of degraded raised bog

As bogs, by their nature, tend to be isolated sites, many of the problems of re-colonisation common to other habitats and species are also experienced. Thus once key species are lost, it is unlikely that they will reappear without management intervention. Other raised bog sites do not, for example, share the diversity of *Sphagna* found at Walton Moss and Bolton Fell (Money & Wheeler, 1996). Whilst other issues, such as environmental pollution, notably nitrate deposition, may also be important in limiting the number of species found at a site (Moore 2002), anthropogenic trauma such as drainage or peat harvesting are critical factors in plant species loss (Soro *et. al*, 1999, Stoneman *et. al.*, 1997). With no nearby communities to re-colonise these species, increasing diversity may have to rely on human intervention, with the attendant difficulties of determining acceptable provenance of donor plants and wider considerations of sustainability (Bullock *et. al*. 1996). Many sites have also undergone dramatic land use change (Money and Wheeler, 1996), such as agricultural improvement, which have completely changed or destroyed the vegetation communities and are therefore out with the scope of this study.

It is with these matters in mind that the importance of preserving the area of uncut bog at Bolton Fell is recognised, particularly in the light of the SAC designation and the raised priority of its restoration. It is envisaged by Natural England that this area may be used as a reservoir of bog species for restoration, once, and if, appropriate hydro-ecological conditions have been achieved in the cut over area (Kee, 2008).

2.4 Alternatives to restoration to active raised bog

If left without intervention, bogs with artificially lowered hydrological regimes tend to move towards a heathland community such as NVC M15 *Scirpus-cespitosus- Erica tetralix* wet heath (Elkington *et. al.*, 2001), with fewer lower plants, and more sedge / grasses in evidence . This can be seen on many of the degraded bogs referred, such as Fenns and Whixhall Mosses and areas of the Solway Basin (Money and Wheeler, 1996). It should also be recognised that conservation priorities are not exclusively concerned with restoring habitats to their original state. For example, the RSPB have restored peat flats to wetlands suitable for wading birds on some areas of cutover peat, where the ecological gains and practical achievability of this form of habitat are judged greater than those of bog restoration (RSPB, 2008).

Many attempted restorations have produced ecologically interesting and valuable wetlands, but have not been able to achieve the necessary sphagnum re-colonisation necessary for the re-establishment of active bog (Rochefort, Gauthier and Lequéré. 1995). In particular, *Eriophorum spp.* are quick to establish, and depending on what, if any, mineratrophic inputs have developed as a consequence of altered hydrology *Juncus* species and *Polytrichum commune* may also be early colonisers (Laitinen *et.al,* 2008). This is often a good habitat for other animal species, especially for wetland birds, but without the intrinsic value and rarity of raised bog.

3 Meteorology and hydrological conditions

3.1 Hydrological conditions required for the development and maintenance of ombrogenous mires

As described in section 1.1.1, ombrogenous mires are entirely dependent on maintaining high groundwater conditions with water input derived exclusively from rainfall. This limits their distribution to areas which typically receive over 800-1000mm rainfall annually (Charman, 2002). In addition a positive water balance is required in order to maintain favourable peat development conditions. Equation 3.1 describes how water balance is explained (van der Schaaf, 2002).

Equation 3.1 $P+E+Qh+Qv+\Delta S=0$

Where
P = precipitation
E = evapo-transpiration
Qh = horizontal flow
Qv = vertical flow
ΔS = change in water storage

To achieve a positive water balance, losses due to drainage or evapo-transpiration must not exceed rainfall inputs. This suggests that cooler climatic conditions and frequent rainfall throughout the year will be more beneficial than infrequent but heavy rainfall in a drier climate (Charman, 2002). The oceanic climate of north western Europe fits these criteria and restricts their occurrence further south and east where a more continental climate prevails, although again, there are exceptions due to local topographic induced climatic variations (Ortu *et. al.* 2003).

In the UK context this generally confines ombrogenous mires to areas in the north and west (Lindsay, 1995). There are some notable exceptions to this, notably Thorne and Hatfield Moors in Lincolnshire and South Yorkshire. It is possible that such sites formed under wetter conditions, and suggests that climatic conditions required for maintaining raised bogs may be drier than those required for formation, providing water is effectively retained on site (Smart *et. al.* 1986). It is also probable that sites such as Thorne and Hatfield have an element of mineratrophic water input.

Notwithstanding these factors, the UK now has a generally drier climate than during the period of mire formation (Barber *et.al.* 2003, Dumayne-Peaty & Barber, 1998). As sites such as Walton Moss appear to be continuing to thrive, this suggests that retaining water is at least as critical to maintaining good hydrological condition as continued high rainwater inputs and that this becomes more important when climatic conditions are more marginal (Holden *et.al*, 2006, Laitinen *et.al*., 2008).

3.2 Spatial variation in hydrology

Within a single site, there are often significant variations in hydrological conditions. There are several factors which may contribute towards this situation.

Hydrological conditions are dependent on a number of factors relating to both the living vegetation and the properties of the peat beneath. Both of these can be expected to display significant spatial variation and, given that the latter is derived from the former, are to an extent inter-related (Van der Schaaf, 2002). Different *Sphagnum* mosses have differing water retention properties, and water retention within the live vegetation above the peat forming zone will also be affected by both the amount and composition of the S*phagnum* and the other plant species found at that location (Price *& Whitehead,* 2004, Robroek *et.al,* 2007_2). For example, Farrick & Price (2009) highlight the role of ericaceous shrubs in drawing down water levels and preventing *Sphagnum* growth on raised bogs where water levels are affected by drainage. Conversely van Breeman (1995) highlights how *Sphagnum* can manipulate the local environment to disadvantage other plants.

The hydraulic conductivity of the underlying peat, although generally low, is dependent on several variables (Bromley *et. al,* 2004), including the nature of the plant material the peat is derived from and past hydrological conditions. The gradient of the bog surface also influences the rate of flow, Q in Equation 1.2, discussed in Section1.4.2. Thus the rate of loss of water from a raised bog is a function of gradient and soil type. However, the size of the site under consideration is also an important consideration, as many of the factors affecting hydrology may be described as edge effects (Baird *et. al., 2008)*, and are influenced by adjacent management and the nature of the bog boundary. For example, drainage from a given site is dependent on whether or not the bog is bounded by a ditch and the topography and land use of the adjacent land (Morgan- Jones *et. al.* 2005). Within larger, uniformly shaped sites, such factors may be incidental to the condition of the bog as a whole, but on smaller sites, or those with significant boundary length for their area, the areas influenced by the boundary may include a significant proportion of affected land (Bragazza *et. al*, 2005).

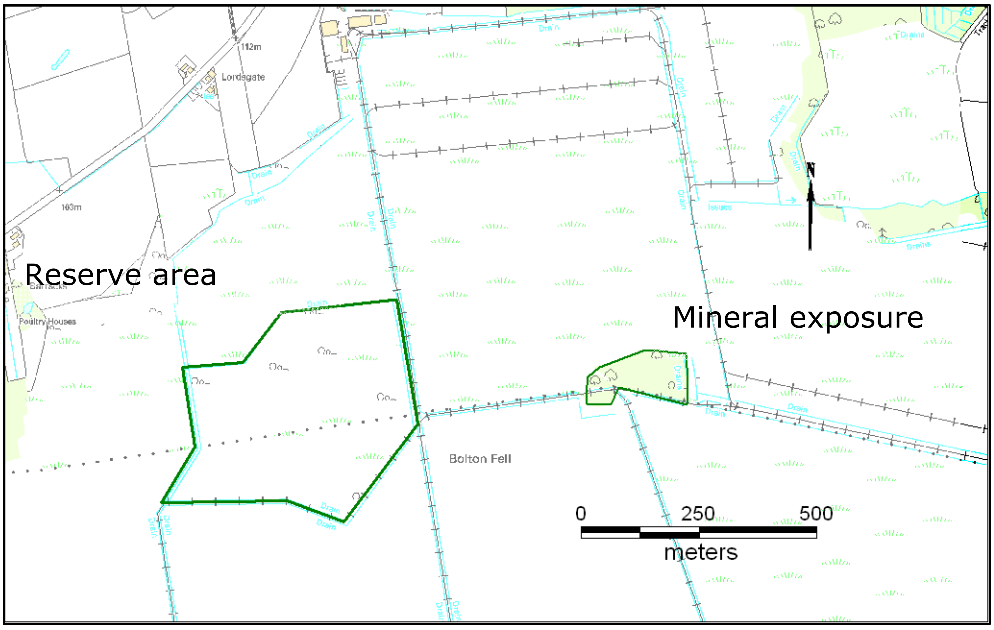
3.2.2 Disparity between hydrological and political or economic boundaries

A single site with a geographical or political boundary, such as an SSSI, may not be a single hydrological unit. Boundaries drawn may link several similar but separate sites within a single boundary. Conversely, history of ownership may lead to sites with a common hydrology being separated into several distinct entities. This may lead to diverging or conflicting management, especially if different owners have different management priorities, as is the case at Roudsea Mosses or the Duddon Mosses in Cumbria (Money and Wheeler, 1996). Over a longer period of time, it is possible that such divergent management may lead to the division of what had been a single hydrological unit into several distinct sites, each with different hydrological conditions, as has occurred in the urban Mersey Basin (Money & Wheeler, 1996) and potentially at the Walton and Bolton Fell Mosses (Barber, 1993). Such habitat fragmentation is not unique to raised bogs, but it is likely to be difficult to reunite such sites through management, as might be the case with ancient woodland or open water wetland habitats (Money & Wheeler, 1999). Again this scenario highlights the importance of maintaining such sites in good hydro-ecological condition, rather than attempting subsequent repair or restoration.

3.2.3 Heterogeneous geology

The usual model of raised bog development presupposes a uniform depression or similar where peat can begin to accumulate, such as illustrated in Fig 1.2 in Section 1.4.1, however it is often the case that such depressions are not uniform and may include pre-existing mineral exposures, which the bog may accommodate in its development, but which will have distinct hydrological characteristics (Graniero & Price, 1999). This may manifest as a localised reduction in peat depth or that peat will form around such a feature. Mineral islands are frequent, and may be identifiable from distinct changes of vegetation, such as discrete, isolated woodlands (Money & Wheeler, 1996). Where peat has formed over such features, there is likely to still be relatively typical bog ecology, however closer inspection may reveal variation in bog vegetation or topography (Graniero & Price, 1999). Such outcropping may also have implications for hydrology lower down the slope, depending on the degree to which it forms a continuous barrier across the bog. Such features can be observed at both Bolton Fell and Walton Mosses. At Bolton Fell the localised mineral outcropping is more obvious as peat extraction surrounding it has left it exposed as an island of woodland in the otherwise bare landscape and its location relative to the reserve area is shown in Figure 3.1. At Walton Moss, a similar outcropping is covered by peat, but is detectable by the change in slope and potentially by changes in vegetation.

Figure 3.1 Location of mineral island on Bolton Fell Moss



3.2.4 Introduction of recent artificial barriers.

Bogs have traditionally been viewed as barriers to communication and transport, however, sites such as Bolton Fell often use temporary light railways to aid with peat extraction. Whilst the rails themselves do not affect hydrology, it is usual to stabilise the ground they run on through drainage, which does have the potential to disrupt hydraulic connectivity, as illustrated in Figure 3.2. Other sites have been crossed by more substantial rail, road and canal links, using a variety of engineering solutions, although these have typically sought lines on the perimeter of bogs to minimise difficulties. Notably the first Manchester to Liverpool railway crossed Chat Moss, spreading the weight by means of a deep brushwood mat (Carter, 2002).

Figure 3.2 Light railway lines and associated drains at Bolton Fell Moss

3.2.5 Variation in hydraulic conductivity

Table 3.1 shows typical hydraulic conductivity for a range of soil types. It should be noted that the given hydraulic conductivity for peat is misleading, as this can vary from this figure ($10md^{-1}$) to practically zero, depending on the nature of the bog and the depth of peat (Baird *et.al.*,2008). Whilst the values for peat are low, they can be affected by prolonged drying, and this can lead to a spatial variation of hydraulic conductivity across sites where there has been prolonged drainage (Bromley *et. al*. 2004). Where the peat has degraded, such areas become more susceptible to ecological damage due to drought (Breeuwer *et.al*., 2009, Moore, 2002)). Drainage also increases the depth at which permanently saturated peat occurs, with an increased cross sectional profile having increased hydraulic conductivity (Holden *et. al*, 2006).

Table 3.1 Hydraulic conductivity of various soil types

Soil Description	Hydraulic Conductivity (k) (m/d)2
Fine Textured	Clay
Silty Clay	0.00001
Silty Clay Loam	0.0001
Silt Loam	0.001
Clay Loam	0.001
Sandy Clay	0.001
Sandy Clay Loam	0.01
Sandy Silt Loam	0.1
Sandy Loam	0.5
Loamy Sand	1
Sand:	
Fine	5
Medium	15
Coarse	80
Peat	10

Simplified from Domenico, P.A. and Schwartz, F. W. (1997)

3.2.6 Hydrology and Vegetation

The vegetation communities and species associated with raised bogs are discussed in Chapter 2, however hydrology and vegetation are interlinked and the principle implications of variation in hydrology are discussed in brief in this section. Historic drainage can have a significant effect on vegetation cover. In particular, drier conditions can lead to the establishment of trees on the surface of the bog, and such trees are often resistant to subsequent re-wetting. They can increase hydraulic conductivity through root action and their large canopy can, individually and collectively, increase evapo-transpiration rates (Moore, 2002). These actions collectively create locally drier conditions which in turn favour the propagation of further trees over other more typical bog vegetation. Whilst in a forestry production context, the removal of trees can lead to localised water-logging of ground, making the ground less favourable to tree propagation (Rackham, 2006), in the context of raised bog, the removal of trees for hydro-ecological reasons needs to be coupled with an ongoing programme of sapling removal until wetter conditions can be re-established. In particular, raised bogs are susceptible to birch invasion (Meade,1992, Lindsay,1995), as *Betula* species are an archetypical pioneer species. Conifer species such as *Pinus sylvestris* are also early colonisers of raised bog and create similar problems with seedlings. It is the cost of the ongoing programme of seedling control that is often the biggest obstacle to effective tree removal from these sites (Rich *et. al.* 2005). Typically a capital project will be funded to remove mature trees, only for the process to have to be repeated several years later as the seedlings which replaced the removed trees reach maturity (Scottish Government, 2009).

Conversely, *Sphagnum* can play an important role in maintaining wet conditions in the surface of the acrotelm/ vegetation interface and help reduce throughflow of water in this layer (Robroek *et.al.*, 2007). It is also possible that the development of sphagnum in drains may also help to retain water within the bog, but that conditions with the drains need to be sufficiently damp and slow moving to enable this process to begin. The blocking of such drains with a variety of temporary dams has become an important area of research in wetland conservation in recent years (Wilkie *et. al.* 2003, *Lavoie et. al*. 2003, Smolders *et.al.* 2003).

3.3 Effects of prevalent meteorological conditions

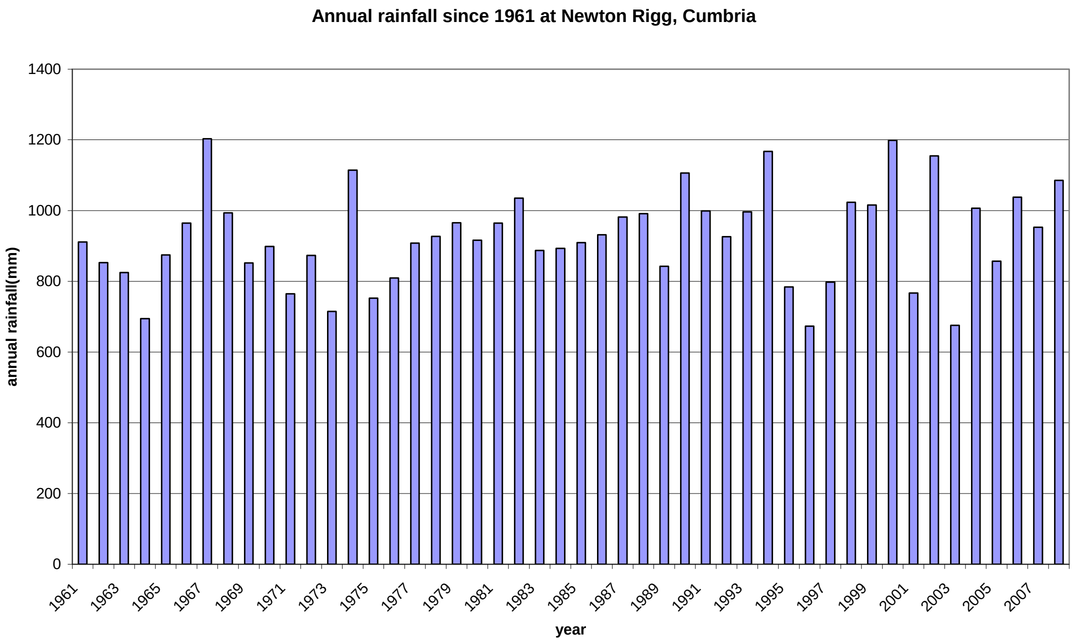
As described in Section 3.1, it is generally accepted that raised bogs require a minimum annual rainfall of 800-1000mm, depending on other local climatic conditions (Charman, 2002). However, it is perhaps more important that this rainfall is delivered at regular and frequent intervals throughout the year. In particular, regular rainfall in the summer months is important in maintaining optimum hydrological conditions (Tiemeyer, 2006). Breeuwer *et.al*. (2009), Ferrick and Price (2009) and Roebroek (2008) suggest that bog plant communities will react to an increase in summer drought conditions with a change in proportions of sphagnum species and a preference for ericaceous higher plants over grass species. This is of concern to bog hydrologists, given that some current models of climate change suggest that there is an increasing probability of drier summers in the coming years, which has implications for maintaining good hydro - ecological conditions (Breeuwer, 2009, Moore, 2002). Current models of climate change also indicate that an increase in temperature of 2-3^{o} by 2050 is likely (UKCP09, 2009). Increased temperature will increase the evapo-transpiration of bog plants, leading to further demands on ground water and a potential further lowering of the water table (Tiemeyer *et. al.* 2006). It is also likely that rainfall temporal distribution may change, giving prolonged dry periods in summer months, whilst maintaining high annual rainfall with increased winter rainfall. Whilst key bog building *Sphagna* species exhibit adaptive measures to such dry conditions (Weltzin, 2001, Breeuwer,2008), such drier conditions are likely to favour the development of woody species with the attendant hydrological implications discussed in Section 3.2.6.

Peat cores and associated paleoecological evidence show that there have been climatic fluctuations historically with bogs maintaining ecological condition (Barber *et. al.* 2003). It should be noted that such changes did not happen against the background of current intensive agricultural management and peat exploitation, so it is likely that ambient hydrological conditions in the surrounding land were much wetter, giving these sites more of an effective hydrological buffer against extremes of low rainfall. Most contemporary bogs are now surrounded by land which is much more intensively managed as productive farmland, with well drained hydrological conditions. Such buffering is therefore much less likely (Morgan-Jones *et.al.* 2005). It has been suggested that periods of drought have led to the development of more heath like vegetation communities and have also enabled the establishment of woody species, which have been able to continue to thrive when conditions have reverted to a wetter norm (Large, 2001).

The closest Met Office recording site to the study sites for this project is at Newton Rigg, approximately 35km to the south of the research sites and provides continuous monthly rainfall data since 1961 (Met Office, 2009).

Further rainfall records from 1880 to the present are available for Durham, 80km to the east. Rainfall records from Newton Rigg are shown in figure 3.1, and whilst there is no overall pattern visible from such a short time frame, the occasional dry periods, such as occurred in the mid 1970s and 1989-1991 are apparent.

Figure 3.3 Rainfall records from Newton Rigg 1961 to 2008 (Met office data, 2009)



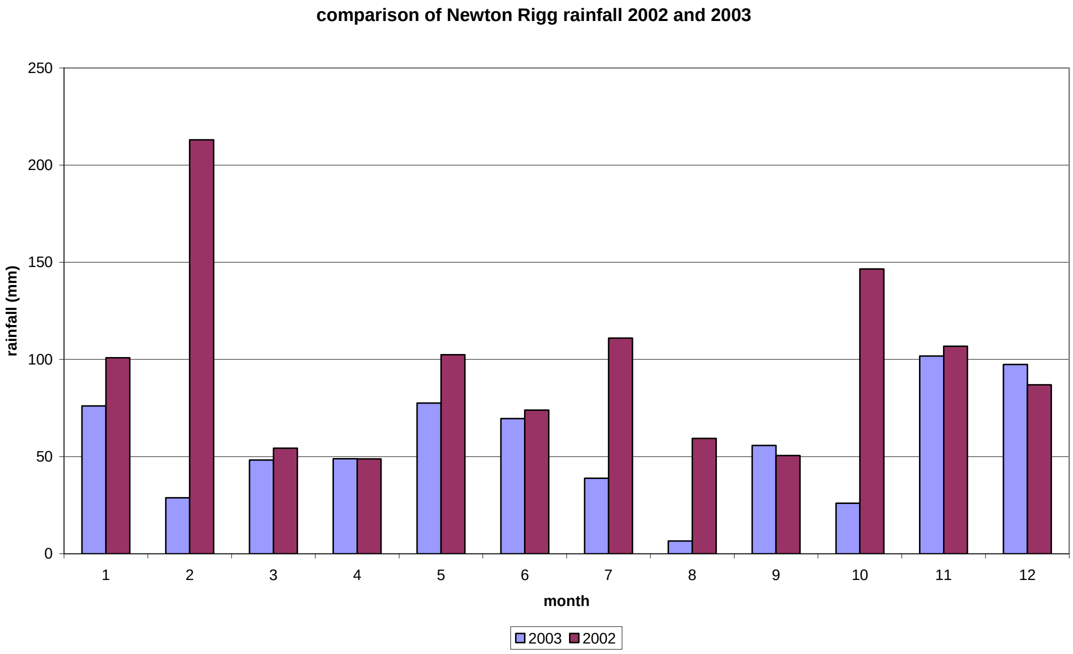
Maintenance of favourable hydrological, and therefore ecological conditions is increasingly dependent on favourable climatic conditions. This is particularly important given that ombrotrophic bogs in favourable condition are becoming increasingly rare and that the surrounding lagg fen and wetlands, which might have historically provided a buffer against adjacent land use drawing down the water table in dry conditions have been lost or degraded due to commercial pressures.

3.4 Hydrology and ecological condition

3.4.1 Short term seasonal variation in water levels

Drivers for seasonal change in hydrological conditions are primarily the meteorological conditions described in section 3.3. Water levels will fall during summer months before being recharged in the autumn. As hydraulic conductivity is generally low, water losses are therefore primarily as a result of evapo-transpiration from plants or from outflow from the site where the drainage has been artificially enhanced for agriculture or peat extraction (Moore, 2002). Where trees or drainage have increased drawdown, this suggests that higher water inputs could be required to maintain hydrological conditions. Whilst there will be significant seasonal variation, there will also be year on year variation; for example 2002 and 2003 had very different rainfall characteristics (Fig. 3.4).

Fig 3.4 comparison of rainfall at Newton Rigg for 2003 and 2004



Whilst such variation puts additional strain on many bog plants, notably, and perhaps most importantly, *Sphagnum*, it is further prolonged dry periods, such as occurred in the mid 1970s which may cause most difficulties as these allow sustained colonisation by invasive heath species such as *Betula sp.* In addition there may also be an increase in ericacious species, such as *Calluna vulgaris* and grasses such as *Mollinea caerulia*, replacing *Eriophorum spp*. (Breeuwer, 2008).

3.4.2 Long term change due to manipulation of drainage

3.4.2.1 Effect of drainage

Whilst long term climate change may lead to changes in the hydrological condition of these sites, more immediate and dramatic changes have been caused by artificial manipulation of water levels. Draining bogs, for agricultural improvement or peat extraction is not a recent phenomenon, although mechanisation of both processes has increased the rate of drainage since the 1940s until relatively recently (Chapman *et. al.* 2003). As outlined in Section 1.4.5, raised bogs have only recently been recognised as ecologically important and worthy of statutory protection. As a consequence, many sites now have different hydrological regimes than the one they developed with (Chambers *et.al*, 2007, Charman, 2002, Tantram *et. al*, 1999).

Many sites have retained the broad characteristic of an ombrotrophic raised mire, but have experienced either changes to their specific NVC community or change in the balance of species relative abundance (Soro *et.al.* 1999). The role of trees has already been discussed in Section 3.2.6, but it should be noted that continued lowering of the water table will favour the development of grasses and woody species over bog specialists and most *Sphagna (S*mith *et.al.*, 1995). Thus ongoing dry conditions of raised bogs leads to a degeneration of their special interest, and a change from M18 communities to M15 *Scirpus cespitosus-Erica tetralix* wet heath or ultimately H9 *Calluna vulgaris - Deschampsia flexuosa* or H12 Calluna *vulgaris - Vaccinium myrtillus* dry Heath and similar communities (Elkington *et. al.* 2001). Such prolonged drying also affects the structure of the soils and may lead to oxidization of the peat to a greater depth. This can lead to degradation of the peat and shrinkage of the peat mass (Baird *et. al.* 2008). Such shrinkage is illustrated in figure 3.5 where an earth anchor on Bolton Fell Moss, installed in the 1980s is shown exposed to over 2metres as a consequence of shrinkage of the bog. This may be due to climate, vegetation change, evapo-transpiration, drainage, or a combination of these factors.

Figure 3.5 Earth Anchor at Bolton Fell Moss

3.4.2.2 Rewetting

In recent times, many bogs, especially those with existing conservation value or potential for restoration of conservation importance have been subject to remediatory management of the ground water in an attempt to raise water levels in the peat to a more natural level (Shaw & Wheeler, 1995, Tantram *et. al.* 1999, Wilkie & Mayhew, 2003),). Usually this re-wetting process is based on drain blocking or impeding the hydraulic conductivity at the boundary, but in some cases additional water pumping has also been used to supplement rainwater inputs, such as at Thorne and Hadfield. In this instance there are inherent problems with bringing in "new" water. Ombrotrophic bogs are, by definition, rainwater fed, and using additional water from storage or groundwater may lead to a raised nutrient condition (Bottrell *et. al.* 2004). It may be argued that a raised bog with some fen characteristics as a consequence of mineratrophic inputs is better than a seriously degraded bog, but this action should nevertheless be regarded as a final option only if there is insufficient water available from other means. Importing water also raises issues of sustainability, as it usually relies on abstraction and pumping.

Ditch blocking has been used successfully on a variety of sites, including mineratrophic fens and blanket, as well as raised, bog. It does rely on the site having sufficient rainwater inputs to maintain good ecological condition if water can be retained on site. It also pre-supposes that ditches are the main vector for loss of water from site; if there is also significant water loss through soil through-flow, then ditch blocking alone may not be the complete solution (Ramchunder *et.al.* 2009, Ruseckas and Grigaliunas, 2008, Schouten *et.al.*,2002).

3.4.2.3 Hydrological protection zones

It is necessary to reduce the hydraulic gradient from the bog perimeter to surrounding land in order to reduce water loss from and through bog boundaries. If raised bogs are surrounded by land which is saturated to similar levels, this gradient will be reduced and losses from through-flow reduced (Fraser *et. al*. 2001) As such land is often being managed for commercial reasons, water levels are often drawn down, with resultant adverse effects on the hydrology of the bog. Work by Capita-Symmonds on behalf or Natural England (Morgan-Jones, 2005) has resulted in the promotion of hydrological protection zones (HPZs) around sites where the hydrology is managed in a sympathetic manner, designed to reduce water loss from the protected site. The width of such sites is derived from a field assessment of boundary features, land use and soil type, with a standard value of hydraulic conductivity based on soil type used to determine the width of boundary required. Work by Labadz *et.al*. (2006) to implement and assess Morgan-Jones' characterisation of HPZs on the South Solway Mosses, to which the author contributed, suggests that these given values differ from those found in the field, which are subject to much more variation.

Such zones also require a compromise with productivity of adjacent land, which is usually in different ownership to the principal area of mire. This suggests that landowners will have to be compensated for income foregone and again raises issues of the long term sustainability of such projects (kee, 2008). In the case of land uses such as peat extraction, it is likely that the establishment of such a zone will prohibit any commercial activity, and in these cases, purchase of the HPZ may prove to be the only practical option for establishment. Although this has greater capital cost implications, the long term sustainability of the HPZ is more assured.

Where there are practical physical or economic reasons to prevent the establishment of a HPZ adjacent to a site, consideration can be given to methodologies which would reduce the hydraulic conductivities of boundaries. Ditch blocking has already been referred to in section 3.2.4.2, but only provides a partial solution where through-flow is high. For example, in circumstances where mole draining, root action or peat drying has increased the pores and cracks in the peat boundary so that water can pass more easily (Bromley and Robinson, 1995). In these circumstances, reduction of through-flow can be achieved with mechanical manipulation of the peat, through compaction or cultivation. In the case of Bolton Fell, the boundary of the reserve area was dug over by mechanical excavation to a width of 10m and a depth of 3m and the material re-deposited and compacted by the excavator travelling across it, hopefully reducing the pores and decreasing the hydraulic conductivity of the acrotelm (Turner, pers.com. 2006).

There are immediate concerns for vegetation loss with this approach, as part of the bog itself is damaged to allow protection of the greater extent. Ecological assessment is required before such action to ensure no critical species or communities will be destroyed during the operation, or that any such losses are considered acceptable within the context of the wider operation. The likely designation of the site as an SAC is likely to mean that both the reserve area and the surrounding area of peat extraction will be managed with a common aim of a wetter hydrological regime in future years, as has happened at Wedholme Flow following its purchase by Natural England in 2004 (Natural England, 2004).

3.5 Context for the development of this research project

The role of microtopography in raised bog hydroecology is still imperfectly understood. This study addresses how these factors, and the related ecological issues discussed in chapter 2 manifest in microtopographic variation of the bog surface. A methodology has been developed to record the hydrological condition and vegetation communities found at such sites, and how these data can be related to microtopographic variation. As has been established, the relationship between hydrology and vegetation is complex, and does not give a complete explanation for the microtopographic variation, however the methodology described in Chapter 4 has provided a relatively large data set with which to assess these relationships.

4 Study Methodology

4.1 Hydrological monitoring

Hydrological monitoring techniques vary in both spatial coverage and temporal resolution. Historically, the specific problems of the variation of water table in the peat and retention of water within such sites, as identified in Section 2.2 have been addressed using a combination of methodologies, depending on resources available and the size of the monitored area (Burt, 2003, van der Schaaf, 2002). Typically, infrequent manual observation has been carried out concurrently with botanical monitoring, and was limited to monitoring water levels in adjacent water bodies and artificial ditches, as many problems with ecological condition were as a consequence of historical land drainage and agricultural reclamation (Stoneman *et al*. 1997).

4.1.1 Monitoring of water table levels

Monitoring of water tables using piezometers or dipwells is often used over larger areas or entire ecological units (van der Schaaf, 2002). Whilst this provides an excellent hydrological snapshot of conditions across a whole site, difficulties arise when considering temporal elements, such as speed of response of the water levels to precipitation (Yazaki *et. al*., 2006). Although water levels in the peat reflect climatic conditions, there is little relationship between long term antecedent rainfall and dipwell response, as changes in water levels tend to reflect recent rainfall events, rather than monthly or seasonal antecedent rainfall (Gilvear and Bradley, 2000, Heathwaite, 1994).

However, dipwells are easy and cheap to install, so it is possible to install many dipwell tubes over a large area. They are also robust and need little maintenance and are therefore suitable for monitoring over several seasons (Baird and Sheila, 1992). Dipwells therefore provide a good spatial representation of water levels across a site or study area on a given day.

The only significant cost is that of labour for checking levels (Bouma *et.al.*, 1980). It should be noted that the reliability of such data is entirely dependent on the number and spacing of the dipwells and the accuracy of the manual monitoring (English Nature, 1994). Temporal resolution can be improved by increasing the frequency of the measurements, but this is dependent on resources being available, and frequent monitoring will lead to a significant increase in costs.

Such a methodology does provide a representation of spatial differences in hydrology and can be obtained relatively quickly, and providing monitoring intervals are not frequent, at a low cost, so it does have a place within a wider monitoring regime, providing these limitations are recognised.

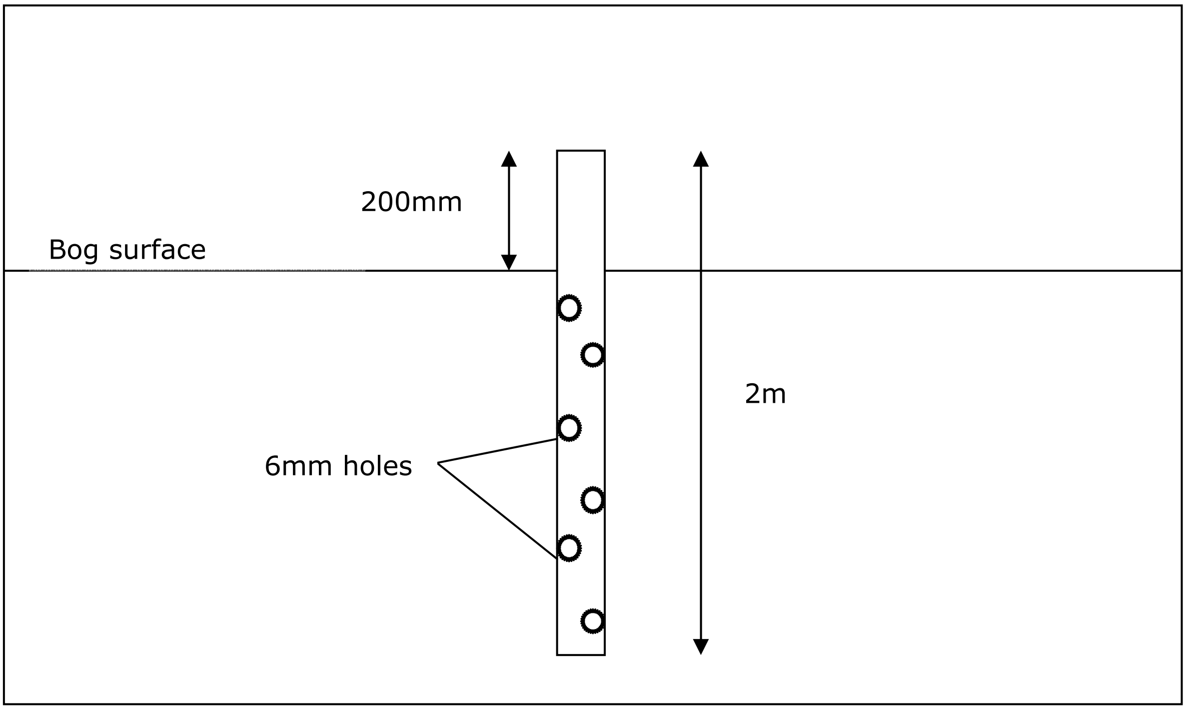
4.1.2 Location of dipwells on Bolton Fell and Walton Mosses

This study builds upon an initial research interest in the variation of hydrology in the two sites (Labadz & Butcher, 2006). Dipwells were initially installed for this study by a group including the author for a Natural England research contract to monitor the effect of drainage and other management activity on the two study sites.

Initially 64 dipwells were installed on 4 transects, the locations of which are shown in Figures 4.4 and 4.5. For the current study, this figure was reduced to 51 on the initial 4 transects, as some outlying and parallel dipwells were not included. However an additional transect of 13 dipwells was installed in the north west of Walton Moss.

The dipwells consist of 2m lengths of 32mm plastic waste pipe, blocked at the bottom and perforated throughout the length with 6mm drilled holes. These are installed by pushing into the peat to either approximately 200mm of the full length, or until a hard substrate is encountered. A typical installation is shown in Figure 4.1.

Figure 4.1 Detail of dipwell installation



The dipwell transects were installed to monitor possible variations in water level due to the effects drainage and adjacent land management and the recording methodology and data incorporated into this study. Depth to water table was recorded using a manual water level meter. An example of such meters is shown in Figure 4.2.

Figure 4.2 Example of manual water level meter (Solinst, 2010)

Depth to water table in the dipwells has been measured at approximately monthly intervals since October 2003, usually over a period of 2 days and for this study, data for water years 2004 to 2007 have been used. The dipwell distribution was intended to illustrate the hydrological condition of both sites. In particular, Bolton Fell Moss has a distribution of dipwells across the entire reserve area. At Walton Moss, this distribution is less satisfactory as they are concentrated in the South Eastern section of the site, as the dipwells were originally installed to answer a specific question about the impact of agricultural drainage grips in part of this area. The south transect crossed an area of herringbone agricultural drains and the north transect was located in and adjacent area to act as a control for the south transect in a part of the moss initially perceived to be typical of raised bog in good hydro-ecological condition. However this transect also crossed an area of lagg fen and an area of mineral soil outcropping, as well as significant areas of representative bog.

In order to assess an area of uniform bog hydro-ecology and to obtain a better spatial representation of the hydrology of the whole site, a further transect of dipwells was installed in 2006 in the north western section of the site. This transect was located in a section of the bog perceived to be more representative of good hydrological condition and in an area of bog which was a very good example of NVC m18 bog *Erica tetralix – Sphagnum papillosum* raised mire (Rodwell 1991).

4.1.3 Fixed automated logging devices for monitoring water table fluctuations

Detailed temporal monitoring, by implication, requires either a permanent presence of monitoring staff on site, or the use of automated equipment (Evans *et.al.* 1999, Gilvear & Bradley, 2000). Automated monitoring is used on many sites (O'Brien *et.al,* 2008, Litaor,2008, Mouchel Parkman Ewan, 2007) and can provide very detailed water depth figures for specific locations. Such equipment is typically float operated or pressure probe type, such as the OTT Thalimedes and Orpheus groundwater data loggers, respectively. This equipment can automatically record water depths at predefined intervals for long periods of a time (OTT Hydrometry, 2008), such periods being dependent on the intended intervals between downloads, but up to several months between downloading is possible. For this study, it was intended to download loggers at the same time as the water depth in dipwells was recorded, but due to the difficulties outlined in Section 7.4, this interval was often significantly longer. The Thalimedes shaft encoder and data logger, of the type used in this study cost approximately £1000 each (OTT Hydrometry, 2004). The equipment was chosen for pragmatic reasons. Loggers were accessible within NTU and the service and repair centre was located nearby (OTT Hydrometry, 2004). Limited budget meant alternatives such as pressure transducers, used for similar work by Holden *et.al* (2006), Price and Whitehead (2004) and others were not considered, even though the manufacturer claim advantages in sensitivity of response and robustness (Hach Environmental, 2009). The Thalimedes shaft encoder and logger, of the type used in this study, is shown in Figure 4.3.

Figure 4.3 Thalimedes shaft encoder and data logger (OTT Hydrometry, 2008)

Using automated equipment, it is possible to monitor hydrological response on a very fine temporal scale. Typically this is at 5 or 15 minute intervals, although these figures can be adjusted depending on the required monitoring regime – more frequent monitoring increased data storage and therefore such units will require more frequent downloading. This resolution allows, for example, response to single rainfall events to be recorded very accurately.

Whilst in theory it would be possible to replace all dipwells with automated loggers, in practice this would prove financially prohibitive within the scope of a small scale monitoring project. Therefore it is likely that for monitoring larger areas with a common hydrological regime, such as a single raised bog, a combination of methodologies would be used, giving an acceptable compromise of spatial representation and temporal definition, within budget constraints (Gilvear & Bradley, 2000).

4.1.4 Shaft Encoder locations at Bolton Fell and Walton Mosses

OTT Thalimedes shaft encoders were installed at the top of all transects at Walton Moss, and at the base of the Walton south transect. At Bolton Fell Moss, shaft encoders were located at the edge of the bog adjacent to cut peat surface, by dipwell N1, at the centre of the area of intact bog by dipwell N4 and near the boundary of the reserve area and the area of re-vegetated hand cut bog near dipwell N7. These were set to record water levels below ground surface at 15 minute intervals. Manual dipwells located adjacent to this equipment allow for manual adjustment of the data obtained from the loggers, which are prone to errors due to internal clock error and pulley slippage. It also permits periodic re-calibration of the equipment. The locations of the dipwells and shaft encoders are shown in Figures 4.4 and 4.5.

Figure 4.4 Bolton Fell Moss dipwell locations

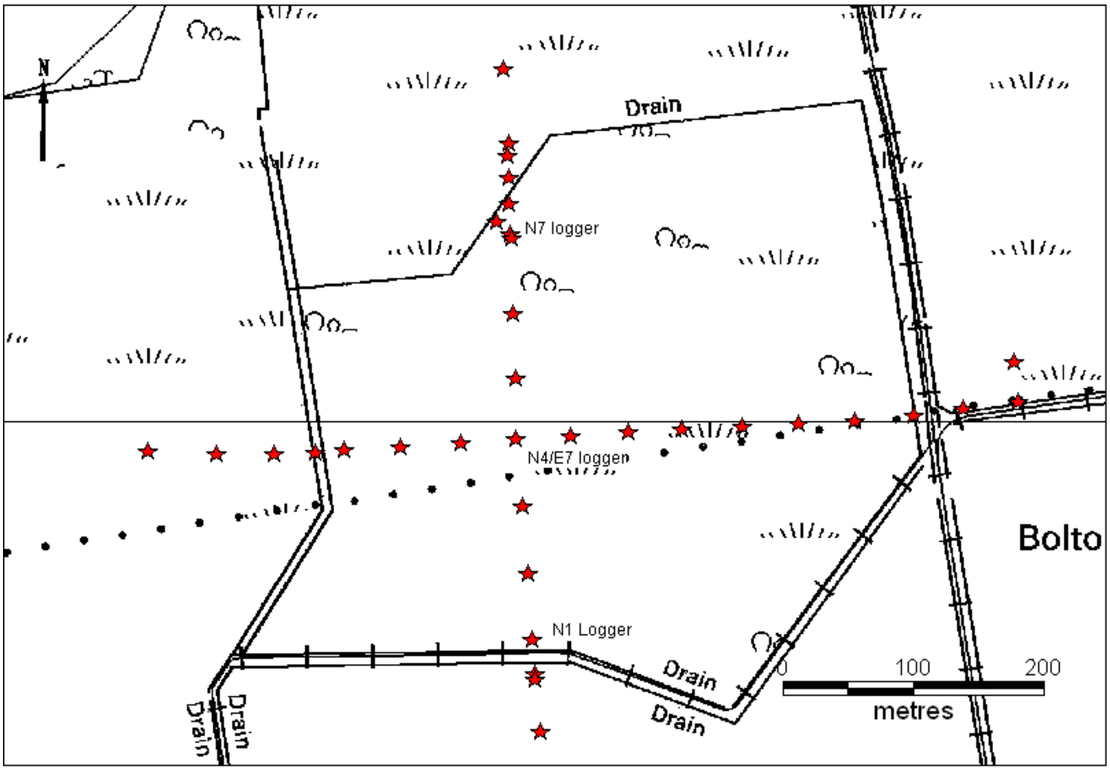
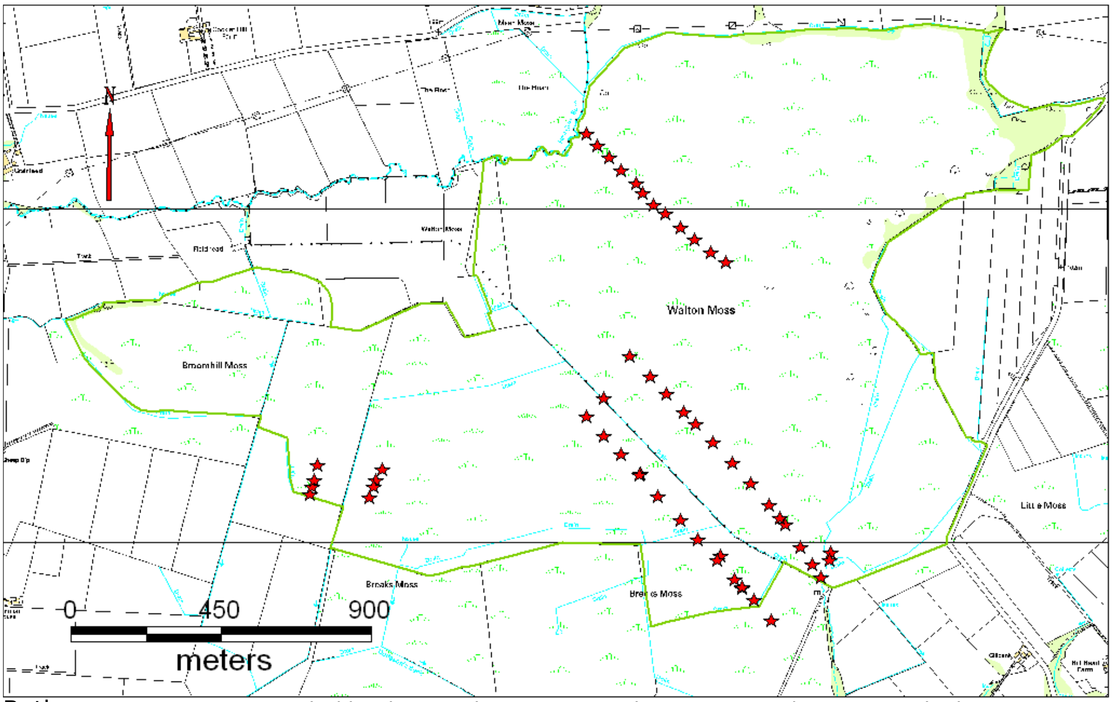


Figure 4.5 Walton Moss dipwell locations



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4.2 Meteorological monitoring

Given the critical importance of climatic conditions, and in particular the high rainfall requirements in the development of raised bogs (Lindsay, 1995, Moore, 1989), any study of such sites will require detailed, cotemporary rainfall data. In particular rainfall inputs are an important consideration when the effects of drainage manipulation are being considered (Bragg, 2002, Large *et.al*., 2007). Whilst general historic weather data is available from the Met Office, this is dependent on the location of the nearest monitoring station, in the case of this study, this is located at Carlisle, approximately 15km to the west (Met Office, 2008). Whilst this data set is potentially useful, site specific meteorological data would be of greater benefit, therefore automated recording equipment was used to obtain direct readings.

Initially, a Casella tipping bucket rain gauge was installed at Bolton Fell to provide rainfall data for both sites. This was replaced in 2005 by an ELE automatic weather station, which also provided temperature, humidity and windspeed & direction data in addition to rainfall (ELE international, 2008). An error in installation resulted in a failure to record any data between October 2005 and May 2006. Daily rainfall totals were available for this period as rainfall was measured manually using a bottle-type rain gauge located at the peat processing works. These data are also used to validate the rainfall recorded by the automated equipment, however these data were only recorded on working weekdays. Data for Mondays, or for periods following closures, such as Christmas were a total of rainfall for the period since it was last recorded, rather than an antecedent daily total.

4.3 Botanical recording

4.3.1 Vegetation as an indicator of hydrological condition

Variation in plant communities usually reflects long term hydrological condition (Laitinen *et.al*., 2008, Bragazza, 2005) . Vegetation community and habit is dependent at least in part on hydrology (Rodwell, 1991), but individual plant species and communities take time to respond to changes which fall short of outright inundation or prolonged drought (Runhaar, 1996, Mead, 1992). It may take several years for such changes to manifest at a recordable level if the change in regime is slight. Although it is not to say that such change is not significant, it is not possible, or at least unlikely, that such change may be judged significant within the timescale of a 3-5 year research project. However vegetation type can be used to illustrate what change is likely to occur if a given hydrological regime is continued, by studying vegetation in an area where said regime has been established for some time, providing other conditions are similar. Factors such as climate or nutrient levels may be important factors when such comparison sites are geographically removed (Montanarella *et.al*., 2006). It is usually of more benefit to study geographically adjacent sites than similar sites in different regions.

Vegetation communities also have distinct infra red signatures which mean that at coarse scales, it is possible to classify distinct communities using remote sensing techniques such as satellite imagery or aerial photography. However, whilst it would be possible to use these techniques to determine gross change, it is more difficult to detect more subtle changes such as variation in the proportion of different S*phagnum* species (Mehner *et.al*., 2004). This is not to say that such techniques cannot be used for higher resolution differentiation, rather it would require specific high resolution data gathering, rather than being able to use commercially available data (Harris, 2006).

This is an important distinction, as different sphagnum species have differing hydrological requirements, and therefore the balance of species may vary with hydrological conditions. Additionally there will be complications arising from multiple vegetation cover. Typically bog plant communities may have a sphagnum carpet overlain by higher plants, such as *Calluna vulgaris* or *Molinia caerulea.* Bog communities may also have *Betula pendula* present, which whilst in and of itself may be an indicator of change, may also screen plants at the herb layer from remote view (Rodwell, 1991).

4.3.2 Historical monitoring methodologies

Historically, botanical monitoring of raised bogs has been undertaken to assess the integrity of vegetation communities, with a view to their ongoing protection. Therefore historical records tend to comprise species lists and abundance records of notable or rare species. Where it has been recognised that these species are dependent on hydrological conditions, then increasingly hydrological condition has also been recorded, usually with a view to identifying areas where water retention is poor, or where the water table is significantly lower than might be expected (Ingram, 1967, Lindsay 1995). Such conditions can be recorded by infrequent manual monitoring and observation, traditionally by amateur naturalists, but also by field officers charged with the maintenance of good ecological condition (Natural England, 2008_1). More detailed monitoring requires more dedicated time and resources, which are often not available to such bodies and individuals. Therefore many historical records tend to comprise ad hoc and incomplete data, although individual records can be very detailed in certain genera or conditions, reflecting the skills of the individuals concerned (Berry, 1988).

Botanical records are likely to give a reasonable overview of the condition of a site as a whole, and may reflect potential areas of concern (Wyatt, 1992). This is particularly true of larger sites where a detailed survey of the entire site would prove difficult to implement within time and budget constraints.

It is also likely that techniques will have varied over time, as both best practice and species priorities will have changed.

Political priorities will also influence this process, particularly within the statutory and government agencies which are driven by wider policies, such as the Habitats Directive (European Union, 1992). This process has led to the production and implementation of species and habitat action plans, within the biodiversity action plan process, as well as the necessary research required as part of the designation process for the study sites as SAC and cSAC, respectively (JNCC, 2006).

The widespread implementation of the National Vegetation Classification has led to more consistent monitoring methodologies being adopted since 1988 (Rodwell *et.al.*, 2000), making inter site records more directly applicable, but time and financial resources still limit how widespread full NVC surveys have been undertaken (Rodwell, 2006). It is therefore unlikely that for detailed small scale projects, detailed historical data for the specific study area will prove to be available, although it has been possible to gain an overall view of botanical condition for a given site, and to observe gross change in botanical condition. Historical vegetation records are available for both Walton Moss and Bolton Fell (Natural England records, unpublished), however these data are not of sufficient resolution to be specifically related to individual dipwells on either site.

4.3.3 Vegetation monitoring methods used at Bolton Fell and Walton Mosses

1m^2 quadrats were established which were associated with each dipwell, using methodology developed by the Scottish Wildlife Trust (English Nature, 1994). Regular monitoring of the dipwells has resulted in a noticeable path becoming evident along the transects. To avoid this damage, quadrats were offset by one metre, locating them in areas of undamaged bog.

Vegetation in these quadrats was assessed by eye and recorded using methodology described by Rodwell (2006 and 1991) with species abundance scored as a percentage of total cover. However, in common with most detailed methodologies, accurate recording of vegetation cover in quadrats is time consuming. Therefore quadrat size was limited to 1m following an initial assessment of vegetation diversity. This allowed for vegetation to be surveyed at most quadrats within the scope of a single field visit. Use of additional field recorders for vegetation surveying was considered, however assessing cover is a subjective exercise and different recorders can yield different data for the same quadrats (Cherrill and McLean,1999). Therefore the recorders were kept to a minimum, comprising the author and a colleague.

In addition to species identity and percentage cover, vegetation structure and grazing intensity were recorded, as per NVC methodology (Rodwell, 2006). Walton Moss is designated common land (Defra, 2008) and is subject to regular year round grazing, although livestock numbers are limited by a countryside stewardship agreement (JNCC, 2003). There is no livestock grazing at Bolton Fell, but roe deer were sighted on a number of occasions during the study, and were also seen at Walton Moss. Brown hare were not seen at either site, although they are recorded historically (Natural England records, unpublished). It is not believed that either site has a permanent rabbit population.

4.4 Topographic monitoring methods used at Bolton Fell and Walton Mosses

Bog topography is a significant factor in overall bog morphology. The large scale bog topography is central to its identity, giving the characteristic dome of the raised bog (Lindsay, 1995). This shape is informed by the hydrological characteristics of peat, but also in turn informs the subsequent hydrological performance of the bog. In particular, surface runoff is determined by the shape and gradient of the bog profile. Saturated peat having very low hydraulic conductivity (Clymo, 2004), the majority of water will be lost from site almost immediately as overland flow. In drier condition a proportion of water is absorbed into the bog to recharge water levels, but except in exceptionally dry conditions, this is still only a small percentage of water inputs (Fraser *et.al.*,2001).

Much research into surface variation of bog micro-topography considers quite large variations in topography, often at a scale of metre plus variation (Graniero & Price, 1999, Nungesser, 2003). Whilst this variation is important in the consideration of large scale bog processes, in particular in the formation of bog pools, it is influenced by longer term morphological processes such as the rate of accumulation of peat and the underlying geology. Peat accumulation is a function of the overlying vegetation, but it is the decay of this vegetation to peat, which informs the formation of the topography (Moore, 1995, Belyea & Clymo,2001). This larger scale topographic variation is better termed meso-topography for the purposes of this study to avoid confusion with the very small scale topographic variation which is the main point of consideration of this study.

4.4.1 Definition of microtopography in the context of this study

The small scale topographic variation associated with vegetation derived hummocks in a bog surface is typically sub 0.5m variation within study areas. For this study, this variation will be referred to as micro-topography. Unlike meso-topography, this topographic variation is the consequence of living vegetation growth patterns, which raises specific difficulties with measurement.

Unlike the horizons found in mineral soil, peat horizons are much more indistinct. There is no definite boundary between vegetation and soil, as the soil is entirely organic and composed of bog plants, primarily *Sphagnum spp*. and *Eriophorum spp.* in varying conditions of decay (Bridgham *et.al*, 2001). This decay is in turn dependent on the degree of saturation of the peat. Decomposition will occur more quickly and more comprehensively in drier peat, usually as a result of drought, or more usually, artificial drainage (Belyea and Warner, 1996). Whilst the peat is very distinct in the lower anaerobic depth of the catotelm, the boundary between what might be considered vegetation and peat in the acrotelm is more difficult, and the decision as to the boundary of growing vegetation and recently deposited peat is subjective. This makes deciding on a surface for the measurement of topography difficult.

The main considerations for the development of a methodology to measure this micro-topographic variation were:

- No significant ecological damage
- Non interference with the topography being measured
- Ease of use
- Speed of use
- Cost

4.4.2 Measuring the topographic variation of bog surface directly

The uncertainties surrounding the definition of the vegetation/ ground boundary mean that measurement of topography, like many other techniques associated with the assessment of the properties of vegetation, will always have an element of subjectivity. Furthermore, particularly in the case of *Sphagnum* mounds, it is the vegetation, rather than the ground surface, which defines the bog topography. Therefore, methods to define the surface must do so on the basis of a consistent base measurement. In many ways, it does not matter if the measured topography differs from that measured using an alternative methodology, providing that the criteria used to determine vegetation height are consistent and used throughout the study, as it is the differences between measured heights that are used to inform the study, rather than the absolute values of the elevations themselves.

Various alternatives were considered for measuring the height of the bog surface. All methods, of necessity, required measurement relative to a common datum. Conventional surveying using either theodolite or total station would accurately measure height relative to a known reference point (Clancy, 1991). This would give accurate relative heights, although these data would require referencing to a known datum. The principal issue with this methodology is that the base station would require frequent relocations as the quadrats to be surveyed are upwards of 100m apart across a broadly convex bog surface, which limits the necessary line of sight between the surveying staff and the base station. Therefore alternative methods, notably stereophotogrammetry and differential GPS (dGPS) were considered.

4.4.2.1 Use of photogrammetry to assess bog surface microtopography

Photogrammetry has been used extensively in remote sensing of landforms, including blanket bogs and glacial geomorphology (Lane *et.al.*, 2000), however, it requires either the availability of an existing, recent, set of stereo photographs, or the commissioning of an overflight for new photographs. Both of these had potential cost implications beyond the budget of this project, unless a third party such as Natural England or the Environment Agency had either bought or commissioned a set.

Use of an alternative photographic platform was considered. Telescopic camera platforms are used extensively in geological surveying (Swanson,2008), but would prove difficult to use in remote areas without vehicle access to study sites as the equipment is typically trailed or bulky . In addition to the cost of hiring such equipment, extra pilot studies in calibration and feasibility would have been required. Remote control camera platforms, such as helicopters or kites have been used elsewhere, but difficulties arise in locating the camera platform accurately, and in maintaining stability (Bigras, 1997). Data for this project had high accuracy requirements, and aerial photography was unable to meet this, notwithstanding the given accuracy, using photographs obtained from any of these sources would also be necessitate the development of a mechanism to account for the influence of overlying vegetation above the ground surface, and would therefore still require ground-truthing to ensure the accuracy of such methodology.

4.4.2.2 Use of Differential GPS to assess bog surface microtopography

Differential GPS is used extensively in building surveying and is capable of 2cm accuracy horizontally and 5cm in the vertical axis (Leica Geosystems, 2008). This is well within the acceptable limits of this project. Far greater variation is expected as a consequence of uncertainties in determining the surface/ vegetation boundary. Although dGPS accuracy may be affected by atmospheric conditions causing interference with the satellite signal, the most significant variation in dGPS surveying is likely to be operator induced, as a consequence of the staff being non vertical during surveying (Higgit and Warburton, 1999, Fitts, 2005). dGPS accuracy assumes that the staff is vertical at all times, working over rough terrain means that it is probable that this is not always the case, therefore diligence was maintained during surveying to minimize this error as far as possible.

The two main limitations to the use of dGPS in the field are satellite visibility and radio reception for the differential correction signal from the base station (Leica Geosystems, 2008). The number of satellites visible to both the reference and rover units depends on a clear view of the sky. A major topographic variation, such as deep, narrow valleys or working on a steep slope will reduce the number of satellites visible, and therefore the accuracy of the dGPS. If too few satellites are available, operation will prove impossible. Similarly using the units under dense tree cover or in or near buildings will similarly obstruct the signal (zheng et.al., 2005, Paulauskas and Ginters, 2006). On most raised bogs, including the study sites, there are no steep slopes. However there is some tree cover on parts of the sites, in particular, the north transect on Bolton Fell crossed a small area of dense woodland, where dGPS operation was occasionally obstructed.

The accuracy of dGPS is obtained, in part, from the correction signal broadcast from the reference signal. If the reference signal is lost, this reduces accuracy to below acceptable levels. This limits operation of the rover unit to within radio receiving range of this signal (Enge, 1994). As the strength of the signal is limited due to legal constraints of radio operation, this means that in practice, operation is limited to with 1-2 miles of the base station in usual conditions. Again, topographic conditions will dictate this distance, depending on the conditions on site. For example, steep terrain or buildings may block this signal. Whilst Bolton Fell is a large site, the study area is relatively compact, although trees occasionally obstructed the signal. Conversely, Walton Moss has a convex profile, which restricts the reception of the base station radio signal.

Given the restrictions of photogrammetry highlighted in section 4.4.2.1, it was decided to use a ground based surveying method for surveying small scale variation in topography. Both dGPS and conventional surveying techniques would have provided the accuracy and consistency for surveying individual sample plots, however this would have necessitated frequent relocation of surveying equipment, particularly at Walton Moss, where survey quadrats were upwards of 100m apart, across convex ground. Using dGPS, the base station only needs erecting at one site, all subsequent surveying being undertaken using the rover unit. In addition dGPS had already been used at the site for initial surveying of boundaries and elevations, meaning equipment was already available and had proven to work effectively at these sites.

4.4.3 Use of LiDAR in determining bog surface microtopography

LiDAR (Light Detection And Ranging) is a technique of measuring topography remotely using an aircraft mounted laser scanner linked to a differential GPS system, which accurately measures the distance from the aircraft to a point on the ground (Cracknell and Hayes, 2007). The vertical distance is linked to the known dGPS location of the aircraft to produce a location on the ground. This process is repeated to build up a grid of locations and point heights.

Remote sensing techniques such as LiDAR rely on a positive response from the surface to determine its precise location (Xharde, 2006). This works very well with a hard reflecting surface such as rock or a discrete mineral soil. Where there is overlying vegetation, there has been much work done (Raber *et.al*.,2002, Deveraux *et.al*.,2005) to develop algorithms to allow post processing of these data to remove the influence of vegetation for analysis. Again this works well when a definite solid surface, such as stone archaeological remains below vegetation (Deveraux *et.al*.,2005). However, where the surface layer is comprised exclusively of vegetation, these algorithms become less reliable (Hopkinson *et.al*., 2005), and one of the objectives of this study is to determine if such data can be used to accurately measure bog microtopography.

For the purpose of this study, a LiDAR dataset was obtained from Natural England for both sites. The LiDAR dataset was produced during an overflight of the study sites commissioned by the Environment Agency in 2003 using Optech ALTM 3033 instrument equipment. Vertical resolution is given as 15cm and these heights were recorded in a British grid x,y,z format and sampled in a 2x2m grid. The data was supplied in 2km^2 tiles (Environment Agency, 2008). Although LiDAR is inherently accurate to centimetre scale, difficulties with accuracy arise because of difficulties in locating the aircraft in which it is housed accurately (Hopkinson *et.al*., 2005), given both the limitations of GPS, and the inevitable three dimensional buffeting of any aircraft, giving certain inaccuracies, which Xharde *et.al.* (2006) judged to be less than 30cm. However this study is primarily concerned with the position of these spot heights relative to each other, and it is judged that such inaccuracies will be acceptable within the overall scope of the study.

4.5 Survey methodology used at Bolton Fell and Walton Mosses

The objective of this element of the study is to obtain an overall representation of the microtopography of the study sites, together with representative data relating to hydrological and vegetative conditions. In order to obtain comparable data, the dipwell transect lines were used as a basis for subsequent data collection. Each dipwell location would therefore have a series of data associated with it: depth to water table, botanical community & species distribution, and LiDAR & dGPS topographic variation data.

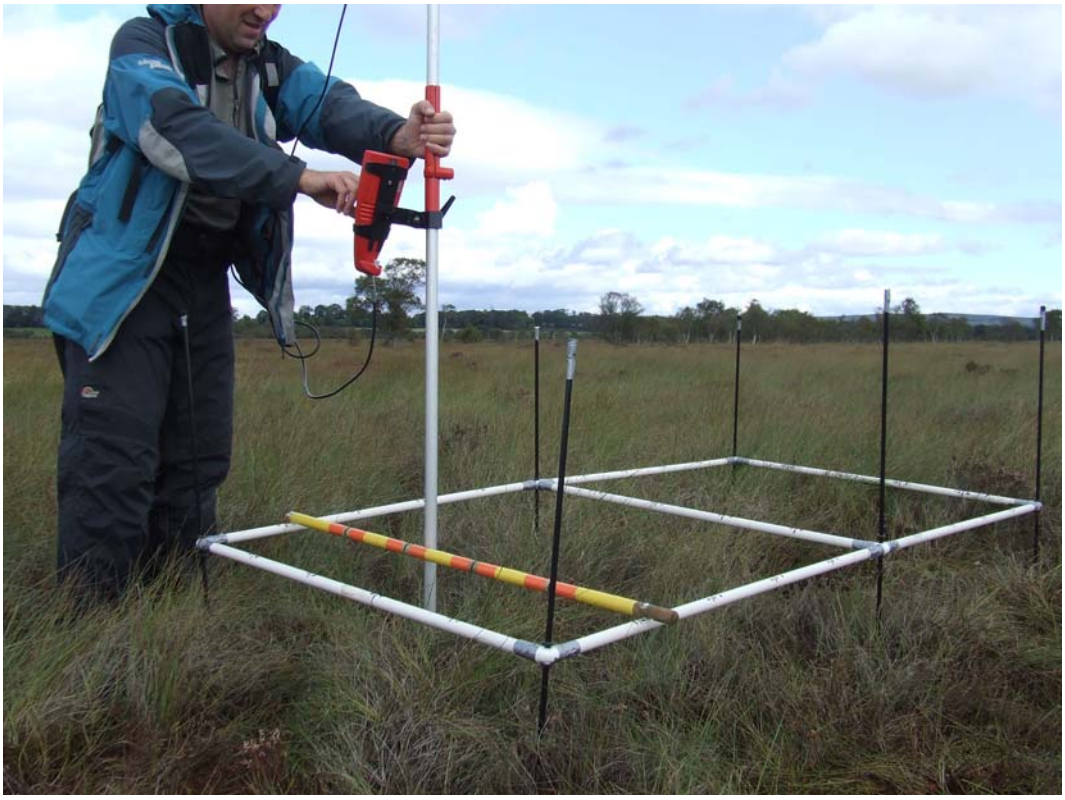
The measured surface in all cases is below the upper surface of the vegetation. Notwithstanding the canopy layer of the wooded quadrats at Bolton Fell Moss, it was necessary to develop a technique to determine at what point the vegetation became consistently dense enough to be considered a coherent surface. A measuring staff was used to provide height. Use of a pointed staff, common in most surveying methods, allowed for the point to penetrate the vegetation or peat. Therefore a variety of alternative flat staff bases were trialed. Through observation, staff heads larger than 10 cm diameter were judged to be prone to catching on higher vegetation canopy, particularly in dense *Calluna* and *Erica* shrubs, and could therefore give misleading heights, whilst smaller bases would penetrate the peat, to give misleading results. Because this degree of penetration was not consistent, this would result in inconsistency of the measurement of relative differences between points. A flat rubber shoe, based on a walking stick ferrule was judged to provide the correct degree of resistance to penetration, but without being blocked by low ericaceous shrubs, and this was fitted to the dGPS survey staff for this study. The base was drilled, so that the base of the shoe contained the tip of the survey staff, therefore there was no difference between recorded and actual height.

Quadrat size was set at $2m^2$. This figure was determined through experimentation to be as large as practical, but as all points are within 1m of the perimeter, it is possible to access each point from the perimeter without interfering with the topography within the quadrat. By locating it on the existing quadrat, it is possible to relocate the quadrats easily. The internal heights were measured using the Leica 500 dGPS in a 20cm^2 grid, to give 120 individual measurements per quadrat. Thus it is possible to access all points inside the quadrat without entering the quadrat, and keeping the survey staff vertical, to maintain dGPS accuracy.

In order to maintain a uniform distribution of measured points across the quadrat, a 2m x 1m frame was constructed, using nominal 21.5 mm plastic pipe, drilled at 200mm intervals. This frame was placed over half the quadrat and a moveable 1m baton attached as shown in Figure 4.6. This baton was also marked at 20cm intervals, thus allowing for the accurate placement of the survey staff. Each point was then measured by resting the modified survey staff on that point and recording its 3-dimensional location. The quadrat was then located over the remaining half of the quadrat and the process repeated.

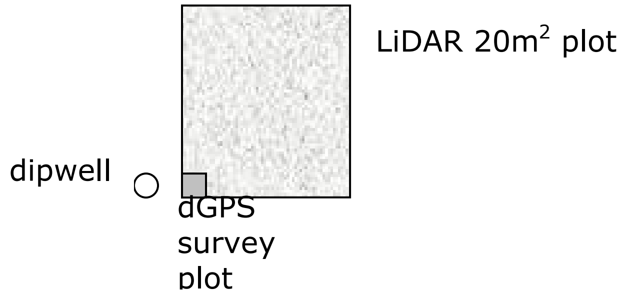
In this manner, the entire quadrat is untrodden. Whilst this methodology does cause some minor temporary trampling to the ground surrounding the quadrat, the topography of the interior is not affected. In view of this potential damage due to trampling, it is not recommended that this survey is repeated in the same year, to allow vegetation to recover.

Figure 4.6 Surveying of surface microtopography at Walton Moss, showing dGPS and surveying frame



The LiDAR dataset was supplied by Natural England from data collected by the Environment Agency. As described in Section 4.4.3 these data are given as point coordinates at 2m intervals. One of the objectives of this study is to assess the suitability of LiDAR for characterizing small scale topographic change, therefore these data were sampled from the same reference points as the dGPS topographic survey quadrats. In order to obtain a representative number of points and to test the assertion, 20m quadrats were taken, giving 121 LiDAR survey points. These data were then compared with the dGPS 2m quadrat points for each dipwell. The relationship between the 2m dGPS plot, the 20m LiDAR plot and the associated dipwell is shown in Figure 4.7.

Figure 4.7 Diagram illustrating the relationship between the dipwells, dGPS and LiDAR survey plots



4.6 Summary

- Each quadrat has a series of data associated with it: Dipwell records from the start of the initial monitoring in October 2003, Vegetation records from the associated quadrat, recorded between 2005 and 2008, topographic point data recorded in 2007 and a set of LiDAR points taken from the 2003 Environment Agency overflight.

- Together, these data provide a detailed picture of the eco-hydrological condition of these study sites. The nature of such studies makes long term temporal studies difficult, but by studying areas with these different stresses simultaneously, it is intended that this methodology will provide a framework which may be used to study ecological change due to external pressures on hydrology from management .

- To this end, these data have been used to investigate the investigation aims as set out in chapter 1. The methodologies used to describe and analyse these data are described in detail in Chapters 5-7.

5 Hydrology, groundwater and rainfall

5.1 Rainfall recorded at Bolton Fell Moss

Rainfall data have been recorded at Bolton Fell Moss by Sinclair Horticulture and are available in detail for the whole study period. In addition summary data are available from 1988. As the two sites are less than 1km apart at their closest, it has been judged that rainfall data from Bolton Fell Moss is also applicable to Walton Moss. During the study period, these daily recorded data have been supplemented by tipping bucket rain gauges located in the reserve area of Bolton Moss, giving a finer resolution of data from October 2003 to September 2007, the end of this study. The Sinclair series runs throughout the study whereas the tipping bucket series has missing data between October 2005 and May 2006, when the initial Cassella tipping bucket raingauge was replaced by an ELE automated weather station, which was later discovered not to be recording rainfall data correctly.

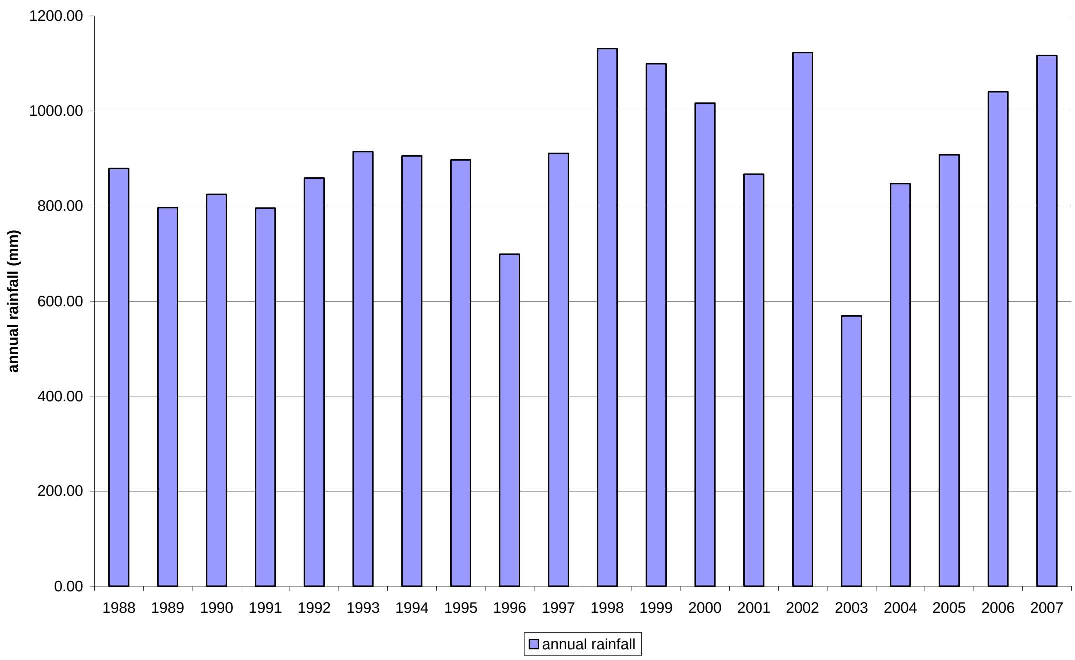
In addition, summary data for 1971 -2000 are available for Carlisle as well as more detailed records from the nearest Met Office recording site at Newton Rigg, near Penrith. This site is approximately 30 kilometres from the study site and 169m above sea level, whereas Bolton Fell is at 90m ASL (Met Office, 2008).

5.1.1 Rainfall recorded by Sinclair Horticulture at Bolton Fell works

Sinclair Horticulture has a manually emptied graduated cylinder rain gauge at the peat processing works at Bolton Fell Moss. This is recorded and emptied daily on working days by Sinclair staff. It is not emptied on weekends or during closure periods such as Easter and Christmas, so data following these closures are composite rainfall for the closure period. These data are therefore useful for determining weekly or monthly averages but are not suitable for fine scale analysis. These data are used in this study to provide an overview of rainfall conditions for the site for a longer period that the study period, to cross check with the data from the automated recorders to verify accuracy and consistency and to compare with the Met office rainfall data to ensure that they are appropriate to this study.

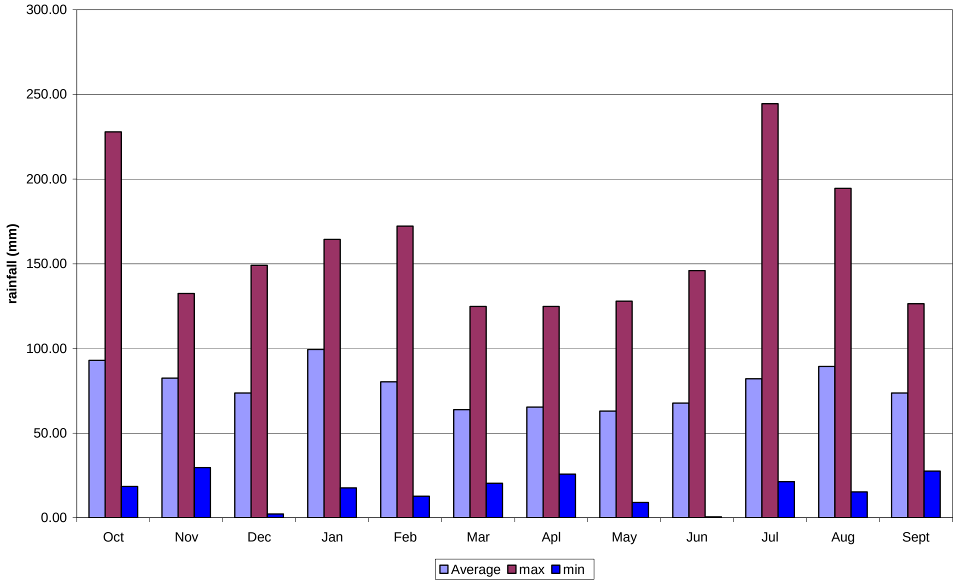
Figure 5.1 shows the annual rainfall recorded at the peat works at Bolton Fell Moss between water years 1988 and 2007. Average annual rainfall for this period was 935.54mm, with a maximum of 1123.1mm in 2003 and a minimum of 698.81 in 1996. Standard deviation for these data was 122.72

Figure 5.1: Annual rainfall as measured by Sinclair Horticulture 1988- 2007



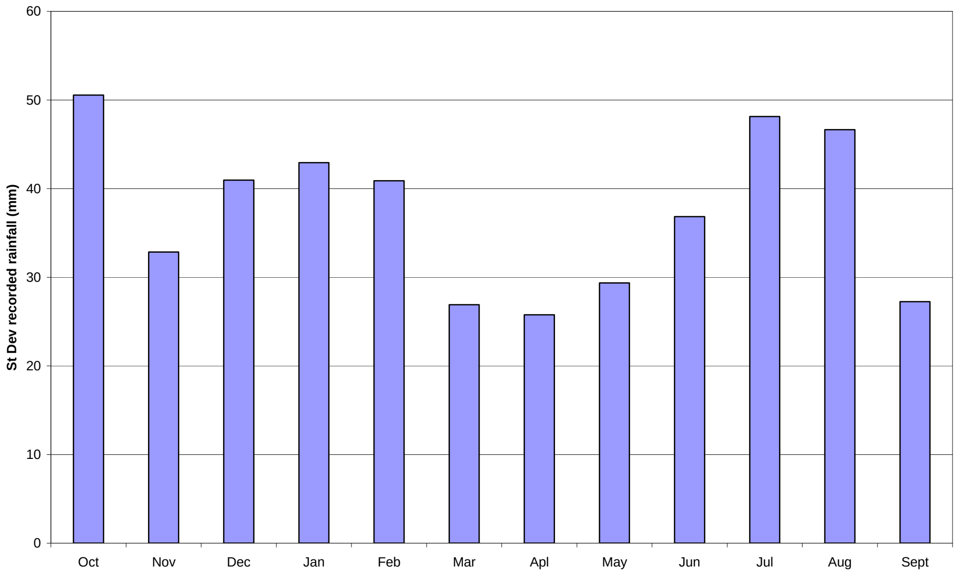
Monthly mean rainfall values are shown in Figure 5.2, together with maximum and minimum monthly values. The minimum average monthly rainfall is 62.92mm in May and the maximum average value is 99.37 in January. However, the absolute minimum recorded was 0.5mm recorded in June 2002 and the maximum rainfall was 227.9 in October 2006.

Figure 5.2 Monthly rainfall as measured by Sinclair Horticulture, 1988-2007



The Standard deviations of these monthly values are shown in Figure 5.3 and reflect the wide variation in rainfall experienced by the site across the whole year.

Figure 5.3 Standard deviation of Sinclair Horticulture monthly rainfall data 1988-2007



5.1.2 Rainfall recorded by tipping bucket rain gauges

When monitoring by Nottingham Trent University began in October 2003, the existing rainfall data from Sinclair Horticulture were initially supplemented by data from a Casella tipping bucket rain gauge, illustrated in Figure 5.4. Data from this equipment are available for the period December 17 2003 to 20 November 2005. This equipment was replaced at this time by an ELE automatic weather station, illustrated in Figure 5.5. Due to mechanical failure, data from this equipment are not available until 23 May 2006, meaning the only rainfall data available for Bolton Fell Moss are derived from the Sinclair Horticulture measurements. Under normal circumstances it would be prudent to run both items simultaneously for a period following installation to avoid such data loss, however mechanical failure of a Casella device at another research site necessitated the immediate relocation of the Bolton Fell rain gauge.

Figure 5.4 Casella tipping bucket rain gauge

(Casella CEL, 2009)

Figure 5.5 ELE Cumulus automatic weather station installed on Bolton Fell Moss

The Casella rain gauge has a stated accuracy of 1% / litre and has a 2mm bucket fitted in this instance. The ELE tipping bucket is the same size. Data are recorded only at times of rainfall, whereas the ELE weather station records antecedent rainfall at hourly intervals. In order to provide comparable data sets, the data from the Casella rain gauge has been converted to an hourly format. It should be noted that although the weather station also records other data including temperature, wind direction and speed and humidity, the lack of comparable data from other periods has meant that these data were not used in this study. The data collected by the casella are shown in Figure 5.6 and the data collected by the ELE weather station are shown in Figure 5.7.

Figure 5.6 Rainfall data collected for this study by the casella rain gauge

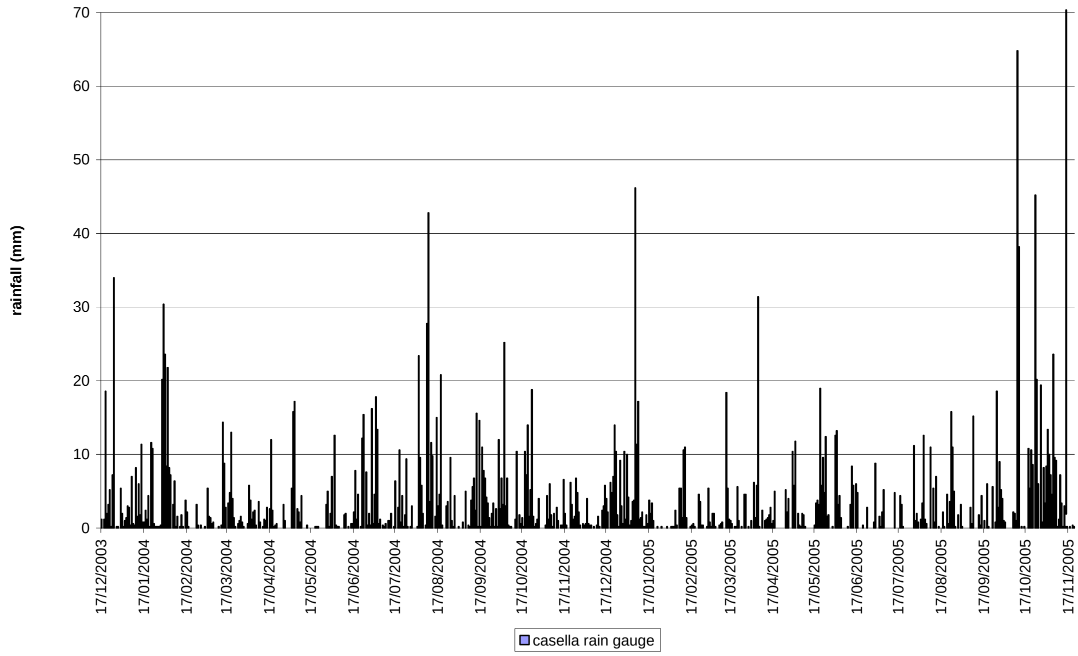
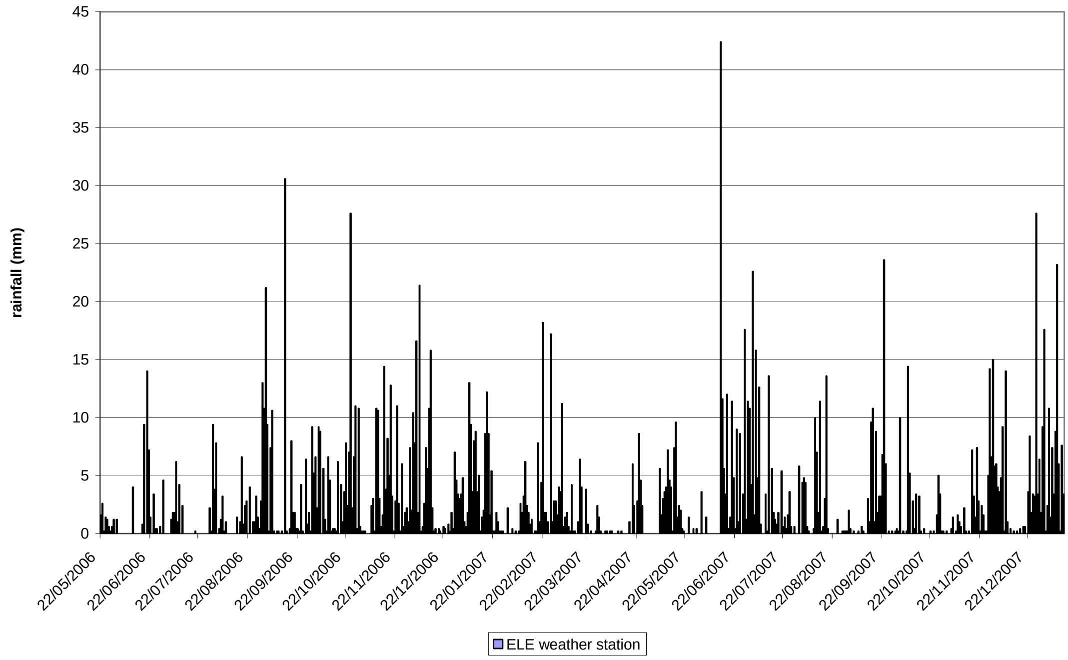


Figure 5.7 Rainfall data collected for this study by the ELE Cumulus automated weather station



Both data sets illustrate typical seasonal variation, with wetter winters and drier summer periods, but it is interesting to note that both Summer 2007 and Summer 2004 have exceptional rainfall.

Figure 5.8 shows a comparison of recorded rainfall for automated and manually recorded rainfall in September 2004. As can be seen, the data are broadly similar. Where there are significant differences, such as for the 19 September 2004, these data were for a Monday, and included rainfall for the weekend, when daily rainfall was not recorded. If the rainfall for the weekend is included, the totals for both the Casella and Sinclair records, 19mm and 21mm respectively, are much closer. It is also of note that very small amounts are often not recorded by Sinclairs. It is likely that small amounts were overlooked by the recorder at the works, or were allowed to accumulate. There are only very occasional substantial anomalies between the data, such as on 14 September, where rainfall recorded automatically is significantly greater than at the works. The possible explanations for this include mechanical error with the logger or recording error on the part of Sinclairs. Whilst mechanical failure of the automated loggers cannot be ruled out, in such circumstances low or zero recordings would be more likely. This was not a date when NTU fieldworkers were on site, and therefore interference due to maintenance of the recorder can be confidently ruled out. It is therefore more likely to be due to an error, such a spillage, at the time of manual recording.

Figure 5.8 Comparison of Casella and manual rain gauge data for September 2004

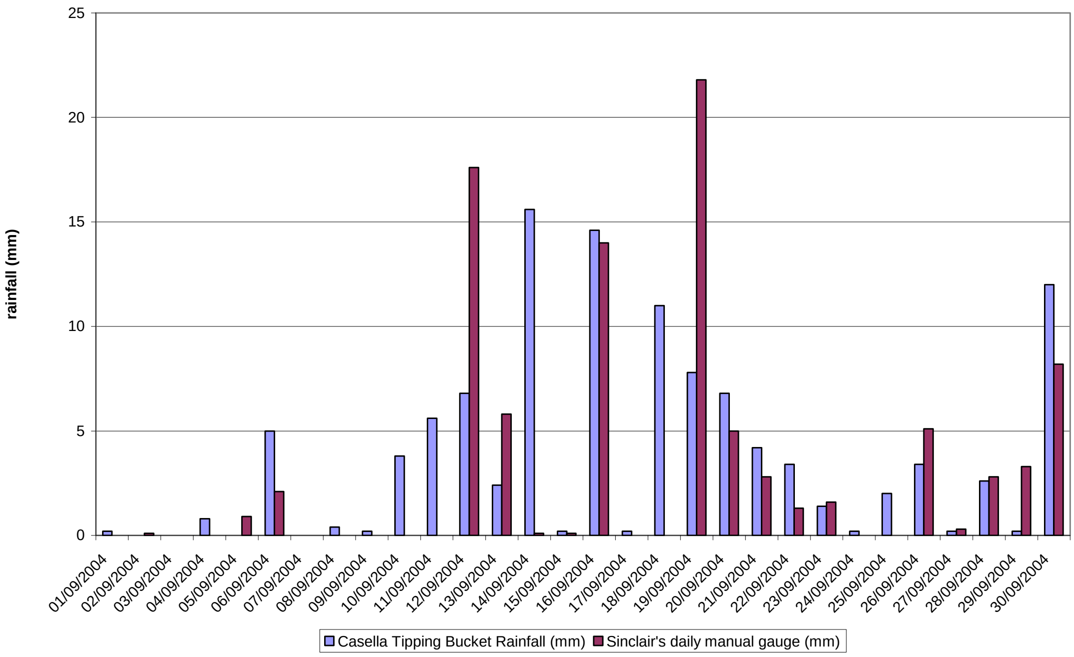


Figure 5.9 Comparison of Automatic weather station and manual rain gauge data for September 2004

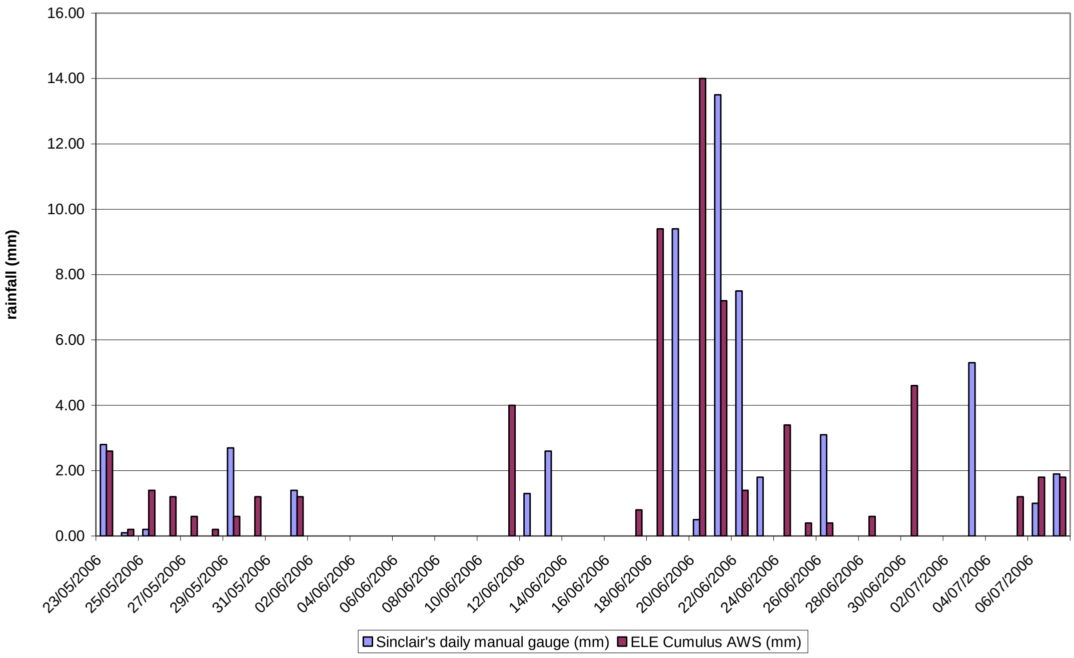
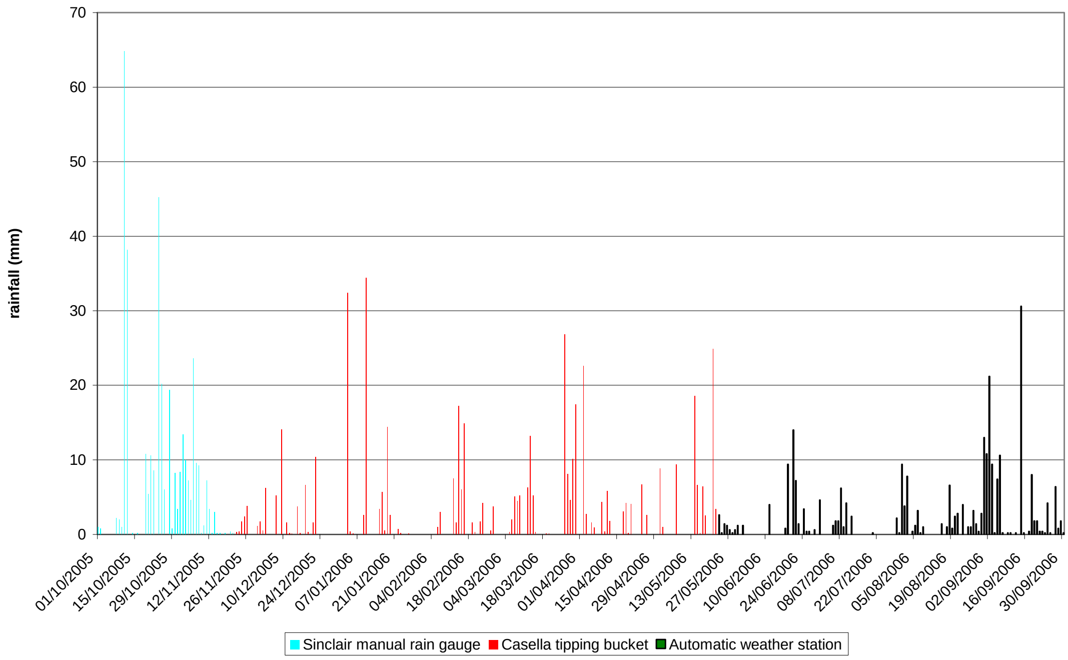


Figure 5.9 shows a comparison of data from the automatic weather station and the manual rainfall data. A similar pattern of correlation can be seen and here and again, temporal differences can be explained by the absence of recording staff at weekends.

5.2 Composite rainfall series for Bolton Fell Moss

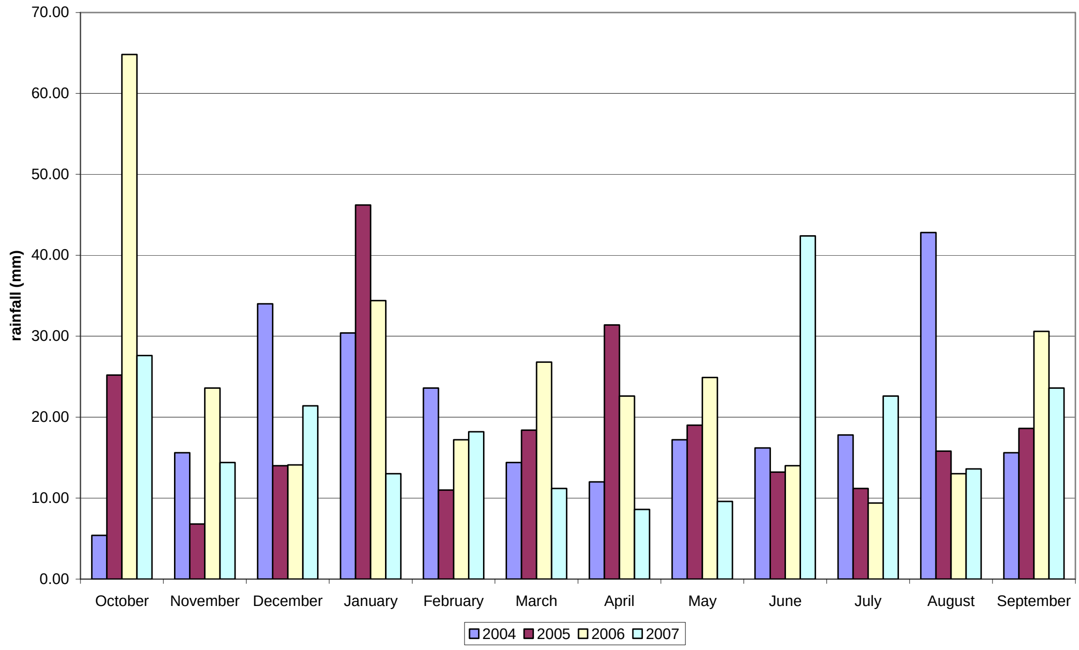
Given that recorded data from all three methodologies have a good degree of consistency, a composite series can be constructed which gives an overall record of rainfall at Bolton Fell and Walton Mosses for the duration of the study without significant breaks. These data are given in Appendix 1. Such a composite series can only be at the resolution of the coarsest data, and the data recorded at the works are recorded daily. However, with weekend and other breaks, these are better considered as weekly or monthly antecedent data, where such breaks can be accounted for. The composite series for 2006 are illustrated in Figure 5.10, where because of the replacement of the Casella rain gauge and the initial failure of the weather station, all three data sources have been used to build the composite series. The break between 23 December 2005 and 1 January 2006 represents the Christmas closure period when no one was available to read the rain gauge. These Christmas closure periods are the longest gaps in the four year series. The rainfall recorded on the 2 January should therefore be regarded as antecedent rainfall for the Christmas period, rather than a single event.

Figure 5.10 Composite rainfall series for water year 2006



Daily rainfall records illustrated in Figure 5.11 show that the mean daily rainfall for each month varies between 0.94 mm in April 2007 and 8.27mm in October 2006, highlighting that notwithstanding exceptional events, rainfall during the study period is consistent and frequent. It has been suggested for healthy bog development and maintenance, ground water levels should remain within 100mm of the surface (Tantram *et.al*, 1999). This in turn suggests that the frequency of rainwater inputs to offset losses from evapotranspiration and runoff are at least as important as the volume of input (Bromley and Robinson, 1995).

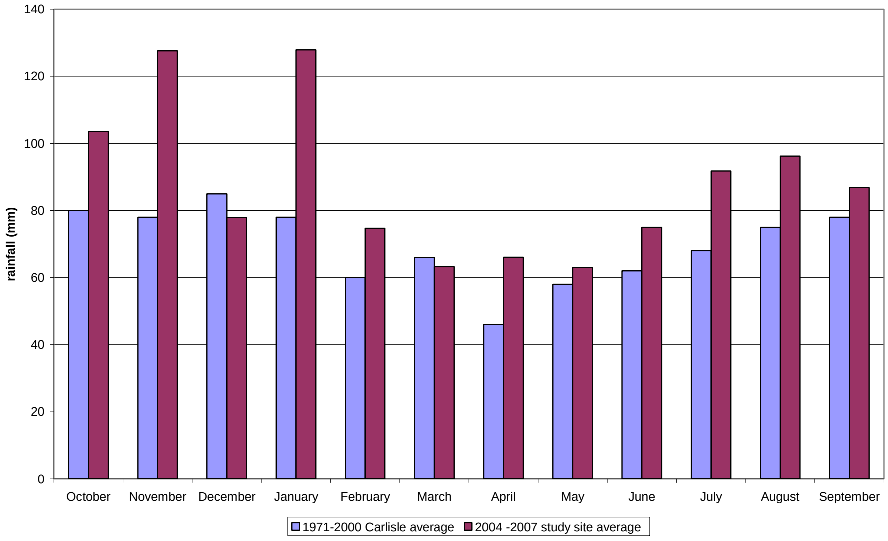
Figure 5.11 Maximum daily rainfall recorded by month for the study period



5.3 Regional and long term data from met office

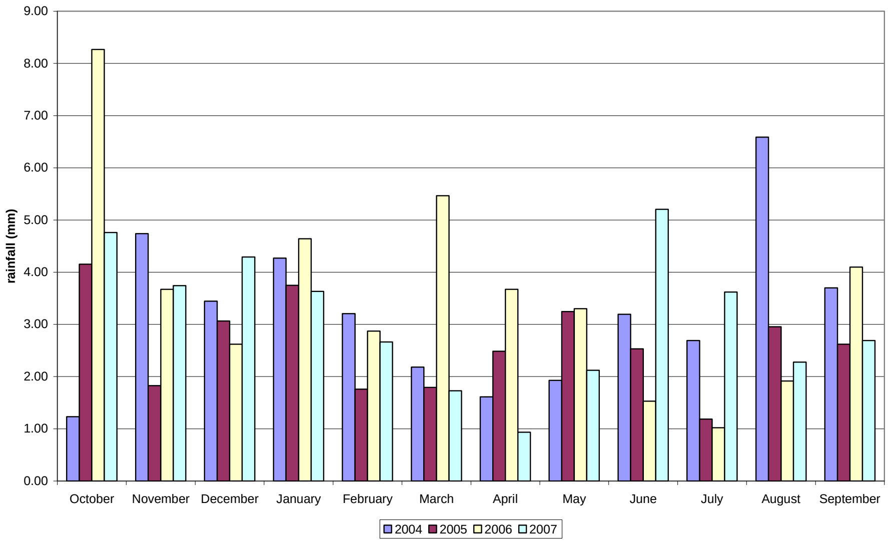
Monthly averages for Carlisle provided by the Met Office for the period 1971 -2000 are shown in Figure 5.12, together with monthly averages for the study site between 2004 and 2007. Using these data for Carlisle, it can be seen that during 2004 to 2007, the period of the study, rainfall was considerably higher in all Autumn and Winter months apart from December, which was close to average. Rainfall was 50mm higher in November and January, whilst study period average was 7mm lower in December. In Spring and Summer, rainfall totals were also consistently higher, with a minimum of 5mm (May) and a maximum of 20mm (July) elevation over the 29 year average. Over the whole period, monthly rainfall was 18mm higher than during the 1971-2000 period at Carlisle.

Figure 5.12 Comparison of average monthly rainfall at Carlisle for the period 1971 – 2000 and average monthly rainfall derived from Bolton Fell composite series



Individual monthly totals for each year are shown in Figure 5.13 and show that there is considerable variation in monthly rainfall between the years of the study period. Whilst none of the years studied conform to the average data, they do all show similar seasonal patterns of variation. It is worth noting that in both 2005 and 2007 the largest single rainfall events occurred in Summer Months, although the frequency and duration of rainfall was greater in the Winter.

Figure 5.13 Mean daily rainfall by month for the study period

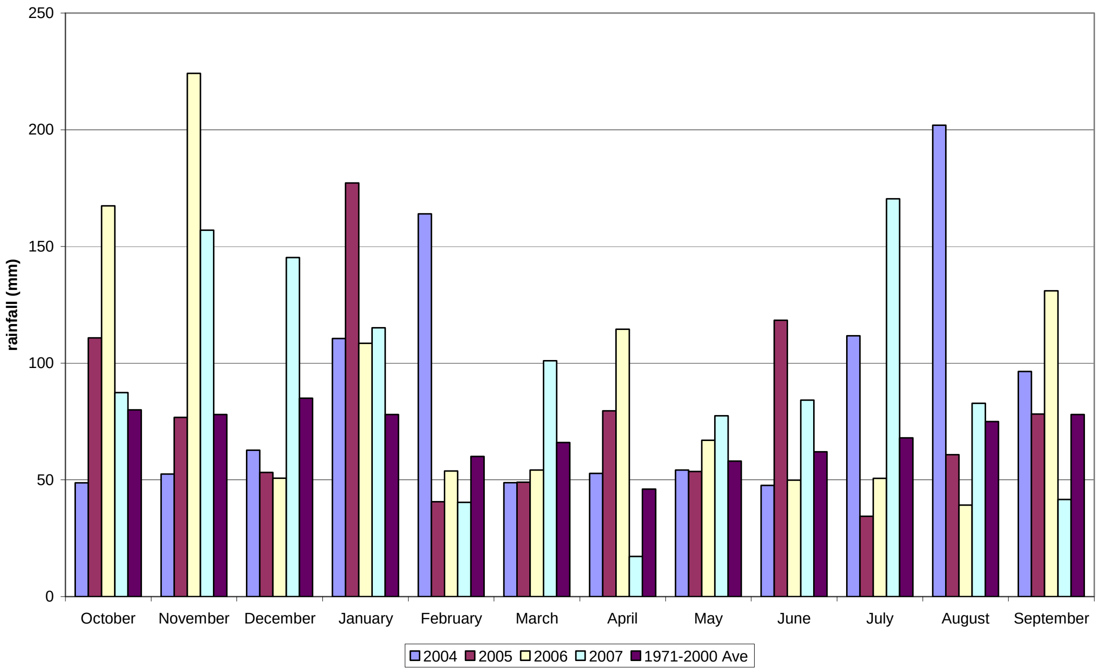


The highest monthly total recorded at the study site was 224mm in November 2006. The lowest monthly total was 17mm in April 2007. From Table 5.3 & Figure 5.14, it can be seen that the driest months during the study period were March and May, and this is reflected in the 1971-2000 figures which also show the Spring period to be the driest months.

Table 5.1 Monthly rainfall totals for each water year of the study.

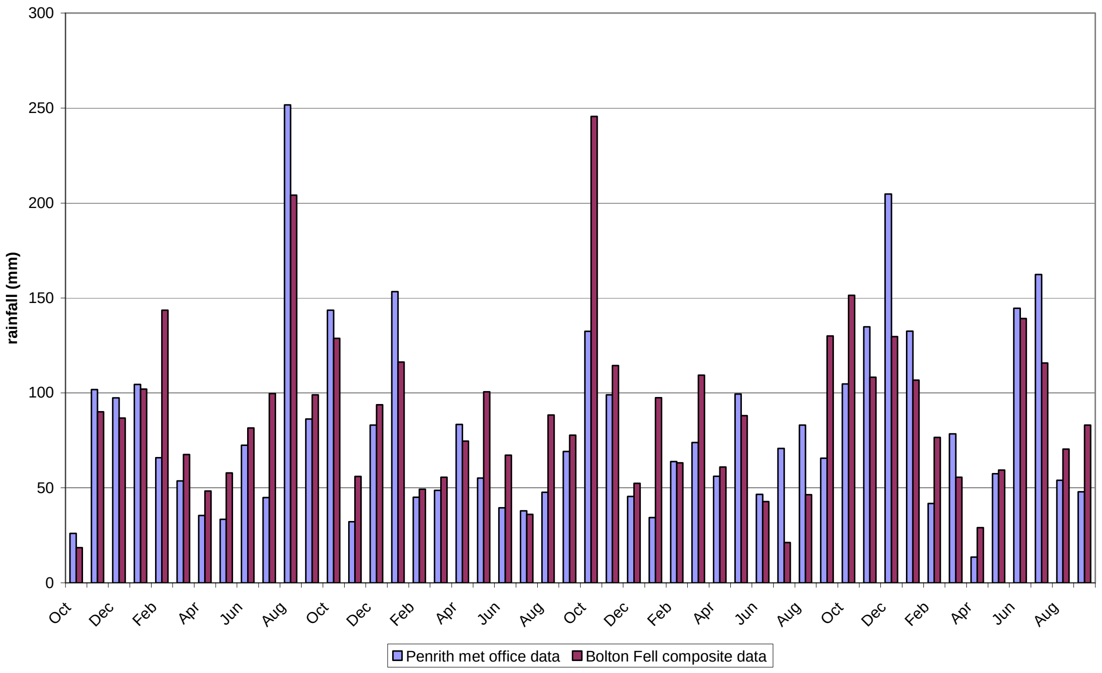
Water Year		2004 (mm)	2005 (mm)	2006 (mm)	2007 (mm)	met office average 1971-2000 (mm)
month	October	48.73	110.8	167.4	87.4	80
	November	52.5	76.8	224.2	157	78
	December	62.7	53.2	50.7	145.2	85
	January	110.6	177.2	108.48	115.2	78
	February	164	40.6	53.8	40.4	60
	March	48.8	49	54.2	101	66
	April	52.8	79.6	114.58	17.2	46
	May	54.2	53.6	66.9	77.4	58
	June	47.6	118.4	49.9	84.2	62
	July	111.8	34.4	50.6	170.40	68
	August	202	60.8	39.2	82.8	75
	September	96.4	78.20	131	41.6	78

Figure 5.14 Comparison of monthly rainfall for each year of the study with Average values for Carlisle.



Whilst Carlisle is closer to Bolton Fell at 8km and at a closer altitude (28m and 100m AOD respectively), Data from the Met Office for Newton Rigg (Met Office, 2008) which is 35 km to the south near Penrith and at an altitude of 171m are more appropriate for more detailed study as they were higher temporal resolution. Monthly rainfall totals for the period of study are given in figure 5.15, together with recorded totals from the composite series for Bolton Fell Moss.

Figure 5.15 Comparison of monthly rainfall at Study site and Newton Rigg.



The Met Office state that average annual rainfall for Newton Rigg is 929.6mm. For the 4 years of the study, mean rainfall for Bolton Fell Moss is given in Table 5.2.

Table 5.2 Newton Rigg mean rainfall 2004-2007

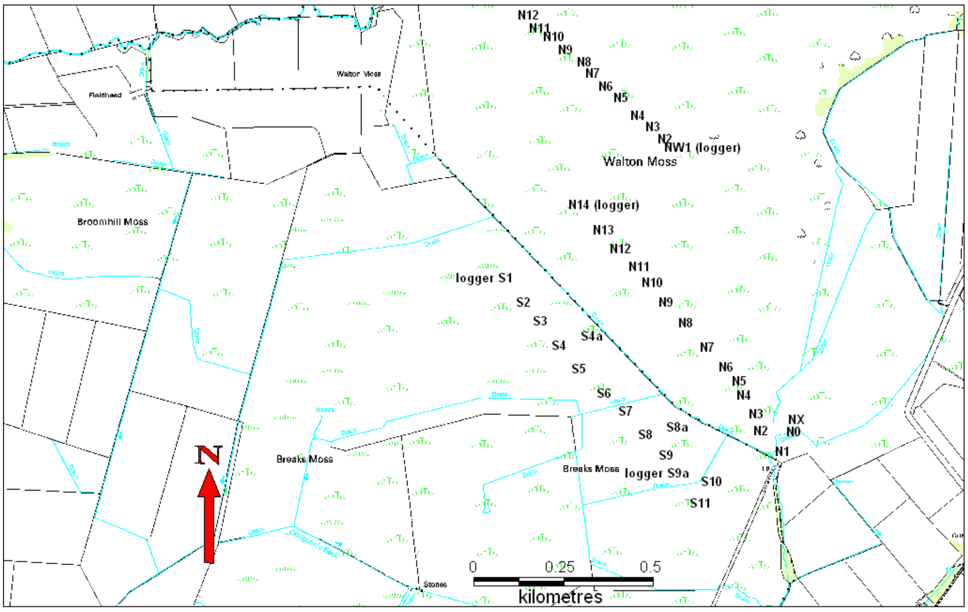
Year	Annual rainfall (mm)	Days rainfall <=1mm
2004	1096.30	137
2005	971.6	157
2006	1087.66	148
2007	1142.4	136
Average Newton Rigg 1971 – 2000	929.6	149

Both the annual rainfall and the number of days with very low or no rainfall are close to the Newton Rigg average figures suggesting that whilst there is variation in monthly rainfall patterns, the years of the study are not notably distinct from the usual rainfall patterns. Even in months of notably high rainfall, such as October 2005, or November 2006, there were no months without at least one dry day. The highest single days rainfall was 64.8mm on 11 October 2005. At this time the Met Office recorded 109mm at Carlisle over the period 11-12 October due to a notably deep low pressure. By contrast the period of nationwide heavy flooding in June 2007 recorded 42mm over the 24 hour period of 13th June. Other notable peaks in rainfall also conform to exceptional rainfall events.

5.4 Data recorded for depth to water table at Walton Moss

Dipwell transects have been regularly monitored for the whole of the study period. The approximate positions of these transects are shown marked on the air photograph in Figure 5.4.1 These data give a good spatial representation of the water tables on both sites for the dates they were read and are used to give an indication of bog hydrological condition on these dates. Results are given for each transect, which is identified by its orientation and, for Walton Moss, by its suggested hydroecological condition. The data recorded for each transect are described. It should be noted that distances between dipwells are not to scale. Summary data for each dipwell are given in Appendix 2 and the complete data for each dipwell in Appendix 3.

Figure 5.16 Map of Walton Moss showing transect locations



Crown Copyright/database right 2007 An Ordnance Survey/EDINA supplied service

5.4.1 Dipwell results for north transect

This transect was installed in October 2003 and is 1300 metre long and lies between grid references NY505665 and NY511659. It crosses an area of Walton Moss which has not been subject to artificial drainage, although it is potentially affected by a mineral ridge crossing the transect midway. It is also still possibly affected by old drainage forms in the lagg area at the bottom of the slope and by the ditch by the fence separating the north transect from the south transect. It was originally installed to monitor what was considered to be a relatively intact area of Walton Moss and to act as a control for monitoring the nearby south transect which was believed to be affected by agricultural herringbone drains. Annual average water levels together with maximum & minimum levels and the standard deviation of depth to water table for each dipwell are given in Appendix 3. Dipwells are spaced at approximately 100m intervals, but are placed more closely in areas where there is an abrupt change in condition, such as the edge of the bog dome.

Annual average depths to water table for each dipwell are show in Figure 5.17. 2006 was the driest year of the study with water depths below 10cm for almost all of the transect apart from the central most dipwells N12, N13 & N14. Dipwells Nx and N0 were installed on the edge of an area of predominately *Juncus spp*. near the outflow stream and although within 20m, are not aligned with the transect. Dipwells N1 to N4 are aligned with the transect, but are located in the lower part of the site in the area of lagg fen, which has different soil and vegetation characteristics, described in section 6.1.2. The possible effect of the mineral ridge may be observed in dipwell N9, which is much drier than the surrounding dipwells.

Figure 5.18 shows the standard deviation of the depth to water table for each dipwell. It can be seen that variation broadly reflects low mean water levels shown in figure 5.17, but that in the centre, notionally the most intact section of bog, the variation in water levels is much lower. This broadly agrees with the concept that healthy bog has a high and constant water table (Lindsay, 1995).

Figure 5.17 Annual average water depth for each dipwell on Walton Moss north transect

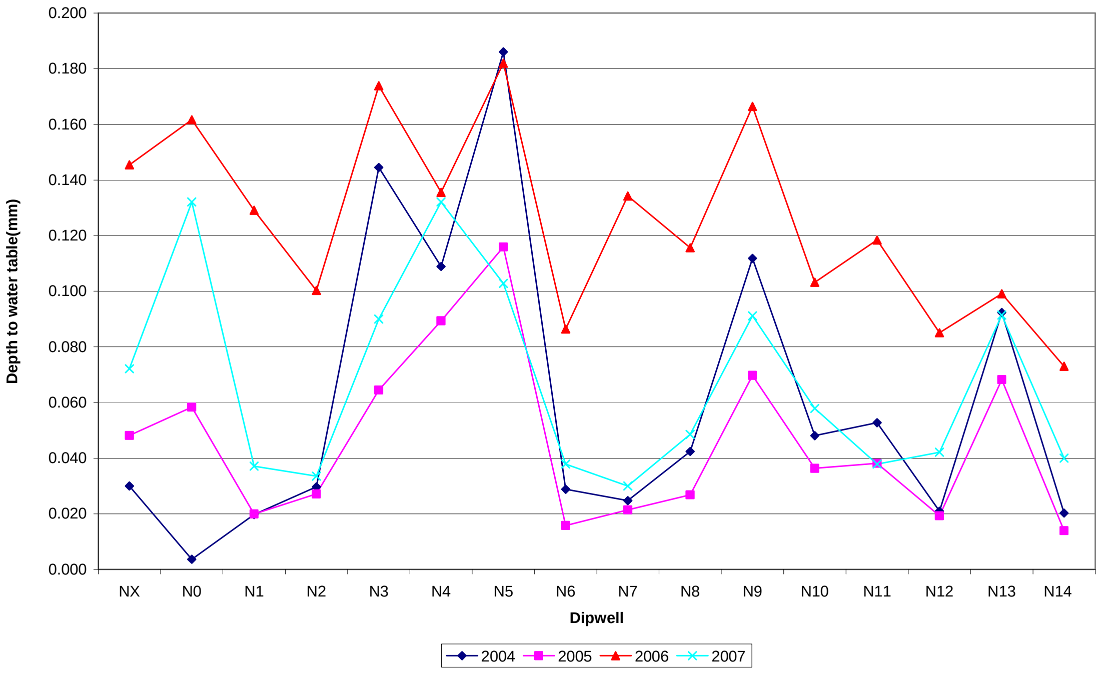
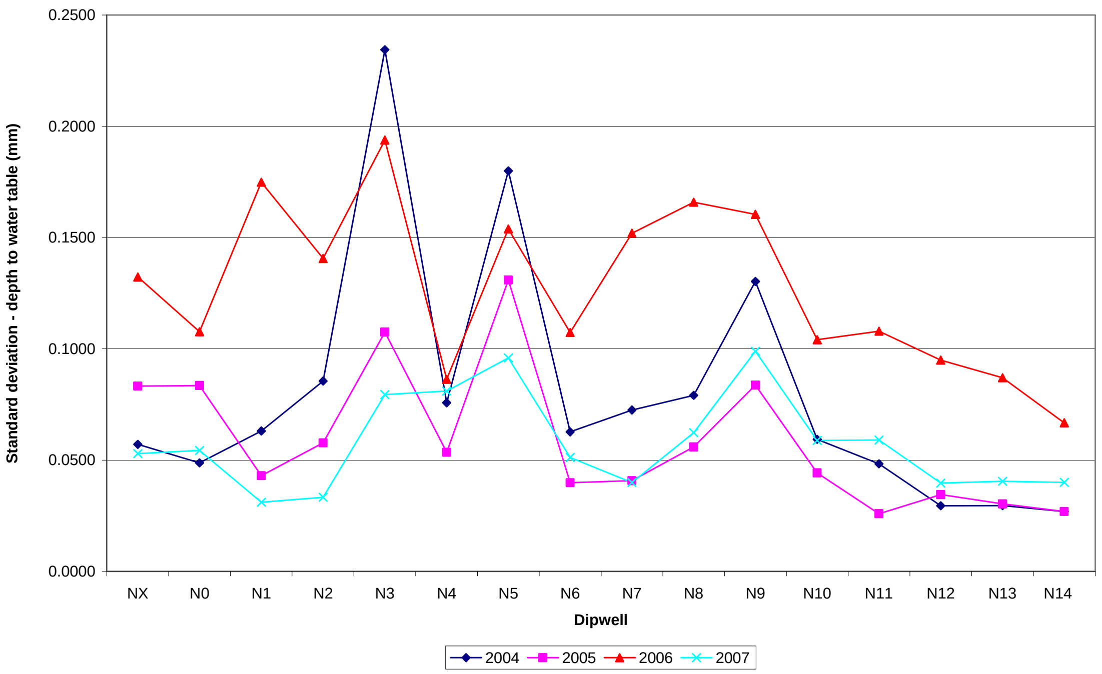


Figure 5.18 Standard deviations of water depths for each dipwell on Walton Moss north transect



5.4.2 Dipwell results for south transect

The south transect was installed in 2003 and is 1200m long and runs between grid reference NY503661 and NY507658. It was originally installed as part of the Labadz and Butcher (2006) report to Natural England to monitor the effect of the herringbone drains. It is influenced along almost all its length by shallow agricultural drains dug in the 1980s to improve the site for grazing. From observation, it appears that these drains are naturally re-vegetating, but that they are continuing to have an effect on the overall hydrology of this section of the bog. Notwithstanding these drains, there is also a continuation of the mineral exposure noted on the northern transect. Dipwells are spaced uniformly at approximately 100m intervals on the line of the main transect, but additional dipwells have been placed to investigate the effects of drainage and at 9a to provide calibration data for the automated logger located there.

Dipwells S4a and S8a were specifically installed to monitor the immediate effect of the minor herringbone drains. dipwells S4a and S8a are located near to minor drains, whereas S4 and S8, although located within 10m of their associated dipwells are further away from the ditches. Dipwells S10 and S11 are located in very shallow peat and into the mineral substrate, and it is believed that they are close to the original boundary of the true raised bog area. In addition S10 is close to the main ditch which takes much of the drainage from the herringbone drain towards the site boundary and lagg stream.

Mean depth to water table, shown in Figure 5.19, shows notable anomalies. There is no obvious reason for S2 to be drier than nearby dipwells and may indicate the effect of an adjacent ditch. S4a and S8a are noticeable drier than their associated dipwell, but the notable peak at 8a is mirrored by a peak at dipwell S5, not 4a. The exceptionally dry dipwell at S10 probably indicates the gross effect of the nearby ditch. Standard deviation of dipwell levels, as shown in Figure 5.20, shows more consistent variation in levels, apart from the large differences observed at S10, again probably as a consequence of drainage.

It is interesting to note that the variations in amplitude between adjacent dipwells is greater on the notionally pristine transect, and that annual variation is also larger. The variation in levels of the dipwells, as reflected by the standard deviation is also greater on the northern transect.

Figure 5.19 Annual average water depth for each dipwell on Walton Moss south transect

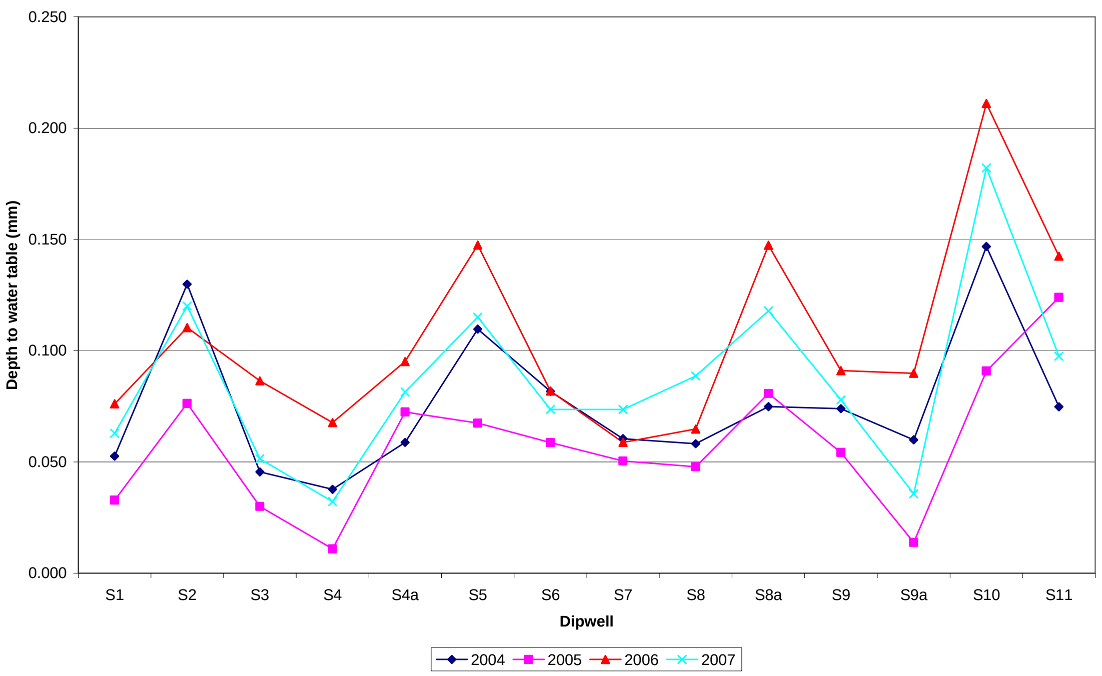
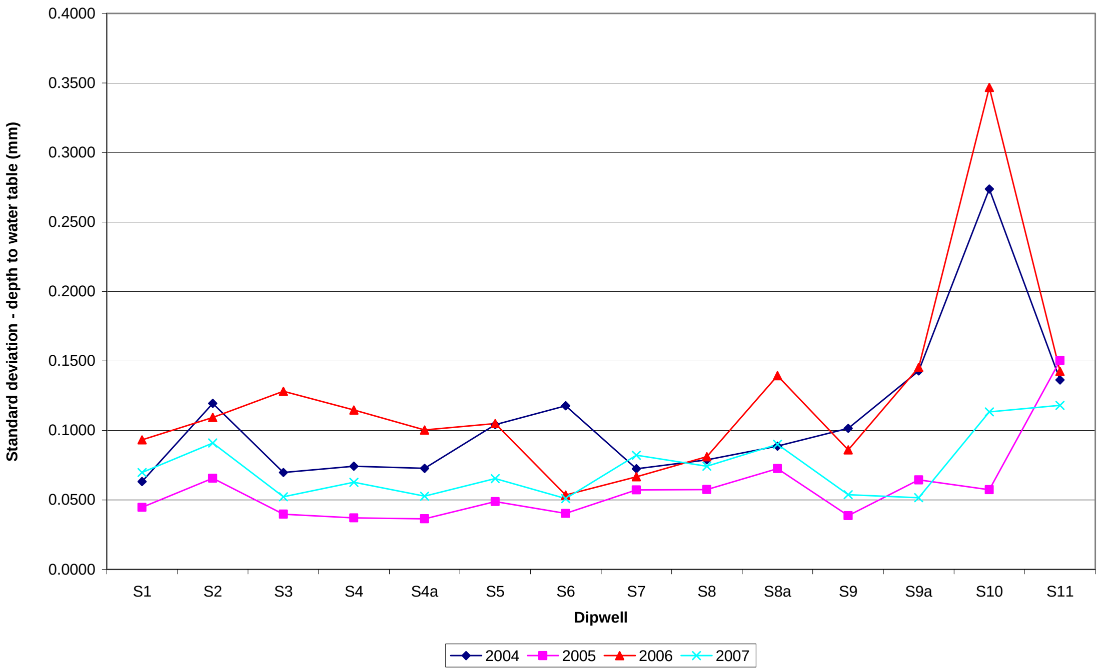


Figure 5.20 Standard deviations of water depths for each dipwell on Walton Moss south transect



5.4.3 Dipwell results for north west transect

Unlike the herringbone and relatively undisturbed transects, the north west transect was specifically installed to assist with this study in 2006. The intention of this transect is to give an overview of the hydrological condition of an area of bog judged to be in ideal ecological condition. It runs from the centre of the site at NY506669 to NY503671 near to the Flosh boundary stream. It is 650m long, which is shorter than the other two transects and the dipwells are more closely spaced together, at a uniform 50m separation. It is also important to note that the time series for these data is much shorter, as it was installed later than the other transects. Notwithstanding these caveats, the water levels here appear to be consistently higher, with much lower variation. These data therefore cast some doubt on the initial description of the north transect as undamaged (Labadz and Butcher, 2006).

Figure 5.21 shows the mean depth to water table. Water levels stay very close to the surface for this transect during the water year 2007, the only year for which data is available. The only substantial low water levels are near the boundary of the site, off the dome of the bog at dipwells N12 and 13. For the remaining dipwells water levels are either above the surface of the bog, due to localised flooding, or within 3cm of the surface. Figure 5.22 shows the standard deviation of dipwell depth for 2007, and again shows little variation compared to the other transects. Whilst this does suggest that water levels remain constant all year, it must be remembered that this is one years data, and that it is not complete, as dipwells were not measured during the winter period. However, it should be expected that the winter period would have been consistently wetter, and that therefore, measuring during summer only would result in more variation in dipwell levels and would therefore increase the standard deviation for the year.

Figure 5.21 Annual average water depth for each dipwell on Walton Moss north west transect

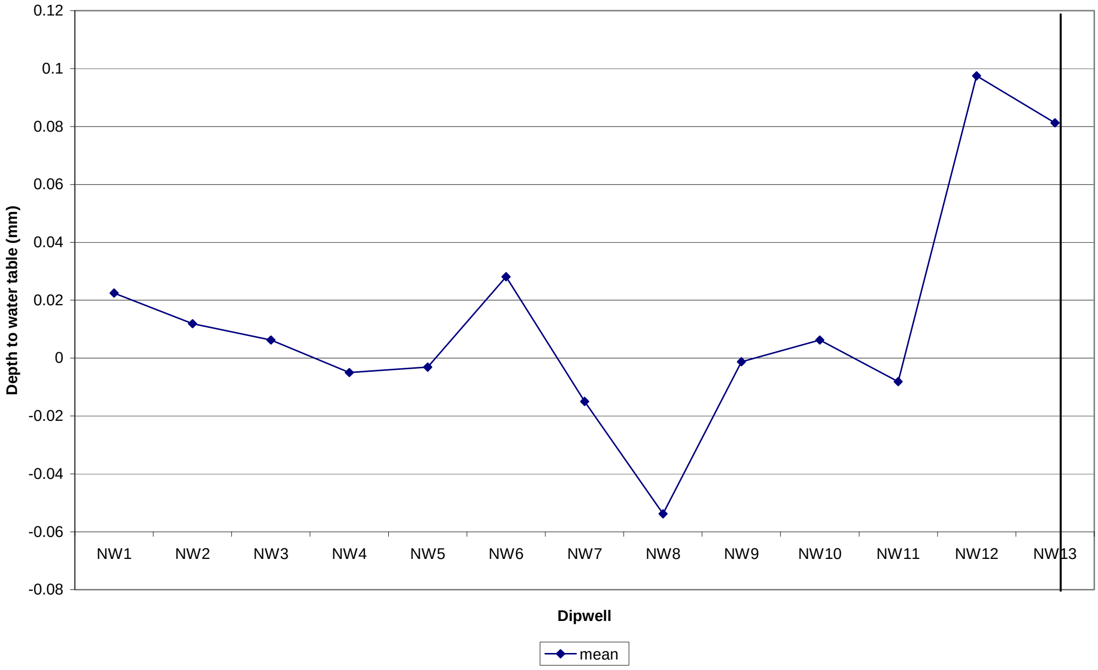
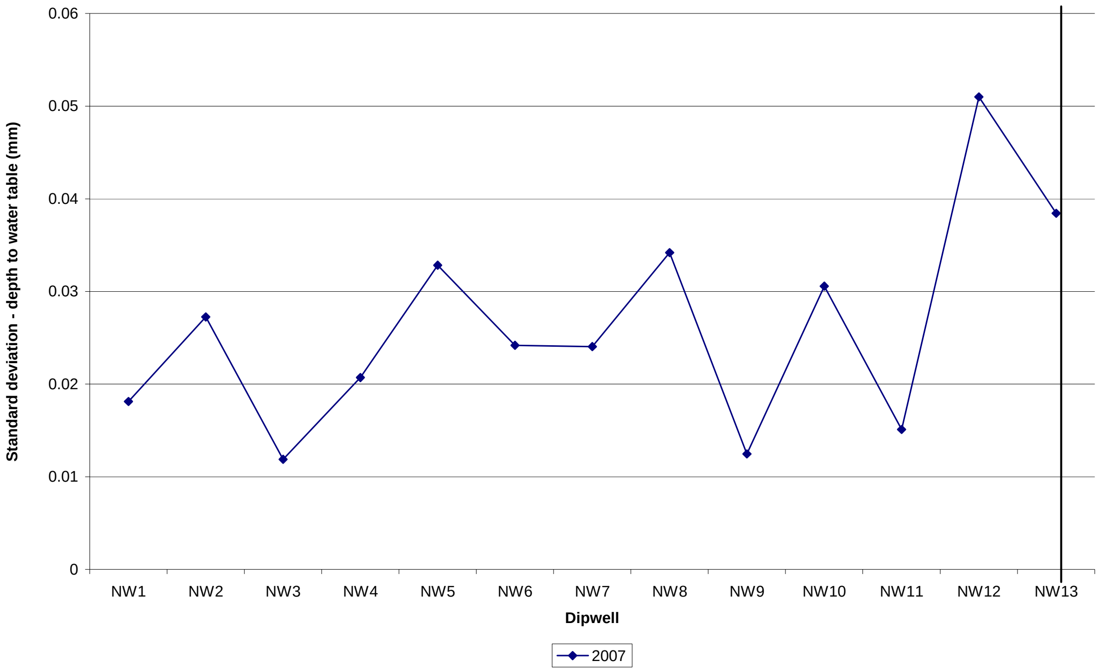


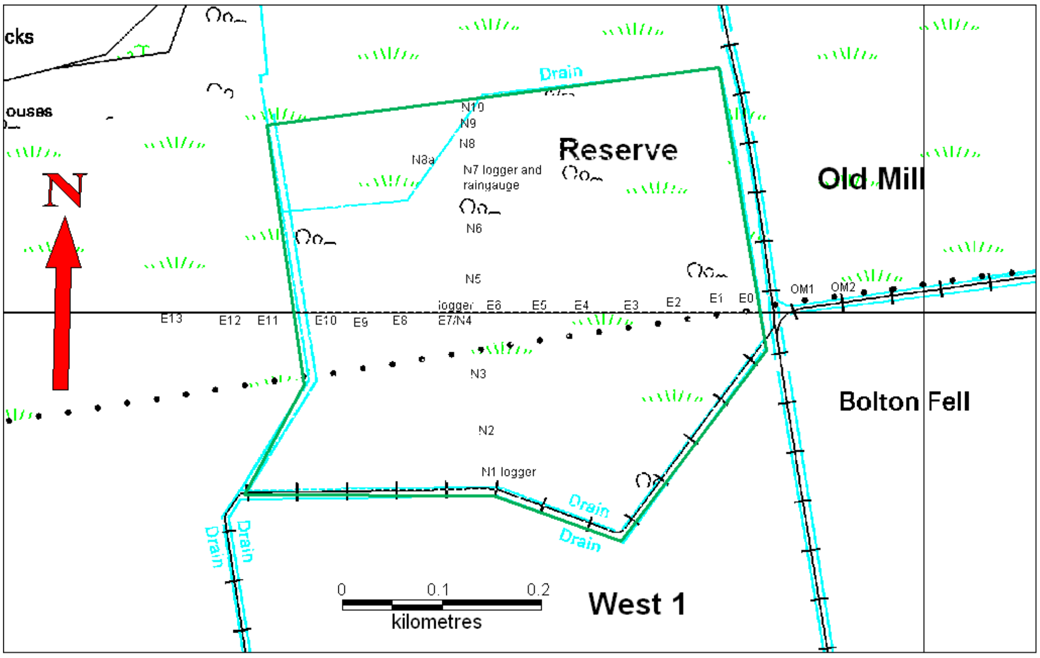
Figure 5.22 Standard deviations of water depths for each dipwell on Walton Moss north west transect



5.5 Data recorded for depth to water table at Bolton Fell Moss

Dipwells were installed at Bolton Fell Moss in 2003 to monitor how adjacent peat extraction and drainage operations were affecting the hydrology of the Reserve area of unexcavated peat in the centre of the site. The locations of the transects are shown in figure 5.23. It should be noted that aerial photographs for this site were not available for use in this study. These transects cross the site on the north-south and east west axes, intersecting at the E4/N7 dipwell, where there is also a thalimedes water level data logger. The North transect is 450m long and runs from NY 485692 to NY485668. The East transect is 600m long and runs from NY483689 to NY488690. The two transects intersect at NY485689. Both transects initially extended into the excavated peat area, but proved dangerous to read in wet conditions due to soft peat, and were also subject to periodic arbitrary relocation to enable peat cutting. It was therefore decided not to use the data obtained from these outlying dipwells.

Figure 5.23. Location of Dipwells at Bolton Fell Moss



The whole of the reserve area has been subject to compaction of a boundary strip approximately 5m wide by Sinclair Horticulture, (Turner , Pers. Com.). This exercise was intended to impede water loss from the site into the surrounding perimeter drain, which is necessary to reduce water levels in the area of peat extraction. This boundary strip effectively isolates internal drains within the reserve area and appears to be having some success in reducing the hydraulic gradient across the reserve area and maintaining water levels to the perimeter. This site is much smaller than the Walton Moss site and both variation across the site and annual variation in water levels are much lower than at Walton. This may be as a result of scale effects or environmental differences and these are discussed in chapter 8.

5.5.1 Dipwell results for north transect

The North transect crosses a small area of bog which has been subject to ditch and baulk cutting which has left a series of ditches and elevated areas. This is a common form of peat extraction, but has been superseded by mechanical methods on the remainder of the site. Dipwells potentially affected by this landform are N8 to NM1. N8a is off the main line of the transect and was installed to monitor the effect of the internal ditch marking the boundary of the cut over area. Both N8 and N8a are affected by this ditch and show much higher mean depth to water table and variation in levels. N9 is much more similar to the remainder of the transect in both depth and variation, suggesting the impact of the cut over area is being partly mitigated by the boundary compaction and subsequent water retention, although the dipwells closer to the boundary are lower and more variable. Dipwell NM1 is within the compacted area. This boundary effect is not as pronounced at the southern edge, near dipwell N1, where levels and variation are more constant. There is a slight lowering in water level at dipwell N3, where the transect crosses an area of semi mature *Pinus sylvestis*. Tree cover increases localised water demand and could therefore be responsible for this. Annual mean dipwell depths are shown in figure 5.24 and the standard deviation of dipwell depths shown in figure 5.25.

Figure 5.24 Annual average water depths for each dipwell on Bolton Fell north transect

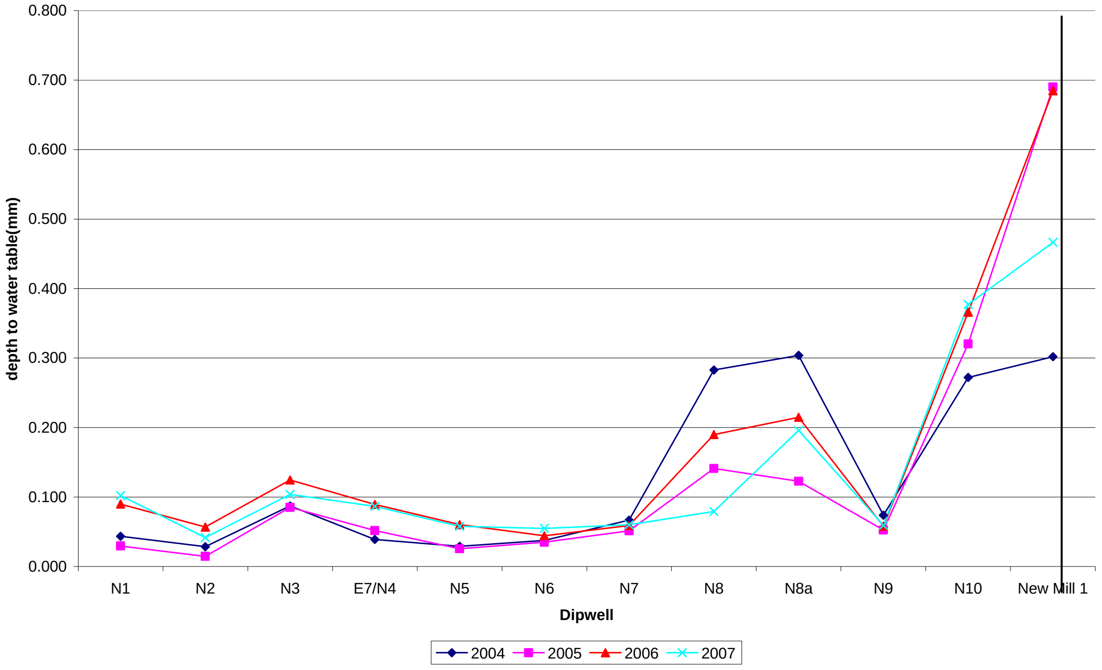
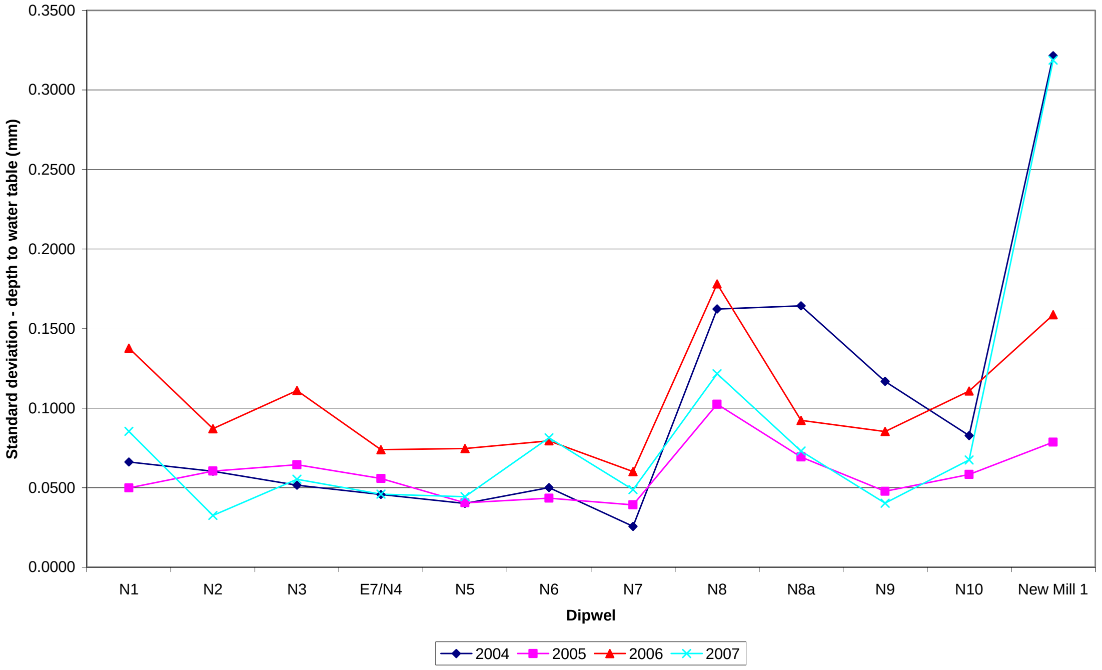


Figure 5.25 Standard deviations of water depths for each dipwell on Bolton Fell north transect



5.5.2 Dipwell results for east transect

The east transect crosses the site from the eastern boundary adjacent to the milled peat area to the area of uncut peat beyond the boundary of peat extraction consent to the west. The boundary of Sinclairs interest is adjacent to dipwell E11a and is marked by a substantial drainage ditch and the track of a light railway, used for removal of milled peat for processing. The transect was continued into an area of undamaged bog adjacent, which is still part of the Bolton Fell Moss ecotope but in different ownership. This area is represented by dipwells E11, E12 and E13.

The transect crosses the reserve area on a line adjacent to the area of Scots Pine crossed by the north transect. Whilst it does not enter the area of mature trees, the woodland area is encroaching into the remainder of the bog area and the transect is increasingly subject to young birch and pine scrub. This has been subject to periodic management to arrest succession, but no such management has happened during the study period. There has been no obvious hydrological management between the ditch and the eastern boundary of the reserve. The consistent increase water depth corresponding to dipwell N5 is therefore potentially a function of vegetation change. This may be of concern as this takes the mean water depth to below 10cm in 2006 and 2007, and indicates dry hydrological conditions in an area of central bog which should be buffered from peat extraction drainage. Water levels on the non drainage influenced dipwells are still lower than on the equivalent dipwells on the north transect, suggesting that the woodland area may be having an influence on ambient hydrological condition. The mean annual dipwell depths are shown in Figure 5.26.

Standard deviation of dipwell depths, given in Figure 5.27, are consistently low, compared to those of Walton Moss, but show greater variation than the north transect. There is also less annual consistency in variation. Low overall variation may again be a result of the shorter transects providing less opportunity for spatial variation and increasing the prominence of boundary effects.

Figure 5.26 Annual average water depths for each dipwell on Bolton Fell east transect

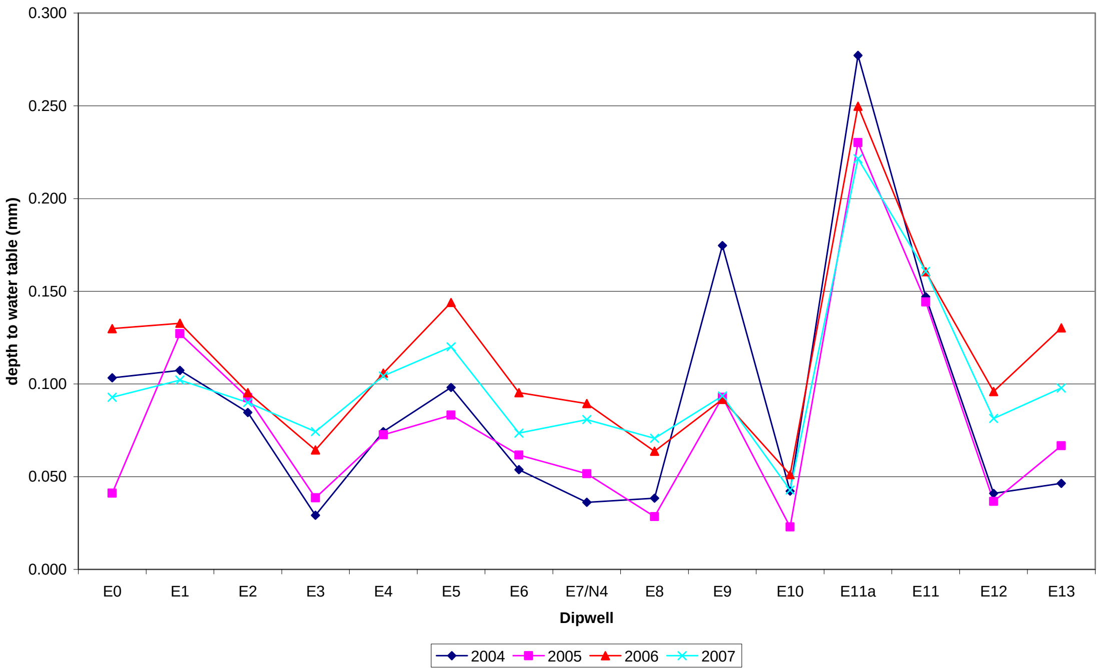
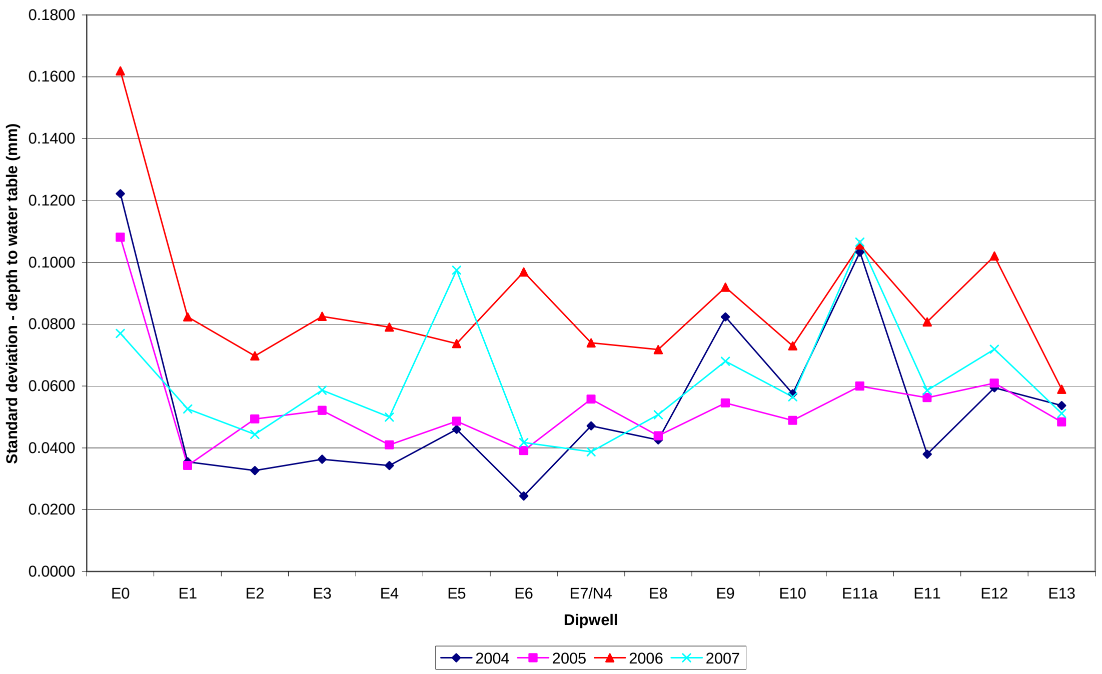


Figure 5.27 Standard deviation of water depths for each dipwell on Bolton Fell east transect



5.6 Short term variations for water table recorded by Thalimedes shaft encoders

To complement the spatial data provided by the dipwells, OTT Thalimedes shaft encoders were installed initially at 6 locations on Bolton Fell and Walton Moss to monitor fine scale variations at the centre and edges of the bogs. A further logger was added at Walton Moss in 2007 at the same time as the north west dipwell transect was established. These loggers were continuously recording at 15 minute intervals throughout the period of this study, although there were persistent problems with loggers which failed and had to be repaired or replaced during this time. This led to gaps in the data collection periods between 2003 and 2008. The data obtained provide very detailed temporal records of water level below surface for a limited number of fixed locations.

The data recorded by these loggers has been used to study the response of specific areas of the site to rainfall events. Difficulties arise with these devices due to slippage of the pulley wheel of the shaft encoder, or catching of the float and counterweight at periods of high and low extremes. This means data have to be calibrated against water levels recorded in adjacent dipwells. Slippage is not consistent or predictable, therefore results from periods long after calibration data are available must be treated cautiously. Additionally, the internal clocks of the data loggers will typically lose up to 10 minutes between downloads, which in practice limits temporal resolution when comparing with other data. As rainfall data is recorded hourly, this effectively dictates the minimum temporal resolution.

5.6.1 Short term variation in water levels at Walton Moss

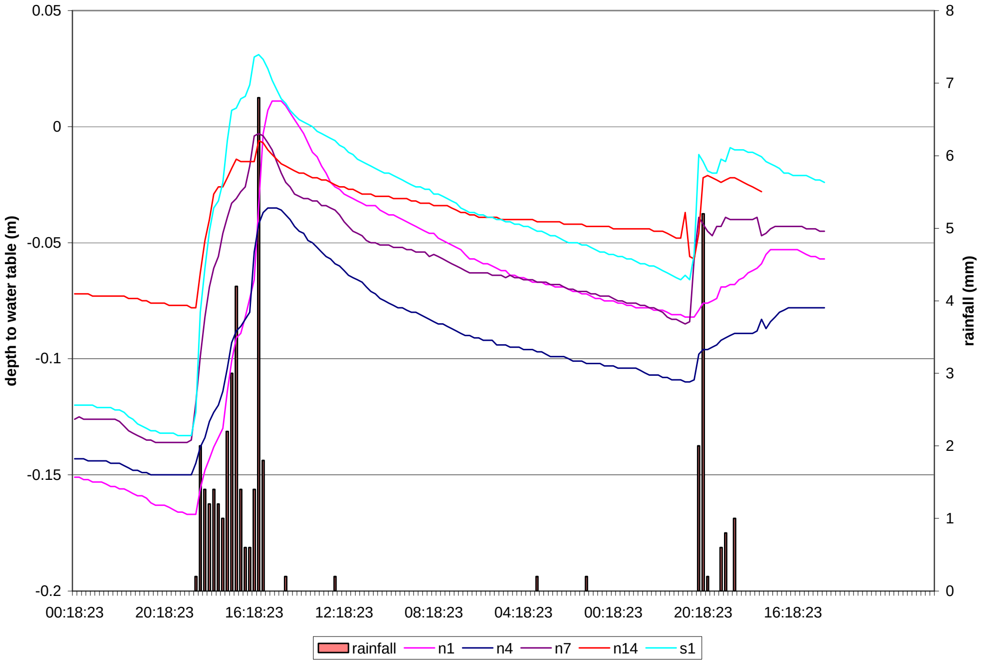
Loggers were initially installed at the top of the north transect, and at the top of the south transect. In addition, a logger was installed near the S9 dipwell at a location judged to be near the bottom of the bog mound of Walton Moss and also near the outflow of the herringbone drainage system in this southern section of the site. It was therefore possible to determine if sufficient additional surface water removed by these drains at times of rainfall would be reflected in the groundwater at this point. The retention of groundwater in the bogs could also be investigated by monitoring water levels in the period following rainfall.

5.6.2 Short term variation in water levels at Bolton Fell Moss

Data loggers were also installed on the Bolton Fell north transect near dipwells N1, the N4/E7 intersection and N7. N1 monitors the edge of the bog, near to the area of hydrological protection by compaction. N4 is a location close to the centre of the bog and is judged to be isolated from boundary hydrological effects. N7 is located towards the northern boundary, but still within the undamaged bog. It is close to the boundary of the cut over section and may give an indication of the effect of the associated drainage ditch.

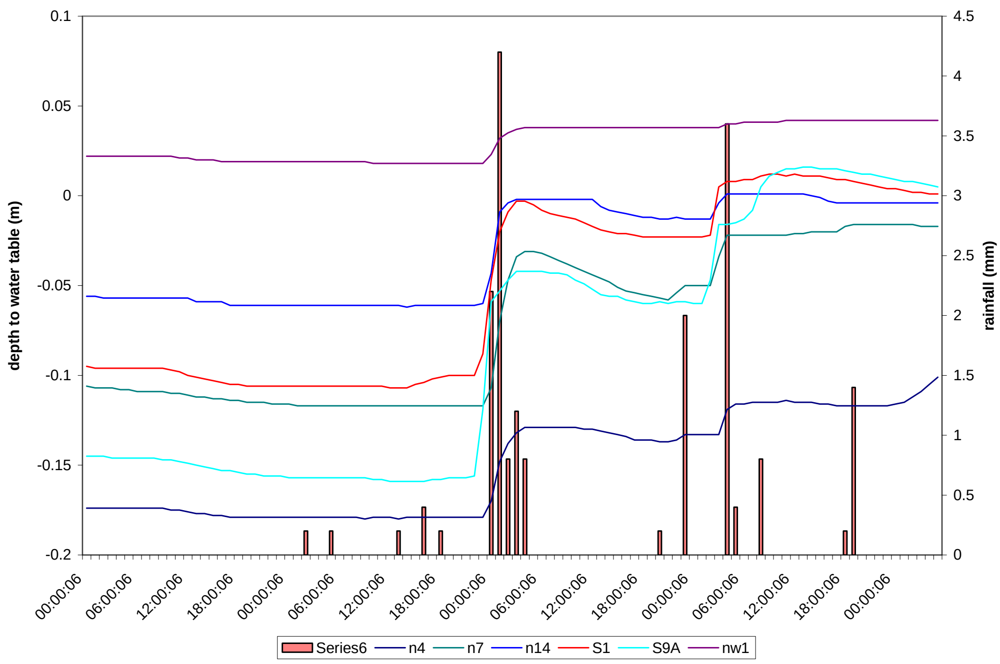
These loggers collect large amounts of data, and so selection of events for study has been driven by selection of suitable, isolated rainfall events where there had been a sufficient dry period previously, so that the response of the water in the peat would not be constrained by the proximity of the surface to the water level. Similarly, a following dry period would allow study of subsequent decline in levels without additional rainwater inputs. It was also necessary to select events where all loggers had data available, which was not a foregone conclusion given their potential for mechanical failure. Two such events are shown in Figures 5.28 and 5.29.

Figure 5.28 Response of loggers to a rainfall even on 15 September 2006



In figure 5.28, the response to initial rainfall is very quick, with water levels rising .15m within a 15 hour period. Subsequent decay is much slower and levels have not reached pre event depth before the secondary event on 18 September. However levels at N14 on Walton Moss, the location which can be considered the most hydrologically intact, are slower to decay than the other locations. A similar, though less pronounced effect can also be seen with the Bolton Fell N7 results, which may suggest that these relatively undisturbed locations may retain water for longer.

Figure 5.29 Response of loggers to a rainfall event on 11 August 2007



In Figure 5.29, it can be seen that the loggers did not respond to the early isolated and light rainfall, but show a strong response to the event on the early morning of 11 August 2007. It is noticeable that the response of the NW1 logger was much less pronounced. This transect is in the most pristine section of bog, and the water level was already at ground level, indicating the peat was almost saturated. There was therefore likely to be very little further infiltration and subsequent water inputs were lost to the site as overland flow. By contrast S9a, subject to a drier regime showed a very strong response. Similarly, although the N14 logger responds to the event, the expected peak is a flat line, indicating that the water had reached surface level and could go no higher. Although the level drops away more quickly than NW1, it quickly re-saturates after the second rainfall. The other loggers continue to respond throughout the entire rainfall period, suggesting that the peat never becomes entirely saturated, although all apart from n4 logger reach a final level close to ground surface. The Bolton loggers, N4 and N7 start from a noticeably drier condition. It should be remembered that all of these levels have been subject to a manual correction and absolute accuracy cannot be guaranteed.

6 Vegetation and topography

The large scale landforms at both study sites are a function of their formation and history. Particularly at Walton Moss, the overall morphology of the peat dome is a function of its nature as a raised bog (Hughes *et. al.*, 2004). Smaller scale changes are related to subsequent land use and drainage, both of the site itself and of the surrounding land. Bolton Fell Moss would probably show a similar morphology, however such large scale features have been obliterated by the drainage and subsequent peat milling the site has undergone in the last 50 years (Natural England, 2001).

Smaller scale topographic variation on Walton Moss and the reserve area of Bolton Fell Moss are almost exclusively dependent on vegetation and drainage structures (Hughes *et. al.*, 2004). These two factors are related, with vegetation communities being determined in part by hydrological conditions and to a lesser extent by vegetation altering the hydrological characteristics of the site (Bragg, 2002). This may occur either through root action and transpiration of tree species, or through recolonisation and impediment of unmaintained drains.

6.1 Vegetation at Walton Moss

Walton Moss is recognised as being one of the best examples of intact raised bog in England (Barber,1993). The vegetation communities of the SSSI area are typically M18 raised bog. This is certainly true of the domed area of bog, but the lagg fen areas to the east adjacent to the road are more variable, with characteristics of H9 *calluna vulgaris-Deschampsia flexuosa* heath and U2 *Deschampsia flexuosa* grassland suggesting mineratrophic groundwater inputs and more mineral soils.

6.1.1 Species list

As is typical of raised bog communities, species found at Walton Moss are limited in numerical abundance and diversity, but tend to be rare or notable in the UK context (Lindsay, 1995, JNCC,1999). More complete species data are available from Natural England and are based on records from several recorders and local naturalists (Natural England, unpublished records). Species data for this study are taken from $1m^2$ quadrats associated with each dipwell. This data does not represent the species present on the entire site, although, given the intrinsic low species diversity of raised bogs, it is likely that few higher plants present on the bog proper are absent from this list. The lagg fenn is a more diverse community, and the transect only includes four quadrats (N1 –N4) typical of this community. It is therefore unlikely that this list represents a representative species list for this area.

Of the lower plants, this study is primarily concerned with those plants which have a significant structural component and as such, will contribute to the microtopography of the site. Non structural mosses and liverworts have not been consistently identified for all quadrats and are included in these data only as indicative records. Natural England suggests that the site has up to 26 *Sphagnum* species present (Natural England, unpublished records). Many of these are rare or uncommon and have not been recorded in these transects. An exhaustive survey and identification of all species was beyond the possibilities of this study, and identification has only been undertaken for significant cover of individual *Sphagnum* species, where the plant is making significant contribution towards vegetation cover in the quadrat. A species list for the quadrats surveyed is given in Table 6.1.

Table 6.1 Species list for Walton Moss

Agrostis canina	velvet bent
Andromeda polifolia	bog rosemary
Aulacomnium palustre	ribbed bog moss
Calluna vulgaris	common heather, ling
Carex rostrata	bottle sedge
Deschampsia flexuosa	wavy hairgrass
Drepanocladus fluitans	a moss
Drosera rotundiflora	common sundew
Empetrum nigrum	Crowberry
Erica tetralix	cross leaved heath
Eriophorum angustifolium	common cottongrass
Eriophorum vaginatum	hare's-tail cottongrass
Festuca ovina	sheeps fescue
Galium saxatile	heath bedstraw
Holcus mollis	creeping soft grass
Hydrocotyle vulgaris	marsh pennywort
Hylocomium splendens	glittering wood moss
Hypnum cupressiforme	a moss
Juncus conglomeratus	compact rush
Juncus effusus	soft rush
Juncus squarrosus	heath rush
Molinia caerulea	purple moorgrass
Narthesium ossigragum	bog asphodel
Polytrichum commune	star moss
Potentilla erecta	common tormentil
Scirpus cespitosus	deer grass
Scirpus setaceus	club rush
Sphagnum capillifolium	
Sphagnum cuspidatum	
Sphagnum magellanicum	
Sphagnum papillosum	Bog Moss
Sphagnum palustre	
Vaccinium myrtillus	
Vaccinium oxycoccus	

6.1.2 Species percentage abundance for each dipwell associated quadrat

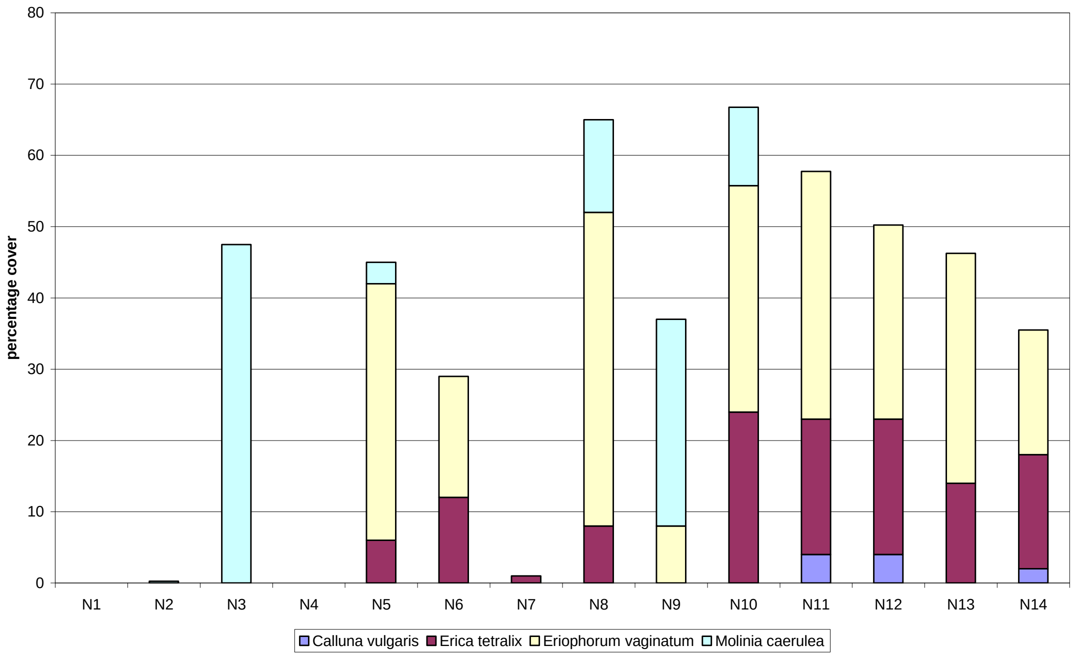
Species abundance by quadrat for each dipwell transect is given in Appendix 4.

6.1.2.1 Walton north transect

The north transect has the greatest species diversity, with 32 species of plant recorded. However it is the only transect to cross the area of lagg fen, and therefore species with more mineratrophic characteristics are also recorded from this transect and dipwells N1 to N4 show more commonality with NVC communities H9 *calluna vulgaris-Deschampsia flexuosa* heath and U2 *Deschampsia flexuosa* grassland and no characteristics of typical M18 raised bog. Sward height across the transect is between 17cm and 25cm for all but the first 2 quadrats, which have a sward height of 85cm and 90cm respectively. This is a function of the vegetation difference in these two quadrats, having an abundance of taller *Juncus* species. A grazing index of 4 or 5 suggests that the transect is in the main not heavily grazed, although the quadrats at N3 and N9 have an index of 3 and suggest animals preferentially graze these areas, possibly as they are somewhat drier.

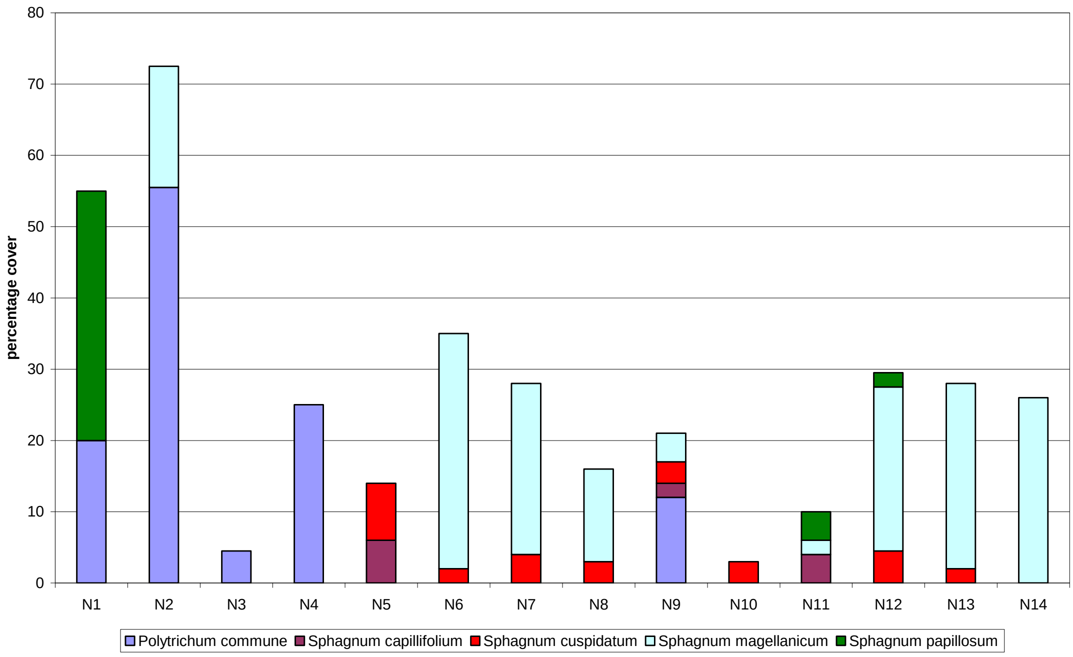
The relative abundance of structural species is shown in Figure 6.1, and shows that *Erica tetralix* and *Eriophorum vaginatum* predominate in the quadrats associated with the dipwells located on the main dome of the bog, N5 to N8 and N10 to N14. *Molinea caerulea* is more abundant in the drier areas on the edge of the dome and where the mineral ridge around dipwell N9 results in thinner peat.

Figure 6.1 Structural species distribution on Walton north transect



The relative abundance of the four principal *Sphagnum* species, and the other consistently abundant moss, *Polytrichum commune* is shown in Figure 6.2. The *Polytrichum* is found primarily in the areas outside the raised dome, and re-occurs at quadrat N9. In the quadrats located on the bog dome, *Sphagnum magellicanum* is the most common species, with small amounts of *Sphagnum cuspidatum* also widespread. Nowhere does growing *Sphagnum* take up more than 33% of quadrat ground cover and the mean sphagnum coverage is 19.85%.

Figure 6.2 Principal moss distribution on Walton North

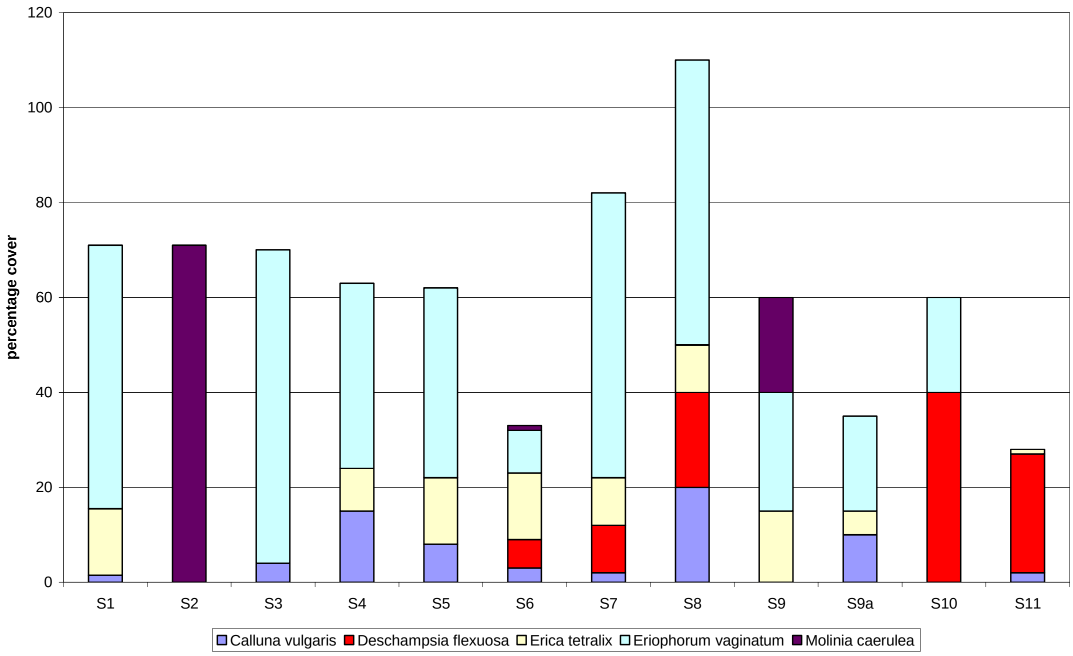


6.1.2.2 Walton south transect

Walton south transect has less species diversity than Walton north, with 24 higher plant species recorded. This again includes a number of less typical species found below quadrat S9a. This area of bog is drier that S1-S9a and may also again have a mineratrophic groundwater component, leading to a more diverse floral community. Sward height is again low, with a range of 16cm to 27cm. However, this area usually has livestock excluded from it and shows a uniform grazing index of 5, suggesting minimal influence of grazing on the sward. A small group of roe deer (*Capreolus capreolus*) were occasionally spotted during the study, so there is a small amount of grazing pressure, but insufficient to have an observable effect on the areas studied.

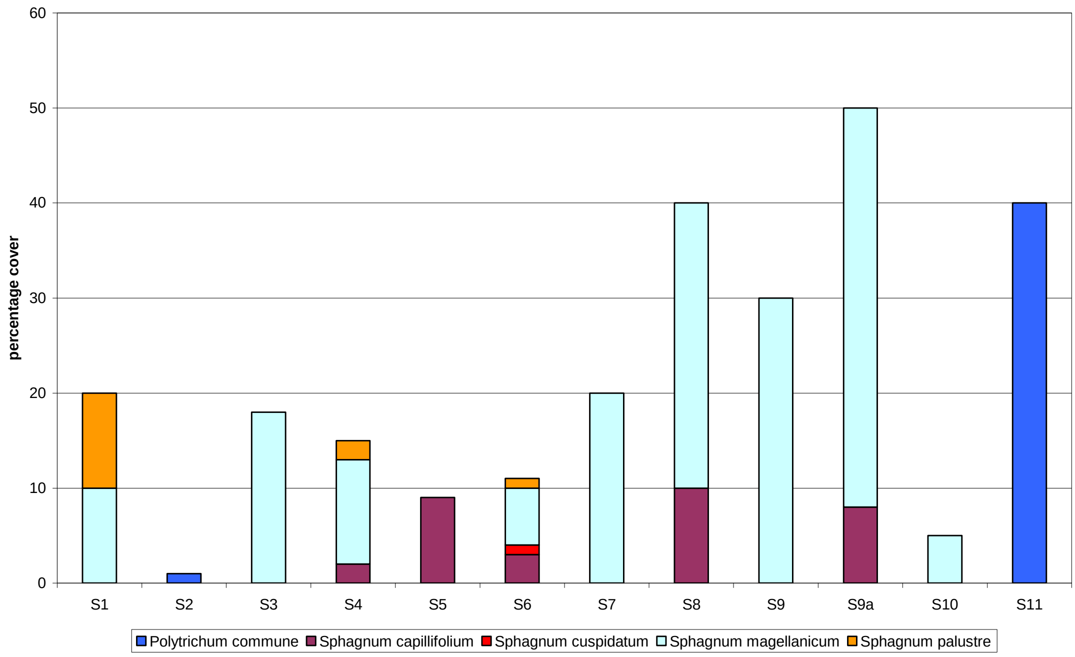
Structural species distribution is given in Figure 6.3 and shows that like the north transect, *Eriophorum vaginatum* and *Erica tetralix* predominate on the quadrats in the main part of the bog, with *Deschampsia flexuosa* and *Molinia caerulea* more common on the periphery, although this is not an absolute rule, and quadrat S2 is dominated by *Molinea*. As was seen in Section 5.4.2, this quadrat also differs hydrologically from its neighbours.

Figure 6.3 Structural species distribution on Walton north transect



The principal *Sphagna* found on this transect, together with *Polytrichum* cover are shown in Figure 6.4. *Sphagnum magellanicum* again predominates. Quadrat S11 is on a drier section of bog and *Polytrichum* appears to replace *Sphagnum* in this circumstance. Quadrat S2, although centrally located in the bog, has a different community, which although not strongly consistent with any one NVC community, has characteristics more in common with U6 *Juncus squarrosus - Festuca ovina* grassland and M15 *Scirpus- cespitosus-Erica tetralix* wet heath, and has no *Sphagnum*. *Sphagnum* does not dominate any one quadrat and the highest percentage cover is 50% in quadrat 9a, with an average cover of 18.17%.

Figure 6.4 Principal moss distribution on Walton south transect



6.1.2.4 Walton north west transect

Walton north west dipwell transect was installed in September 2006 and the vegetation surveyed the following year, two years after the north and south transects. However, whilst vegetation on this site does have the potential for change over time, it is likely that such change occurs over a longer timespan than two years and that therefore the data will be equivalent. The author participated in the survey of all three transects to ensure consistency of results.

This transect has the lowest overall species diversity, with 17 species recorded. Whilst this transect is also shorter than the other transects on this site, the diversity of individual quadrats is consistently low, with the exception of quadrat NW4, the other bog quadrats have a species count of between 8 and 10. Quadrat NW13 is located on the edge of the bog adjacent to the Flosh lagg stream and in common with the perimeter quadrats of the other transects, has different vegetative properties.

Species potentially contributing to surface microtopography are shown in Figure 6.5. Unlike the other transects on this site, the north west transect has substantial quantities of *Empetrum nigrum*. This dwarf shrub may also have a role in forming microtopography in the manner of the heather species and has therefore been included in this figure. *Eriophorum angustifolium* is also included as whilst it is present in all transects, it has a more substantial presence on this transect. *Calluna vulgaris* is present in all quadrats except NW13, which is comprised almost exclusively of *Molinea caerulea*. *Eriophorum vaginatum* is present in most quadrats, however it is not as dominant in these quadrats. Whilst overall diversity is lower, the quadrats tend to have a more even distribution of species, with less prevalence of one or two species giving the structural component of the quadrat.

Figure 6.5 Structural species distribution on Walton north west transect

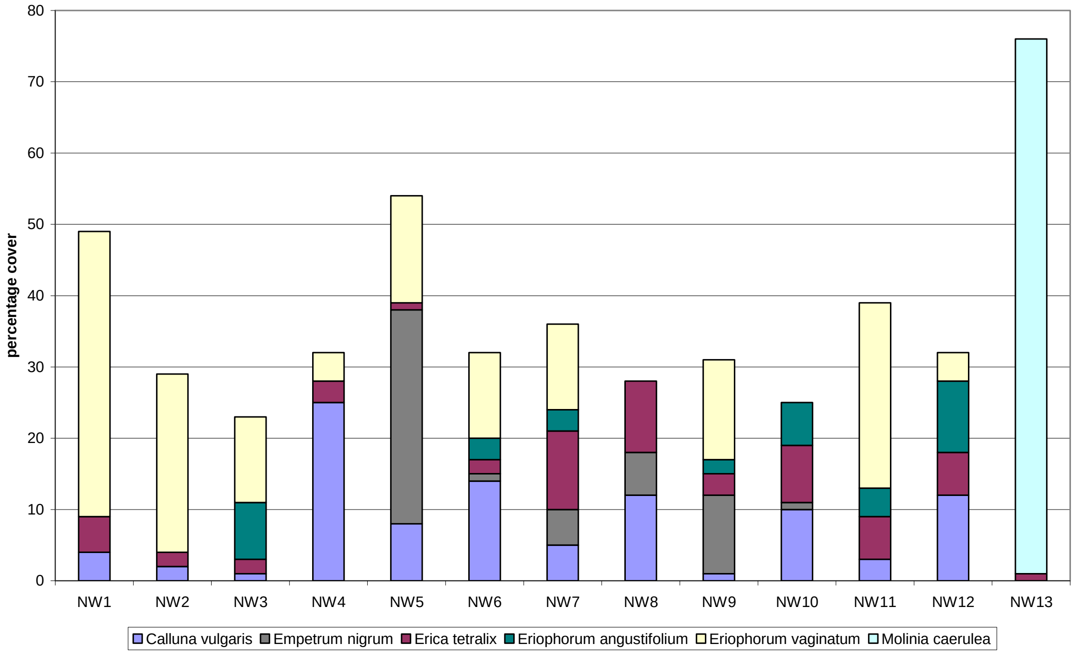
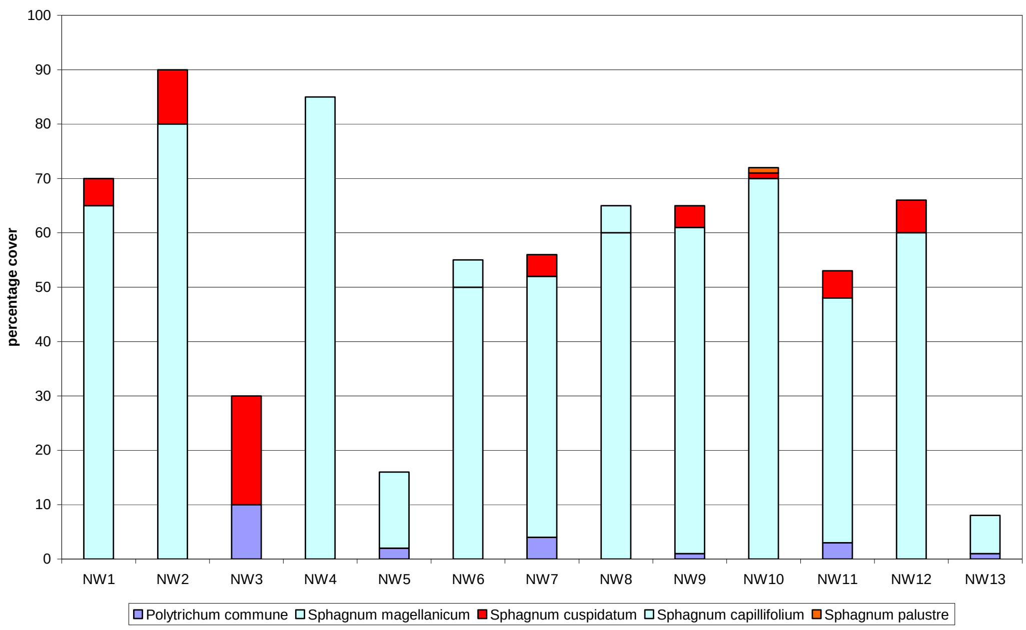


Figure 6.6 shows the distribution of mosses. This transect is dominated by *Sphagnum magellicanum*, with a higher moss ground coverage than seen on the other two quadrats. Up to 90% *Sphagnum* cover is achieved on quadrat NW2, and the average cover in each quadrat is 54.62%. *Sphagnum* may therefore have a greater role in determining overall surface topography here than on the other transects.

Figure 6.6 Principal moss distribution on Walton north west transect



6.1.3 MAVIS analysis of NVC types for each quadrat

The NVC 18 communities under consideration here are described in detail by Rodwell (1991), but may be summarised as a *Sphagnum* carpet with a low canopy of vascular plants primarily consisting of *Calluna vulgaris*, *Erica tetralix* and *Eriophororum vaginatum*. The rarer vascular bog specialists, such as *Narthecium ossifragum*, *Vaccinium oxycoccus* and *Andromeda polifolia* are also frequently occurring in these communities.

MAVIS (Modular Analysis of Vegetation Information System) software was developed by Dart computing and CEH in 2000 (Smart, 2000) and has been used to process these data for this study. It automates the process of classifying the fit of study data to NVC communities and gives a percentage score for each quadrat or group of quadrat for several possible NVC types. It is also capable of determining Ellenberg environmental indicators for each quadrat and has been used to generate Ellenberg indexes for this study, which are discussed in sections 6.1.4 and 6.2.4.

Morris and Therivel (2001) discuss the use of Mavis to classify NVC data. Mavis shows how closely a community matches the criteria for a specific community. It therefore will show matches with other communities and the results need careful interpretation. As the sites under consideration in this study are broadly recognised as M18 communities, the M18 subcommunities have been highlighted. In addition M20 degraded *Eriophorum vaginitum* and M2 *Sphagnum cuspidatum/recurvum* communities have also been selected. Closeness of fit with the M20 community can suggest the degree of degradation of such sites (Rodwell 1991) and the M2 bog pool community shares many of the characteristics of healthy bog as M18. Rodwell (1991) also suggests it may indicate slight enrichment or recolonisation of peat cutting or drained areas. The M18 sub community differentiation is important, as the m18b *Empetrum nigrum spp*. sub community is markedly more tussocky than the m18a *Sphagnum magellanicum-Andromeda polifolia* sub community, which may have implications in the consideration of topographic variation.

The complete data for the MAVIS analysis of the vegetation surveyed for this study are given in appendix 5. Data for M18 communities of the Walton Moss transects are shown in Table 6.2.

Table 6.2 Walton Moss M18 communities

north transect	m18	m18a	m18b	south transect	m18	m18a	m18b	north west transect	M18	M18a	m18b
n1	0	0	0	s1	41	45	35	nw1	39	50	0
n2	0	0	0	s2	0	0	0	nw2	31	41	0
n3	0	0	0	s3	36	45	0	nw3	40	47	37
n4	0	0	0	s4	46	54	40	nw4	36	41	30
n5	37.8	42	0	s5	44	51	39	nw5	31	37	0
n6	34.7	44	0	s6	49	56	43	nw6	45	53	39
n7	36.1	50	0	s7	36	47	0	nw7	42	50	37
n8	36.2	41	31	s8	36	39	32	nw8	33	44	0
n9	0	33	0	s9	30	35	0	nw9	41	47	35
n10	39.2	50	0	s9a	44	55	37	nw10	36	44	29
n11	47	57	39	s10	0	0	0	nw11	45	56	38
n12	47.4	57	0	s11	0	0	0	nw12	46	57	37
n13	31.2	43	24					nw13	0	29	0
n14	37.8	50	0								
max	47.4	57	39		49	56	43		46	57	39
min	31.2	33	24		30	35	32		31	29	29
mean	38.6	47	31		40	47	38		39	46	35
stDev	5.37	7.4	7.7		6	7.3	3.8		5.4	7.8	3.8

These data show that despite the sites as complete units being recognised as some of the best raised mire m18 communities (Hughes *et.al*. 2000), the individual quadrats have less distinct m18 characteristics. All mean values are below 50%, although the strongest similarities are with the m18a sub community. If the transects are amalgamated and considered as a single group, the data become rather more distinct and the results given in table 6.3, with both the north and south transects showing 63.17% and 55.68% of the characteristics of M18a. It is interesting to note that the north west transect shows the clearest characteristics of M2 *Sphagnum cuspidatum /recurvum* bog pool communities with 62.08% association. This may be a function of the lower variation in water levels of this transect, although the south transect also demonstrate a relatively high level of similarity with this type. Walton north has a 61.47% similarity with M2 and Walton south 56.25%. The data for the transects exclude data for quadrats outside the area of raised bog.

Table 6.3 MAVIS NVC classifications for Walton Moss transects

	walton north	walton south	Walton north west
m18	50.52	48.12	45.76
m18a	63.17	55.68	55.09
m18b			37.3
m2	61.47	56.25	62.08
m2a	45.26		47.76
m2b	57.2	52.07	56.19

6.1.4 Ellenberg indicators for vegetation data from Bolton Fell and Walton Mosses

Ellenberg indicators were developed by Ellenberg to attribute values for key environmental factors, specifically light, water, pH and fertility, to plant species. By assessing vegetation communities, a value for each of these factors could be determined as a substitute for direct analysis, with resulting savings in both time and cost (Ellenberg 1988). This process could also be applied retrospectively to previously acquired data. Initially Ellenberg values were determined for central European species only, but in 2000 the Centre for Ecology and Hydrology produced a set of indicator values for British plant species (Hill *et. al*, 2000). MAVIS software was used in determining Ellenberg values.

Given the open and uniform nature of the study sites, light has not been considered in this study. However the Ellenberg indicators for fertility, pH and wetness are of interest and are given in Appendix 6.

Summary statistics for the Ellenberg indicators for Walton Moss are given in Table 6.4. For all three transects, pH and fertility are uniformly low, mean pH between 2.98 and 4.35 and mean fertility between 2.22 and 3.39. Conversely, wetness values are consistently high, between 6.71 and 7.25. Although all three indices have relatively extreme outliers. Low standard deviation for all factors suggests that there is little variation in each factor when the whole transect is considered. High wetness, combined with low pH and fertility may be considered typical of the ambient conditions to be expected on a raised bog (Lindsay, 1995, Ingram, 1981).

Table 6.4 Summary Ellenberg statistics for Walton Moss

Walton north					
	max	min	st dev	mean	range
wetness	8.2	5.8	0.75	7.22	2.4
Ph	5.4	2.2	0.99	3.51	3.2
Fertility	5.1	1.2	1.15	2.65	3.9
Walton south					
wetness	8	5.7	0.68	7.25	2.3
Ph	4	2.3	0.51	2.98	1.7
Fertility	3.9	1.5	0.65	2.22	2.4
Walton north west					
wetness	7.7	6.2	0.48	6.71	1.5
Ph	5.6	3.1	0.72	4.35	2.5
Fertility	4.7	2	0.77	3.39	2.7

Figures 6.7, 6.8 and 6.9 illustrate how these factors vary across the transect. On the north transect, the effect of the mineral ridge near dipwell n9 can again be noted, and the large variations between n1 and n4 indicate the change of conditions between the edge of the bog dome and the lagg fen.

The south transect has few extremes of value, but shows a gradual decline in wetness as the bog is traversed downslope from S1 to S11. There is a similar slight increase in pH and fertility. After the main drain at S9a, wetness decreases sharply from 7.2 to 5.7 and fertility and pH increase to reflect this. The slightly dryer condition of dipwell S2 is again evident. The north west transect has no obvious downslope trend, but does have some variation in the upper dipwells. A similar dryer area was recorded from the dipwell data discussed in Section 5.4.3, but as with all these data derived from botanical records, error in the identification of species must also be considered as a source of error. The different conditions at the edge of the bog at nw13 may again be noted. All transects show similar edge effects and this suggests such data should be excluded from analysis when studying the condition of the bog proper.

Figure 6.7 Ellenberg Indicators for north transect

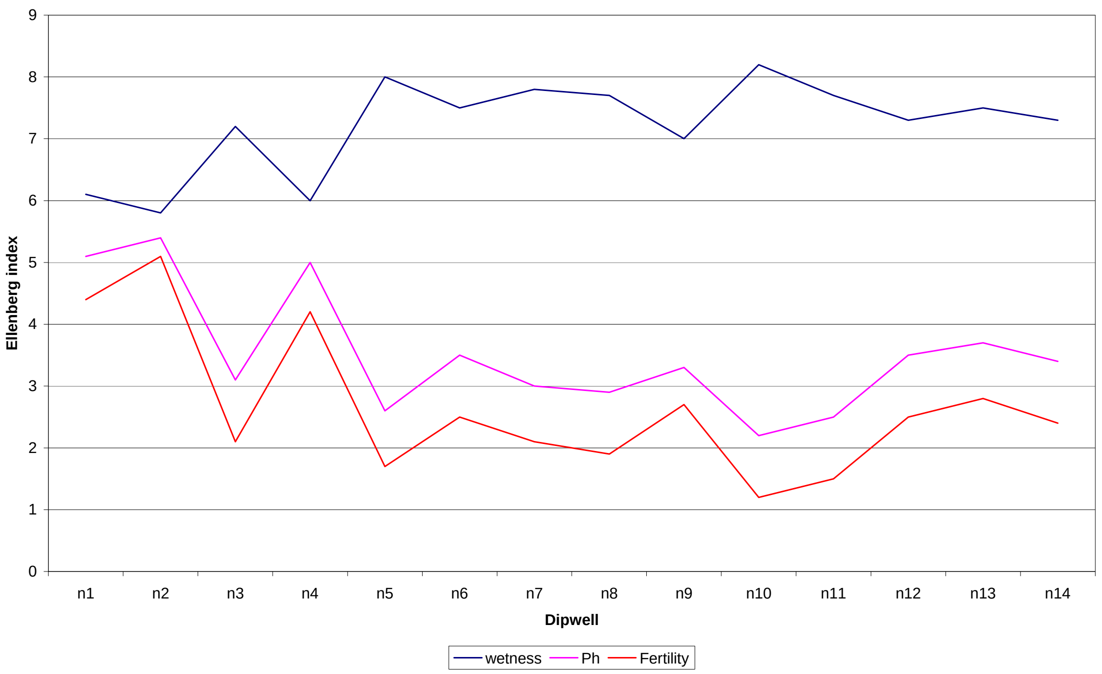


Figure 6.8 Ellenberg indicators for south transect

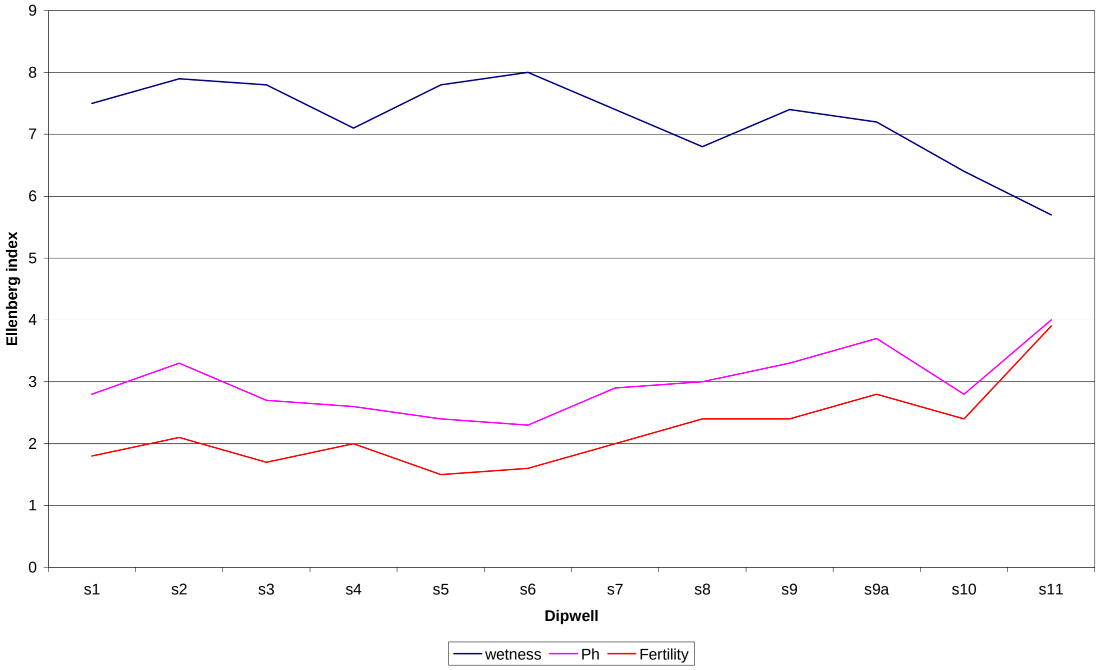
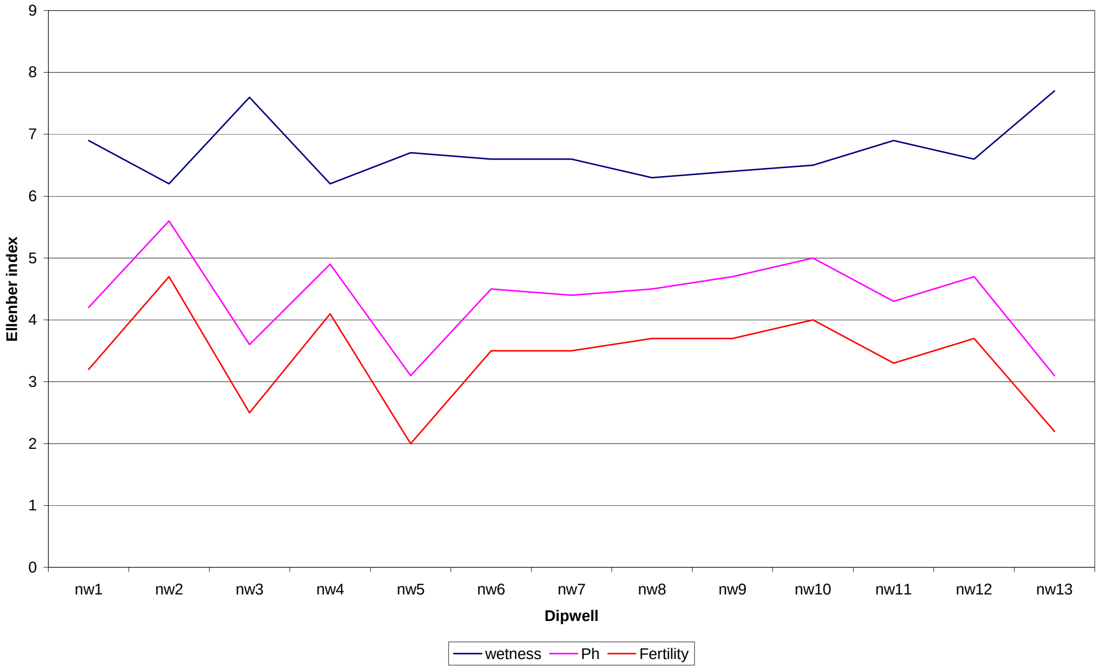


Figure 6.9 Ellenberg indicators for north west transect



6.2 Vegetation at Bolton Fell Moss

6.2.1 Species list

The list of species found in the survey quadrats at Bolton Fell Moss is given in Table 6.5. As at Walton Moss, this is not a complete species list for the site, although it is probably representative of the species found within the reserve area. It does not represent the species found within the SSSI boundary as the majority of this area is subject to peat milling, and what little vegetation remains is not typical of undamaged raised bogs. The reserve area is more homogeneous than Walton Moss and it is a much smaller area. It has very little of the marginal vegetation characteristic of lagg fenn as the boundaries are anthropogenic and the transition to cut over bog is abrupt. There are other woody species recorded, notably *Pinus sylvestris* and *Betula pendula*. Birch in particular is encroaching into more of the bog in the absence of management. Lower mosses, other than *Polytrichum* have not been consistently recorded due to time constraints when the east transect was surveyed in 2008.

Table 6.5 Species list for Bolton Fell Moss

Agrostis canina	velvet bent
Andromeda polifolia	bog rosemary
Aulacomnium palustre	Moss
Betula pendula	silver birch
Cladonia portentosa	reindeer lichen
Calluna vulgaris	common heather, ling
Drosera rotundifolia	common sundew
Empetrum nigrum	Crowberry
Erica tetralix	cross leaved heath
Eriophorum angustifolium	common cottongrass
Eriophorum vaginatum	hare's-tail cottongrass
Hylocomnium splendens	Moss

Molinia caerulea	purple moorgrass
Narthesium ossigragum	bog asphodel
Pinus sylvestris	scots pine
Pleurozium schreberi	Moss
Polytrichum commune	star moss
Psuedoschleropodium purum	Moss
Sphagnum papillosum	bog moss
Sphagnum capillifolium	
Sphagnum magellanicum	
Sphagnum subnitens	
sphagnum cuspidatum	
Vacinnium myrtillus	Bilberry
Vacinnium oxycoccus	Cranberry

6.2.2 Species percentage abundance for each dipwell

Species abundance by quadrat for each dipwell transect is given in Appendix 4. It should be noted that the two transects intersect and that the data for N4 and E7 quadrats represent the same area.

6.2.2.1 Bolton Fell north transect

The distribution of key structural plant species is shown in Figure 6.10. *Calluna vulgaris* is present across the whole transect apart from N7. *Erica tetralix* is also widespread, although not ubiquitous. Ericatious species have a lower cover in the quadrats nearer the centre of the area and on quadrats N2 to N5, the most common shrub species is *Emptrum nigrum*, which is characteristic of wetter ground. Both *Eriophorum* species are present, although the more disturbed quadrats at the southern edge of the bog contain *E. angustifolium*. The quadrat identified as “outside bund” has 67% *E. angustifolium* cover, which may be indicative of impeded drainage as a result of the drainage compaction measures discussed in Section 5.5.

Figure 6.10 Structural species distribution on Bolton Fell north transect

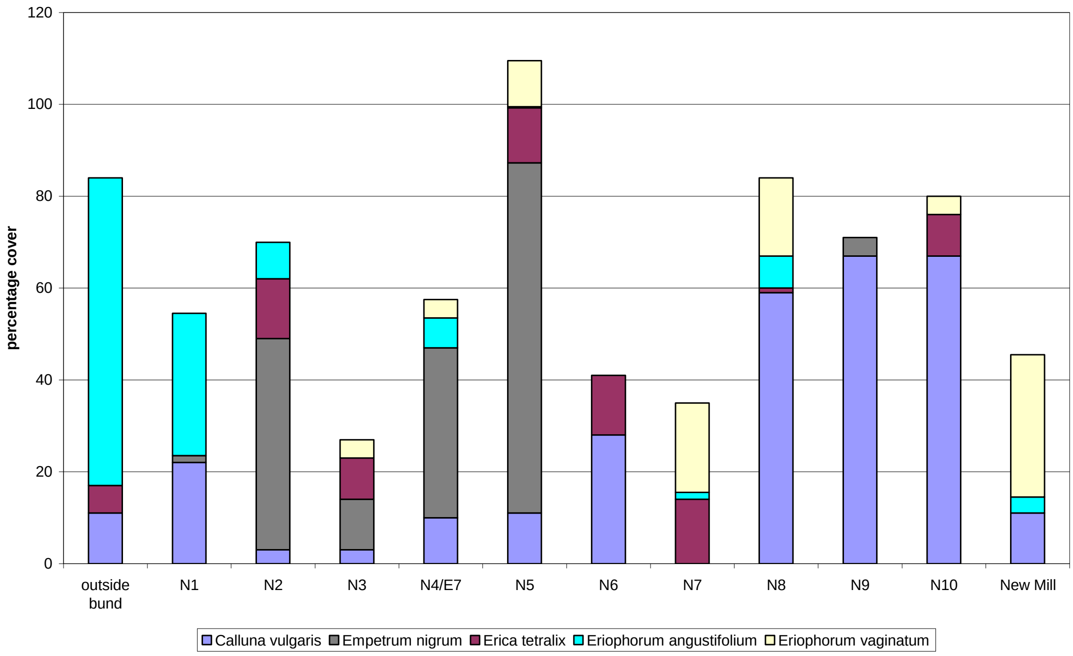
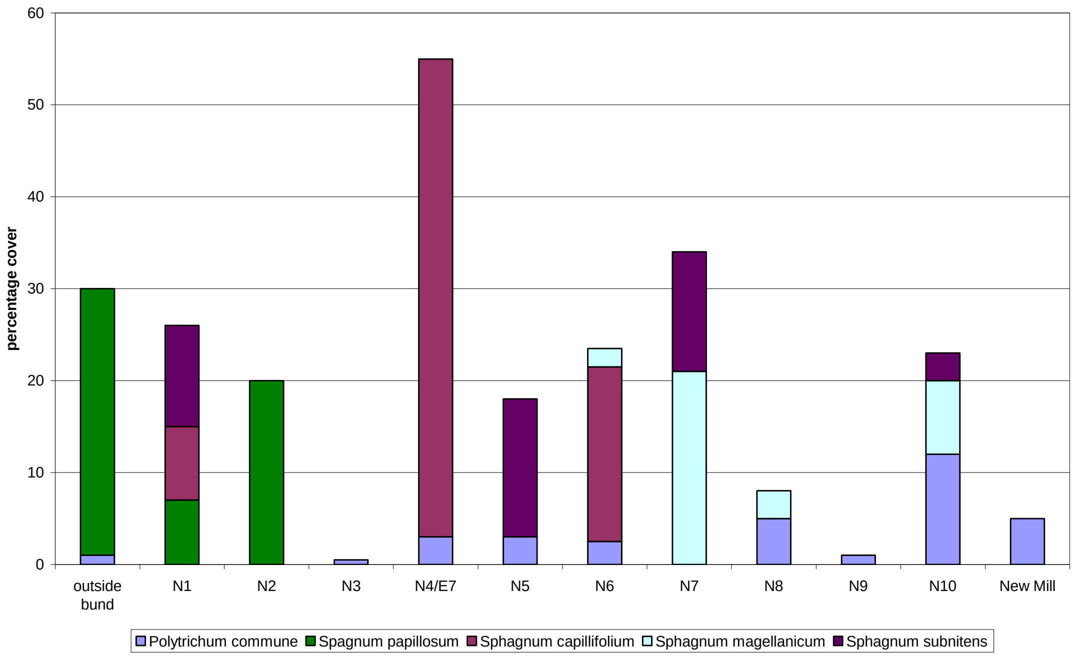


Figure 6.11 illustrates the distribution of mosses on this transect. No single species dominates the transect, and the highest percentage cover of Sphagnum is 55% at N4. Average sphagnum cover is 17.58%. These figures are lower than typical figures from Walton Moss and perhaps reflect the more disturbed drainage history of this site. Similarly Polytrichum commune occurs more frequently across the whole trasect and not just in the disturbed areas. It should be noted in particular that the quadrat "outside bund", together with N9, N10 and "new mill" have been subject to excavation, both for peat extraction and for the more recent drainage impediment works.

Figure 6.11 Principal moss distribution on Bolton Fell north transect



6.2.2.2 Bolton Fell east transect

Figure 6.12 shows the distribution of structural plants across the east transect. *Calluna vulgaris*, *empetrum nigrum* and *Eriophorum vaginatum* are widespread and suggest that this quadrat is perhaps more typical of other raised bog communities and shows less evidence of disturbance than the north transect. The low percentage but frequent occurrence of *Betula pendula* suggests that birch scrub is encroaching into this area from the woodland block to the immediate south of the transect. *Eriophorum angustifolium* is only recorded from the eastern quadrats, and the only substantial cover of 20% is recorded from E11a, which coincides with the drainage and other works associated with the railway line and site boundary ditches.

Figure 6.12 Structural species distribution on Bolton Fell north transect

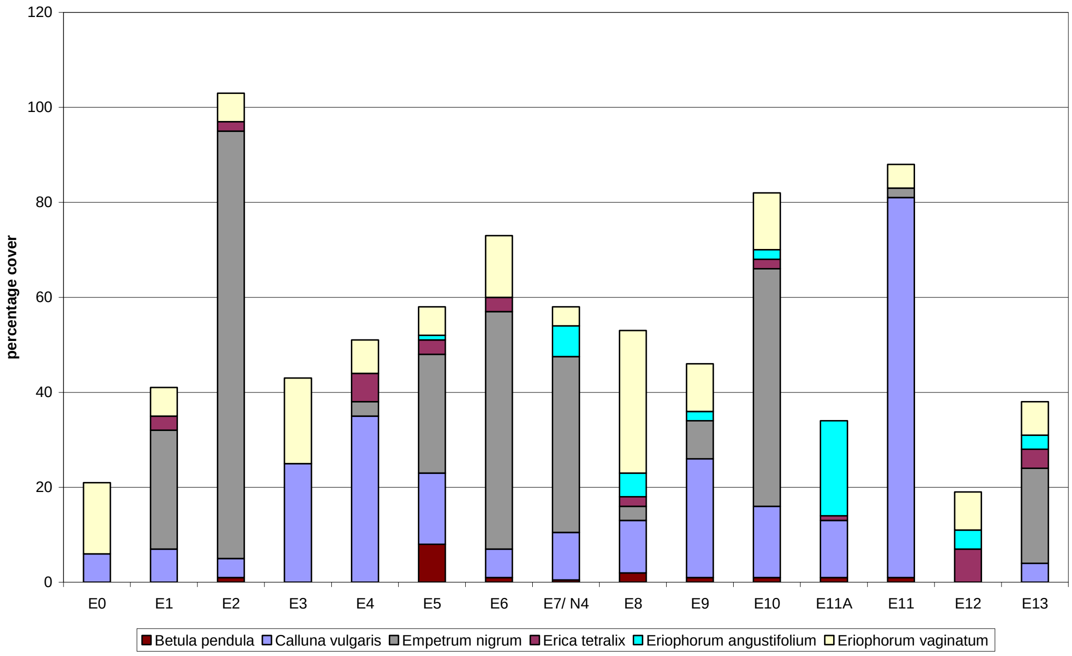
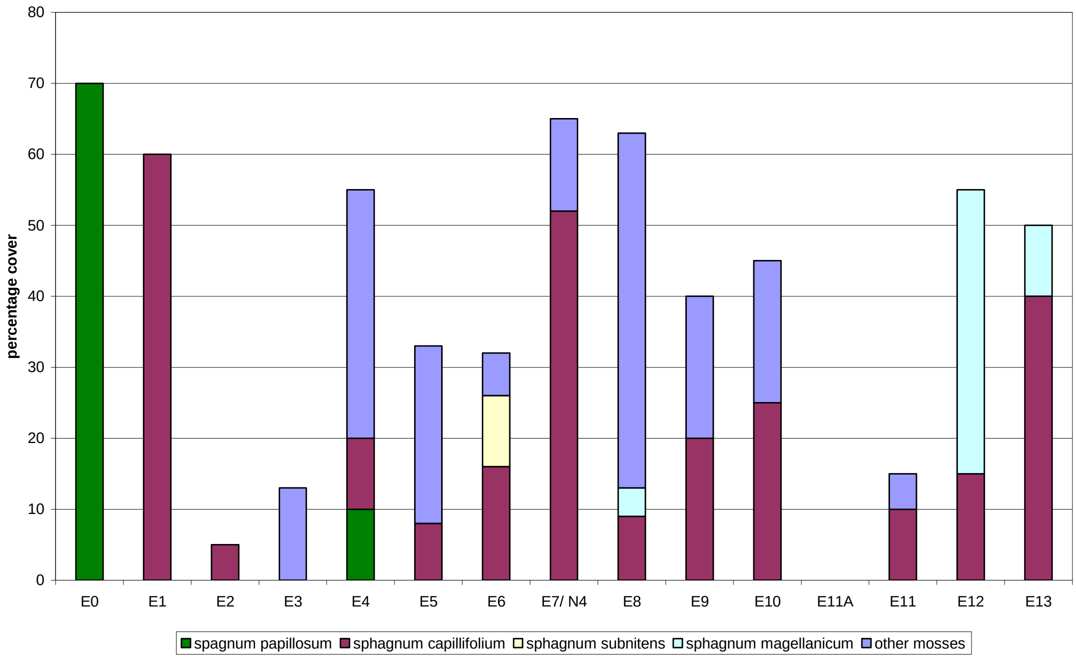


Figure 6.13 illustrates the distribution of *Sphagnum* and other mosses across the transect. Due to time constraints, individual non *Sphagnum* species were not identified separately, however the majority of the cover comprised *Polytrichum Commune* with other species making a small percentage of the remainder. Therefore the "other mosses" element may be used to indicate approximate distribution of *Polytrichum*. There was no moss evident at quadrat E11a. This quadrat was 60% bare ground, where mosses might be expected to form the ground cover suggesting a recent localised disturbance.

Figure 6.13 Principal moss distribution on Bolton Fell north transect



6.2.3 MAVIS NVC analysis for each transect at Bolton Fell Moss

MAVIS was used to categorise the quadrates of Bolton Fell using the methodology described in Section 6.1.3. The results for the distribution of m18 communities are given in Table 6.6 and show a similar pattern of relatively low individual quadrat m18 characteristics to Walton Moss. Low values for the outlying quadrats reflect the disturbance to the ground for hydrological protection and the impact of former peat excavation on the north quadrat from N9 to NM. The E2 quadrat is particularly poorly representative of all m18 communities, and may reflect the incursion of birch scrub. The complete NVC data are given in Appendix 5, and data for this quadrat show that this quadrat has heathland characteristics which would support this argument, but the possibility of recording or sampling error cannot be discounted.

Descriptive statistics were calculated for those quadrats where m18 communities were present. Mean values for each community are between

33.99% and 44.24%, and variation within each community is similarly restricted between 8.55% and 3.87% percent, suggesting that away from the perimeter, the moss is relatively homogeneous, and notwithstanding the tree cover, this is supported by walkover inspection.

Table 6.6 Bolton Fell Moss M18 communities

east transect north transect

	m18	m18a	m18b	OB	M18	m18a	m18b
e0	29.11	33.93	24.85	OB	45.42	52.07	39.27
e1	37.77	44.44	0	n1	39.47	45.45	34.24
e2	36.07	39.25	33.38	n2	41.1	42.86	35.09
e3	22.47	29.41	0	n3	37.59	38.77	36.56
e4	42.69	47.86	38.08	n4	37.68	43.78	35.57
e5	42.69	49.57	38.08	n5	37.6	41.79	35.65
e6	35.86	42.41	32.24	n6	37.59	43.94	32.5
e7	34.48	41.03	31.03	n7	41.92	49.69	34.05
e8	45.74	54.1	39.51	n8	44.33	52.59	37.84
e9	37.67	44.64	32.16	n9	0	0	0
e10	34.48	41.03	31.03	n10	0	42	0
e11a	0	33.33	0	NM	0	33.66	0
e11	26.22	31.37	0				
e12	44.01	56.69	0				
e13	45.74	54.1	39.51				
max	45.74	56.69	39.51		45.42	52.59	39.27
min	22.47	29.41	24.85		37.59	33.66	32.5
mean	36.79	42.88	33.99		40.3	44.24	35.64
stdev	7.187	8.548	4.74		3.067	5.633	2.047

The individual plots have been aggregated in MAVIS to give characteristics of each transect. Data from individual quadrats affected by drainage or old peat cutting have been excluded to give the characteristics of the relatively undisturbed areas of bog. This summary is given in Table 6.7. These data suggest that as a whole the north transect is reasonably characteristic of M18 raised mire. In particular it is 58.78% characteristic of M18a. However it is also characteristic of M2 *Sphagnum cuspidatum* bog pool community. The east transect appears to have more in common with this community than it does with any m18 community, however it should be remembered that appropriate lower plant data were not available for this transect and that these can be important in classifying raised bog NVC communities.

Table 6.7 MAVIS NVC classifications for Bolton Fell Moss transects

	Bolton north	Bolton East
m18	54.05	41.37
m18a	58.78	47.97
m18b	46.51	37.06
m2	58.59	50.31
m2a		35.76
m2b	57.69	45.87

6.2.4 Ellenberg indicators for Bolton Fell Moss

Ellenberg indices for Bolton Fell Moss are given in Appendix 6. Summary statistics for these data are given in Table 6.8. These show a similar pattern to Walton Moss, with low standard deviation when the transect as a whole is considered. Although there is little variation in wetness across the transects, the east transect shows a greater variation in pH and fertility. In particular, it suggests relatively high fertility, wetness and pH for dipwell E11a. Much of this quadrat is bare ground, and it may be that the relatively restricted species list and low ground cover have forced an error as a consequence of the algorithm and limited data available, rather than this being a consequence of an actual highly localised change in ground conditions.

Table 6.8 Summary Ellenberg statistics for Bolton Fell Moss

Bolton Fell north					
	max	min	st dev	mean	Range
Wetness	7.8	6.1	0.52	6.69	1.7
pH	4.7	2.5	0.71	3.71	2.2
Fertility	4.8	1.8	0.8	2.63	3
Bolton Fell east					
Wetness	7.5	6.1	0.35	6.57	1.4
pH	5.9	2.2	1.08	3.54	3.7
Fertility	6.6	1.3	1.28	2.85	5.3

Figures 6.14 and 6.15 illustrate variation in Ellenberg indicators on the two transects at Bolton Fell Moss. The anomaly in data from quadrat E11a can be seen in Figure 6.12. Whilst the same general pattern of low pH and fertility and high wetness index are still evident, any relationship between these factors is less apparent. pH and fertility appear to vary in similar fashion but moisture is less variable. The north transect is affected by internal drainage and the woodland area, and both transects are short by comparison with those of Walton Moss, which may reduce the potential for observable spatial difference in these data, However the east transect, which is more homogenous, apart from the E11 boundary does show some evidence of a raised interior water table away from the boundaries.

Figure 6.14 Ellenberg indicators for Bolton Fell Moss north transect

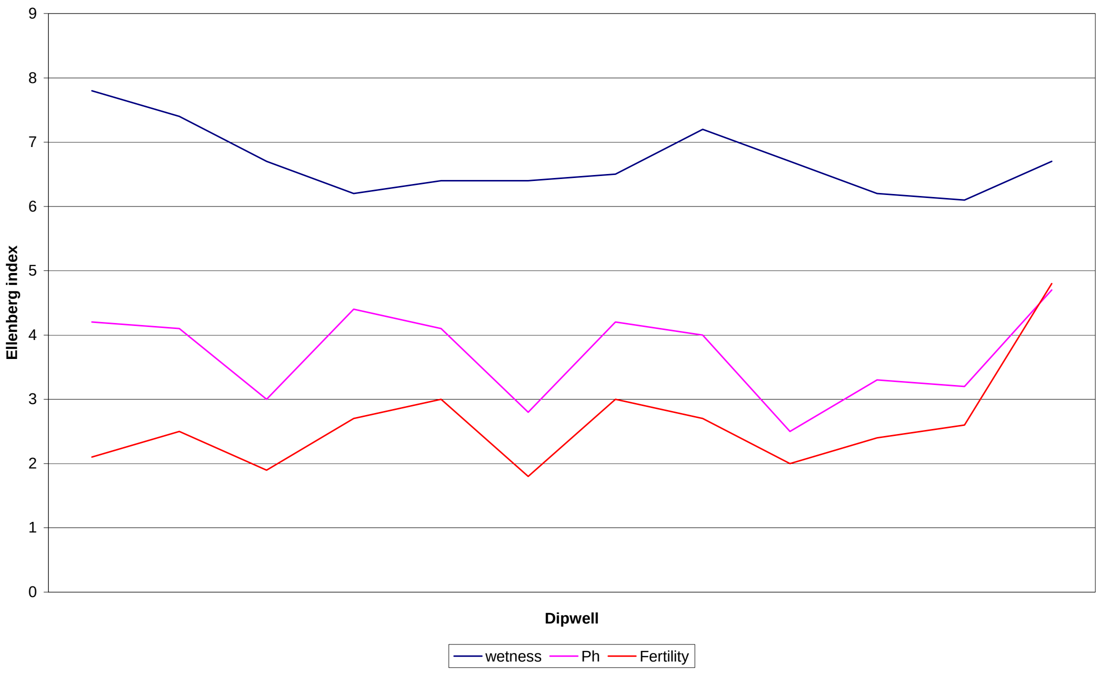
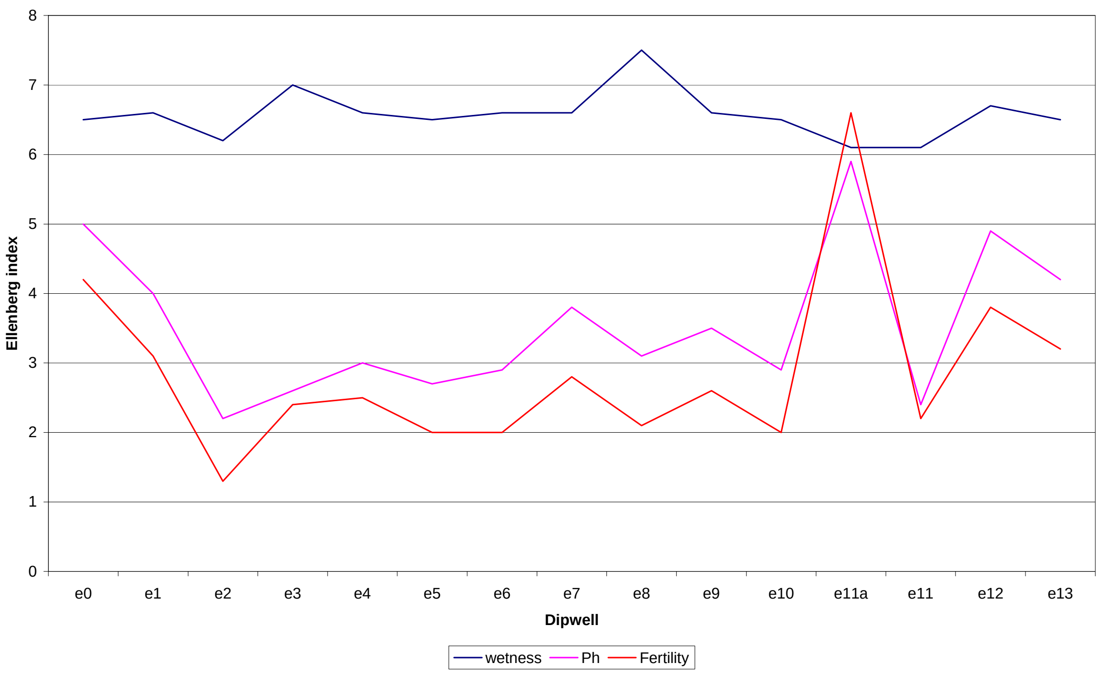


Figure 6.15 Ellenberg indicators for Bolton Fell Moss east transect



6.2.4.1 Boxplot comparisons of Ellenberg indicators for both sites

Box plots for each of the selected Ellenberg indicators for each site illustrate how these indicators differ between transects. Figure 6.16 shows wetness, Figure 6.17 shows ph and Figure 6.18 illustrates fertility. Whilst these plots do highlight some differences between transects, the absolute values are smallWalton Moss north and south transects show substantial similarity in wetness, with the north west transect apparently drier. Both Bolton Fell transects show a similar mean, but with much less variation in the east transect. This is not unexpected when distribution over a small area is being considered, the wider variation in Bolton Fell north data is attributable to the presence of the ditches and cut over area. Similarly, the outliers of Bolton Fell east may be attributed to the effect of the boundary drainage ditches.

Both Walton Moss and Bolton Fell Mosses show similar values and distribution for fertility and pH, although the Walton northwest transect has slightly elevated values in both instances. This transect has a limited species list which may have resulted in distortion if the Ellenberg values. It is recognised that Ellenberg data are more robust when a larger number of species are present for which values can be attributed. Walton south has a smaller range in these factors than Walton north, but this transect does not include an area of lagg fen, unlike Walton north.

Figure 6.16 Ellenberg indicators for wetness for both sites

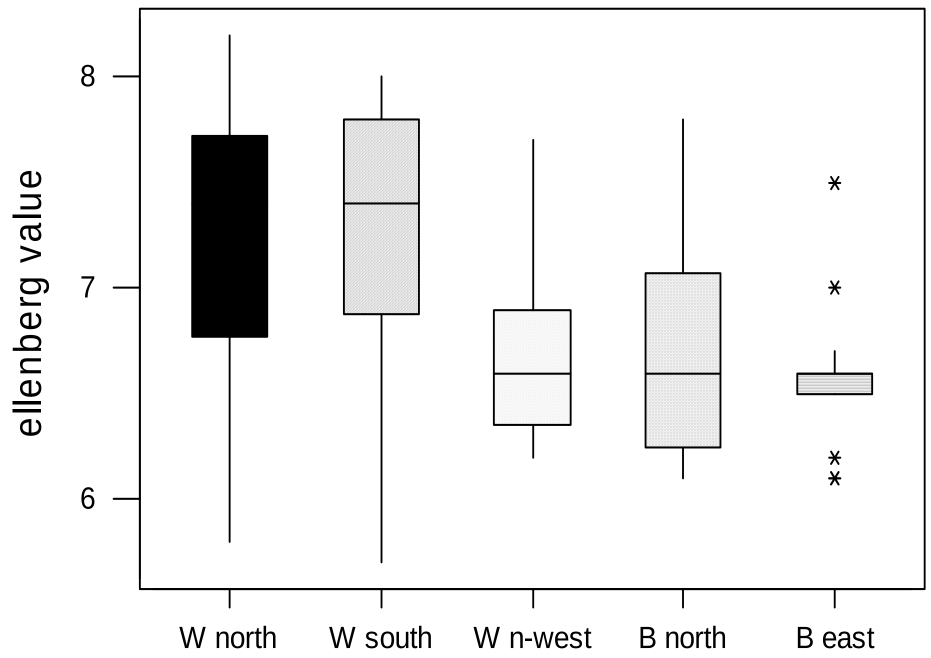


Figure 6.17 Ellenberg values for pH for both sites

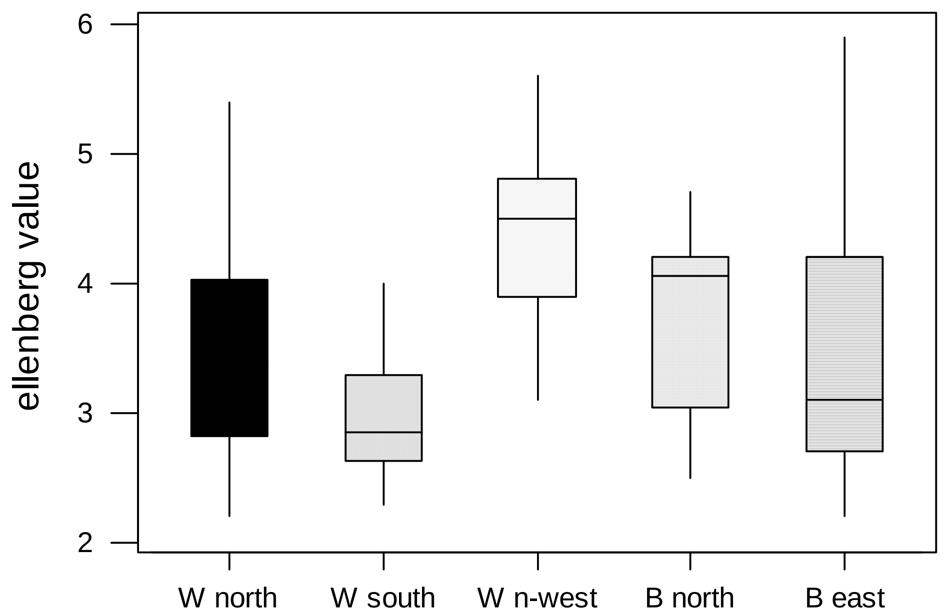


Figure 6.18 Ellenberg values for fertility for both sites

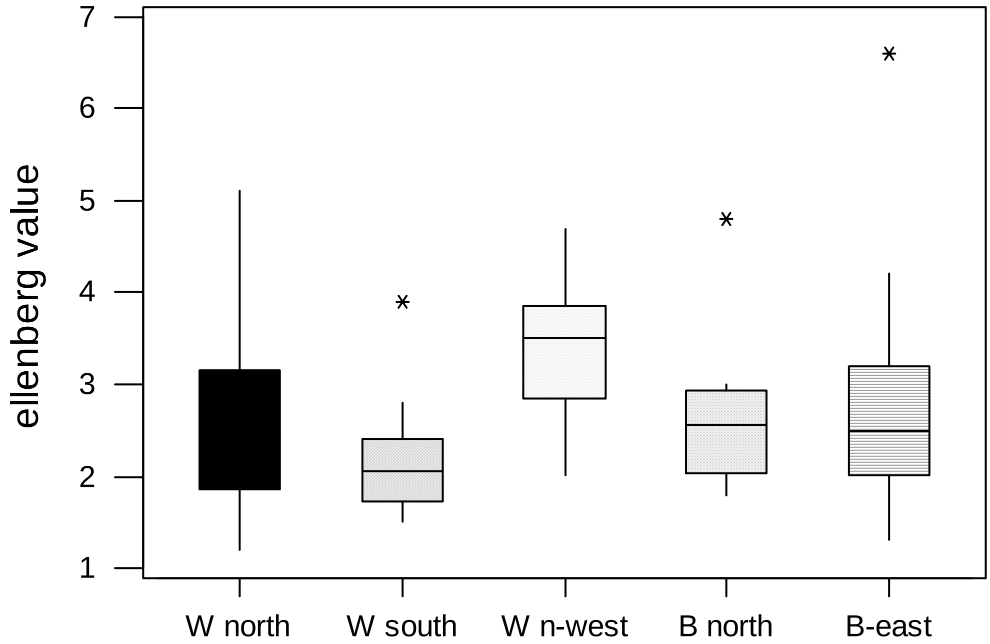


Table 6.9 key to Ellenberg box plot comparisons

abbreviation	W north	W south	W n-west	B north	B east
Transect name	Walton north	Walton South	Walton north west	Bolton Fell north	Bolton Fell east

6.3 Description of microtopography data for the study sites

Topography of a typical raised bog is driven by several factors, including the underlying geology, the hydrological conditions, in particular the amount of rainfall and the degree of drainage of the bog and the surrounding land, and the resultant vegetation communities which have developed (Nungesser, 2003, Swanson, 2007). Geology and rainfall help to drive the development of the characteristic raised dome macrotope and the overall dimensions of the site, whilst vegetation is most influential on the development of microtopography (Robichaud & Begin, 2009). Drainage and hydraulic conductivity affect both large scale and small scale topographic process, as available water influences both the development of the dome and the nature of the vegetation (Bromley *et.al*, 2004). In particular the ratio of sphagnum and higher plants may have a role in characterising the resulting microtopography (Robroek, 2007).

This study investigates the characteristics of certain aspects of bog microtopography. However, it is important to consider the larger scale topography of the bog macrotope, as this will have an important impact on the drainage of the whole system, and larger scale variation in topography may obscure the small scale variation in surface microtopography. It is also a potentially useful indicator of bog condition as the characteristic dome of a healthy raised bog may not be evident if the site has been subject to external impacts, as is the case at Bolton Fell Moss.

6.3 Topography at Walton Moss

Walton Moss is a relatively undisturbed site. Therefore the topography adheres quite closely to the idealised model of a domed raised bog, as described by Ingram (1967, 1982) and Lindsay (1995).

6.3.1 Characteristics of the macrotope of Walton Moss

The site sits in a shallow clay bowl formed from glacial till and rises from xm where the unclassified road from Walton village crosses the margin to a high point of 105m AOD at the centre NY508669. It also falls away on the western boundary to the Flosh at NY503673 and a height of 93m. The Flosh together with the lagg stream on the eastern boundary at NY510658 take the majority of drainage from the site. On the south west boundary, the site has been subject to limited manual peat cutting and the natural topography has been obscured.

The overall topography of the macrotope has been recorded in 2003 using LiDAR, as described in Section 4.4.3. The Lidar dataset predates the installation of dipwells and data loggers. Both the flosh and the northern lagg stream are also evident.

When the original dipwell transects were installed, the transect lines were surveyed using Leica 500 dGPS equipment. These data allowed the production of profiles for these slopes and are given in Figures 6.19, 6.20, and 6.21. It should be noted that dipwell locations are not to scale and that the vertical axis is therefore exaggerated.

The boundary between the lagg and the start of the bog dome can be seen on the north profile in Figure 6.19 at dipwell N4 and the mineral ridge is also evidenced by a flattening of the profile at N9. The more uniform profile of the new northwest transect, shown in Figure 6.21 again suggests that this transect is more characteristic of pristine bog than the original north transect was initially considered to be. The profile of the southern transect in Figure 6.20 is again relatively uniform, although it does show the boundary of the peat dome and the location of the base of the herringbone drain complex at S9a.

The north transect falls 18.41m in 880m, the south transect falls 12m in 830m and the north west transect falls 4m in 620m.

Figure 6.19 Profile of Walton Moss north transect, surveyed using dGPS

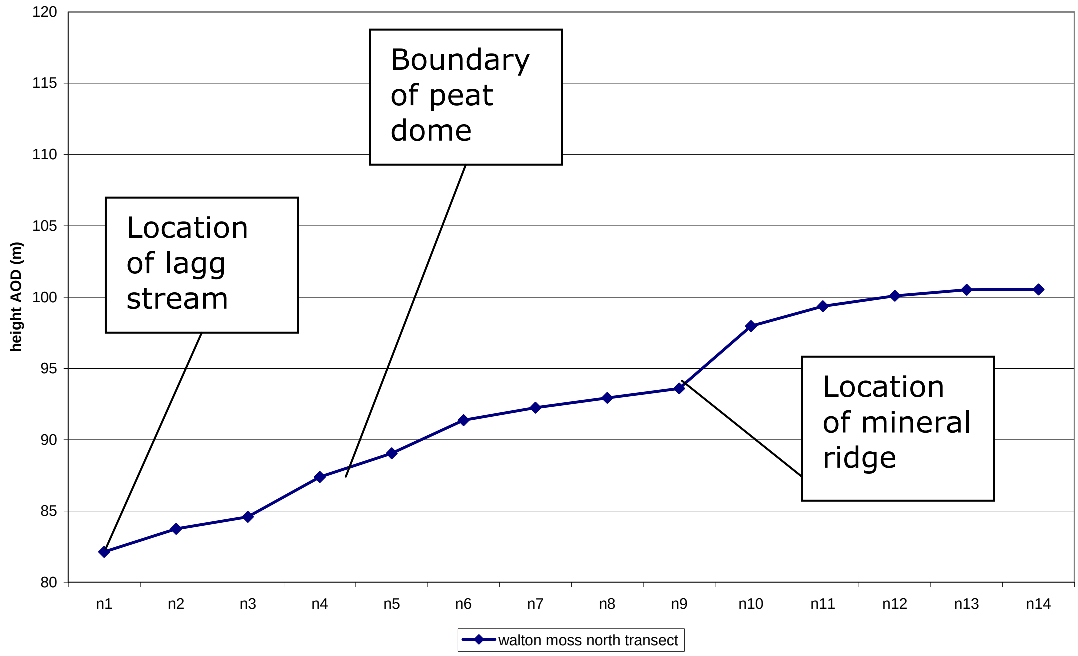


Figure 6.20 Profile of Walton Moss south transect, surveyed using dGPS

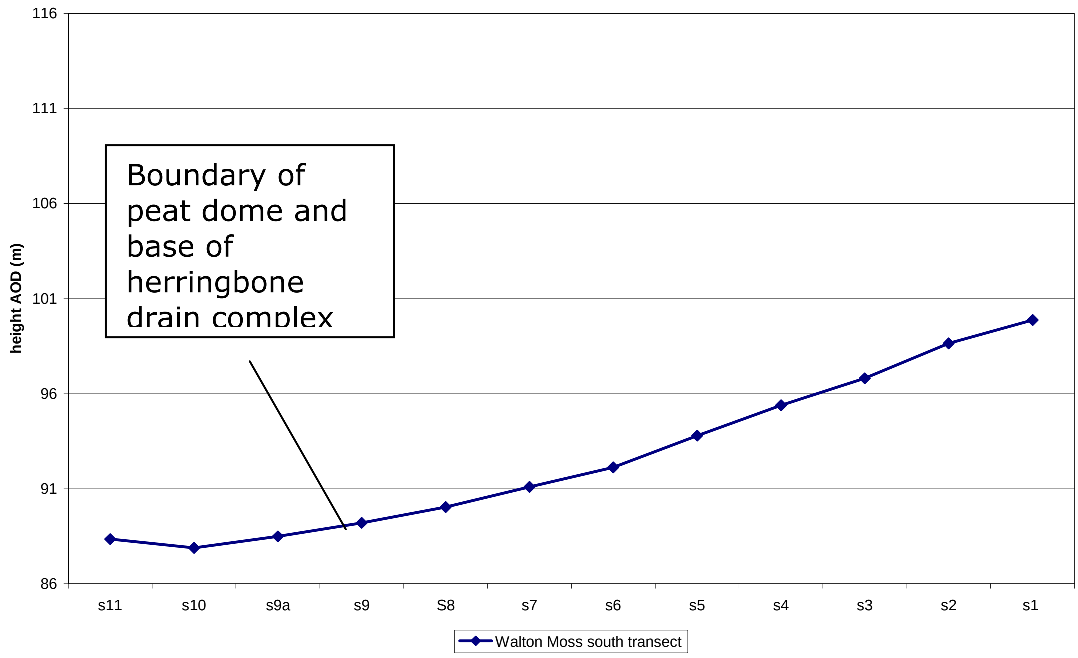
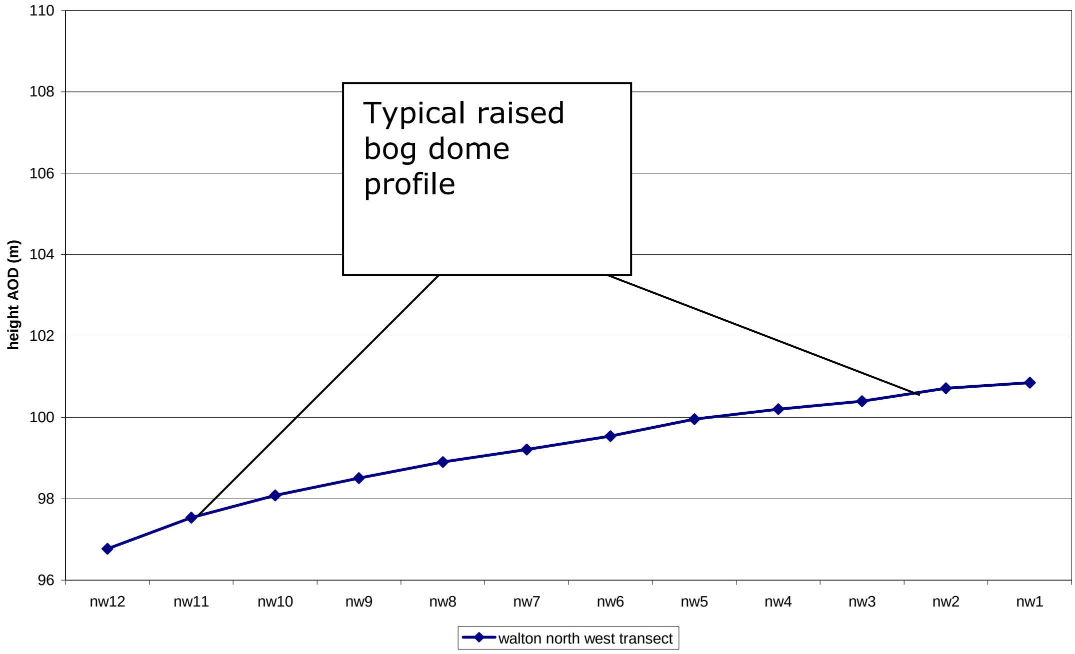


Figure 6.21 Profile of Walton Moss north west transect, surveyed using dGPS



6.3.2 microtopography at Walton Moss

Data describing microtopographic variation are derived from the dGPS surveys of 2 metre plots associated with each dipwell, undertaken in the summer of 2008. 2m resolution LiDAR data are available for the whole site, but have been selected for 20m plots associated with the 2m dGPS plots to assess compatibility of the two data sets

6.3.2.1 Summary statistics for the 2m LiDAR data for Walton Moss 20 m^2 plots

The data shown are summary statistics derived from the 2m LiDAR survey of the study site. Table 6.10 shows data for the north transect, Table 6.11 shows data for the south transect and Table 6.12 shows data for the north west transect. The data are for 200 points contained within a 20m^2 study plot with the south east corner coinciding with the south east corner of the dGPS 2m surveyed plots. These data show the degree to which spot heights vary within these plots. In particular the standard deviation gives an indication of topographic variation for these larger plots.

Table 6.10 Descriptive statistics for Walton Moss north transect LiDAR data

Dipwell	Min	Max	Range	Mean	StDev
N1	81.4683	83.4527	1.98439	82.6296	0.417678
N2	83.9664	84.4703	0.503845	84.1439	0.096202
N3	85.0224	86.1283	1.10595	85.5985	0.260636
N4	87.3073	87.9868	0.679436	87.699	0.126296
N5	88.0975	89.7692	1.67161	89.3609	0.324602
N6	91.2358	91.9997	0.763832	91.6647	0.169625
N7	92.3787	92.8334	0.454704	92.5503	0.081741
N8	93.0671	93.4551	0.387932	93.236	0.082931
N9	93.6485	95.3917	1.74323	94.3119	0.441046
N10	97.9025	98.7798	0.877228	98.3556	0.205729
N11	99.3377	99.8623	0.524643	99.5819	0.109004
N12	100.211	100.479	0.267502	100.327	0.058507
N13	100.587	100.861	0.273804	100.703	0.057992
N14	100.627	100.974	0.346909	100.763	0.062792

Table 6.11 Descriptive statistics for Walton Moss south transect LiDAR data

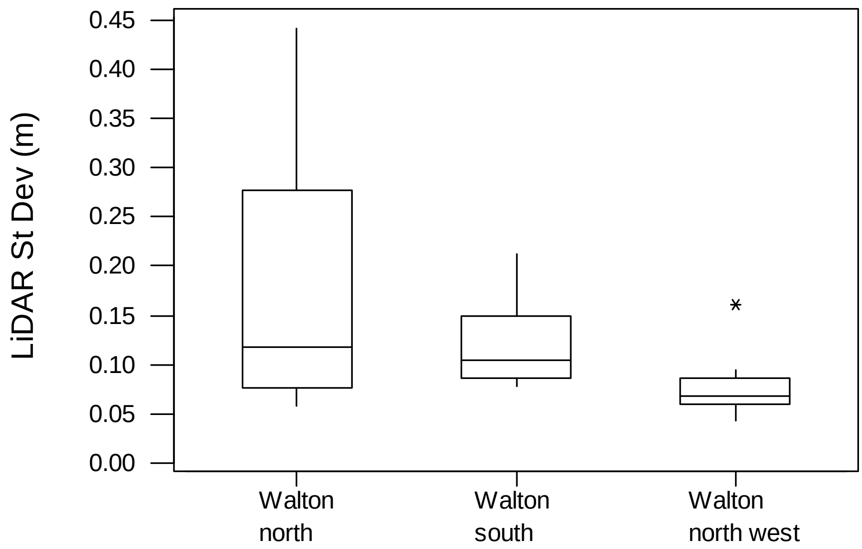
Dipwell	Min	Max	Range	Mean	StDev
S1	100.071	100.615	0.544098	100.273	0.097393
S2	98.8327	99.5806	0.74791	99.273	0.146392
S3	96.6477	97.5192	0.871483	97.0461	0.149932
S4	95.3822	95.802	0.419708	95.5949	0.095255
S5	93.5731	94.1803	0.607147	93.913	0.14926
S6	92.1074	92.5103	0.402939	92.2788	0.077399
S7	90.9543	91.4278	0.473495	91.1813	0.086582
S8	89.9489	90.3961	0.447159	90.194	0.104617
S9	88.8944	89.5427	0.648247	89.2149	0.15679
S10	87.3439	88.1656	0.821693	87.8137	0.212458
S11	88.1907	88.6016	0.410919	88.3872	0.086013

Table 6.12 Descriptive statistics for Walton Moss north west transect LiDAR data

Dipwell	Min	Max	Range	Mean	StDev
NW1	100.428	100.705	0.277702	100.56	0.055663
NW2	100.26	100.473	0.212601	100.376	0.043347
NW3	99.8745	100.247	0.372749	100.059	0.078011
NW4	99.7276	99.9638	0.236214	99.8516	0.059135
NW5	99.4713	99.7803	0.308998	99.6305	0.068764
NW6	99.1006	99.5023	0.401749	99.2665	0.094495
NW7	98.7892	99.0634	0.274254	98.9102	0.063407
NW8	98.3599	98.6996	0.339684	98.5285	0.065701
NW9	98.0335	98.4095	0.376022	98.2127	0.07374
NW10	97.5234	97.85	0.326637	97.6844	0.066573
NW11	97.104	97.5333	0.429367	97.3449	0.088147
NW12	96.0891	96.8349	0.745773	96.5512	0.161309

The standard deviations for each transect are shown in the box plots in Figure 6.22 and illustrates how the topographic variation for each transect differs between the transects. As these data are derived from 20m plots, some of this variation may be attributable to changes in the topography of the dome, rather than variation of the vegetation surface. Using standard deviation as a representation of topographic variation, it can be observed from the box plot that the mean value of the standard deviation for each quadrat is very similar, but that there is different variation of each transect, possibly a representation of the larger scale variation in the topography of the bog.

Figure 6.22 Boxplots of the standard deviation of quadrats on each transect for Walton Moss



6.3.2.2 Descriptive statistics for the dGPS 2m^2 plots

Descriptive statistics for the points contained in each plot surveyed are given in Tables 6.13, 6.14 and 6.15. It should be noted that the quadrats outside of the raised bog area on the north transect N1-N3 were not surveyed using dGPS.

Table 6.13 Descriptive statistics for Walton Moss north transect dGPS data

Dipwell	max	Min	Mean	St Dev
N4	88.132	87.853	87.94931	0.062096
N5	90.575	90.383	90.45567	0.073369
N6	91.426	91.313	91.37063	0.022479
N7	92.506	92.27	92.31626	0.044049
N8	93.148	92.887	92.97896	0.061719
N9	93.865	93.511	93.65864	0.076193

N10	98.188	97.921	98.0162	0.060299
N11	99.522	99.278	99.35816	0.050317
N12	100.797	100.612	100.6693	0.034113
N13	101.152	100.934	101.0071	0.037117
N14	101.228	101.046	101.112	0.035238

Table 6.14 Descriptive statistics for Walton Moss south transect

Dipwell	max	min	mean	StDev
S1	97.673	97.369	97.4934	0.054709
S2	96.402	95.892	96.25541	0.061834
S3	94.704	94.255	94.44228	0.093864
S4	93.058	92.906	92.97456	0.031122
S5	91.508	91.266	91.35031	0.045622
S6	89.737	89.593	89.66199	0.031722
S7	88.78	88.564	88.64717	0.042137
S8	87.766	87.538	87.61695	0.041723
S9	86.915	86.666	86.78729	0.051937
S10	85.581	85.24	85.41176	0.06189
S11	86.098	85.854	85.96534	0.056066

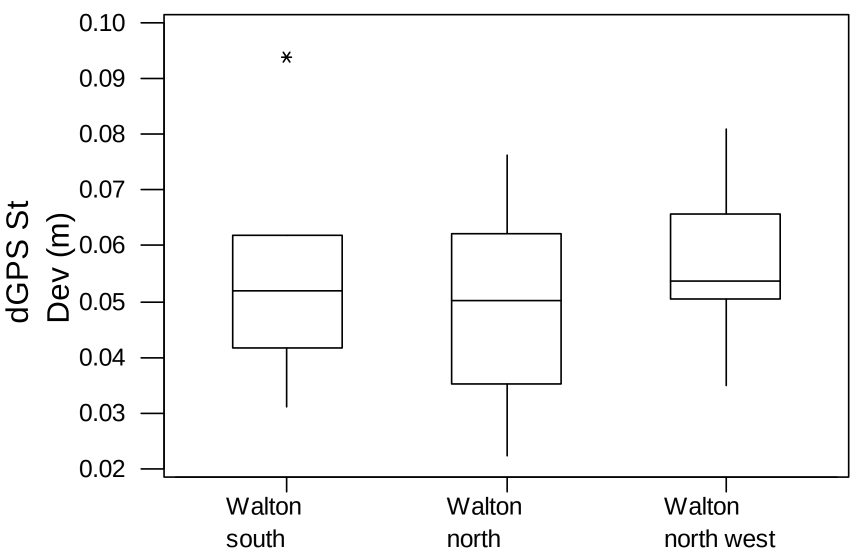
Table 6.15 Descriptive statistics for Walton Moss north west transect

Dipwell	max	min	Mean	StDev
NW1	100.982	100.554	100.8596	0.04991
NW2	100.859	100.597	100.6983	0.050328
NW3	100.59	100.297	100.4286	0.054217
NW4	100.32	100.092	100.2215	0.050889
NW5	100.109	99.828	99.947	0.059623
NW6	99.798	99.416	99.54466	0.068273
NW7	99.358	99.068	99.1799	0.053236

NW8	99.063	98.717	98.83681	0.053253
NW9	98.743	98.426	98.57245	0.067131
NW10	98.26	97.914	98.04269	0.080993
NW11	97.723	97.448	97.58223	0.061468
NW12	96.897	96.734	96.79819	0.034928

The standard deviations for each transect are shown in the box plots in Figure 6.23 and illustrates how the topographic variation for each transect differs only slightly between the transects, suggesting that the gross topography of the individual plots are quite similar when considered at this small scale where larger topographic variation of the macrotope is not considered.

Figure 6.23 Boxplots of the standard deviation of quadrats on each transect for Walton Moss



6.3.2.3 Comparison of dGPS and LiDAR derived topographic data

The standard deviations of both the LiDAR and dGPS quadrat summaries have been used to show topographic variation along these transects in Figures 6.24, 6.25 and 6.26. These data are shown as error bars on the line graph of the appropriate transect. Data derived from dGPS survey are shown above the line and data derived from LiDAR below. This gives a graphic representation of the topographic data and an indication of the location of the topographic data. It must be noted that the value of the standard deviation has been multiplied by ten for clarity, the locations of the dipwells are not to scale and the vertical scale has been exaggerated.

Where there is little large scale topographic change, the LiDAR and dGPS variations are very similar, as can be seen in Figure 6.26 for the north west transect. There appears to be a greater difference on the north transect, but particularly where there are abrupt changes in elevation, such as at N9 and N10. Where topographic change is constant, such as on the south transect, the difference between dGPS and LiDAR variation is greater, but appears to remain more consistent. These differences are explored further in Chapter 7.

Figure 6.24 Topographic variation along the north transect of Walton Moss

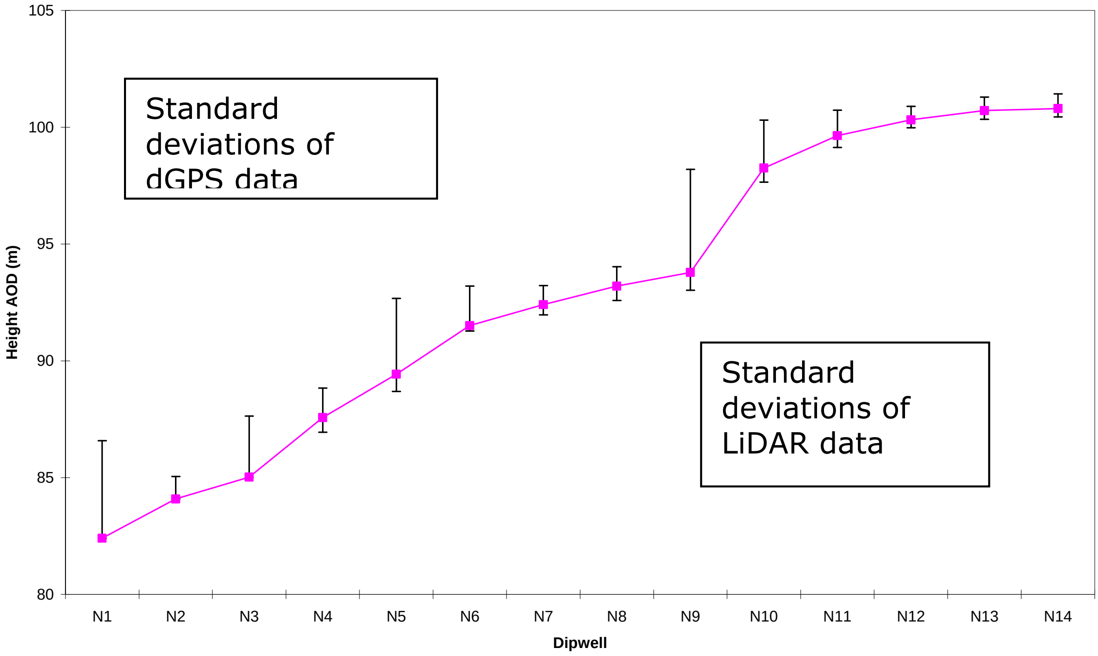


Figure 6.25 Topographic variation along the south transect of Walton Moss

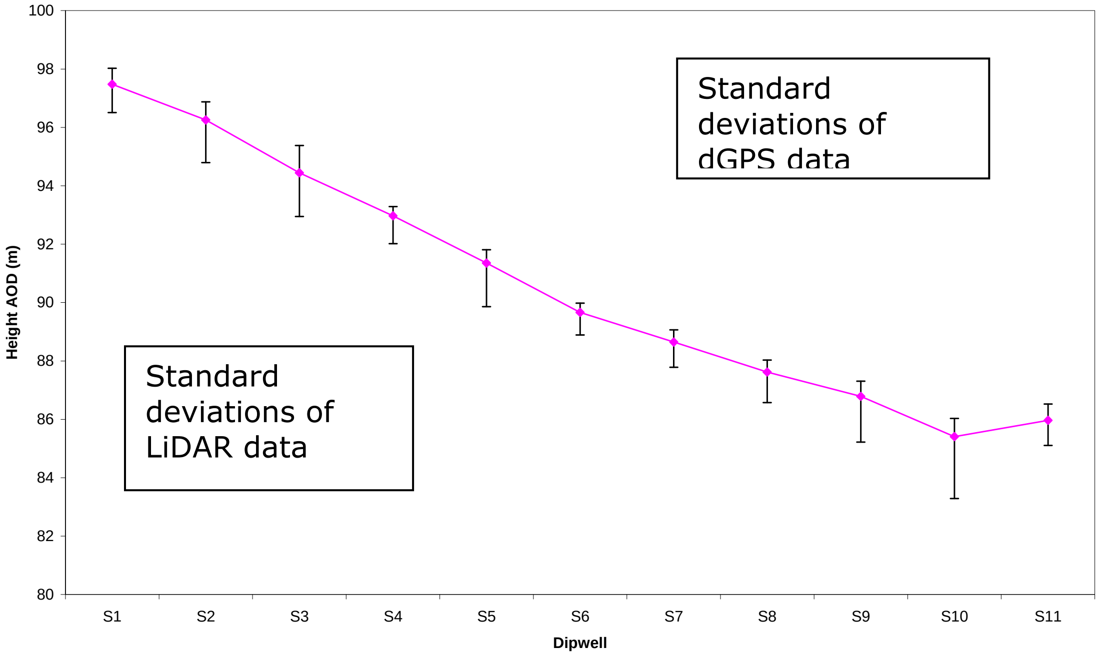
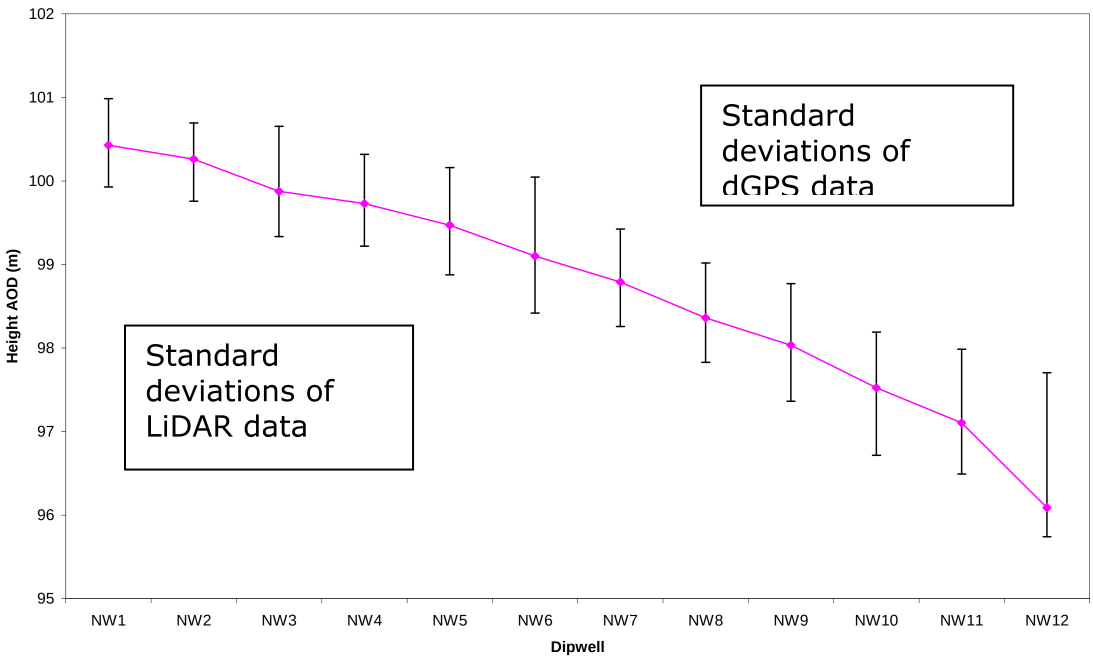


Figure 6.26 Topographic variation along the north west transect of Walton Moss



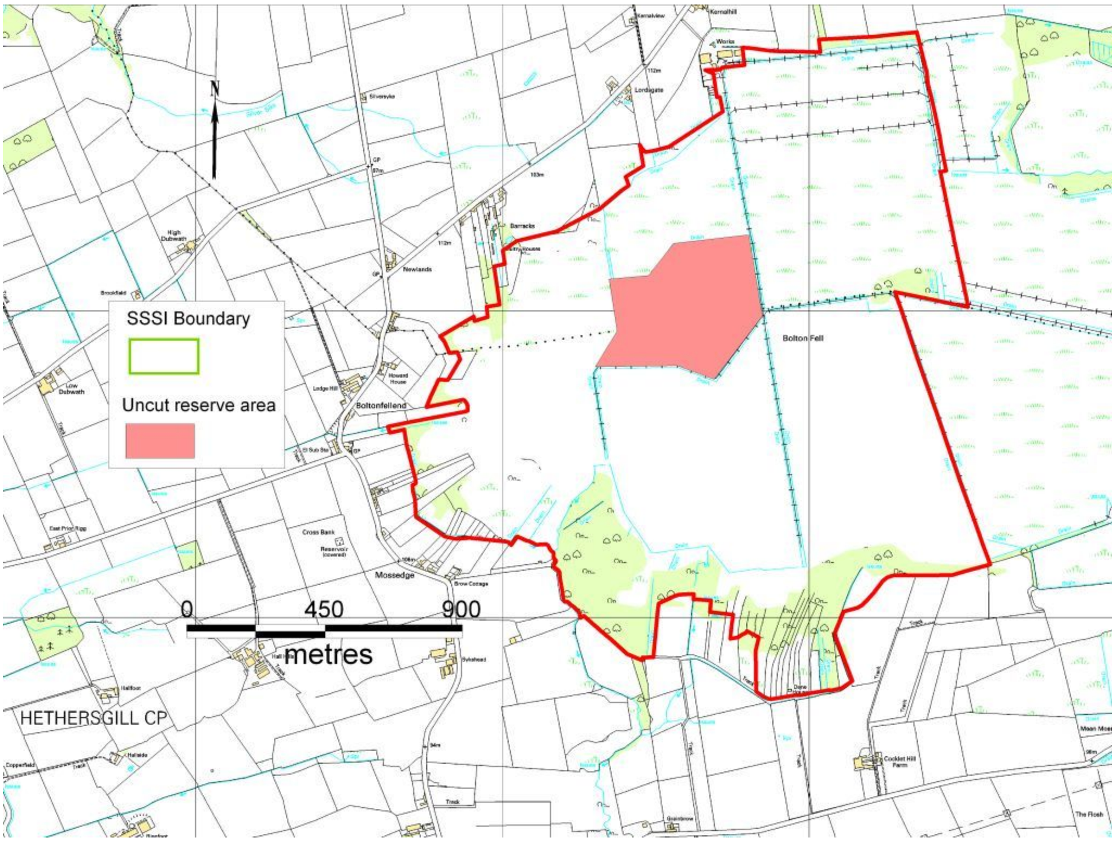
6.4 Topography at Bolton Fell Moss

6.4.1 Characteristics of the macrotope

Bolton Fell Moss reserve area is not a complete microtope. The site has a long history of peat extraction and much of the original area of peat has been removed for horticultural use. This has distorted the shape of the dome, both through physical removal and through consequential shrinkage.

The boundary of the SSSI, as determined by Natural England in 1991 is shown in Figure 6.27, together with the area of the reserve. This illustrates that the reserve is only a small proportion of the overall former area of bog, and it is to be remembered that the SSSI does not cover the whole of the cut over area.

Figure 6.27 Map of Bolton Fell Moss showing the area of SSSI and uncut reserve area.



The degree of shrinkage of the peat can be seen from the photograph in Figure 3.5 in Section 3.4.2.1. Such shrinkage can also be observed at the boundary of the bog and the cut over area, shown in Figure 6.28, the height difference between the cut area and the intact bog should be in excess of 2m.

Figure 6.28 Shrinkage of peat at edge of cut over area of Bolton Fell Moss

6.4.1.2 dGPS surveys of transects cross sections

The dGPS survey of the Bolton Fell Moss transects extends out into the cut over peat surface and included dipwells which were lost due to peat harvesting operations. The profiles are shown in Figures 6.29 and 6.30. It is especially important to note that these profiles are not to scale horizontally and have an exaggerated vertical scale.

On the north transect, the highest point is 109.24m, whilst the height of the milled peat surface is 105.76. The height of the bog boundary at n1 is 106.98, a height increase of 2.27m to the approximate centre of the bog at dipwell N6. A similar range is observed on the east transect. The lowest point is at dipwell E11a at 107.58, whilst the high point is 109.95 at dipwell E2. This dipwell is towards the eastern boundary of the reserve area and may indicate that the former centre of the dome was towards this side, however gross shrinkage of the remaining undug peat makes such assumptions difficult without additional evidence.

Figure 6.29 Relative heights of dipwells on Bolton Fell Moss east transect

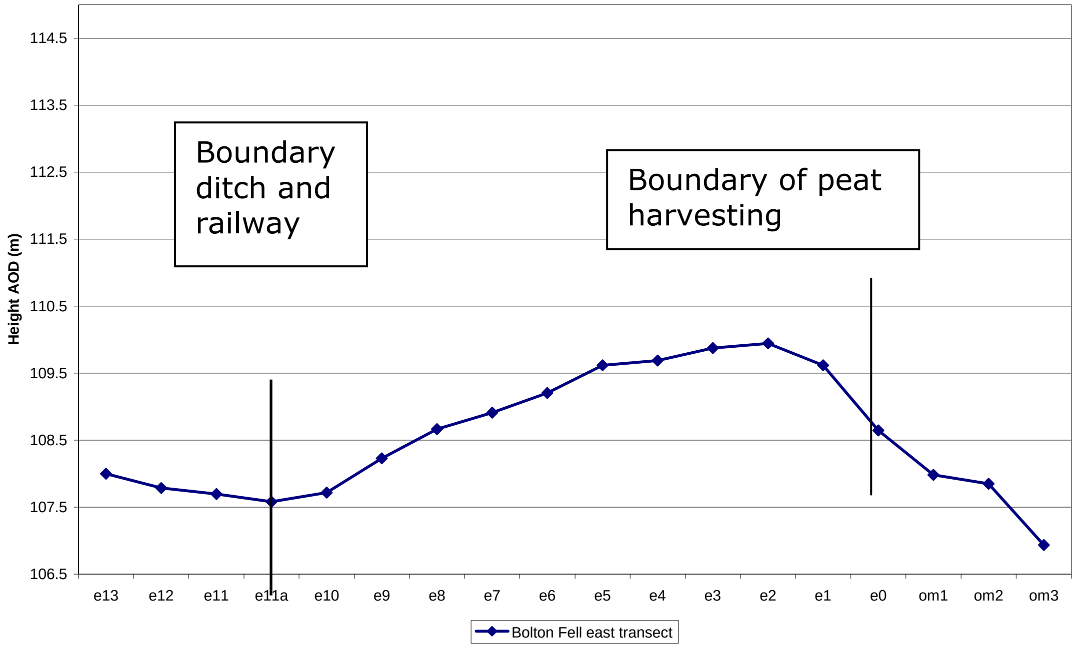
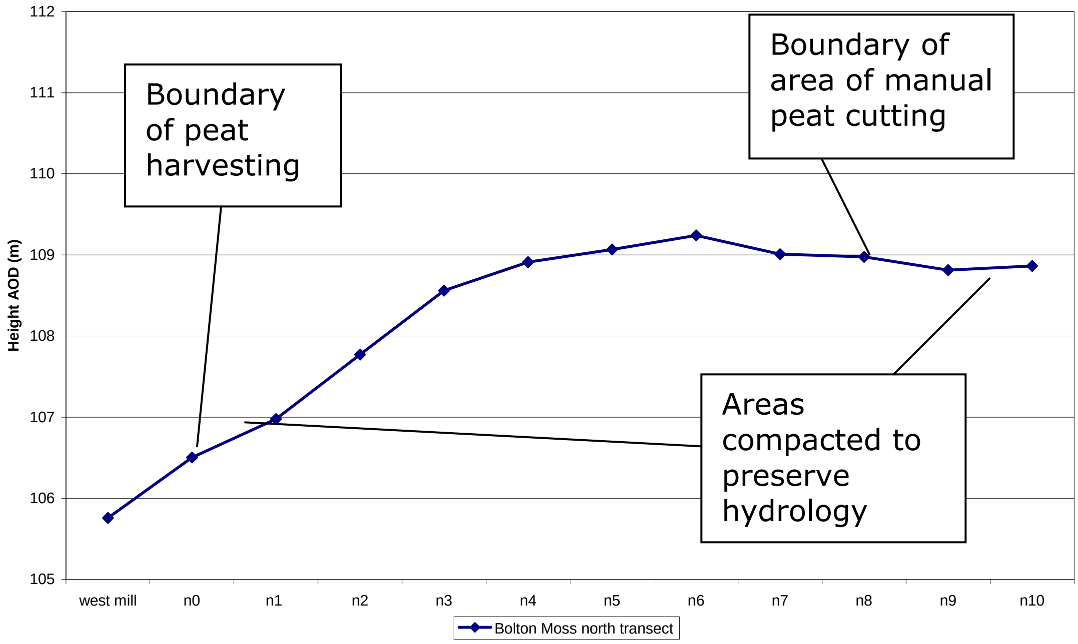


Figure 6.30 Relative heights of dipwells on Bolton Fell Moss north transect



6.4.2 Microtopography at Bolton Fell Moss

6.4.2.1 Summary statistics for the 2m LiDAR data for Bolton Fell Moss 20 m^2 plots

Bolton Fell Moss is covered by the same 2m Environment Agency LiDAR data as Walton Moss. The 20m plots share the south east corner of the 2m dGPS plots. There is less large scale topographic variation across Bolton Fell Moss, but there are more artificial topographic features, such as drainage ditches, which may hide smaller scale topographic features. Summary statistics for these data are shown in Tables 6.16 and 6.17. Values for N10 and N11 include land outside the reserve area which is part of the milled peat area which is at a lower height than the rest of the site. This explains why these plots have a higher range and standard deviation than the remainder. On the east transect, E11a is also different in this respect. This is likely to be as a consequence of the ditch and railway lines which cross the site here, marking the perimeter of Sinclair owned land.

Table 6.16 Descriptive statistics for Bolton Fell Moss north transect LiDAR data

Dipwell	Min	Max	Range	Mean	StDev
N1	107.346	108.141	0.794998	107.786	0.152417
N2	108.064	108.851	0.786499	108.489	0.165785
N3	108.907	109.575	0.667603	109.213	0.140747
N4/E7	109.168	109.711	0.542809	109.449	0.112602
N5	109.422	109.934	0.512306	109.665	0.099843
N6	109.518	109.873	0.354591	109.646	0.077818
N7	109.1	109.728	0.627792	109.438	0.151498
N8	108.264	109.765	1.501	109.351	0.255052
N9	108.95	109.63	0.6791	109.39	0.136152
N10	107.923	109.436	1.5131	108.724	0.371424
N11	107.663	109.001	1.3377	108.38	0.233656

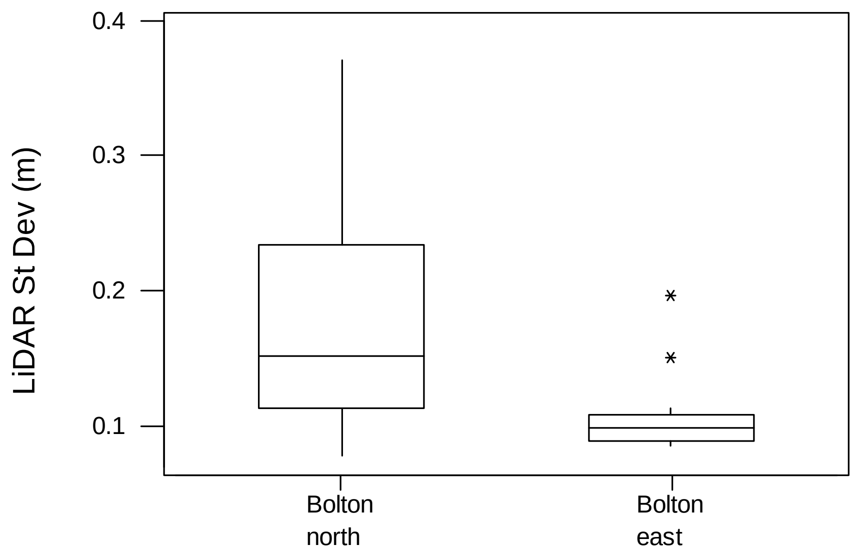
Table 6.17 Descriptive statistics for Bolton Fell Moss east transect

Dipwell	Min	Max	Range	Mean	StDev
E1	109.507	110.115	0.607903	109.819	0.150492
E2	110.091	110.65	0.559296	110.279	0.103947
E3	110.153	110.614	0.460899	110.397	0.087276
E4	110.081	110.51	0.428406	110.279	0.088525
E5	109.882	110.329	0.447098	110.133	0.087536
E6	109.6	110.094	0.493599	109.824	0.10563
E7/N4	109.168	109.711	0.542809	109.449	0.112602
E8	109.003	109.467	0.4645	109.195	0.084621
E9	108.56	109.055	0.495598	108.774	0.102463
E10	108.062	108.563	0.501701	108.287	0.095782
E11a	107.284	108.411	1.1264	107.961	0.195882
E11	108.105	108.551	0.446404	108.312	0.097752
E12	108.25	108.637	0.387398	108.441	0.094013
E13	108.311	108.741	0.43	108.515	0.099459

Figure 6.31 shows a boxplot comparison of the standard deviation of the two transects. The numbers for the eastern transect are lower than those

for Walton Moss, reflecting the lack of macrotope scale topographic change. The north transect shows a greater range of variation, reflecting the extent of the impact of peat digging and drainage related topographic change and reflecting the inclusion of these data

Figure 6.31 Boxplots of the standard deviation of 20m LiDAR plots on each transect for Walton Moss



6.4.2.2 Summary statistics for the dGPS data for Bolton Fell Moss $2m^2$ plots

The dGPS data summary given in Figures 6.18 and 6.19 show similar mean, maximum and minimum heights to the LiDAR plots, reflecting the fact that this site has less macrotopographic variation than Walton Moss. The overall range of data is also less than that of Walton Moss. In part this is again a function of the lack of macrotopographic variation, but it also reflects the small size of the site and the fact that the plots are much closer together. The total range of height across the site is 3.65m, and the standard deviation for the plots is in all cases less than 0.1m.

Table 6.18 Descriptive statistics for Bolton Fell Moss north transect dGPS data

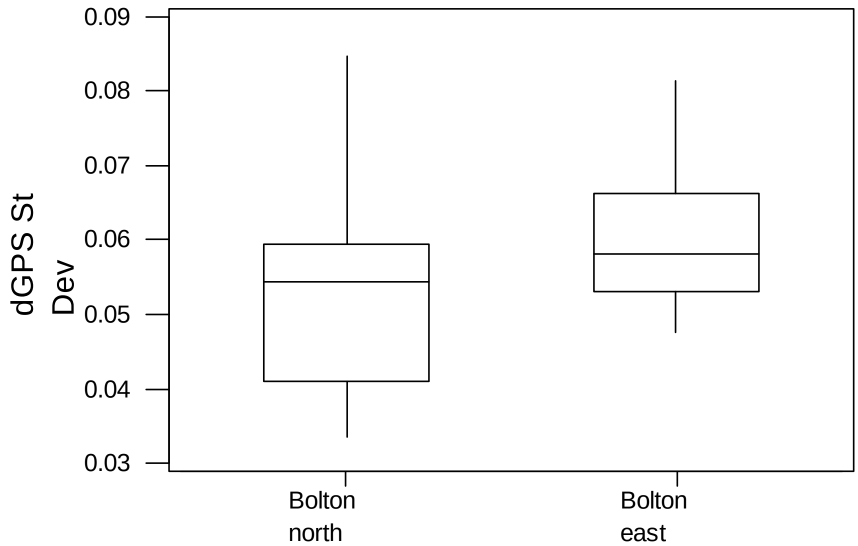
Dipwell	max	min	Mean	StDev
N1	107.252	106.963	107.1318	0.054993
N2	108.156	107.986	108.0792	0.043957
N3	109.019	108.753	108.9148	0.054469
N4	109.545	109.267	109.3628	0.059532
N5	109.736	109.47	109.5883	0.055659
N6	109.958	109.612	109.7461	0.084687
N7	109.676	109.408	109.5017	0.052679
N8	109.554	109.375	109.4433	0.033515
N9	109.568	109.348	109.4291	0.040979
N10	109.337	109.053	109.1794	0.062135
Newmill1	109.119	108.97	109.0473	0.0359

Table 6.19 Descriptive statistics for Bolton Fell Moss east transect dGPS data

Dipwell	max	min	mean	StDev
E1	110.0955	109.8865	109.9581	0.047532
E2	110.3671	110.0531	110.2867	0.054892
E3	110.4172	110.1622	110.3363	0.05739
E4	110.5907	110.1047	110.2398	0.081325
E5	110.106	109.786	110.0235	0.065792
E6	109.802	109.526	109.6285	0.067274
E7	109.5364	109.2584	109.3628	0.059532
E8	109.1988	108.8768	109.107	0.056461
E9	108.8376	108.5936	108.6568	0.051071
E10	108.276	107.957	108.261	0.060166
E11A	108.1959	107.9099	107.9357	0.053828
E11	108.7192	108.2982	108.1503	0.07938
E12	108.3768	108.0308	108.0561	0.058823
E13	108.5647	108.3547	108.3546	0.048521

The box plot of the dGPS standard deviations shown in Figure 6.32 illustrates this small range and lack of variation.

Figure 6.32 Boxplot of the standard deviation of 2m dGPS plots on each transect for Walton Moss



6.4.2.3 Comparison of dGPS and LiDAR derived topographic data

The variation of these topographic data across the transect, and the differences between the dGPS and LiDAR data are illustrated by Figures 6.33 and 6.34. As with the data for Walton Moss, the standard deviation of the topographic data are shown as error bars on the line graph of the appropriate transect. Data derived from dGPS survey are shown above the line and data derived from LiDAR below. This allows a graphic representation of the topographic data and to give an indication of the location of the topographic data. The value of the standard deviation has been multiplied by ten for clarity, the locations of the dipwells are not to scale and the vertical scale has been exaggerated.

Figure 6.33 Topographic variation along the east transect of Bolton Fell Moss

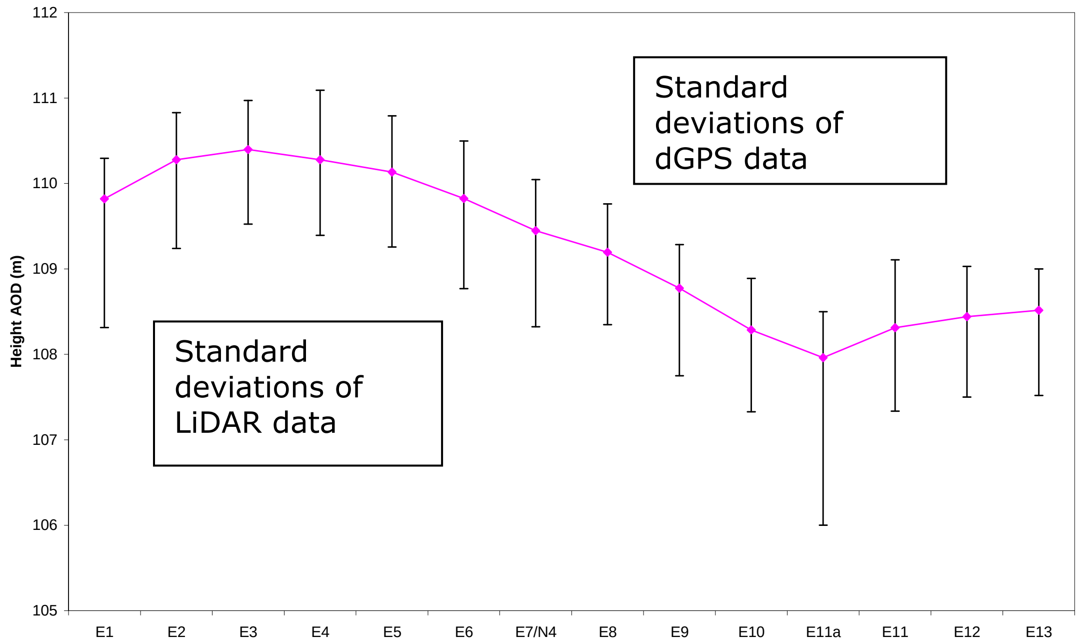
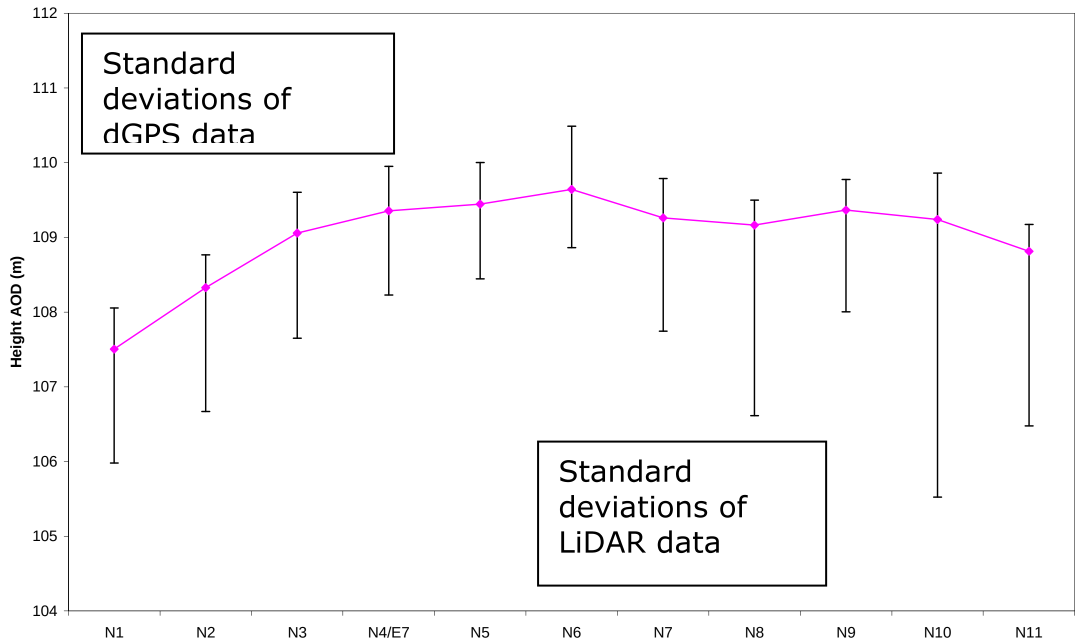


Figure 6.34 Topographic variation along the east transect of Bolton Fell Moss



Analyses of the data described in these data are undertaken in Chapter 7 and focus on the relationships between the hydrological data described in Chapter 5 and the vegetative and topographic factors described in this Chapter.

7 Introduction to analysis of data

The data described in chapters five and six illustrate the hydrological and ecological condition of the study site between October 2003 and September 2007, showing spatial variation in species distribution and depth to water table as represented by 5 dipwell transects and their associated vegetation survey quadrats. These data are supplemented by detailed records of temporal water depth variations, as recorded using OTT Thalimedes automated shaft encoders at 7 selected points and additional rainfall data recorded from Bolton Fell Moss and Met Office records at Carlisle, which give a broader explanation of the prevailing hydrological conditions between 1970 and the present. In addition to these data, information on micro-topographic variation has been obtained through ground based measurement using dGPS and remotely sensed data measured using LiDAR data obtained from the Environment Agency.

This study considers the relationships between hydrological and ecological condition and seeks to determine what if any relationship exists between these data and the degree of topographic variation, as illustrated by the degree of variation in $2m^2$ dGPS and $20m^2$ LiDAR plots associated with each dipwell.

7.1 Hypotheses for investigation

In order to interpret these data, the following relationships are investigated:

1 The relationship between the average depth to water table over the period of this study and ecological condition, as represented by species abundance and distribution.

2 The relationship between variation in depth to water table over the period of this study and ecological condition.

3 The relationship between hydrological & ecological condition and topographic variation.

7.1.1 Assessment of ecological condition

Vegetation distribution on the study sites cannot be completely described by this study. Whilst at Bolton Fell Moss, the dipwells, and therefore the quadrats, are distributed so as to give a representation of communities under a representative range of hydrological conditions, the distribution was designed to represent the hydrology primarily. It is the small size of the site which means there is a more complete representation. At Walton Moss, a much larger site, the dipwell transects were designed to study the hydrology of a specific part of the site. The vegetation quadrats on the north and south transects therefore also only represent that section of the bog. The recent north west transect is probably more representative of the larger part of pristine bog, but resources prohibited a fuller spatial sampling or walkover botanical survey prior to its installation, as recommended by Mitchley, Birch and Lawson(1998), Rodwell (1991) Large *et.al* (2007) and others. It was therefore installed on the basis of apparent hydrological condition and a subjective assessment of the vegetative condition. The following quantifications of this condition must therefore be considered with this limited caveat.

7.1.1.1 Bray Curtis cluster Analysis

The vegetation quadrats have been grouped and assessed by transect to establish what, if any associative patterns are apparent. Within the short distance of these transects, it is likely that similar environmental conditions should produce similar vegetative conditions. Bray-Curtis cluster analysis has initially been used to determine similarities between quadrats within transects (Vandervalk, Squires and Welling,1994 using methodology devised by Bray and Curtis, 1957). These analyses were undertaken using Biodiversity Pro software developed by McAleese et. al. (1997) for the Natural History Museum, London. Cluster analysis is a common methodology for assessing such vegetative data (Quinn and Keogh, 2002) and has been used in this study, although Beals (1984) recognises that this may be considered a simpler form of correspondence analysis, which has also been used to assess these data for similarity. However, Beals asserts that it is a robust assessment and provides a good initial display of similarity as a hierarchical dendrogram, with a percentage similarity scale.

From these dendrograms it is possible to identify those quadrats which are closely associated with each other. It is also possible to assess the differences between transects and to identify quadrats from different transects or different sites with similar characteristics, however it is important to consider that such data, surveyed at different times and by different individuals in different conditions, may contain associated errors which may distort the analyses (Scott and Hallam, 2003).

7.1.1.2 Detrended correspondence analysis

Detrended correspondence analysis (DCA) has been used to subsequently identify associations between species, using Canoco software (ter Braak and Smilauer, 2002). This can be used to produce a scatter plot of species and dipwells, showing their relationships. This has advantages over cluster analysis, notably that both species and quadrats can be plotted to show their associations and these are shown on a single diagram (Leps and Smilaur, 2003). The distance between individual samples and species is a measure of how the relative abundance of the species vary across the samples, using multiple chi-squared tests. Close proximity of species shows they often occur together or are associated strongly with specific dipwells or groups of dipwells (Cooper *et.al*. 2005). Similarly, dipwells shown close together will have similar characteristics. Dipwells and species assemblages judged to be most typical of the transect have been highlighted within the blue areas marked on the diagrams.

This analysis also produces gradient lengths, which show the degree of species turnover across the sample, which in turn is used to select the form of ordination used subsequently when environmental data is also assessed.

Due to software and space limitations it is not possible to give the full name of species in Canoco output, therefore the species are abbreviated. A list of species abbreviations used for Canoco analyses is given in Appendix 6.1.

7.1.2 Investigation of relationships between vegetation and dipwell levels

Each dipwell has an associated $1m^2$ quadrat. The species were identified and the percentage cover recorded, as described in section 6.2.3. In addition, MAVIS software (Smart, 2000) was used to determine percentage fit with the characteristics of M18 NVC raised bog habitat for each quadrat, as described in Section 6.2.3.

A series of Spearman rank correlation tests were undertaken for each transect to determine if there was a relationship between M18 fit and hydrological condition. This test was selected as it is a robust test for similarity between two aspects recorded from a single set of samples (Shaw & Wheeler, 1994) and has been used by Large *et. al*. (2007) and Gilvear & Bradley (2000) amongst others to look at the relationship between dipwells and ecological condition.

For the relationships between individual species and quadrat communities further analyses of the data using Canoco was undertaken. On the basis of the initial assessment using DCA, Canonical Correspondence Analysis (CCA) was undertaken, together with a Monte Carlo permutation test, which determines the statistical significance of the analysis (ter Braak & Smilaur, 2002). The relationship between vegetation and both average water depth and variation (as standard deviation) of water depth were assessed.

R^2 values are given for all comparisons, as a useful indicator of goodness of fit, however for these initial smaller data sets, they should be treated with caution, and a full regression analysis has not been undertaken. Regression analysis for data from both sites is given in sections 7.2.3 and 7.3.4

7.1.3 Investigation of relationships between micro-topography and depth to water table

The relationships between variation in microtopography and dipwell variation, as measured by LiDAR and dGPS have been investigated, initially using correlation between the standard deviation of the measured topography in the plots and average dipwell levels for the period of study. As the rainfall for any given year in the study period has been untypical of the longer means, as discussed in Section 5.3, it was judged more representative to take longer periods for comparison. It is also noted that vegetation communities reflect more general hydrological conditions than any short term variation (Ruseckas and Grigaliunas, 2008), particularly for larger sites as bogs are a long-term recharge system (Fraser *et.al*., 2001). In addition, the correlation between the LiDAR and dGPS data was calculated to see if the locally measured topographic variation was reflected in the coarser variation of the measured 20m LiDAR plots.

These data have been collected on a transect by transect basis, so other analyses have initially followed this pattern. Final analyses have been undertaken on data collected from each site as a whole and on all data collected from both sites to investigate whether relationships observed on individual transects can also be observed when larger, more spatially diverse samples are considered. These larger data sets have also been assessed using linear regression. The potential value of topographic variation as a predictor for hydrological condition is discussed in Chapter 8.

A summary of these data is given in Table 7.1

Table 7.1 Summary of LiDAR, dGPS, dipwell variation and vegetation NVC community
Walton Moss

Dipwell name	**std dgps 2m quadrat**	**STD LiDAR**	mean dipwell	stDev dipwell	percentage fit m18
N1	N/A	0.417678	0.044269	0.096207	N/A
N2	N/A	0.0962019	0.041133	0.083396	N/A
N3	N/A	0.260636	0.114148	0.136407	N/A
N4	0.06209643	0.126296	0.108258	0.065268	N/A
N5	0.07336939	0.324602	0.140938	0.123737	37.77
N6	0.02247946	0.169625	0.036786	0.065413	34.74
N7	0.04404915	0.0817405	0.045482	0.089412	36.12
N8	0.06171896	0.0829305	0.053696	0.092926	36.24
N9	0.07619347	0.441046	0.101467	0.107024	0
N10	0.06029879	0.205729	0.055605	0.066413	39.22
N11	0.0503173	0.109004	0.057754	0.066914	47.04
N12	0.03411289	0.0585074	0.035517	0.05653	47.36
N13	0.03711742	0.0579919	0.081786	0.051365	31.2
N14	0.03523789	0.0627921	0.032644	0.044066	37.77
S1	0.0547089	0.097393	0.050886	0.062249	40.72
S2	0.0618339	0.146392	0.101477	0.082854	0
S3	0.0938636	0.149932	0.050148	0.069496	36.24
S4	0.0311223	0.095255	0.032	0.070857	46.41
S5	0.0456215	0.14926	0.104955	0.074926	44.01
S6	0.0317218	0.077399	0.072727	0.042152	48.75
S7	0.0421374	0.086582	0.05725	0.058054	35.93
S8	0.0417234	0.104617	0.060136	0.062706	36.12
S9	0.0519373	0.15679	0.070727	0.056632	30.41
S10	0.0618901	0.212458	0.148477	0.197297	0
S11	0.0560656	0.086013	0.102305	0.131568	39.15
NW1	0.04990952	0.055663	0.021818	0.017069	30.82
NW2	0.05032757	0.043347	0.008636	0.023884	40.44
NW3	0.0542167	0.078011	0.002727	0.012721	35.88
NW4	0.05088872	0.0591351	0.01090909	0.0524318	31.1
NW5	0.05962311	0.0687639	-0.005	0.0280179	45.21
NW6	0.06827268	0.094495	0.02954545	0.0215005	42.2
NW7	0.05323617	0.0634073	-0.0072727	0.0242243	32.84
NW8	0.05325322	0.0657005	-0.0527273	0.0310132	40.72
NW9	0.06713107	0.0737398	0.00090909	0.0122103	36.17
NW10	0.08099342	0.066573	0.01272727	0.0289278	45.21
NW11	0.0614677	0.088147	-0.005909	0.018817	45.74
NW12	0.0349283	0.161309	0.081818	0.051782	45.45

Table 7.1 (cont)

Bolton fell Moss

Dipwell name	**st dev dgps quadrat (m)**	**St Dev LiDAR (m)**	mean dipwell (m)	st Dev dipwell (m)	percentage fit m18
N1	0.0549933	0.152417	0.06275	0.087373	42.86
N2	0.0439572	0.165785	0.033354	0.061125	38.77
N3	0.054469	0.140747	0.097938	0.070069	43.78
N4/E7	0.0595322	0.112602	0.063813	0.057101	41.79
N5	0.0556589	0.099843	0.0415	0.049184	43.94
N6	0.084687	0.077818	0.038625	0.058353	49.69
N7	0.0526795	0.151498	0.059063	0.041719	52.59
N8	0.0335147	0.255052	0.1895	0.157369	0
N9	0.0409789	0.136152	0.22075	0.125543	42
N10	0.0621345	0.371424	0.06166	0.073552	33.66
N11	0.0358997	0.233656	0.327106	0.084493	0
E1	0.0475316	0.150492	0.115333	0.052093	33.38
E2	0.0548922	0.103947	0.090625	0.046001	0
E3	0.0573902	0.087276	0.048604	0.057212	38.08
E4	0.0813247	0.088525	0.08775	0.050756	38.08
E5	0.0657919	0.087536	0.113021	0.063644	32.24
E6	0.0672742	0.10563	0.068438	0.053322	31.03
E7/N4	0.0595322	0.112602	0.062167	0.056684	39.51
E8	0.0564614	0.084621	0.049479	0.051369	32.16
E9	0.0510711	0.102463	0.124208	0.086448	31.03
E10	0.0601657	0.095782	0.039833	0.056221	0
E11a	0.0538281	0.195882	0.249341	0.088852	0
E11	0.0793802	0.097752	0.154574	0.057436	0
E12	0.0588232	0.094013	0.064396	0.076037	39.51
E13	0.0485208	0.099459	0.082565	0.06453	

7.2 Assessment of data from Walton Moss transects

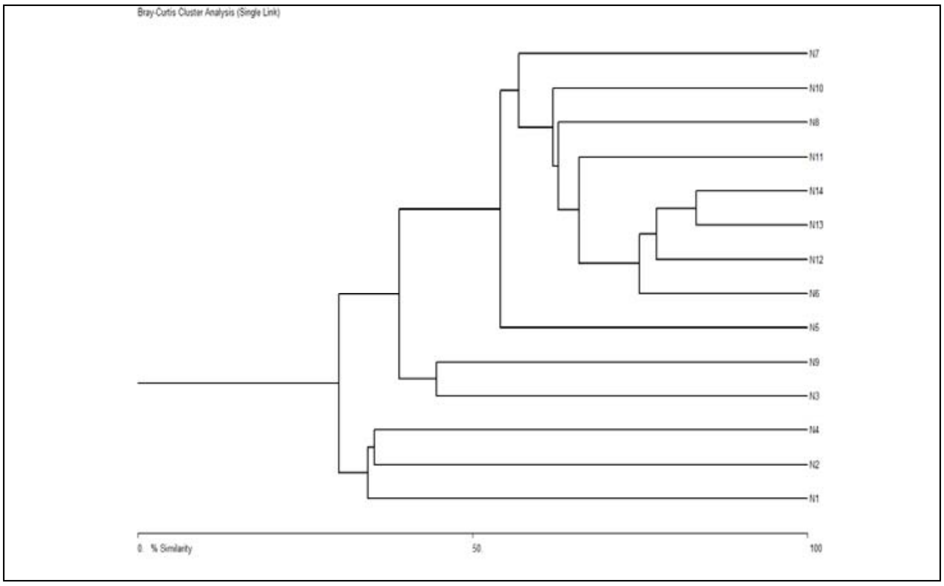
7.2.1 Walton Moss north transect

7.2.1.1 North transect Bray Curtis cluster analysis

The Dendrogram for the north transect shows a higher level of heterogeneity than that of the north west transect, shown in Figure 7.15, confirming that the transect is not necessarily representative of pristine bog. This transect had initially been created as an unmodified comparison for the adjacent south transect (Labadz *et.al*,2006), so this is important when considering any comparison of these transects. The Dendrogram for the north transect is shown in Figure 7.1. It is unsurprising that the vegetation of quadrats N1 and N2, N3 and N4 on the north transect show little similarity with the rest of the transect as they are located below the dome of the raised bog in the Lagg fen area, which is subject to higher mineratrophic inputs (Hughes and Barber,2003). Quadrat N1 shows less than 10% similarity with all quadrats on the transect which may be considered on the dome of the bog, apart from dipwell N9 at 14.65% similarity. Quadrats N3 and N4 also show a similar, but low degree of similarity with N9 with similarities of 44.6% and 30.1% respectively. Quadrat N9 has already been identified as being on the drier mineral ridge in Section 6.1.2.1 and appears to have some of the vegetative characteristics of the bog margin.

The quadrats closer to the centre of the bog show greater homogeneity N14, N13 and N14 showing over 70% similarity. Typically results from bog quadrats below N9 show less similarity, with similarities to the top of the site between 40.26% and 44.2%. However quadrat N6, at 73.5% is more typical of the vegetation at the top of the moss.

Figure 7.1 Dendrogram showing Walton Moss north transect vegetation cluster analysis



7.2.1.2 North transect DCA

As noted from the initial Bray-Curtis analysis in Section 7.2.1.1 the N1-N3 quadrats are not typical of raised bog. As there is also incomplete topographic data from these stations, they have been excluded from this analysis. It is possible to see a distinct grouping of the quadrats associated with the intact bog with N4 on the edge of the bog mound showing different characteristics, together with, in this instance, the N9 quadrat. The N9 quadrat is associated with the mineral ridge feature, and is associated with *Molinea caerulea*, a potential indicator of drier conditions. On the edge of the bog mound, quadrat N4 shows associations with *Deschampsia flexuosa* and Polytrichum commune, more typical of mineratrophic fen (Rodwell, 1991), which is to be expected given its location on the boundary of raised bog and mineratrophic lag fen.

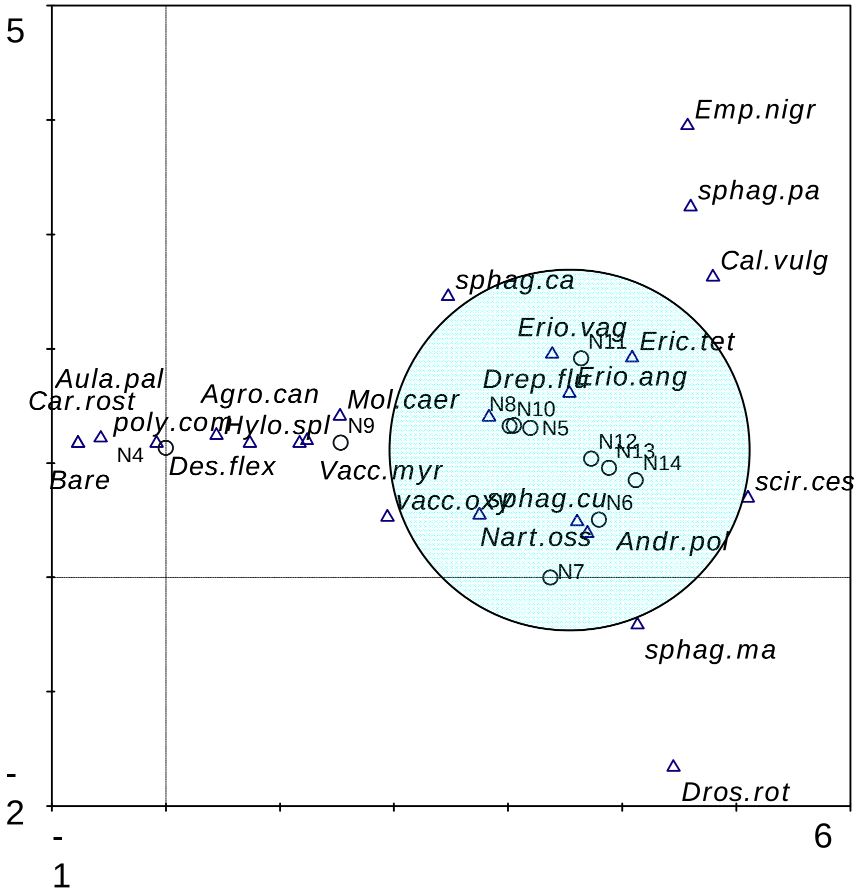
The summary of the initial DCA Canoco run is shown in Table 7.2. As the largest gradient is over 3, this indicates the data are suitable for subsequent CCA analysis as the data show a moderate unimodal response (Leps and Smilaur, 2003). All subsequent analyses of these data have yielded similar values, indicating that CCA analysis is appropriate. These analyses are shown in Section 7.5.

Table 7.2 Example of Canoco DCA analyisis for Walton Moss north transect

Axes	1	2	3	4	Total inertia
Eigenvalues:	0.711	0.234	0.069	0.017	1.811
Lengths of gradient:	3.515	2.2	0.983	1.38	
Cumulative percentage variance of species data	39.3	52.2	56	56.9	

The DCA plot for species and quadrat similarities is shown in Figure 7.2. The grouping of species which are most associated with the bog dome quadrats are highlighted by the shaded elipse. Again the quadrat N9, which might be expected to be more typical of the bog dome shows a closer association with the quadrat N3 and is also near to species of drier conditions – *Molinea caerulea* and *Vaccinium myrtillus*.

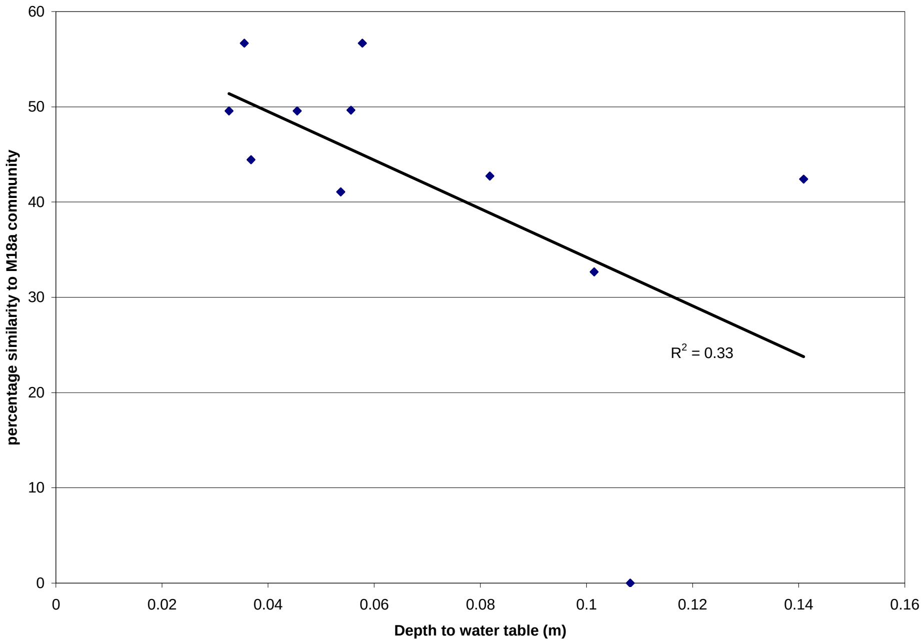
Figure 7.2 Detrended correspondence analysis scatter plot for Walton Moss north transect



7.2.2.3 Correlation between raised bog NVC community M18a and depth to water table

The correlation between m18a community and depth to water table is -0.574, although as P = 0.065, this cannot be considered a significant relationship. The corresponding scatter plot is shown in Figure 7.3.
The P value is, however sufficiently close to 0.05 that this relationship is deserving of further investigation. In particular, if the anomalous value from N5 is excluded, the correlation value becomes -0.788, and is significant at P = 0.007. Possible justification for the exclusion of such data are discussed in Chapter 8.

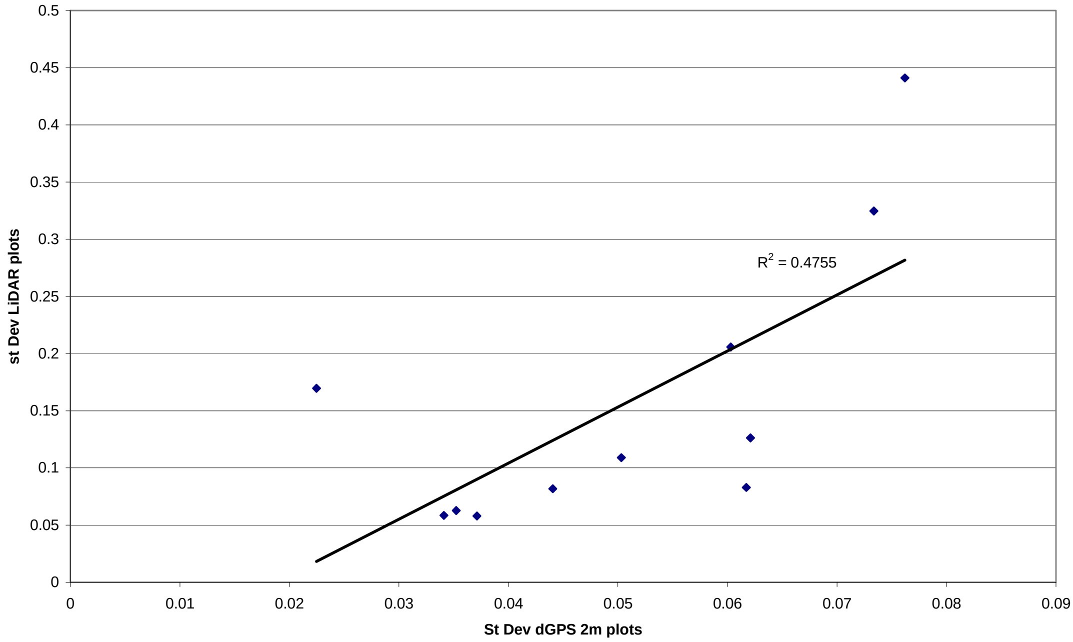
Figure 7.3 Scatter plot showing the relationship between m18a community similarity and average depth to water table for Walton Moss north transect



7.1.2.4 Relationship between depth to water table and surface microtopography for Walton Moss north transect

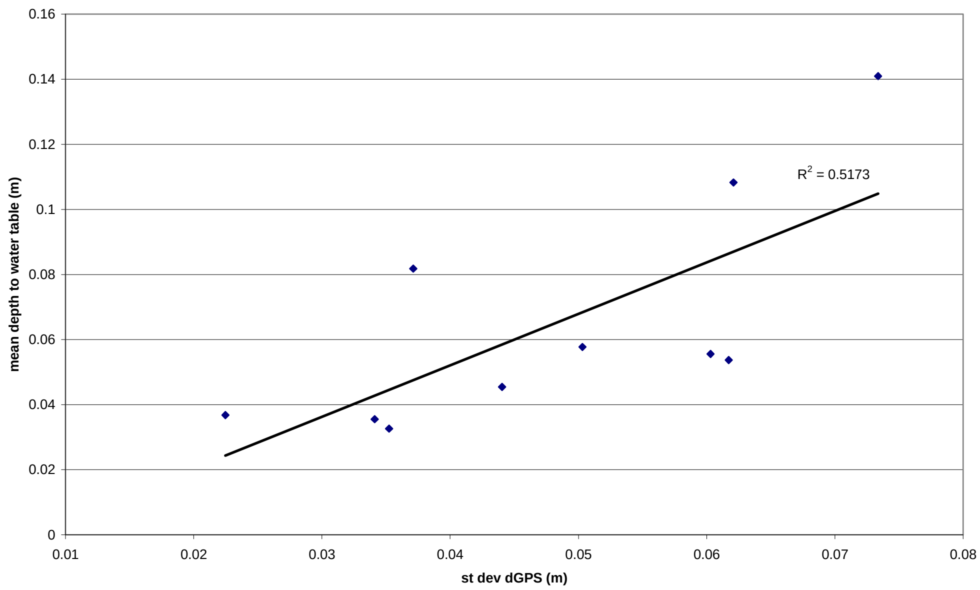
The relationship between dGPS and LiDAR for this transect is shown in figure 7.4. They are strongly correlated at 0.690, P = 0.019. The value ofR^2 = 0.48, however, suggests that there is still substantial difference between the measured topographic variation at that point and the topographic variation of the local area, as described by the LiDAR topographic variation.

Figure 7.4 Scatter plot of LiDAR plot standard deviation and dGPS plot standard deviation for north transect.



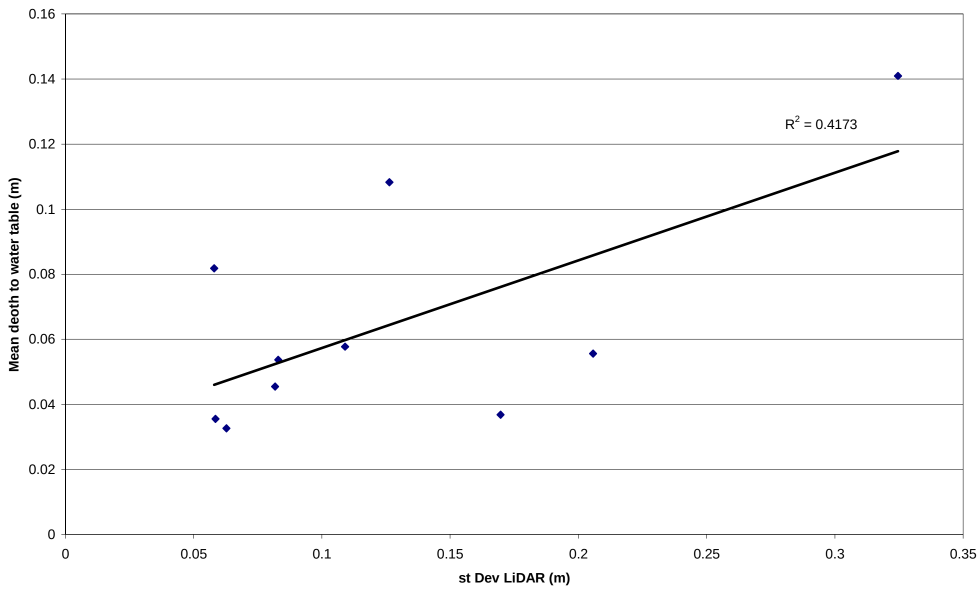
The relationship between the directly measured $2m^2$ dGPS plots and the average depth to water table shows a positive correlation of 0.646 and is significant at P = 0.044. The corresponding scatterplot for these data is shown in Figure 7.5

Figure 7.5 Scatterplot to show the relationship between measured variation in dGPS spot heights and depth to water table for Walton Moss north transect



This relationship is also apparent when the data from 20m[2] are considered. The relationship between the depth to water table and the LiDAR data is more strongly correlated at 0.719 and is again significant at P = 0.019. These data are illustrated in Figure 7.6.

Figure 7.6 Scatterplot showing the relationship between measured variation in LiDAR spot heights and depth to water table for Walton Moss north transect

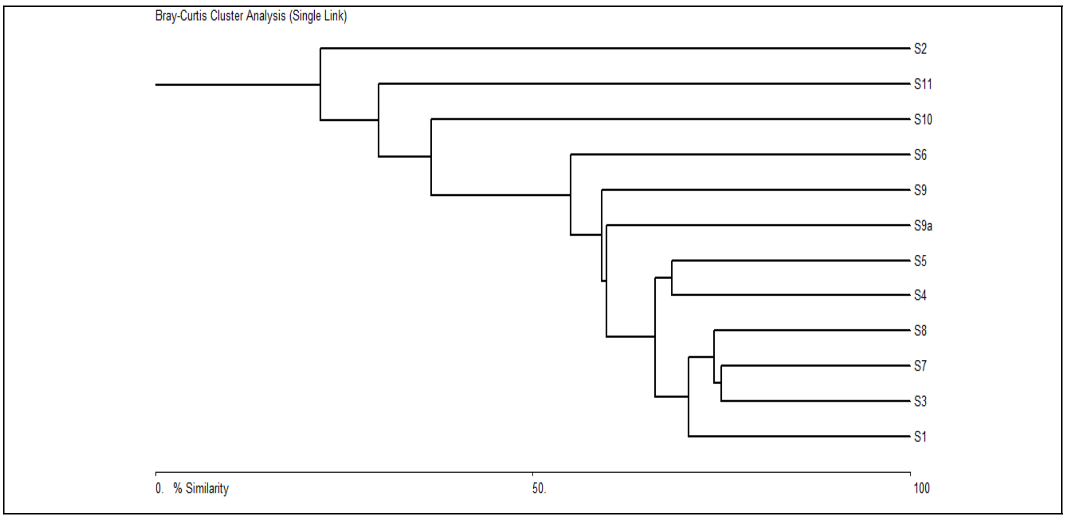


7.2.2 South transect

7.2.2.1 South transect Bray-Curtis cluster analysis

The dendrogram for the cluster analysis of the South transect is shown in Figure 7.7. Although lacking the distinct area of Lagg fenn that is present on the north transect, there are still many differences between the quadrats of the southern transect. S10 and S11 quadrats are located on slightly higher, mineral ground at the edge of the bog, which for the purposes of this study may be considered to be at S9/ S9a. They show little similarity with the rest of the bog. In particular S11 only has between 1.85% and 15.5% similarity with any other quadrat apart from S10. Conversely, the quadrats from higher in the transect show a better degree of homogeneity, between 64.56% and 75%. However there are some exceptions. The quadrat at S2 appears to have markedly different vegetation than other quadrats, with between 2.88% similarity to the nearest quadrat at S3 and 21.91% similarity to S9 at the boundary of the bog. This may be a consequence of further mineral outcropping, similar to that at N9.

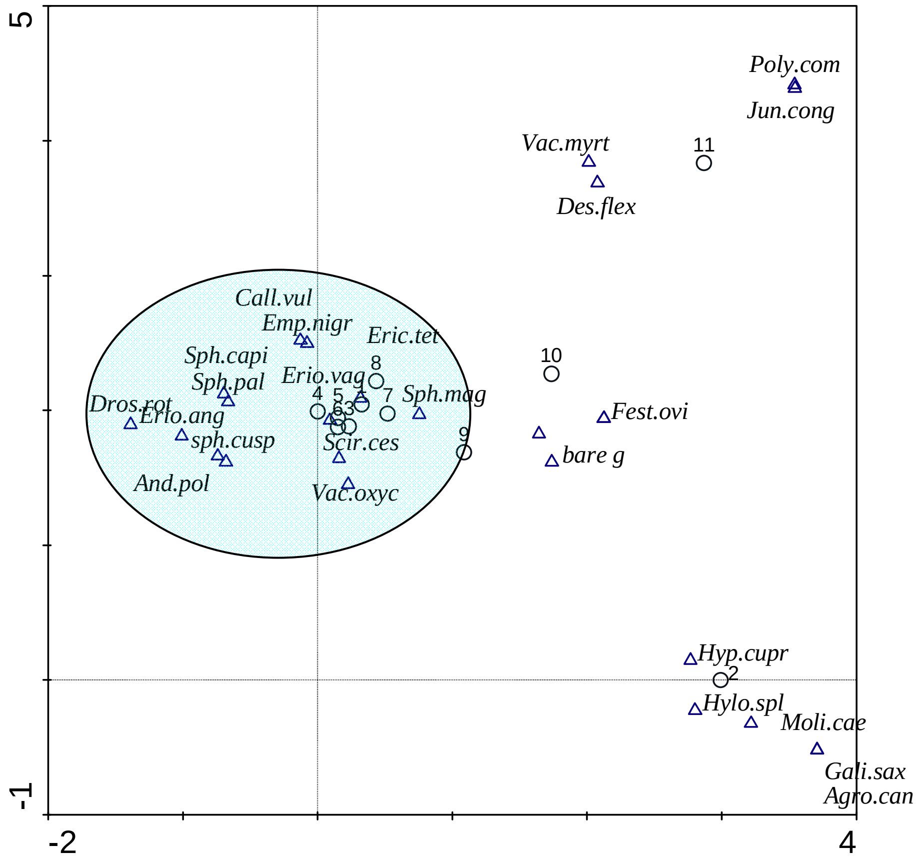
Figure 7.7 Walton Moss vegetation south transect cluster analysis dendrogram



7.2.2.2 Walton south vegetation Detrended Correspondence Analysis

Figure 7.8 shows the DCA for the south transect. It can be seen that this quadrat shows a high degree of homogeneity between the majority of quadrats and a close relationship between these dipwells and species such as *Sphagnum spp*., *Eriophorum vaginatum*, *Vaccinium oxycoccus* and *Erica tetralix*. These can be considered as classic species of healthy bog (Tantram *et.al*, 2000, Rodwell, 1991) and correspond with the majority of dipwells on the south transect. quadrats 10 and 11 are more dissimilar and show association with species of bog margins, such as *Polytrichum commune*, as would be expected from their location whilst quadrat 9, whilst not strongly associated with the main group, is closer to them. It is interesting to note that quadrat 2 shows unusual characteristics which show little similarity to any other quadrat and also has a distinct, drier hydrological condition.

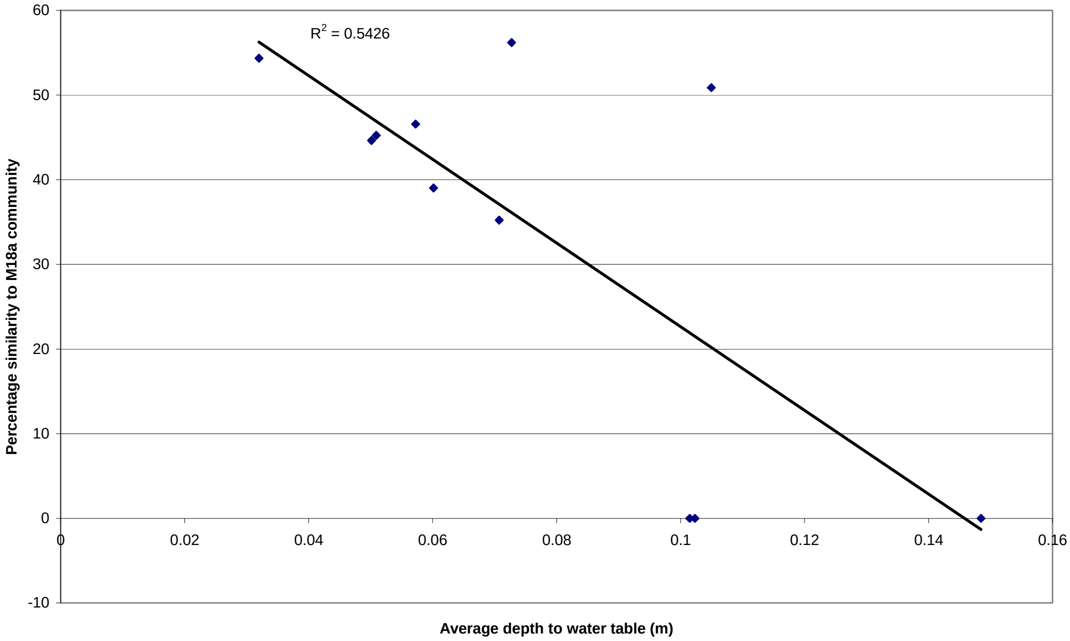
Figure 7.8 DCA ordination plot of dipwells and species for Walton south transect



7.2.2.3 Correlation between raised bog NVC community M18a and depth to water table

The correlation between percentage m18a community similarity and dipwell depth is -0.737, a strong negative correlation, significant at P = 0.010. The scatter plot of this data is shown in figure 7.9 This is a similar relationship as for the data for Walton north transect, but the distribution of the data suggests that although it would seem to be a useful general relationship, the data are too widely dispersed to make any informed predictions on bog community based on water levels alone.

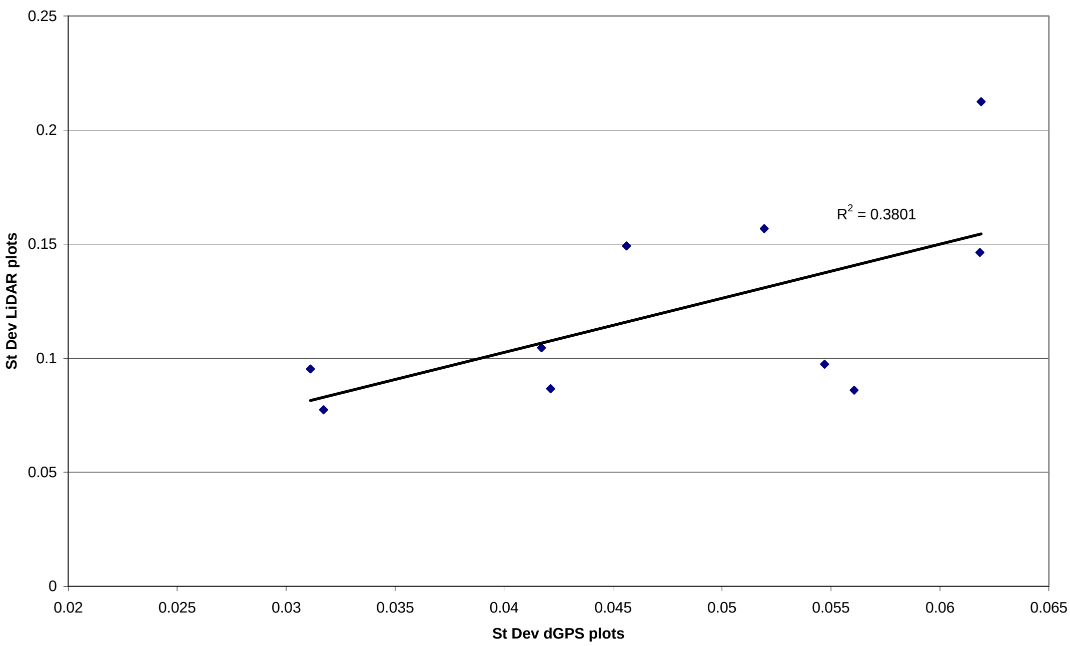
Figure 7.9 Scatter plot showing the relationship between m18a community similarity and average depth to water table for Walton Moss south transect



7.2.2.4 Relationship between depth to water table and surface microtopography for Walton Moss south transect

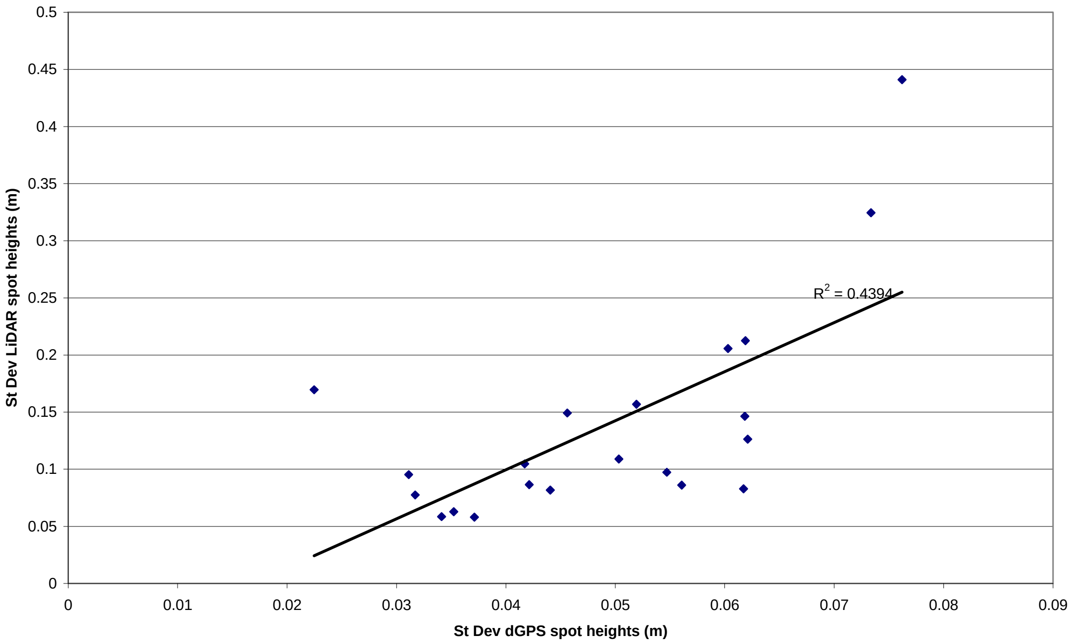
The correlation between the LiDAR and dGPS data for this quadrat is 0.617, however this result is not significant as P = 0.058. The scatterplot for these data is shown in Figure 7.10. However, using a larger combined data set from both the north and south transect, as shown in figure 7.11, a similar relationship is observed, with a similar degree of correlation, 0.663, but a much lower P value, P = 0.001. These results also broadly reflect the data for Walton Moss north transect.

Figure 7.10 Scatterplot showing the relationship between dGPS and LiDAR data for Walton Moss south transect



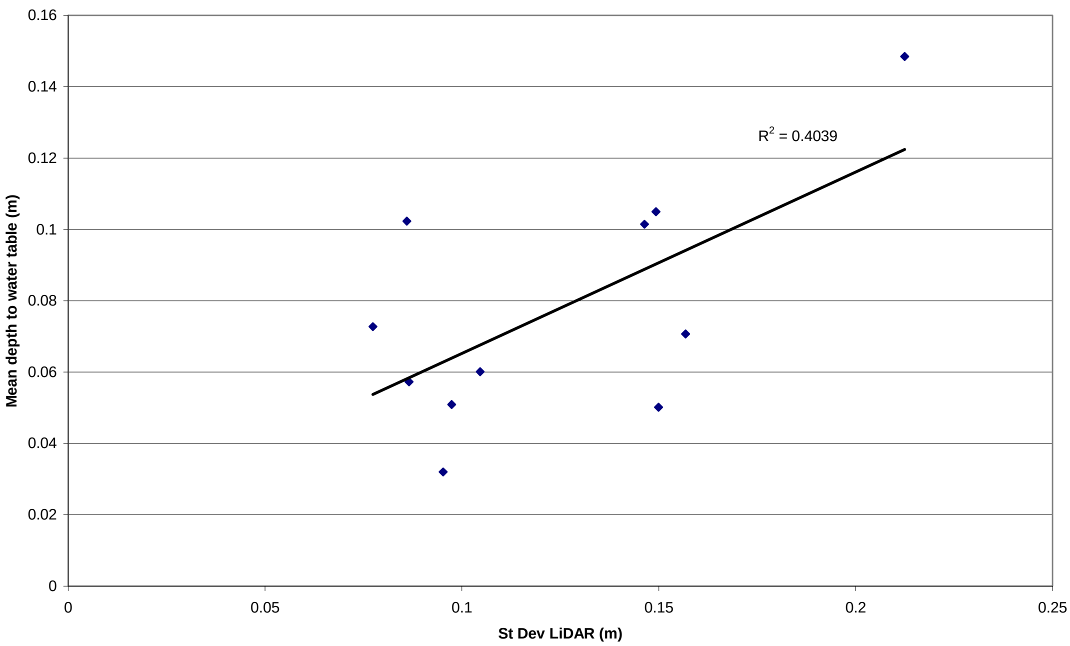
Using a combined data set from both the north and south transect, as shown in Figure 7.11, a similar relationship is observed, with a similar degree of correlation, 0.663, but a much lower P value, P = 0.001.

Figure 7.11 Combined scatterplot showing the relationship between dGPS and LiDAR data for Walton Moss north and south transects



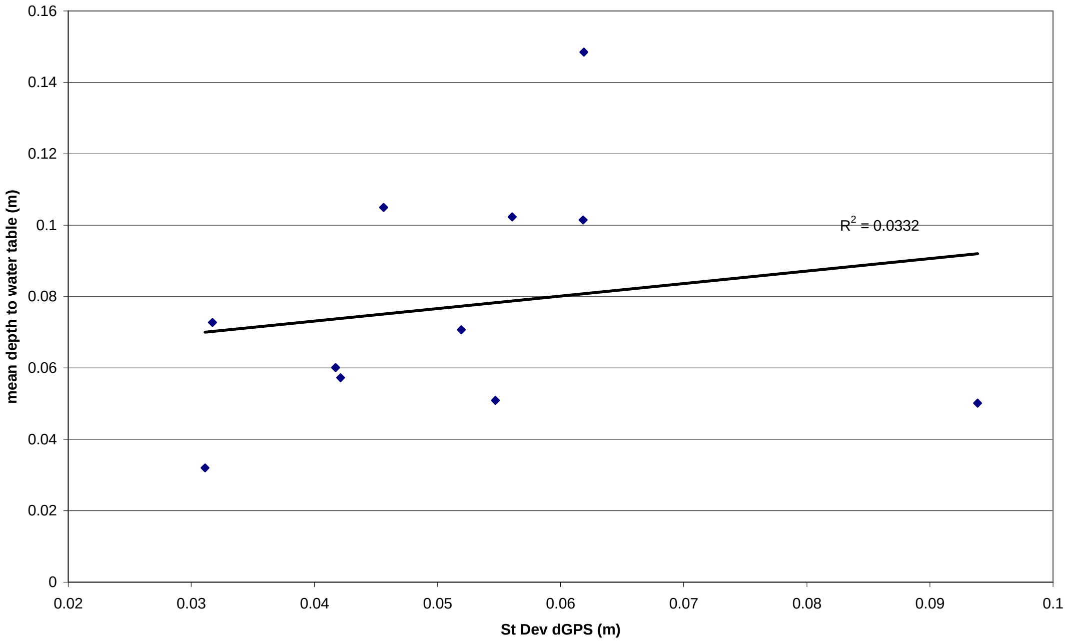
A comparison of Lidar variation and mean water depth shows a significant positive correlation of 0.719, P = 0.019, as illustrated in figure 7.12.

Figure 7.12 Scatterplot showing the relationship between measured variation in LiDAR spot heights and depth to water table for Walton Moss south transect



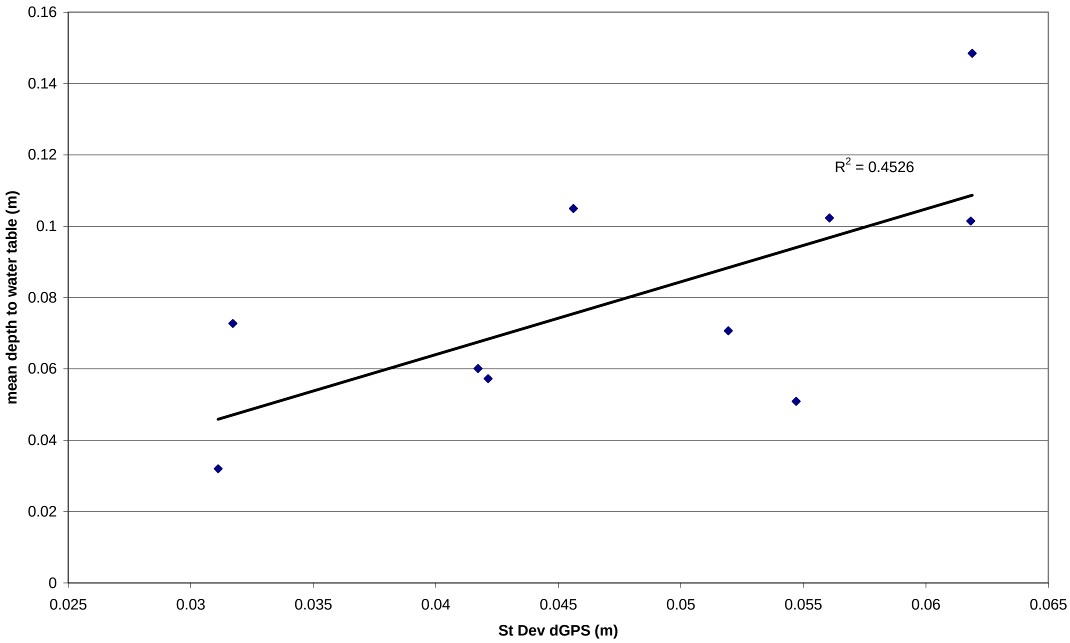
For dGPS variation If the data recorded for the S3 plot are included, the plot in Figure 7.13 is obtained. This has a slight positive correlation of 0.182 but is statistically insignificant as P = 0.592. However, if the anomalous outlying values for plot S3 are removed, the plot show in Figure 7.14 is obtained, showing a much stronger positive correlation of 0.673, P = 0.033. Plot P3 overlaid a drainage grip, and it is likely that the topographic variation for this plot was exaggerated as a consequence.

Figure 7.13 Scatterplot showing the relationship between measured variation in dGPS spot heights and depth to water table for Walton Moss south transect



However, if the anomalous outlying values for plot S3 are removed, the plot show in figure x is obtained, showing a much stronger positive correlation of 0.673, P = 0.033. Plot S3 overlaid a drainage grip, and it is likely that the topographic variation for this plot was exaggerated as a consequence.

Figure 7.14 Scatterplot showing the relationship between measured variation in dGPS spot heights and depth to water table for Walton Moss south transect excluding data for dipwell S3

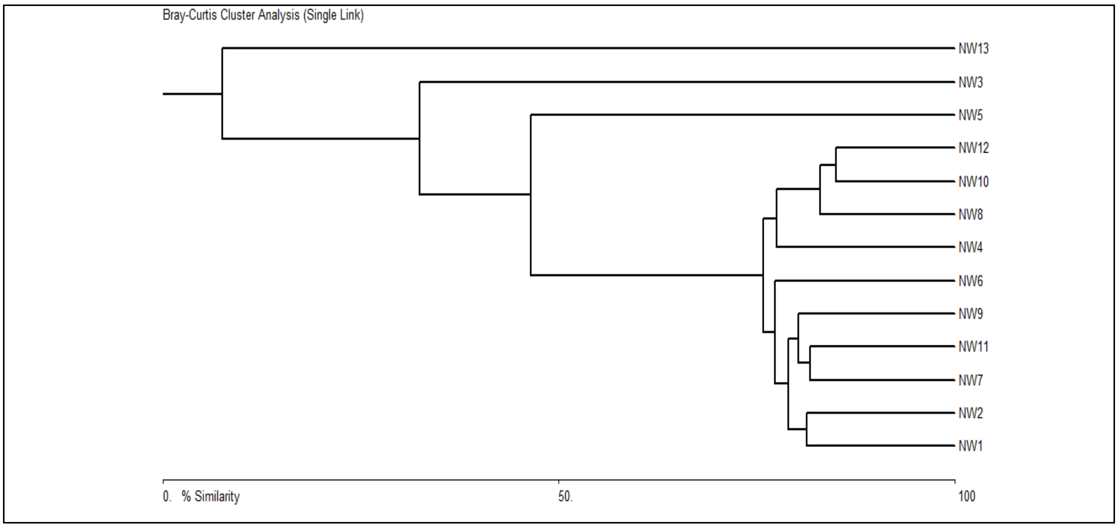


7.2.3 North west transect

7.2.3.1 North west transect Bray-Curtis cluster analysis

The dendrogram for the north west transect is shown in Figure 7.15. It illustrates that there is much less botanical variation between quadrats along this quadrat, with values for the majority of these between 57.01% and 82.93%. This is a reflection of the uniformity of healthy bog. The majority of low similarity of the other transects may be explained by drainage or underlying geomorphological differences. There are non apparent on this transect, although no soil investigation was undertaken. Again there are interesting exceptions, which require further explanation. The quadrat at NW13 is off the raised bog in the strip of mineral soil adjacent to the Flosh watercourse. As a consequence it has very low similarity with the rest of the site – between 0.91% and 7.57%. The differences of NW3 and NW5 are of more interest, as there is no obvious physical reason for their difference in vegetation.

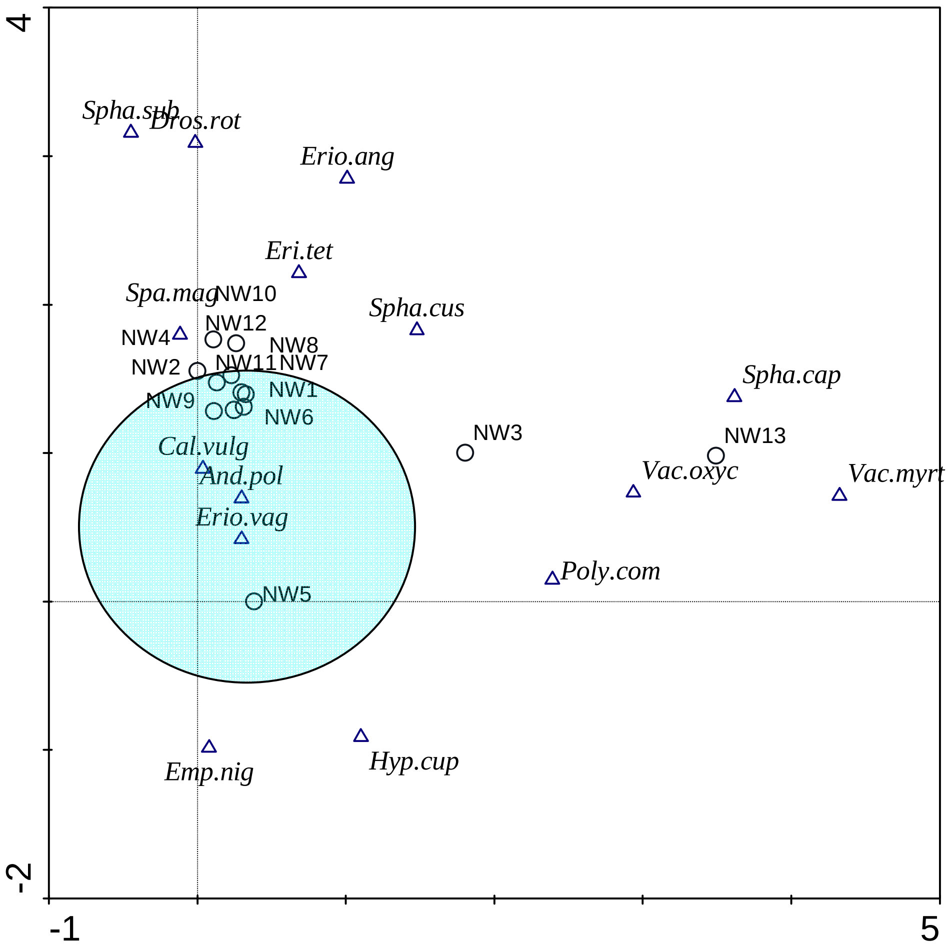
Figure 7.15 Walton Moss vegetation north west transect cluster analysis dendrogram



7.2.3.2 Walton north west vegetation Detrended Correspondence Analysis

Figure 7.16 shows the Detrended Correspondence analysis for Walton north west transect. This transect is more homogeneous than the north and south transects, and this is reflected in the very tight grouping of dipwells and their close association with a few key species, notably *Calluna vulgaris, Eriophorum vaginatum* and *Sphagnum magellicum*. NW13 is outside of the bog area and adjacent to the lagg stream, so it is unsurprising that it shows different characteristics, However NW3 and NW5 are also more heterogenous compared to the remaining quadrats.

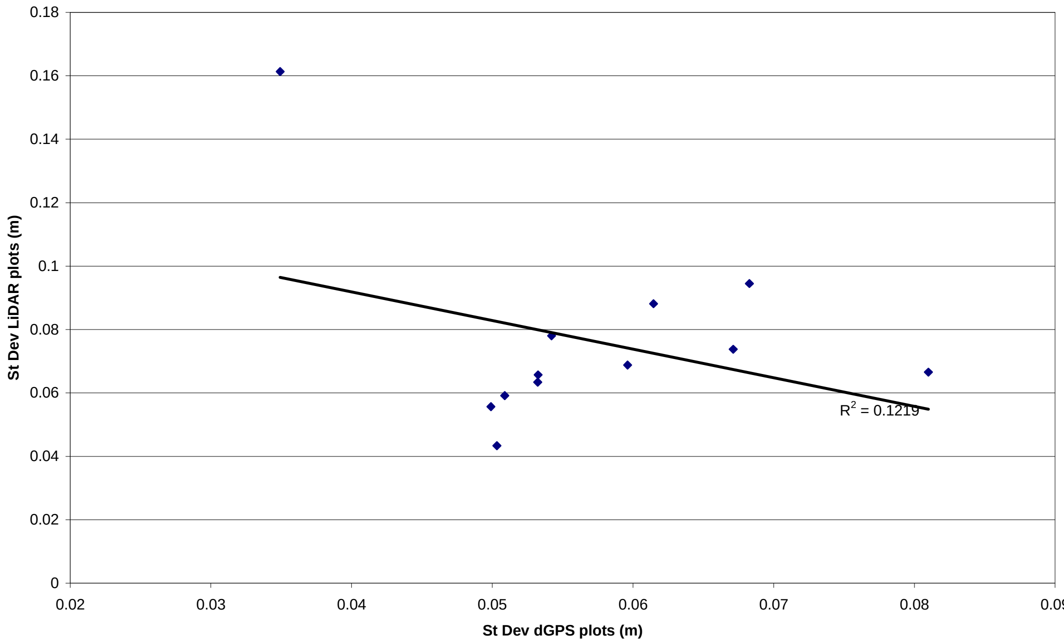
Figure 7.16 DCA ordination plot of dipwells and species for Walton north west transect



7.2.3.3 Relationship between depth to water table and surface microtopography for Walton Moss north west transect

There is no significant relationship between the dGPS and LiDAR data for this transect. The data are shown in Figure 7.17, but the trendline is misleading, as a consequence of very small variations in the dGPS data. Given the range of the data, with one exception is less than 4cm, much of this variation could be accounted for by operator error and accuracy limitations of the dGPS unit (Leica geosystems, 2008) . When tested for correlation, a small correlation of -0.349 is obtained, but with P= 0.266, this result may be disregarded.

Figure 7.17 Scatterplot showing that there is no relationship between dGPS and LiDAR data for Walton Moss north west transect



There is no evident correlation between dGPS derived micro-topography and depth to water table for the north west transect. A slight negative correlation of -0.319 is observed, but the results are not significant with P= 0.312. This transect is substantially shorter than the other transect, and the variation in dipwells and measured topography is much smaller. It is therefore likely that the variation in this relationship may be attributed to "noise" or error in recording.

Figure 7.18 shows the weak relation ship between the dGPS plot standard deviation and depth to water table. There is no significant relationship between the two, with a correlation value of -0.319 but P= 0.31. Again the very small range of variation suggests that recording error may outweigh any relationship in these data. Conversely, the LiDAR data shown in figure 7.19 again shows a strong positive relationship of 0.690, significant at P= 0.013.

Figure 7.18 Scatterplot showing the relationship between measured variation in dGPS spot heights and depth to water table

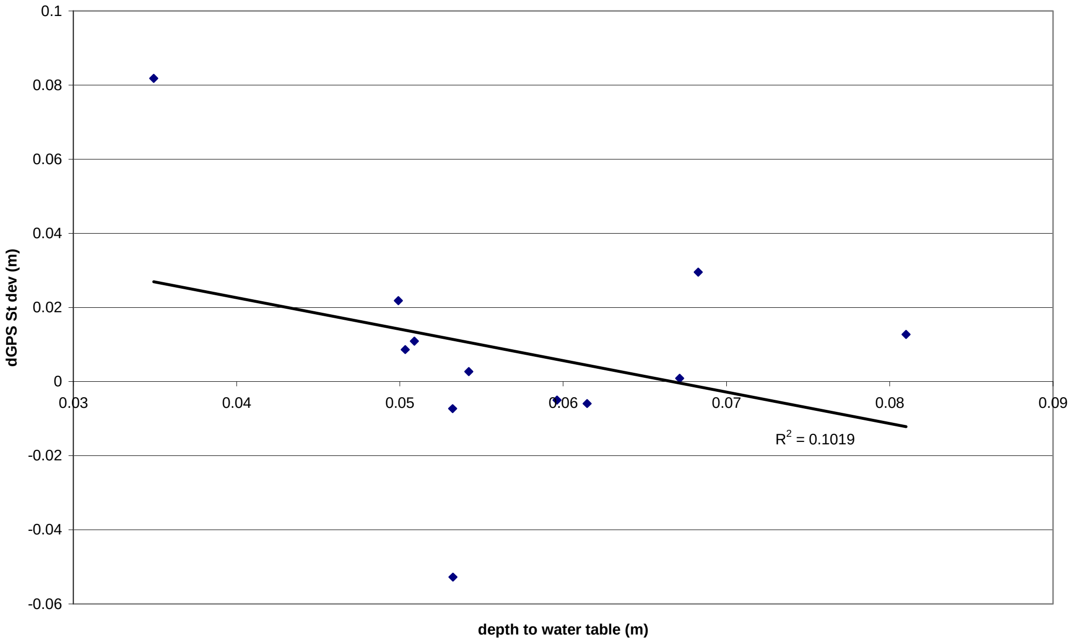
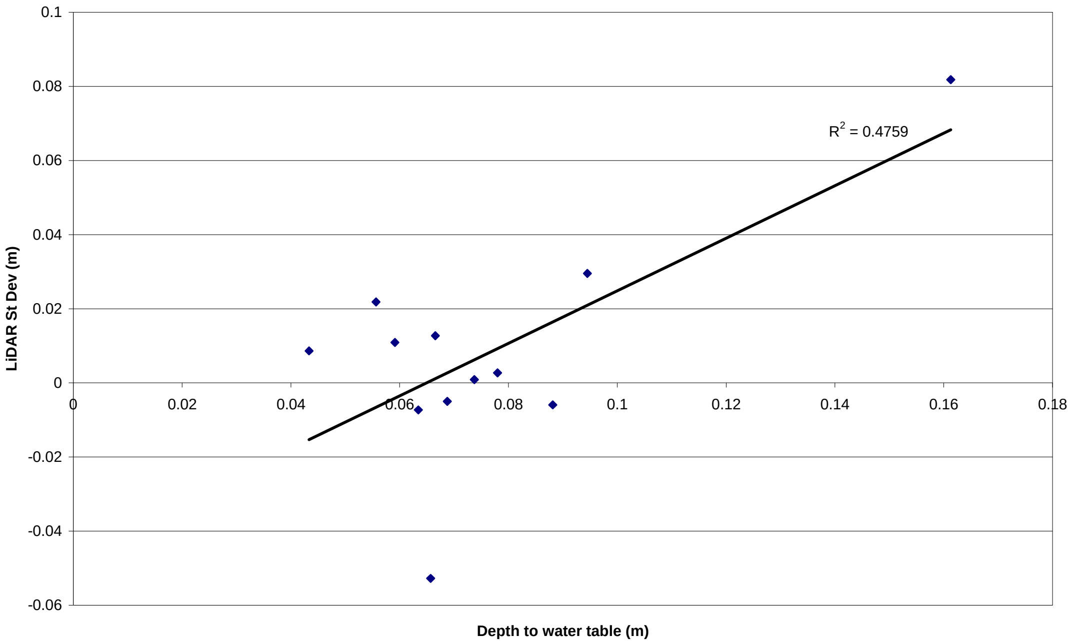


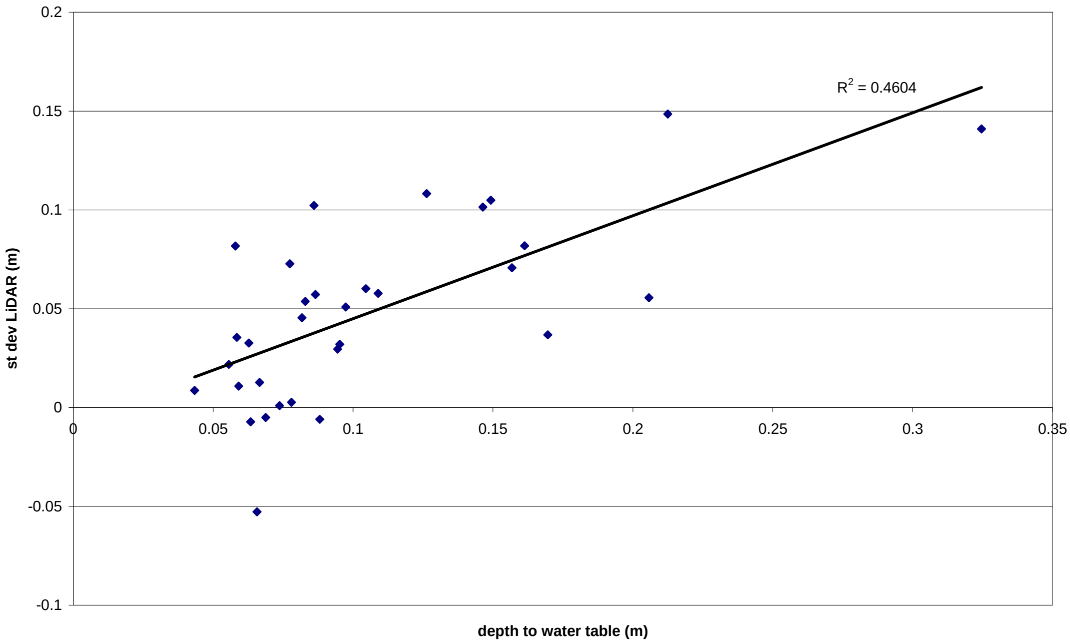
Figure 7.19 Scatterplot showing the relationship between measured variation in LiDAR spot heights and depth to water table for Walton Moss north west transect



7.2.4 Walton Moss combined dipwell and LiDAR variation

When all of Walton Moss is considered, The scatterplot shown in figure 7.20 is obtained. These data are strongly correlated at 0.679, and highly significant with P = 0.000.

Figure 7.20 Scatterplot showing the relationship between measured variation in LiDAR spot heights and depth to water table for all Walton Moss transects



Regression analysis can be used where there appears to be a simple straight line relationship. Figure 7.20 suggests that this relationship is broadly linear and suitable for analysis. Regression analysis of this combined data set, shown in Table 7.3 gives the following results. The R^2 value of 46% suggests these data do have a relationship, and the F value of 25.6 confirms this, significant at P=0. However R^2 = 46% suggests that this could not be used to make confident predictions of the degree of topographic variation caused by a given water depth.

Table 7.3 Regression analysis for standard deviation of LiDAR and depth to water table

The regression equation is
dipwell = - 0.0071 + 0.521 lidar

Predictor	Coef	StDev	T	P
Constant	-0.00714	0.01251	-0.57	0.573
lidar	0.5209	0.1029	5.06	0.000

S = 0.03404 R-Sq = 46.0% R-Sq(adj) = 44.2%

Source	DF	SS	MS	F	P
Regression	1	0.029656	0.029656	25.60	0.000
Residual Error	30	0.034755	0.001159		
Total	31	0.064411			

Unusual Observations

Obs	lidar	dipwell	Fit	StDev Fit	Residual	St Resid
N5	0.325	0.14094	0.16194	0.02324	-0.02100	-0.84
NW8	0.066	-0.05273	0.02708	0.00734	-0.07981	-2.40

N5 observation with a large standardized residual
NW8 denotes an observation whose X value gives it large influence

.
The anomalous value of N5 has been noted previously in section 7.2.1.1, however the DCA described in Figure 7.16 suggests that NW8 is characteristic of this transect.

7.2.5 Walton Moss combined M18a characteristics and microtopographic variation

There is no relationship between overall NVC community and either LiDAR or dGPS variation, as can be seen in Figures 7.21 and 7.22. Both of these figures show an apparently random distribution of m18a data. These plots exclude those plots with no element of m18 similarity. As can be observed, those plots which do not have raised bog characteristics do have substantially larger topographic variation. This has been explored in the work of Anderson *et.al* (2009) in developing a methodology for determining gross hydro-ecological condition.

Figure 7.21 Comparison of Walton Moss percentage m18a and LiDAR variation

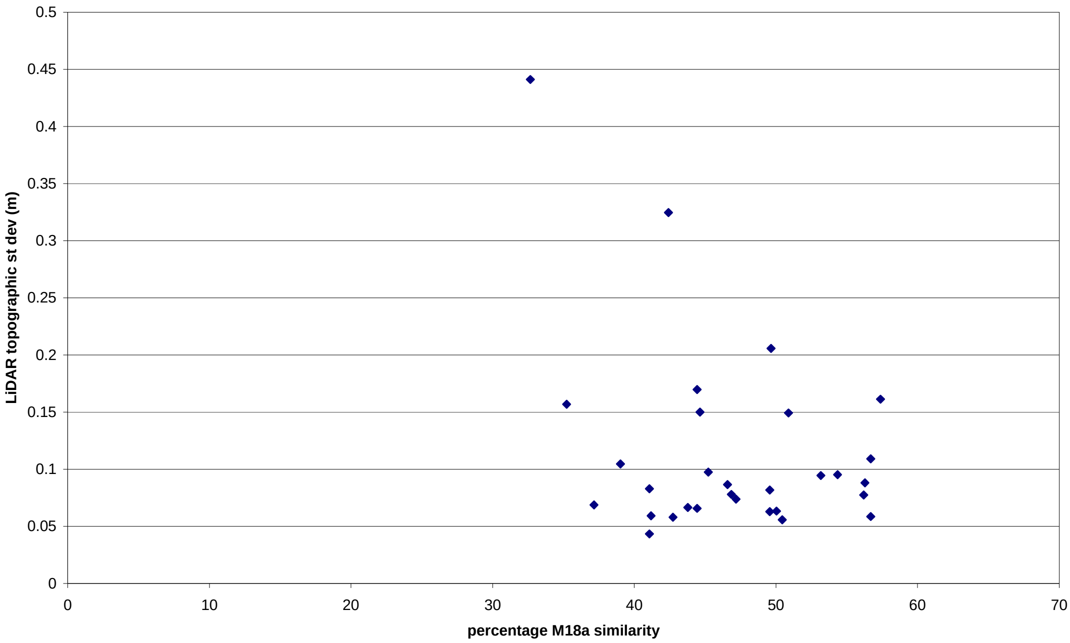
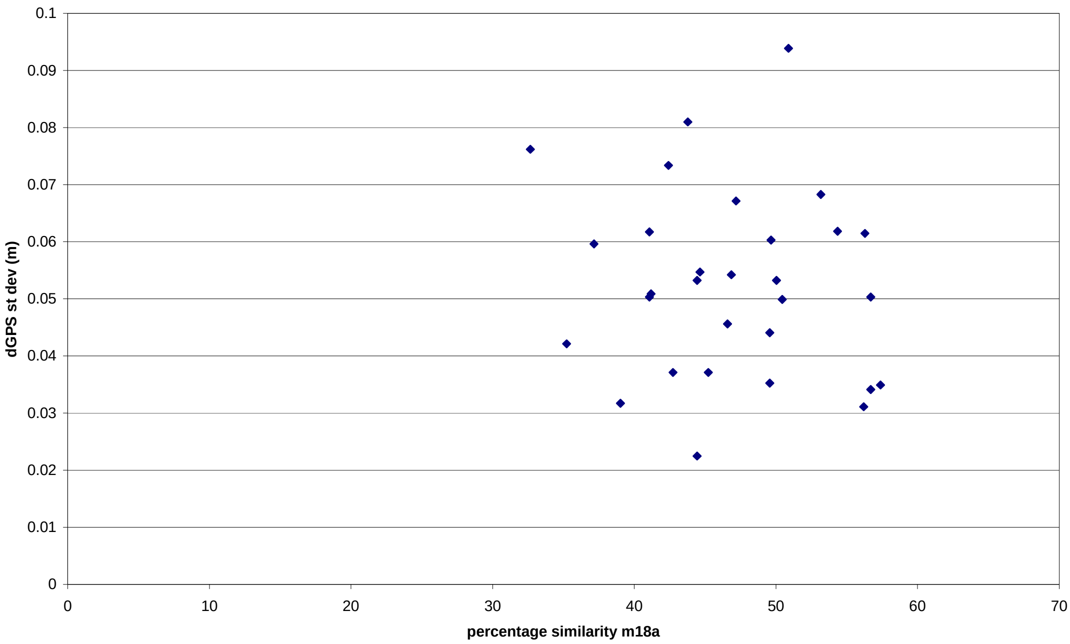


Figure 7.22 Comparison of Walton Moss percentage m18a and dGPS variation



7.3 Bolton Fell Moss

Bolton Fell moss is a much smaller site than Walton Moss and the plots and dipwells are much closer together. There is also much more disturbance and intrusive past management within the study area, notably old manual peat cuttings, the light railway and an area of woodland, covered with decomposing brash from past habitat management exercises (Natural England, 2008). This makes these data harder to interpret. The Lidar data have been subject to a tree removal algorithm, but this process in itself makes the topographic data for the ground below it less reliable.

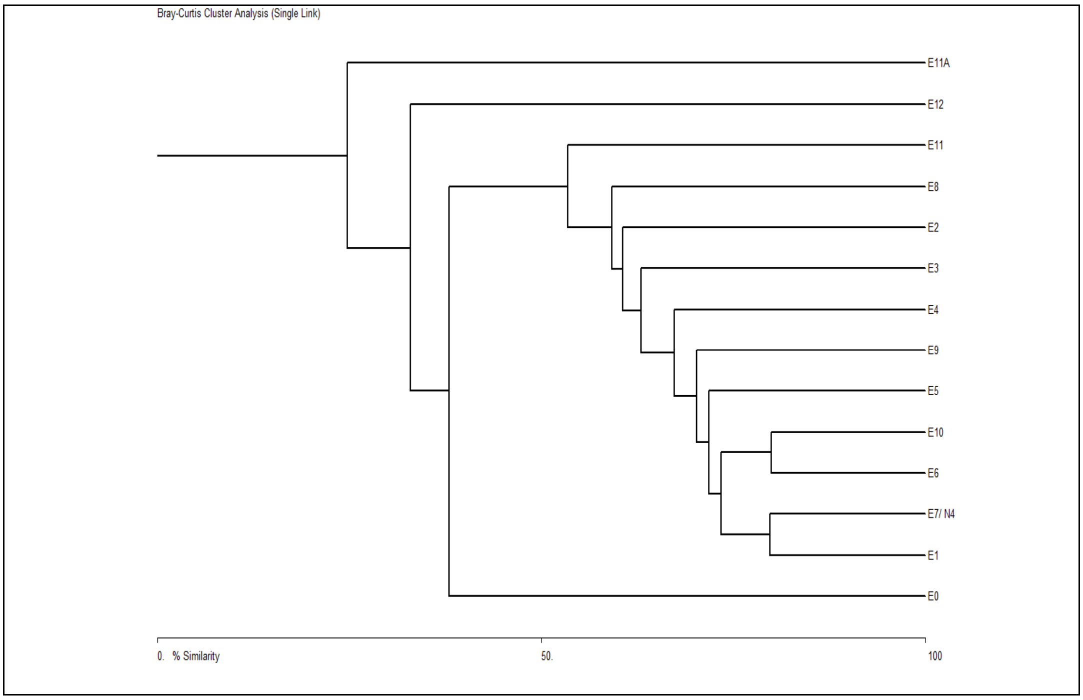
7.3.1 Bolton Fell East transect

7.3.1.1 Bolton Fell Moss east transect Bray-Curtis cluster analysis of vegetation data

This analysis is shown in Figure 7.23. The quadrats used to survey vegetation on this quadrat cross the reserve area of Bolton Fell Moss from boundary to boundary, unlike at Walton Fell Moss. Although a smaller study site than Walton Moss, this complete transect of the site means a wide variety of hydrological conditions were sampled, although the underlying geology and morphology were uniform. As a consequence, there is substantial diversity between the quadrats. E11a, the quadrat adjacent to the western boundary of the reserve and subject to both a substantial boundary drain and the light railway is most distinct from the other quadrats, although E0, at the eastern boundary is also quite distinctive. It should also be noted that with 13.79% similarity, E0 and E11a are also substantially different from each other.

Away from the potential effects of drainage and the encroaching woodland to the south, the internal quadrats of E1, E4, E5, E6, E7 and E10 show between 62.56% and 73.39% similarity. Quadrats E11a – E12 transect the boundary of the site and into an adjacent area of uncut bog, which although physically undamaged, is not subject to the drainage impediment work described in Chapter 5, undertaken to protect the hydrological condition of the reserve. Similarly E0 is located above these works and has therefore been subject to significant historical disturbance.

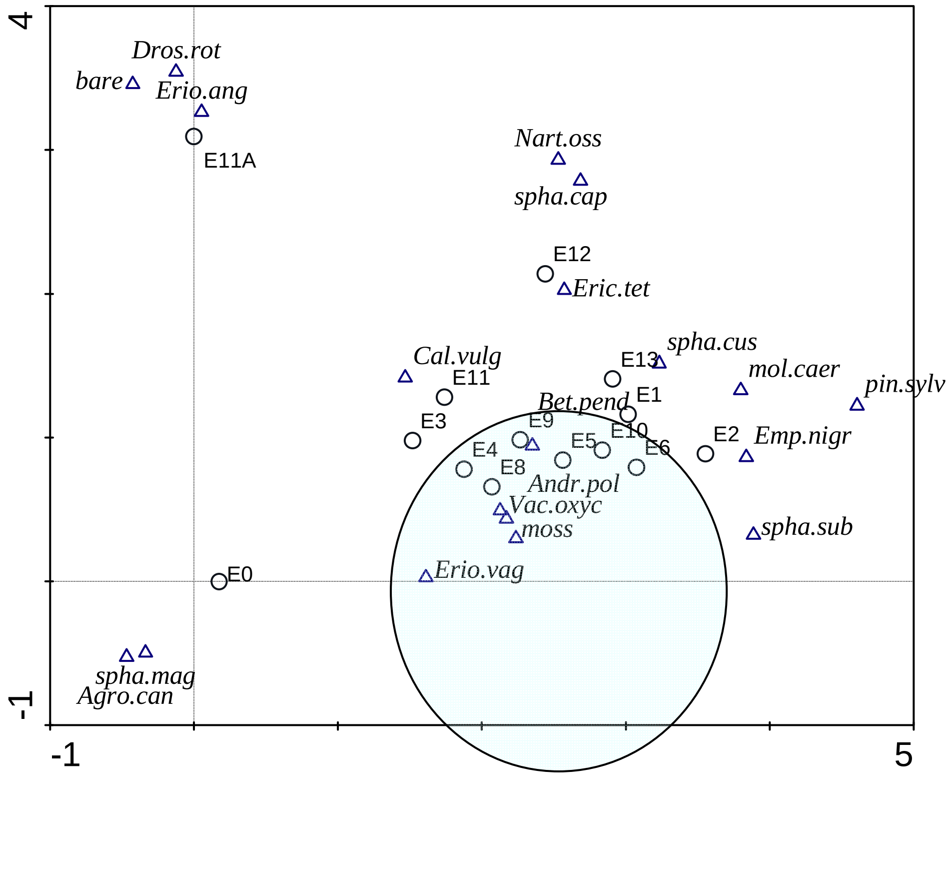
Figure 7.23 Bolton Fell Moss vegetation east transect cluster analysis dendrogram



7.3.1.2 Bolton Fell east transect vegetation Detrended Correspondence Analysis

The DCA plot for Bolton Fell Moss east transect is shown in Figure 7.24. Species and dipwells show a strong association between the heather species, Eriophorum vaginatum and Sphagnum, as has been observed at Walton Moss, however it is important to note the presence of *Betula pendula*. Larger woody species are much more prevalent on Bolton Fell Moss that on Walton Moss, and this is reflected in the species associations. Again, the edge quadrats at E 11a and E0 have clearly distinct species associations. It should be noted that E11a marks the boundary of the peat company managed area, although, E12 and 13 are in a further area of unexcavated bog. It is therefore consistent that both E12 and E2 are less typical of the expected species assemblages as they are both on the fringes of the transect and subject to hydrological changes as a result of adjacent land use.

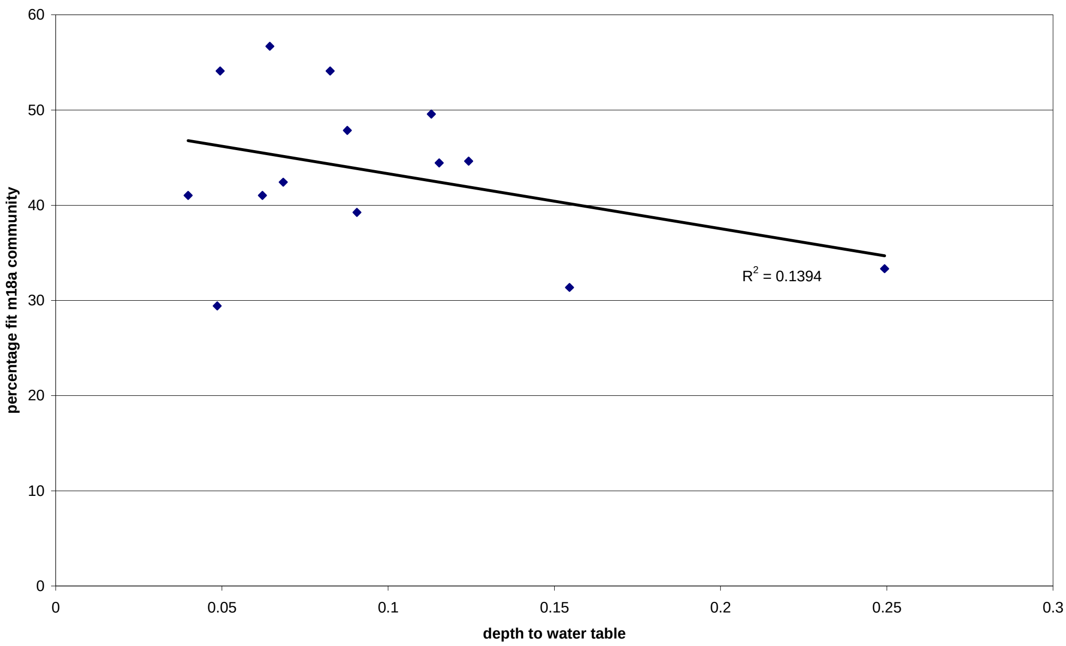
Figure 7.24 DCA ordination plot of dipwells and species for Walton south transect



7.3.1.3 Correlation between raised bog NVC community M18a and depth to water table

There is a very weak relationship between M18a community and depth to water table for this transect. These data have a correlation of -0.373, P = 0.188. These data were surveyed later than the other transects and it was not possible to make a complete assessment of the lower plants and mosses, particularly the non-sphagnum mosses which were not identified separately, and which are important indicators for this habitat type (Rodwell *et.al*, 1992). Therefore it is likely that the MAVIS software may not have been able to classify these data correctly. However, the proximity of the wooded area may also have affected the hydrological data (Farrick and Price,2009), together with the length of the transect and the homogeneity of the dipwell data. It is perhaps of note that an inverse relationship was noted for the N11a quadrat, which had the greatest depth to water table. The scatterplot for these data is shown in Figure 7.25.

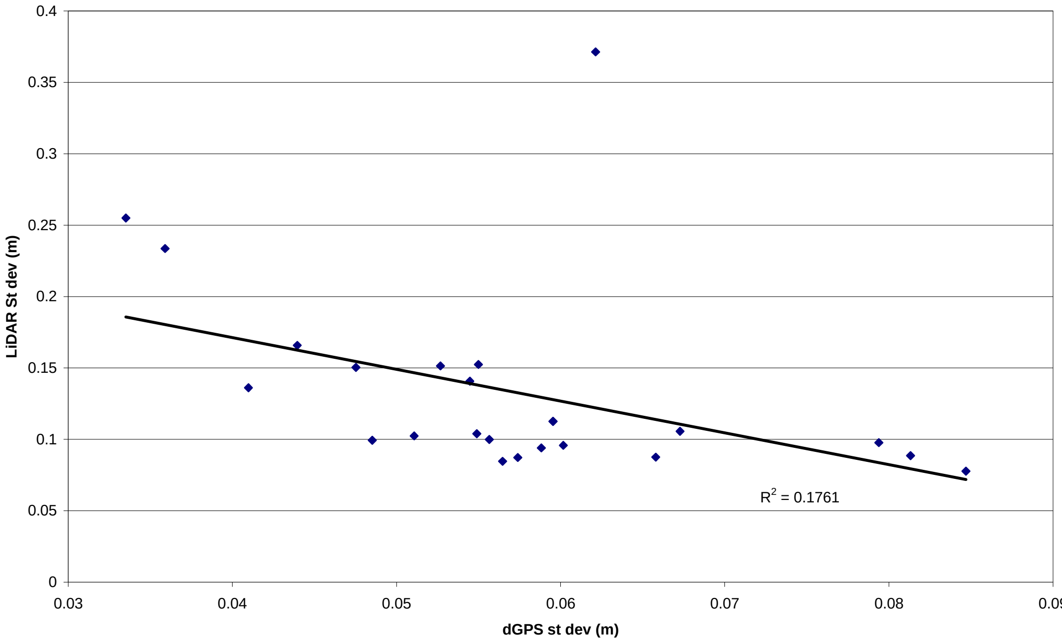
Figure 7.25 Scatterplot of percentage m18a NVC community and depth to water table



7.3.1.4 Comparison of dGPS and LiDAR data for Bolton Fell Moss

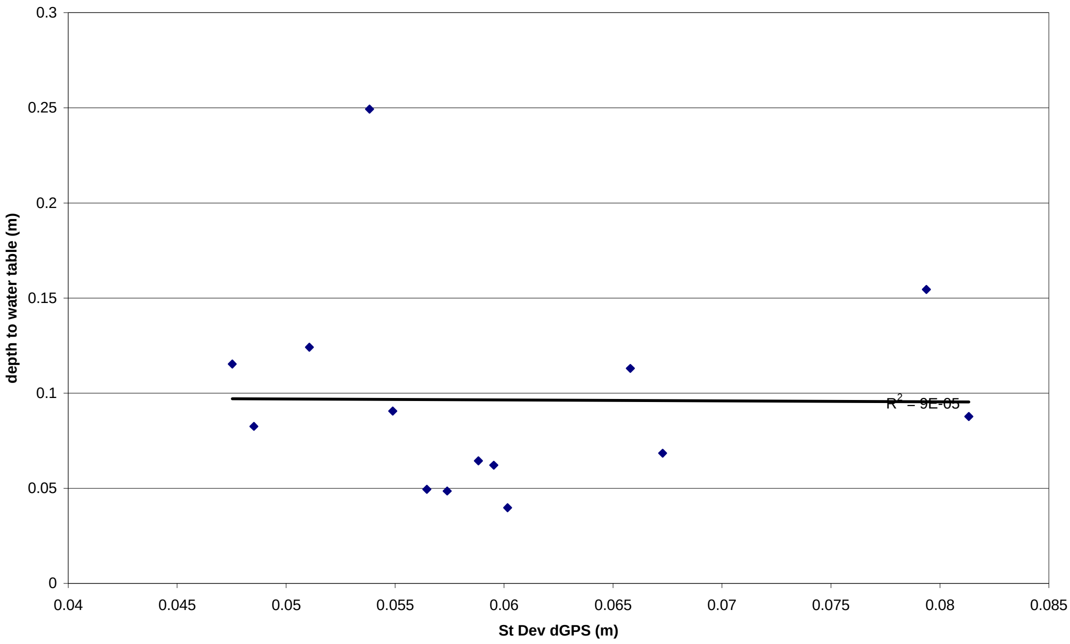
The LiDAR and dGPS correlation illustrated in Figure 7.26 shows a strong negative correlation, -0.420, significant at P = 0.041. unlike the situation at Walton Moss, where a positive correlation was observed, as might more generally be expected. Again, the reason may be a consequence of very small variations in LiDAR data, a total range of less than 6cm. It is also possible that the influence of trees on the LiDAR data has been to decrease the apparent topography under wooded areas.

Figure 7.26 Scatterplot of LiDAR and dGPS variation at Bolton Fell Moss



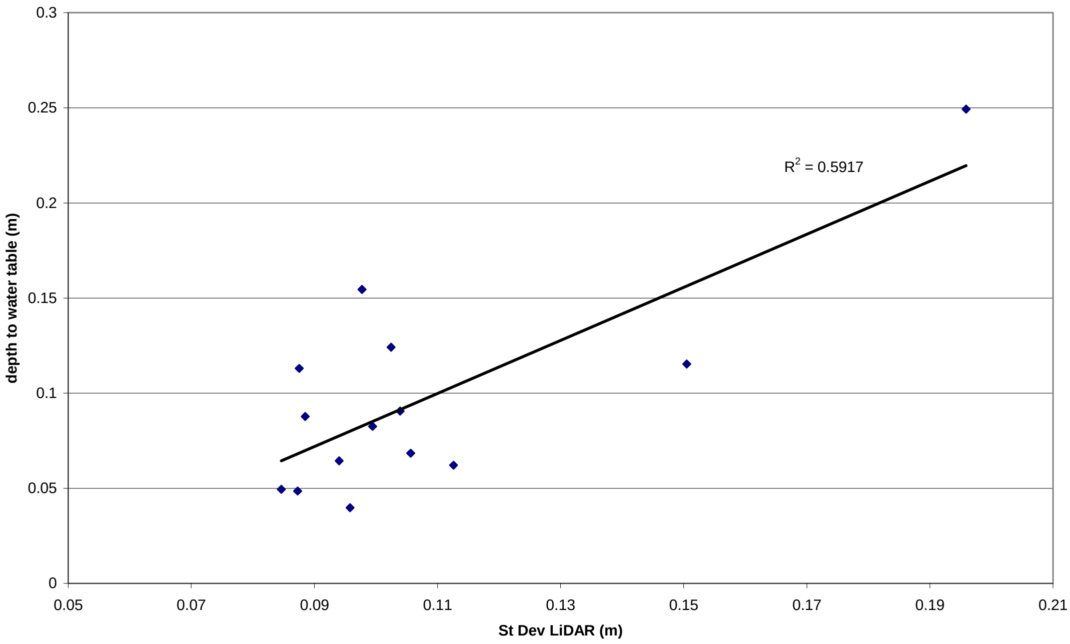
As can be seen from Figure 7.27, there is no relationship between topography as measured by dGPS and depth to water table. Further analysis of these data is not necessary. The small topographic variation and the small variation of the majority of the dipwells makes any statistical analysis of the data impossible.

Figure 7.27 Scatterplot showing the relationship between measured variation in dGPS spot heights and depth to water table



The relationship between water depth and LiDAR, shown in Figure 7.28 is more apparent at 0.769, P = 0.001, however these results should be considered in the context of the post processing of the LiDAR data and the fact that the larger scale topographic variation of the site is much smaller than that of Walton Moss as the dome has been damaged due to shrinkage and peat excavation.

Figure 7.28 Scatterplot showing the relationship between measured variation in LiDAR spot heights and depth to water table

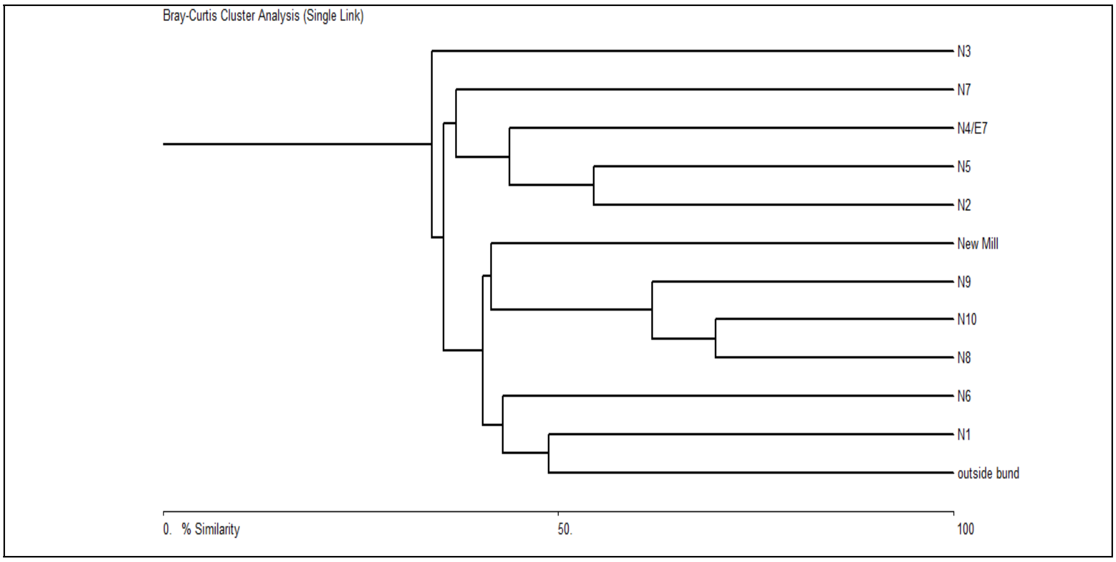


7.3.1 Bolton Fell north transect

7.3.1.1 Bolton Fell Moss north transect Bray-Curtis cluster analysis of vegetation data

The cluster analysis is shown in Figure 7.29. The north transect is notably heterogeneous, with only 5 quadrats showing greater than 50% similarity with any other quadrats. This transect has very different physical condition across the transect, and the botany of the quadrats appears to reflect this. The most similar group are N8, N9 and N10, but these are not typical of the site and are located in the area of former hand cut peat workings and it is important to consider that homogeneity is not necessarily reflective of good condition, as in this instance. Where uniformity might be expected, in the quadrats within the reserve area proper, there is low similarity, for example the adjacent quadrats of N4 and N5 show 43.8% similarity and N3 and N2, 20.68%. This transect crosses a band of semi mature woodland, two areas of compacted peat and a former drained and cut over section, so it is perhaps to be expected that hydrological and physical diversity is reflected in the differences between the quadrats.

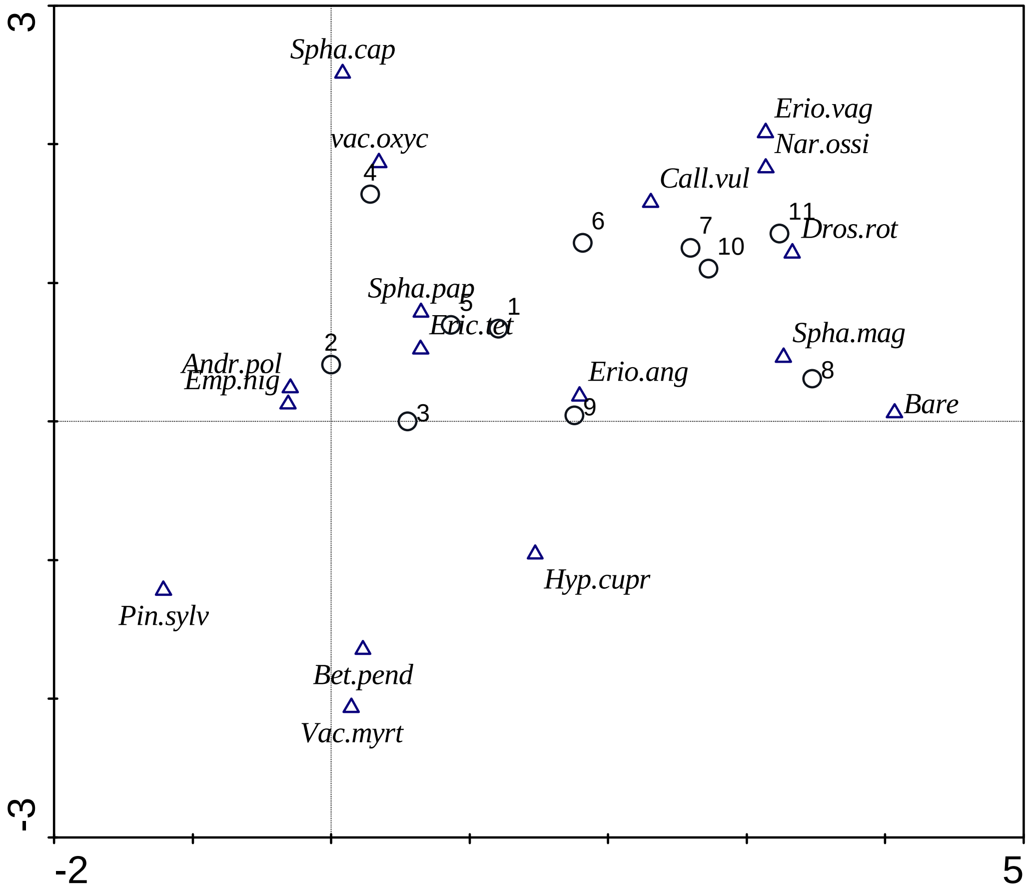
Figure 7.29 Bolton Fell Moss vegetation north transect Bray-Cutis cluster analysis dendrogram.



7.3.3.2 Bolton Fell north transect vegetation Detrended Correspondence Analysis

The ordination plot for this transect, shown in Figure 7.30, shows very little association between dipwell plot, and similarly, there are few associations between individual species. It is therefore inappropriate to highlight any associations, as in the diagrams for the other transects, although there is an association between some quadrats from the centre of the site (N6,N7,N10, and NM, referred to a 11 in this analysis) which are associated with typical raised bog higher plants of *Calluna vulgaris* and *Eriophorum vaginitum*. This mirrors the diverse pattern seen in the cluster analysis. This is possibly a consequence of the diverse changes to the site across the transect, including tree cover, drainage and former peat cutting.

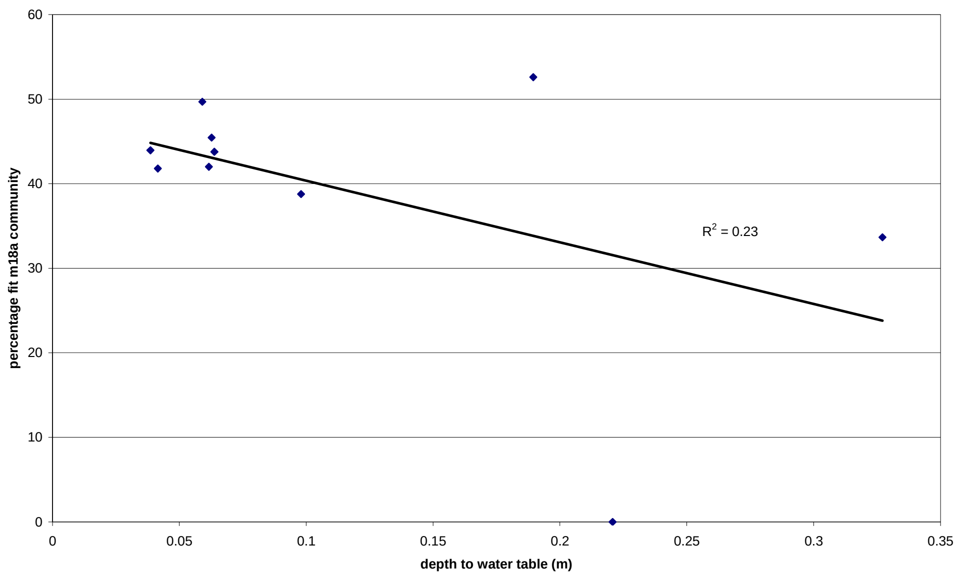
Figure 7.30 DCA ordination plot of dipwells and species for Bolton north transect



7.3.3.3 Correlation between raised bog NVC community M18a and depth to water table

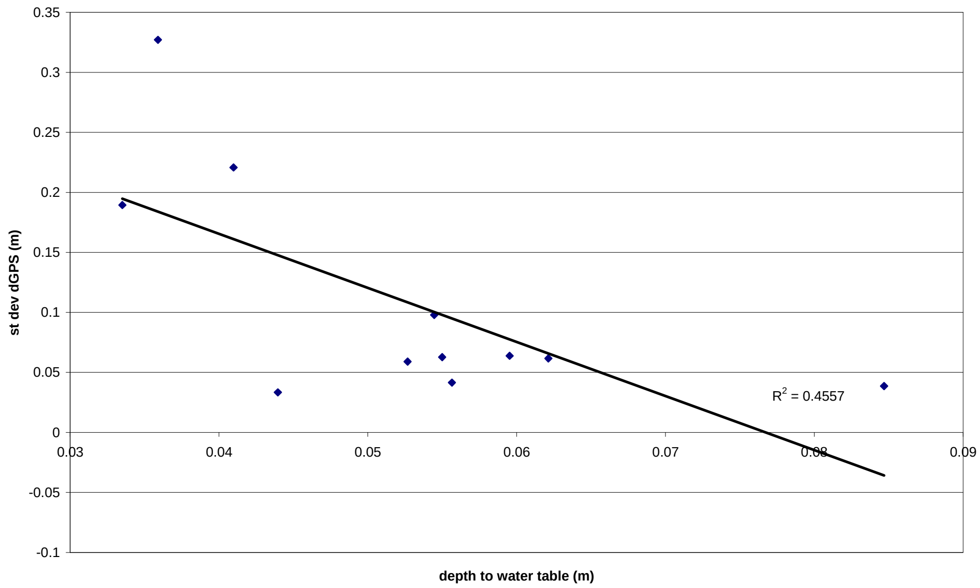
The relationship between depth to water table and similarity to m18a community, shown in figure 7.31 is similar to those of other transects, but is not statistically significant at -0.480, P = 0.161. This transect was surveyed contemporaneously with the Walton Moss vegetation surveys, so these data are more consistent than those for the Bolton Fell east transect, but are possibly complicated by other environmental factors, notably the presence of trees and disturbance.

Figure 7.31 Scatterplot of percentage m18a NVC community and depth to water table for Bolton Fell east transect



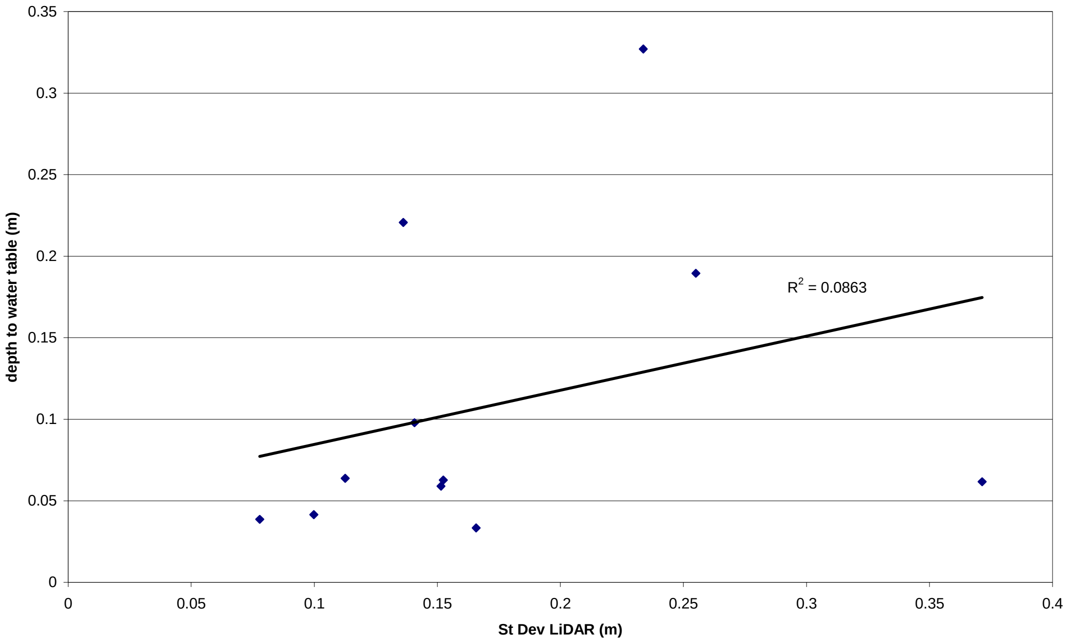
The relationship between dGPS and depth to water table is shown in Figure 7.32. It is anomalous when considered alongside the data from other transects insofar as it is a negative relationship. This is not an error in data transcription but has a real value of -0.675, significant at P = 0.023.

Figure 7.32 Scatterplot showing the relationship between measured variation in dGPS spot heights and depth to water table for Bolton Fell north transect



When the Lidar variation is considered, there is no clear relationship. A notional trend line has been added to Figure 7.33 for completeness, but should not be considered when assessing the data.

Figure 7.33 Scatterplot showing the relationship between measured variation in LiDAR spot heights and depth to water table for Bolton Fell north transect



7.3.4 Consideration of data from both transects

When all Bolton Fell data are considered, a significant negative correlation is found between dGPS variation and depth to water table of -0.443, significant at P = 0.027. Again, this negative correlation is not consistent with data from Walton Moss. The relationship is shown in figure 7.34.

The corresponding analysis for LiDAR data, illustrated in figure 7.35 shows the expected positive relationship, but it weak at 0.378 and as P= 0.063, cannot be considered significant.

Figure 7.34 Scatterplot showing the relationship between measured variation in dGPS spot heights and depth to water table for both Bolton Fell transects

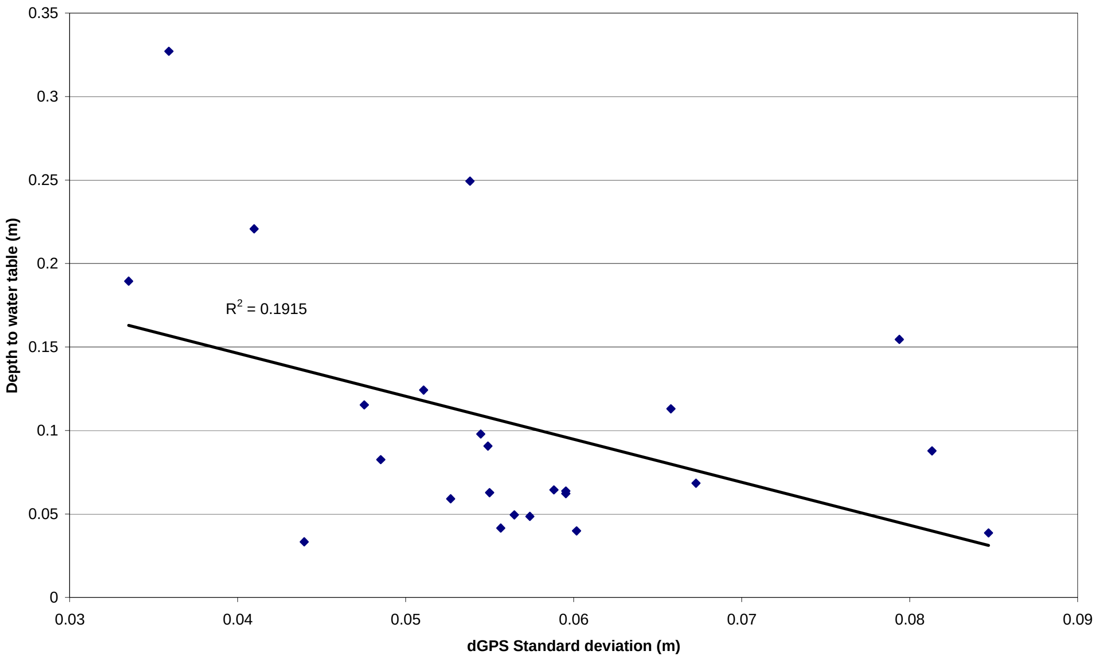
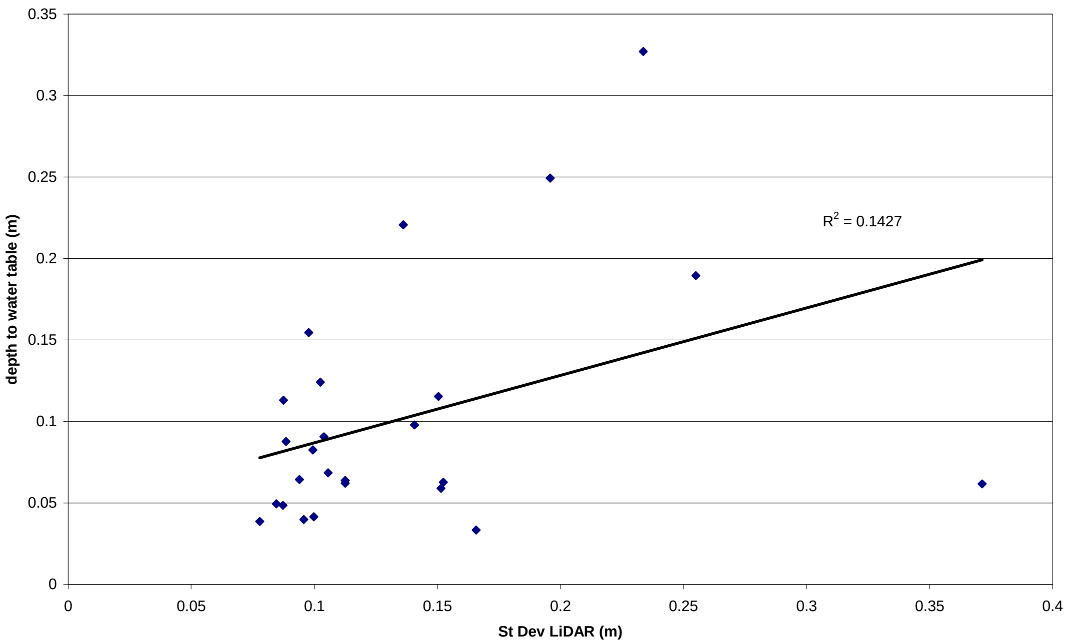
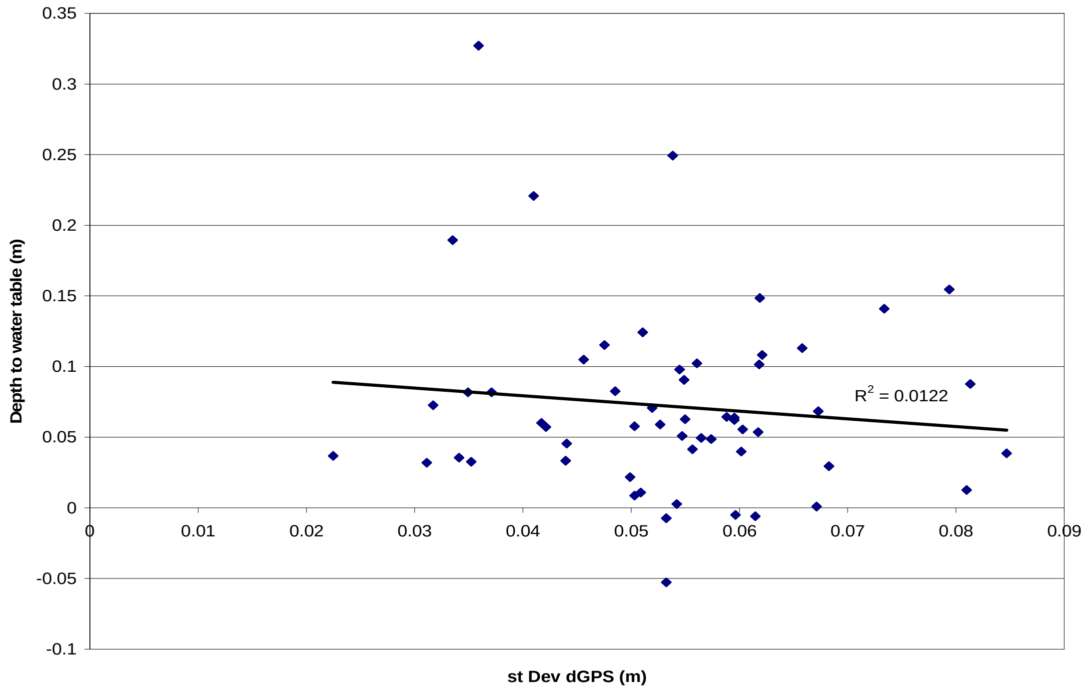


Figure 7.35 Scatterplot showing the relationship between measured variation in LiDAR spot heights and depth to water table for both Bolton Fell transects



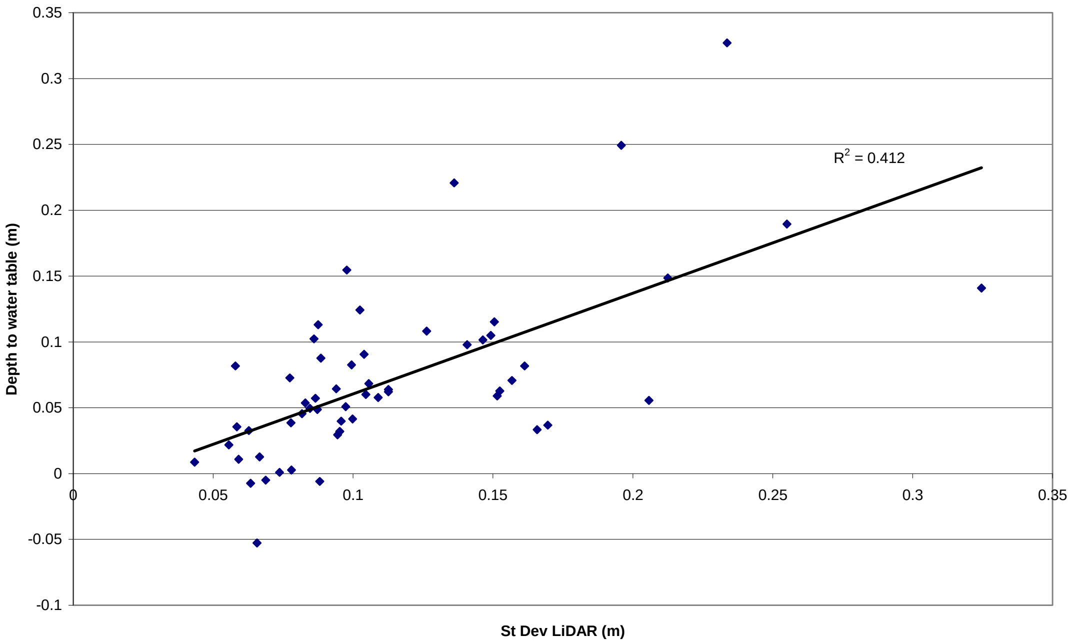
The data from both research sites has been considered and correlated. For the dGPS derived data, there is no correlation at all. A value of -0.111 is calculated but as P = 0.417 this cannot be considered significant. This is reflected in the plot shown in figure 7.36. The trend line is included for illustration only, but the individual data points show a seemingly random distribution.

Figure 7.36 Scatterplot showing the relationship between measured variation in dGPS spot heights and depth to water table for all transects



However, when the data from both transects is considered, there is a correlation of 0.642 between LiDAR and depth to water table, which is strongly significant as P= 0. This relationship is shown in Figure 7.37.

Figure 7.37 Scatterplot showing the relationship between measured variation in LiDAR spot heights and depth to water table for all transects



Regression analysis of these data give the results in Table 7.4. These data are similar to those from Bolton Fell Moss, although the slightly lower R^2 value of value of 41% reflects the more heterogenous data from Walton Moss. The extreme data reported at the end of the table includes N5 from Walton Moss, already identified as unusual, and 4 plots from Walton Moss. Although the data are strongly correlated, it would not be prudent to use the regression fit to precisely predict hydrological condition from LiDAR data.

Table 7.4 Regression analysis for LiDAR data from both sites.

The regression equation is
dipwell = - 0.0159 + 0.764 Lidar variation

Predictor	Coef	StDev	T	P
Constant	-0.01590	0.01581	-1.01	0.319
Lidar al	0.7643	0.1243	6.15	0.000

S = 0.05062   R-Sq = 41.2%   R-Sq(adj) = 40.1%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.096957	0.096957	37.83	0.000
Residual Error	54	0.138394	0.002563		
Total	55	0.235351			

Unusual Observations

Obs	Lidar al	dipwell	Fit	StDev Fit	Residual	St Resid
N5	0.325	0.14094	0.23218	0.02691	-0.09124	-2.13RX
E8	0.255	0.18950	0.17902	0.01867	0.01048	0.22 X
E9	0.136	0.22075	0.08815	0.00726	0.13260	2.65R
N11	0.234	0.32711	0.16267	0.01622	0.16443	3.43R
E11a	0.196	0.24934	0.13380	0.01211	0.11554	2.35R

R denotes an observation with a large standardized residual
X denotes an observation whose X value gives it large influence

7.4 Temporal variation in water levels

In the preceding sections, the average depth of water has been the main covariable when topographic characteristics and vegetation have been considered, however the series of data loggers have also provided a detailed description of temporal variation.

Data recorded from the Thalimedes shaft encoders have proved difficult to isolate for analysis due to unreliability of the devices, mechanical slippage and inaccurate time recording by the internal clocks. These factors are not limited to this study and have been reported by others (O'Brien *et al*., 2008, Vilibi *et.al*., 2005). However, whilst absolute data may be difficult to compare, it is possible to assess variation over selected periods.

Within this restricted availability, data recorded in July was chosen for analysis as summer months are times of both low rainfall and high evapo-transpiration (Met Office, 2009). For the study period, data recorded from the raingauges and automated weather station shown in Figure 7.38, show that rainfall in July for this site is actually slightly higher than the preceding months, however preceding dry periods suggest that this is the period when drought stress is likely to be greatest. Similarly, the variation of rainfall, as illustrated in Figure 7.39 tends to be high in July. Although April and May are drier months, it is likely that the surface water table will still be affected by rainfall in the summer months. This is reflected by the mean dipwell water levels shown in Figure 7.40. As has been previously noted, the summer of 2007 was subject to exceptional rainfall and the results for this period reflect this.

Figure 7.38 Comparison of average monthly rainfall at Carlisle for the period 1971 – 2000 and average monthly rainfall derived from Bolton Fell composite series

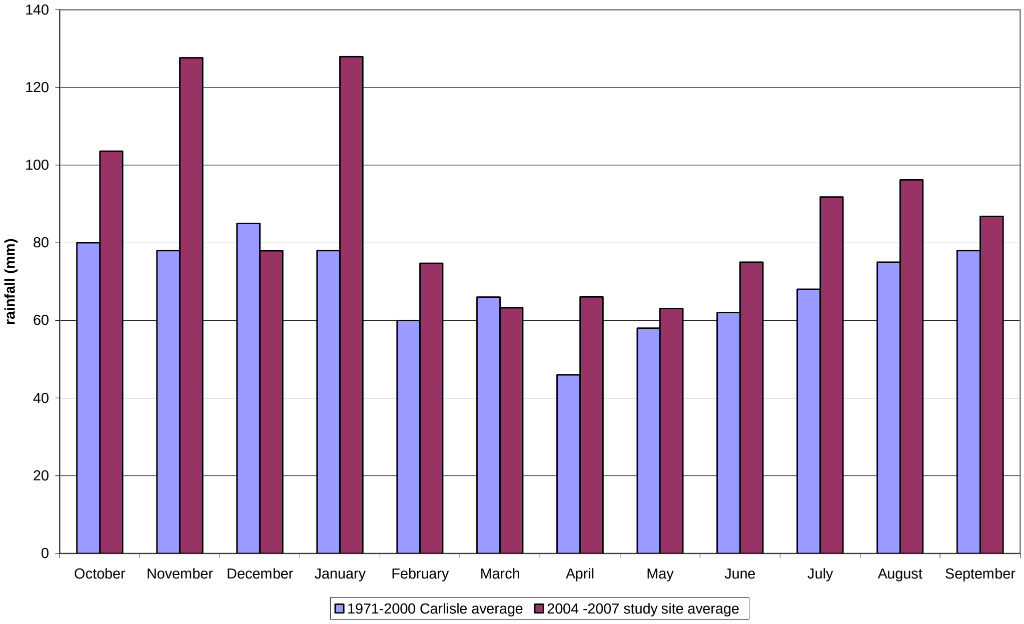


Figure 7.39 Standard deviations of Sinclair Horticulture monthly rainfall data

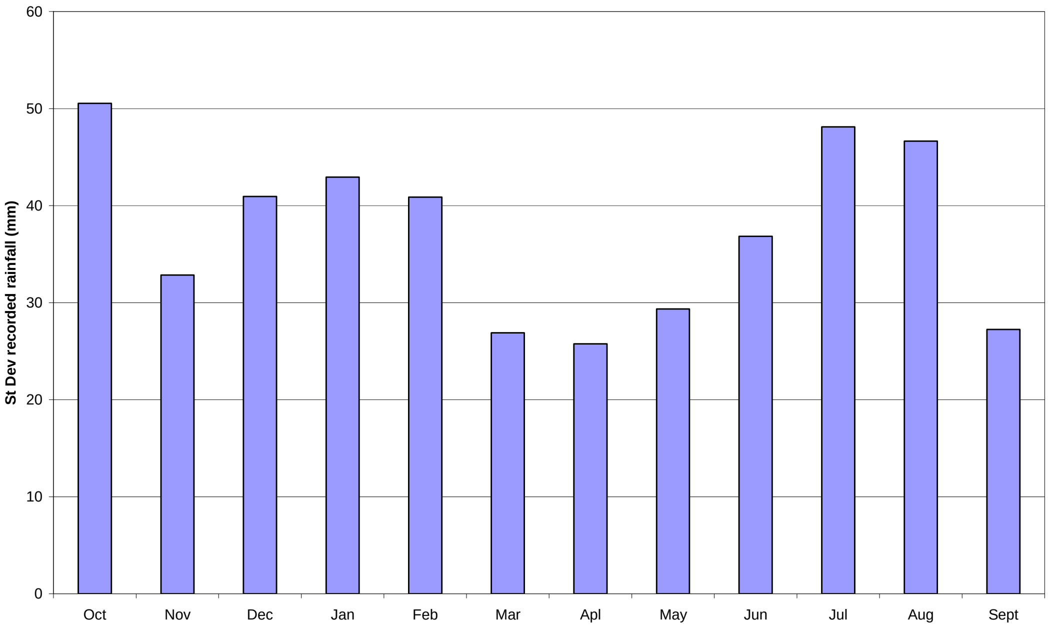
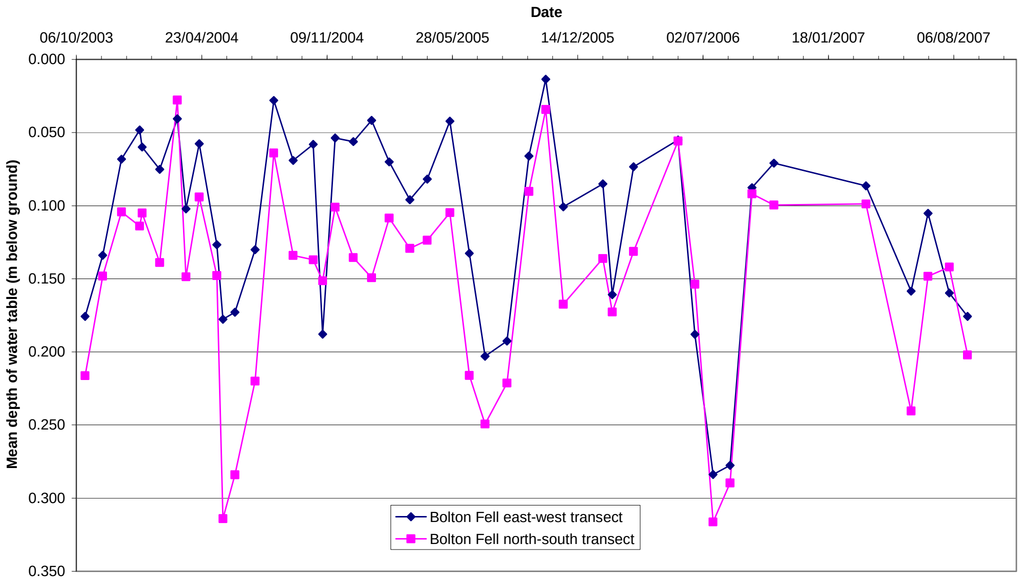


Figure 7.40 Mean dipwell water levels for Bolton Moss transects 2003 to 2007



7.4.1 Comparison and correlation of logger data recorded for the months of July with dGPS and LiDAR data

A comparison of the topographic and water level fluctuation was undertaken for data recorded by the loggers in July for the period 2004-2007. The results are shown in Figures 7.41, 7.42, 7.43 and 7.44.

The standard deviation of the water depth recorded by loggers at seven locations on both study sites was plotted against the standard deviation of the topographic variation obtained from LiDAR, on the basis that the LiDAR data has shown a consistently stronger relationship with water level. However, as can be seen from these charts, there appears to be no significant relationship between the degree of short term variation in water levels and topographic variation. Several researchers have identified general hydrological condition as the key driver for ecological condition (for example, Ramchunder *et. al*, 2009, Breeuwer *et.al*., 2009, Bragazza *et.al*., 2005) and this study seems to support this hypothesis, and that there is no relationship between short term hydrological change and topographic condition, although it is important to note that the logger locations are limited and do not necessarily reflect the range of topographic variation found on these sites.

Figure 7.41 Comparison of logger variation and LiDAR data for July 2007

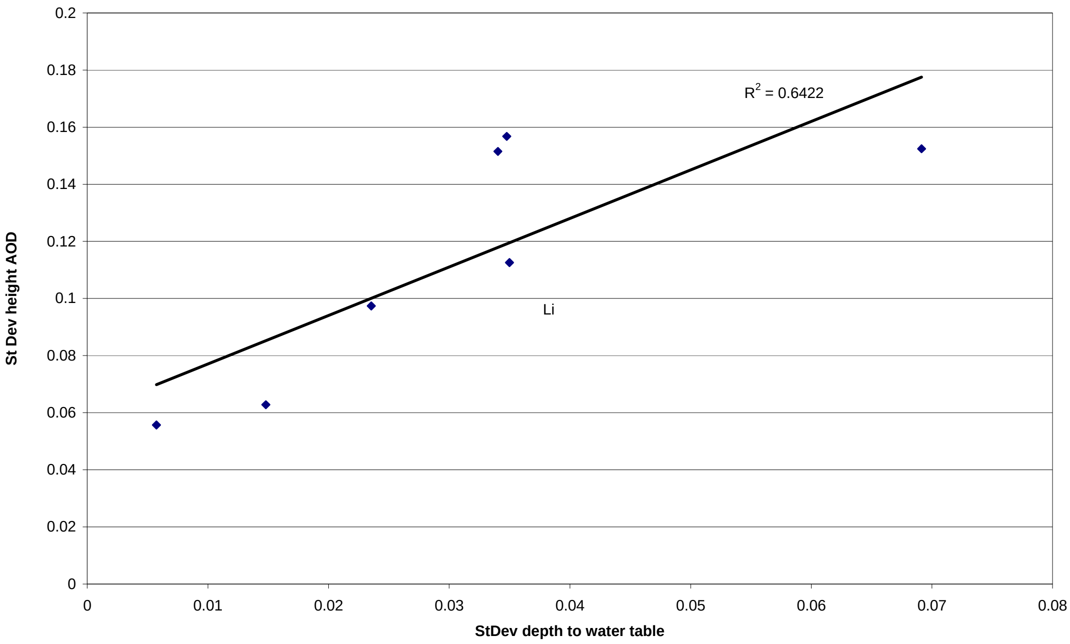


Figure 7.42 Comparison of logger variation and LiDAR data for July 2006

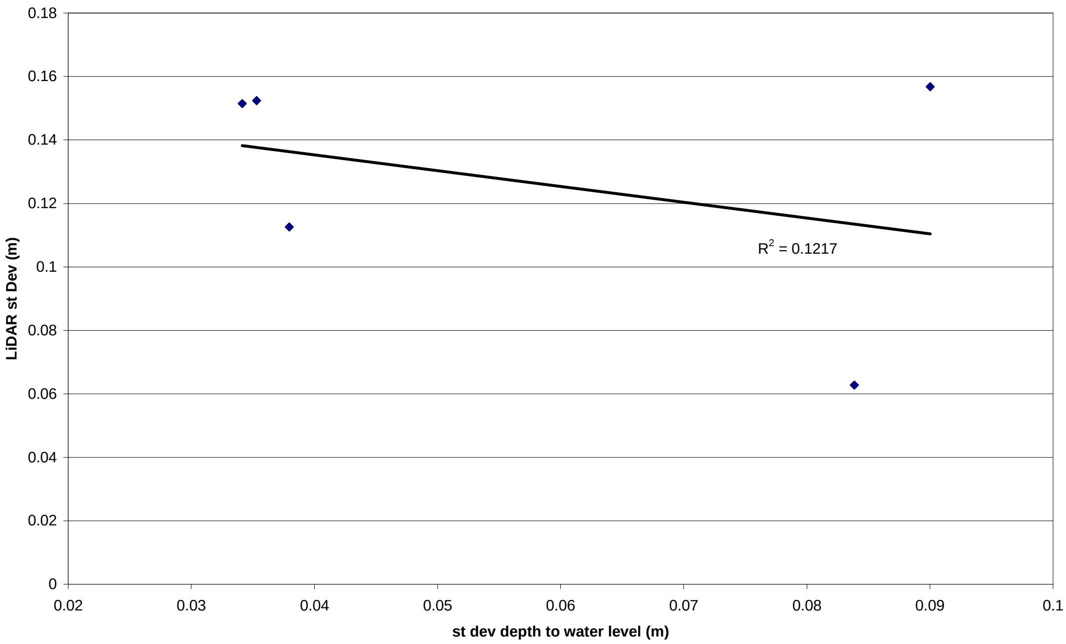


Figure 7.43 Comparison of logger variation and LiDAR data for July 2005

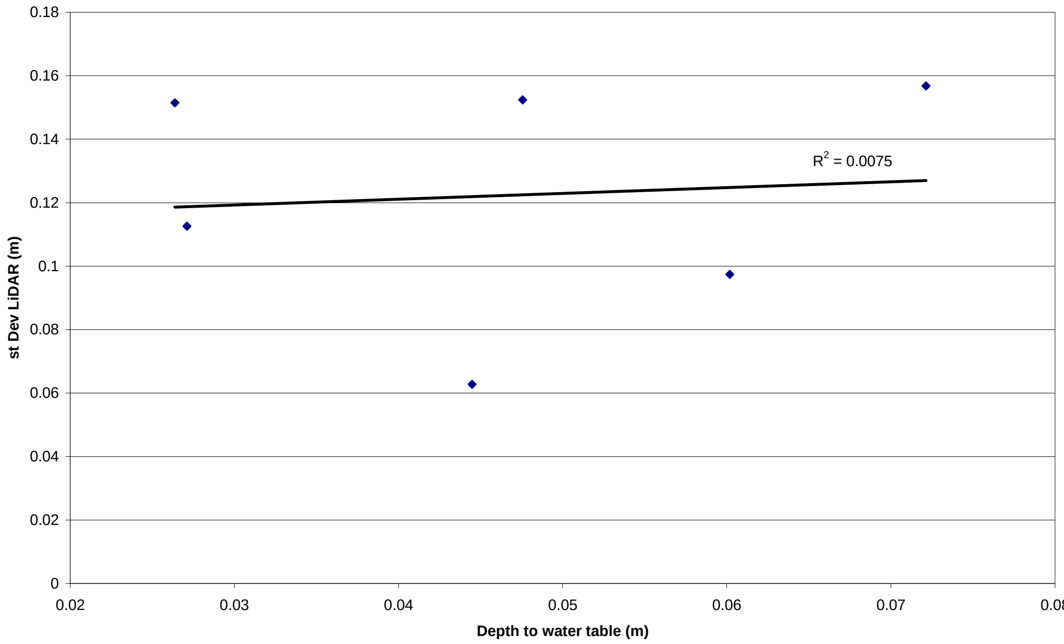
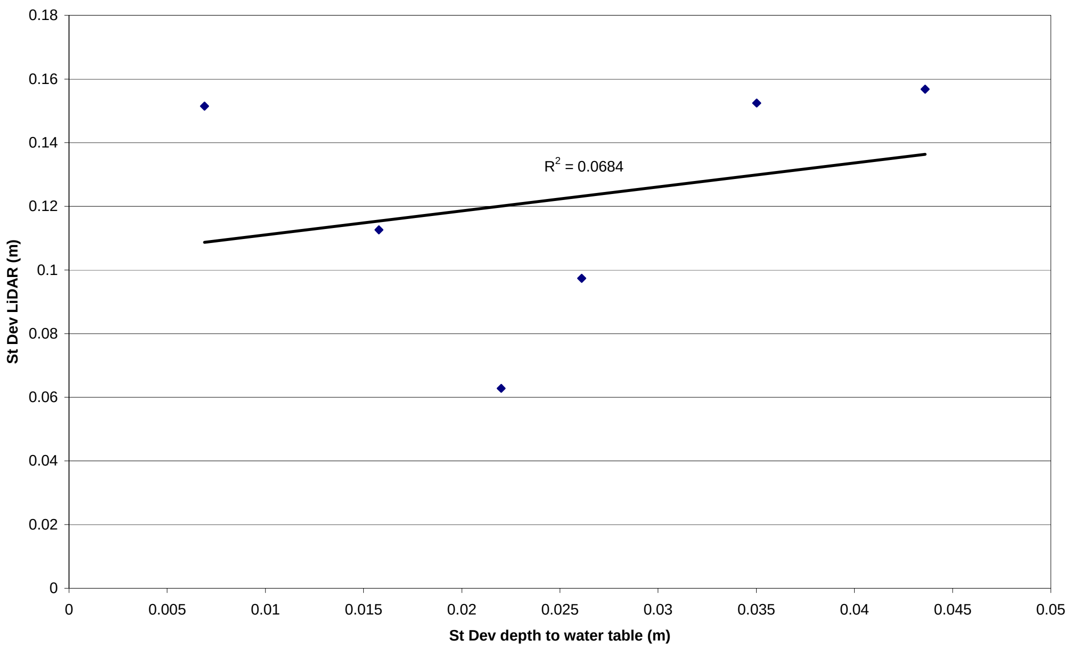


Figure 7.44 Comparison of logger variation and LiDAR data for July 2004



The implications of these findings are discussed in Chapter 8.

7.5 Canonical Correspondence Analysis analysis

Appendix 7 contains the guidance for interpretation of the following ordination diagrams from Canoco 4.54 (ter Braak and Smilaur, 2006). Appendix 8 shows the full analyses of the data, transect by transect. These analyses include Monte-Carlo significance tests which indicate that none of these tests may be considered statistically significant. However, there are some general trends which are worthy of a narrative discussion.

7.5.1 Walton Moss north transect DCA analysis of species, plots and environmental variables

Figure 7.42 shows that the majority of species associated with good ecological condition. Species of drier conditions, such as *Molinea caerulea* and *Vaccinium myrtillus* show an association with increased microtopographic variation, and also with dipwell variation, although less strongly. *Polytrichum commune*, *Deschampsia flexuosa* are associated with lower water levels, less strongly with LiDAR variation. However, it can be seen that both LiDAR and drier conditions do appear to be associated. Whilst subtle variations in bog community do not seem particularly dependent on these environmental factors, LiDAR does seem to respond tlarger scale vegetation changes.

Figure 7.43 Shows the relationships between the vegetation quadrats and associated environmental data. The most noteable results are from N9, which has already been identified as having atypical characteristics for a sample from the centre of the bog, and N4 and N5 from the edge of the dome. It is worth noting that N4 plots much less strongly to both LiDAR and dipwell. This plot is from the lower edge of the dome, and whilst it might be expected to have unusual vegetative characteristics, is likely to have a high water input from hydraulic transmissivity from the bog dome (Lindsay, 1995).

Figure 7.42 CCA analysis of vegetation and environmental factors for Walton Moss north transect

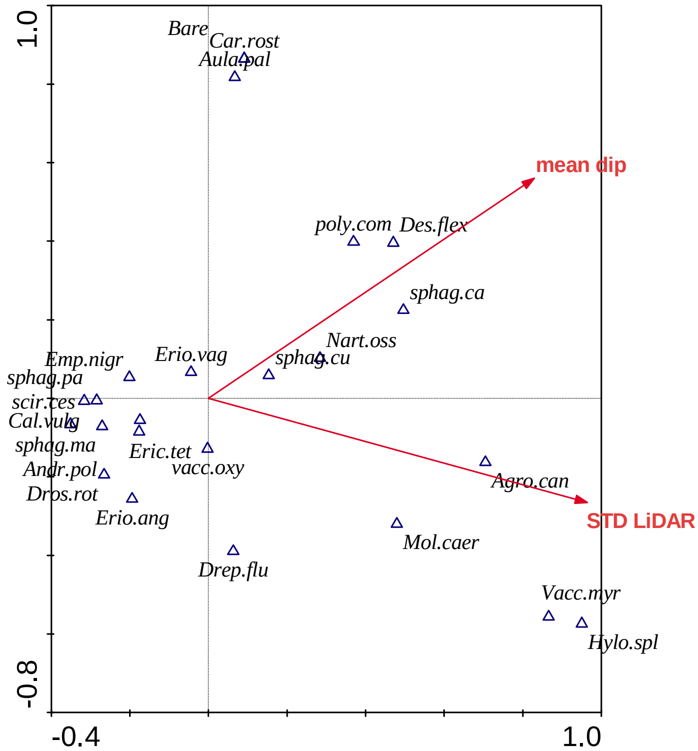
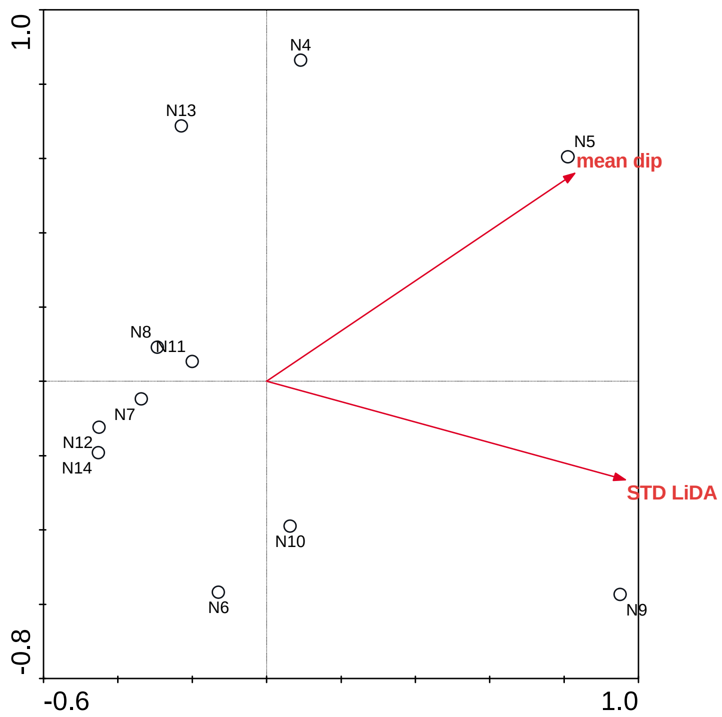


Figure 7.43 CCA analysis of quadrat and environmental factors for Walton Moss north transect



7.5.2 Walton Moss south transect DCA analysis of species, plots and environmental variables

These data show similar patterns to those for the north transect, and again illustrate the association between LiDAR and depth to water table. Again higher LiDAR values are associated with grasses, notably *Molinia caerulea* and *Festuca ovina*. Lower water depth associated with non *Sphagnum* mosses and , to a lesser extent rushes. It is interesting to note that the only quadrat strongly associated with LiDAR variation is S10. Again, it is suggested that LiDAR and depth to water table are associated, although the distribution of quadrats is less clustered than might be expected.

Figure 7.44 CCA analysis of species and environmental factors for Walton Moss south transect

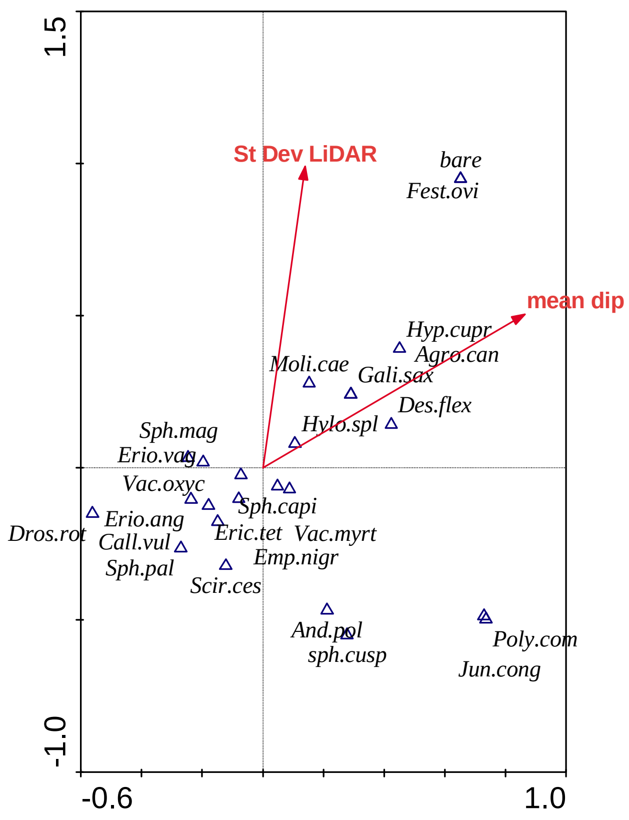
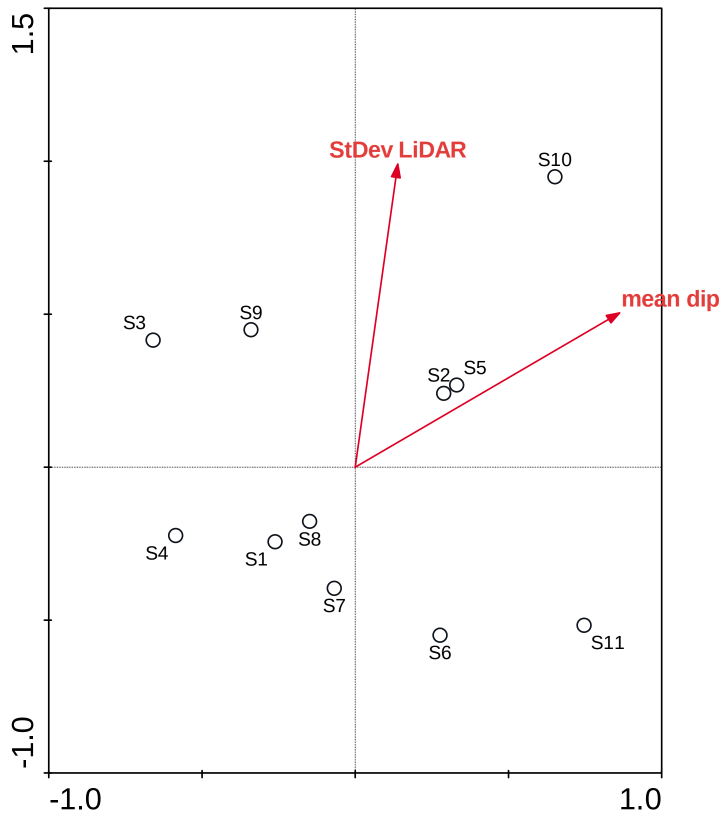


Figure 7.45 CCA analysis of quadrat and environmental factors for Walton Moss south transect



7.5.3 Walton Moss north west transect DCA analysis of species, plots and environmental variables

This transect again shows very homogeneous characteristics, and there are no particular patterns to be drawn. The N13 quadrat is identified as having different characteristics, but this is unsurprising given its location away from the bog adjacent to the Flosh lag stream. It is interesting to note that *Eriophorum angustifolium* is associated with LiDAR. This is possibly a function of small changes in a very uniform pattern being given undue prominence.

Figure 7.46 CCA analysis of species and environmental factors for Walton Moss north west transect

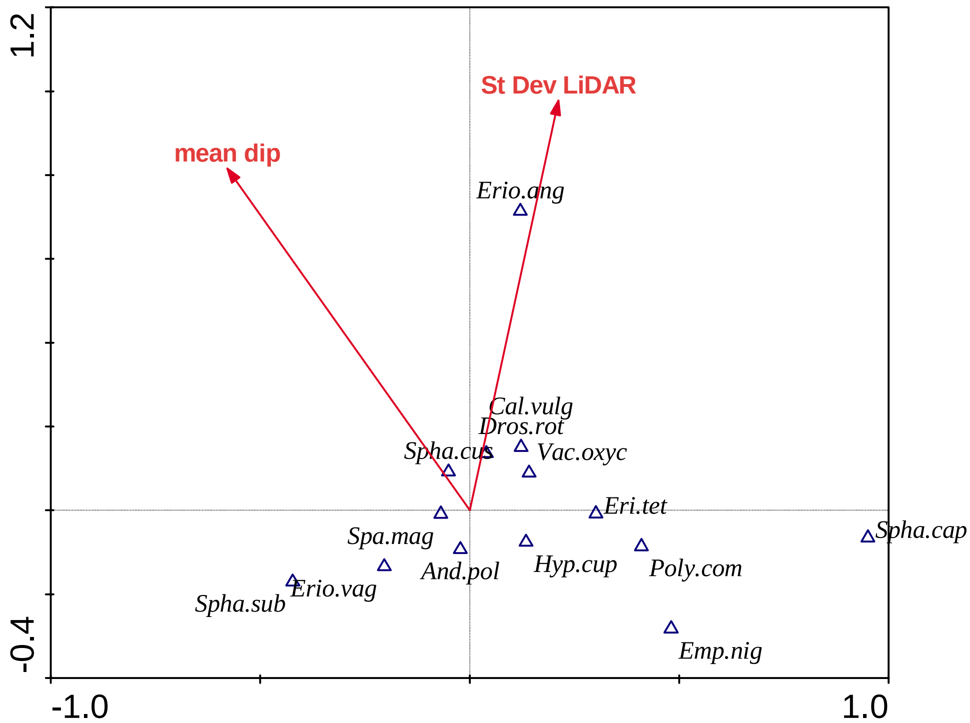
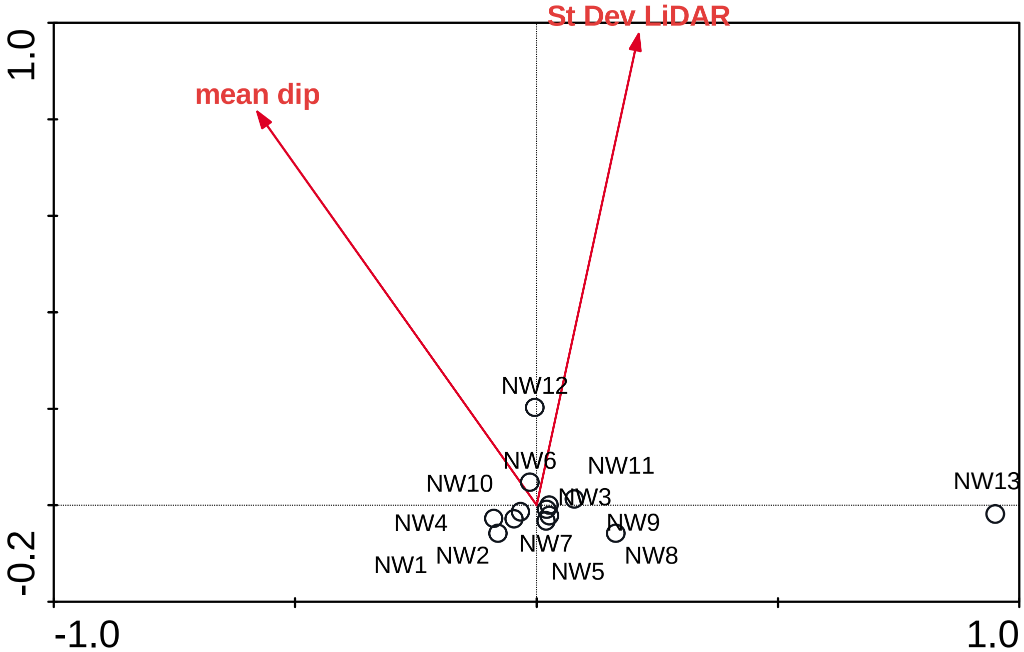


Figure 7.47 CCA analysis of quadrat and environmental factors for Walton Moss north west transect



7.5.4 Bolton Fell Moss east transect

These data are sufficiently heterogeneous to show no significant relationships between environmental factors and either species or quadrats.

Figure 7.48 CCA analysis of species and environmental factors for Bolton Fell Moss east transect

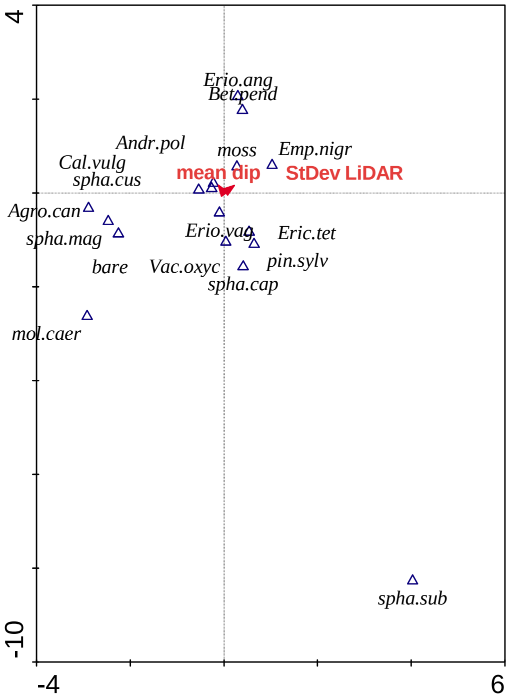
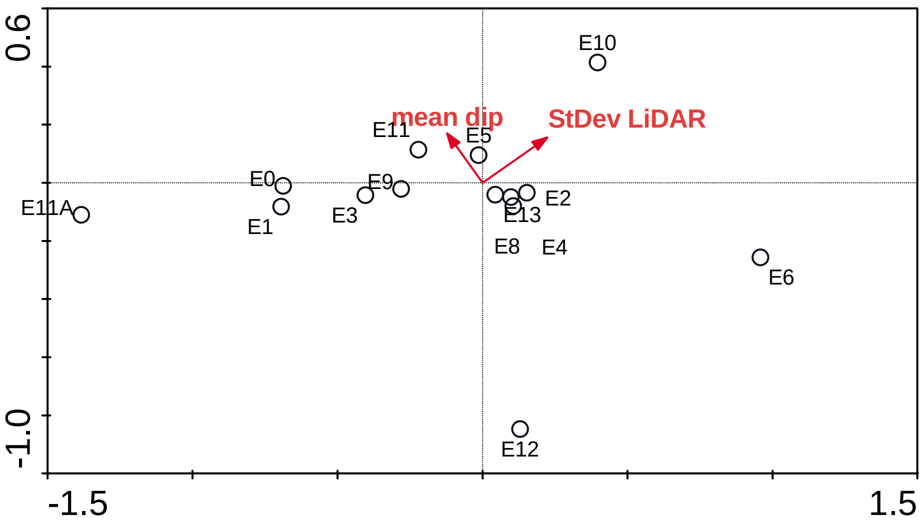


Figure 7.49 CCA analysis of quadrat and environmental factors for Bolton Fell east transect



7.5.5 Bolton Fell Moss north transect

Here, the diversity of the transect over such a short distance makes interpretation of these data difficult. The relation ship between Lidar variation and depth to water table is more pronounced than at Walton Moss, but it must be remembered that the hydrology at Bolton Fell has been repeatedly modified, both in terms of retaining water on site and the impact of the drains of the hand dug area. There is no particular association with any particular species and either topography or hydrological condition, although the two *Eriophorum* species do seem to have a n association with slightly drier conditions.

This dug area is also an area of greatly modified topography, which reflects the strong association of dipwell N9 with high topographic variation. The vegetation stripping algorithm used on the LiDAR data may also make study of the tree covered area unreliable. Low dipwells are, with the exception of N7 all subject to external influence from drains or edge effects.

Figure 7.50 CCA analysis of species and environmental factors for Bolton Fell Moss east transect

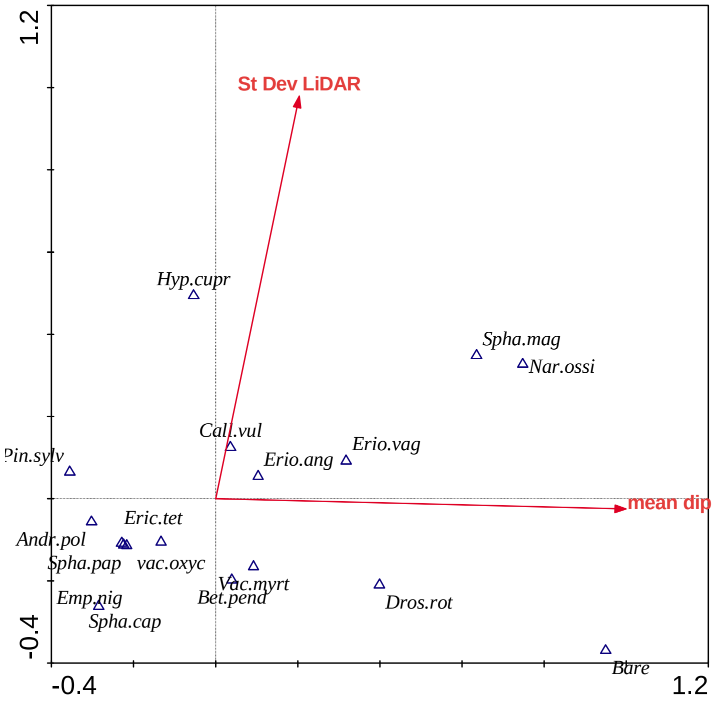
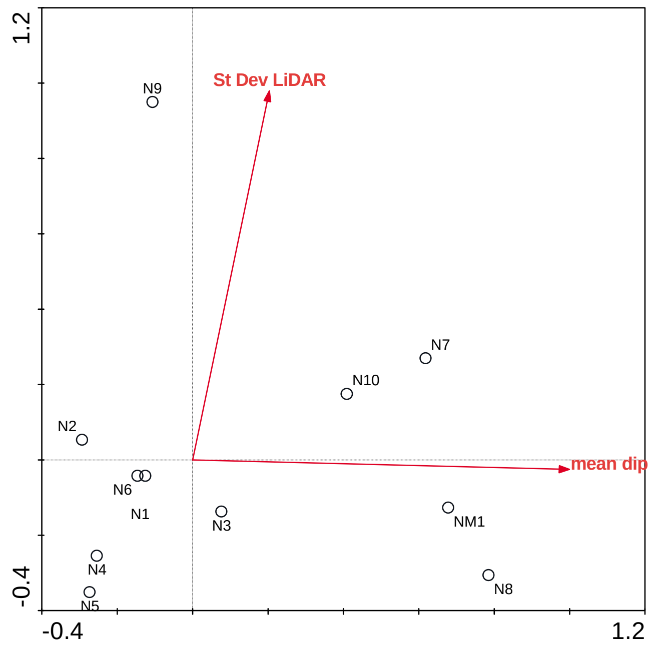


Figure 7.51 CCA analysis of species and environmental factors for Bolton Fell Moss north transect



Whilst the Monte Carlo significance tests for these CCA analyses of these data have not proved significant, the distribution patterns themselves are of interest in the context of the associations shown between certain species and topographic variation. It is also of note that whilst most of the plots from intact bog in good condition are homogeneous, the plots from untypical quadrats that are already known to have unusual vegetation or hydrological condition do appear to stand out in these analyses. The implications of these analyses are discussed in Chapter 8.

8 Discussion

8.1 Overview

This study has investigated the role of vegetation and hydrology in defining the characteristics of the surface micro-topography of raised mires. The focus of this work has been to establish if a change in micro-topographic variation at either centimetre scale across a $2m^2$ plot or sub-metre variation over a larger $20m^2$ plot reflects a significant difference in either the components of the associated vegetation community or in hydrological condition of the adjacent bog.

The conservation status and statutory protection of raised mires is primarily to conserve their botanical communities (JNCC, 1999). That other notable and rare animal species are also associated with raised mires is primarily a function of these species' dependency on these communities (Bracken *et.al.* 2008, Scott *et.al*., 2006). Scott *et.al*. aso note that this relationship can be reversed and that such species can also be used as indicators of good ecological condition, however, as is the case with *Sphagnum*, reliable identification of invertebrate species in the field is difficult and may require laboratory analyses (Hill *et.al*., 1992, Oliver and Beattie, 1996). Therefore this study has concentrated on establishing how the broader plant NVC communities, and by implication the conservation status of the site, are reflected in non ecological survey dependent factors. In particular, hydrological condition is straightforward to monitor and in some instances can be recorded automatically (van der Schaaf, 2002). Topographic and general vegetation condition is also straightforward to record and can potentially be observed remotely (Anderson *et.al*, 2009, Chapman *et.al*., 2010). Both of these techniques can be potentially accomplished much more rapidly than botanical survey, and without specialist identification skills.

However, such methodologies are limited in both applicability and resolution. Within the context of the two study sites at Bolton Fell Moss and

Walton Moss, this study investigated the practical applicability of such methodologies to assessing the hydro-ecological condition of such sites.

8.2 Monitoring techniques used in this study

The methodology for the monitoring and data recording carried out for this study is discussed in Chapter 4. The hydrology of the site was monitored for 4 years using a combination of manually recorded dipwells and automated OTT Thalimedes loggers. Vegetation cover in quadrats associated with each dipwell was surveyed by the author, together with surface microtopography, surveyed in associated $2m^2$ plots using Leica 500 dGPS equipment. 2m resolution LiDAR aerial survey data from Natural England were also used in this study.

8.2.1 Hydrology

8.2.1.1 Issues with automatic monitoring of rainfall and hydrology

From the outset of the research, the Thalimedes loggers proved unreliable, both in their ability to download consistently, and in the accuracy of the data recorded. The sites were typically visited monthly for the duration of the project, and on each occasion, the depth to water table in the dipwells was recorded and the Thalimedes loggers and automated weather station were downloaded. It was unusual for all loggers to download on any given occasion and loggers had to be replaced entirely on several occasions. This has also been the experience of other researchers using this equipment in similar circumstances. (*O'Brien et.al., 2008).* Replacement of infra-red data association (IrDA) transmitter/receivers improved reliability of downloading in the later period of the study, however the internal clocks kept poor time and the shaft encoder elements were prone to slippage, making comparison of data between loggers difficult. In addition, the infrequency of site visits made correction of errors slow to implement. However the data from individual loggers provided a very detailed record of water table reaction to specific rainfall events and whilst absolute depths need correction, the degree and rate of change is very accurate and the logger data provides a useful corollary to the spatial variation data provided by the dipwells.

The automated rainfall recorders (ELE automated weather station and Casella tipping bucket rainguage) proved to be reliable, and their data was consistent with both the manual raingauge at the Peat processing works at Bolton Fell Moss and with the rainfall data recorded at Carlisle by the Met Office, as described in Section 5.1.

These data, an example of which for 2005 is illustrated in Figure 8.1 did illustrate that the short term response of ground water to single rainfall events meant that the monthly data recorded at the dipwells did not show a close relationship with antecedent rainfall. The logger responses, an example of which is shown in Figure 8.2, show that groundwater response to rainfall is almost instantaneous, but that the subsequent decline of levels is much slower and that subsequent rainfall will quickly restore levels. Therefore the data derived from dipwells is much more useful when considering overall hydrological condition for a location. Figure 8.2 also illustrates that logger response is much more subdued in already saturated conditions. Given that this study focuses on the relationship between vegetation derived environmental indicators, these very short term fluctuations were therefore not considered when relationships between vegetation and topography with hydrological conditions were considered and the majority of hydro-ecological analyses were undertaken using data from dipwell monitoring as the hydrological variable.

Figure 8.1 Relationship of Walton Moss depth to water table to antecedent rainfall for 2005

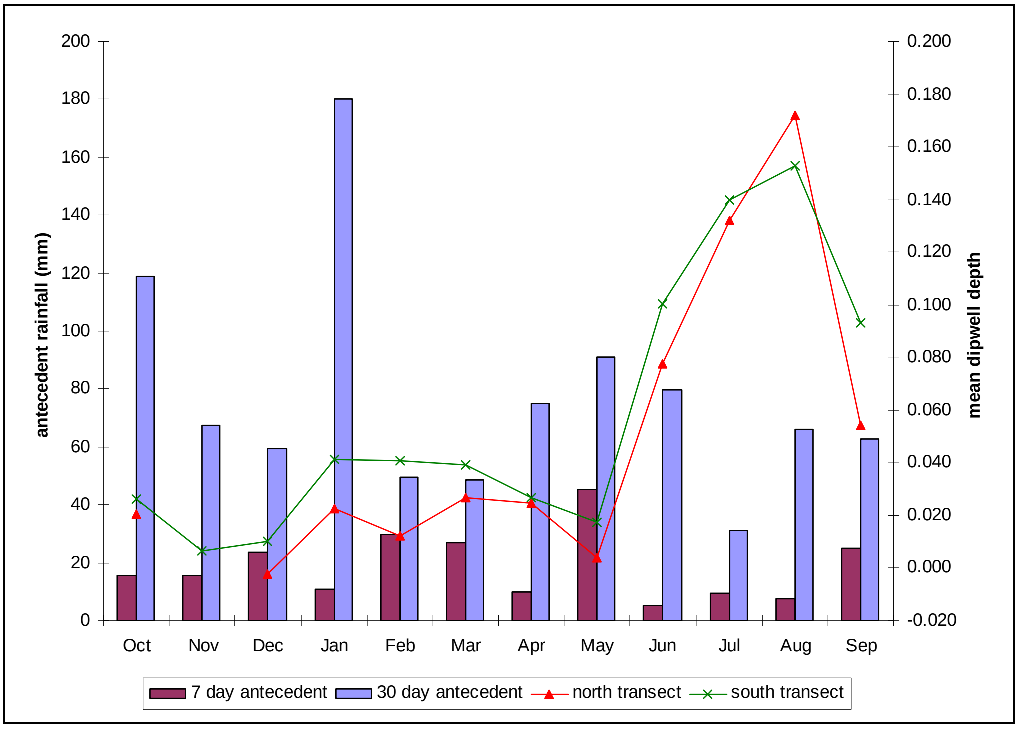
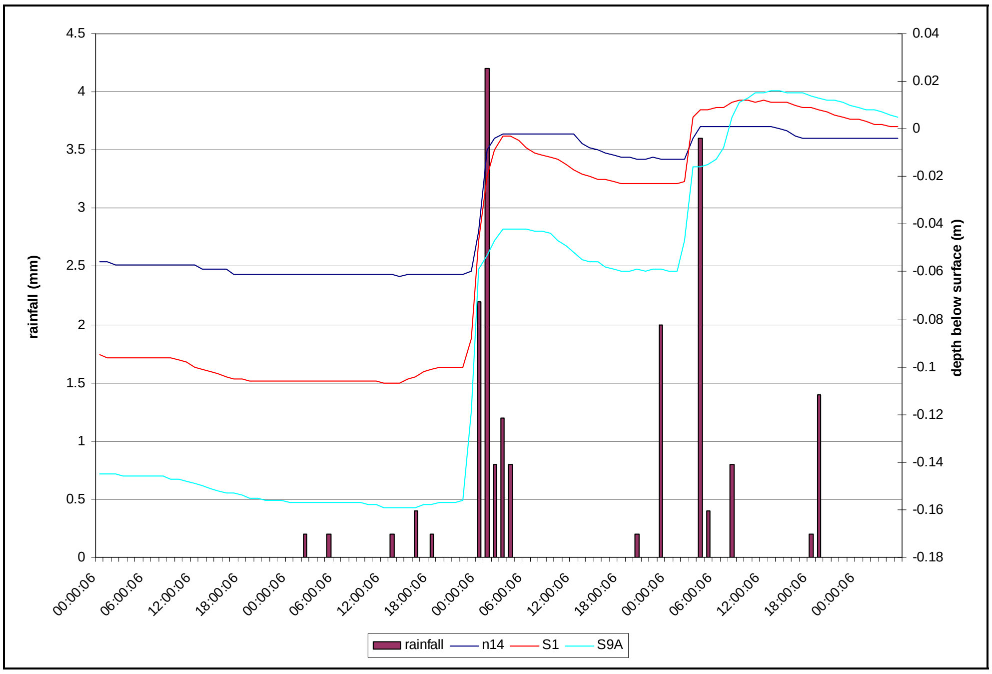


Figure 8.2 Thalimedes logger response to a rainfall event 10-14 August, 2007



8.2.2 Manual monitoring of dipwells

The dipwell transects proved to be a robust and reliable method of recording depth to water table. A widely used technique in monitoring water levels in peat (Baird *et.al*., 2008, O'Brien, 2008, van der Schaaf, 2002, Gilvear and Bradley, 2000,), the dipwell data are straightforward to record and give an excellent representation of hydrological conditions across the monitored area on the day they were recorded. The recorded data also give a good long term representation of broad hydrological condition, however as can be seen from Figures 8.1 and 8.2, they do not give an accurate picture of shorter term variation, because, as Fraser (2001), Yazaki *et.al* (2006) and others have stated, the loggers show that water levels in the peat respond quickly to rainfall events. Notwithstanding these short term limitations, the repeated measuring of these dipwells over the period of the study gives a good representation of the ambient hydrological conditions of the study site. This study is primarily concerned with microtopographic variation across the study site and the linking of the subsequent botanical and topographic surveys to these dipwell locations has enabled the most spatially diverse analyses to be undertaken

8.2.3 Botanical survey data

This study uses vegetation data recorded during 2005, 2007 and 2008. Species abundance and associated environmental data of grazing indices and sward heights were recorded for 1m^2 quadrats associated with each dipwell. The quadrats were offset by 1m from the dipwell to avoid recording in areas trampled by field workers servicing the dipwell transect. These quadrats were also used to locate the 2m^2 plots used for recording microtopographic variation using dGPS and the 20m^2 LiDAR plots.

The data for the majority of the quadrats were recorded over 3 days during May 2005. Due to time restrictions no survey was undertaken for Bolton Fell east transect on this occasion. The Walton Moss north west transect was installed in September 2006 and the vegetation survey was undertaken in the following June 2007. Following a review of available data by the author, the Bolton Fell Moss east transect was surveyed in June 2008, but the lower plant data was not identified to the same degree of accuracy as for the other transects due to time constraints. Following initial study of the botanical survey data already collected, the author also considered that these lower plants were not individually contributing to topographic variation. Whilst substantial change in vegetation communities can be identified using higher plant data and *Sphagnum* alone, some of the non *Sphagnum* lower plant species are significant in the MAVIS community analyses (Smart, 2000). The MAVIS analyses for this transect, described in Section 6.1.3, are by inference, less reliable than those for the other transects.

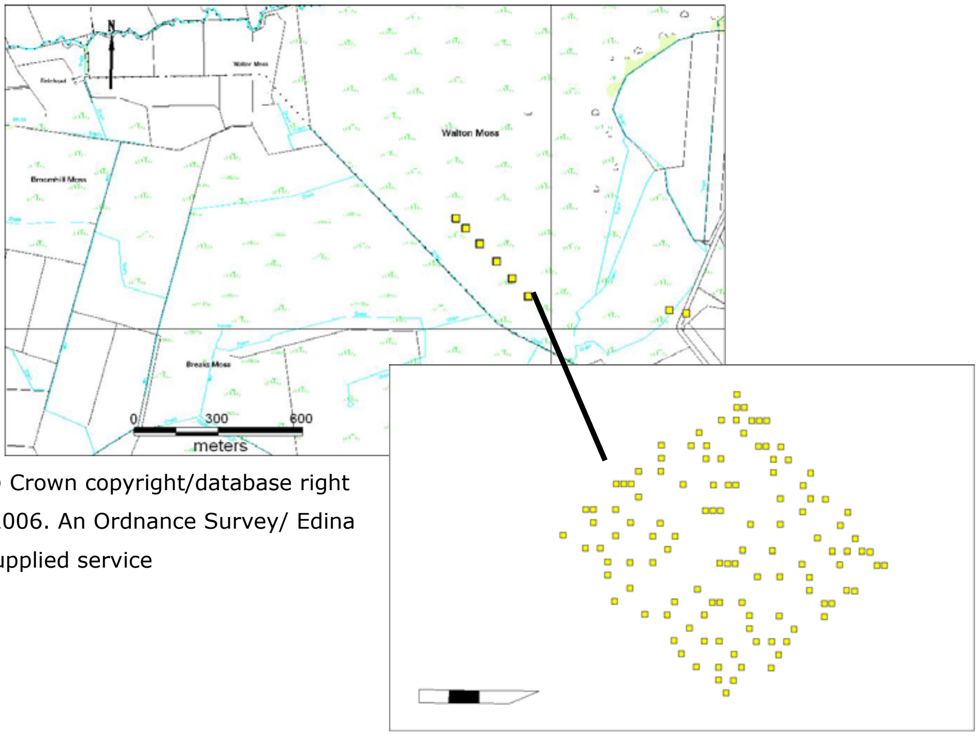
8.2.4 Topographic variation

8.2.4.1 Measurement of topographic variation using dGPS

The measurement of topographic variation using differential GPS is described in Section 4.5. Spot heights for the $2m^2$ quadrats were recorded at 0.2m intervals and the standard deviation of this figure taken as a measure of topographic complexity for the plot. The relationship of these points to the relevant dipwell and vegetation quadrat is shown in Figure 8.3. Using standard deviation as a measure of topographic variation has been used by others such as Cavalli and Marchi (2008) and Everson and Boucher (1998) to produce similar representations. In particular, Cavalli and Marchi used this methodology with LiDAR data comparable to that used in this study to produce a roughness index for alluvial fans, which may be considered to have similar properties of size and variation to the research sites of this study.

The dGPS system has stated centimetre accuracy (Leica Geosystems, 2008), however the methodology used in this study suggests that error due to subjective identification of the surface of the vegetation or failure to keep the surveying staff stable and vertical may introduce errors which outweigh this. In addition it is recognised that the accuracy of dGPS is dependent on a clear satellite signal which trees may obstruct (Zheng *et.al*., 2005) and parts of Bolton Fell Moss are obstructed by *Betula pendula* and *Pinus silvestre.* All of the dGPS surveying was undertaken by the same surveyors which included the author, therefore subjective judgement of the vegetation surface is likely to be consistent. Errors due to inconsistencies between surveyors is a recognised problem with botanical surveying (Cherril and Mclean, 1999), but by using the same personnel, such errors should be minimised.

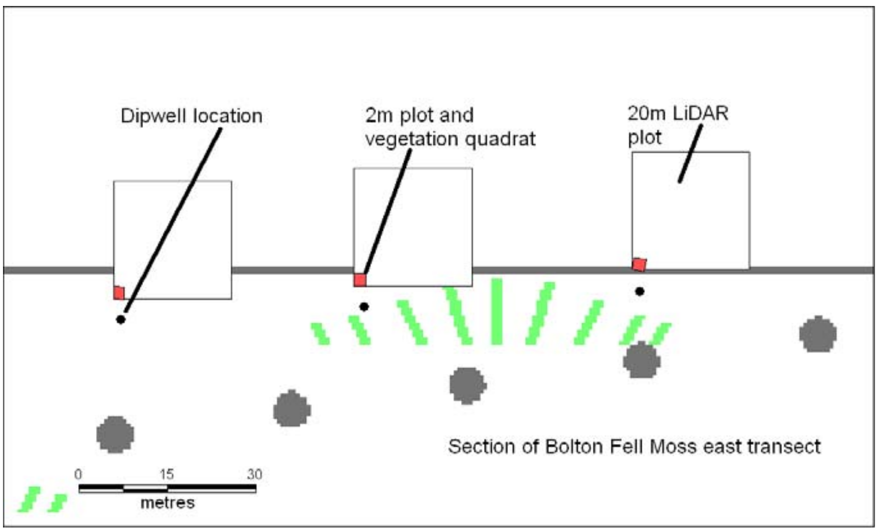
Figure 8.3 Detail of dGPS surveyed 2m^2 plot at Walton Fell Moss



8.2.4.2 Measurement of topographic variation using LiDAR

Section 4.4.3 describes how LiDAR measurements are taken using aircraft mounted laser scanners. The data set used for this study was obtained by Natural England from the Environment Agency and has a given accuracy of 5-15cm for each measured point (Environment Agency, 1997). Xharde *et.al* (2006) state that accuracy in both the vertical and horizontal planes is sub 30cm, principally as a result of aircraft position error, calculated using GPS. Horizontal spacing of data is a 2m intervals. LiDAR data is easy and quick to collect. The Environment Agency state that up to 90km^2 can be surveyed in an hour and that the process is almost entirely automated, meaning large areas can be surveyed, so the technique would be applicable to larger areas of boreal peatland and blanket bog. Whilst the accuracy of dGPS is far greater, the time and resources required to survey large areas of bog surface accurately and consistently would make it unsuitable for any large scale practical application. The relationship between dGPS surveyed plots and the 20m2 LiDAR data plots is illustrated in Figure 8.4 and the effectiveness of the two survey methodologies in this study is discussed in section 8.3.2.

Figure 8.4 An example of the spatial relationship for dipwells, 2m vegetation/ dGPS plots and 20m LiDAR plots



8.3 Discussion of data analyses

Data analyses undertaken in Chapter 7 highlighted several characteristics of the ecological and hydrological data collected during this study. The spatial distribution of the vegetation communities and individual species were considered using Bray Curtis Cluster analysis and detrended correspondence analysis. The relationship between hydrology, as represented by the average depth to water table of the dipwell transects and similarity to M18 *Erica tetralix-Sphagnum papillosum* raised and blanket bog was assessed using correlation. Microtopographic variation, as measured by dGPS and LiDAR was assessed for correlation with depth to water table, and Canonical Correspondence Analysis (CCA) was use to investigated associations between key species and communities associated with specific dipwells and the environmental factors of topographic variation and depth to water table.

8.3.1 Analyses of vegetation communities

8.3.1.1 Walton Moss

The data for each transect was assessed using detrended correspondence analysis and Bray-Curtis cluster analysis. The cluster analysis showed some strong associations between quadrats on Walton Moss. In particular, it identified those plots of the mire dome mesotope (Cowenberg and Joosten, 2005) as being strongly similar. On the south transect, S1-S8, with the notable exception of S2 were identified as being over 60% similar. It is of interest that S2 is dissimilar as this is an area within the main area of bog that had provisionally been identified as in good condition, and was superficially similar to the other quadrats on this transect, only detailed survey had revealed that it was ecologically different. It also displayed correspondingly anomalous hydrological characteristics, a much lower average depth to water table recorded at the associated dipwell. It is possible that this dipwell is an indication of the continuation of the mineral exposure, noted on the north transect. However, this supposition would require follow up investigation, through peat coring or soil sampling, for example. The dipwells at the lower end of the transect display more heterogenous characteristics. This is probably as a consequence of them being representative of the outlying edge of the bog, although they do not display the characteristics of lagg fen, unlike the eastern end of the north transect. The north transect again shows a series of broadly homogeneous dipwells, within the range of N6 to N14. The anomalous quadrat at N9 has different vegetative characteristics and has been identified as indicative of the mineral outcropping observed here from Natural England records (Natural England, unpublished) and recorded by Hughes *et.al.* (2000) and Labadz and Butcher (2006). The lagg fen quadrats show strong heterogeneity from the other quadrats. On the north west transect, the vegetation is very strongly homogeneous. N13 is distinct, but this quadrat is located off the main bog and adjacent to the Floss watercourse. Of more interest is that NW3 and NW5 also show unusual characteristics, when compared with the 70% similarity displayed by the other quadrats. There is no immediate explanation for this, but consideration of the other transects suggests that this may have a geological explanation, but without analysis such as ground penetrating radar or peat coring, it is impossible to confirm this from these data alone (Ketteridge *et.al*, 2008).

The DCA analyses of these transects broadly mirrors the results from cluster analysis, however DCA also permits the association of individual species with quadrats. The homogeneous areas of bog show associations with species such as *Calluna vulgaris*, *Eriophorum vaginatum* and the recognised bog specialists, such as *Narthecium ossifragum*, *Andromeda polifolia* and the *Sphagna*. On the north and south transects, the anomalous transects within the bog are associated with grass species such as *Molinea caerulea* and *Deschampsia flexuosa. Vaccinium myrtillus* is also associated with these quadrats. These species are of interest as they are substantial structural plants and may have an influence on topography (Soro *et.al*., 1999, Smith *et.al*., 1995)). On the north west transect, these differences are less apparent, although there is a weaker association between the anomalous quadrats at N3 and N5 and *Vaccinium myrtillus* and *Empetrum nigrum*, a plant not recorded from the other quadrats.

8.3.1.2 Bolton Fell Moss

The vegetation at Bolton Fell Moss is much more heterogeneous. Whilst the east transect does show a similar pattern to Walton Moss, of broadly similar quadrats in the centre of the site, with quadrats at the edges showing different characteristics, the situation is complicated because Bolton Fell does not represent a complete raised bog mesotope. The area under study represents a smaller area of intact bog dome which has been completely cut off by systematic peat harvesting over the surrounding area. This creates two difficulties in interpreting the data: firstly the data is for a much smaller area, therefore large scale changes possibly observed at Walton Moss over long transects would not be apparent on this site, and secondly, the hydrology has been historically compromised, even though there have been recent attempts to restore and safeguard it (Turner, pers. comm.). The north transect is even more disturbed, as it includes both an area of cut over peat and a small woodland, which appears to be spreading into the remaining area of bog. The cluster analysis of this transect shows very little association between any of the quadrats. Whilst any definitive associations are difficult to detect, there does seem to be some association in the DCA analyses between the better, central quadrats and *Erica tetralix* and *Eriophorum vaginatum*, and *Empetrum Nigrum* and the tree species with quadrats less typical of raised bog in good condition.

8.3.2 Issues relating to the measurement of microtopography

Analyses of the relationship between hydrology and surface microtopography in Chapter 7 illustrate the difficulties in definitively defining bog surface. Whilst the dGPS methodology is ostensibly the most accurate, there are always potential difficulties relating to the subjectivity of the process. The process used for defining topographic variability, through taking the standard deviation of the surveyed plots means that any potential errors in dGPS post processing are minimised (Monteiro *et.al*., 2005). Providing the errors in determining absolute height are consistent throughout the plot surveyed, the Standard deviation for the plot will be the same, and these data can therefore be used for comparison with data surveyed on another occasion with a different error.

Issues with LiDAR accuracy have been discussed in Section 4.4.3. for this study, the biggest difficulty with the application of this data has been with it's applicability to areas with small topographic change. At Bolton Fell Moss, the topographic variation is small across short transects. At Walton Moss, distances of over a kilometre are assessed and the bog undergoes several structural and ecohydrological changes within the length of the quadrat. It would appear that at Bolton Fell, the topography recorded as a result of peat cutting and internal drainage masks any difference as a result of subtler changes in vegetation surface microtopography.

When the relationship between results from dGPS survey and LiDAR are considered, this difficulty becomes apparent. Figure 8.5 shows the Walton north transect profile surveyed by both methods. At this scale the results can be seen to be very similar, although the small scale variations assessed in Chapter 7 are more substantial. Figure 8.6 shows the same comparison for Bolton Fell Moss. Even at this coarse scale, the differences between the two methodologies can be seen to be greater. This is likely to be as a consequence of both the issues of man made disturbance, but also the vegetation removal algorithm used on the LiDAR data. This mechanism produces a good representation of underlying topography, but for assessment of very small scale variation, this may render the data unrepresentative (Barbarella and Gordini, 2006, Raber *et.al*. 2002, Devereux, 2005). This is because the algorithm is effectively interpolating data from adjacent areas, rather than recreating the actual topography. It is also not able to consistently differentiate between low vegetation and tree cover (Hopkinson *et.al*, 2005).

Figure 8.5 Comparison of LiDAR and DGPS survey for Walton Moss north transect

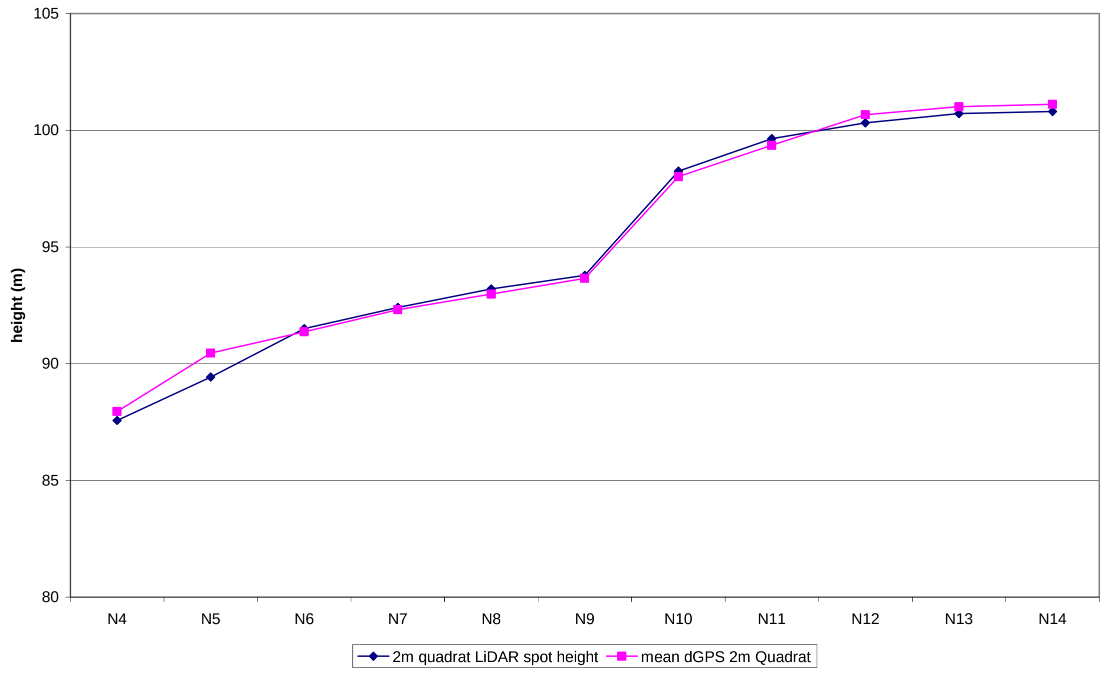
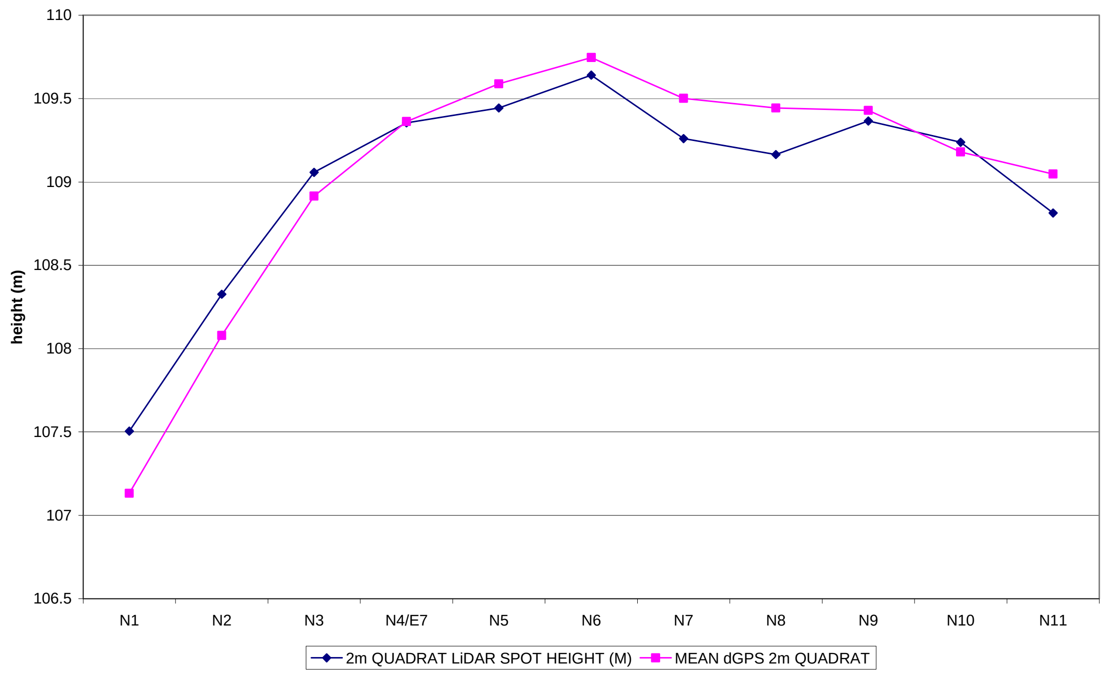


Figure 8.6 Comparison of LiDAR and DGPS survey for Bolton Fell Moss north transect



8.3.3 Relationship of data derived from dipwell transects and topographic variation

The dipwell series have been simplified to give an effective indication of broad hydrological condition for each site. By using mean levels for the entire study period, the effects of extremes of weather may be minimised. For example, the rainfall input for the study period has been marked by several extremes, notably the extreme rainfall which affected many parts of the UK in 2007 (Met Office, 2007). These summary dipwell data were used in Chapter 7 to determine if there was a relationship between the topographic variation recorded by dGPS and LiDAR.

Table 8.1 Summary of Correlation of topographic variation and depth to water table

	dGPS			LiDAR		
Transect	Correlation	Significance	R^2	Correlation	Significance	R^2
Walton north	.646	.044	.476	.719	.019	.417
Walton south	.673	.033	.453	.719	.019	.404
Walton north west	-.319	.31	.102	.679	0	.476
All Walton transects				.679	0	.460
Bolton north	-.675	.023	.456	No measurable relationship		
Bolton East	No measurable relationship			.769	.01	.592
All Bolton Transects	-.443	.027	.196	.378	.063	.143
All transects	-.111	.417	.012	.642	0	.412

These results illustrate that there would appear to be a relationship between the hydrological condition of a bog area and depth to water table, but that it is not particularly strong or consistent. This relationship is not as apparent at Bolton Fell Moss, nor is it as clear in the dGPS results,

8.3.3.1 Microtopography and hydrological conditions at Walton Moss

The dGPS results from Walton Moss suggest that a there does seem to be an increase in microtopographic variation associated with lower water levels. However this relationship is only apparent on the longer and more hydro-ecologically diverse north and south transects. The vegetation and limited water table monitoring on this transect suggest that there is little spatial variation across this transect and that it is therefore unsurprising if there is little observable relationship. It is important to consider that the dipwell record for this transect is much more limited than for the others. Not only was it installed later, in 2006, but financial limitations meant that there was no monthly monitoring between November 2006 and March 2007. Whilst it is reasonable to suggest that the overall high water levels on this transect indicate that there would have been little variation in water levels over the winter period, it is of note that the rainfall records for Bolton Fell show that the late winter and early spring of 2007 saw less rainfall than would be expected for this site.

The LiDAR results for Walton Moss show a consistent relationship between hydrology and larger scale variation. These results suggest that on a larger scale, that an increase in topographic variation does indicate drier conditions. It is possible that the LiDAR is detecting more widespread change in landscape classification. In recent work, Anderson *et. al* (2009). have used LiDAR and satellite imagery to classify condition of raised bog, but their work at Wedholme Flow categorised sites according to broad habitat types, rather than investigating more specific species-microtopography associations. This work at Walton Moss suggests that the LiDAR data is definitely differentiating the bog habitat from lagg fenn or surrounding land use, but also seems to be reflecting change within the site where there are substantial differences, and reflecting subtler changes in the bog mesotope. This methodology would appear to have some success in detecting substantially drier areas within what is superficially considered healthy bog. This both validates the work of Anderson, but also suggests that LiDAR may have a role in detecting substantial change in vegetation condition *within* bog habitat, as well as detecting the habitat itself.

There is a good degree of correlation (r= .663, p=0.001) between the dGPS and LiDAR data for Walton Moss, suggesting that for this site, the topographic variation at the small vegetative scale measured by the dGPS is a good representation of the wider variation in the surrounding area. It is possible that for larger areas of unobstructed raised moss, an increase in topographic variation is indicative of drier hydrological conditions.

8.3.3.2 Microtopography and hydrological conditions at Bolton Fell Moss

Microtopography at Bolton Fell Moss is much less representative of hydrological condition. For the north transect there is a negative relationship observable in variation of the dGPS surveyed plots and depth to water table, a form of relationship not observed in any of the other topographic data. The dipwell data for this site suggest that the wettest section of this site is the central area, which is subject to gradual encroachment by tree species, there is also a great deal of old branched material left in this area from previous management by Natural England (Natural England records, unpublished), which has acted as a framework for other vegetation. It is possible that this material has distorted the direct measurements. At the edges of the site, where water levels are lower, there has been much management both from historical peat cutting and attempts to compact the ground and decrease hydraulic conductivity. This management makes any attempt to interpret the topography impossible, therefore the relationships for this data are at best unreliable and at worst meaningless.

For the east transect, the issues relating to reliability of the dGPS data highlighted for the north transect also apply, and this is reflected in the absence of any relationship between these data and hydrology. There is a good relationship between hydrology and the LiDAR data, which is potentially because the 20m plots from where LiDAR topographic variation was recorded are located to the north of the transect and away from the wooded area. Where tree cover has not interfered with results and there is no artificial manipulation of the bog topography. Here there is a correlation of 0.769, P=0.01. This transect also has a relatively good regression fit of R^2=0.592.

It would appear that the tree cover has caused difficulties with both the dGPS and LiDAR data. The issues relating to lost of accuracy through vegetation removal algorithms are well documented (Xharde *et.al*., 2006, Hopkinson *et.al*, 2005, Raber *et.al.*, 2002), but the impact of felled brash and dead vegetation had not been anticipated in the design of this study. It was also noted that maintaining satellite and correction signal contact under the trees had been problematic, and this could have contributed to absolute errors in the recording of these points (Enge, 1994, Monteiro *et.al*., 2005), leading to misleading aggregate variation figures.

8.3.3 Discussion of the relationship between species, communities and topography

The NVC m18a community, representative of raised bog habitat in good ecological condition (Rodwell, 1991) does not show any strong association with topographic variation. Figures 7.21 and 7.22 illustrate this absence of relationship with a near random distribution of points. For both dGPS and LiDAR there is no relationship specific to a specific community and this would seem to suggest that within raised bog communities, topographic variation is a function of structural change in existing communities, rather than a change in community or species distribution, as suggested by Swanson (2007), Robroek *et.al*. (2007), Nungesser (2003) and others. This is potentially important as, whilst far from conclusive, it is possible that topographic change does precede ecological change, and has potential as an early indicator of change in hydrological condition before ecological degradation begins to occur.

The canonical correspondence analysis is harder to interpret, because of the poor significance results obtained from the corresponding Monte Carlo analyses, however when the plots are inspected, there would appear to be associations between the environmental factors of topography and LiDAR variation. These relationships are stronger for Walton Moss. The CCA analyses described in Section 7.5 show that the ordinations for LiDAR variation and depth to water table are in a similar direction. The interpretation for such diagrams (ter Braak and Smilaur, 2002) suggests that the smaller the angle between these vectors, the closer the relationship. At Bolton Moss, this angle is much larger, suggesting a weaker relationship. The ordinations highlight that dipwells identified with untypical vegetation communities, for example S2 or N9 at Walton Moss, tend to be associated with both of these vectors. This again highlights the inter-relation of topography and hydrology in defining the ecological characteristics of raised mires.

When the ordinations for individual species are assessed, it can be seen that species associated with increased bog topography tend to be those that are not associated with raised bog in good condition, such as *Molinea caerulea* and *Agrostis Canina.* On Walton Moss north west transect, where there is no untypical vegetation, there is a positive association between increased microtopographic variation and *Eriophorum angostifolium.* Whilst *E. angustifolium* is in some cases associated with increased waterlogging (Gebaur *et.al*., 1995, Lindsay, 1995), in healthy raised bogs it is often associated with areas of stressed or damaged bog, often as a result of management intervention (Breeuwer *et.al.,* 2009, Anderson *et.al*., 2009). Anderson *et.al*. were able to use remote sensing to differentiate healthy raised bog from *Eriophorum* dominated degraded bog, but it is unlikely that their methodology would be able to differentiate a change in the proportion of cover between *E. angustifolium* and *E. vaginatum.*

Relationships at Bolton Fell Moss are much less distinct than at Walton Moss, reflecting the difficulties with accurate measurement of topography and the distorting factors of past management. Even on the east transect, judged to be the more representative, no overarching ecological influence on topography is evident. It is possible that this analyses is inconclusive due to the absence of detailed lower plant identification, but given the data collection methodology for the transect was consistent, it would be expected that this analysis could still detect associations if they were apparent. On the north transect, the CCA suggests an association between *Hypnum cupressiform* and an increase in microtopographic variation. It is unlikely that *Hypnum* is directly influencing the microtopography, rather that hypnum is a characteristic species of the vegetation communities of drier bog margins (Rodwell, 1991) and the vegetation associated with the *Betula* brash, both instances of increased microtopographic variation.

8.4 Preliminary conclusions, based on original investigation aims.

8.4.1 To investigate relationships between hydrology and vegetation in lowland raised bogs.

This study has established a weak but discernible link between hydrology and vegetation for the two Cumbrian raised bogs in this study. This relationship is most easily distinguished over whole bog profiles and is therefore more apparent at Walton Moss, than at Bolton Moss, where only a fragment of the centre of the bog dome is retained.

8.4.2 To determine the effect of drainage on ecological condition, how hydrology influences the development of such vegetation and if hydrological change is a precursor to adverse change in hydrological condition

At Walton Moss there is a clear relationship between depth to water table and hydrological condition. The minor drainage grips on the southern transect do not appear to be having a substantial effect on the main area of the bog dome, but the drainage does seem to be drawing down the water table at the perimeter of the transect – dipwells S9, S10 and S11, and also in areas where peat depth is decreased by underlying geology at dipwells S2 and N10. However there is no relationship between the degree of similarity with M18a NVC community and depth to water table, suggesting that minor changes in water level are not substantially affecting the bog vegetation communities at this time.

At Bolton Fell Moss, where more dramatic drainage can be observed, there is a distinct difference between the vegetation observed in the cutover areas or those areas adjacent to internal drains and the vegetation of the centre of the site. There is also a definite degradation of vegetation in the areas of bog where the peat has been compacted to retain water. These areas may be considered as sacrificial areas where the vegetation has effectively been destroyed and only partly recolonised to preserve the ecology of the remainder of the site. The hydrological results described in Chapter 5 suggest that this has been an effective and necessary strategy, considering the small overall size of the site and the dramatic drainage works required for peat cutting.

8.4.3 To determine how vegetation relates to the topography of these areas.

This study has established that there is an association between some plant species and surface topography. However it appears that the species identified, notably *Molinea caerulea*, *vaccinium myrtillus*, *Agrostis spp*. are species associated with non M18 communities, rather than identifying change within bog communities, therefore the methodology appears more suited to differentiating raised bog from associated different habitats, such as lagg fen, rather than identifying change within bog communities themselves.

8.4.4 To develop a methodology for investigating whether LiDAR data obtained from aerial monitoring can be used to characterise small scale topographic variation on such sites, and to obtain a representative ground truthed data set for comparison with the LiDAR data.

The dGPS data for small plots correlates well with the equivalent LiDAR plot providing there are no external factors affecting topographic variation. This relationship was strongest on the north and south transects of Walton Moss, but was unclear at Bolton Fell Moss, this was probably due to the absence of trees, and the absence of strong man made topographic change due to large scale drains or peat cutting. Where there were such factors, the relationship was much less clear, suggesting such small sites with artificial microtopography may not prove appropriate to this methodology.

The LiDAR derived data appear to be better suited to use as an indicator of topographic change. The reason for this is deserving of more detailed study but could be as a consequence of the effect of drainage on peat surface topography, rather than the influence of the vegetation itself. i.e. The surface of the bog is subject to microtopographic variation, rather than the vegetation growing on, however this aspect was not considered in this study. Tree cover rendered the LiDAR data unreliable and meant that only limited assessment of the data from Bolton Fell Moss was possible, however the inclusion of Bolton Fell Moss in the study did allow this limitation to be investigated.

8.4.5 To test the assertion that there are relationships between vegetation, hydrology and surface micro-topography and to determine if it is possible to use either LiDAR or ground based topographic data to predict early ecological change in lowland raised bogs before such change becomes a significant problem for site managers.

This study established that there was a relationship between surface micro-topography and hydrology. This relationship is strongest in areas of uninterrupted raised bog and is easily obscured by other factors, such as tree cover or artificial topographic features like ditch and baulk peat cutting. The study also established a weaker relationship between some species of vegetation and topography, and CCA suggested that it might in future be possible to predict vegetation community make up from topographic data, but only at the scale of whether or not an area is raised bog or other associated habitat. Remote sensing is useful in detecting larger scale variations in topographic variation, and to use this in differentiating between these broad habitat types, as observed by Anderson *et.al.*, (2009), but not fine scale variation. It can detect the presence or absence of M18 NVC community, but cannot detect changes in similarity within a large area of habitat with the broad characteristics of M18.

Therefore the study proves that microtopographic variation is useful in detecting areas of bog which have undergone a change in vegetation, but not ones in the early stages of change. More promisingly, the study has detected a relationship between hydrological condition and microtopographic variation. If, as many workers such as Gilvear (2000), Kennedy *et.al*, (2006) or Large et.al. (2007) suggest, that dry hydrological conditions lead to a degeneration of bog communities, the use of microtopographic variation to detect hydrological condition may prove of use, particularly if this methodology can be applied to blanket bog, which is often much larger and more remote, making intensive hydrological monitoring much more difficult (Holden *et.al*., 2006, Holden and Burt, 2003). These habitats are also less likely to be subject to the dramatic interventions of agricultural improvement and peat cutting.

8.5 Limitations of the study

This study has been undertaken on two specific sites, and has only established substantive relationships on one site. The studies applicability to other similar sites, though strongly indicated, should be undertaken with caution. It would appear from work at Bolton Fell Moss that the methodology is unsuited to sites with a strong anthropogenic element to their topography, in particular sites which have a history of peat cutting, or which have been invaded by trees. This limits its applicability to sites in lowland England as the overwhelming majority of these sites have been subject to intensive exploitation (Berry, 1997, JNCC, 1999). The data collected for this study are comprehensive, and the dipwell data have been summarised for this study. A study of annual variations of water level might reveal other patterns not revealed in this study because of this summarisation.

Similarly, the surface microtopography was only monitored once using each methodology. It would be possible with additional resources to repeat the dGPS study in future years to determine if there is a change in this topography over time. Given that this is a measure of a growing plant, absolute change is likely, but there has been no study to date in whether the index of variability used in this study would also change. As different species grow at different rates, a change in this topographic variability is also possible over time; it would be of interest to researchers in this field to see if a relationship between topographic variability and depth to water table is maintained, regardless of plant growth variability.

Commissioning a specific LiDAR overflight was beyond the resources of this study, so an existing dataset was used. Given that this was recorded in 2003, and the dGPS data were recorded in 2006/7, it is possible that change in microtopographic variation had already occurred in this time. It would therefore be informative to compare contemporaneous datasets. As the LiDAR resource held by the Environment Agency is renewed periodically, it would be possible to resurvey the dGPS plots at a similar time.

The issues of vegetation identification on the east transect have already been identified in Chapter 6, and although there appear to be other issues with the topographic data for Bolton Fell, it would be of interest to survey the lower plants on this transect.

8.6 Recommendations for further work

- **Further assessment of topography using annual dipwell data**

It would be of interest to determine if the 4 year mean depth to water table and the annual mean of the dipwells depths were similar, it would also be of interest to investigate if variation in dipwells has a role in determining vegetation community or topographic characteristics. It would be possible to investigate this with the data available, but was initially excluded from this study in order to focus on overall depth for the study period.

- **Further validation of LiDAR measured topography**

The LiDAR data as applied to the study has had promising, but ultimately inconclusive results. From the available data it is difficult to determine if this is as a consequence of difficulties with applying the data to the study or an inherent weakness in the relationship. Therefore it is recommended that further assessment of this data is undertaken by studying further topographic plots at both sites. Ideally a methodology to predict hydrological relationship should be worked towards. This was initially a goal of this study, but data resources and fieldwork opportunities prohibited this

- **Extension to other raised bogs**

This study has been limited to two specific sites in geographical proximity. It would be of great interest to test the relationship of topography to hydrology and ecological factors on other sites to determine its wider applicability in assessing ecological condition

- **Applicability to blanket bog**

It would appear from the limited data that this methodology is more suited to sites with no strong imposed structural element, such as drainage or peat digging. In such circumstances the microtopography becomes much harder to determine accurately. Conversely blanket bog areas, such as the Pennine moors or the Flow Country in Caithness, have similar topographic characteristics to Walton Moss, and given that such sites are very similar hydrologically to raised bog (Moore, 2002, Lindsay, 1995), this seems a promising line of research with greater applicability

- **Investigation of other methodologies for measuring topography**

Use of aerial photography was initially considered for this study, but discounted due to budget and time constraints. This methodology is not without merit, and could perhaps be used in conjunction with hydrological data as an alternative to topographic variation. Methodologies for differentiating vegetation types are becoming more precise (e.g. Chapman et.al, 2010) and it may potentially provide a cost effective alternative to LiDAR scanning. Terrestrial laser scanning has been used in related areas of mire topography research (Guarnieri, 2009), and without the necessity for an overflight may also prove to be a more convenient and versatile alternative

9 References

Alexander, P. D., Bragg, N. C., Meade, R., Padelopoulos and Watts5, O. (2008) Peat in horticulture and conservation: the UK response to a changing world *Mires and Peat*, **3**

Anderson, K., Bennie, J. J., Milton, E. J., Hughes, P. D. M., Lindsay, R. and Meade, R. (2009) Combining LiDAR and IKONOS Data for Eco-Hydrological Classification of an Ombrotrophic Peatland *Journal of Environmental Quality*, **39,** 260-273

Almquist-Jacobson, H and Foster D.R (1995) Toward an Integrated Model for Raised-Bog Development: Theory and Field Evidence, Ecology, **76**, 8. 2503-2516

Backeus, I (1988) Weather variables as predictors of *Sphagnum* growth on a bog Holarctic Ecology **11**, 146-150

Baird, A. J., Eades, P. A. and Surridge, B. W. J. (2008) The hydraulic structure of a raised bog and its implications for ecohydrological modelling of bog development *Ecohydrology*, **1,** 289-298

Baird, AJ & Sheila, MR (1992) Modelling transient water tables and soil moisture conditions in drained peats *in* **Peatland ecosystems and man: an impact assessment** Bragg, O M, Ingram, HAP and Robertson, RA (eds) Department of Biological Science, University of Dundee

Barbarella, M. and Gordini, C. (2006) Kinematic GPS survey as validation of LIDAR strips accuracy *Annals of Geophysics*, **49**, 21-33.

Barber, K. E., Chambers, F. M. and Maddy, D. (2003) Holocene palaeoclimates from peat stratigraphy: macrofossil proxy climate records from three oceanic raised bogs in England and Ireland *Quaternary Science Reviews*, **22,** 521-539

Barber, K. E. (1993) Peatlands as Scientific Archives of Past Biodiversity *Biodiversity and Conservation*, **2,** 474-489

Beals, E (1984) Bray-Curtis ordination: An effective strategy for analysis of multivariate data in **Advances in ecological research vol 14** (Ed. MacFayden,A) Academic Press, London

Belyea, L. R. and Clymo, R. S. (2001) Feedback control of the rate of peat formation *Proceedings of the Royal Society of London Series B-Biological Sciences*, **268**, 1315-1321

Belyea, L. R. and Warner, B. G. (1996) Temporal scale and the accumulation of peat in a Sphagnum bog *Canadian Journal of Botany-Revue Canadienne De Botanique*, **74,** 366-377

Berry, A. (1997) Conservation, culture and conflict: managing degraded mires *Peatland Ecology and Archaeology: Management of a Cultural Landscape*, **4,** 52-54

Berry , R.J., ed. (1988) *Biological* **survey: need and network** Linnean Society. London

Bigras, C. (1997) Kite aerial photography of the Axel Heiberg Island Fossil Forest **First North American Symposium on Small Format Aerial Photography,** 147-153

Bottrell, S., Coulson, J., Spence, M., Roworth, P., Novak, M. and Forbes, L. (2004) Impacts of pollutant loading, climate variability and site management on the surface water quality of a lowland raised bog, Thorne Moors, E. England, UK *Applied Geochemistry*, **19**, 413-422

Boumer, J Dekker, LW and Haans, JCFM (1980) Measurement of depth to water table in a heavy clay soil *Soil Science*, **130** 264-270

Bracken, F., McMahon, B. J. and Whelan, J. (2008) Breeding bird populations of Irish peatlands *Bird Study,* **55,** 169-178

Bragazza, L., Rydin, H. and Gerdol, R. (2005) Multiple gradients in mire vegetation: a comparison of a Swedish and an Italian bog *Plant Ecology*, **177**, 223-236

Breeuwer, A., Robroek, B. J. M., Limpens, J., Heijmans, M., Schouten, M. G. C. and Berendse, F. (2009) Decreased summer water table depth affects peatland vegetation *Basic and Applied Ecology,* **10,** 330-339.

Bridgham,S Ping, C Richardson,J & Updegraff,K (2001) Soils of Northern Peatlands: Histosols and Gelisols in **Wetland Soils** 343-370 ed. Richardson, J & Vepraskas, M Lewis Publishers London

Bullock, J Hodder, K Manchester, S & Stevenson, M (1996) **JNCC Report No. 261Review of information, policy and legislation on species translocation** JNCC Peterborough

ter Braak,C & Smilaur,P Canoco **Reference manual and CanoDraw for Windows user's guide: software for canonical community ordination v4.5** Microcomputer Power Ithaca USA
Bragazza, L., Rydin, H. and Gerdol, R. (2005) Multiple gradients in mire vegetation: a comparison of a Swedish and an Italian bog *Plant Ecology,* **177,** 223-236
Bragg, O. M. (2002) Hydrology of peat-forming wetlands in Scotland *The Science of The Total Environment,* **294,** 111-129

Bragg, O and Tallis J (2001) The sensitivity of peat-covered upland landscapes *Catena* **42**, 2-4, 345-360

Bray, JR & Curtis, JT (1957) An Ordination of the Upland Forest Communities of Southern Wisconsin. *Ecological Monographs* 27, **4**, 325-349

van Breemen, N. (1995) How *Sphagnum* bogs down other plants *Trends in Ecology & Evolution*, **10,** 270-275

Breeuwer, A., Robroek, B. J. M., Limpens, J., Heijmans, M. M. P. D., Schouten, M. G. C. and Berendse, F. (2009) Decreased summer water table depth affects peatland vegetation *Basic and Applied Ecology*, **10,** 330-339

Bromley, J., Robinson, M. and Barker, J. A. (2004) Scale-dependency of hydraulic conductivity: an example from Thorne Moor, a raised mire in South Yorkshire, UK *Hydrological Processes*, **18,** 973-985

Bromley, J & Robinson, M (1995) Groundwater in Raised Mire Systems: Models, Mounds and Myths in **Hydrology and hydrochemistry of British Waterways** ed Hughes,J and Heathwaite A

Brown, A.E., Bum, A.J., Hopkins, J.J. & Way, S.F. (1997). **The Habitats Directive: selection of Special Areas of Conservation in the UK. JNCC Report No. 270**, Peterborough

Carter, I (2002) **Railways and Culture in Britain: The Epitome of Modernity (Studies in Popular Culture)** Manchester University Press

Chambers, F. M., Mauquoy, D., Gent, A., Pearson, F., Daniell, J. R. G. and Jones, P. S. (2007) Palaeoecology of degraded blanket mire in South Wales: Data to inform conservation management *Biological Conservation*, **137,** 197-209

Chapman, D.S, Bonn, A, Kunin W, and Cornell S.J (2010) Random Forest characterization of upland vegetation and management burning from aerial imagery *Journal of Biogeography* **37**, 37–46

Chapman, S., Buttler, A., Francez, A.-J., Laggoun-Defarge, F., Vasander, H., Schloter, M., Combe, J., Grosvernier, P., Harms, H., Epron, D., Gilbert, D. and Mitchell, E. (2003) Exploitation of northern peatlands and biodiversity maintenance: a conflict between economy and ecology *Frontiers in Ecology and the Environment*, **1,** 525-532

Charman, DJ (2002) **Peatlands and environmental change** John Wiley & sons, England

Cherrill, A. and McClean, C. The reliability of Phase 1 habitat mapping in the UK: the extent and types of observer bias (1999) *Landscape and Urban Planning*, **45,** 131-143.

Chirino, C., Campeau, S. and Rochefort, L. (2006) *Sphagnum* establishment on bare peat: The importance of climatic variability and *Sphagnum* species richness *Applied Vegetation Science*, **9**, 285-294

Clancy John (1991) Site surveying and levelling, Butterworth-Heinemann, Oxford

Clymo, R. S. (2004) Hydraulic conductivity of peat at Ellergower Moss, Scotland *Hydrological Processes*, **18,** 261-274.

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

Cooper, A., McCann, T. P. and Hamill, B. (2001) Vegetation regeneration on blanket mire after mechanized peat-cutting *Global Ecology and Biogeography*, **10**, 275-289

Cooper, A. and McCann, T. (1995) Machine peat cutting and land use change on blanket bog in Northern Ireland *Journal of Environmental Management*, **43,** 153-170

Cosgrove, T (2004) **English Nature General Committee of Council Position Statement on Non-Aggregate Extraction and Nature Conservation** English Nature Peterborough

Cowenberg, J. and Joosten, H. (2005) Self-organization in raised bog patterning: the origin of microtope zonation and mesotope *diversity Journal of Ecology*, **93**, 1238 – 1248

Cracknell, A & Hayes, L (2007), **Introduction to Remote Sensing (2 ed.),** Taylor and Francis

Craft (2001) **Biology of Wetland Soils** in Wetland Soils ed Richardson,J & Vepraskas, M pp107-135 Lewis Publishers, London

Cruickshank, M., Tomlinson, R., Bond, D., Devine, P. and Edwards, C. (1995) Peat extraction, conservation and the rural economy in Northern Ireland *Applied Geography,* **15,** 365-383

Department for the environment, food and rural affairs (2008) **The Common Lands of Cumbria** Available at URL:<http://www.defra.gov.uk/wildlife-countryside/pdf/protected-areas/common-land/biosurvey-cumbria.pdf>

Devereux, B. J., Amable, G. S., Crow, P. and Cliff, A. D. (2005) The potential of airborne lidar for detection of archaeological features under woodland canopies *Antiquity,* **79,** 648-660

Domenico, P and Schwartz, R. W. (1997) **Physical and Chemical Hydrogeology**, **2nd Edition**, John Wiley and Sons Inc

Dumayne-Peaty, L & Barber, K (1998) Late Holocene vegetational history, human impact and pollen representivity variations in northern Cumbria, England *Journal of Quaternary Science*, **6**, 377-381

Mouchel Parkman Ewan (2007) **Hydrological and Condition Assessment of Lenzie Moss: Final report October 2007** East Dunbartonshire Council

Elkington, T Dayton,n Jackson, D & Strachan, I (2001) **National Vegetation Classification: Field guide to mires and heaths** JNCC Peterborough

Ellenberg, H. (1988) **Vegetation ecology of Central Europe, 4th edition**. Cambridge University Press

Enge, P. K. (1994) The Global Positioning System: Signals, measurements, and performance *International Journal of Wireless Information Networks*, **1,** 83-105.

Environment Agency, 1997, **Evaluation of the LiDAR technique to produce elevation data for use within the agency, National Centre for Environmental Data and Surveillance Report**, September 1997

European Union (1992) **Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora** European Council, Brussels

Evans, M. G., Burt, T. P., Holden, J. and Adamson, J. K. (1999) Runoff generation and water table fluctuations in blanket peat: evidence from UK data spanning the dry summer of 1995 *Journal of Hydrology*, **221,** 141-160.

Everson, D. A. and H. Boucher, D. (1998) Tree species-richness and topographic complexity along the riparian edge of the Potomac River *Forest Ecology and Management*, **109,** 305-314

Farrick, K. K. and Price, J. S. (2009) Ericaceous shrubs on abandoned block-cut peatlands: Implications for soil water availability and *Sphagnum* restoration *Ecohydrology*, **2,** 530-540

Fitts, W (2005) Precision GPS Surveying at Medieval Cottam, East Yorkshire, England *Journal of Field Archaeology*, **30**, 2, 181-190

Fraser, C. J. D., Roulet, N. T. and Lafleur, M. (2001) Groundwater flow patterns in a large peatland *Journal of Hydrology*, **246**, 142-154

Grazing Animals Project (2001) **A Guide to Animal Welfare in Nature Conservation Grazing** Natural England, Peterborough

Gebauer, R. L. E., Reynolds, J. F. and Tenhunen, J. D. (1995) Growth and allocation of the arctic sedges *Eriophorum angustifolium* and *E. vaginatum*: effects of variable soil oxygen and nutrient availability *Oecologia*, **104,** 330-339

Gilvear, D. J. and Bradley, C. (2000) Hydrological monitoring and surveillance for wetland conservation and management; a UK perspective *Physics and Chemistry of the Earth Part B-Hydrology Oceans and Atmosphere*, **25,** 571-588

Graniero, P. A. and Price, J. S. (1999) The importance of topographic factors on the distribution of bog and heath in a Newfoundland blanket bog complex *Catena*, **36**, 233-254

Guarnieri, A., Vettore, A., Pirotti, F., Menenti, M. and Marani, M. (2009) Retrieval of small-relief marsh morphology from Terrestrial Laser Scanner, optimal spatial filtering, and laser return intensity *Geomorphology*, **113,** 12-20.

Guinan, L O'Connor, A O'Connor, M Sheehy-Skeffington,M (1998) Small scale vegetation patterns on a raised bog, Co. Offaly and an atlantic bog, CO. Galloway, Ireland in **Patterned Mires and Mire Pools: Proceedings of the Durham Conference of the Mires Research Group** British Ecological Society

Hach Environmental (2009) **Orpheus Mini Groundwater Pressure & Temperature Sensor with Integrated Logger** Available at URL:<http://www.hydrolab.com/news/orpheus.asp> [Accessed 2 February, 2010)

Harris, A., Bryant, R. G. and Baird, A. J. (2006) Mapping the effects of water stress on Sphagnum: Preliminary observations using airborne remote sensing *Remote Sensing of Environment*, **100,** 363-378.

Heathwaite, A. L. (1994) Hydrological management of a cutover peatland *Hydrological Processes*, **8,** 245-262.

Higgitt, D. L. and Warburton, J. (1999) Applications of differential GPS in upland fluvial geomorphology *Geomorphology*, **29,** 121-134.

Hill, D Fasham, F Tucker, G Shewry, M Shaw P (2005) **Handbook of Biodiversity Methods** Cambridge University Press

Hill, R. A. and Thomson, A. G. (2005) Mapping woodland species composition and structure using airborne spectral and LiDAR data *International Journal of Remote Sensing*, **26,** 3763-3779

Hill, M Hodgetts, N and Payne, A (2002) **Sphagnum: A Field Guide** JNCC Peterborough

Hill, M Roy, D Mountford, O and Bunce, R (2000) Extending Ellenberg's Indicator Values to a New Area: An Algorithmic Approach *Journal of Applied Ecology*, **37**, 1 , pp. 3-15

Holden, J., Evans, M. G., Burt, T. P. and Horton, M. (2006) Impact of land drainage on peatland hydrology *Journal of Environmental Quality*, **35,** 1764-1778

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

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

Hopkinson, C., Chasmer, L. E., Sass, G., Creed, I. F., Sitar, M., Kalbfleisch, W. and Treitz, P. (2005) Vegetation class dependent errors in lidar ground elevation and canopy height estimates in a boreal wetland environment *Canadian Journal of Remote Sensing*, **31**, 191-206

Hughes, P. D. M., Mauquoy, D., Barber, K. E. and Langdon, P. G. (2000) Mire-development pathways and palaeoclimatic records from a full Holocene peat archive at Walton Moss, Cumbria, England *Holocene*, **10,** 465-479

Hughes, P. D. M. and Barber, K. E. (2004) Contrasting pathways to ombrotrophy in three raised bogs from Ireland and Cumbria, England *Holocene*, **14,** 65-77

Ingram, H. A. P. (1982) Size and Shape in Raised Mire Ecosystems - a Geophysical Model *Nature*, **297,** 300-303

Ingram, H.A.P. (1967) Problems of hydrology and plant distribution in mires. *Journal of Ecology*, **55**, 711–724

Ivanov, K.E., **1981**. *Water Movement in Mirelands*. Translated by Thomson, A. and Ingram, H.A.P. Academic Press, London

Joint Nature Conservation Committee (2009) **Protected sites** Available at: URL< http://www.jncc.gov.uk/page-4> [Accessed 01 March 2009]

JNCC (2008) **South Solway mosses** Available at URL <http://www.jncc.gov.uk/protectedsites/SACselection/sac.asp?EUCode=UK0030310> [accessed at 01 March 2009]

Joint Nature Conservation Committee (2006) **SACs in the United Kingdom** HMSO Available at <http://www.jncc.gov.uk/page-1458> [accessed at December 20 2008]

Joint Nature Conservation Committee (2003) **NATURA 2000 STANDARD DATA FORM,** JNCC Peterborough

Joint Nature Conservation Council (1999), **UK Biodiversity Action Plan for Raised Bogs in UK Biodiversity Group Tranche 2 Action Plans - Volume VI: Terrestrial and freshwater species and habitats**, JNCC Peterborough

Joosten, J. H. J. (1985) A 130 year micro- and macrofossil record from regeneration peat in former peasant peat pits in the peel, the Netherlands: A palaeoecological study with agricultural and climatological implications *Palaeogeography, Palaeoclimatology, Palaeoecology,* **49,** 277-312

Kechavarzi, C., Dawson, Q., Leeds-Harrison, P. B., SzatyLowicz, J. and Gnatowski, T (2007). Water-table management in lowland UK peat soils and its potential impact on CO2 emission Soil Use & Management. **23,** 4, 359-367

Kennedy, M. P., Murphy, K. J. and Gilvear, D. J. (2006) Predicting interactions between wetland vegetation and the soil-water and surface-water environment using diversity, abundance and attribute values *Hydrobiologia,* **570,** 189-196.

Kettridge, N., Comas, X., Baird, A., Slater, L., Strack, M., Thompson, D., Jol, H. and Binley, A. (2008) Ecohydrologically important subsurface structures in peatlands revealed by ground-penetrating radar and complex conductivity surveys *Journal of Geophysical Research-Biogeosciences,* **113.**

Kirkby, M.J., P.E. Kneale, S.L. Lewis and R.T. Smith, (1995) Modelling the form and distribution of peat mires in **Hydrology and hydrochemistry of British Wetlands** Ed. J.M.R. Hughes & A.L. Heathwaite, 83-94, John Wiley

Leica Geosystems (2008) **GPS Basics – Introduction to GPS** Leica Geosystems, Switzerland

Labadz,J & Butcher,D (2006) **Peatland Hydrology Research Contract no. JB130 Report to English Nature** Nottingham Trent University

Labadz, J Butcher, D, Norris, J (2006) **Definition of hydrological protection zones at the margins of the south Solway mosses Environment Agency Contract ref 15088** Nottingham Trent University / Environment Agency

Labadz, J Butcher, D, Sinnott, D (2002) Wetlands and Still Waters in **Handbook of Ecological Restoration, volume1** ed. Perrow,M & Davey,A 106-132 Cambridge University Press

Laitinen, J., Rehell, S. and Oksanen, J. (2008) Community and species responses to water level fluctuations with reference to soil layers in different habitats of mid-boreal mire complexes *Plant Ecology*, **194,** 17-36

Lane, S. N., James, T. D. and Crowell, M. D. (2000) Application of digital photogrammetry to complex topography for geomorphological research *Photogrammetric Record*, **16,** 793-821.

Large, A. R. G., Mayes, W. M., Newson, M. D. and Parkin, G. (2007) Using long-term monitoring of fen hydrology and vegetation to underpin wetland restoration strategies *Applied Vegetation Science*, **10,** 417-428

Large, A. R. G. (2001) Reversing Spontaneous Succession to Protect High-Value Vegetation: Assessment of Two Scottish Mires Using Rapid Survey Techniques *Applied Vegetation Science*, **4**, 103-110

Lavoie, C., Grosvernier, P., Girard, M. and Marcoux, K. (2003) Spontaneous revegetation of mined peatlands: An useful restoration tool? *Wetlands Ecology and Management*, **11**, 97-107

Leps,J and Smilauer,P (2003) **Multivariate analysis of ecological data using CANOCO** Cambridge University Press

Leps,J & Hadincova,V (1992) How reliable are our vegetation analyses? *Journal of Vegetation Science* **3**: 119-124

Lindsay R and Immiriz, P (1996**) An inventory of lowland raised bogs in Great Britain: Scottish National Heritage Research Report no 78** SNH Edinburgh

Lindsay, R (1995) Bogs: **The Ecology, Classification and Conservation of Ombrotrophic Mires** Scottish Natural Heritage, Perth

Litaor, M. I., Eshel, G., Sade, R., Rimmer, A. and Shenker, M. (2008) Hydrogeological characterization of an altered wetland *Journal of Hydrology*, **349,** 333-349.

Malmer, N., Albinsson, C., Svensson, B. M. and Wallen, B. (2003) Interferences between *Sphagnum* and vascular plants: effects on plant community structure and peat formation *Oikos*, **100,** 469-482

Malmer, N., Svensson, B. M. and Wallén, B. (1994) Interactions between Sphagnum mosses and field layer vascular plants in the development of peat-forming systems *Folia Geobotanica*, **29**, 1874-9348

McAleece, N P.J.D. Lambshead, P.J.D and Paterson, G.L.J (1997) **Biodiversity Pro** The Natural History Museum, London

McLeod, CR, Yeo, M, Brown, AE, Burn, AJ, Hopkins, JJ, & Way, SF (eds.) (2005) **The Habitats Directive: selection of Special Areas of**

Conservation in the UK. 2nd edn. Joint Nature Conservation Committee, Peterborough

McMullen, J. A., Barber, K. E. and Johnson, B. (2004) A paleoecological perspective of vegetation succession on raised bog microforms *Ecological Monographs*, **74,** 45-77

Meade, R. (1992) Some early changes following the rewitting of a vegetated cutover peatland surface at Danes Moss, Cheshire, UK, and their relevance to conservation management *Biological Conservation*, **61**, 31-40

Mehner, H., Cutler, M., Fairbairn, D. and Thompson, G. (2004) Remote sensing of upland vegetation: the potential of high spatial resolution satellite sensors *Global Ecology and Biogeography*, **13,** 359-369

Met Office (2009) **Newton Rigg station data 1961- 2009** Met Office London

Met Office (2008) **Carlisle station data** 1961 – 2007 Met Office, London

Met Office (20007) **News Release: Record-breaking rainfall figures** Available at URL:<http://www.metoffice.gov.uk/corporate/pressoffice/2007/pr20070726.html> [Accessed 1 December 2008]

Mitchley, J., Burch, J. and Lawson, C., 1998. **Habitat restoration project: development of monitoring guidelines**. English Nature Research Reports, No. 284 Natural England, Perborough

Money, R. and Wheeler , D. (1999) Some Critical Questions concerning the Restorability of Damaged Raised Bogs *Applied Vegetation Science*, **2**, 107-116

Money, R. and Wheeler , D. (1996) **English Nature Research Report 179: Prioritisation of Lowland Peat Programme Resources** Natural England, Peterborough

Moore, P. D. (2002) The future of cool temperate bogs *Environmental Conservation*, **29**, 3-20

Montanarella, L., Jones R.J.A. and Hiederer, R. (2006): The distribution of peatland in Europe. *Mires and Peat* **1,** 1-10

Monteiro, L, Moore, T. and Hill, C. (2005) What is the accuracy of DGPS? *Journal of Navigation*, **58,** 207-225.

Moore, P. D. (1995) Biological processes controlling the development of modern peat-forming ecosystems *International Journal of Coal Geology*, **28,** 99-110

Moore, P. D. (1989) The ecology of peat-forming processes: a review *International Journal of Coal Geology*, **12,** 89-103.

Morgan-Jones, W. Poole, J.S, Goodall, R (2005) **Report 365: Characterisation of Hydrological Protection Zones at the Margins of Designated Lowland Raised Peat Bog Sites** JNCC Peterborough

Morris,P & Therivel, R (2001) **Methods of Environmental Impact Assessment** (2nd Edition) Spon Press, London

Natural England (2009) **Wedholme Flow SSSI, part of the South Solway Mosses SAC and NNR** Available at: URL<http://www.naturalengland.org.uk/regions/north_west/sone/sonewedholmeflow.aspx> [accessed 01 March 2009]

Natural England (2008_1) **SSSI condition assessment -A guide for owners and occupiers** Natural England, Peterborough

Natural England (2008_2) **Sites of Special Scientific Interest (SSSIs)** Natural England, Peterborough

Natural England (2004) **Agreement between The Scotts Company (UK) Limited and English Nature relating to property at Hatfield Moor, South Yorkshire, Thorne Moor, North Humberside and Wedholme Flow, Cumbria** Natural England, Peterborough

Natural England (2002) **Walton Moss SSSI Condition Assessment** Available at: URL:<http:// www.english- nature.org.uk/Special/sssi /unit_details.cfm?situnt_id=1010614> [accessed 1 may 2009]

Natural England (2001) **Bolton Fell Moss SSSI citation** Natural England, Peterborough

Natural England (1986) **Wedholme Flow SSSI citation** Natural England Peterborough

Natural England (1985) **Walton Moss SSSI citation** Natural England, Peterborough

Natural England (1994) **Monitoring Raised Bogs Workshop Report** Natural England Peterborough

Natural England (undated) **Historical office and file records for Bolton Fell and Walton Mosses**. Unpublished, NE Kendal Office

Nungesser, M. K. (2003) Modelling microtopography in boreal peatlands: hummocks and hollows *Ecological Modelling*, **165**, 175-207

Ortu, E., David, F. and Caramiello, R. (2003) Man's role in the vegetation history in the Ellero Valley (Maritime Alps, Italy) *Comptes Rendus Biologies*, **326**, 631-637

O'Brien, H Labadz, J Butcher, D (2008) **The role of blanket peat moorland management in the generation and amelioration of discolouration of surface water supplies: Final report to Severn Trent Water, National Trust and Natural England**. Nottingham Trent University

O'Brien, H Labadz, J Woods,M Butcher,D (2003) Upland catchment management and discolouration of water supplies **British Hydrological Society occasional paper 1**

Oliver, I. and Beattie, A. J. (1996) Designing a cost-effective invertebrate survey: A test of methods for rapid assessment of biodiversity *Ecological Applications*, **6,** 594-607

OTT Hydrometry (2008) **Thalimedes shaft encoder** available at: URL:<http://www.otthydrometry.de/web/ott_uk.nsf/id/pa_thalimedesog_e.html> [accessed 20 December 2008]

Palejs, M. (2006) The impact of drainage and peat extraction on hydrology in Palsu bog **Assessing of Soil and Water Conditions in Forests,** 111-122

Paulauskas, V. and Ginters, E. (2006) Investigations on limited visibility of the GPS satellites **Transport Means 2006, Proceedings,** 200-203.

Pellerin, S., Huot, J. and Cote, S. D. (2006) Long-term effects of deer browsing and trampling on the vegetation of peatlands *Biological Conservation*, **128,** 316-326

Phillips, M Studies in the Quantitative Morphology and Ecology of Eriophorum Angustifolium 1953 *Journal of Ecology*, **41**, 2, pp. 295-318

Price, J. S. and Whitehead, G. S. (2004) The influence of past and present hydrological conditions on *Sphagnum* recolonization and succession in a block-cut bog, Quebec *Hydrological Processes*, **18,** 315-328

Quinn,G and Keough,M **(2002) Experimental Design and Data Analysis for Biologist** Cambridge University Press

Raber, G. T., Jensen, J. R., Schill, S. R. and Schuckman, K. (2002) Creation of digital terrain models using an adaptive lidar vegetation point removal process *Photogrammetric Engineering and Remote Sensing,* **68,** 1307-1315.

Rackham, O (2006) **New Naturalist 100: Woodlands** Collins, London

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

Ramsar Convention Secretariat (2009) **Information Sheet on Ramsar Wetlands 2009-2012** Ramsar Convention Secretariat Gland, Switzerland

Rich, T Peterken, G Tucker, F McMeechan, F & Dobson, D (2005) Habitat requirements and issues in **Handbook of Biodiversity method**s ed. Hill,D Fasham, M Tucker, G Shewry, M and Shaw, P Cambridge University Press

Robichaud, A. and Bégin, Y. (2009) Development of a raised bog over 9000 years in Atlantic Canada *Mires and Peat*, **5**, 1-19

Robroek, B. J. M., Limpens, J., Breeuwer, A. and Schouten, M. G. C. (2007) Effects of water level and temperature on performance of four Sphagnum mosses *Plant Ecology,* **190,** 97-107

Rochefort, L., R. Gauthier, and D. Lequéré. 1995. *Sphagnum* regeneration–Toward an optimisation of bog restoration. pp. 423–434. In B.D. Wheeler, S.C. Shaw, W.J. Fojt, R.A. Robertson (eds.). **Restoration of Temperate Wetlands**. John Wiley and Son, Chichester, UK

Rockall, E., Milton, E.J. and Anderson, K. (2008) The potential of land cover classification techniques for conservation of Wedholme Flow, a lowland raised peat bog in Cumbria. In **Proceedings of the Remote Sensing and Photogrammetry Society Conference: "Measuring Change in the Earth System".** University of Exeter, 15-17 September 2008

Rodwell, J.S., Dring, J.C., Averis, A.B.G., Proctor, M.C.F., Malloch, A.J.C., Schaminée, J.N.J. & Dargie, T.C.D. (2000)***.Review of coverage of the National Vegetation Classification.*** **Joint Nature Conservation Committee *Report* No. 302**. JNCC Peterborough

Rodwell, JS (2006) **National Vegetation Classification: Users Handbook** JNCC Peterborough

Rodwell, JS (ed.) (1991) **British Plant Communities Volume 2: Mires and Heaths** Cambridge University Press

Royal Society for the Protection of Birds (2008) **Campfield Marsh** Available at URL:< http://www.rspb.org. uk/ reserves/guide/c/campfieldmarsh /about.asp> [accessed at 03 March 2009]

Runhaar, J., van Gool, C. R. and Groen, C. L. G. (1996) Impact of hydrological changes on nature conservation areas in The Netherlands *Biological Conservation*, **76,** 269-276.

Ruseckas, J. and Grigaliunas, V. (2008) Effect of Drain-Blocking and Meteorological Factors on Groundwater Table Fluctuations in Kamanos Mire *Journal of Environmental Engineering and Landscape Management*, **16,** 168-177

Rycroft, D.W., Williams, D.J.A. and Ingram, H.A.P., 1975. The transmission of water through peat: I. Review. *Journal of Ecology* **63**, pp. 535–556

Scott, A. G., Oxford, G. S. and Selden, P. A. (2006) Epigeic spiders as ecological indicators of conservation value for peat *Biological Conservation*, **127,** 420-428

Scott, W. A. and Hallam, C. J. (2003) Assessing species misidentification rates through quality assurance of vegetation monitoring *Plant Ecology*, **165,** 101-115

Scottish Government (2009) **Scottish Rural Development Programme: Management / restoration of lowland raised bogs** Available at: <URL: http://www.scotland.gov.uk/Topics/Rural/SRDP /RuralPriorities/ Packages/SustainableFloodManagem/Managementoflowlandraised> [Accessed 1 May 2009]

Scottish Natural Heritage (2003) **Scotlands Living Landscapes: Boglands** SNH, Perth

Segerstrom, U. and Emanuelsson, M. (2002) Extensive forest grazing and hay-making on mires - vegetation changes in south-central Sweden due to land use since Medieval times *Vegetation History and Archaeobotany*, **11,** 181-190

Swanson, D (2007) Interaction of mire microtopography, water supply, and peat accumulation in boreal mires *Suo (Helsinki*). **58(2),** 37-47

van Seters, T. E. and Price, J. S. (2002) Towards a conceptual model of hydrological change on an abandoned cutover bog, Quebec *Hydrological Processes*, **16,** 1965-19

van der Schaaf (2002) Bog Hydrology in **Conservation and restoration of raised bogs** ed. Schouten, M Duchas, Dublin

Schouten, M Streefkerk, J van der Schaaf, S and Ryan, J (2002) General conclusions: Implications for management and restoration in **Conservation and restoration of raised bogs** (ed Schouten, M) Duchas, Dublin

Shaw, S. and Wheeler, B. (1995) **Monitoring rehabilitation work on lowland peatlands**, English Nature

Shaw,G and Wheeler,D (1984) **Statistical Techniques in Geographical Analysis** Whiley

Smart, P. J., Wheeler, B. D. and Willis, A. J. (1986) Plants and Peat Cuttings: Historical Ecology of a Much Exploited Peatland- Thorne Waste, Yorkshire, UK *New Phytologist*, **104,** 731-748

Smart, S (2000) **Modular Analysis of Vegetation Information System** Centre for Ecology and hydrology, Lancaster

Smith, R. S., Lunn, A. G. and Newson, M. D. (1995) The Border Mires in Kielder Forest: A review of their ecology and conservation management *Forest Ecology and Management* , **79,** 47-61

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

Solinst (2010) **Water level meter** Available at URL:<http://www.solinst.com/Prod/Data/Water_Level_Meters.html> [Accessed 02 February 2010]

Soro, A., Sundberg, S. and Hakan, R. (1999) Species diversity, niche metrics and species associations in harvested and undisturbed bogs *Journal of Vegetation Science*, **10**, 549-560

Stoneman, R Parkyn, L & Ingram, HAP (ed) (1997) **Conserving Peatlands** CABI international, Oxford

Swanson, (2008) Digital camera-pole photography: a useful research tool for outcrop scale geologic mapping *Geological Society of America Abstracts with Programs*, **40**, 2, 71

Swanson, DK (2007) Interaction of mire microtopography, water supply, and peat accumulation in boreal mires *Suo (Helsinki).* **58(2),** 37-47,

Tantram, D, Dargie, T, Dargie, M (1999**) English Nature Research Report 365 Nailing the Paradox: demonstrating favourable condition on damaged raised bogs** English Nature Peterborough

Tiemeyer, B., Lennartz, B. and Vegelin, K. (2006) Hydrological modelling of a re-wetted peatland on the basis of a limited dataset for water management *Journal of Hydrology*, **325**, 376-389

Tomassen, H. B. M., Smolders, A. J. P., Lamers, L. P. M. and Roelofs, J. G. M. (2003) Stimulated growth of *Betula pubescens* and *Molinia caerulea* on ombrotrophic bogs: role of high levels of atmospheric nitrogen deposition *Journal of Ecology*, **91**, 357-370

Tucker, G Willis, K & Doyle, P (2004) **Cost Effectiveness Study of Approaches for Delivery of PSA Target Relating to SSSIs** Defra London

Turner, C (2006) Bolton Fell Moss site manager for William Sinclair Holdings personal communication

UKCP09 (2009) **UK Climate Change Projections** Defra London

Vandervalk, A. G., Squires, L. and Welling, C. H. (1994) Assessing the Impacts of an Increase in Water-Level on Wetland Vegetation *Ecological Applications*, **4,** 525-534

Vilibi,I Orli,M, Upi,S, Domijan, N Leder,N Mihanovi,H, Pasari,M, Pasari,Z, Srdeli,M Strini,G (2005) A new approach to sea level observations in Croatia *Geofizika* **22**

Warburton, J., Holden, J. and Mills, A. J. (2004) Hydrological controls of surficial mass movements in peat *Earth-Science Reviews*, **67,** 139-156

Watson,E (1981) **British Mosses and Liverworts** Cambridge University Press

Weltzin, J. F., Harth, C., Bridgham, S. D., Pastor, J. and Vonderharr, M. (2001) Production and microtopography of bog bryophytes: response to warming and water-table manipulations *Oecologia*, **128**, 557-565

Wheeler, B.D. & Shaw, S.C. 1995. **Restoration of damaged peatlands with particular reference to lowland raised bogs affected by peat extraction**. DoE, London

Whickman, FE (1951) The maximum height of raised bogs and a note on the motion of water in soligenous mires. Geologiska Foreningens I Stockholm Forhandlingar, **73**, 413-422

Wilkie, N. M. and Mayhew, P. W. (2003) The management and restoration of damaged blanket bog in the north of *Scotland Botanical Journal of Scotland*, **55**, 125 - 133

William Sinclair Holdings (2009) **Press Release: Update regarding compensation at the Company's Bolton Fell facility** Lincoln

Williams, J.M., ed. (2006). **Common Standards Monitoring for Designated Sites: First Six Year Report.** Peterborough, JNCC

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

Worrall, F., Burt, T., Adamson, J., Reed, M., Warburton, J., Armstrong, A. and Evans, M. (2007_b) Predicting the future carbon budget of an upland peat catchment *Climatic Change*, **85,** 139-158

Wyatt, B.K. (1992). Resources for documenting changes in species and habitats. In **Biological recording of changes in British wildlife** ed P.T. Harding, 20-26. HMSO, London

Xharde, R., Long, B. F. and Forbes, D. L. (2006) Accuracy and Limitations of Airborne LiDAR Surveys in Coastal Environments *Ieee International Geoscience and Remote Sensing Symposium*, ***1-8*****,** 2412-2415

Yazaki, T., Urano, S. and Yabe, K. (2006) Water balance and water movement in unsaturated zones of *Sphagnum* hummocks in Fuhrengawa Mire, Hokkaido, Japan *Journal of Hydrology*, **319,** 312-327

Yeloff, D.; Bennett, K.; Blaauw, M.; Chambers, F.; van Geel, B.; van der Linden, M.; Mauquoy, D.; van der Plicht, J.; Sillasoo, Ü.; Toms, P.; Newberry, J.; Brain, S. 2006 High Precision Dating of Holocene Peat Deposits American Geophysical Union, **Fall Meeting 2006**, PP54-05

Yu, Z., Campbell, I. D., Vitt, D. H. and Apps, M. J. (2001) Modelling long-term peatland dynamics. I. Concepts, review, and proposed design *Ecological Modelling*, **145,** 197-210

Zheng, J. Y., Wang, Y. H. and Nihan, N. L. (2005) Quantitative evaluation of GPS perfonnance under forest canopies **IEEE Networking, Sensing and Control Proceedings,** 777-782

Appendix 1 Rainfall series for Bolton Fell Moss

Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)
01/10/2003	0.00	30/11/2003	9.40	29/01/2004	0.4
02/10/2003	0.00	01/12/2003	2.60	30/01/2004	20.2
03/10/2003		02/12/2003	1.50	31/01/2004	30.4
04/10/2003		03/12/2003	0.00	01/02/2004	23.6
05/10/2003	3.40	04/12/2003	0.00	02/02/2004	8.4
06/10/2003	1.80	05/12/2003		03/02/2004	21.8
07/10/2003		06/12/2003		04/02/2004	8.2
08/10/2003	1.20	07/12/2003	0.00	05/02/2004	7.2
09/10/2003	2.20	08/12/2003	0.00	06/02/2004	0
10/10/2003		09/12/2003	0.00	07/02/2004	3.2
11/10/2003		10/12/2003	0.00	08/02/2004	6.4
12/10/2003	0.70	11/12/2003	0.00	09/02/2004	0.2
13/10/2003	0.00	12/12/2003		10/02/2004	1.6
14/10/2003	0.00	13/12/2003		11/02/2004	0
15/10/2003	0.00	14/12/2003		12/02/2004	0.2
16/10/2003	0.00	15/12/2003		13/02/2004	1.8
17/10/2003		16/12/2003		14/02/2004	0.2
18/10/2003		17/12/2003	1.2	15/02/2004	0
19/10/2003		18/12/2003	0	16/02/2004	3.8
20/10/2003		19/12/2003	1.2	17/02/2004	2.2
21/10/2003		20/12/2003	18.6	18/02/2004	0.2
22/10/2003		21/12/2003	2	19/02/2004	0
23/10/2003		22/12/2003	3.2	20/02/2004	0
24/10/2003		23/12/2003	5.2	21/02/2004	0
25/10/2003		24/12/2003	0.2	22/02/2004	0
26/10/2003	5.40	25/12/2003	7.2	23/02/2004	0
27/10/2003	0.80	26/12/2003	34	24/02/2004	3.2
28/10/2003	3.00	27/12/2003	0	25/02/2004	0.4
29/10/2003	0.00	28/12/2003	0.2	26/02/2004	0
30/10/2003	0.00	29/12/2003	0.2	27/02/2004	0.4
31/10/2003		30/12/2003	0	28/02/2004	0
01/11/2003		31/12/2003	5.4	29/02/2004	0
02/11/2003	15.60	01/01/2004	2	01/03/2004	0.2
03/11/2003	0.40	02/01/2004	0.2	02/03/2004	0
04/11/2003	0.00	03/01/2004	1	03/03/2004	5.4
05/11/2003	0.00	04/01/2004	1.4	04/03/2004	1.6
06/11/2003	0.00	05/01/2004	3	05/03/2004	1.4
07/11/2003		06/01/2004	2.8	06/03/2004	0.6
08/11/2003		07/01/2004	0.4	07/03/2004	0.8
09/11/2003	3.00	08/01/2004	7	08/03/2004	0
10/11/2003	5.00	09/01/2004	0.6	09/03/2004	0
11/11/2003	3.00	10/01/2004	0.4	10/03/2004	0
12/11/2003	5.00	11/01/2004	8.2	11/03/2004	0.2
13/11/2003	4.00	12/01/2004	1.6	12/03/2004	0
14/11/2003		13/01/2004	6	13/03/2004	0.4

Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)
15/11/2003		14/01/2004	1.8	14/03/2004	14.4
16/11/2003	2.30	15/01/2004	11.4	15/03/2004	8.8
17/11/2003	3.80	16/01/2004	0.8	16/03/2004	2.8
18/11/2003	1.20	17/01/2004	0.8	17/03/2004	0
19/11/2003	8.80	18/01/2004	2.4	18/03/2004	3.4
20/11/2003	6.00	19/01/2004	1.2	19/03/2004	4.8
21/11/2003		20/01/2004	4.4	20/03/2004	13
22/11/2003		21/01/2004	0.2	21/03/2004	4
23/11/2003	1.40	22/01/2004	11.6	22/03/2004	1.4
24/11/2003	8.40	23/01/2004	10.8	23/03/2004	0.2
25/11/2003		24/01/2004	0.6	24/03/2004	0
26/11/2003	14.10	25/01/2004	0.2	25/03/2004	0.6
27/11/2003	1.70	26/01/2004	0.2	26/03/2004	1
28/11/2003	6.40	27/01/2004	0.2	27/03/2004	1.6
29/11/2003		28/01/2004	0.2	28/03/2004	0.8
29/03/2004	0.2	28/05/2004	3.2	27/07/2004	0
30/03/2004	0	29/05/2004	5	28/07/2004	0.2
31/03/2004	0	30/05/2004	0.2	29/07/2004	3
01/04/2004	0.6	31/05/2004	2	30/07/2004	0
02/04/2004	5.8	01/06/2004	7	31/07/2004	0
03/04/2004	3.8	02/06/2004	0	01/08/2004	0
04/04/2004	1.2	03/06/2004	12.6	02/08/2004	0.2
05/04/2004	2.2	04/06/2004	0.4	03/08/2004	23.4
06/04/2004	2.4	05/06/2004	0.2	04/08/2004	9.6
07/04/2004	0.4	06/06/2004	0.2	05/08/2004	5.8
08/04/2004	0	07/06/2004	0	06/08/2004	2
09/04/2004	3.6	08/06/2004	0	07/08/2004	0
10/04/2004	0.8	09/06/2004	0	08/08/2004	0.4
11/04/2004	0	10/06/2004	1.8	09/08/2004	27.8
12/04/2004	0.2	11/06/2004	2	10/08/2004	42.8
13/04/2004	1.2	12/06/2004	0	11/08/2004	3.6
14/04/2004	1	13/06/2004	0.2	12/08/2004	11.6
15/04/2004	2.8	14/06/2004	0	13/08/2004	9.8
16/04/2004	0	15/06/2004	0.6	14/08/2004	0
17/04/2004	2.6	16/06/2004	0.6	15/08/2004	1.6
18/04/2004	12	17/06/2004	2.2	16/08/2004	15
19/04/2004	2.4	18/06/2004	7.8	17/08/2004	3
20/04/2004	0.2	19/06/2004	1.2	18/08/2004	4.6
21/04/2004	0.4	20/06/2004	4.6	19/08/2004	20.8
22/04/2004	0.6	21/06/2004	0	20/08/2004	0.4
23/04/2004	0	22/06/2004	0.2	21/08/2004	0
24/04/2004	0	23/06/2004	12.2	22/08/2004	0
25/04/2004	0	24/06/2004	15.4	23/08/2004	3
26/04/2004	0	25/06/2004	0	24/08/2004	3.6
27/04/2004	3.2	26/06/2004	7.6	25/08/2004	0
28/04/2004	1	27/06/2004	0.4	26/08/2004	9.6
29/04/2004	0	28/06/2004	2	27/08/2004	1

Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)
30/04/2004	0	29/06/2004	0.4	28/08/2004	0.2
01/05/2004	0	30/06/2004	16.2	29/08/2004	4.4
02/05/2004	0	01/07/2004	0.6	30/08/2004	0
03/05/2004	5.4	02/07/2004	4.6	31/08/2004	0
04/05/2004	15.8	03/07/2004	17.8	01/09/2004	0.2
05/05/2004	17.2	04/07/2004	13.4	02/09/2004	0
06/05/2004	0	05/07/2004	0.6	03/09/2004	0
07/05/2004	2.6	06/07/2004	1.2	04/09/2004	0.8
08/05/2004	2.2	07/07/2004	0	05/09/2004	0
09/05/2004	0.8	08/07/2004	0.4	06/09/2004	5
10/05/2004	4.4	09/07/2004	0.2	07/09/2004	0
11/05/2004	0	10/07/2004	0.6	08/09/2004	0.4
12/05/2004	0	11/07/2004	0	09/09/2004	0.2
13/05/2004	0	12/07/2004	1	10/09/2004	3.8
14/05/2004	0.4	13/07/2004	1	11/09/2004	5.6
15/05/2004	0	14/07/2004	2	12/09/2004	6.8
16/05/2004	0	15/07/2004	0	13/09/2004	2.4
17/05/2004	0	16/07/2004	0.2	14/09/2004	15.6
18/05/2004	0	17/07/2004	6.4	15/09/2004	0.2
19/05/2004	0	18/07/2004	0	16/09/2004	14.6
20/05/2004	0.2	19/07/2004	2.8	17/09/2004	0.2
21/05/2004	0.2	20/07/2004	10.6	18/09/2004	11
22/05/2004	0.2	21/07/2004	0.8	19/09/2004	7.8
23/05/2004	0	22/07/2004	4.4	20/09/2004	6.8
24/05/2004	0	23/07/2004	0.2	21/09/2004	4.2
25/05/2004	0	24/07/2004	1.8	22/09/2004	3.4
26/05/2004	0	25/07/2004	9.4	23/09/2004	1.4
27/05/2004	0	26/07/2004	0.2	24/09/2004	0.2
25/09/2004	2	24/11/2004	1.6	23/01/2005	0.2
26/09/2004	3.4	25/11/2004	6.8	24/01/2005	0
27/09/2004	0.2	26/11/2004	4.8	25/01/2005	0
28/09/2004	2.6	27/11/2004	2.2	26/01/2005	0.2
29/09/2004	0.2	28/11/2004	0.4	27/01/2005	0
30/09/2004	12	29/11/2004	0	28/01/2005	0
01/10/2004	2.6	30/11/2004	0.6	29/01/2005	0
02/10/2004	6.8	01/12/2004	0.4	30/01/2005	0.2
03/10/2004	3.2	02/12/2004	0.6	31/01/2005	0
04/10/2004	25.2	03/12/2004	4	01/02/2005	0
05/10/2004	3	04/12/2004	0.6	02/02/2005	0.2
06/10/2004	6.8	05/12/2004	0.4	03/02/2005	0.2
07/10/2004	0.4	06/12/2004	0.4	04/02/2005	0.2
08/10/2004	0.2	07/12/2004	0	05/02/2005	2.4
09/10/2004	0.2	08/12/2004	0.2	06/02/2005	0.4
10/10/2004	0	09/12/2004	0	07/02/2005	0
11/10/2004	0	10/12/2004	0.4	08/02/2005	5.4
12/10/2004	1.2	11/12/2004	1.6	09/02/2005	5.4
13/10/2004	10.4	12/12/2004	0.2	10/02/2005	1.4

Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)
14/10/2004	0	13/12/2004	0	11/02/2005	10.6
15/10/2004	1.8	14/12/2004	2.4	12/02/2005	11
16/10/2004	0.6	15/12/2004	3	13/02/2005	1.4
17/10/2004	1.4	16/12/2004	5.8	14/02/2005	0
18/10/2004	0.2	17/12/2004	4	15/02/2005	0
19/10/2004	10.4	18/12/2004	2.2	16/02/2005	0.2
20/10/2004	7.2	19/12/2004	0	17/02/2005	0.4
21/10/2004	14	20/12/2004	6.2	18/02/2005	0.6
22/10/2004	1.6	21/12/2004	4.8	19/02/2005	0.2
23/10/2004	5.2	22/12/2004	7	20/02/2005	0
24/10/2004	18.8	23/12/2004	14	21/02/2005	0
25/10/2004	1.6	24/12/2004	10.4	22/02/2005	4.6
26/10/2004	0.2	25/12/2004	1.8	23/02/2005	3.6
27/10/2004	0.6	26/12/2004	0.2	24/02/2005	0.4
28/10/2004	1.2	27/12/2004	9.2	25/02/2005	0.4
30/10/2004	0	29/12/2004	0.6	27/02/2005	0
31/10/2004	0	30/12/2004	10.4	28/02/2005	0.2
01/11/2004	0	31/12/2004	1.2	01/03/2005	5.4
02/11/2004	0	01/01/2005	10	02/03/2005	0.8
03/11/2004	0.4	02/01/2005	4.2	03/03/2005	0.2
04/11/2004	4.4	03/01/2005	0.4	04/03/2005	2
05/11/2004	1.2	04/01/2005	1	05/03/2005	2
06/11/2004	6	05/01/2005	3.6	06/03/2005	0.2
07/11/2004	1.8	06/01/2005	3.8	07/03/2005	0
08/11/2004	0.2	07/01/2005	46.2	08/03/2005	0
09/11/2004	2	08/01/2005	11.4	09/03/2005	0.4
10/11/2004	0	09/01/2005	17.2	10/03/2005	0.6
11/11/2004	2.8	10/01/2005	1.2	11/03/2005	0.8
12/11/2004	1	11/01/2005	1.4	12/03/2005	0
13/11/2004	0	12/01/2005	2.2	13/03/2005	0
14/11/2004	0.4	13/01/2005	0.2	14/03/2005	18.4
15/11/2004	0.4	14/01/2005	0.2	15/03/2005	5.4
16/11/2004	6.6	15/01/2005	1.8	16/03/2005	1.2
17/11/2004	2	16/01/2005	0.6	17/03/2005	1
18/11/2004	0.4	17/01/2005	3.8	18/03/2005	0.6
19/11/2004	0	18/01/2005	2	19/03/2005	0
20/11/2004	0	19/01/2005	3.4	20/03/2005	0.2
21/11/2004	6.2	20/01/2005	1	21/03/2005	0.2
22/11/2004	3.2	21/01/2005	0	22/03/2005	5.6
23/11/2004	1.2	22/01/2005	0	23/03/2005	1
24/03/2005	0	23/05/2005	9.6	22/07/2005	0
25/03/2005	0.2	24/05/2005	4.8	23/07/2005	0
26/03/2005	0	25/05/2005	12.4	24/07/2005	0
27/03/2005	4.6	26/05/2005	1.6	25/07/2005	0
28/03/2005	4.6	27/05/2005	1.8	26/07/2005	0
29/03/2005	0	28/05/2005	0	27/07/2005	0
30/03/2005	0.2	29/05/2005	0	28/07/2005	11.2

Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)
31/03/2005	0	30/05/2005	0.2	29/07/2005	1
01/04/2005	1	31/05/2005	0	30/07/2005	2
02/04/2005	0	01/06/2005	12.6	31/07/2005	0.8
03/04/2005	6.2	02/06/2005	13.2	01/08/2005	0
04/04/2005	1.4	03/06/2005	3.2	02/08/2005	1.2
05/04/2005	5.8	04/06/2005	4.4	03/08/2005	3.4
06/04/2005	31.4	05/06/2005	1.4	04/08/2005	12.6
07/04/2005	0.2	06/06/2005	0	05/08/2005	1.2
08/04/2005	0	07/06/2005	0	06/08/2005	0.6
09/04/2005	2.4	08/06/2005	0	07/08/2005	0
10/04/2005	0	09/06/2005	0	08/08/2005	0
11/04/2005	1	10/06/2005	0.2	09/08/2005	11
12/04/2005	1.2	11/06/2005	0	10/08/2005	0
13/04/2005	1.4	12/06/2005	3.2	11/08/2005	5.4
14/04/2005	1.8	13/06/2005	8.4	12/08/2005	0.8
15/04/2005	2.8	14/06/2005	5.8	13/08/2005	7
16/04/2005	0.6	15/06/2005	0	14/08/2005	0
17/04/2005	1	16/06/2005	6	15/08/2005	0.2
18/04/2005	5	17/06/2005	4.8	16/08/2005	0
19/04/2005	0	18/06/2005	0	17/08/2005	0
20/04/2005	0	19/06/2005	0	18/08/2005	2.2
21/04/2005	0	20/06/2005	0	19/08/2005	0.2
22/04/2005	0	21/06/2005	0.4	20/08/2005	0
23/04/2005	0	22/06/2005	0	21/08/2005	4.6
24/04/2005	0	23/06/2005	0	22/08/2005	0.6
25/04/2005	0	24/06/2005	2.8	23/08/2005	3.6
26/04/2005	5.2	25/06/2005	0	24/08/2005	15.8
27/04/2005	2.2	26/06/2005	0	25/08/2005	11
28/04/2005	4	27/06/2005	0	26/08/2005	5
29/04/2005	0	28/06/2005	0	27/08/2005	0.2
30/04/2005	0	29/06/2005	0.8	28/08/2005	0
01/05/2005	10.4	30/06/2005	8.8	29/08/2005	1.8
02/05/2005	5.8	01/07/2005	0	30/08/2005	0
03/05/2005	11.8	02/07/2005	0	31/08/2005	3.2
04/05/2005	0	03/07/2005	1.6	01/09/2005	0.2
05/05/2005	2	04/07/2005	0.2	02/09/2005	0
06/05/2005	0.4	05/07/2005	2.2	03/09/2005	0
07/05/2005	0.2	06/07/2005	5.2	04/09/2005	0
08/05/2005	2	07/07/2005	0	05/09/2005	0
09/05/2005	1.8	08/07/2005	0	06/09/2005	0
10/05/2005	0.2	09/07/2005	0	07/09/2005	2.8
11/05/2005	0	10/07/2005	0	08/09/2005	0.6
12/05/2005	0	11/07/2005	0	09/09/2005	15.2
13/05/2005	0	12/07/2005	0	10/09/2005	0
14/05/2005	0	13/07/2005	0	11/09/2005	0
15/05/2005	0	14/07/2005	4.8	12/09/2005	0
16/05/2005	0	15/07/2005	0	13/09/2005	1.8

Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)
17/05/2005	0.4	16/07/2005	0	14/09/2005	0.4
18/05/2005	3.4	17/07/2005	0	15/09/2005	4.4
19/05/2005	3.8	18/07/2005	4.4	16/09/2005	0
20/05/2005	3.2	19/07/2005	3.2	17/09/2005	1
21/05/2005	19	20/07/2005	0.2	18/09/2005	0
22/05/2005	5.8	21/07/2005	0	19/09/2005	6
20/09/2005	0.2	19/11/2005	0	18/01/2006	14.40
21/09/2005	0	20/11/2005	0.4	19/01/2006	2.58
22/09/2005	0	21/11/2005	0.2	20/01/2006	
23/09/2005	5.6	22/11/2005	0.30	21/01/2006	
24/09/2005	0	23/11/2005	0.40	22/01/2006	0.70
25/09/2005	0.8	24/11/2005	1.70	23/01/2006	0.20
26/09/2005	18.6	25/11/2005	2.40	24/01/2006	0.00
27/09/2005	2.8	26/11/2005	3.80	25/01/2006	0.00
28/09/2005	9	27/11/2005	0.00	26/01/2006	0.10
29/09/2005	5.2	28/11/2005	0.00	27/01/2006	
30/09/2005	4	29/11/2005	0.00	28/01/2006	
01/10/2005	1	30/11/2005	1.10	29/01/2006	0.00
02/10/2005	0.8	01/12/2005	1.70	30/01/2006	0.00
03/10/2005	0	02/12/2005	0.50	31/01/2006	0.00
04/10/2005	0	03/12/2005	6.20	01/02/2006	0.00
05/10/2005	0	04/12/2005	0.00	02/02/2006	0.00
06/10/2005	0	05/12/2005	0.00	03/02/2006	
07/10/2005	0	06/12/2005	0.00	04/02/2006	
08/10/2005	2.2	07/12/2005	5.20	05/02/2006	0.00
09/10/2005	2	08/12/2005	0.00	06/02/2006	1.00
10/10/2005	1	09/12/2005	14.10	07/02/2006	3.00
11/10/2005	64.8	10/12/2005	0.00	08/02/2006	0.00
12/10/2005	38.2	11/12/2005	1.60	09/02/2006	0.00
13/10/2005	0	12/12/2005	0.20	10/02/2006	
14/10/2005	0.2	13/12/2005	0.10	11/02/2006	
15/10/2005	0	14/12/2005	0.00	12/02/2006	7.50
16/10/2005	0.2	15/12/2005	3.70	13/02/2006	1.60
17/10/2005	0	16/12/2005	0.20	14/02/2006	17.20
18/10/2005	0	17/12/2005		15/02/2006	6.00
19/10/2005	10.8	18/12/2005	6.60	16/02/2006	14.90
20/10/2005	5.4	19/12/2005	0.30	17/02/2006	
21/10/2005	10.6	20/12/2005		18/02/2006	
22/10/2005	8.6	21/12/2005	1.60	19/02/2006	1.60
23/10/2005	0	22/12/2005	10.40	20/02/2006	0.30
24/10/2005	45.2	23/12/2005		21/02/2006	0.00
25/10/2005	20.2	24/12/2005		22/02/2006	1.70
26/10/2005	6	25/12/2005		23/02/2006	4.20
27/10/2005	0	26/12/2005		24/02/2006	
28/10/2005	19.4	27/12/2005		25/02/2006	
29/10/2005	0.8	28/12/2005		26/02/2006	0.50
					3.70
30/10/2005	8.2	29/12/2005		27/02/2006	

Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)
31/10/2005	3.4	30/12/2005		28/02/2006	0.00
01/11/2005	8.4	31/12/2005		01/03/2006	0.00
02/11/2005	13.4	01/01/2006		02/03/2006	0.00
03/11/2005	10	02/01/2006		03/03/2006	
04/11/2005	7.2	03/01/2006	32.40	04/03/2006	
05/11/2005	4.6	04/01/2006	0.40	05/03/2006	0.30
06/11/2005	23.6	05/01/2006	0.10	06/03/2006	2.00
07/11/2005	9.6	06/01/2006		07/03/2006	5.10
08/11/2005	9.2	07/01/2006		08/03/2006	4.50
09/11/2005	0.2	08/01/2006	0.00	09/03/2006	5.20
10/11/2005	1.2	09/01/2006	2.60	10/03/2006	
11/11/2005	7.2	10/01/2006	34.40	11/03/2006	
12/11/2005	3.4	11/01/2006	0.00	12/03/2006	6.30
13/11/2005	0.2	12/01/2006	0.00	13/03/2006	13.20
14/11/2005	3	13/01/2006		14/03/2006	5.20
15/11/2005	0.2	14/01/2006		15/03/2006	0.30
16/11/2005	0.2	15/01/2006	3.40	16/03/2006	0.00
17/11/2005	0	16/01/2006	5.70	17/03/2006	
18/11/2005	0.2	17/01/2006	0.50	18/03/2006	
19/03/2006	0.10	18/05/2006	2.50	17/07/2006	0
20/03/2006	0.10	19/05/2006		18/07/2006	0
21/03/2006	0.00	20/05/2006		19/07/2006	0
22/03/2006	0.00	21/05/2006	24.90	20/07/2006	0.2
23/03/2006	0.00	22/05/2006	1.6	21/07/2006	0
24/03/2006		23/05/2006	2.6	22/07/2006	0
25/03/2006		24/05/2006	0.2	23/07/2006	0
26/03/2006	26.80	25/05/2006	1.4	24/07/2006	0
27/03/2006	8.10	26/05/2006	1.2	25/07/2006	0
28/03/2006	4.60	27/05/2006	0.6	26/07/2006	0
29/03/2006	10.08	28/05/2006	0.2	27/07/2006	0
30/03/2006	17.40	29/05/2006	0.6	28/07/2006	0
31/03/2006		30/05/2006	1.2	29/07/2006	2.2
01/04/2006		31/05/2006	0	30/07/2006	0.2
02/04/2006	22.60	01/06/2006	1.2	31/07/2006	9.4
03/04/2006	2.70	02/06/2006	0	01/08/2006	3.8
04/04/2006	0.00	03/06/2006	0	02/08/2006	7.8
05/04/2006	1.60	04/06/2006	0	03/08/2006	0
06/04/2006	0.90	05/06/2006	0	04/08/2006	0.4
07/04/2006		06/06/2006	0	05/08/2006	1.2
08/04/2006		07/06/2006	0	06/08/2006	3.2
09/04/2006	4.30	08/06/2006	0	07/08/2006	0.2
10/04/2006	0.40	09/06/2006	0	08/08/2006	1
11/04/2006	5.80	10/06/2006	0	09/08/2006	0
12/04/2006	1.80	11/06/2006	4	10/08/2006	0
13/04/2006		12/06/2006	0	11/08/2006	0
14/04/2006		13/06/2006	0	12/08/2006	0
15/04/2006		14/06/2006	0	13/08/2006	0

Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)
16/04/2006		15/06/2006	0	14/08/2006	0
17/04/2006	3.10	16/06/2006	0	15/08/2006	1.4
18/04/2006	4.20	17/06/2006	0.8	16/08/2006	0
19/04/2006	0.20	18/06/2006	9.4	17/08/2006	1
20/04/2006	4.10	19/06/2006	0	18/08/2006	6.6
21/04/2006		20/06/2006	14	19/08/2006	0.8
22/04/2006		21/06/2006	7.2	20/08/2006	2.4
23/04/2006	0.00	22/06/2006	1.4	21/08/2006	2.8
24/04/2006	6.70	23/06/2006	0	22/08/2006	0
25/04/2006	0.00	24/06/2006	3.4	23/08/2006	4
26/04/2006	2.60	25/06/2006	0.4	24/08/2006	0
27/04/2006	0.00	26/06/2006	0.4	25/08/2006	1
28/04/2006		27/06/2006	0	26/08/2006	1
29/04/2006		28/06/2006	0.6	27/08/2006	3.2
30/04/2006		29/06/2006	0	28/08/2006	1.4
01/05/2006	8.80	30/06/2006	4.6	29/08/2006	0.4
02/05/2006	1.00	01/07/2006	0	30/08/2006	2.8
03/05/2006	0.00	02/07/2006	0	31/08/2006	13
04/05/2006	0.00	03/07/2006	0	01/09/2006	10.8
05/05/2006		04/07/2006	0	02/09/2006	21.2
06/05/2006		05/07/2006	1.2	03/09/2006	9.4
07/05/2006	9.40	06/07/2006	1.8	04/09/2006	0.2
08/05/2006	0.00	07/07/2006	1.8	05/09/2006	7.4
09/05/2006	0.00	08/07/2006	6.2	06/09/2006	10.6
10/05/2006	0.00	09/07/2006	1	07/09/2006	0.2
11/05/2006	0.00	10/07/2006	4.2	08/09/2006	0
12/05/2006		11/07/2006	0	09/09/2006	0.2
13/05/2006		12/07/2006	2.4	10/09/2006	0.2
14/05/2006	18.60	13/07/2006	0	11/09/2006	0
15/05/2006	6.60	14/07/2006	0	12/09/2006	0.2
16/05/2006	0.20	15/07/2006	0	13/09/2006	0
17/05/2006	6.40	16/07/2006	0	14/09/2006	30.6
15/09/2006	0.2	14/11/2006	1.6	13/01/2007	5
16/09/2006	0	15/11/2006	14.4	14/01/2007	0.2
17/09/2006	0.4	16/11/2006	3.8	15/01/2007	1.4
18/09/2006	8	17/11/2006	8.2	16/01/2007	2
19/09/2006	1.8	18/11/2006	5	17/01/2007	8.6
20/09/2006	1.8	19/11/2006	12.8	18/01/2007	12.2
21/09/2006	0.4	20/11/2006	3.2	19/01/2007	8.6
22/09/2006	0.4	21/11/2006	0.2	20/01/2007	1.6
23/09/2006	0.2	22/11/2006	2.8	21/01/2007	5.4
24/09/2006	4.2	23/11/2006	11	22/01/2007	0.2
25/09/2006	0.2	24/11/2006	2.6	23/01/2007	0.2
26/09/2006	0	25/11/2006	0.2	24/01/2007	1.8
27/09/2006	6.4	26/11/2006	6	25/01/2007	1
28/09/2006	0.8	27/11/2006	0.6	26/01/2007	0.2
29/09/2006	1.8	28/11/2006	1.8	27/01/2007	0.2

Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)
30/09/2006	0.2	29/11/2006	2.2	28/01/2007	0.2
01/10/2006	9.2	30/11/2006	1	29/01/2007	0
02/10/2006	5.2	01/12/2006	7.4	30/01/2007	0
03/10/2006	6.6	02/12/2006	2	31/01/2007	2.2
04/10/2006	2.2	03/12/2006	10.4	01/02/2007	0
05/10/2006	9.2	04/12/2006	7.8	02/02/2007	0
06/10/2006	8.8	05/12/2006	16.6	03/02/2007	0.4
07/10/2006	0	06/12/2006	1.8	04/02/2007	0
08/10/2006	5.6	07/12/2006	21.4	05/02/2007	0.2
09/10/2006	1.2	08/12/2006	0.2	06/02/2007	0
10/10/2006	0.2	09/12/2006	0.6	07/02/2007	0.2
11/10/2006	6.6	10/12/2006	2.6	08/02/2007	2.6
12/10/2006	4.6	11/12/2006	7.4	09/02/2007	1.8
13/10/2006	0.2	12/12/2006	5.6	10/02/2007	3.2
14/10/2006	0.4	13/12/2006	10.8	11/02/2007	6.2
15/10/2006	0.4	14/12/2006	15.8	12/02/2007	2.4
16/10/2006	0.2	15/12/2006	2.2	13/02/2007	1.8
17/10/2006	6.2	16/12/2006	0.2	14/02/2007	0.8
18/10/2006	0	17/12/2006	0.4	15/02/2007	1.2
19/10/2006	4.2	18/12/2006	0	16/02/2007	0
20/10/2006	1	19/12/2006	0.4	17/02/2007	0.2
21/10/2006	3.6	20/12/2006	0.2	18/02/2007	0.2
22/10/2006	7.8	21/12/2006	0	19/02/2007	7.8
23/10/2006	2.4	22/12/2006	0.6	20/02/2007	1
24/10/2006	7	23/12/2006	0.4	21/02/2007	4.4
25/10/2006	27.6	24/12/2006	0	22/02/2007	18.2
26/10/2006	2.2	25/12/2006	0.8	23/02/2007	1.8
27/10/2006	6.6	26/12/2006	0.2	24/02/2007	1.8
28/10/2006	11	27/12/2006	1.8	25/02/2007	1
29/10/2006	0.4	28/12/2006	0.4	26/02/2007	0
30/10/2006	10.8	29/12/2006	7	27/02/2007	17.2
31/10/2006	0.6	30/12/2006	4.6	28/02/2007	1
01/11/2006	0.2	31/12/2006	3.4	01/03/2007	2.8
02/11/2006	0.2	01/01/2007	3	02/03/2007	2.8
03/11/2006	0.2	02/01/2007	3.4	03/03/2007	1.6
04/11/2006	0	03/01/2007	4.8	04/03/2007	4
05/11/2006	0	04/01/2007	1	05/03/2007	3.6
06/11/2006	0	05/01/2007	0.6	06/03/2007	11.2
07/11/2006	2.4	06/01/2007	1.8	07/03/2007	0.6
08/11/2006	3	07/01/2007	13	08/03/2007	1.4
09/11/2006	0.2	08/01/2007	9.4	09/03/2007	1.8
10/11/2006	10.8	09/01/2007	3.6	10/03/2007	0.6
11/11/2006	10.6	10/01/2007	8	11/03/2007	0.2
12/11/2006	3	11/01/2007	8.8	12/03/2007	4.2
13/11/2006	0.6	12/01/2007	3.6	13/03/2007	0.2
14/03/2007	0.2	13/05/2007	4	09/08/2007	0
15/03/2007	0	14/05/2007	0.2	10/08/2007	0.4

Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)
16/03/2007	1	15/05/2007	7.4	11/08/2007	10
17/03/2007	6.4	16/05/2007	9.6	12/08/2007	7
18/03/2007	4	17/05/2007	1.4	13/08/2007	1.8
19/03/2007	0	18/05/2007	2.4	14/08/2007	11.4
20/03/2007	0	19/05/2007	2	15/08/2007	0.2
21/03/2007	3.8	20/05/2007	0.4	16/08/2007	0.6
22/03/2007	0.8	21/05/2007	0.2	17/08/2007	3
23/03/2007	0	22/05/2007	0	18/08/2007	13.6
24/03/2007	0.2	23/05/2007	0	19/08/2007	0.4
25/03/2007	0	24/05/2007	1.4	20/08/2007	0
26/03/2007	0	25/05/2007	0	21/08/2007	0
27/03/2007	0.2	26/05/2007	0	22/08/2007	0
28/03/2007	2.4	27/05/2007	0.4	23/08/2007	0
29/03/2007	1.4	28/05/2007	0	24/08/2007	0
30/03/2007	0.2	29/05/2007	0.4	25/08/2007	1.2
31/03/2007	0	27/06/2007	3.4	26/08/2007	0
01/04/2007	0	28/06/2007	17.6	27/08/2007	0
02/04/2007	0.2	29/06/2007	1.2	28/08/2007	0.2
03/04/2007	0.2	30/06/2007	11.4	29/08/2007	0.2
04/04/2007	0	01/07/2007	10.8	30/08/2007	0.2
05/04/2007	0.2	02/07/2007	4.2	31/08/2007	0.2
06/04/2007	0.2	03/07/2007	22.6	01/09/2007	2
07/04/2007	0	04/07/2007	1.6	02/09/2007	0.4
08/04/2007	0	05/07/2007	15.8	03/09/2007	0
09/04/2007	0	06/07/2007	4.8	04/09/2007	0.2
10/04/2007	0.2	07/07/2007	12.6	05/09/2007	0
11/04/2007	0	08/07/2007	0.8	06/09/2007	0
12/04/2007	0.2	09/07/2007	0	07/09/2007	0.2
13/04/2007	0	10/07/2007	0	08/09/2007	0
14/04/2007	0	11/07/2007	3.4	09/09/2007	0.6
15/04/2007	0	12/07/2007	0.2	10/09/2007	0.2
16/04/2007	0	13/07/2007	13.6	11/09/2007	0
17/04/2007	1	14/07/2007	0	12/09/2007	0
18/04/2007	0	15/07/2007	5.6	13/09/2007	3
19/04/2007	6	16/07/2007	1.8	14/09/2007	1
20/04/2007	2.4	17/07/2007	1.2	15/09/2007	9.6
21/04/2007	0	18/07/2007	0.8	16/09/2007	10.8
22/04/2007	2.8	19/07/2007	1.8	17/09/2007	1
23/04/2007	8.6	20/07/2007	0	18/09/2007	8.8
24/04/2007	4.6	21/07/2007	5.4	19/09/2007	1.8
25/04/2007	2.4	22/07/2007	0.6	20/09/2007	3.2
26/04/2007	0	23/07/2007	1.4	21/09/2007	3.2
27/04/2007	0	24/07/2007	0.4	22/09/2007	6.8
28/04/2007	0	25/07/2007	1.6	23/09/2007	23.6
29/04/2007	0	26/07/2007	3.6	24/09/2007	6
30/04/2007	0	27/07/2007	0.6	25/09/2007	0

Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)	Date	Composite rainfall series (mm)
01/05/2007	0	28/07/2007	0	26/09/2007	0.2
02/05/2007	0	29/07/2007	0.6	27/09/2007	0
03/05/2007	0	30/07/2007		28/09/2007	0.2
04/05/2007	0	31/07/2007	0	29/09/2007	0
05/05/2007	0	01/08/2007	5.8	30/09/2007	0.2
06/05/2007	5.6	02/08/2007	0		
07/05/2007	1.6	03/08/2007	4.4		
08/05/2007	3	04/08/2007	4.8		
09/05/2007	3.6	05/08/2007	4.4		
10/05/2007	4	06/08/2007	0.6		
11/05/2007	7.2	07/08/2007	0.2		
12/05/2007	4.6	08/08/2007	0		

Appendix 2 Dipwell results for Walton and Bolton Fell Mosses

Bolton Fell Moss Dipwells installed 7.10.03 and 8.10.03

east transect

	20.10.03	17.11.03	17.12.03	19.01.04	15.01.04 J Bowman	16.02.04	15.03.04	29.03.04 J Bowman	19.04.04	17.05.04	27.05.04
E1	0.169	0.115	0.075	0.059	0.06	0.08	0.095	0.08	0.075	0.125	0.16
E2	0.153	0.065	0.07	0.061	0.07	0.08	0.073	0.08	0.059	0.114	0.12
E3	0.112	0.035	0.02	0.01	0.02	0.04	-0.014	0	0.004	0.065	0.11
E4	0.148	0.065	0.05	0.059	0.07	0.08	0.048	0.06	0.064	0.104	0.14
E5	0.213	0.08	0.065	0.104	0.15	0.13	0.093	0.1	0.05	0.086	0.18
E6	0.093	0.065	0.035	0.05	0.01	0.045	0.037	0.06	0.03	0.086	0.09
E7 / N4	0.153	0.077	0.025	0.009	0.02	0.055	0.007	0.03	0.01	0	0.12
E8	0.121	0.055	0.035	0.018	0	0.02	0.013	0.06	0.002	0.078	0.1
E9	0.279	0.275	0.175	0.141	0.14	0.21	0.105	0.2	0.11	0.179	0.25
E10	0.168	0.045	0.01	0.009	-0.01	0.02	0.017	0	0.015	0.064	0.1
E11a								0.35	0.314	0.324	0.35
E11	0.216	0.18	0.125	0.113	0.1	0.15	0.099	0.15	0.126	0.175	0.19
E12	0.14	0.05	0.015	-0.004	0.01	-0.01	0.002	0.09	0.007	0.098	0.15
E13	0.145	0.02	0.01	0.002	0	0	0.022	0.14	0.005	0.088	0.18

south transect

	20.10.03	17.11.03	17.12.03	19.01.04	15.01.04 J Bowman	16.02.04	15.03.04	29.03.04 J Bowman	19.04.04	17.05.04	27.05.04
N1	0.14	0.04	0.015	0.005	0	-0.001	-0.019	0.04	0.005	0.084	0.17
N2	0.135	0.03	-0.015	0.009	0.02	-0.045	-0.018	0	0.013	0.044	0.11
N3	0.193	0.08	0.07	0.076	0.05	0.053	0.029	0.09	0.052	0.12	0.18
E7 / N4	0.153	0.077	0.025	0.009	0.02	0.055	0.007	0.03	0.01	0.034	0.12
N5	0.105	0.05	0.03	0.013	0	0	-0.03	0.04	0.002	0.042	0.09
N6	0.116	0.105	0.015	0.027	-0.01	0.01	-0.025	0	0.029	0.069	0.11
N7	0.082	0.075	0.06	0.021	0.02	0.069	0.031	0.08	0.057	0.096	0.11
N8	0.503	0.465	0.43	0.289	0.3	0.35	0.061	0.34	0.297	0.247	0.46
N8a	0.519	0.423	0.39	0.323	0.39	0.404	0.054	0.37	0.11	0.405	0.32
N9		0.068	0.01	0.007	0.06	0.018	-0.008	0.07	0.14	0.08	0.14
N10		0.372	0.23	0.195	0.26	0.251	0.167	0.33	0.207	0.296	0.39

east transect

	15.06.04	17.07.04	16.08.04	16.09.04	18.10.04	02.11.04	22.11.04	21.12.04	19.01.05	16.02.05	21.03.05
E1	0.16	0.14	0.085	0.11	0.078	0.15	0.107	0.098	0.11	0.095	0.126
E2	0.11	0.121	0.04	0.069	0.045	0.13	0.058	0.053	0.14	0.173	0.072
E3	0.06	0.026	-0.012	0.005	-0.008	0.12	0.04	0.013	0.02	0.06	0.012
E4	0.06	0.126	0.035	0.053	0.039	0.15	0.04	0.061	0.07	0.068	0.07
E5	0.1	0.111	0.03	0.115	0.111	0.17	0.045	0.041	0.06	0.04	0.1
E6	0.07	0.079	0.015	0.041	0.044	0.09	0.06	0.01	0.03	0.093	0.045
E7 / N4	0.081	-0.001	0	0.018	0.034	0.13	0.093	0.041	-0.01	0.006	0.025
E8	0.105	0.026	-0.006	-0.006	-0.003	0.09	-0.002	0.009	0	0.012	0.023
E9	0.285	0.221	0.04	0.076	0.126	0.26	0.08	0.065	0.05	0.098	0.095
E10	0.145	0.029	-0.02	0.004	-0.002	0.11	-0.014	-0.005	-0.01	0	0.001
E11a	0.375	0.31	0.08	0.26	0.228	0.36	0.217	0.224	0.13	0.164	0.253
E11	0.182	0.172	0.095	0.131	0.121	0.27	0.126	0.151	0	0.148	0.153
E12	0.15	0.057	-0.03	0.017	0.019	0.21	-0.007	-0.018	-0.06	0.038	0.047
E13	0.145	0.065	0.005	0.05	0.037	0.19	0.02	0.001	0.02	0.058	0.092

south transect

	15.06.04	17.07.04	16.08.04	16.09.04	18.10.04	02.11.04	22.11.04	21.12.04	19.01.05	16.02.05	21.03.05
N1	0.17	0.113	-0.02	-0.009	0.009	0.03	0.004	-0.002	0.04	0.01	0.005
N2	0.15	0.057	0	-0.017	-0.013	0	-0.003	-0.032	-0.04	-0.034	0.008
N3	0.18	0.081	0.05	0.062	0.065	0.09	0.067	0.011	0.03	0.054	0.084
E7 / N4	0.081	-0.001	0	0.018	0.034	0.13	0.093	0.041	-0.01	0.006	0.025
N5	0.073	0.071	-0.015	0.008	-0.003	0.06	-0.01	0.008	0.01	0.018	0.014
N6	0.108	-0.022	-0.005	0.025	-0.014	0.04	-0.005	0.011	0.06	0.019	0.045
N7	0.11	0.081	0.045	0.072	0.018	0.09	0.021	0.022	0.04	0.071	0.048
N8	0.329	0.348	-0.01	0.085	0.192	0.24	0.025	0.162	0.11	0.06	0.184
N8a	0.476	0.301	0.045	0.195	0.205	0.32	0.021	0.134	0.12	0.103	0.13
N9	0.4	0.068	0.005	0.024	0.012	0.03	0.051	0.034	0.07	0.044	0.032
N10	0.427	0.364	0.23	0.254	0.269	0.31	0.255	0.286	0.29	0.29	0.309

east transect

	18.04.05	24.04.05	24.06.05	19.07.05	22.08.05	27.09.05	24.10.05	21.11.05	21.01.06	07.02.06	13.03.06
E1	0.121	0.135	0.14	0.181	0.195	0.14	0.068	0.101	0.1	0.147	0.05
E2	0.075	0.03	0.127	0.142	0.147	0.05	0.025	0.077	0.06	0.103	0.05
E3	0.01	-0.005	0.06	0.16	0.111	-0.01	-0.013	0.02	0.005	0.05	0.01
E4	0.055	0.03	0.1	0.173	0.121	0.045	0.018	0.092	0.055	0.093	0.06
E5	0.107	0.005	0.16	0.14	0.135	0.055	0.06	0.111	0.125	0.14	0.105
E6	0.05	0.033	0.09	0.128	0.128	0.03	0.034	0.033	0.035	0.085	0.01
E7 / N4	0.04	0.008	0.08	0.147	0.156	0	-0.009	0.05	0.04	0.087	0.07
E8	0.025	-0.005	0.055	0.115	0.115	-0.002	-0.025	0.051	0.02	0.098	0
E9	0.08	0.01	0.12	0.17	0.195	0.025	-0.024	0.033	0.02	0.077	0.03
E10	0.002	0	0.065	0.127	0.109	0.002	-0.045	0.016	0.01	0.087	-0.01
E11a	0.244	0.17	0.27	0.336	0.316	0.21	0.054	0.231	0.23	0.313	0.24
E11	0.14	0.17	0.175	0.207	0.225	0.115	0.045	0.173	0.12	0.185	
E12	0.055	-0.01	0.1	0.119	0.147	0.01	-0.033	0.071	0.075	0.132	0.03
E13	0.074	0.058	0.13		0.16	0.084		0.096	0.105	0.126	0.09

south transect

	18.04.05	24.04.05	24.06.05	19.07.05	22.08.05	27.09.05	24.10.05	21.11.05	21.01.06	07.02.06	13.03.06
N1	0.01	0.037	0.06	0.176	0.007	0	-0.085	0.038	0.015	0.072	0.015
N2	-0.005	-0.035	0.04	0.131	0.135	0.025	-0.033	0.025	0.005	0.053	0
N3	0.073	0.03	0.12	0.205	0.213	0.07	0.003	0.079	0.09	0.128	0.045
E7 / N4	0.04	0.008	0.08	0.147	0.156	0	-0.009	0.05	0.04	0.087	0.07
N5	-0.001	0.015	0.04	0.116	0.099	0	-0.034	0.043	0.008	0.08	0.025
N6	0.03	-0.015	0.07	0.115	0.099	0.005	-0.036	0.037	-0.005	0.025	0
N7	0.035	0.003	0.1	0.119	0.11	0.03	-0.023	0.069	0.052	0.05	0.03
N8	0.185	-0.022	0.169	0.274	0.318	0.035	-0.008	0.296	0.2	0.307	0.18
N8a	0.087	-0.005	0.165	0.232	0.181	0.1	-0.003	0.25	0.248	0.267	0.19
N9	0.014	-0.01	0.08	0.134	0.146	0.025	0.008	0.054	0.045	0.074	0.015
N10	0.342	0.29	0.39	0.418	0.422	0.285	0.228	0.34	0.3	0.362	0.31

east transect

	17.04.06	19.06.06	18.07.06	14.08.06	18.09.06	23.10.06	19.03.07	30.05.07	26.06.07	30.07.07	28.08.07
E1	0.092	0.22	0.264	0.245	0.04	0.07	0.075	0.18	0.08	0.13	0.15
E2	0.042	0.085	0.211	0.23	0.07	0.06	0.05	0.15	0.1	0.13	0.11
E3	0.012	0.145	0.195	0.2	0.02	0.01	0.045	0.13	0.09	0.155	0.09
E4	0.043	0.145	0.232	0.25	0.07	0.07	0.06	0.19	0.1	0.12	0.14
E5	0.063	0.16	0.26	0.28	0.135	0.11	0.07	0.19	0.15	0.17	0.22
E6	0.028	0.14	0.288	0.24	0.06	0.045	0.04	0.12	0.07	0.09	0.13
E7 / N4	0.03	0.135	0.246	0.16	0.085	0.055	0.04	0.14	0.06	0.11	0.111
E8	0.009	0.07	0.184	0.18	0.05	0.02	0.055	0.13	0.06	0.11	0.12
E9	0.089	0.155	0.207	0.27	0.06	0.04	0.09	0.21	0.075	0.1	0.14
E10	0.065	0.1	0.148	0.165	-0.025	0	0.01	0	0.02	0.09	0.15
E11a	0.138	0.31	0.407	0.37	0.205	0.18	0.21	0.33	0.24	0.29	0.29
E11	0.064	0.18	0.278	0.27	0.13	0.115	0.115	0.22	0.165	0.2	0.23
E12	-0.006	0.155	0.275	0.235	0.025	0.015	0.015	0.19	0.06	0.12	0.15
E13	0.07	0.155	0.245	0.2	0.085	0.06	0.075	0.14	0.03	0.15	0.16

south transect

	19.06.06	Depth to water table (m)19.06.06	18.07.06	14.08.06	18.09.06	23.10.06	19.03.07	30.05.07	26.06.07	30.07.07	28.08.07
N1	-0.033	0.2	0.301	0.32	0.055	0.03	0.015	0.21	0.08	0.18	0.18
N2	-0.004	0.09	0.223	0.195	0.015	0	0.01	0.07	0.015	0.07	0.077
N3	0.034	0.165	0.352	0.275	0.075	0.05	0.055	0.18	0.12	0.15	0.132
E7 / N4	0.03	0.135	0.246	0.16	0.085	0.055	0.04	0.14	0.06	0.15	0.111
N5	-0.02	0.12	0.155	0.19	0.035	0.02	0	0.12	0.08	0.08	0.085
N6	-0.03	0.07	0.186	0.18	0.015	0	0	0.19	0.01	0.15	0.045
N7	0.007	0.04	0.154	0.17	0.04	0.025	0.02	0.13	0.055	0.08	0.11
N8	0.005	0.31	0.36	0.385	-0.135	0.055	0.04	0.285	0.09	-0.09	0.175
N8a	0.185	0.295	0.286	0.29	0.14	0.13	0.12	0.28	0.205	0.26	0.26
N9	0.016	0.115	0.187	0.17	-0.105	0.04	0.025	0.1	0.06	0.08	0.11
N10	0.254	0.45	0.511	0.57	0.335	0.34	0.38	0.42	0.375	0.455	0.42

east transect

	29.10.07	26.11.07	14.01.08
E1	0.13	0.06	0.04
E2	0.09	0.1	0.05
E3	0.065	0.04	0
E4	0.09	0.09	0.06
E5	0.16	0.12	0.09
E6	0.06	0.05	0.07
E7 / N4	0.1	0.06	0.01
E8	0.09	0.07	0.03
E9	0.24	0.13	-0.04
E10	0.06	0.05	0.01
E11a	0.28	0.24	0.17
E11	0.2	0.2	0.09
E12	0.12	0.05	0
E13	0.14	0.01	-0.01

south transect

	29.10.07	26.11.07	14.01.08
N1	0.14	0.14	0
N2	0.06	0.03	0
N3	0.14	0.08	0.03
E7 / N4	0.1	0.065	0.01
N5	0.07	0.05	0.02
N6	0.025	0	-0.01
N7	0.07	0.04	0
N8	0.16	0.065	-0.01
N8a	0.23	0.2	0.13
N9	0.08	0.06	0.02
N10	0.37	0.335	0.24

Walton Moss

Northern transect (on intact moss)

	21.10.03	18.11.03	18.12.03	20.1.04	17.2.04	16.3.04	20.4.04	18.5.04	16.6.04	17.7.04	16.8.04	17.9.04	17.10.04
NX			0	0.008	0.01	-0.007	0.013	0.021	0.16	0.108	-0.015	0.002	0.009
N0			-0.025	0.011	-0.03	-0.05	-0.021	0.003	0.12	0.047	0	-0.018	-0.005
N1	0.144	0.025	0	-0.003	0	-0.021	-0.012	-0.023	0.16	-0.007	-0.015	-0.011	0.009
N2	0.231	0.08	0	-0.023	-0.04	-0.051	-0.007	0.002	0.16	0.021	0.005	-0.022	0.01
N3	0.724	0.51	0.02	-0.01	0.005	0.025	0.018	0.082	0.21	0.136	0.01	0.004	0.015
N4	0.319	0.105	0.07	0.046	0.065	0.085	0.084	0.118	0.175	0.126	0.045	0.069	0.066
N5	0.625	0.31	0.155	0.078	0.075	0.054	0.075	0.154	0.4	0.232	0.02	0.055	0.05
N6	0.179	-0.01	0.01	0.005	0	0	-0.001	0.032	0.135	0.031	-0.025	-0.01	-0.015
N7	0.205	-0.01	-0.005	0.005	-0.01	-0.013	-0.003	0.031	0.145	-0.013	-0.015	-0.02	-0.005
N8	0.239	-0.005	0	0.009	-0.01	0.017	0.034	0.027	0.165	0.058	-0.01	-0.015	0.023
N9	0.442	0.035	0.055	0.015	0.035	0.054	0.067	0.123	0.265	0.205	0.02	0.026	0.042
N10	0.173	0.005	0.01	0.007	0.015	0.049	0.022	0.093	0.15	0.046	0	0.007	0.018
N11	0.133	0.025	0.055	0.014	0.02	0.034	0.025	0.084	0.155	0.063	0.01	0.015	0.036
N12	0.08	0.01	0.035	0.019	0.02	0.003	-0.005	0.016	0.075	0.014	-0.015	-0.001	0.015
N13	0.144	0.055	0.115	0.11	0.06	0.094	0.088	0.095	0.13	0.099	0.06	0.058	0.064
N14	0.078	0.015	0.015	0	0	0.021	0.022	0.016	0.06	0.035	0	-0.019	-0.004

	21.11.04	22.12.04	16.1.05	15.2.05	20.3.05	19.4.05	23.5.05	23.6.05	18.7.05	22.8.05	26.9.05	25.10.05	22.11.05
NX	-0.003	-0.002	0.005	-0.024	0.01	-0.01	0.015	0.085	0.21	0.218	0.065	-0.012	0.074
N0	0.002	-0.003	-0.015	-0.015	0.05	0.04	0.04	0.065	0.195	0.241	0.105	0.035	0.096
N1	-0.036	-0.033	0.015	0.06	0	0.013	0	0.01	0.085	0.106	0.01	-0.038	-0.02
N2	0.006	-0.02	0.005	0	0	0.008	-0.003	0.03	0.075	0.195	0.02	-0.042	-0.028
N3	0.008	-0.019	-0.003	0.007	0.02	0.02	0.005	0.105	0.175	0.356	0.085	-0.034	0.015
N4	0.037	0.049	0.075	0.043	0.04	0.08	0.052	0.145	0.175	0.18	0.13	0.009	0.076
N5	0.013	0.006	0.07	0.076	0.115	0.086	-0.01	0.128	0.268	0.459	0.13	0.009	0.081
N6	0.004	-0.029	-0.005	-0.008	0.005	-0.005	-0.013	0.048	0.092	0.086	0.03	-0.01	0.033
N7	-0.011	0.008	0.01	-0.013	0	-0.01	0.01	0.038	0.101	0.104	0.025	-0.028	0.05
N8	-0.01	-0.016	0.035	-0.028	0.007	0.01	-0.025	0.04	0.115	0.156	0.015	-0.009	-0.071
N9	0.026	0.001	0.03	0.017	0.041	0.035	-0.003	0.17	0.16	0.268	0.05	-0.001	0.045
N10	0	-0.016	0.015	0.009	0.034	0.011	0.01	0.083	0.128	0.099	0.045	-0.01	0.029
N11	0.027	0.007	0.04	0.028	0.029	0.023	0	0.07	0.085	0.073	0.04	-0.01	0.074
N12	-0.014	0.002	-0.005	0.013	0.003	0.016	-0.035	0.045	0.075	0.081	0.035	-0.008	0.019
N13	0.045	0.044	0.07	0.04	0.061	0.05	0.04	0.13	0.11	0.105	0.06	0.014	0.057
N14	0.004	-0.019	0.018	-0.01	0.01	0.025	-0.025	0.05	0.065	0.028	0.025	0	0.065

Northern transect (on intact moss)

	6.2.06	14.3.06	23.5.06	19.6.06	18.7.06	15.8.06	20.9.06	23.10.06	19.3.07	30.5.07	27.6.07	30.7.07	28.8.07
NX	0.047	0.036	0.245	0.245	0.255	0.365	0.054	0.025	0.05	0.18	0.04	0.09	0.08
N0	0.069	0.08	0.22	0.22	0.305	0.325	0.105	0.095	0.19	0.215	0.085	0.14	0.13
N1	-0.005	0.025	0.225	0.225	0.255	0.475	0.02	0.035	0	0.07	0.045	0.03	0.08
N2	-0.005	0.008	0.2	0.2	0.18	0.365	0.025	0.02	0.025	0.095	0.045	0.05	0
N3	0.059	0.035	0.26	0.26	0.435	0.49	0.045	-0.025	0.095	0.205	0.045	0.07	0.18
N4	0.085	0.085	0.235	0.235	0.195	0.225	0.075	0.05	0.065	0.25	0.13	0.17	0.21
N5	0.105	0.035	0.265	0.265	0.358	0.44	0.08	0.03	0.08	0.245	0.015	0.16	0.19
N6	0.025	0	0.105	0.105	0.245	0.275	0	0	-0.005	0.135	0.005	0.05	0.07
N7	0.025	0.011	0.21	0.21	0.3	0.405	0.025	0.015	0.015	0.1	-0.01	0.04	0.06
N8	0.015	-0.004	0.195	0.195	0.315	0.4	0.005	-0.005	0	0.15	0.005	0.05	0.12
N9	0.044	0.03	0.34	0.34	0.29	0.365	0.045	0.028	0.03	0.275	0.025	0.1	0.17
N10	0.037	0.013	0.18	0.18	0.19	0.28	0.03	0.02	0.02	0.17	0.005	0.06	0.1
N11	0.047	0.01	0.21	0.21	0.245	0.25	0.03	0	0	0.16	0.01	0.015	0.07
N12	0.02	-0.015	0.125	0.125	0.2	0.25	0.05	0.015	0.005	0.115	0.01	0.03	0.07
N13	0.06	-0.03	0.145	0.145	0.166	0.255	0.08	0.06	0.045	0.165	0.09	0.12	0.09
N14	0.032	0.005	0.085	0.085	0.175	0.18	0.03	0.02	0.02	0.12	0.02	0.04	0.06

Northern transect (on intact moss)

	22.10.07	26.11.07	15.1.08
NX	0.11	0.02	0
N0	0.1	0.08	0.07
N1	0.03	0	0.02
N2	-0.05	0.02	0.02
N3	0.09	0.09	0.14
N4	0.1	0.09	0.05
N5	0.11	0.06	0.05
N6	0.03	0.01	0
N7	0.03	0.01	-0.01
N8	0.09	0.05	0.01
N9	0.07	0.04	0.04
N10	0.06	0.03	0.01
N11	0.06	0.05	0.01
N12	0.01	0.01	0
N13	0.11	-0.01	0.04
N14	0.04	0.02	0.03

Southern transect (on area with herringbone drain pattern)

	21.10.03	18.11.03	18.12.03	20.1.04	17.02.04	16.03.04	20.04.04	18.05.04	16.06.04	17.07.04	16.08.04	17.09.04	17.10.04
S1	0.194	0.032	0.045	0	0.025	0.008	0.021	0.09	0.155	0.056	0	0.005	0.012
S2	0.424	0.307	0.125	0.02	0.04	0.105	0.072	0.096	0.13	0.142	0.03	0.068	0.035
S3	0.236	0.037	0	0.009	-0.035	0.033	0.044	0.077	0.085	0.0625	0	-0.002	-0.004
S4	0.161	-0.005	0	-0.014	-0.022	-0.014	-0.006	0.016	0.18	0.122	-0.02	0.054	0.005
S4a	0.234	0.01	0.02	0.061	-0.031	0.062	0.086	0.077	0.138	0.019	0.05	-0.021	0.061
S5	0.367	0.21	0.1	0.032	0.005	-0.001	0.085	0.077	0.162	0.167	0.045	0.067	0.065
S6	0.446	0.032	0.07	0.036	0.02	0.009	0.069	0.04	0.11	0.06	0.035	0.053	0.052
S7	0.244	0.005	0.08	0.009	0.01	-0.004	0.028	0.064	0.125	0.115	0.01	0.039	0.015
S8	0.258	0	0.035	0.011	0.01	-0.018	0.057	0.101	0.14	0.073	-0.015	0.046	0.045
S8a	0.279	0.05	-0.015	0.048	0	0.064	0.056	0	0.19	0.159	0.03	0.037	0.043
S9	0.362	0.052	-0.04	0.023	0.005	0.029	0.055	0.095	0.125	0.108	0.025	0.048	0.034
S9a	0.475	0.075	-0.02	0	0	0	0.002	-0.007	0.187	0.024	-0.015	-0.002	-0.045
S10	0.74	0.685	0.06	0.043	-0.045	0.066	-0.077	0.076	0.13	0.139	0.02	-0.075	0.074
S11			0.04	0.029	-0.045	-0.002	-0.02	0.141	0.31	0.319	-0.02	-0.004	-0.022

	22.11.04	22.12.04	16.1.05	15.2.05	20.3.05	19.4.05	23.5.05	23.6.05	18.7.05	22.8.05	26.9.05	25.10.05	22.11.05
S1	0.016	-0.007	0.01	0.015	0.009	0.015	-0.025	0.09	0.117	0.097	0.045	-0.015	0.019
S2	0.04	0.005	0.06	0.039	0.062	0.048	0.021	0.08	0.124	0.216	0.185	0.043	0.06
S3	0.014	-0.009	0.012	0.015	0.027	0.01	-0.005	0.055	0.098	0.114	0.033	-0.014	0.038
S4	-0.042	-0.021	0.018	-0.012	0.005	-0.005	-0.032	0.057	0.063	0.07	0.025	-0.03	0.011
S4a	0.031	0.059	0.07	0.026	0.09	0.057	0.025	0.11	0.125	0.13	0.085	0.04	0.07
S5	-0.011	0.025	0.067	0.07	0.069	0.05	0.002	0.07	0.12	0.145	0.137	0.04	0.107
S6	0.024	-0.014	0.068	0.049	0.054	0.038	0.017	0.105	0.095	0.091	0.125	0.015	0.048
S7	0.012	-0.004	0.05	0.026	0.033	0.005	-0.013	0.115	0.16	0.131	0.075	-0.013	0.034
S8	-0.005	-0.008	0.04	0.04	0.033	0.035	-0.05	0.135	0.12	0.134	0.055	-0.008	0.029
S8a	0.035	0.027	0.063	0.06	0.055	0.04	0	0.093	0.22	0.228	0.105	-0.005	0.059
S9	0.023	0.028	0.023	0.05	0.036	0.025	0.015	0.125	0.105	0.092	0.095	0	0.039
S9a	-0.034	-0.02	-0.015	0.008	-0.001	-0.015	-0.03	0.035	0.155	0.133	-0.005	-0.028	0.023
S10	0.032	0.063	0.082	0.082	0.081	0.092	0.023	0.09	0.095	0.251	0.125	0.064	0.105
S11	-0.042	0.018	0.03	0.099	-0.005	-0.018	0.293	0.245	0.36	0.309	0.22	0	0

Southern transect (on area with herringbone drain pattern)

	6.2.06	14.3.06	23.5.06	19.6.06	18.7.06	15.8.06	20.9.06	23.10.06	19.3.07	30.5.07	27.6.07	30.7.07	28.8.07
S1	0.015	0.02	0.019	0.135	0.177	0.26	0.055	0.02	0.01	0.19	0.02	0.05	0.13
S2	0.079	0.015	-0.042	0.17	0.153	0.315	0.2	0.03	0.04	0.25	0.05	0.18	0.21
S3	0.03	-0.03	0.002	0.14	0.177	0.375	0.06	0.015	0.015	0.14	0	0.08	0.09
S4	0.073	-0.02	-0.029	0.15	0.179	0.29	-0.015	0	-0.02	0.145	0	0.03	0.09
S4a	0.012	-0.01	0.035	0.205	0.144	0.295	0.065	0.06	0.04	0.17	0.03	0.11	0.12
S5	0.16	0.025	0.041	0.245	0.234	0.325	0.15	0.115	0.035	0.195	0.075	0.14	0.195
S6	0.089	0.01	0.054	0.12	0.101	0.16	0.14	0.035	0.02	0.14	0.05	0.12	0.12
S7	0.04	-0.005	0.015	0.17	0.158	0.04	0.09	0.01	0.01	0.18	0.035	0.11	0.18
S8	0.023	-0.03	0.001	0.18	0.148	0.17	0.07	0.01	0	0.17	0.07	0.12	0.19
S8a	0.04		0.053	0.275	0.242	0.39	0.125	0.07	0.06	0.29	0.07	0.13	0.175
S9	0.048	0.02	0.06	0.095	0.207	0.255	0.095	0.015	0.03	0.11	0.065	0.09	0.175
S9a	-0.003	-0.03	-0.024	0.17	0.296	0.345	0.06	-0.02	0	0.08	0	0.09	0.1
S10	0.105	0.04	0.086	0.17	0.135	1.13	0.065	0.11	0.15	0.36	0.065	0.28	0.24
S11	0.115		0.007	0.35	0.258	0.3	0.11	0.015	0	0.23	-0.0025	0.23	0.21

Southern transect (on area with herringbone drain pattern)

	22.10.07	26.11.07	15.1.08
S1	0.07	0.03	-0.03
S2	0.06	0.08	0.06
S3	0.05	0.06	0.05
S4	0.02	0.01	-0.01
S4a	0.09	0.07	0.04
S5	0.17	0.11	0.04
S6	0.12	0.05	0.04
S7	0.08	0.04	0.01
S8	0.09	0.07	0.01
S8a	0.16	0.09	0.03
S9	0.11	0.04	0
S9a	0.01	0	-0.01
S10	0.2	0.13	0.09
S11	0.1	0.03	0

north west transect

	20.9.06	23.10.06	19.3.07	30.5.07	27.6.07	30.7.07	28.8.07	24.9.07	22.10.07	26.11.07	15.1.08
NW1	0.025	0.01	0.01	0.06	0.03	0.02	0.025	0	0.04	0.01	0.01
NW2	0.01	0	0.005	0.06	0	0.01	0.04	-0.03	0.01	0	-0.01
NW3	0	0	0.01	0.01	0.03	-0.01	0	0.01	0	0	-0.02
NW4	-0.02	-0.01	-0.03	0.04	-0.01	0	-0.01	0	0.16	0	0
NW5	-0.06	-0.02	0.015	0.05	-0.02	0	0.02	-0.01	0	-0.01	-0.02
NW6	0.03	0.01	0.02	0.07	-0.01	0.04	0.045	0.02	0.05	0.02	0.03
NW7	0	-0.01	-0.01	0.015	-0.03	-0.03	0.005	-0.06	0.02	0.01	0.01
NW8	-0.04	-0.08	-0.07	-0.02	-0.08	-0.04	0	-0.1	-0.03	-0.04	-0.08
NW9	0	-0.01	-0.01	0.02	0.01	0	0	-0.02	0.02	0	0
NW10	0	0.015	0.015	0.06	-0.03	0.03	-0.03	-0.01	0.04	0.04	0.01
NW11	-0.03	-0.015	-0.02	0.01	0.01	0	0	-0.02	0.03	0	-0.03
NW12	0.1	0.1	0.095	0.18	0.105	0.07	0.13	0	0.07	0.02	0.03
NW13	0.04	0.06	0.09	0.165	0.05	0.075	0.09	0.08	0.05	0.03	0.02

Appendix 3 Summary of dipwell and LiDAR survey data for Walton and Bolton Fell Mosses

Walton Moss

Dipwell name	Standard deviation dGPS (m)	Standard deviation LiDAR (m)	mean depth to water table (m)	Standard deviation depth to water table (m)
N1	N/A	0.417678	0.0442686	0.0962065
N2	N/A	0.0962019	0.0411332	0.08339621
N3	N/A	0.260636	0.114148	0.13640706
N4	0.0620964	0.126296	0.1082575	0.06526849
N5	0.0733694	0.324602	0.1409382	0.1237365
N6	0.0224795	0.169625	0.0367857	0.06541256
N7	0.0440491	0.0817405	0.0454823	0.08941222
N8	0.061719	0.0829305	0.0536959	0.09292639
N9	0.0761935	0.441046	0.1014668	0.10702435
N10	0.0602988	0.205729	0.0556048	0.06641282
N11	0.0503173	0.109004	0.0577536	0.06691391
N12	0.0341129	0.0585074	0.0355166	0.05652969
N13	0.0371174	0.0579919	0.0817857	0.05136542
N14	0.0352379	0.0627921	0.0326443	0.04406645
S1	0.0547089	0.0973925	0.0508864	0.06224923
S2	0.0618339	0.146392	0.1014773	0.082854
S3	0.0938636	0.149932	0.0501477	0.06949596
S4	0.0311223	0.0952548	0.032	0.07085666
S5	0.0456215	0.14926	0.1049545	0.07492554
S6	0.0317218	0.0773985	0.0727273	0.04215219
S7	0.0421374	0.0865819	0.05725	0.0580545
S8	0.0417234	0.104617	0.0601364	0.06270617
S9	0.0519373	0.15679	0.0707273	0.05663204
S10	0.0618901	0.212458	0.1484773	0.19729737
S11	0.0560656	0.0860132	0.1023049	0.13156799
NW1	0.0499095	0.055663	0.0218182	0.01706938
NW2	0.0503276	0.0433472	0.0086364	0.02388419
NW3	0.0542167	0.0780114	0.0027273	0.01272078
NW4	0.0508887	0.0591351	0.0109091	0.05243177
NW5	0.0596231	0.0687639	-0.005	0.02801785
NW6	0.0682727	0.094495	0.0295455	0.02150053
NW7	0.0532362	0.0634073	-0.007273	0.02422433
NW8	0.0532532	0.0657005	-0.052727	0.03101319
NW9	0.0671311	0.0737398	0.0009091	0.01221028
NW10	0.0809934	0.066573	0.0127273	0.02892781
NW11	0.0614677	0.0881468	-0.005909	0.0188173
NW12	0.0349283	0.161309	0.0818182	0.05178189

Bolton fell Moss

Dipwell name	Standard deviation dGPS (m)	Standard deviation LiDAR (m)	mean depth to water table (m)	Standard deviation depth to water table (m)
N1	0.0549933	0.152417	0.06275	0.08737337
N2	0.0439572	0.165785	0.0333542	0.06112474
N3	0.054469	0.140747	0.0979375	0.07006878
N4/E7	0.0595322	0.112602	0.0638125	0.05710113
N5	0.0556589	0.099843	0.0415	0.04918441
N6	0.084687	0.0778182	0.038625	0.05835315
N7	0.0526795	0.151498	0.0590625	0.04171912
N8	0.0335147	0.255052	0.1895	0.15736933
N9	0.0409789	0.136152	0.22075	0.12554299
N10	0.0621345	0.371424	0.0616596	0.07355219
N11	0.0358997	0.233656	0.3271064	0.08449292
E1	0.0475316	0.150492	0.1153333	0.05209253
E2	0.0548922	0.103947	0.090625	0.04600075
E3	0.0573902	0.0872759	0.0486042	0.05721246
E4	0.0813247	0.0885249	0.08775	0.05075578
E5	0.0657919	0.0875362	0.1130208	0.06364445
E6	0.0672742	0.10563	0.0684375	0.05332235
E7/N4	0.0595322	0.112602	0.0621667	0.05668439
E8	0.0564614	0.0846211	0.0494792	0.0513685
E9	0.0510711	0.102463	0.1242083	0.0864481
E10	0.0601657	0.0957819	0.0398333	0.05622119
E11a	0.0538281	0.195882	0.2493415	0.08885173
E11	0.0793802	0.097752	0.1545745	0.05743645
E12	0.0588232	0.0940131	0.0643958	0.07603687
E13	0.0485208	0.0994588	0.0825652	0.06452998

Appendix 4 Species Abundance for each quadrat

Walton Moss north transect

Surveyors: Helen O'Brien, Roger Hart, Louise Gentle

Surveyed 18 July 2005

Associated dipwell	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14
Mean Sward Ht (m)	0.85	0.9	0.18	0.25	0.13	0.23	0.17	0.22	0.17	0.21	0.23	0.17	0.2	0.22
Grazing Index	4	4	4	3	4	4	4	5	3	4	5	5	5	5
Species														
Agrostis canina				2					5					
Andromeda polifolia							5			7	2		2.5	2.5
Aulacomnium palustre				23				1.5						
Bare ground			3	1										
Calluna vulgaris											4	4		2
Carex rostrata		3		4										
Deschampsia flexuosa	1.5	2	2	9	3				5					
Drepanocladus fluitans			3							1				
Drosera rotundiflora						6	4.5			0.25	1.25	2.75	1.25	1
Empetrum nigrum											4			
Erica tetralix					6	12	1	8		24	19	19	14	16
Eriophorum angustifolium		0.25								1		1		
Eriophorum vaginatum					36	17		44	8	31.75	34.75	27.25	32.25	17.5
Festuca ovina			15											
Flower A (purple)							1	0.5						
Galium saxatile	7		1											
Holcus mollis	3.5													
Hydrocotyle vulgaris	1													
Hylocomium splendens			2						3					
Juncus auriculatus	21	7												
Juncus effusus	5	14	1											
Juncus squarrosus			7											

Molinia caerulea		0.25	47.5		3			13	29	11				
Narthesium ossigragum					31	14	5			7		5		3
Polytrichum commune	20	55.5	4.5	25					12					
Potentilla erecta	1		13											
Scirpus cespitosus						9						6	12	14
Scirpus setaceus			1											
Sphagnum capillifolium					6				2		4			
Sphagnum cuspidatum					8	2	4	3	3	3		4.5	2	
Sphagnum magellanicum		17				33	24	13	4		2	23	26	26
Sphagnum papillosum	35										4	2		
Vaccinium myrtillus									19	2				
Vaccinium oxycoccus	1		20	7	3	10	17	10	12	25	5.5	10	3	

Walton Moss south transect
Surveyors: Helen O'Brien, Roger Hart, Louise Gentle
Surveyed 18 July 2005

Associated Dipwell	S1	S2	S3	S4	S5	S6	S7	S8	S9	S9a	S10	S11
Mean Sward Ht (m)	0.21	0.31	0.16	0.28	0.19	0.28	0.21	0.2	0.3	0.16	0.23	0.27
Grazing Index	5	5	5	5	5	5	5	5	5	5	5	5
Species												
Agrostis canina		2										
Andromeda polifolia				2	2	25	1			5		
Bare ground											5	
Calluna vulgaris	1.5		4	15	8	3	2	20		10		2
Deschampsia flexuosa						6	10	20			40	25
Drosera rotundiflora			2	12			1					
Empetrum nigrum								5				
Erica tetralix	14			9	14	14	10	10	15	5		1
Eriophorum angustifolium	2		2	2	1	2						
Eriophorum vaginatum	55.5		66	39	40	9	60	60	25	20	20	
Festuca ovina											5	
Galium saxatile		2										
Hylocomium splendens	1	2										
Hypnum cupressiforme		18					5				20	5
Juncus conglomeratus		1										25
Molinia caerulea		71				1			20			
Narthesium ossigragum										5		
Polytrichum commune		1										40
Scirpus cespitosus			1				10					
Sphagnum capillifolium				2	9	3		10		8		
Sphagnum cuspidatum						1						

Sphagnum magellanicum	10		18	11		6	20	30	30	42	5	
Sphagnum palustre				2		1						
Vaccinium myrtillus	8				2				10			10
Vaccinium oxycoccus	8	3	15	6	20	22	5	10	10	20		

Walton Moss north west transect
Surveyors: Roger Hart, David Topliss
Surveyed 21 June 2007

Associated dipwell	NW1	NW2	NW3	NW4	NW5	NW6	NW7	NW8	NW9	NW10	NW11	NW12	NW13
Mean sward height	15	23	18	20	20	20	18	15	14	14	16	22	25
Grazing index	5	5	5	5	5	5	5	5	5	5	5	5	5
Species													
Andromeda polifolia	1	3	1		1	1	2	1	1	1	1	1	
Calluna vulgaris	4	2	1	25	8	14	5	12	1	10	3	12	
Drosera rotundiflora	1	1						1		0.5	1	1	
Empetrum nigrum					30	1	5	6	11	1			
Erica tetralix	5	2	2	3	1	2	11	10	3	8	6	6	1
Eriophorum angustifolium			8			3	3		2	6	4	10	
Eriophorum vaginatum	40	25	12	4	15	12	12		14		26	4	
Hypnum cupressiforme	1	1	5			5							
Hypnum cupressiforme					15								
Molinia caerulea													75
Polytrichum commune			10		2		4		1		3		1
Vaccinium myrtilus													7
Vaccinium oxycoccus	5		30	2	2	1	1	1		2	2	3	5
Sphagnum magellanicum	65	80		85	14	50	48	60	60	70	45	60	
Sphagnum cuspidatum	5	10	20				4		4	1	5	6	
Sphagnum capillifolium						5		5					7
Sphagnum palustre										1			

Bolton Fell Moss north transect vegetation.
Surveyors: Helen O'Brien, Roger Hart, Louise Gentle
Surveyed 20.07.05

Associated Dipwell	outside bund	N1	N2	N3	N4/E7	N5	N6	N7	N8	N9	N10	New Mill
Mean Sward Ht (m)	0.19	0.18	0.26	0.11	0.2	0.18	0.36	0.19	0.15	0.5	0.275	0.18
Grazing Index	5	5	5	5	5	5	5	5	5	5	5	5
Species												
Andromeda polifolia	1	4	9		0.5	2	5	2				
Aulacomnium palustre				9	5.5							
Bare ground	3								5		4	51
Betula pendula				80	0.5							0.25
Cladonia portentosa		7				0.5	5					
Cladonia sp						0.75						
Calluna vulgaris	11	22	3	3	10	11	28		59	67	67	11
Drosera rotundifolia	0.5	0.5						7	3		1	0.5
Empetrum nigrum		1.5	46	11	37	76.25				4		
Erica tetralix	6		13	9		12	13	14	1		9	
Eriophorum angustifolium	67	31	8		6.5	0.25		1.5	7			3.5
Eriophorum vaginatum				4	4	10		19.5	17		4	31
Hylocomnium splendens					2	2				15		
Molinia caerulea											2	
Narthesium ossigragum								4				
Pinus sylvestris			1									
Pleurozium schreberi	2	1	3	22		4	24	12		13		
Polytrichum commune	1			0.5	3	3	2.5		5	1	12	5
Psuedoschleropodium purum											10	
Spagnum papillosum	29	7	20									

Sphagnum capillifolium		8			52		19					
Sphagnum magellanicum							2	21	3		8	
Sphagnum subnitens		11				15		13			3	
Vacinnium myrtillus				1								
Vacinnium oxyccocus	2	4		9	13	3.25	9	6	0.25			

Bolton Fell Moss east transect vegetation.
Surveyors: Roger Hart, Jane Robbins
Surveyed 20.05.08

Associated Dipwell	E0	E1	E2	E3	E4	E5	E6	E7/ N4	E8	E9	E10	E11A	E11	E12	E13
Species															
Agrostis canina	2														
Andromeda polifolia	1	1		1	1	2	1	0.5	1	1	1		1	1	3
Bare ground	7			8								60		1	
Betula pendula			1			8	1	0.5	2	1	1	1	1		
Calluna vulgaris	6	7	4	25	35	15	6	10	11	25	15	12	80		4
Drosera rotundiflora												2		1	
Empetrum nigrum		25	90		3	25	50	37	3	8	50		2		20
Erica tetralix		3	2		6	3	3		2		2	1		7	4
Eriophorum angustifolium						1		6.5	5	2	2	20		4	3
Eriophorum vaginatum	15	6	6	18	7	6	13	4	30	10	12		5	8	7
Molinia caerulea		1													
Narthecium ossifragum														1	
Pinus sylvestris			2												
Vaccinium oxycoccus	5	15	2	8	6	5	13	13	20	2	8	1		3	3
spagnum papillosum	70				10										
sphagnum capillifolium		60	5		10	8	16	52	9	20	25		10	15	40
sphagnum subnitens							10								
sphagnum magellanicum									4					40	10
other mosses				13	35	25	6	13	50	20	20		5		

NB non *sphagna* were collectively recorded as "other mosses"
Grazing index and sward height were not recorded, however there was no apparent evidence of grazing

Appendix 5 Modular Analysis of Vegetation Information System (MAVIS) analysis of NVC type by dipwell location

n1			n2			n3			n4			n5	
H9d	38.91		M4	35.26		U5a	42.09		M4	31.29		M18a	42.41
U2	32.83		H9e	35.09		U5b	40.79		M2b	30.99		M21b	42.17
M6c	32.68		M6c	29.67		H9d	40.44		S9a	27.03		M2	40.87
U2a	30.09		U2b	27.5		U5d	40.21		U6b	26.17		M17a	40.72
U4e	29.88		S9a	25.05		U4e	39.86		S9	25.32		M17	39.97
U5b	29.41		M6a	24.07		U2b	39.68		S12d	24.81		M2b	39.13
U5a	29.31		W4	24.06		U5	39.63		U16c	22.68		M21	38.99
U2b	28.89		W4c	24.01		U2	39.55		M5	21.9		M19a	38.85
W4b	28.85		S9	23.81		M15d	39.22		M2	21.81		M18	37.77
U16c	27.43		S12d	23.44		U2a	39.14		H9e	21.28		M17b	37.4
n6			n7			n8			n9			n10	
M2	46.51		M2	51.68		M2	43.66		U2b	38		M2	54.11
M18a	44.44		M18a	49.57		M2b	42.45		H22a	36.41		M2b	51.49
M2b	42.3		M2a	47.5		M18a	41.07		M18a	32.67		M21b	51.01
M21	38.99		M2b	47		M21b	36.29		M19a	32.26		M21	49.7
M21b	38.5		M21	38.99		M18	36.24		W18d	32.21		M18a	49.66
M2a	37.5		M21b	38.5		M21	32.49		M2b	31.4		M2a	48.88
M18	34.74		M18	36.12		M16a	30.73		M4	29.91		M21a	41.35
M21a	32.87		M21a	32.87		M18b	30.7		M19	29.52		M3	40.11
M17a	31.32		M17a	31.32		M2a	29.69		M2	29.44		M17a	39.49
M17	30.16		M17	30.16		M19a	29.1		M15d	29.01		M18	39.22
n11			n12			n13			n14				
M18a	56.69		M2	59.5		M2	49.67		M18a	49.57			
M2	48.55		M18a	56.69		M2a	45.51		M2	43.93			
M18	47.04		M2b	54.68		M2b	45.13		M21	38.99			
M2b	46.71		M21b	51.52		M18a	42.74		M17a	37.85			
M17a	40.94		M21	51.51		M18	31.2		M18	37.77			
M21	40.53		M18	47.36		M21	29.24		M2a	37.08			

M18b	39.29		M2a	46.2		M21b	28.37		M17	36.77			
M17	38.49		M21a	44.59		M21a	24.22		M21b	36.47			
M21b	38.32		M17a	42.12		M18b	23.83		M21a	36.33			
M19a	36.7		M17	41.18		M17a	23.49		M2b	35.25			
s1			s2			s3			s4			s5	
M2	48.54		U6d	27.23		M2	50.35		M18a	54.35		M2	52.91
M18a	45.23		M15c	26.13		M2b	47.98		M2	52.1		M18a	50.89
M2b	44.4		U5b	24.6		M18a	44.64		M2b	47.92		M19a	49.95
M19a	43.52		U5	24.26		M18	36.24		M18	46.41		M2b	49.88
M18	40.72		U5a	23.24		M21	34.84		M19a	45.38		M18	44.01
M19	36.65		H10a	22.04		M21b	34.15		M18b	40.36		M19	40.13
M18b	34.99		H9d	21.92		M20	33.85		M17a	39.22		M18b	39.24
M20	34.56		H1d	21.24		M20a	32.56		M17	38.24		M20	38.69
M21b	34.42		M6a	20.83		M19a	30.77		M19	36.78		M19b	38.37
M17b	34.13		U20	20.81		M17a	29.56		M17b	35.85		M2a	37.93
s6			s7			s8			s9			s9a	
M18a	56.2		M18a	46.58		M19a	39.18		M2	35.61		M18a	54.7
M2	54.44		M2	45.77		M18a	39.02		M18a	35.22		M18	44.33
M2b	50.51		M2b	42.06		M18	36.12		M19a	32.62		M2	43.93
M18	48.75		H9a	36.95		M17	33.57		M2b	31.96		M19a	40.7
M19a	44.96		M18	35.93		M17a	32.89		M18	30.41		M2b	39.95
M17a	44.41		M19a	35.29		H9e	32.26		M21b	29.31		M17a	39.43
M21b	43.15		M17	32.57		M18b	32.24		H4	29.22		M17	38.37
M18b	42.79		M2a	31.11		M19	31.77		H3a	28.69		M17b	37.67
M17	42.21		M17a	30.3		M2	31.01		M16a	28.28		M18b	36.67
M2a	42		M21	30.2		M17b	30.89		H4d	28.24		M21b	36.14
s10			s11										
H1d	40		H9a	51.36									
H9a	35.59		U2b	45									
H1c	34.42		H9c	39.74									
H1	32.37		H9	38.81									

U2	31.5		H8e	38.77									
U2b	31.03		H2b	38.27									
U2a	30.96		H9d	38.24									
H1a	28.53		U2	38.1									
U6b	28.35		H12a	38.1									
U5a	27.08		H9e	38									
nw1			nw2			nw3			nw4			nw5	
M2	53.99		M2a	48.58		M2	58.9		M2	45.53		M18a	37.16
M18a	50.45		M2	44.76		M2b	58.3		M18a	41.18		M2	33.98
M2b	49.33		M18a	41.07		M2a	47.56		M2b	40.46		M19a	33.87
M2a	44.71		M2b	35.35		M18a	46.85		M18	35.88		M18	31.1
M18	39.15		M21	34.84		M19a	42.44		M19a	34.37		M2b	29.15
M21	35.32		M21a	32.55		M18	40.44		H1e	31.06		M15c	28.96
M21b	34.72		M21b	32.02		M21b	38.24		H3a	30.91		H1d	28.94
M19a	33.33		M16a	31.4		M18b	36.56		H2c	30.89		M17b	28.13
M17	32.06		M18	30.82		M21	35.32		M16a	30.22		M17	27.48
M17a	31.44		M16	27.09		M17b	34.38		M18b	29.97		M19	27.29
nw6			nw7			nw8			nw9			nw10	
M18a	53.17		M2	57.21		M2	49.67		M2	53.4		M2	52.1
M2	48.55		M2b	55.2		M2a	45.51		M2a	49.41		M2a	46.67
M18	45.21		M18a	50.04		M2b	45.13		M18a	47.19		M2b	46.27
M2b	44.59		M2a	46.67		M18a	44.44		M2b	47.09		M18a	43.78
M19a	44.03		M18	42.2		M21	37.04		M18	40.72		M21	36.71
M18b	39.29		M19a	37.26		M21b	36.47		M19a	37.43		M21b	36.5
M17b	37.85		M18b	36.89		M18	32.84		M18b	35.42		M18	36.17
M17	37.01		M21b	36.5		M21a	31.14		M3	33.96		M21a	31.85
M17a	36.31		M21	35.24		M16a	29.61		M21	33.18		M18b	28.81
M2a	35.56		M3	31.3		M16	25.64		M21b	32.5		M16a	28.37
nw11			nw12			nw13							
M2	64.07		M2	66.26		M19a	34.66						
M2b	61.57		M2b	60.54		M21b	33.15						

M18a	56.29		M18a	57.38		M25a	31.9						
M2a	53.33		M2a	56.47		M15c	31.6						
M18	45.21		M18	45.74		M15	30.77						
M21	44.05		M21	44.61		M15d	30.6						
M21b	43.8		M21b	44.36		M21	29.95						
M19a	38.66		M21a	38.14		M18a	29.41						
M18b	37.98		M19a	36.84		M2b	29.29						
M21a	36.62		M18b	36.56		H4	29.22						
OB			n1			n2			n3			n4	
M2b	58.3		M18a	45.45		M2	45.33		M19a	47.75		M2b	46.71
M2	56.44		M2b	42.34		M18a	42.86		M2b	40.36		M18a	43.78
M18a	52.07		M2	39.74		M18	41.1		U2b	40		M2	41.19
M21	50.19		M18	39.47		M2a	40.49		M18a	38.77		M19a	40.34
M21b	49.71		M21	37.41		M2b	40.4		M19	38.52		M19	38.58
M18	45.42		M21b	36.65		M21	39.3		M18	37.59		M18	37.68
M2a	42.81		M18b	34.24		M21b	38.42		M18b	36.56		M19b	36.95
M19a	40.03		M19a	32.03		M19a	36.86		M2	36.41		M18b	35.57
M21a	39.8		M17a	31.23		M18b	35.09		H12a	35.83		M19c	32.21
M18b	39.27		M21a	30.42		M21a	34.36		M19b	35.23		M20	32.05
n5			n6			n7			n8			n9	
M2b	44.15		M18a	43.94		M18a	49.69		M2	59.43		H22a	35.46
M2	43.52		M18	37.59		M2	45.3		M2b	57.01		W18a	33.52
M19a	43.11		M19a	35.09		M18	41.92		M18a	52.59		H12a	32.83
M18a	41.79		M2	33.98		M2a	40		M21	44.44		H1e	31.06
M18	37.6		M18b	32.5		M2b	39.96		M18	44.33		W18d	30.02
M19	37.01		M2b	31.08		M19a	36.97		M21b	44.18		W18b	29.17
M18b	35.65		W18d	28.64		M21	35.52		M19a	42.2		H12b	29.01
M19c	33.96		M19	27.09		M17	35.06		M18b	37.84		H16b	28.99
M19b	33.87		M17	25.78		M21b	34.67		M17a	37.59		U2b	28.57
M17	32.68		M15c	25.32		M18b	34.05		M2a	37.5		H12	28.46
n10			NM										

M21	42.4		M2	41.96									
M17a	42.2		M2b	40.4									
M18a	42		M20	36.04									
M16a	40.55		M20a	34.85									
M17	39.69		M18a	33.66									
M2	38.42		M19a	32.98									
M21a	38.14		M3	32.72									
M21b	37.91		M19b	31.33									
M19a	36.84		M19	31.17									
H2c	36.21		M21	30.74									
e0			e1			e2			e3			e4	
M2b	42.45		M18a	44.44		M19a	40.77		M2b	37.57		M18a	47.86
M2	39.16		M2	41.83		M2	39.63		M2	36.3		M2b	45.13
M18a	33.93		M19a	40.7		M18a	39.25		H1e	31.06		M2	44.97
M18	29.11		M2b	39.95		M2b	37.74		M18a	29.41		M18	42.69
M18b	24.85		H2c	38.92		M18	36.07		M20	23.95		M19a	38.53
M17c	24.69		M17a	38.13		M18b	33.38		M19a	23.63		M18b	38.08
H1e	23.7		M18	37.77		M17a	32.79		M18	22.47		M17a	36.54
M21b	23.48		H3a	37.64		M17	31.52		M20a	21.98		M17	35.43
M17	23.31		M15c	36.85		M19	31.02		H9e	21.28		M21b	34.14
M20	23.17		M16a	36.45		M17b	30.58		M19	21.03		M21	33.14
e5			e6			e7			e8			e9	
M2	52.91		M18a	42.41		M2b	42.76		M18a	54.1		M2	48.16
M2b	49.88		M2	39.68		M2	42.33		M2	51.53		M2b	45.45
M18a	49.57		M19a	38.53		M18a	41.03		M2b	47.09		M18a	44.64
M19a	44.4		M2b	38		M19a	35.15		M18	45.74		M2a	38.25
M18	42.69		M18	35.86		M18	34.48		M19a	42.44		M21b	38.05
M18b	38.08		M17a	34.95		M20	33.86		M18b	39.51		M18	37.67
M2a	37.93		M17	33.82		M19b	33.36		M2a	37.65		M19a	36.86
M17a	36.54		M18b	32.24		M19	33.2		M17a	36.42		M21	34.84
M21b	36.14		M19	29.88		M20a	32.66		M17	35.36		M18b	32.16

M17	35.43		M17b	29.48		M18b	31.03		M17b	34.62		M17a	31.43
e10			e11a			e11			e12			e13	
M2b	42.76		M2	42.9		M18a	31.37		M18a	56.69		M18a	54.1
M2	42.33		M2b	40.46		H1e	31.06		M2	50.34		M2	51.53
M18a	41.03		M21b	38.23		M19a	30.37		M2b	46.27		M2b	47.09
M19a	35.15		M21	36.91		M19	27		M18	44.01		M18	45.74
M18	34.48		M16a	33.38		M19b	26.92		M21	42.29		M19a	42.44
M20	33.86		M18a	33.33		M20	26.59		M2a	42.22		M18b	39.51
M20a	32.66		H1e	31.06		M2	26.4		M21b	41.97		M2a	37.65
M19b	31.93		H3a	30.91		M18	26.22		M17a	40.94		M17a	36.42
M19	31.77		H2c	30.89		M17a	25.25		M17	38.49		M17	35.36
M18b	31.03		M16	28.31		M20a	24.77		M19a	36.97		M17b	34.62

Appendix 6 Ellenberg indices for each transect by dipwell

Ellenberg indices for each transect by dipwell

Walton north

quadrat	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	n11	n12	n13	n14
wetness	6.1	5.8	7.2	6	8	7.5	7.8	7.7	7	8.2	7.7	7.3	7.5	7.3
Ph	5.1	5.4	3.1	5	2.6	3.5	3	2.9	3.3	2.2	2.5	3.5	3.7	3.4
Fertility	4.4	5.1	2.1	4.2	1.7	2.5	2.1	1.9	2.7	1.2	1.5	2.5	2.8	2.4

Walton south

quadrat	s1	s2	s3	s4	s5	s6	s7	s8	s9	s9a	s10	s11
wetness	7.5	7.9	7.8	7.1	7.8	8	7.4	6.8	7.4	7.2	6.4	5.7
Ph	2.8	3.3	2.7	2.6	2.4	2.3	2.9	3	3.3	3.7	2.8	4
Fertility	1.8	2.1	1.7	2	1.5	1.6	2	2.4	2.4	2.8	2.4	3.9

Walton north west

quadrat	nw1	nw2	nw3	nw4	nw5	nw6	nw7	nw8	nw9	nw10	nw11	nw12	nw13
wetness	6.9	6.2	7.6	6.2	6.7	6.6	6.6	6.3	6.4	6.5	6.9	6.6	7.7
Ph	4.2	5.6	3.6	4.9	3.1	4.5	4.4	4.5	4.7	5	4.3	4.7	3.1
Fertility	3.2	4.7	2.5	4.1	2	3.5	3.5	3.7	3.7	4	3.3	3.7	2.2

Bolton north

quadrat	outside bund	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	new mill
wetness	7.8	7.4	6.7	6.2	6.4	6.4	6.5	7.2	6.7	6.2	6.1	6.7
Ph	4.2	4.1	3	4.4	4.1	2.8	4.2	4	2.5	3.3	3.2	4.7
Fertility	2.1	2.5	1.9	2.7	3	1.8	3	2.7	2	2.4	2.6	4.8

Bolton east

quadrat	e0	e1	e2	e3	e4	e5	e6	e7	e8	e9	e10	e11a	e11	e12	e13
wetness	6.5	6.6	6.2	7	6.6	6.5	6.6	6.6	7.5	6.6	6.5	6.1	6.1	6.7	6.5
Ph	5	4	2.2	2.6	3	2.7	2.9	3.8	3.1	3.5	2.9	5.9	2.4	4.9	4.2
Fertility	4.2	3.1	1.3	2.4	2.5	2	2	2.8	2.1	2.6	2	6.6	2.2	3.8	3.2

Appendix 7 Interpretation of canonical analysis results

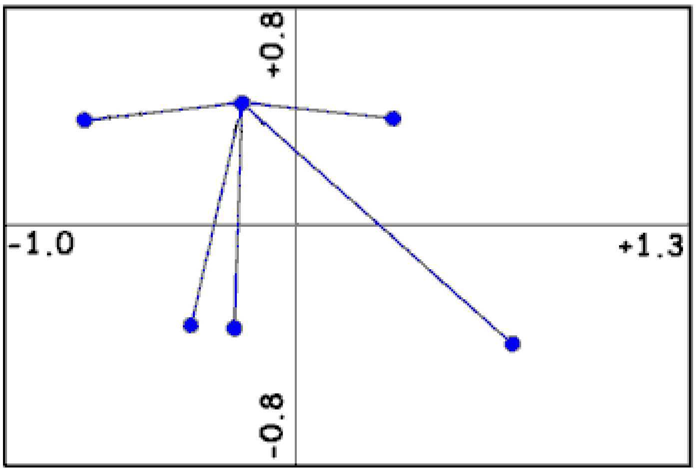
Interpretation of DCA analyses described in section 7.4.

The following text and diagrams are taken from Canoco 4.54 (ter Braak and Smilaur, 2006)

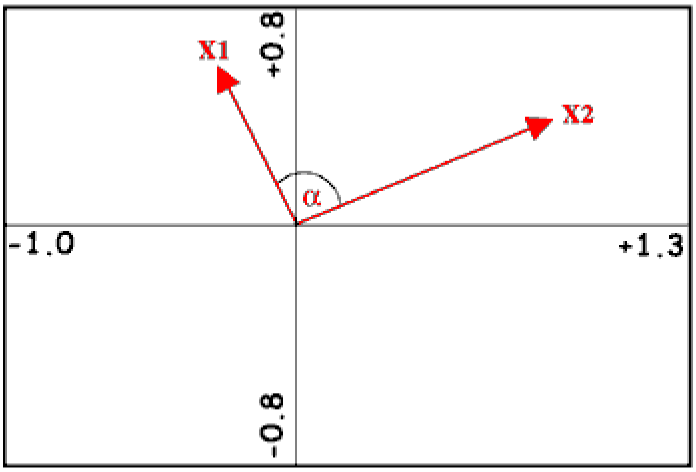
Diagram Interpretation for species and environmental variables

Ordination diagram [Axis 1 x Axis 2] with species, env. variables
There are two types of scores and the following paragraphs suggest how to interpret them separately and in their combinations.
The individual paragraphs are usually followed by simple diagrams illustrating the method of interpretation.

Species points: the distance between the symbols in the diagram approximates the dissimilarity of distribution of relative abundance of those species across the samples, measured by their Chi-square distance. Points in proximity correspond to species often occurring together.



Env. variable arrows: each arrow points in the expected direction of the steepest increase of values of env. variable. The angles between arrows indicate correlations between individual env. variables. More precisely, we can read the approximated correlations of one env. variable with the others by projecting their arrowheads onto the imaginary axis running in the direction of that variable's arrow.



The species symbols can be projected perpendicularly onto the line overlaying the arrow of particular environmental variable. These projections can be used to approximate the optima of individual species in respect to values of that environmental variable. Species projection points are in the order of the predicted increase of optimum value for that variable.

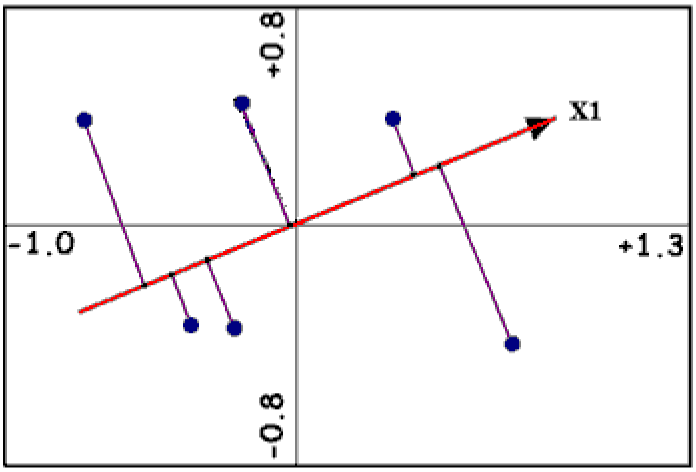
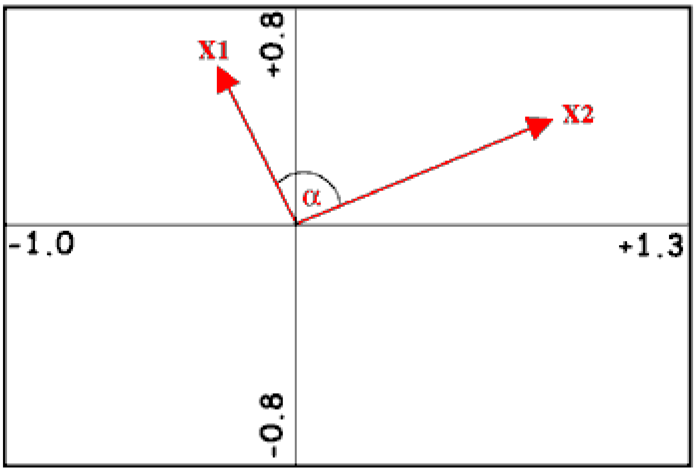


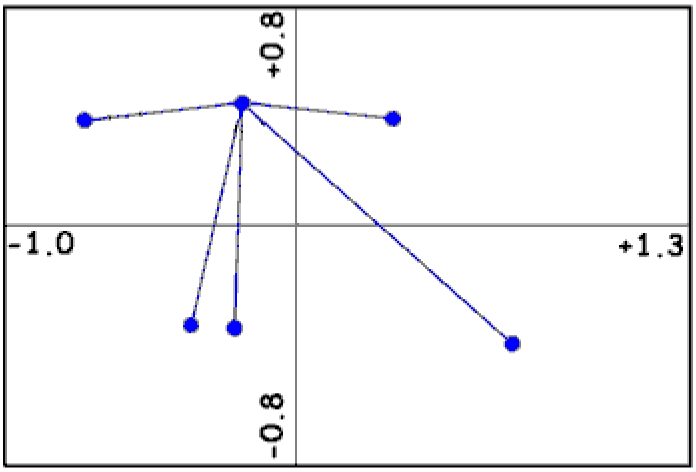
Diagram Interpretation for quadrats and environmental variables

Ordination diagram [Axis 1 x Axis 2] with env. variables, samples
There are two types of scores and the following paragraphs suggest how to interpret them separately and in their combinations.
The individual paragraphs are usually followed by simple diagrams illustrating the method of interpretation.

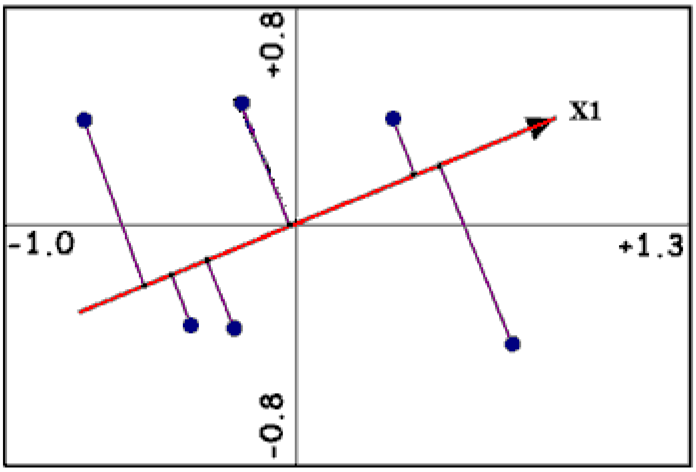
Env. variable arrows: each arrow points in the expected direction of the steepest increase of values of env. variable. The angles between arrows indicate correlations between individual env. variables. More precisely, we can read the approximated correlations of one env. variable with the others by projecting their arrowheads onto the imaginary axis running in the direction of that variable's arrow.



Sample points: the distance between the symbols in the diagram approximates the dissimilarity of their species composition, measured by their Chi-square distance.



The sample symbols can be projected perpendicularly onto the line overlaying the arrow of particular environmental variable. These projections can be used to approximate the variable values in individual samples. The sample points are in the order of predicted increase of values of the particular environmental variable. The predicted increase occurs in the direction indicated by the arrow. The sample points projecting onto the coordinate origin are predicted to correspond to samples with an average value of that environmental variable.



Appendix 8 Summary of Canonical Correspondence Analyses for Bolton Fell and Walton Mosses

Walton Moss north transect

Axes	1	2	3	4	Total inertia
Eigenvalues :	0.298	0.614	0.366	0.198	1.808
Species-environment correlations :	0.753	0.000	0.000	0.000	
Cumulative percentage variance					
of species data :	16.5	50.4	70.7	81.7	
of species-environment relation:	100.0	0.0	0.0	0.0	

Sum of all eigenvalues 1.808
Sum of all canonical eigenvalues 0.298

**** Summary of Monte Carlo test ****

Test of significance of all canonical axes : Trace = 0.298
F-ratio = 1.777
P-value = 0.1140

Walton Moss south transect

Axes	1	2	3	4	Total inertia
Eigenvalues :	0.447	0.232	0.615	0.440	2.409
Species-environment correlations :	0.855	0.739	0.000	0.000	
Cumulative percentage variance					
of species data :	18.6	28.2	53.8	72.0	
of species-environment relation:	65.8	100.0	0.0	0.0	

Sum of all eigenvalues 2.409
Sum of all canonical eigenvalues 0.680

**** Summary of Monte Carlo test ****

Test of significance of first canonical axis: eigenvalue = 0.447
F-ratio = 1.825
P-value = 0.1600

Walton Moss north west transect

Axes	1	2	3	4	Total inertia
Eigenvalues :	0.048	0.033	0.364	0.261	0.902
Species-environment correlations :	0.607	0.533	0.000	0.000	
Cumulative percentage variance					
of species data :	5.3	8.9	49.3	78.3	
of species-environment relation:	59.6		100.0	0.0	0.0

Sum of all eigenvalues 0.902
Sum of all canonical eigenvalues 0.081

**** Summary of Monte Carlo test ****

Test of significance of first canonical axis: eigenvalue = 0.048
F-ratio = 0.506
P-value = 0.8960

Bolton Fell east axis

Axes	1	2	3	4	Total inertia
Eigenvalues :	0.238	0.031	0.510	0.351	1.471
Species-environment correlations :	0.698	0.529	0.000	0.000	
Cumulative percentage variance					
of species data :	16.2	18.3	53.0	76.8	
of species-environment relation:	88.5	100.0	0.0	0.0	

Sum of all eigenvalues 1.471
Sum of all canonical eigenvalues 0.269

**** Summary of Monte Carlo test ****

Test of significance of first canonical axis: eigenvalue = 0.238
F-ratio = 1.351
P-value = 0.3880

Bolton Fell Moss north transect

Axes	1	2	3	4	Total inertia
Eigenvalues :	0.546	0.275	0.507	0.369	2.360
Species-environment correlations :	0.913	0.804	0.000	0.000	
Cumulative percentage variance					
of species data :	23.1	34.8	56.3	71.9	
of species-environment relation:	66.5	100.0	0.0	0.0	

Sum of all eigenvalues 2.360
Sum of all canonical eigenvalues 0.821

**** Summary of Monte Carlo test ****

Test of significance of first canonical axis: eigenvalue = 0.546
F-ratio = 1.806
P-value = 0.1140