

Cranfield University

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An evaluation of the restoration programme for a cut over section
of Wedholme Flow raised mire

SCHOOL OF APPLIED SCIENCES

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Wedholme Flow raised mire

Supervisor: Dr. Nicholas Howden

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for the degree of Master of Science

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ABSTRACT

Wedholme Flow, Cumbria is the site of the largest lowland raised mire remaining in the UK. It forms part of a group of ombrotrophic mires known as the Solway mosses, situated in the north west of England. As with all remaining raised mires in the UK, Wedholme Flow has suffered some historical degradation largely caused by cutting of peat at the site's periphery for fuel. More recently large sections of the mire surface have been commercially mined mainly for horticultural use. These include sections which have been cut over by hand leaving baulks or upstanding strips of unmolested peat between cuttings but also sections of the mire surface that have been strip mined or milled using machinery. Because of the complete loss of *Sphagnum* the sections of the mire surface that have been milled represent a particular challenge in terms of restoration.

The reinstatement of the *Sphagnum* layer or acrotelm typical of raised mire sites is an important restoration objective. In order for *Sphagnum* to re-colonise a cut over mire site the water table must remain in close proximity to the surface of the peat throughout the year. The absence of an acrotelm however contributes to seasonal water table fluctuation by decreasing surface storage and allowing increased evaporation from the surface. On cutover mire sites primary restoration efforts centre on raising the water table sufficiently to facilitate *Sphagnum* re-colonisation and growth with a view to restoring a functioning acrotelm.

This study provides a critical appraisal of a restoration programme that aims to raise water levels on a cutover section of Wedholme Flow in Cumbria. The restoration programme was undertaken by Natural England who own and manage the site. Since acquiring the cut-over section of the site bunds and peat plugs have been installed to reduce drainage and raise the water table. Boreholes have been installed on site to monitor changes in water level during and after the restoration. The progress of the restoration programme is evaluated through examination of the water balance, available groundwater data and a review of contemporary literature. Recommendations for further restoration and monitoring are made.

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‘You listened and pulled me up from a lonely pit full of mud and mire. You let me stand on a rock with my feet firm.’ Psalms 40:2, CEV.

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1 INTRODUCTION

1.1 Background

Lowland raised peat bogs are one of Europe's rarest and most vulnerable habitats. In the UK, the majority of their extent has been lost (Fojt, 1995). The remaining mires provide essential habitat for wetland birds such as Curlew and Snipe as well as the invertebrates that provide their food (RSPB, 2008). Less than 6,000 hectares remain in a near-natural condition. Healthy peat absorbs and stores carbon; but as it degrades, the carbon is released, in to the atmosphere as carbon dioxide (Immirzi et al., 1992). In Britain, particularly England, peat has been badly affected by drainage - which has allowed bogs to dry out - burning, overgrazing and industrial pollution. Given the importance of such areas both in terms of habitat and greenhouse gas exchanges, there are increasing efforts to restore mire and peat bog systems.

1.2 Wedholme Flow

Wedholme Flow is situated approximately 20 miles west of Carlisle, in north-west England. (Figure 1-1)

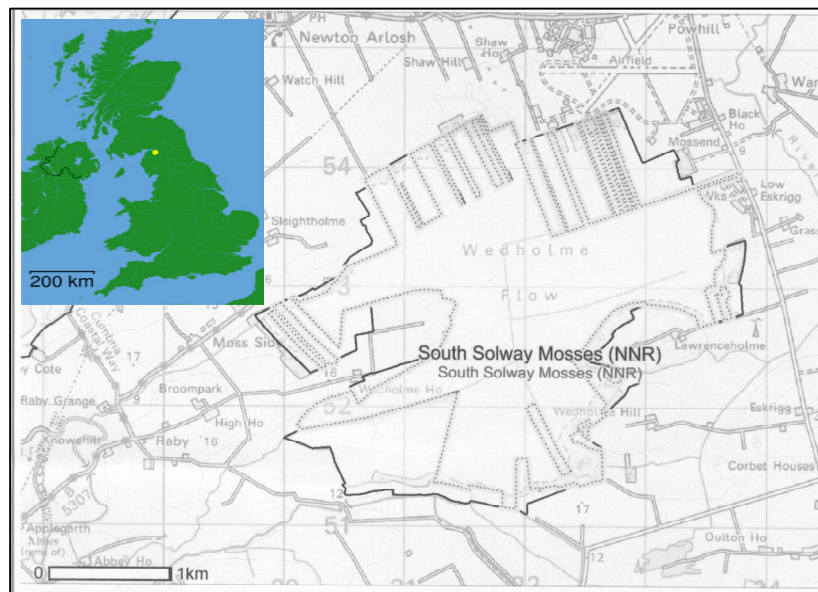


Figure 1-1 Location and plan view of Wedholme Flow raised mire. (N.England, 2008)

Wedholme Flow is a lowland raised mire or peat bog currently covering about 790 ha of the Solway Plain to the west of Carlisle. It is one of four mires that comprise the south Solway Mosses Special Area of Conservation (SAC), which once probably covered 6000 ha, but is now reduced to just less than 2000 ha, due to commercial peat extraction and drainage for agriculture. Despite being reduced in size, the Solway mosses represent the largest area of intact functioning raised mire in England (Natural England, 2008). The mires have been dated at just under 10,000 years old, have up to 14 metres in depth of peat and are an increasingly rare habitat in England supporting an unusual assemblage of peat forming Sphagnum mosses, carnivorous plants, dragonflies, damselflies as well as a few specialist birds (Natural England, 2008).

This study focuses on the restoration and monitoring of 160 ha of Wedholme Flow. The study site was milled for horticultural supply of peat until 2000 when it was acquired by Natural England as part of an ongoing restoration programme. After taking control, the primary objective was to raise water levels to encourage Sphagnum growth, as Sphagnum are a non vascular species requiring a water table at or in close proximity to the surface. In addition, a network of 1m high bunds was constructed on the site in order to prevent surface runoff and encourage increased infiltration.

It is generally accepted that ombrotrophic raised mires predominantly lose water through horizontal flow, their having been formed on a largely impermeable underlying bedrock geology. It is also accepted that the height and shape of the water table in raised mire systems is greatly influenced by proximity to drains at the perimeter; and the flows of water in such drains (Ingram, 1982). Thus it is likely that increased drainage both in terms of flow and proximity has contributed to lowered water levels at the site. Natural England have also tried to reduce lateral drainage from the site by blocking drains and installing peat plugs to restore water levels and thus natural bog function. A number of boreholes were installed, with automatic loggers, to monitor water levels post-restoration works.

1.3 Thesis aims and objectives

The aim of this study is to assess the effectiveness of a restoration project on a section of degraded mire at Wedholme Flow, Cumbria. In order to achieve this, the following objectives were identified:

- Review contemporary literature to provide an explanation of what constitutes raised mire and highlight the importance of preservation of this habitat in both the global and UK environment.
- Review literature relating to conservation and restoration of raised mire with particular reference to ground water levels required for re-establishment of mire vegetation on degraded sites such as Wedholme Flow.
- Calculate a simple water budget for the site in order to establish the approximate net input of water which will then be contrasted with water table response.
- Use historical data to compare antecedent climatic conditions with the long term average in order to establish context for water level change during the post-restoration monitoring period.
- Evaluate restoration by comparing water table levels on site with those required by raised mire vegetation as discussed in literature, thereby identifying whether intervention measures have been successful.
- Evaluate site specific restoration and monitoring techniques and make recommendations for future improvement.

1.4 Summary

In Chapter 2 contemporary literature is reviewed as described in the thesis objectives. This is followed by an appraisal of the study site. The methodology for assessing the

site restoration is then explained followed by analysis of results, discussion and the study conclusions and recommendations.

2 LITERATURE REVIEW

In this section contemporary literature of mire development, function, flora and restoration are reviewed.

2.1 Types of wetland

Bogs and fens generate and support specifically adapted vegetation communities that are dependent on the ground being permanently or intermittently waterlogged. The water supply for this raised water table largely defines what type of wetland is formed. In ombrotrophic wetlands this is derived only from precipitation.

Geotrophic mires receive their water from groundwater sources and rheotrophic wetlands water supply stems from faster moving water such as a stream or a river. In the UK ombrotrophic mires are usually referred to as bogs. These differ from fens in that they derive nutrition purely from atmospheric precipitation, whereas a fen supports vegetation that is at least partially sustained by mineral nutrients from groundwater.

2.2 Formation of bogs or mires

Unlike fens, bogs are entirely composed of vegetation both living and decomposed. Because fens are usually, at least in part, groundwater fed, this contributes a mineral component not present in bogs. Rain-fed bogs result in the creation of an oligotrophic (nutrient poor) and usually acidic environment. These tend to be inhabited by 'specialist' plant communities that are specially adapted to cope with such conditions. Specialist communities typical of raised mires are dominated by Sphagnum species which will thrive in such environment partly due to the lack of competition (Lindsay, 1995). The remains of these mosses and associated plant communities decay slowly in the anaerobic waterlogged conditions of the bog allowing the accumulation of humic material known as peat. This process also occurs in fens but there is usually a much higher proportion of inorganic matter in fen peat and because of the mineral content different vegetation communities occur.

The process of peat accumulation is likely to have taken many thousands of years. In Britain it is estimated that most peat bogs have accumulated over a period of between

3000 and 9000 years, although there are some that are more recently established including those that are now being formed (Lindsay, 1995).

2.3 Raised Mires

Ombrotrophic mires are divided into two main categories: blanket mires and raised mires. Both types are rain-fed and peat generating, but generally form in different parts of the landscape, depending upon local topography.

Blanket mires tend to form on upland areas in where there is relatively high precipitation. In the UK this tends to be in the north-west, where soil water logging is common, causing mire to develop both through terrestrialisation and paludification (Lindsay, 1995). As their name suggests they cover large areas of varying topography. The thickness of peat may vary according to topography with the greatest accumulations likely to form in localised depressions but generally peat layers are unlikely to be greater than 1m (DEFRA, 2007).

The term 'raised mire' is used to describe the formation of an isolated and distinct ombrotrophic bog (Wickman, 1951). These typically form a symmetrical, elliptical shape, as described by (Ingram, 1982), and are usually formed over a depression or low lying flat areas such as lake basins or flood plains (Proctor, 1995). This type of mire is called 'raised' because like blanket bogs the living layer of vegetation is raised above the mineral substrate on a bed of peat created from decayed vegetation. Unlike blanket bogs the peat may reach many metres in depth, especially at the centre (Ingram, 1982).

2.4 Importance of bogs

2.4.1 The conservation importance of lowland raised mires

In the UK the area covered by lowland raised mire has been drastically reduced. It is estimated that originally an area of approximately 67,000 ha of raised bog has now been reduced to approximately 4000 ha of natural unspoilt raised bog (Plantlife, 1992,

cited in Fojt, 1995). This remaining intact mire largely consists of unspoilt areas of cutover bog. Losses of lowland raised bogs in recent history have been mainly due to agricultural reclamation although factors such as peat extraction and afforestation have also contributed to the loss of this environment. Table 2-1 below indicates the extent of twentieth century erosion of this habitat.

Table 2-1: Extent of mire loss UK (Nature Conservancy Council, 1985) in (Fojt, 1995).

Area/ County	Area of raised mire in existence 1948	Area of raised mire in existence 1978	% loss in period
Lancashire	247	11	95
South Cumbria	494	156	68
Solway (Cumbria)	1124	796	32
Solway (Dumfries & Galloway)	1194	190	84
Forth Valley	1087	632	42

Bogs tend to be the least bio-diverse of British wetlands probably largely due to the low nutrient environment generated by a purely rain-fed water supply. They also tend to present a homogenous platform providing little opportunity for ecological variation beyond that of the clearly defined niches associated with the rand and lagg zones (Fojt, 1995). Fojt (1995), cites Wheeler (1993) demonstrating that 193 species could be found in bogs compared with the 653 species that could be found on nutrient rich fens. However, the species that are found in bogs tend to be specialists due to the tough nutrient poor conditions and as a result, like the habitat, are endangered.

2.4.2 Bogs as a carbon store and sink

Because bogs of all descriptions are mostly derived from decayed plant material, they contain a far higher proportion of carbon than mineral soils. Although peatlands comprise approximately 3% of the earths total land area, it is estimated that they may account for between 16-24% of all carbon stored in soils (Immirzi et al., 1992). Mires in particular, because of their isolation from mineral rich ground waters, are likely to be almost formed completely of carbon-based material. This means that all bogs are effectively stores of fossilised carbon. This carbon is likely to have been taken from the atmosphere over many millennia and accounts for a significant amount of carbon.

On average a single hectare of 1m deep peat contains 1000 tonnes of carbon (Lindsay, 1995). It is clear that if all carbon currently stored in the peat bogs was allowed to oxidise and be released into the atmosphere it could make a significant contribution to the greenhouse effect and therefore possibly impact climate change (Immirzi et al., 1992). There is some debate as to whether bogs can be considered carbon neutral even when intact. This is because most bogs emit methane as part of their normal function. Immirzi et al., (1992) point out that as mires age they become increasingly inefficient carbon sinks and release increased amounts of methane.

2.4.3 How disturbance effects release of carbon from peat generating systems

It is argued that when mires are disturbed they will continue to release stored carbon until that store has been exhausted (Immirzi et al., 1992). Where raised mire systems have been cutover they cease to function normally, the loss of the acrotelm and its living Sphagnum layer will remove the mires ability to sequester atmospheric carbon through photosynthesis. Loss of the acrotelm is also likely to result in a lowering of the water table exposing the peat catotelm to increased oxidation and decay (Hobbs, 1986).

2.5 Climate – the geographical limits of raised mires

Lindsay (1995) cites Ratcliffe (1968) in stating that a large part of eastern British Isles may be less suitable for the development of bogs because these areas experience less than 120 rain days a year. He also makes the point that most of the British Isles enjoy an oceanic climate and that this is supported by evidence of the growth of bog species in Cambridgeshire as late as the 19th century where the demise of bogs has been due to drainage and not climatic change.

It is well documented that in order for ombrotrophic bog to be maintained, water input in the form of precipitation must exceed or at least match water loss through evaporation and leakage (Ingram, 1982; Ivanov, 1981, cited in Lindsay, 1995). Wickham (1951) & Gore (1983) are cited in Lindsay (1995) as claiming that a minimum of 475mm of rainfall was required for domed bogs in northern and central

Europe. Lindsay (1995) claims that this approach is of limited value because bog development will depend on other factors dictated by specific location, not least rates of seepage dictated by porosity and depth of peat but also regularity of rainfall and extent of any dry period. Backeus (1988) argues that the distribution of rainfall and consequent moisture is more important for Sphagnum development than annual total or averages of precipitation. Proctor (1995) confirms the importance of summer dry periods by asserting that all ombrogenous bogs require a summer precipitation deficit of less than 100-150mm and blanket bogs in particular occur where summer precipitation deficit is less than 25mm. Backeus (1988) has also shown that moisture condition in August of the previous year is more important than temperature throughout the year as this tends to be the first month when depleted water levels are replaced in the UK.

2.6 Raised Mire shape and structure

The classic raised mire has two distinct components as described by (Ingram, 1982): the acrotelm and the catotelm (Figure 2-1). The acrotelm is the layer that includes the living Sphagnum comprising both this and an underlying, partially decomposed Sphagnum layer between 20 and 30cm thick (Proctor, 1995). The catotelm is made up of fully decomposed vegetation that has degraded to become peat and may reach up to 10m in depth.

The rate at which the Sphagnum grows and degrades to become peat ultimately dictates the shape and structure of a raised mire. In turn the biological processes which govern the production and degradation of Sphagnum are influenced by hydrological processes and the water table they create.

Kirkby et al., (1995) summarised that mire development is best illustrated by two distinct models; hydrological and biological. This is reasonable as the final structure and shape of raised mire is predominantly dictated by a combination hydrological and biological processes.

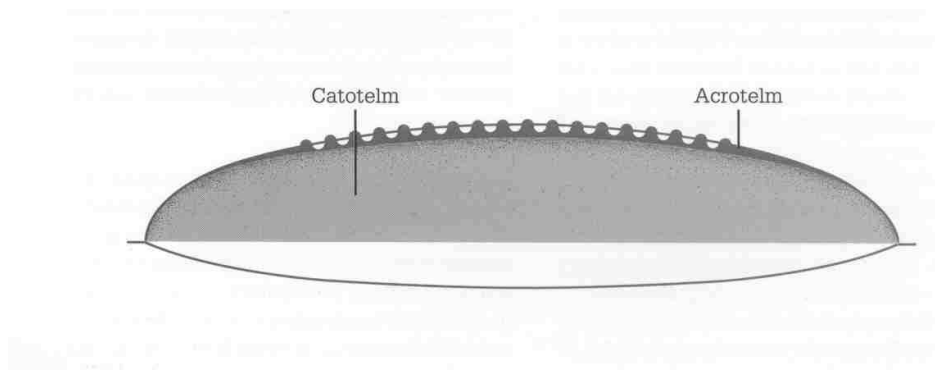


Figure 2-1 Schematic of idealised raised mire structure (Lindsay, 1995).

2.7 Biological processes in mire development

Raised mires form by a process of terrestrialisation or paludification. Sphagnum species have a greater resistance to decay than other species (Richardson, 1981) and this, combined with a ready supply of oligotrophic rainwater, causes the Sphagnum and other ombrotrophic species to be raised further above geotrophic material on a bed of it's own litter (known as the acrotelm). The acrotelm eventually decays further to form peat which accumulates to form the catotelm lying beneath the acrotelm. Accumulated peat supports a community of vegetation largely Sphagnum-based and is able to thrive in the nutrient-poor acidic conditions in the bog. These moss species are ectohydric hygrophytes meaning that they lack vascular physiology necessary to transport water and nutrients necessary for photosynthesis through their tissue; instead the tissue in the leaves and stems traps water which is absorbed directly into the immediate area of plant tissue (Richradson, 1981). To do this effectively Sphagnum species require permanently damp or moist conditions. The underlying partially decayed moss in the acrotelm provides moist damp conditions close to the newly generated Sphagnum by holding rain-fed water close to the Sphagnum, delaying runoff and reducing evaporation, effectively creating its own microclimate (Longton, 1979). As water travels down through the catotelm the older peat becomes denser with depth and so water transmission is slower, which helps to keep the mire water table high and prevents the mixing of mineral-rich groundwater.

Kirkby et al., (1995) state that net peat production is dependant on two primary factors: the growth of new Sphagnum and the oxidisation rate of existing peat. In order to achieve net peat production the rate of production of new peat via Sphagnum

production must exceed the rate of peat decay via oxidisation. In a functioning raised mire both Sphagnum production and decay rate of peat are affected by the level of the water table.

As discussed, Sphagnum species are considered to be ectohydric hygrophytes. This means that in order to carry out normal functions necessary to life such as photosynthesis and reproduction they can only exist, grow and produce in close proximity to water (Richardson, 1981). Conversely the rate of decay is also affected by water level. When the water level is high and covers peat it creates anoxic conditions which prevent or slow the rate of decay (Hobbs, 1986). Consequently when the water table is high in a mire, the rate of decay is less than the rate of production resulting in net peat production. When the water table is low, growth of new Sphagnum is reduced and oxic conditions accelerate decay, possibly resulting in net loss of peat.

2.8 Hydrological processes in raised mire development

Raised mires or ombrotrophic peat bogs tend to form in a half-elliptical or mound shape, although this may differ in terms of both surrounding topography and prevailing weather conditions (Ingram, 1982). This is initially because of the way in which raised mires tend to form by terrestrialisation whereby they spread outward from a central point, most isolated from geotrophic nutrients, resulting in the oldest and most abundant accumulation of peat being at the centre. This form is generally maintained throughout the natural life of the bog by hydrological processes.

The water table in peat tends to follow the general shape of water tables in mineral soils as modelled by Houghoudt's equation (Childs, 1961 and Hilliel, 1971). The water table will not follow a flat or level surface but will instead lower close to points of drainage such as a ditch. As a result the water table will be at its highest point where it is furthest from a point of drainage. This point will naturally form midway between surrounding drainage points resulting in a mound or half-elliptical shaped water table. The mound shape of the bog is closely linked to the water table in the

bog because *Sphagnum* production, which produces material for peat production, is limited by its non-vascular nature and can only thrive close to the water table (Richardson, 1981). Therefore the greatest build up of peat tends to be at the centre increasing the depth of the mound at this point and causing the peat growth to mimic the shape of the water table.

In stable raised mire systems the acrotelm and catotelm work in harmony to control water table fluctuation (Quinty and Rochefort, 2003; Price, 1997). Individually, however these components have distinct hydrological properties. The acrotelm has a low bulk density and high pore space so it can transport water more rapidly than the catotelm, and also has a greater storage capacity due to the large pore space (Price, 1997). This enables rapid resupply of water to the catotelm when the water table drops ensuring that ground water levels are stable. Overall the catotelm stores more water than the acrotelm but this is purely because of its depth. The catotelm increases in bulk density with depth due to both compaction and humification (Price, 1997). The older peat at lower levels is more degraded and compacted by the weight of the newer peat above. This results in less porosity per unit volume and therefore reduced water storage and increased water tension as the pores holding water get smaller with depth (Quinty and Rochefort, 2003). These properties help control water loss through seepage and contribute to groundwater stability in the mire.

2.9 Raised mire vegetation

Although, as with all vegetation communities, there is a degree of variation from site to site, most commentators agree that the vegetation most typical of active raised mire would be one that could be classified as M18a under the United Kingdom's National Vegetation Classification (NVC) system (Rodwell, 1991). M18a broadly comprises non-vascular plant species or bryophytes, dominated by *Sphagnum* spp. In disturbed or drier areas, the flora may contain a few shallow rooted vascular plant species such as *Calluna vulgaris*, *Eriophorum vaginatum* and *Scirpus cespitosus* (Lindsay, 1995). The type of plant community that occupies a raised mire is important in several respects. Plants that occur on a raised mire, in particular *Sphagnum* species, are confined to ombrotrophic environments. The nutrient

deficient, often acidic environment that raised mire provides, allows them a competitive advantage over the vascular species that would normally have the advantage by claiming available water supply from the ground (Lindsay, 1995). Conversely, the absence of vascular plant species prevents the water that is stored in the raised mire mound being depleted. During dry periods caused by seasonal climatic variation the roots of vascular plants extract water from deeper regions of the ground as the Soil Moisture Deficit (SMD) increases. If this was to occur in raised mire systems, it would prevent the necessary accumulation of rain fed water in the mire as supply from periods of greater precipitation would be used to restore saturation to lower echelons of the peat horizon.

It is widely acknowledged that vegetation communities that occupy functioning raised mire sites require a water table that is at or very near the surface. However there is some debate about the exact level of water that is necessary to sustain this community. Lindsay (1995) states that all of living vegetation are generally within 25-30cm of the water table but also states that typical bog species such as Sphagnum cannot survive unless they are ‘*very close*’ to the saturated zone. Bragg (1995) argues that ‘*the water table remains within 0.5-1m of every part of the mire surface*’. Richardson (1981) cites Proctor (1979), claiming that Sphagnum species are confined to living within decimetres of the water table. Heathwaite (1995) cites Steefkerk & Casparie (1989), indicating the best possible range of the water table for Sphagnum is 0-15cm below the surface.

The range of water table depths suitable for sustaining mire vegetation given in literature may be because even in a well functioning bog water table levels will not remain static and are likely to experience some seasonal variation. The degree of water table fluctuation will depend on the thickness of the acrotelm which is likely to vary from mire to mire. As discussed in the hydrology section the permanently moist acrotelm consisting of layers of increasingly decayed Sphagnum is important to control of water levels on the mire, it acts to prevent evaporation at the peat surface and has greater porosity that can store a larger amount of water than the peat below (Quinty and Rochefort, 2003). The water held in the acrotelm holds moisture next to

the live Sphagnum layer during periods of seasonal variation (Longton, 1979), compensating for the lowered ground water table. Although ectohydric Sphagnum species have some ability to store water it is limited and consequently, as they lack roots, must remain in close proximity to moisture in order to survive (Richardson, 1981). The range of water table depths discussed may also be in part due to the degree of diversity amongst bryophytes that make up the vast majority of raised mire communities. Even amongst peat generating Sphagnum spp. the requirement for proximity to the water table varies (Lindsay, 1988). Although the mire surface is generally seen as homogenous and is less diverse than fenland or other geotrophic environments, it is not a monoculture. In practice small variations in topography in the mire surface provide a mosaic of habitat (Lindsay, 1995). Small depressions may retain pools of water for significant periods of time providing habitat for species capable of hydroserral colonisation (e.g. *Sphagnum cuspidatum*) while small raised areas may generate hummocks supporting species that do not require such close proximity to the water table (such as *Sphagnum imbricatum*). Figure 2-2 shows an idealised approximation of proximity to water table for six species of Sphagnum.

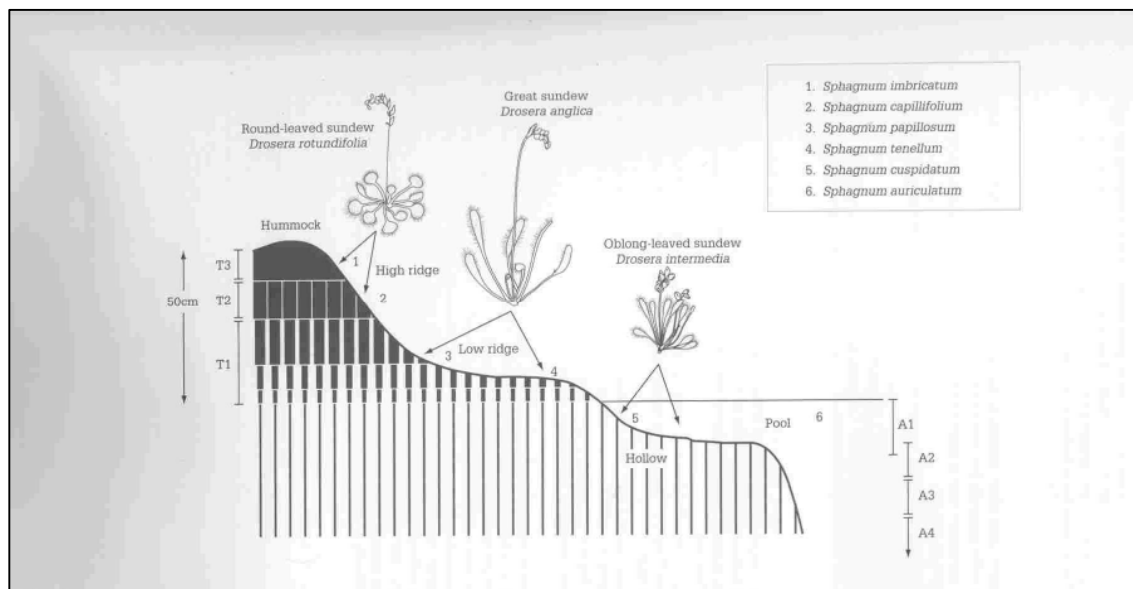


Figure 2-2 Water table depth preferences for six Sphagnum species (from Lindsay, 1995).

2.10 Raised mire restoration

2.10.1 Degraded mire - Bog dimensions

Although the ultimate goal of raised mire restoration is to reinstate the complete mire as it was in size and shape, the short and medium term objectives might be more modest. Where mires have been degraded as a result of human activity, it is likely that their dimensions will have been significantly changed and this is likely to affect maximum water levels achievable. Where sections of the mire have been cut to different heights it might prove difficult to keep the water table in close proximity to the peat surface across the entire mire. Unless the differences in height of peat are minimal it may be advisable to treat these sections as different mires in terms of restoration.

It stands to reason that where the distance across a raised mire site has been reduced, the groundwater mound and therefore the water table are likely to be lowered. As Wickman (1951) and Ingram (1982) have summarised, there is a strong relationship between the length of a raised mire and its height. As in mineral soils, where the height of groundwater mounds as described by Hillel (1971) are dependent on the distance from the centre to peripheral drains, the height of the water table in peat is dependent on the same factors. Where drainage ditches or channels have been placed in the catotelm it is likely that these will have the same affect as shortening the length of the mire. Where mire surfaces have been strip mined or milled it is likely that the surface of the mire will have been uniformly lowered. This may mitigate the effects any shortening of the mire base and consequent reduction in water table.

2.10.2 Degraded mire - Porosity, Water tension and water table stability

Where peat has been milled, the remaining peat is that from the lower more humified layers of the catotelm. This peat will have a higher bulk density and lower porosity resulting in reduced storage capacity for water and the pore water being held under higher tension from increased capillary forces. This presents two problems firstly the higher bulk density in the peat surface layer means that per unit change in storage,

there will be an increased change in water table level leading to greater water table level fluctuation (Quinty & Rochefort, 2003; Heathwaite, 1995). When describing water table fluctuation on undisturbed sections of the study site at Wedholme Flow Mawby (1993) indicated that water table fluctuation was less than 20cm compared to a 70cm range on cutover areas. Secondly the increase in water tension caused by decreased porosity would make it more difficult for colonising Sphagnum to extract moisture from the peat surface. Price (1997) suggested that although water table fluctuation and porosity are linked, it is higher water tension or capillary pressure that could be the more significant factor in preventing Sphagnum from re-colonising cutover mires. On a milled or completely cutover site one of the primary objectives in restoring normal raised mire function would be to restore the Sphagnum acrotelm, both increased pore water tension and more widely fluctuating water tables could make this difficult to achieve.

2.10.3 Degraded mire - Surface topography

Milled peat does not provide the varied topography of an undisturbed mire surface. Natural pools that form on the milled surface act as a surface water store replacing the function of the acrotelm during periods when the water table is lowered. The value of varied topography that maintains residual surface water can be seen where peat has been cut retaining surface baulks (Money, 1995). These pools also act as a platform for Sphagnum re-colonisation as they are favoured by hydrosereal pioneering species such as *Sphagnum. cuspidate* (Money, 1995).

3 STUDY SITE

3.1 Introduction

Wedholme Flow is a raised mire situated approximately 20 miles outside Carlisle in the north west of England. The entire site covers 790 ha and the condition of the mire varies across the site. The condition ranges from intact functioning mire to that which has been degraded largely due to drainage and cutting. In more recent history the horticultural industry adopted a more systematic approach to peat extraction which has involved large areas being efficiently drained and strip mined of surface peat or 'milled'. It has been observed that unlike traditional baulk cut areas of raised mire, mire that has been milled is resistant to repopulation by native raised mire species, essential to the functioning of a raised mire, despite being in close proximity to areas of functioning mire. In this respect milled mire appears to represent a particular challenge in terms of restoration. This study evaluates the restoration of an area of Wedholme Flow comprising approximately 160 ha that has been subject to peat extraction by milling.

3.2 Previous restoration at Wedholme Flow

Wedholme Flow National Nature Reserve was cut for peat until the 1990s for horticultural use. English Nature conducted a programme of restoration from 1986 to 1993 which involved blocking drains and peat cuttings with the aim of preventing water loss. It was hoped that this would raise the level of the water table and consequently encourage Sphagnum growth on cutover areas (Mawby, 1993). In order to monitor progress three transects of boreholes were established and cutover areas were monitored for returning vegetation

Vegetation such as *C.vulgaris* tended to remain a prolific species in many of the sample quadrats indicating that water tables were low or unstable. Sphagnum species did achieve some colonisation but only in close proximity to existing cover or in the case of *S.cuspidatum*, around surface pools. It was noted that where Sphagnum species did colonise bare peat, it was *S.papillosum* and *S.tenellum* Spp. that appeared first (Mawby, 1993).

Dip-wells were installed across the site in early 1990. Dip-wells were installed in both cutover and intact areas of the mire prior to damming taking place in those sections. A total of 70 dip-wells were deployed over three transects. On the site where dip-well transects were installed, damming took place in February 1992. Three years of monitoring data were analysed from these dip-wells and the results were discussed in Mawby (1993). Wells on the undisturbed Sphagnum bog showed annual fluctuation of less than 200mm with some surface flooding noted. The water table in wells in cutover areas fluctuated over a much greater range (100-700mm below the surface); dropping sharply in the summer months and prior to damming, failed to come within 100mm of the surface. Post damming (Feb 92) water tables showed some increase in height

Mawby (1993) noted that there was only a small rise in mean minimum and maximum levels where topography was unfavourable (*i.e.* on slopes). The point was made that summer water levels failed to remain consistently high even after damming and this was a critical period for Sphagnum growth. It was noted that peat expansion followed damming, indicating that water was being stored. These data only referred to one years post damming monitoring.

3.3 Restoration site

In 2000, English Nature acquired an area of 160 ha of Wedholme Flow representing the last area of the mire to be commercially cut. Their aim was to protect any remaining uncut area and rehabilitate cutover areas. When commercial peat extraction ceased on the study site circa 2004, a programme of restoration commenced with the general aim of raising water levels sufficiently to allow re-vegetation of the peat surface. The restoration programme involved building a network of bunds approximately 1m high. These bunds made from dense peat, form a grid dividing the site into smaller sections. The aim of these bunds is to reduce surface runoff and maximise infiltration of available precipitation. There are outflows in some of the bunds to allow escape of flood water to peripheral drains. Where it was deemed that topography of the cutover surface was such that it would encourage rapid loss of water through rapid runoff or throughflow, dense sections of peat or peat

plugs were inserted into the peat body to slow progress of water towards the nearest drainage point. There are two main peripheral drains LWSO 001 and LOWS 001 to the north and east, respectively, of the study site. These drains are fully functional and are maintained by the Environment Agency (E.A.) in the absence of a local Internal Drainage Board. The blocking of these drains was considered by the E.A. and Natural England in order to raise the water table on the site; however this idea was abandoned upon the objections of neighbouring land owners (Brock, 2008).

On the 7th and 8th January 2005, severe weather affected the Cumbria area (E.A., 2005). This resulted in major flooding of the Wedholme site and the destruction of bunds to the north of study site (Brock, 2008). All restoration including installation of bunds was finally completed on the site in December 2006. Future restoration plans include the inoculation of Sphagnum on the cutover surface in order to accelerate Sphagnum re-colonisation and restoration of the acrotelm. This work will however be dependent on future funding.

4 METHODOLOGY

4.1 Overview

As discussed in Chapter 2, re-establishment of raised mire vegetation depends on the water table remaining in close proximity to the peat surface throughout the year. As the study site has been extensively cut over and drained, restoration efforts have been focussed on slowing drainage and raising water levels with the eventual aim of reinstating the *Sphagnum* acrotelm. Because the success of restoration depends on the raising of the water table, a series of boreholes were established. The boreholes were equipped with automatic data loggers to monitor water level change in relation to the peat surface over a four year period post restoration (Water years 2004 – 2007).

Because Ombrotrophic mires such as Wedholme Flow rely entirely on atmospheric precipitation for their water supply, a water budget for the site was calculated using rainfall data and estimated potential evaporation. This enabled a comparison between net water inputs and change in water storage to be made, thus testing the effectiveness of restoration efforts to slow drainage at the site and raise the water table throughout the year. Finally long term average climatic conditions for the site were compared with antecedent climatic conditions in order to put post restoration climatic conditions in context.

4.2 Monitoring of water levels

Water levels were recorded every hour at the restoration site using thirteen boreholes equipped with automatic data loggers. For the analysis presented in this study a subset of five boreholes were used because these provided the most complete sets of data. Water levels for water years 2004 to 2007 were analysed. Water level data for water year 2006 were however, omitted because they were incomplete. Figure 4-1 shows the location of the boreholes used and their respective numbers. In the interest of continuity the original numbers assigned by Natural England were used (An explanation of Borehole Assembly and water level calculation can be seen in Appendix 1). As mire water levels fluctuate naturally with climatic conditions, the monthly average water level was used for the purpose of analysis.

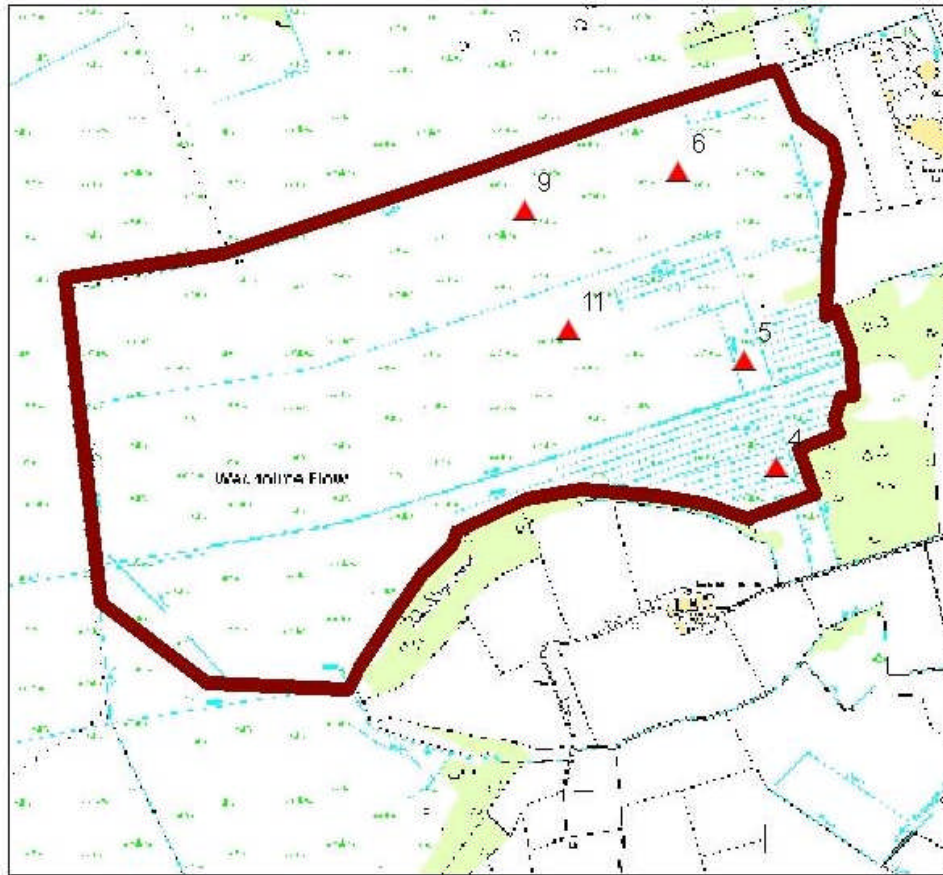


Figure 4-1 Section of Wedholme Flow, 160 ha restoration site highlighted. Boreholes and their respective numbers are shown.

4.2.1 Disregarded data

Out of a total of thirteen boreholes data from five were selected for analysis (Numbers 4,5,6,9 and 11). The datasets from the remaining eight boreholes to the west of the study site were disregarded because they were incomplete. As seasonal variation in the water table is particularly important to the re-establishment of mire vegetation, it was felt that it would be misrepresentative to use datasets that only represented the water table for part of the year. Water levels for the year 2006 were disregarded as they were incomplete for all boreholes.

4.3 Water Budget

A water budget for the site was calculated to identify net input of water over the monitoring period (2004-2007). As water in ombrotrophic mires is supplied entirely by atmospheric precipitation the maximum amount of water available to the mire over a given period is equal to total precipitation less total evaporation. The calculation of a water budget enabled a comparison between water level and water supply in order to enable an analysis of how successful restoration efforts had been in slowing loss of water from the mire.

The water budget was calculated:

$$\text{Total Precipitation} - \text{Potential Evaporation (PE)} = \text{Net precipitation}$$

Precipitation was calculated using monthly rainfall data for the UK Meteorological Office weather station at Newton Rigg situated approximately 20 miles from the study site.

4.3.1 Calculation of Evaporation

Potential Evaporation (PE) was calculated using the Thornthwaite method (See calculation below), an empirical calculation which uses temperature with an adjustment for daylight hours to provide monthly figure for total evaporation. Temperature data for this calculation was taken from Newton Rigg weather station. This method was chosen because it only requires daylight and temperature data which is readily available for the site throughout the monitoring period and historically.

$$PE_m = 16 N_m (10 T_m / I)^a$$

$$I = \sum i_m = \sum (T_m / 5)^{1.5} \text{ for } m = 1 \dots 12$$

$$a = 6.7 \times 10^{-7} I^3 - 7.7 \times 10^{-5} I^2 + 1.8 \times 10^{-2} I + 0.49 \text{ (to 2 significant figures)}$$

Where:

PE_m is monthly potential evaporation in mm

T_m is the monthly mean temperature in °C

The adjustment for daylight hours N_m is calculated by dividing the possible sunshine hours for the appropriate latitude by 12

Adapted from (Shaw, 1983).

4.4 Long term climatic conditions

Precipitation, evaporation and net precipitation for water years 1962 to 2003 were analysed to provide a context for the climatic conditions during the monitoring. This period was used because it represents the limit of publically available rainfall data from Newton Rigg weather station. Evaporation and net precipitation were derived using the same methods already described.

4.5 Data analysis made

As discussed in the literature review, mire vegetation such as *Sphagnum* sp. require a water table that is in close proximity to the mire surface throughout the year. Literature also indicates that water levels in degraded mire tend to be unstable, particularly in summer months when evaporation is high and rainfall is lower. Because stability of groundwater levels as well as proximity to the mire surface is important to the re-establishment of raised mire species such as *Sphagnum*, analyses of water levels post restoration needs to examine the consistency as well as the height of groundwater levels in order to establish effective restoration.

For this reason monthly average water levels were calculated to give a general indication of water levels throughout each month. In addition, because seasonal variation in the groundwater table is important to *Sphagnum* regeneration and survival, six monthly average water levels (Autumn/Winter and Spring/Summer) were also calculated. Water levels for successive years post restoration were then compared on both a monthly and seasonal basis in order to establish if restoration had been effective in raising and reducing seasonal variation in water levels. The proximity to the mire surface on both a monthly and seasonal basis were also compared with those levels deemed necessary in literature for *Sphagnum* re-colonisation.

4.6 A summary statement of the methodology

1. Rainfall and temperature data were used with Thornthwaites equation to approximate net rainfall and establish input of water to the mire during the monitoring period.
2. A long term record of rainfall and temperature data were used to set climatic conditions during the monitoring period into context.
3. Water level data from selected boreholes was used to identify water table fluctuations over the monitoring period.
4. Observed water table fluctuations were compared with net rainfall data to characterise the mire response post restoration.
5. Water levels achieved in the mire were compared with those deemed necessary in literature for Sphagnum re-colonisation in order to establish if restoration objectives have been achieved.

5 WATER BUDGET

5.1 Introduction

In order to evaluate the water retention capabilities of the restored section of raised mire it was necessary to compile a simple water budget for the site. Since ombrotrophic mires are entirely rain fed the water budget for the site is equivalent to net precipitation which was calculated by precipitation less evaporation ∴

Total Precipitation – Potential Evaporation (PE) = Net precipitation.

The derivation of total precipitation and potential evaporation are described in the methodology above.

A monthly water budget for the site was calculated for the study period (2004-2007). The water budget enables a comparison between approximate net atmospheric input of water and the change in ground water level for the period post restoration. This in turn enables an evaluation of the restoration in terms of its effectiveness in increasing water retention and raising ground water levels at the site.

A long term, 42 year (1962-2003) water budget for the site was also calculated to set a context for the water budget during the study period (2004-2007). In this chapter characteristics and trends of both the long term net precipitation record and that of the study period are highlighted. These characteristics are then used in the analysis to examine how representative net precipitation during the study period is of the long term record.

5.2 Precipitation

The long term average annual (42 year) precipitation for the site is 920mm. Annual precipitation figures for the four year monitoring period are shown in the Table 5-1. These produce an average annual precipitation of 964 mm over the four year period, which is in excess of the 42 year average of 920mm. It can be seen that the excess precipitation in the study period is due to water years 2004 and 2007 which are 53mm

and 257mm over the 42 year average respectively. In contrast 2005 and 2006 are both below the 42 year average by 81mm and 51mm respectively.

Table 5-1 Total precipitation water years 2004 -2007

Water Year	Annual Rainfall total (mm)
2004	973
2005	838
2006	870
2007	1177

5.2.1 Seasonal variation

It can be seen from Figure 5-1 that rainfall tends to be lower through spring and summer (March to August) than winter and autumn (September to February) in the 42 year average. The average for the four year monitoring period broadly conforms to this pattern although it shows rainfall for August as being higher than the long term normal. The fact that rainfall for Wedholme flow is higher through June to August may have particular significance in terms of ground water levels as it is acknowledged that August in particular is an important period for recovery of ground water after the summer dry period (Backeus, 1988).

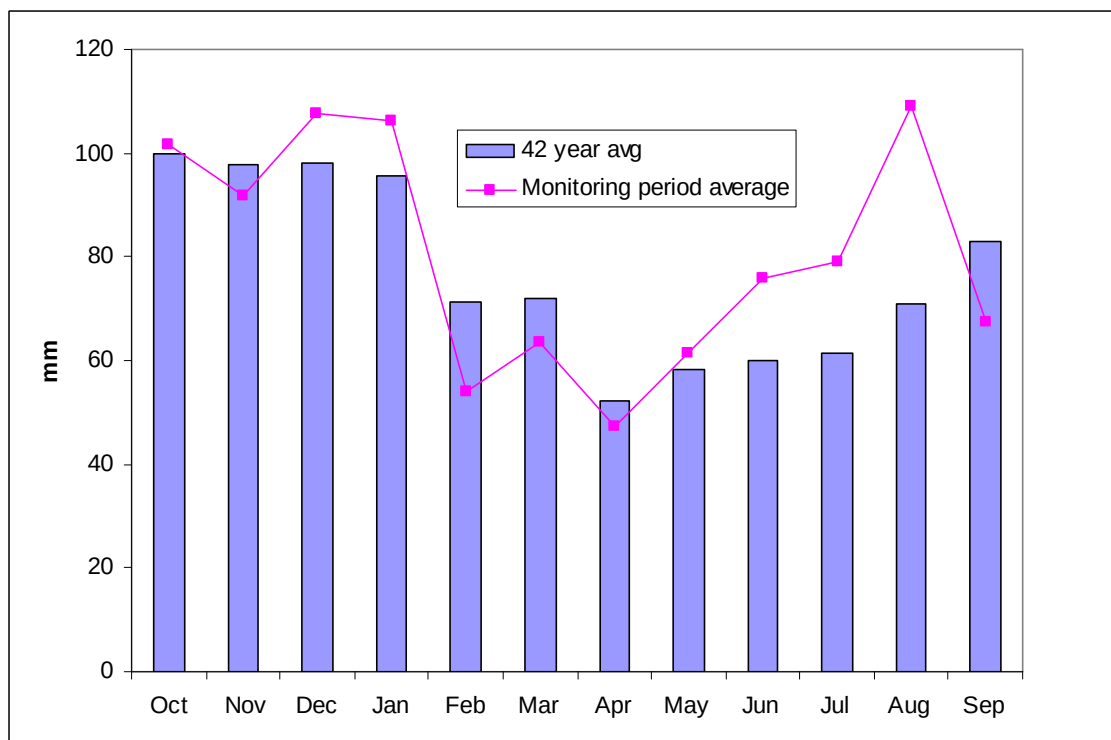


Figure 5-1 Comparison of 42 year and 4 year average monthly precipitation

Figure 5-2 shows cumulative precipitation for each of the years in the four year study period. It can be seen that water year 2004 has a particularly high rainfall in August in fact so high that it raises the annual average of 2004 above that of 2005 and 2006 as up until that point it had produced less precipitation than the latter. 2007 which has the highest annual precipitation total clearly exhibits higher rainfall throughout the water year although it too shows a large increase over the period June to July demonstrated by the increase in positive gradient over this period. Wedholme Flow experienced extreme rainfall during January 2005 and this resulted in localised surface flooding (E.A., 2005).

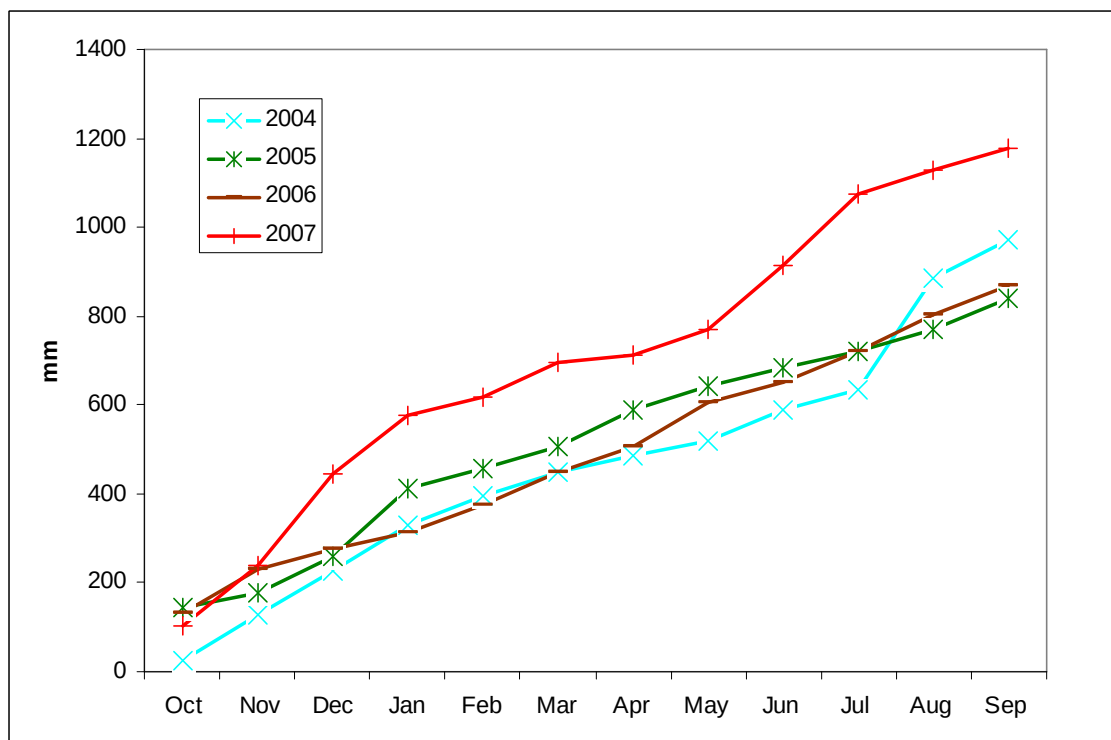


Figure 5-2 Cumulative precipitation for study period (Water Years 2004 to 2007)

5.3 Evaporation

Annual total PE figures for the four year monitoring period are shown Table5-2. These produce an average annual PE figure for the study period of 531.04mm which is marginally higher than the 42 year average figure of 506mm. Three out of the four years in the study period produce a PE in excess of the long term average. Water years 2004, 2005 and 2007 have PE of 25mm, 32mm and 43mm over the long term average respectively only 2006 has an annual PE the same as the long term average. Overall PE has remained consistent with the long term average throughout the monitoring period

Table 5-2 Annual total PE figures water years 2004 to 2007

Water Years	Annual PE Total
2004	530
2005	537
2006	506
2007	549

5.3.1 Seasonal Variation

It can be seen from figure 5-3 that potential evaporation tends to be higher through the spring and summer months (March to August) than the winter and autumn (September to February) for the long term 42 year average. The average monthly level of PE for the four year monitoring period broadly conforms to the same pattern as the long term monthly average.

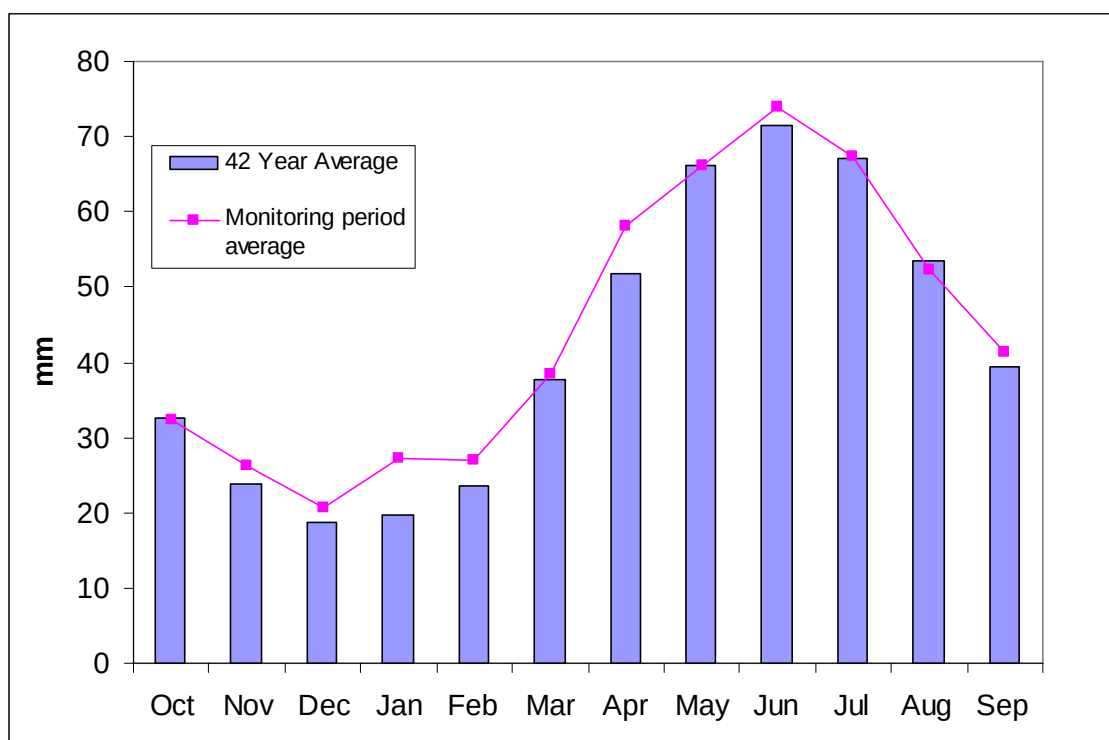


Figure 5-3 Comparison of 42 year and 4 year average monthly PE

Figure 5-4 shows cumulative evaporation for each of the years in the four year monitoring period. It can be seen that the water year 2007 enjoyed consistently

higher levels of evaporation throughout the year than other years in the monitoring period. For water year 2006 monthly PE was consistently lower than the other years. Although producing lower levels of PE overall, water year 2004 exhibits higher levels of PE from April to September than either 2005 or 2007(demonstrated by the steeper positive gradient). Overall, the variation of PE throughout each year of the monitoring period has been consistent.

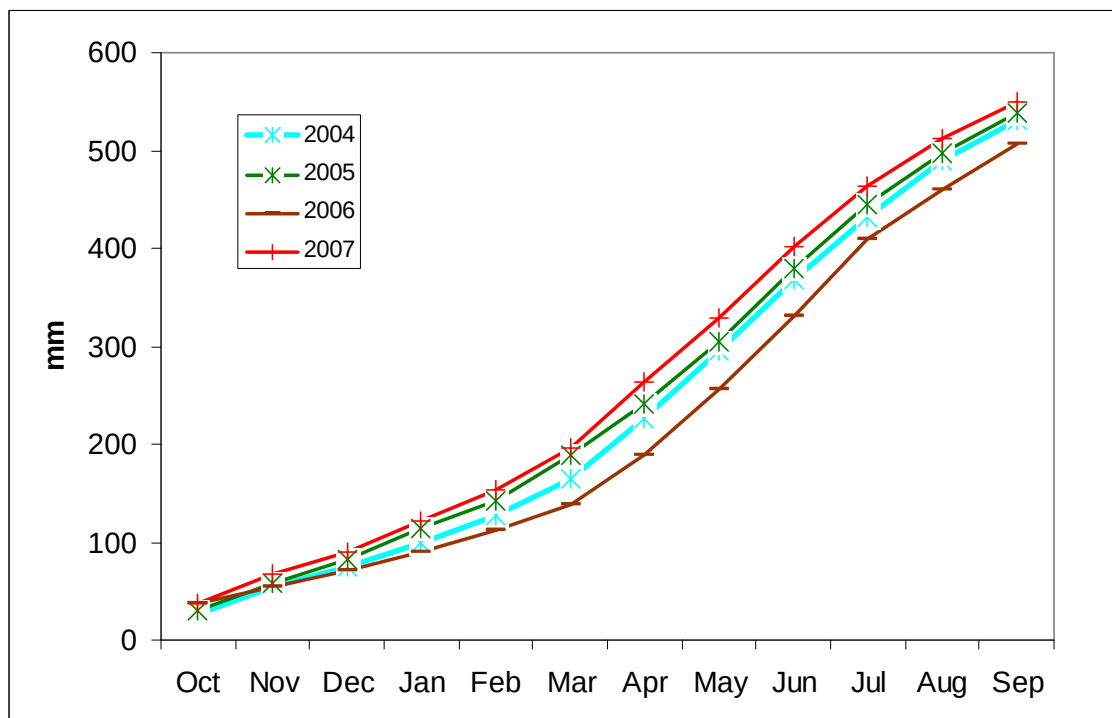


Figure 5-4 Cumulative PE for study period (Water Years 2004 – 2007)

5.4 Net Precipitation

Annual net precipitation figures for the four year monitoring period (Table 5-3) produce an average annual net precipitation of 434mm over the four year study period which is in excess of the 42 year average of 415mm. It can be seen that the increase in average over the study period is due to water years 2004 and 2007 which are 27mm and 213mm over the 42 year average respectively. Conversely 2005 and 2006 are both below the 42 year average by 114mm and 51mm respectively. The variation in net precipitation has been driven by the variation of precipitation over the monitoring period as PE has remained consistent during the same period. Overall the study period has enjoyed more effective rainfall than the 42 year average but this is

due to water years 2004 and 2007. Water years 2005 and 2006 have lower effective rainfall than the long term average.

Table 5-3 Annual total net precipitation figures water years 2004 to 2007

Water Year	Annual net rainfall (mm)
2004	442
2005	300
2006	364
2007	628

5.4.1 Seasonal variation

Net precipitation tends to be lower through spring and summer (Mar to Aug) than autumn and winter (September to February) in the 42 year average (Figure 5-5). As with precipitation and evaporation the four year monitoring period broadly conforms to this pattern although net precipitation for the month of August seems to be far higher in the four year monitoring period than the long term normal. Average net precipitation in the four year study period is higher for the months Oct, Dec, Jan, Jun, Jul and Aug and lower for Nov, Feb, Mar, Apr, May and Sept. As already discussed the high rainfall levels through Jun to Aug in the study period may be significant as August is acknowledged as an important month for groundwater recharge in the UK.

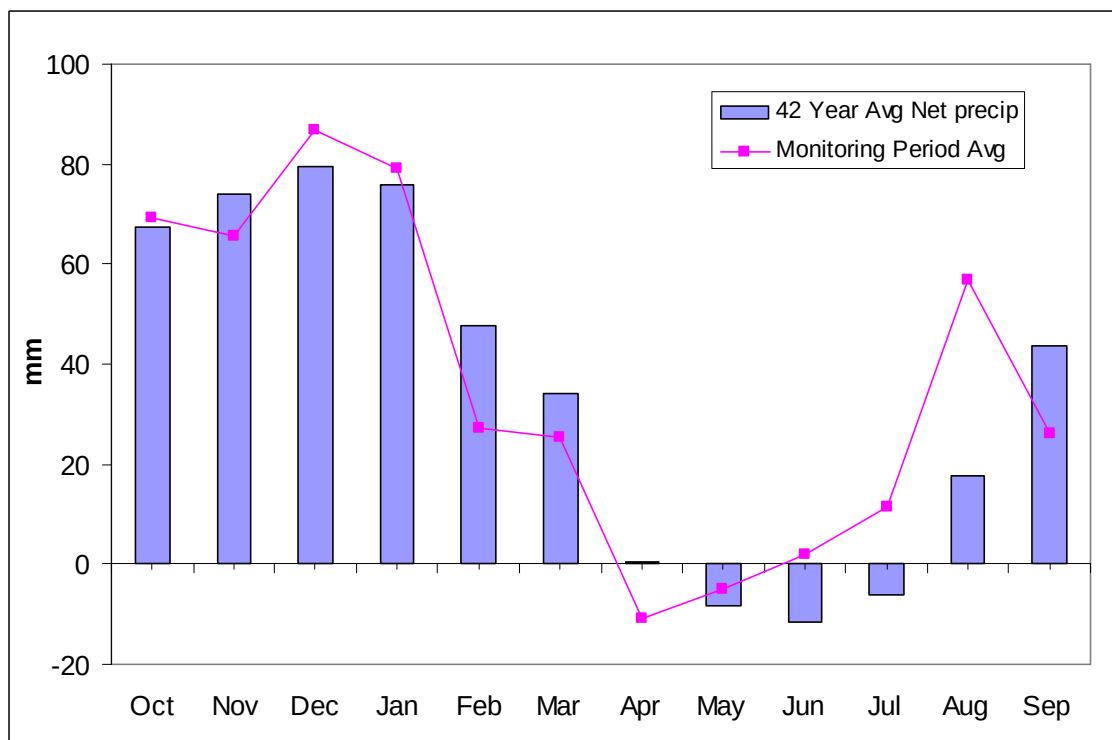


Figure 5-5 Comparison of 42 year and 4 year average monthly Net precipitation

It can be seen in water year 2004 that August has a particularly high net precipitation denoted in the chart by the steepness of the positive gradient from July to Aug (Figure 5-6). This high monthly value of net precipitation for August in 2004 is predominantly due to the high rainfall of 251.6mm in that month which has been little moderated by PE of 57.8mm in the same month despite this figure for PE being higher than the annual and monthly average for August. As with the precipitation figures August 03/04 lifts the running total for net precipitation above that of 2005 and 2006 when up until that month it had produced less effective precipitation than either 2005 or 2006. As with precipitation figures, water year 2007 exhibits the highest annual net precipitation total and exhibits the highest monthly net precipitation for the study period over the majority of the year.

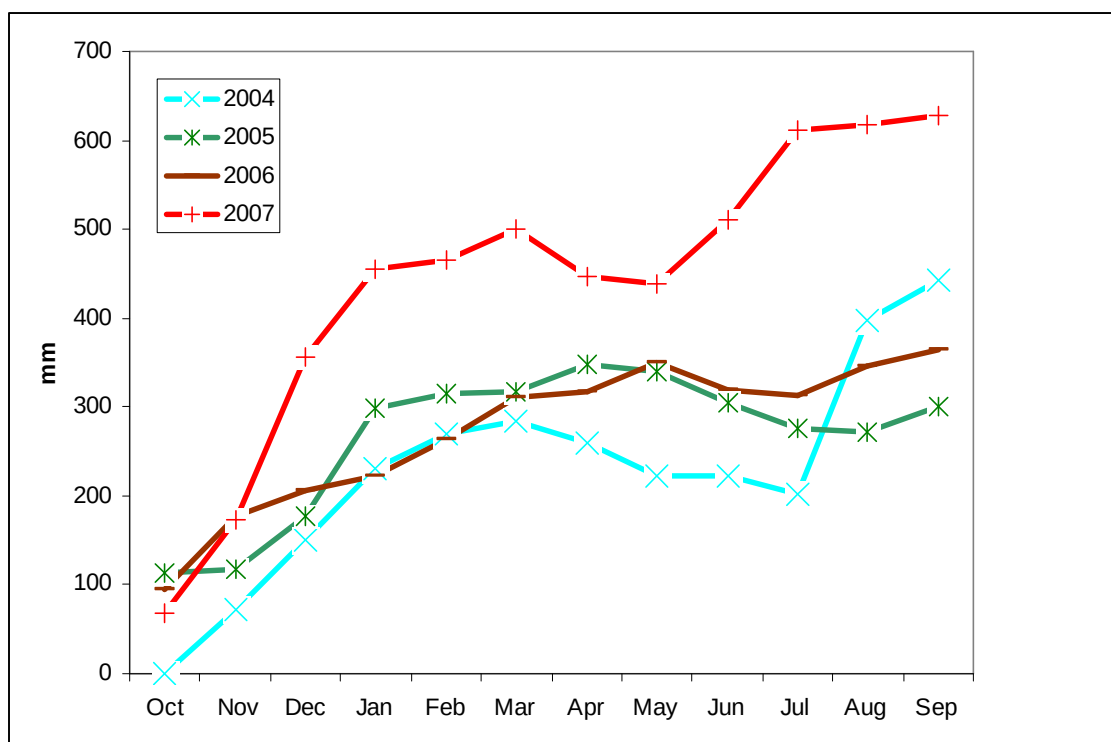


Figure 5-6 Cumulative net precipitation for monitoring period (2004 to 2007)

5.5 Summary

In summary the average net precipitation during the monitoring period (2004 – 2007) broadly corresponds to the long term normal for the study site (415mm and 434mm respectively). However, while levels of potential evaporation have remained consistent, annual levels of precipitation have varied considerably during the same period and this has affected net precipitation levels for individual years (Summarised in Table 5-4). High annual net precipitation was experienced throughout 2007 (582mm) although 2005 levels (301mm) were lower than the long term normal.

Seasonal variation during the monitoring period differed from the long term record as net precipitation in the summer months (Apr-Sept) was high for 2004, 2006 and 2007. Conversely, 2005 summer levels of net precipitation were lower than the long term normal. An extreme rainfall event in Jan 2005 resulted in surface flooding and residual surface water remaining throughout the year in areas of the study site.

Table 5-4 Annual and seasonal net precipitation by water year

Water Year	Net Precipitation Annual	Net Precipitation Oct-Mar	Net Precipitation Apr-Sept
2004	443	285	158
2005	301	317	-16
2006	364	311	53
2007	582	501	81
42 Year Average	415	379	36

6 RESULTS/ ANALYSIS

In the following section, change in water level throughout the four year monitoring period (2004 to 2007) is discussed. As discussed in the methodology, there was insufficient data available for analysis of water year 2006 and so the data for this year is omitted. Water levels relative to the peat surface throughout 2004, 2005 and 2007 can be seen in figures 6.1, 6.2 and 6.3 respectively. Climatic conditions are summarised using data from the water budget to give context water level change. A summary of seasonal variation for each borehole, in each year is given. This includes average water levels for the year and average water levels for the first and second halves of each year. Change in storage (the difference between the highest and lowest monthly average water level AOD in a year) is given to reflect the maximum change in water level during the year. Finally, peat expansion for the year at each borehole is reported. Peat expansion is factored into figures 6-1, 6-2 and 6-3.

6.1 Water Year 2004

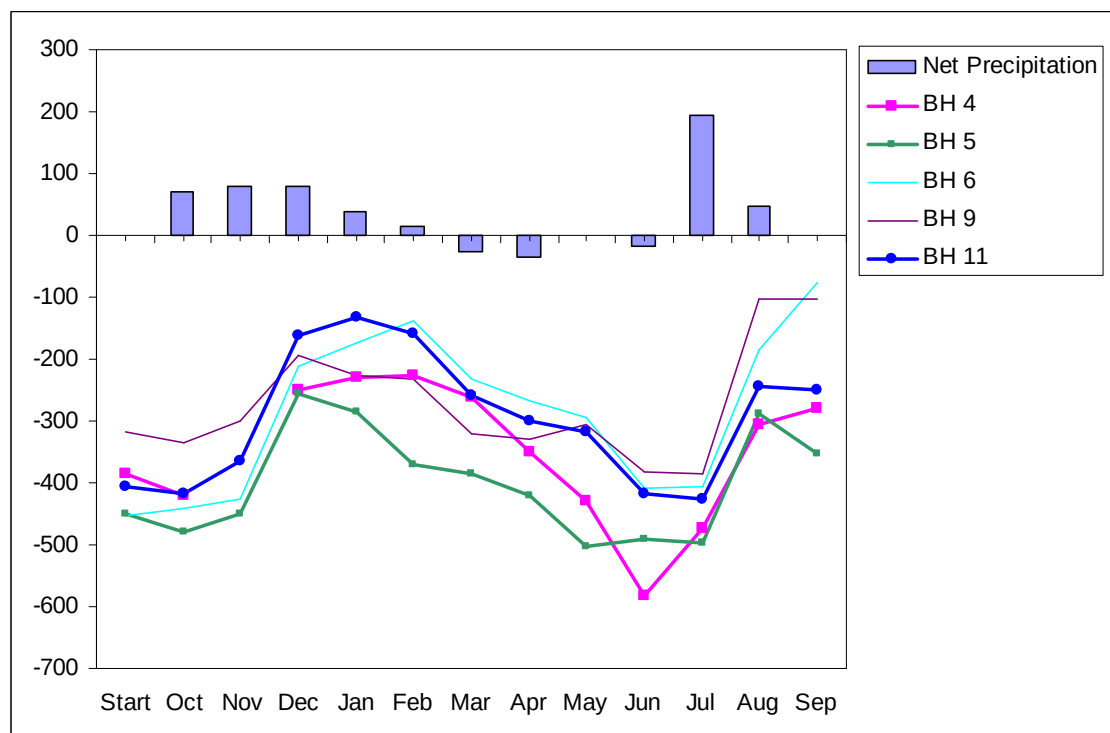


Figure 6-1 Borehole levels and net precipitation water year 2004.

6.1.1 Climatic conditions 2004

The site had experienced higher net precipitation than the long term average during the first year (422mm, long term average 415mm). The average was raised by high rainfall in August of 2004. Until August of the 2004, cumulative net rainfall had been generally lower than the other three years of the study period.

6.1.2 Borehole data 2004

Borehole 4: In the first year of the study period borehole number 4 showed an annual average water level that was approximately 350mm from the peat surface. During the period Oct to Mar the water table was an average of 280mm below the surface peat and averaged approximately 120mm lower for the period of Apr to Sep. The change in storage at borehole 4 is approximately 355mm. During 2004 the peat surface at borehole 4 expanded by 10mm.

Borehole 5: In year 03/04 of the study period borehole 5 showed an average annual water level that was approximately 400mm below the peat surface. During the period Oct to Mar the water table was at an average of 370mm below the peat surface. The average water table for the period of Apr to Sep was approximately 55mm lower than this at 425mm. The change in storage at borehole 5 for the period was 246mm. During 2004 the peat surface expanded by 14mm.

Borehole 6: The average annual water level for borehole number 6 for water year 03/04 was approximately 270mm below the peat surface. During the period Oct to Mar the average water table depth below the peat surface remained at 270mm. The average water table for the second half of the water year Apr to Sep was also approximately 270mm below the peat surface. Despite the consistency in average water table depth throughout 2004 there is clear seasonal variation. Water levels drop from Feb to Jul and recover dramatically with heavy rainfall in August. This variation in water level is confirmed by a change in storage of 363mm. During 2004 the peat surface expanded by 10mm.

Borehole 9: The average annual water level was approximately 270mm below the peat surface. During Oct to Mar and Apr to Sep the average water level remained at 270mm. As with borehole 6, despite this consistency in average levels it can be seen from the Figure 6.1 that water levels fall from Feb to Jul and recover dramatically with heavy rainfall in August. This variation in water level is confirmed by a change in storage of 282mm. There was no peat expansion measured.

Borehole 11: The average annual water level for borehole number 11 was approximately 290mm below the peat surface. During the period Oct to Mar the average water table depth below the peat surface was 250mm. The average water table depth for Apr to Sep dropped to 325mm below the peat surface. The change in storage at borehole 11 for 2004 was 293mm. During 2004 peat expansion was measured as 10mm.

6.2 Water Year 2005

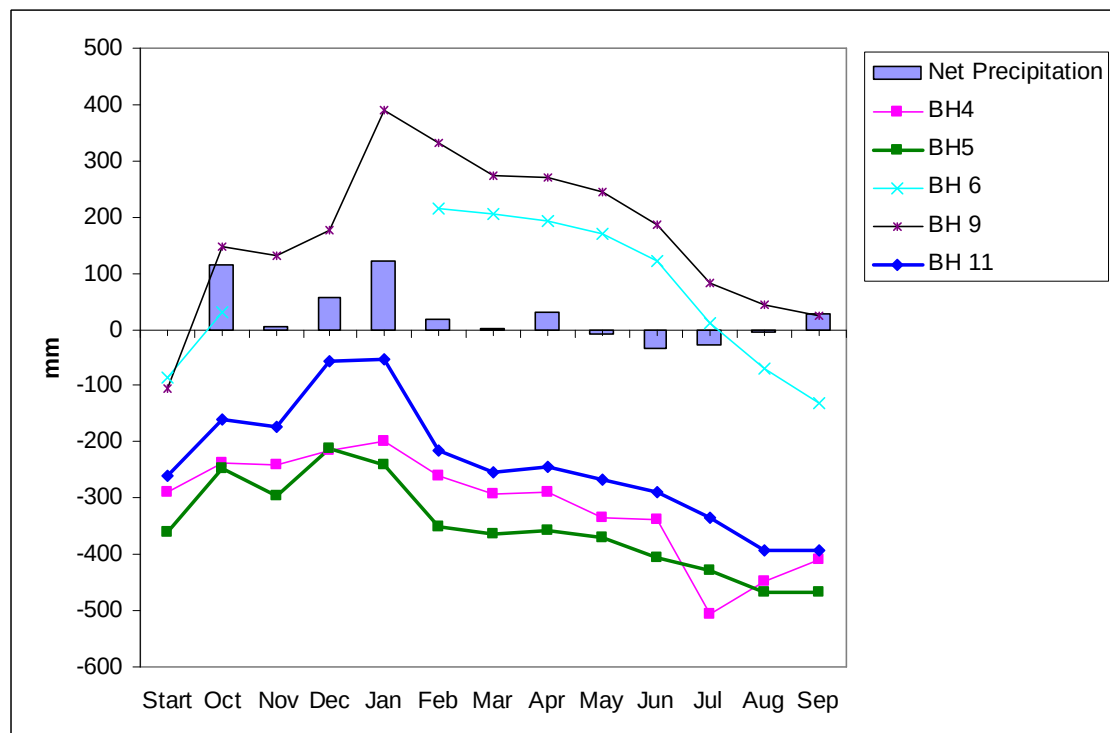


Figure 6-2 Borehole levels and net precipitation water year 2005.

6.2.1 Climatic conditions 2005

During the second year of the study period the site experienced annual net precipitation lower than the long term average (301mm). In January of this year however net precipitation was much higher than the 42 year average (76mm), reaching 121mm. As with the rest of Cumbria, the site experienced particularly severe weather conditions during the nights of Friday 7th Jan and Saturday 8th Jan (EA, 2005). This resulted in flooding and damage to bunds on the Wedholme site particularly at the northern end.

6.2.2 Borehole Data 2005

Borehole 4: The annual average water level was 315mm below the peat surface. During the period Oct to Mar the water table was an average of 240mm below the surface peat and averaged approximately 145mm lower for the period of Apr to Sep at 385mm below the surface. The change in storage was approximately 290mm. During year 2005 the peat surface at borehole 4 shrunk by 40mm.

Borehole 5: The annual average water level was 350mm below the peat surface. During the period Oct to Mar the water table was an average of 285mm below the surface peat and averaged approximately 130mm lower for the period of Apr to Sep at 415mm below the surface. The change in storage was approximately 260mm. During 2005 the peat surface at borehole 5 shrunk by 50mm.

Borehole 6: The annual average water level was 83cm above the peat surface. During the period Oct to Mar the average water table level was 150mm above the peat surface. The average water table level for Apr to Sep dropped, but still remained 49mm above the peat surface. It should be noted that data for Nov to Jan was unavailable. It would be reasonable to assume that the water table was above the surface for this period as it is known anecdotally that the northern end of the study site where borehole 6 is situated was flooded during severe weather in Jan 05. The change in storage was 348mm. This figure is greater than the total net rainfall calculated for water year 2005 (301mm). This could indicate that the increase in water level is attributable to sources other than direct rainfall, such as water flowing

from other parts of the site or outside from the site. During 2005 peat expansion at borehole 6 was measured as 14mm.

Borehole 9: The average annual water level was 192mm above the peat surface. During the period Oct to Mar the average water table level was 242mm above the peat surface. The average water table level for Apr to Sep dropped, but still remained 10mm above the peat surface. Unlike borehole 6, data for borehole 9 is available for the period Nov to Jan 04/05. It can be clearly seen that the largest rise in the water table for this period occurs in Jan 05. This would seem to confirm that the increased water level present in Feb at borehole 6 is also likely to be due to weather conditions in Jan 05 as both boreholes 9 and 6 are located at the northern end of the study site. The change in storage at borehole 9 for the year 04/05 was 494mm. It can be seen that this change in storage was due to the water level increase in between Oct 04 and Jan 05. At the beginning of the water year on 1st Oct, the water level was 104mm beneath the peat surface. By the end of Oct the monthly average water level was 249mm higher at 145mm above the peat surface. The average water level then rose a further 245mm from Nov to Jan resulting in a total rise of 494mm. This figure is greater than the total net rainfall calculated for water year 2005 (301mm). This indicates that the increase in water level described is attributable to sources other than direct rainfall, such as water flowing from other parts of the site or from outside the site. It is likely this additional water resulted from flooding caused by the severe weather conditions in Jan 05. During 2005 peat expansion was measured as 14mm.

Borehole 11: The annual average water level was 236mm below the peat surface. During the period Oct to Mar the water table was an average of 152mm below the peat surface and averaged approximately 170mm lower for the period of Apr to Sep at 320mm below the surface. The change in storage was approximately 324mm perhaps indicating that the site was affected by flood water. During 2005 the peat surface remained stable.

6.3 Water Year 2007

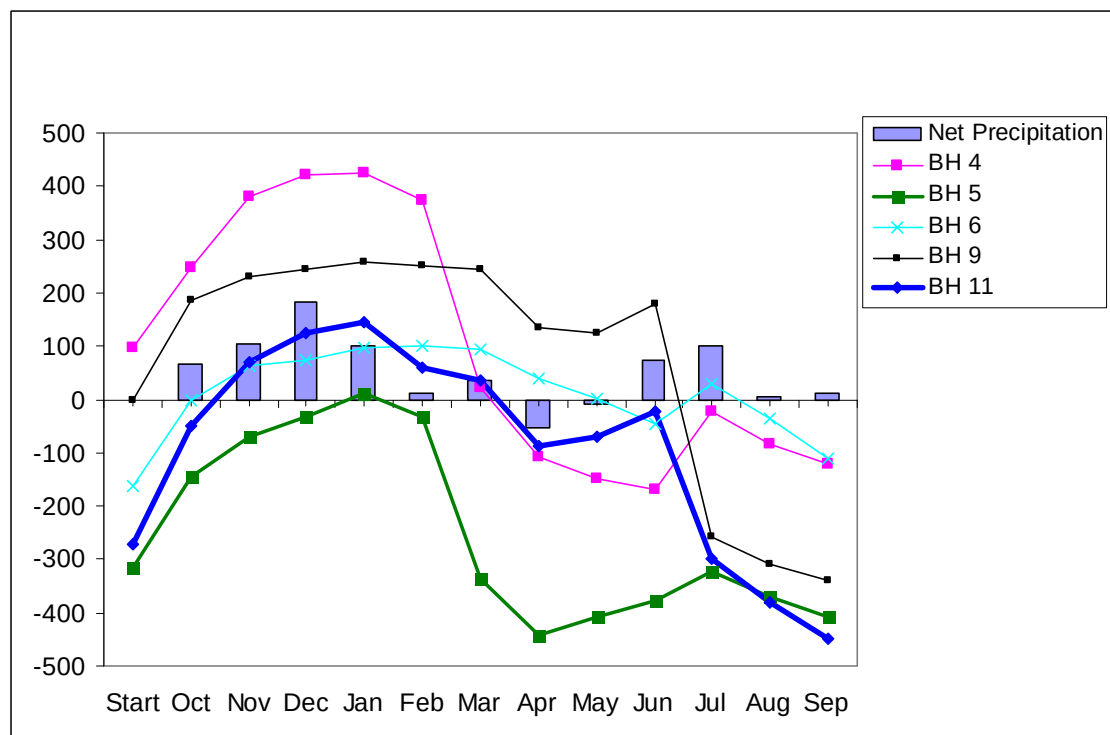


Figure 6-3 Borehole levels and net precipitation water year 2007.

6.3.1 Climatic conditions 2007

The net precipitation of 628mm for the year 2007 was well above that of the 42 year average of 415mm. Net precipitation was consistently higher than throughout the other three years of the study period. Only Oct 2007 was lower than Oct 2005 and Oct 2006. This was predominantly due to precipitation at 1177mm being far in excess of the 42 year average of 920mm. This high precipitation figure was little countered by the annual PE figure for 2007 of 549mm which despite being the highest in the study period was only marginally higher than the 42 year average of 531mm. Net precipitation was highest in Dec at 182mm which is more than double the 42 year average for Dec (74mm). Net precipitation was also high in Jun and Jul at 73mm and 100mm respectively. The 42 year average produces negative net precipitation figures for these months.

6.3.2 Borehole Data 2007

Borehole 4: The annual average water level was 102mm above the peat surface. During the period Oct to Mar the water table was an average of 312mm above the peat surface and averaged approximately 420mm lower for the period of Apr to Sep at 108mm below the surface. The change in storage was approximately 595mm. During year 2007 the peat surface at borehole 4 remained stable.

Borehole 5: The annual average water level that was 244mm below the peat surface. During the period Oct to Mar the water table was an average of 101mm below the peat surface and averaged approximately 287mm lower for the period of Apr to Sep at 388mm below the surface. The change in storage was approximately 453mm. During year 2007 the peat surface at borehole 5 shrunk by 30mm.

Borehole 6: The annual average water level that was 25mm above the peat surface. During the period Oct to Mar the water table was an average of 70mm above the peat surface and averaged approximately 90mm lower for the period of Apr to Sep at 20mm below the surface. The change in storage at was approximately 261mm. During year 2007 the peat surface at borehole 6 shrunk by 11mm.

Borehole 9: The annual average water level that was 80mm above the peat surface. During the period Oct to Mar the water table was an average of 236mm above the peat surface and averaged approximately 314mm lower for the period of Apr to Sep at 78mm below the surface. The change in storage was approximately 598mm. During year 06/07 the peat surface at borehole number 9 expanded by 16mm.

Borehole 11: The annual average water level that was approximately 77mm below the peat surface. During the period Oct to Mar the water table was an average of 64mm above the peat surface and averaged approximately 282mm lower for the period of Apr to Sep at 218mm below the surface. The change in storage was approximately 594mm. During year 2007 the peat surface at borehole 11 remained stable.

6.4 The influence of antecedent weather conditions

As already stated, Ombrotrophic bogs receive their supply of water from precipitation (Wickham, 1951; Ingram, 1982). Therefore all changes in water table level should be examined in the context of the prevailing weather conditions, specifically the extent of which supply through precipitation and extraction through evaporation has occurred. This was achieved in the study by calculating net precipitation (as discussed in the methodology) which in theory represents the minimum amount of precipitation available after all evaporative capacity has been realised.

The average net precipitation for the monitoring period (2004 to 2007) was consummate with the long term average (434mm and 415mm respectively) calculated for the study site. A study conducted by Clothier and Newson, (1995) in Labadz et al., (2004), estimated annual net precipitation for the site to be 428.5mm. This indicates that the net input of water during the monitoring period is likely to reflect the sort of net water input that can be expected on the site in future years notwithstanding climate change.

However there were some extreme values for individual years within the monitoring period. Water year 2005 had net precipitation of 301mm. There are only 10 years where net precipitation is lower than this in the 42 years of preceding data. Water year 2007, the last in the four year monitoring period, had net precipitation of 628mm. There are only two years where net precipitation is higher than this in the 42 years of preceding data. As well as having a net precipitation far lower than the 42 year average, the site experienced severe weather conditions in January 2005 (Environment Agency, 2005) resulting in a net precipitation of 121mm, nearly double that of the 42 year average for the month of January. October 2005 also had net precipitation nearly double that of the 42year average. This means that the vast majority of net precipitation for water year 2005 fell in just two months. Both water years 2005 and 2007 do not represent ideal weather conditions for monitoring change in water table levels in raised mires. 2005 has extremely low values of precipitation from April to September including a lower than average value for August which is identified as a critical period for water level recovery in mires situated in the UK due to it being the end of a period of high evaporation when water levels typically recover

(Backeus, 1988). This has resulted in the average monthly net precipitation for the last six months of water year 2005 (April to September) being – 2.7mm. Conversely, water year 2007 had net precipitation values higher than the long term average for nine out of twelve months. Both years 2005 and 2007 of the monitoring period have values of net precipitation that are within the range of values from the 42 years preceding data. It is clear however, that these years exhibit extreme values for net precipitation when compared to the long term average and this should be considered when drawing any conclusions about water levels on the site.

6.5 Extent and spatial variation of water table rise at the study site

Although as already stated, average water table levels at the study site have increased for all five boreholes during the monitoring period. There is a sizeable drop in the water table levels during the summer and it is this inconsistency that is likely to prevent the reinstatement of Sphagnum at the study site.

The area of the study site represented by borehole number 6 appears to demonstrate a water level that is consistently in close proximity to the surface for the majority of the monitoring period. In water year 2004 the water table at borehole 6 averaged approximately 270mm below the peat surface; although there was a drop in water table level from April to September, the average water table depths for both the first and second halves of the year were also 270mm. This demonstrates that the water table at borehole number 6 was relatively stable when compared to the water levels at other boreholes. During water year 2005 the water table averaged 83mm above the peat surface. The average level for the first six months (October to March) was approximately 150mm above the peat surface and the average for the second half of the year (April to September) remained above the peat surface by 49mm. The height of water over the peat was likely to be due to severe weather conditions in 2005 which caused flooding reported at the northern end of the site where borehole 6 is situated (Brock, 2008). As stated in the methodology there was insufficient data available to perform an analysis of borehole data for the water year 2006. In water year 2007 the water table at borehole 6 averaged 25mm above the peat surface over the whole year with an October to March average of 70mm above the surface and an April to September average of 20mm below the surface. The exceptionally high level of net

precipitation in water year 2007 (628mm) undoubtedly contributed to the high water levels in this area of the mire, nevertheless the water table at this point demonstrated more stability and consistently high water table levels than any other area monitored in this study

On the contrary, water table levels at borehole 5 appeared to show repeated seasonal instability characterised by high water table levels (October to March) and much lower water tables from (April to September). It is also noteworthy that in the three years of the monitoring period for which there is sufficient data, borehole 5 is the only one analysed in the study at which water never breaches the peat surface. This is despite the occurrence of severe weather conditions (E.A., 2005) and a very high rainfall year (2007) which contributed to periodic surface flooding on other areas of the study site. The relative low level of the water table at this point on the study site may indicate that drainage at this location is too efficient and consequently the peat at this point cannot store water long enough to raise the water level.

With regard to the data from the other three boreholes (4, 9 & 11) it is clear that they all appear to experience very large seasonal fluctuations. This has included prolonged and excessive surface flooding in the first half of the water year (October to March). This is particularly true at the area of the site occupied by boreholes 9 and 4. Data showed that for the first half of water years 2005 and 2007 standing water over the peat surface at these locations reached between 200 and 400mm. This amount of water over the peat surface for this amount of time may be a barrier to those *Sphagnum* species which are not able to colonise through hydrosere succession (Lindsay, 1995).

It is notable that the water table around borehole 4 rose significantly and did not drop more than 150mm below the surface in water year 2007 during the second half of the water year (April to September). Borehole 4 did however show less stability in 2005, dropping sharply post June. Raised levels at borehole 4 from Apr to Sept may be due to high levels of precipitation. Although borehole 11 shows a year on year increase in average water levels, levels during Apr to Sept are consistently lowered in all monitored years.

6.6 Summary

Climatic conditions for the monitoring period were not representative of the long term normal. Extreme weather conditions during this period meant that there was insufficient opportunity to assess how the mire would retain water during periods of low supply, especially through the critical summer period when rainfall tends to be lower and evaporative capacity high. Although as shown in table 6-1, both water years 2005 and 2006 produced low annual net precipitation in comparison to the 42 year average, during the critical summer period the site experienced elevated supplies of water due to extreme weather conditions in both years. In 2005 residual surface flood water from the January flood event remained on the mire during Apr to Sept and despite having low annual net precipitation, water year 2006 produced a relatively high net precipitation for the period Apr to Sept.

Water year 2007 produced a high level on net precipitation when compared to the 42 year average making increased groundwater levels likely, regardless of the effect of restoration. Although 2004 produced levels of net precipitation closest to the 42 year normal it was the first year in the monitoring period and so groundwater response could not be compared to prior years.

Table 6-1 Relative net precipitation (actual height of water in mm indicated in brackets) and borehole response by year.

Water year	Net Precipitation Annual	Net Precipitation Oct-Mar	Net Precipitation Apr-Sept	Borehole Response
2004	High (443)	Low (285)	High (158)	Base Line Data
2005	Low (301)	Low (317)	Low (-16)	Elevated ground water but surface flooding residual from January
2006	Low (364)	Low (311)	High (53)	No Data
2007	High (582)	High (501)	High (81)	Elevated groundwater levels until July
42 Year Average	415	379	36	

Table 6-2 shows that in general the water level had risen both annually and seasonally over the monitoring period 2004-2007. Only the water level Apr to Sept for borehole 5 was lower in 2007 than it was in 2004, indicating that restoration has not been effective at raising average water levels in this area of the study site. Although average water levels have tended to rise during the monitoring period, water levels have not tended to remain stable or consistent at most of the boreholes. This is demonstrated in table 6-2 by the increase in change in storage for the period 2004 – 2007. Only borehole 6 has shown a decreased change in storage over the monitoring period, demonstrating that water levels have become more consistent and stable at this point in the study site

Table 6-2: A comparison of water years 2004 and 2007 indicating direction of change for each borehole (+ indicates an increase and - indicates a decrease).

Borehole	Avg. water level (Oct-Mar)	Avg. water level (Apr-Sept)	Avg. Water level (Annual)	Change in storage
4	+	+	+	+
5	+	-	+	+
6	+	+	+	-
9	+	+	+	+
11	+	+	+	+

Water levels on the study site rose but summer water levels remained much lower than those in the winter. Of the five boreholes analysed only borehole 6 exhibited a water level that was consistently close (within 100mm) to the surface in the final year of monitoring.

6.7 Main Indications of Results/Analysis

- Antecedent weather conditions at the study site during the monitoring period have not been typical of the long term normal. This makes analysis of water table response to restoration difficult. Difficulties with analysis were further aggravated by no borehole data being available for the year 2006.

- Average annual water levels at all monitored areas of the site have risen since restoration when 2004 levels are compared with those in 2007.
- Change in storage has increased post restoration in all areas of the site monitored except for the area in proximity to borehole 6. This indicates that the water level in all but one area of the monitored study site has become less consistent. The increased change in storage over the monitoring period is largely due to increased seasonal variation in groundwater levels.
- Although water levels have increased, they have failed to achieve consistent proximity to the peat surface. Winter levels have resulted in surface flooding and summer levels have dropped sharply. Only the area around borehole 6 remained consistently in proximity (within 100mm) to the peat surface in 2007.

7 DISCUSSION

7.1 Has restoration at the study site been successful in raising water levels?

Restoration efforts to date have focussed on raising water table levels in the peat by reducing drainage on site. Because the impermeable layer that caused the mire to form is likely to be intact, drainage will be in the form of lateral seepage to the periphery of the mire. As described by Wickham (1951), Hilell (1971) and Childs (1969), the height of a water mound that causes mires to form is dependent on the length of the base of the mire. When the base of the mire effectively is shortened by the insertion of drains, there is less of a barrier to water loss and the rate of loss will be increased from that of any undisturbed mire. Because neighbouring land owners have objected to the blocking of peripheral drains, restoration efforts have been restricted to blocking of internal drains and slowing water loss through methods such as the insertion of peat plugs and the construction of bunds. This would seem to be a prudent strategy because the peat plugs have a lower porosity than the surrounding peat body and as is established by Darcy's law, flow of water through a porous medium is dependent on the porosity of the medium.

Over the four year monitoring period (water years 2004-2007), average water levels rose in all five boreholes used in the study. It was clear however, that certain boreholes indicated a much more stable water level than others. Although all five boreholes demonstrated elevated average water levels year on year throughout the first six months (October to March) it was clear that average water levels in the second half of the water year (April to September) did not respond as well. This is significant because during the summer period (April to September) input from net precipitation at the study site is drastically reduced, often producing negative net precipitation for certain months. The lowered summer groundwater levels indicate that drainage post restoration is too efficient and that restoration has failed enable sufficient storage of winter rainfall to maintain groundwater levels during summer months when net input from precipitation is low. Maintenance of stable water tables is problematic in cut over peat surfaces because there is no porous acrotelm to act as a store that can resupply the peat below, but also because the inherent higher bulk

densities and consequent lower porosities cause a greater retreat in the water table for unit volume of water lost (Quinty and Rochefort, 2003; Heathwaite, 1995).

Overall monitored water levels have increased year on year, only the average water level Apr- Sept for borehole 5 failed to do so over the monitoring period 2004-2007. These increases are not however necessarily sufficient to achieve the restoration objectives.

7.2 Have water levels risen sufficiently to achieve restoration objectives?

Natural England cited no formal restoration objectives other than the desire to return this cutover section to functioning raised mire. They propose to do this by encouraging Sphagnum colonisation with the aim of eventually reinstating the acrotelm. As discussed, the restoration strategy has focussed on reducing drainage and raising groundwater levels in the hope that Sphagnum will re-colonise from neighbouring sites naturally. Natural England set an informal target for the water table to remain within 200mm of the surface. This may be too deep for Sphagnum to re-colonise as the higher bulk density and lower porosity of cutover peat generates an increased pore pressure at the surface making extraction of moisture by Sphagnum difficult (Price, 1997). Although this is indicated as an acceptable level for the water table in some literature (Lindsay, 1995; Bragg, 1995) this level only applies in functioning mire. This is because when the water table retreats in a functioning mire, the lower layers of the acrotelm, made up of partially decayed Sphagnum, have a higher porosity than the peat in the catotelm below, allowing storage of water near the surface and easier release of that water to the Sphagnum above (Longton, 1979). Therefore, the informal objective of 200mm set by Natural England is not compatible with the ultimate objective of returning the cutover mire to a functioning status. In order to compensate for the moisture normally supplied to Sphagnum via the lower layers of the acrotelm in a functioning mire, water levels in the cutover mire must be maintained at or as near as possible to the surface.

Despite the completion of restoration works at the beginning of water year 2007 and the advent of heavy rainfall in that year, no area of the mire that was monitored maintained a water level that was at or close to the surface throughout the entire year. Three out of the five boreholes analysed in this study failed to remain within the

200mm limit set by Natural England. The other two boreholes, namely boreholes 4 and 6 did remain within the 200mm target but in the case of borehole number 4 only within the last year of the monitoring period. Perhaps more importantly summer water levels, critical to Sphagnum survival, remained low even when winter levels were elevated. This was characterised by the increased change in storage during the period 2004-2007 for all but borehole 6.

From the five boreholes analysed it can be seen that the water table in the mire proximate to borehole 6 responded to restoration most favourably, demonstrating a level that was consistently within 100mm of the surface throughout the final year of monitoring. The stability of the water table at this point of the site was confirmed by the reduced change in storage during the period 2004-2007. This may not however be close enough to the mire surface to allow the natural re-colonisation of *Sphagnum*.sp. Indeed, when the site was visited in June 2008 there was no evidence of *Sphagnum* re-colonisation at borehole 6 or any other monitored area of the site.

Regardless of *Sphagnum* re-colonisation, it is clear that water levels across the site have been raised. Increased submergence in water will create anoxic conditions for the peat covered by the raised water table. The anaerobic conditions created by submergence will help prevent oxidation and will therefore reduce wastage preserving peat for future restoration (Hobbs, 1986) and preventing release of carbon to the atmosphere (Immirzi et al., 1992). The preservation of the remaining peat where *Sphagnum* has not re-colonised is essential to any future restoration of Weddholme and therefore must be considered to be an overarching restoration objective even if not explicitly stated. This considered, it is clear that restoration has been successful in reducing peat loss by raising the water table and in so doing has reduced CO₂ emissions from the site.

7.3 Have adequate targets been set?

Natural England's overall restoration aim is to restore Weddholme Flow to a functioning mire. Although this is a worthy long term aim, it does not define what steps will need to be taken to achieve this. Westman (1991), emphasises the importance of setting unambiguous objectives in ecological restoration projects. He

argues that failure to set clear targets makes reliable evaluation of restoration success difficult.

Wedholme Flow is not in one homogenous condition. The construction of drains and the cutting of peat to different heights on different parts of the site are likely to have left each area having its own restoration requirements. The dimensions of a raised mire, particularly the base, significantly affect the height of the water table (Wickham, 1951). This means that from a restoration perspective individual sections of Wedholme Flow have to be treated as separate mires, each with their own individual restoration programme and objectives.

Any analysis of the study site water levels should acknowledge that the boreholes were installed on the study site before restoration had been completed and restoration was not fully completed until the last year of the monitoring period (December 2006). As no detailed chronology of works is available it is difficult to ascertain whether or not water level change at individual boreholes is as a direct result of restoration.

7.4 Limitations of methodology

Although actual rainfall figures were used in calculating the water budget, actual evaporation from land depends on many factors such as crop cover and soil saturation. Methods for predicting actual evaporation such as the Penman Monteith method, require measurements additional to temperature, including wind speed above canopy (Shaw, 1983). These additional data were not readily available for the study site.

The water budget for the study site was derived using potential evaporation figures calculated by the Thornthwaite method. The Thornthwaite method is an empirical calculation that estimates total atmospheric evaporative potential rather than actual evaporation that occurred on site. This method was developed and calibrated for the eastern seaboard of the United States and is suitable for oceanic, humid, temperate climates (Davie, 2002). When compared with more detailed methods, such as Penman Monteith, Thornthwaite tends to overestimate PE for the UK climate (Shaw, 1983). Shaw (1983) notes that Thornthwaite's is particularly sensitive to high

temperatures and so can produce inaccurate estimates in the summer months or when used in arid or semi- arid climates. Since the west coast of England, where Wedholme Flow is situated is not an arid or semi arid region and enjoys an oceanic, humid, temperate, climate, it is therefore reasonable to assume that Thornthwaite's method will produce useful results. This would seem to be confirmed by a previous hydrological assessment for Wedholme using Meteorological Office maps deriving mean annual net precipitation as 428.5mm (415mm in this study), (Clothier and Newson, 1995 in Labadz et al., 2004). Thornthwaite provides a monthly figure for PE by using average monthly temperature and so is compatible with the lowest degree of temporal resolution in the historical weather data publically available from the UK Meteorological for Wedholme Flow, i.e. average monthly temperature.

In this study net precipitation is calculated as total precipitation – potential evaporation. However, potential evaporation is unlikely to be fully realised because this presumes consistent availability of water (Shaw, 1983). In reality this will not be the case especially in months where PE is greater than total precipitation. The amount of water that will be lost to evaporative energy from soils in these months is limited (Grindley, 1969). This means that Thornthwaite provides a worst case scenario and actual losses from the system are likely to be less.

7.5 Future strategies

Because of the remoteness of parts of the site from existing Sphagnum communities, Natural England is considering inoculating some sections with Sphagnum in an effort to try and encourage rapid re-colonisation. Grosvernier et al., (1997) suggest that when inoculating, choice of Sphagnum species may be as important as water table depth and depth that peat is cut to. They found that certain species of Sphagnum make better pioneer species than others. These species may facilitate the return of the wider Sphagnum community. This may result in a 'trade off' whereby the reinstatement of specific species is substituted for strong pioneers to restore a whole ecosystem. The spreading of mulch such as straw, in areas where inoculation is to be used, may also facilitate Sphagnum re-colonisation by increasing moisture levels at the peat surface (Quinty & Rochefort, 2003).

8 CONCLUSIONS

Natural England set a broad restoration target of restoring a *Sphagnum* acrotelm to the cut over surface of the peat. They hoped to achieve this by raising the water table level to within 200mm of the peat surface for the entirety of the year. Although this objective may be appropriate for unmolested mire, it fails to take into account the higher bulk density and lower porosity of cutover peat when compared to the surface of functioning mire. In cutover peat these factors will result in a reduced volume of water being stored at the mire surface and increased pore water pressure making it difficult for *Sphagnum* to become established. Consequently the aim should be to establish the water table at or as close to the peat surface as possible throughout the year.

It is clear from analysis of the results in section 6 that overall water levels have been raised post restoration on the study site. It is also clear that the water level in proximity to all but one of the boreholes (Number 6) continues to lower significantly through the critical second half of the water year (April to September) when evaporation tends to be higher.

During the monitoring period (2004-2007), borehole number 6 demonstrated the most stable water table consistently remaining within 100mm of the peat surface throughout the final year. Conversely borehole number 5 did not demonstrate any lasting elevation in the water table, remaining more than 200mm below the peat surface for the majority of the monitoring period, especially through the critical summer period. By the final year, of the remaining three boreholes analysed only borehole 4 had a water table level consistently less than 200mm from the peat surface. None of the boreholes demonstrated a water table that remained within the immediate proximity of the surface throughout the year for any year during the monitoring period (2004-2007).

The apparent rise in water levels achieved at the site during the monitoring period must be viewed in the context of the prevailing weather conditions. Two out of the

three years for which borehole data was available exhibited extreme weather conditions when compared with the long term average, specifically high rainfall in January 2005 resulting in severe flooding and consistently high rainfall throughout 2007. These weather conditions are likely to have contributed to higher water levels than could be expected for most years.

Effective analysis of groundwater response to restoration at the study site was hindered by inconsistent data collection and the lack of a detailed chronology for the restoration, some of which took place during the monitoring period.

In summary this study suggests that the water table has risen as a result of restoration but that it is not consistently high enough anywhere on the study site to support the re-establishment of *Sphagnum* without further intervention. Although not elevated sufficiently to encourage rapid *Sphagnum* re-colonisation, water levels on the site have risen sufficiently to reduce peat loss through oxidation, preserving it for future restoration.

It is recommended that monitoring is continued, accompanied by consistent data collection, in order to view the full affect of the completed site restoration under weather conditions closer to the long term average. Options for further restoration include inoculation with 'pioneer' *Sphagnum* species in proximity to areas of the site with elevated water tables. The use of mulch in these areas may increase availability of moisture at the peat surface allowing the inoculant species to gain a foothold.

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10 APPENDICES

10.1 Appendix A: Parameters of borehole assembly

The conduit not only acts as an anchor for the chain which suspends the sensor but also as a reference point for the entire borehole assembly. The height of the conduit top Above Ordnance Datum (AOD) was measured upon installation of each borehole. From this measurement it is possible to calculate the height AOD of the sensor and other components of the borehole assembly and therefore the height of the water table AOD.

Measurements were routinely taken at all the boreholes on site in order to monitor changes in dimensions. These primarily occurred in the distance from conduit top to the bracket where the bracket had slipped down the conduit or from the bracket to the peat surface where the peat had expanded upon saturation.

10.1.1 Water height calculation

Since pressure (**P**) generated by water in Pa or Nm^2 equals ρgh , where (ρ) is density of water in kg/m^3 , (g) is acceleration due to gravity in m/s^2 and (h) is the height of water in m.

Therefore height of water over the sensor (**h**) = $(\text{P} - \text{Atmos. pressure})/\rho g$

Density of water is presumed to be 1000 kg/m^3 and acceleration due to gravity is taken as 9.81 m/s^2 .

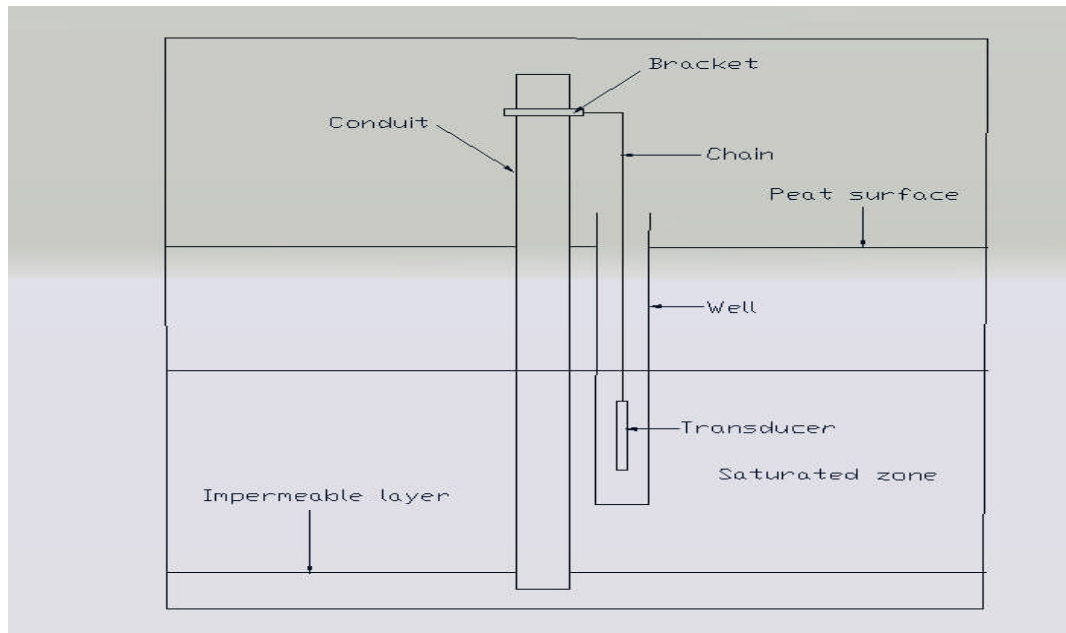


Figure 10-1 Simple schematic of borehole assembly. Source: Author