Peat bog restoration: Implications of erosion and sediment transfer at Flow Moss, North Pennines

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Peat bog restoration: Implications of erosion and sediment transfer at Flow Moss, North Pennines

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July 2012

Declaration

I confirm that no part of the material presented in this thesis has previously been submitted by me or any other person for a degree in this or any other university. In all cases, where it is relevant, material from the work of others has been acknowledged.

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Abstract

The impacts of peatland management strategies used to restore degraded bare peat flats have received little attention. This study aims to improve the understanding of geomorphological processes acting on an upland bare peat flat which is undergoing restoration at Flow Moss, North Pennines, UK. A sediment budget is constructed which provides a baseline framework for assessing the effectiveness of peatland restoration measures in reducing peat erosion rates.

Erosion monitoring of aeolian and active slope processes was undertaken between October 2010 and July 2011 using a network of sediment traps and erosion pins installed across the 7 hectare site. Meteorological conditions were monitored using an Automatic Weather Station and local water table was recorded using a pressure transducer. This allowed relationships between weather patterns, hydrology and sediment transfer to be developed.

Meteorological conditions are important in controlling the wind erosion of peat with the highest rates of erosion occurring when heavy rainfall (> 5 mm hr^{-1}) was combined with high wind-speeds (> 18 m s^{-1}). Windward facing traps collected up to 8 times the peat collected by leeward facing traps. Freeze-thaw weathering and surface desiccation are important in generating loose material on the surface for subsequent sediment transport. A two-phase model is proposed to explain wind splash erosion dynamics where weathered material is transported preferentially before the intact peat layer is eroded. Sediment transport across bare peat flats is very active (3.2 t a^{-1}) but the eroding flats are disconnected from the ephemeral channel system. Moreover, the channel system contains pools where the majority of suspended peat is deposited. This leads to a low net overall sediment yield for the catchment of approximately 0.01 t a^{-1}.

The terrestrial carbon store (~2060 tonnes) at Flow Moss is relatively stable as, in the worst case scenario, it is losing 117 gC m^{-2} yr $^{-1}$, amounting to just 0.4% of the total store. It is estimated that Flow Moss will become a carbon sink when 90% of the bare peat areas have been re-vegetated so it is therefore vital that the restoration measures are successful. Continued monitoring of sediment transfer will allow a full evaluation of the impact of the restoration measures in reducing erosion rates.

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Chapter 1. Introduction

Peatland landscapes make up much of the UK upland environment and are mostly covered by heather moorland. Peatlands are an important global environmental resource as they cover just 2% of the global land surface (3.5 million km^2) yet contain 455 Gt of carbon (Moore, 2002) which accounts for 30% of the global soil carbon pool (Crowe *et al.,* 2008). They are formed in areas of positive water balance and are a result of decaying organic matter that has accumulated in waterlogged conditions (Holden *et al.,* 2004). Peatlands therefore form in areas such as Newfoundland, Tasmania, boreal lowland regions such as Siberia and temperate upland environments, such as the Pennines and Cheviots in the UK (Figure 1.1). The focus of this thesis is the study of this type of landscape in the North Pennines, UK.

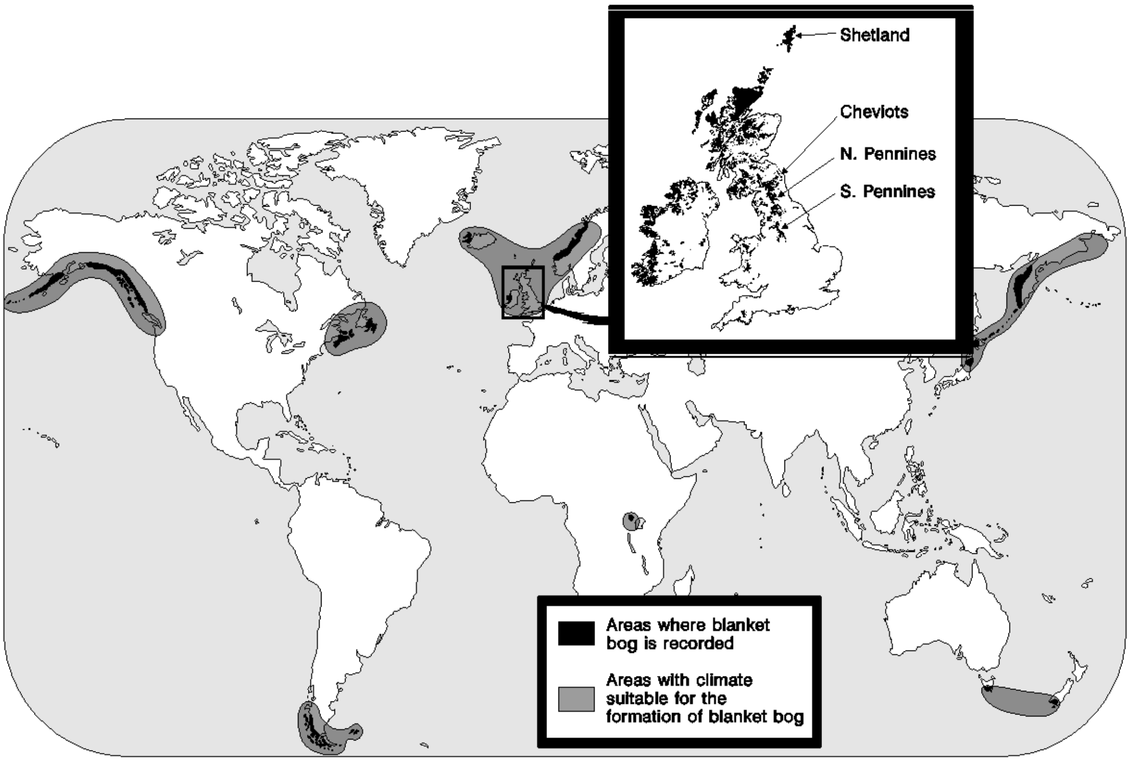


Figure 1.1: Global distribution of blanket bog (*Source: Evans and Warburton, 2007 modified after Lindsay et al., 1988*)

This chapter will introduce the research project by first discussing literature surrounding the global importance of peatlands and the impact of peatland degradation before introducing the restoration and management of peatlands which has characterised much of the recent interest in these important environments. This discussion provides the context for the current research and frames the research aims and the justification of the three key research objectives.

1.1 The global importance of peatlands

Peatlands play an important role in the global carbon cycle (Robroek *et al.,* 2010) as their long term ability to sequester carbon can moderate the atmospheric CO_2 concentration (Holden, 2005). It is therefore crucial to protect and maintain the functionality of peatlands because their large carbon sink could help mitigate the impacts of future climate change (Rowson *et al.,* 2010). Evans *et al*. (2006) clearly demonstrate through a schematic diagram (Figure 1.2) the principal carbon fluxes from peatlands. They suggest that these fluxes need to remain in equilibrium to maintain peatland functionality as a terrestrial carbon store.

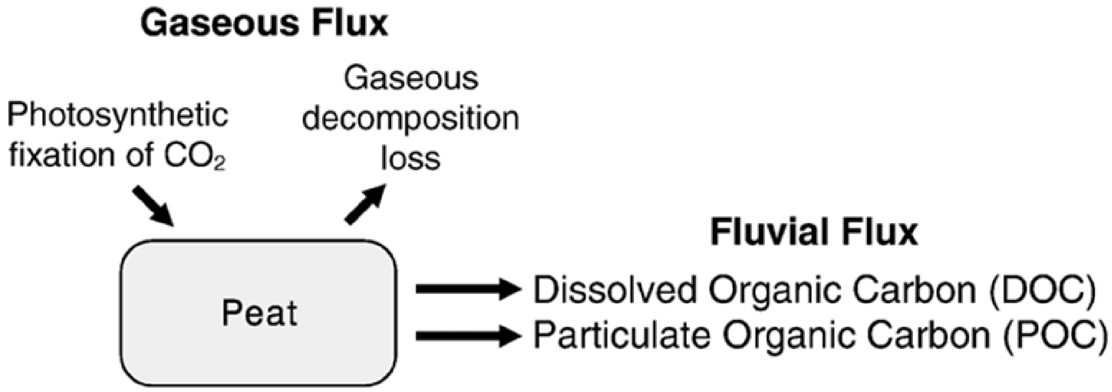


Figure 1.2: The principal carbon flux pathways from a peatland (*source: Evans et al., 2006*)

The balance of these fluxes is potentially under threat in the future due to the possibility of a warming climate. Houghton and Woodwell (1989) suggest that more carbon will be released from peatlands as increasing temperatures will increase the rate of respiration and gaseous decomposition loss more than the rate of photosynthesis, thus changing the weighting of these processes in the carbon cycle. Furthermore, a decrease in the height of the water table, induced by drier conditions, can lead to an increase in the export of carbon as oxygen can penetrate further into the peat column. Thus, the ingression of oxygen increases the activity of the enzyme phenyl oxidase in the peat, which in turn destroys the phenolic compounds present in the soil (Freeman *et al.,* 2001). These compounds repress the activity of hydrolase enzymes which leads to increased rates of microbial respiration and rates of decomposition (Freeman *et* *al.,* 2001). The rate of microbial respiration and rate of decomposition is a key control on the potential flux of dissolved organic carbon (DOC) (Gorham, 1991; Holden, 2005; Holden *et al.,* 2006; Holden *et al.,* 2007a; Tuittila *et al*., 1999; Rowson *et al.,* 2010). This has been shown by Alm *et al.* (1999) who monitored the carbon balance of a peatland in Finland during a dry summer and found that during the drought, the lowering of the water table increased the loss of carbon substantially.

Present evidence suggests that the UK peatlands are currently a slight net carbon sink (Holden *et al.,* 2007b) estimated to be at 1.2 x 10^{12} g C yr^{-1} (Worrall *et al.,* 2009a). However, the potential of an increase in the frequency of droughts in the future, predicted by the IPCC Fourth Assessment Report (AR4) (2007), will cause longer periods of water table drawdown and is subsequently likely to affect the carbon balance. Furthermore, Klove (1998) found the dominant cause of erosion from mire surfaces was as a result of intense rainfall and the IPCC (2007) report states that it is likely that there will be an increase in the number of extreme precipitation events in the future. It is therefore possible that the degree of peat erosion will increase. It is suggested that the physical degradation of peatlands could become a significant positive feedback of global climatic warming as increased erosion will release carbon from the terrestrial store into the atmosphere thus accelerating climate change and further increasing the pressure on the peatlands.

UK peatlands are of international importance (Ratcliffe and Thompson, 1988; Tallis, 1998; Ellis and Tallis, 2001) but they are more extensively degraded than other peatlands around the world. Tallis (1998) classified 3500 km^2 of UK peatlands as ‘either obviously damaged or modified from a supposedly natural state’ which is 14% of the total peatland area in the UK (25000 km^2) (Yeloff *et al*., 2005). Furthermore, Bragg and Tallis (2001) claim that blanket peat environments are extremely sensitive to external pressures including management practices such as vegetation change and developed a conceptual diagram showing important factors that can lead to the degradation of a peatland environment (Figure 1.3).

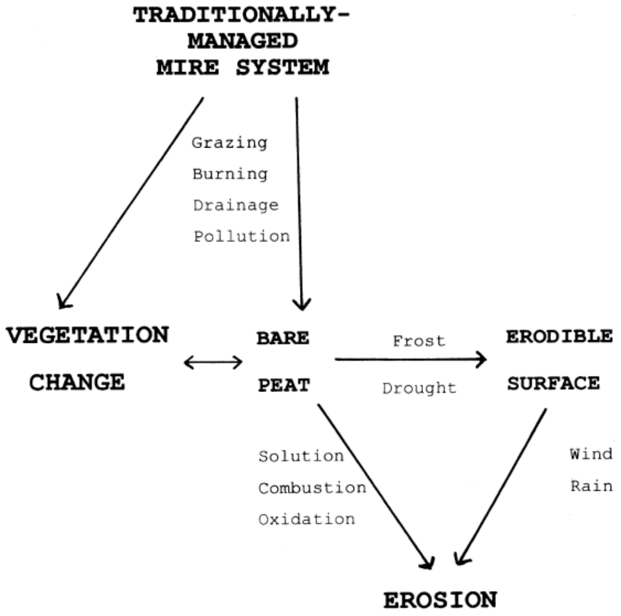


Figure 1.3: Conceptual diagram showing factors that can lead to degradation of UK peatlands. *(source: Bragg and Tallis, 2001*)

The majority of global peatlands, which are located in permafrost regions, are currently relatively stable but could come under threat from melting from increased temperatures induced by global climate change (Evans and Warburton, 2007). Although some localised erosion caused by fire or high grazing pressures does occur, the phenomenon of regional scale extensive erosion occurs almost uniquely in the UK (Evans and Warburton, 2007); however the causes are not fully understood. It is therefore important to understand the erosion processes occurring in UK peatlands in order to help inform the future balances in peat in other regions of the globe, as they come under pressure from external factors induced by climate change or management practices.

1.2 The effects of peatland erosion

The erosion and degradation of peatlands can cause major modifications to the terrestrial carbon store (Quinton *et al.,* 2010). Evans *et al.* (2006) found that in an actively eroding peatland, the output of particulate organic carbon (POC) can be the largest single flux in the carbon system. Table 1.1 summarises a range of studies of POC flux from eroding peatlands in the UK. The median value of POC flux is 15.63 g C m^{-2} a^{-1} but the fluxes from eroded peatlands; ranging from 15.6 to 92.5 g C m^{-2} a^{-1}, are significantly higher than the fluxes from intact moorland; 0.1 to 8.5 g C m^{-2} a^{-1}. In addition to the POC flux, Worrall *et al.* (2003)

showed that the flux of dissolved organic carbon (DOC) and loss of carbon through gaseous flux also increases when a peatland is being eroded.

Location	**Character**	**POC gC m^{-2} a^{-1}**	**Source**
NE Scotland	Intact moorland	0.1-8.5	Hope et al., 1997
Mid Wales	Intact grass covered moor	2.7	Dawson et al., 2002
North Pennines, England	Eroded and re-vegetated	14.7	Worrall et al., 2009a
North Pennines, England	Eroded and Re-vegetated	15.6	Evans et al., 2006
South Pennines, England	Eroding blanket peat data based on reservoir coring	15.7	Hutchinson, 1995
Plynlimon, Mid Wales	Eroding blanket peat	17.2	Francis, 1990
South Pennines, England	Eroding peatland	19.4	Labadz et al., 1991
South Pennines, England	Eroding blanket peat	92.5	Pawson et al., 2008

Table 1.1: Summary of studies of POC flux from eroding peatlands in the UK. Where POC is not reported directly in the source publication it has been calculated assuming 50% Carbon content in the organic sediment fraction (Evans and Warburton, 2007).

The erosion and degradation of peatlands can also have significant ecological and economic impacts over a variety of scales (Yeloff *et al.,* 2006). This is due to the high sensitivity of peatlands to slight environmental change such as periods of drought leading to surface desiccation (Bragg and Tallis, 2001). For example, a reduction in the water table by as little as 20 mm is enough to prevent the growth of Sphagnum mosses which is an important peat forming species (Ivanov, 1981). This can have a severe effect on the peatland system as the removal of vegetation cover can lead to an increase in sediment loss from the site. The modification of vegetation cover by erosion can lead to a loss of grazing land (Yalden, 1981); the associated lowering of the water table leads to a reduction of reservoir capacity (Labadz *et al.,* 1991) and the increase in DOC flux discolours drinking water (Pattinson *et al.,* 1994). The removal of the natural vegetation cover further increases the hydrological connectivity of the system as weathered material can be transported from the slope to the channel much faster when there is no vegetation or root network to block the channels (Evans and Warburton, 2007).

Peatland degradation can also severely impact the hydrology of a catchment. Daniels *et al.* (2008) show that there are significant differences in water flow pathways between intact and degraded peat. Widespread gully erosion of upland blanket peat in the UK provides natural drainage which can locally lower the water table in the affected area (Tallis, 1997a). The typical hydrological regime of a peatland area is ‘flashy’ (Holden and Burt, 2003); hydrographs have large peaks and short lag times between peak precipitation and peak discharge. Reductions in the height of the water table induced by drought or drainage can accelerate the hydrological connectivity of the system through increased macropore flow caused by structural changes to the peat (Holden, 2005; Daniels *et al.,* 2008). Peatland drainage through grip cutting was an extensive management practice during the 19th and 20th centuries with up to 100,000 hectares of blanket bog drained each year. The purpose was to lower the water table and remove surface water to improve vegetation and the habitat for grazing and game (Holden *et al.,* 2004). However, there is no evidence that the drainage of peatlands fulfilled the claims made for its extensive implementation (Stewart and Lance, 1983) as the economic benefits are low while the environmental effects are high (Newson and Robinson, 1983).

1.3 Peatland restoration

There is evidence that peatland systems can recover naturally from a degraded state. Evans *et al.* (2006) calculated the sediment yield from Rough Sike, a 0.83 km^2 blanket peat catchment in the North Pennines, as 44 t km^{-2} a^{-1}. Crisp (1966) first calculated the sediment yield from Rough Sike to be 92 t a^{-1} which is significantly greater than the contemporary measurements. The reduction in sediment yield was due to the extensive natural re-vegetation of the drainage gullies which reduced the sediment flux by 55.5 t a^{-1} and has also restored some of the peatland function. For comparison, Evans *et al.* (2006) calculated the yield from an actively eroding catchment, Upper North Grain in the South Pennines, to be 267 t km^{-2} a^{-1}.

A higher degree of plant material decomposition decreases the water content of peat which increases the bulk density. This can lead to significant variability in the bulk density with depth below the surface. Despite this density variability, it is always is very low and typically of the order of 0.1 t m^{-3} (Evans and Warburton, 2007). Therefore the sediment yield from peat catchments requires the transport of a larger dry mass of material than from a non-peat covered catchment for the volumetric erosion yields to be the same.

The re-vegetation of bare peat or gullies can significantly reduce the magnitude of POC flux (Evans and Warburton, 2005) and can also initiate fresh peat growth promoting the recovery of the water table (Crowe *et al.,* 2008). However, Holden *et al.* (2007b) found that natural re-vegetation of gullies is limited to slopes with an angle of less than 2^{o} due to the erosive power of water flowing over the surface. Furthermore, it is very unlikely that gullies or drains with an angle greater than 4^{o} will infill naturally (Holden *et al.,* 2007b). However, the process of natural re-vegetation can be accelerated through human intervention and the restoration of degraded peatlands has recently become an important land management priority (Wheeler *et al.,* 1995). Large scale projects such as 'Moors for the Future' in the South Pennines have been developed and have been funded by a range of organisations including Natural England, United Utilities, Environment Agency, Yorkshire Water, National Trust and the Peak District National Park Authority (Moors for the Future, 2011). The objective of these peatland restoration projects is to bring back a naturally functioning mire ecosystem (Tuittila *et al.,* 1999). However it is difficult to judge the success of such projects as it is often difficult to determine when a peatland is 'working' to its maximum function (Holden, 2005).

1.3.1 Current measures used to restore peatlands

There are a range of measures that have been used to restore peatlands from a degraded state and this section will discuss some of the most commonly implemented. A primary method used to restore areas of blanket peat is to block erosion gullies or drainage ditches known as 'grips'. This method aims to reverse the impact of peatland drainage by artificially re-instating the water table back to a height that is 'normal' for blanket peat. The relative position of the water table within the peat is crucial in determining the functionality and stability of the peatland as it controls the balance between accumulation and decomposition (Holden *et al.,* 2004). As discussed previously, a lower water table allows more oxygen ingression into the peat which increases the rate of decomposition and increases the carbon flux. A fundamental aim of many restoration projects is to restore the peatland system to a positive carbon balance, therefore increasing the water table is commonly the first step in this process. Without human intervention, it can take over 100 years after the abandonment of peat workings for the full re-establishment of hydrological function to occur (Van Seters and Price, 2002).

The implementation of grip-blocking has been widespread across UK upland environments, particularly in the North Pennines where the North Pennines Area of Outstanding Natural Beauty (AONB) Partnership's Peatscapes project have used 100,000 peat dams to block 950 km of drains to date. The project aims to block 1000 km of drains by 2012 which will hydrologically restore over 4000 ha of blanket bog (Peatscapes, 2011). This will result in the ditches holding water which will maintain and increase the water table in the surrounding peat and subsequently encourage the re-vegetation of Sphagnum mosses and other blanket bog plant species (Peatscapes, 2011).

Another established restoration method is the restriction of grazing animals. Excessive trampling by animals such as sheep not only damages vegetation but also prevents the re-colonisation of seeds during the growing season (Gore and Godfrey, 1981; Tallis and Yalden, 1983; Evans, 1997). After 10 years of grazing restrictions at Kinder Scout in the South Pennines, which began in 1983, the vegetation of an area of eroding peat had changed from acid grassland to a rich moorland community with bilberry and heather dominating (Evans, 1997).

As well as the hydrological restoration of blanket bog by grip-blocking, recent efforts have been made to restore areas of actively eroding bare peat by applying a 'quick-fix' approach. This aims to reduce losses from the terrestrial carbon store quickly, in particular the loss of particulate organic carbon, and has been carried out largely in the South Pennines by the '*Moors for the Future*' project. A common practice is to first limit grazing pressure by fencing off the bare areas before the spreading of heather (*Calluna Vulgaris*) cuttings, known as brash. The application of brash provides a seed base so that vegetation can grow and creates a surface microclimate amongst the brash cuttings that protects the seeds from harsh weather (Price *et al.,* 1998). In the South

Pennines, over 1500 tonnes of heather brash along with 8 million grass and heather seeds has been spread over 600 ha of degraded peat (Moors for the Future, 2011). Areas of bare peat are especially prone to erosive processes such when rainsplash as the peat surface is exposed to direct rainfall impact. The application of a thick cover of brash protects bare peat as the heather cuttings reduce the number of direct raindrop impacts that can dislodge loose peat from the surface. This in turn leads to a reduction of peat lost through hydraulic transport as the overall flux of material into the channel network is lower. Therefore brash cover, as a restoration tool, initially reduces sediment flux from areas of bare peat, and in the longer term encourages vegetation cover through seed colonisation.

Other methods employed by the '*Moors for the Future'* project include the use of geo-textiles to stabilise bare peat slopes and fertiliser to aid vegetation growth. In 2012, the '*Moors for the Future'* project plan to publish a report from a five year monitoring period that identifies the most effective species and all possible methods for *Sphagnum* culture, transportation and inoculation (Moors for the Future, 2011).

1.3.2 Evidence for the successful implementation of peatland restoration measures

Waddington *et al.* (2008) studied the impact of peatland restoration on the export of carbon from a catchment in Quebec, Canada by comparing two sites; one which had been restored and one which was still in a 'cutover' state following peat extraction. The restoration measures implemented included the construction of peat dykes to encourage water retention and the managed cutting of the vegetation. In all three of the study years (1999-2001), the release of DOC was higher for the cutover site than for the restored site and the water table was found to have increased in height over the course of the study period at the restored site (Waddington *et al.,* 2008). At a site in Finland, Tuittila *et al.* (1999) found that the water table was 26 cm higher in the summer months following restoration than previously recorded. Jauhiainen *et al.* (2002) examined the impact of restoration on the hydrology and vegetation coverage of two sites in Finland that had been drained to improve the land for forestry. Before restoration, the water table ranged between 20 and 65 cm below the bog surface during the growing season but three years following the filling in of the ditches and the removal of tree stands, the water table had increased to between 5 and 20 cm from the bog surface (Jauhiainen *et al.*, 2002). After restoration, forest species declined rapidly and there was an increase in the number of wetland species such as Sphagnum mosses and moorland grasses (Jauhiainen *et al.*, 2002). These studies all show that with human intervention it is possible to improve degraded peatlands by improving the hydrological functionality and ecological condition.

In the UK, three reports (Philips *et al.,* 1981; Tallis and Yalden, 1983; Anderson *et al.,* 1997) were commissioned by the Peak District National Park to examine the effect of restoration on erosion. These studies suggest that management practices can be effective in restoring peatland functionality but the results must also be interpreted carefully. The causal factors for peat erosion differ with topography, severity of atmospheric pollution or the climate regime in each peatland area and results from one study area should not be extrapolated. For example, the peatlands of the South Pennines are located at the climatic margins required for peat growth and are therefore more sensitive to external perturbations, making them less likely to recover naturally and will thus require more intensive restoration measures (Holden, 2005). Therefore, a number of studies of the impacts of peatland restoration at a range of sites are required in order to be able to produce a clearer understanding of erosion processes and identify the best techniques for restoring peatland function.

1.4 Context for this research

The North Pennines Area of Outstanding Natural Beauty (AONB) Partnership's Peatscapes project was established in 2006 to conserve and enhance the functionality and resource of peatlands in the North Pennines AONB (Peatscapes, 2011). As discussed previously, the primary method used by *Peatscapes* is the use of peat dams to block grips (moorland drains) but the project also aims to restore actively eroding bare peat flats. The first site of peat flats to be restored by *Peatscapes* is a 7 ha area at Flow Moss, near Allendale Town (Figure 1.4). The removal of the pressure of grazing animals by building a temporary fence was carried out in April 2010 and the bare areas re-seeded by the spreading of heather brash over the bare surface peat in December 2010.

Subsequent to this research the original fence was modified in November 2011 to exclude rabbits. While these methods have been used extensively over large areas in the South Pennines as part of the ‘*Moors for the Future’* project, Flow Moss is the first site in the North Pennines to be restored in this way by the ‘*Peatscapes’* project and it is not known how successful the restoration measures will be, particularly in terms of reducing the erosion rates of peat and therefore the export of particulate carbon from the site. This is partly due to the lack of a detailed extensive geomorphological assessment of the impacts of bare peat restoration but also due to the current limited understanding of the dynamics of the processes acting during bare peat erosion.

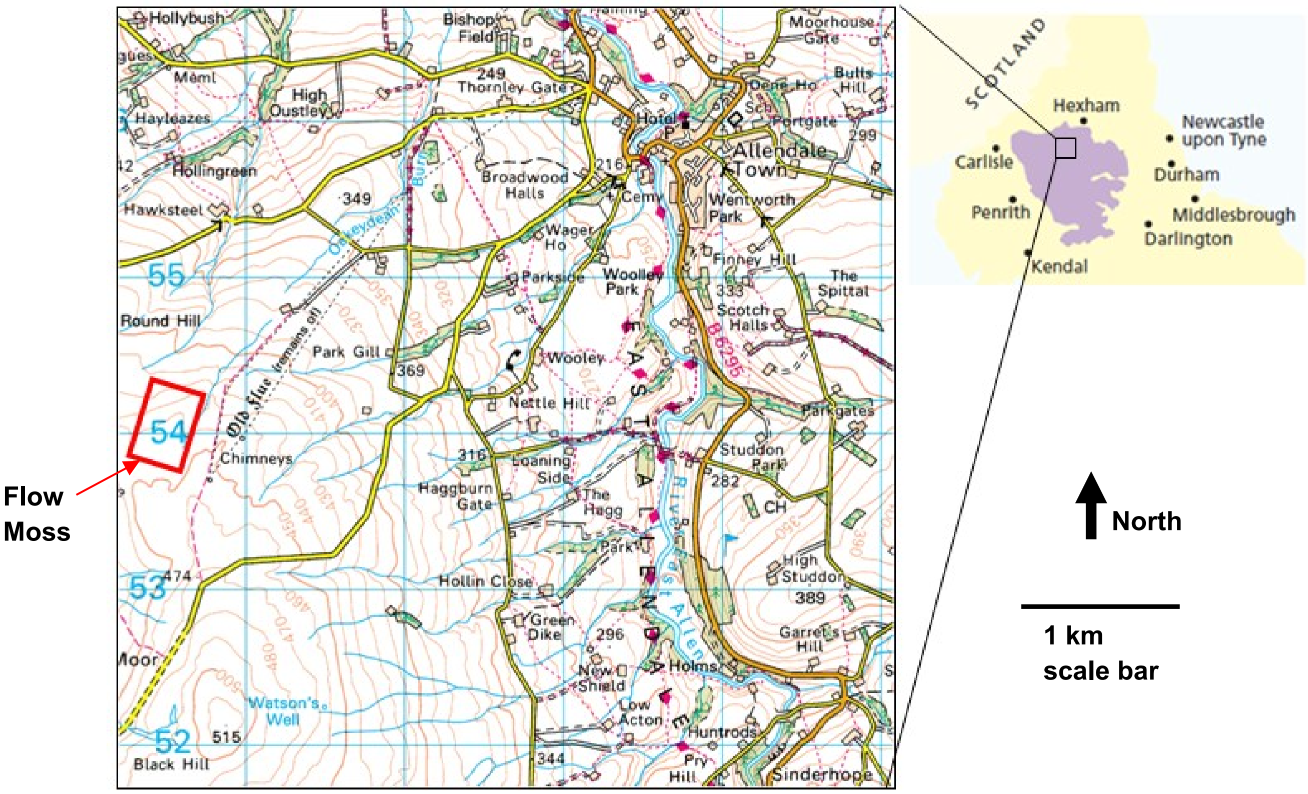


Figure 1.4: Location map of Flow Moss. Grid Ref NY 806 537. The purple shaded area on the large scale map is the North Pennines AONB. The red square on the OS 1:50000 scale map indicates the fenced off area that is being restored and monitored by this project. *Source:* http://edina.ac.uk/digimap/.

1.5 Research aim and objectives

The general aim of this study is to carry out *a geomorphological assessment of the initial effectiveness of restoration methods in reducing erosion and sediment loss from bare peat surfaces.* Three research objectives have been structured that allow the broader research aim to be achieved. The research objectives are to:

1. Improve the understanding of the erosion dynamics and nature of the physical processes acting on bare peat at Flow Moss.
2. Produce a preliminary sediment budget for the Flow Moss peat flats by quantifying the main erosion processes, sediment storage elements and process linkages operating at the site.
3. Provide a quantitative assessment of the effectiveness of peatland restoration measures in terms of reducing erosion and peat-sediment loss.

1.6 Justification of the research objectives

There have been many studies that have described the morphology of eroding peat (Bower, 1960, 1961, 1962; Mosley, 1964; Wishart and Warburton, 2003) but the processes of erosion are less well understood (Foulds and Warburton, 2007a). It is essential that the understanding of the processes at work is improved in order to help with the assessment of whether peatland restoration measures are successful (Holden, 2005). Table 1.2 provides a summary of some of the previous work on rates of peat erosion (surface retreat) in the UK. The main drivers of erosion differ in each case and this leads to a wide range in the surface retreat rates; 3 to 74 mm a^{-1} with a median of 17.25 mm a^{-1}.

Location	Context	Period (years)	Surface retreat rate (mm a^{-1})	Source
Moss Flats, Moor House, North Pennines	Wind erosion of sparsely vegetated peat	1	~3	Warburton 2003
Snake Pass, S Pennines	Peat margin	1	5.4	Philips et al. 1981
Snake Pass, S Pennines	Gully walls	1	7.8	Philips et al. 1981
Doctors Gate, S Pennines	Low-angled eroded face	2	9.6	Tallis and Yalden 1983
Shetland Islands	Summit peat	5	10-40	Birnie 1993
Moor House, N Pennines	Gully walls	1	10.5	Philips et al. 1981
Harrop Moss, Pennines	Bare peat surface	7	13.2	Anderson et al. 1997
Upper North Grain, S Pennines	Gully walls	3	14	Unpublished
Plynlimon, Wales	Peat faces	2	16	Francis 1990
S Pennines	Low angled flats	1	18.4-24.2	Anderson 1986
Cabin Clough, S Pennines	Low-angled eroded face	2	18.5	Tallis and Yalden 1983
Moor House, N Pennines	Gully walls	4	19.3	Evans and Warburton 2005
Forest of Bowland	Summit Peat	1	20.4	Mackay and Tallis 1994
Mid-Wales	Ditch walls	1.4	23.4	Francis and Taylor 1989
Holme Moss, S Pennines	Low-angled peat margin	2	33.5	Tallis and Yalden 1983
Upper North Grain	Pin recession (gully walls)	1	34	Evans et al. 2006
North York Moors	Low-angled bare peat surface	2	40.9	Imeson 1974
Holme Moss, S Pennines	Peat margin	1	73.8	Philips et al. 1981

Table 1.2: Summary of peat erosion rate studies in the UK arranged in increasing surface retreat rate. Adapted from Evans and Warburton (2007)

The erosion and degradation of peatlands is controlled by the balance of several agents of erosion; wind, frost, rainfall and runoff (Evans and Warburton, 2007). The dominance of a particular agent of erosion can be the result of a number of factors although topography and more importantly slope form can dictate which erosion process dominates. For steeper slopes erosion is more likely to be dominated through surface wash and runoff rather than aeolian processes (Evans and Warburton, 2007). For example, Bower (1961) described two types of gully formation by water which are dependent on topography. Bower (1961) classified these are ‘Type 1’ where surface dissection is confined to slopes of less than 5° and produces a closed network of freely and intricately branching gullies whereas ‘type 2’ dissection commonly occurs on steeper slopes and produces a more open pattern of gullies that rarely branch (Bower, 1961).

While erosion caused by runoff is dominant on slopes, other processes such as wind erosion are likely to become more important on flatter surfaces and are likely to have an influence on the peat flats at Flow Moss. There has been some detailed work on aeolian erosion of peat by Warburton (2003) and Foulds and Warburton (2007a, 2007b). Warburton (2003) calculated the annual horizontal net erosion flux as 0.46 t ha^{-1} at Moor House in the North Pennines. Wind direction was also found to be a strong control as the peat flux collected in wind-facing traps were 3-12 times greater than the flux collected in the leeward-facing traps (Warburton, 2003). However, the greatest difference between windward and leeward fluxes occurred during the summer months suggesting that particle detachment by wind is more significant in the summer than during the winter when wind-driven rain processes are dominant (Warburton, 2003).

Foulds and Warburton (2007a) used a similar methodology to that of Warburton (2003) at Moss Flats and studied the aeolian processes acting on the site during a dry period (13-27 May 2004). The surface peat underwent desiccation, producing a fine layer of peat at the surface that could be entrained by the wind and transported from the site by saltation and suspension (Foulds and Warburton, 2007a). However, the peat flux rates under wet conditions can be typically two orders of magnitude greater than under dry conditions and rain therefore enhances the effectiveness of wind in transferring peat. Foulds and Warburton (2007b) detail the results of a study of wind erosion at Moss Flats during a period of wet and stormy conditions (June 2004) and the importance of rainfall is shown by the maximum peat fluxes being directly associated with moderate intensity, frontal rainfall. Wind-driven rain causes more erosion because of the more intensive processes of ballistic impact and lift (de Lima *et al.,* 1992). The distance travelled by particles that have eroded by wind-splash is generally shorter (1-10 m) than disturbed particles under dry conditions (in excess of 50m), due to the fact that dry peat has a very low density so can be entrained easily (Warburton, 2003). The research into aeolian erosion has shown that it is a very significant process as local sediment fluxes can be high (Warburton, 2003) but research by Foulds and Warburton (2007a, 2007b) has highlighted the differences between the process regime of dry blow and wind-driven rainfall. As the process regime can switch between dry and wet rapidly, this exemplifies the temporally dynamic nature of wind erosion. This is in addition to the influence of spatial factors such as site location and susceptibility to wind erosion; which is most frequent and vigorous in exposed locations (Radley, 1962). More research is required to gain a fuller understanding of the dynamics of the processes. The successful completion of the first research question will result in data that will increase knowledge of peatland aeolian system dynamics and erosion rates.

In order to fully understand the balance of erosion processes acting on a particular site, a sediment budget needs to be constructed (Evans and Warburton, 2005). Constructing a sediment budget will allow the important processes acting at Flow Moss to be identified. Evans *et al.* (2006) calculated a sediment budget for Upper North Grain, an actively eroding catchment in the South Pennines, and compared it to a sediment budget constructed by Evans and Warburton (2005) for Rough Sike in the North Pennines. The large difference in the sediment yields between the two catchments has already been discussed but the structure of the sediment budgets allows the identification of the dominant processes within each catchment (Figure 1.5). It can be clearly seen that the slope and channel system at Upper North Grain is much more connected because of a network of actively eroding dendritic gullies while the gullies in Rough Sike are re-vegetating (Evans *et al.,* 2006).

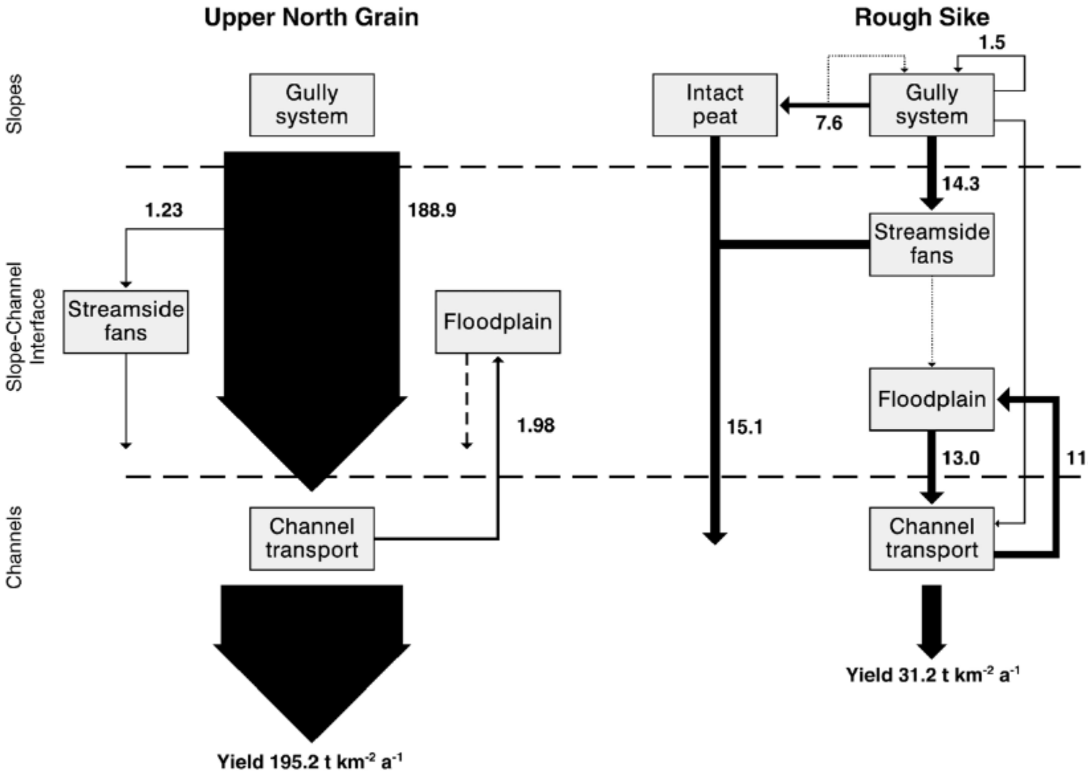


Figure 1.5: The sediment budgets for Upper North Grain and Rough Sike. All units in t km^{-2} a^{-1}. Evans *et al.* (2006)

The construction of a sediment budget for Flow Moss will allow the identification of the roles of the various agents of erosion, sediment storage elements and process linkages operating at the site. This will help target future restoration measures to stop erosion at sensitive loci (Evans and Warburton, 2005). For example, if the sediment budget identifies that the dominant process acting at Flow Moss to be the removal of sediment in the channels, the channels could be blocked reducing the flux of sediment. As the restoration of the bare peat is on-going, the initial budget is representative of the pre-restoration state. The sediment budget will also allow the direct comparison to other catchments and its place on the spectrum between actively eroding catchments (e.g. Upper North Grain) and naturally re-vegetating catchments (e.g. Rough Sike) to aid in the wider understanding on peatland dynamics and add to the findings from the first research objective.

It is important to try and quantify the impact of the restoration measures at Flow Moss so the findings can be used to improve our understanding of how management strategies can alter the environment. Flow Moss is the first bare peat area to be restored by the *Peatscapes* project so an understanding of the impact of the restoration will help the project when assessing other sites that could be restored in a similar manner. An established methodology for isolating the impact of restoration from external factors is a technique used extensively in ecology; the before-after control-impact (BACI) method (Bried and Ervin, 2011). In a BACI experiment, a response is measured before and after treatment in both an impact site, where treatment is applied, and in a reference unit without treatment. The technique examines the difference between the control and the impact units instead of raw measurements which are difficult to interpret accurately (Bried and Ervin, 2011). The BACI method has been used extensively to analyse the role of management intervention in a range of contexts including dragonfly populations (Bried and Ervin, 2011), fish populations following stream restoration (Baldigo and Warren, 2008) and the impact of fish removal on eutrophication (Catalano *et al.*, 2010). Ideally, a BACI design should monitor a large number of study sites, both ‘impact’ and ‘control’ in order to separate the effects of experimental manipulations from spatial and temporal variations from background noise (Bried and Ervin, 2011). The research carried out here does not use a BACI approach although this could be applied in the future if a suitable ‘control’ site could be found nearby.

1.7 Summary

This chapter has introduced the importance of peatlands both at a local and global scale, considered the issue of peatland degradation and the recent shift towards peatland restoration management practices. This has framed and justified the research aim and objectives for this study and discussed how these objectives can be completed successfully. The rest of this thesis will describe the research, beginning with a detailed description of the study site (Chapter 2) and the methodologies used (Chapter 3), before presenting the results (Chapter 4) and discussing and interpreting the findings (Chapters 5 and 6). An important conclusion derived from this study will be practical recommendations for the management and restoration of bare peat areas as the results will identify the effectiveness of the measures implemented at Flow Moss in terms of reducing sediment transfer and erosion rates.

Chapter 2. The Research Site: Flow Moss, North Pennines, UK

This chapter describes Flow Moss, the location for the research presented in this thesis. It discusses some of the features and characteristics of the site before outlining the restoration measures being implemented as part of the North Pennines AONB Partnership's *Peatscapes* project.

2.1 Historical and contemporary land use

The peatland restoration site at Flow Moss in the North Pennines is a 7 hectare area located at Ordnance Survey grid reference NY 806 537, 450 m above sea level (Figure 1.4). It is located on the broad moorland interfluve between the River West Allen and River East Allen, which drains the northern part of the North Pennines orefield, which was historically the most productive Lead and Zinc mining area in Britain (Dunham, 1944). The mining industry contaminated the local river systems with large quantities of fine mining waste until the practice was outlawed in the latter part of the 19th century but the mining legacy has resulted in floodplains in the catchments remaining highly polluted (Macklin *et al.*, 1994). The mining heritage of the area is clearly visible at the peatland restoration site as two large ruined chimneys, part of an extensive smelter-flue system, are located nearby on the small ridge to the east of the site.

The upland areas of the Allendale catchment are characterised by heather moorland that is actively managed for grouse shooting. The peatland restoration area is located on one of the grouse shooting areas of the Allendale estate which is also common land and is shared by the other major land use of the area; which is low density sheep grazing (0.33 sheep per hectare) (Rawes and Hobbs, 1979).

2.2 Geology and surface features of Flow Moss

The geology of the North Pennines, especially the Moor House National Nature Reserve (NNR) 20km south of Flow Moss, has been described in detail by Johnson and Dunham (1963). At Flow Moss, the bedrock geology of the area is composed mainly of sandstone, millstone grit and limestone (British Geological Survey, 2011) which was formed during the Upper Carboniferous series (c. 300 Ma) and the Lower Carboniferous series (c. 350 Ma) (Johnson and Dunham, 1963). The surface of the basement rocks is weathered and partially mantled, by local colluvial and diamict deposits.

Across much of the North Pennines uplands, blanket peat has formed during the Holocene up to a thickness of 2 to 3 m. The trigger for peat formation was the widespread decline in deciduous woodland c. 3,800 years ago as a result of deterioration in the climatic conditions across the area (Pounder, 1989). Beneath the peat are periglacial deposits of reworked till and overbank deposits which have a clay-rich nature allowing the formation of peat even on limestone bedrock (Evans and Warburton, 2005). At Flow Moss, the deepest areas of peat measured were between 1.5 to 2 m but the peat does not have uniform depth across the whole 7 ha area. In some areas of the site, particularly along the course of small channels, the peat has been eroded to the mineral layer where weathered bedrock is now visible on the surface. In addition, preserved pieces of bark and roots from the deciduous ‘wildwood’ woodland that were once buried beneath the peat are also now visible on the surface.

2.3 Climate

The upland climate regime of the North Pennines favours the formation and development of blanket peat as it is dominated by cool, wet and cloudy weather under the sub-Arctic oceanic regime (Manley, 1943). No long-term record of climate is available for Flow Moss but the longest upland climate record in the UK is located approximately 20 km south of Flow Moss at Moor House (Holden and Adamson, 2002). Long-term averages of weather conditions have been calculated from the Moor House record and despite Moor House being approximately 100 m higher in altitude, the average climate values should be indicative of the climate at Flow Moss.

Between 1931 and 2000, the average annual temperature at Moor House was 5.3 ^{o}C and the average annual precipitation was 1,982 mm (Holden and Adamson, 2001). The mean number of frost days was calculated to be 105 per year with snow lying on the ground on average for 55 days per year (Archer and Stewart, 1995; Holden, 2001). The recorded prevailing wind direction at Moor House is 256.1^{o} (Warburton, 2003). Due to the lower altitude of Flow Moss, it can be expected that there are not as many snow-covered days or frost days per year and rainfall will be somewhat less but the pattern of the climate will be broadly similar.

2.4 Vegetation cover

Like many other blanket peatlands, the vegetation coverage of the site is characterised by three main types of vegetation species; heather (*Calluna sp.*), grasses (*Eriophorum sp.*) and mosses (*Sphagnum sp.)* in the wetter areas. The surrounding heather moorland is managed for the shooting industry and is burnt to maintain dwarf shrub habitats; the optimum conditions for the breeding and growth of Red Grouse (Yallop *et al.*, 2006). In UK uplands, the median burn repeat rate of consistently managed sites is approximately 20 years (Yallop *et al.*, 2006). Within the fenced area of the 7 hectare peat restoration site, 1.75 hectares (~ 25%) has no vegetation cover and is classified as bare peat. The vegetation has been lost as a result of peatland degradation and one of the main aims of the restoration project is to restore the vegetation across the bare peat area. The exact cause and timing of the peat degradation at Flow Moss is not known although it has been suggested that it is the result of a number of factors including over-grazing by sheep, managed moorland burning, peat-cutting or atmospheric pollution leading to a reduction in the extent of peat-forming *Sphagnum* mosses.

2.5 The significant geomorphological features at Flow Moss

The 7 hectare fenced area at the restoration site contains many features that are typical of an eroding area of blanket bog. These key features are identified on the aerial image of the site (Figure 2.1). The largest uniform feature at the site is a large area of peat flats (1.75 ha) without any significant vegetation cover apart from small vegetated islands that stand ca. 0.2 to 1.5 metres above the surrounding area, termed ‘haggs’. These features are similar to those found at Moss Flats, an area of bare peat in the Rough Sike sub-catchment of the Moor House NNR (Warburton, 2003; Evans and Warburton, 2007). This bare area of peat is the focus of the restoration project due to the active erosion of this surface.

The site slopes gently (c. 2^{o}) from the South-West to the North-East and there are two small ephemeral channels that drain either side of the bare peat area.

The size of these channels depends on the prevailing environmental conditions as during a wet period, they can be approximately two metres wide with a relatively high flow velocity and, during dry conditions, the channels dry out completely.

In order to collect a detailed picture of the site, an aerial image mosaic of the site was generated using images taken from a survey using an Unmanned Aerial Vehicle (UAV) in April 2011 (Figure 2.1). This image clearly identifies the important areas and features of the site due to the very high pixel resolution of 3.7cm. The bare peat areas are clearly visible as well as the peat pools and wet areas that contain very bright green *Sphagnum* mosses. The courses of the two drainage channels that flow either side of the bare peat area are visible and the larger drainage pool at the northern edge of the site near the fenceline can also be clearly seen. There will be an error associated with Figure 2.1 as the image mosaic was produced via image stitching rather than ortho-photos. This automated method identifies patterns within the images and combines them to produce the mosaic. The mosaic was then geo-referenced using differential GPS points collected in the field for points along the fenceline. Therefore, while there is a small amount of un-quantifiable error in the image mosaic and geo-referencing, it is unlikely to be significant enough to substantially alter results generated through use of the mosaic.

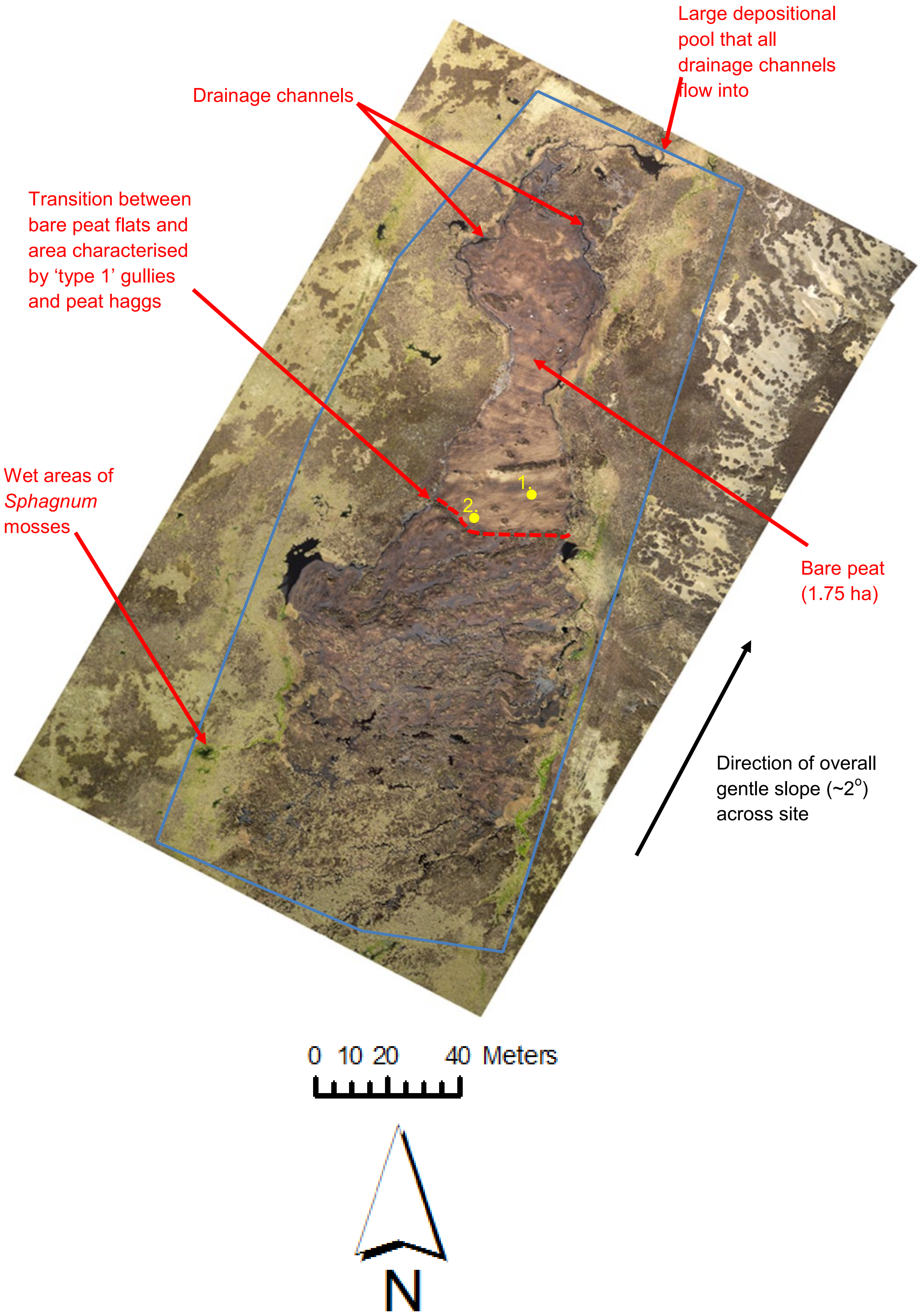


Figure 2.1: The image mosaic of Flow Moss generated from the UAV survey. The blue line marks the fenceline of the restoration area (7 ha). Yellow dots indicate the location of the cores discussed in section 2.6

The two channels join to the north of the peat flats before flowing into a large pool located at the north-eastern edge of the site close to the fence marking the limit of the restoration area.

The area to the south of the bare peat flats is characterised by a series of larger peat haggs and a ‘Type 1’ gully system of freely and intricately branching gullies (Bower, 1961). These gullies dissect the site producing a series of low ridges which have an approximately southeast-northwest orientation. As discussed previously, ‘Type 1’ gully networks typically form in areas of less than 5^{o} slope where fluvial processes dominate but do not have the energy available to form deep straight ‘Type 2’ gullies. The type 1 gully system area has a slightly higher slope angle than the bare peat flats to the north where aeolian processes are important in controlling landform development.

2.6 Characterisation of peat type

Two cores were taken at the site (Figure 2.1) and subjected to Troels-Smith and Von Post classification in order to characterise the nature of the peat and the degree of decomposition. The cores were taken in July 2011 when the nature of the peat was much drier than conditions experienced during the winter months. The cores were deliberately taken from two different places within the bare peat area to represent the variability in the peat that can be found at the site. The differences between the core depths indicate that the peat depth across the whole site is not consistent possibly due to localised variations in peat erosion rates. The results of the Troels-Smith and Von Post analyses are shown in Tables 2.1 and 2.2.

Core 1: 106cm deep						
Depth (cm)	**Code**	**Darkness**	**Stratification**	**Dryness**	**Joint between units**	**Von Post**
0 - 43 (unit 1)	*Th 4* – 100% 'Roots, stems and rhizomes of herbaceous plants'	*Nig 4* – Black peat	*Strf 0* – No stratification	*Sicc 2* – Deposit saturated with water		*7* – Strong decompo sition
43 – 93 (unit 2)	*Tb 3, Th 1* – 75% 'Protonema, rhizods, stems, leaves etc. of mosses'. 25% 'Roots, stems and rhizomes of herbaceous plants'	*Nig 3* – Brown peat with dark shades	*Strf 0* – No stratification	*Sicc 2* – Deposit saturated with water	*Lim 1* – Boundary between unit 1 and 2 is < 1 cm & > 2 mm	*7* – Strong decompo sition
93 – 106 (unit 3)	*Th 4* – 100% 'Roots, stems and rhizomes of herbaceous plants'	*Nig 4* – Black peat	*Strf 0* – No stratification	*Sicc 2* – Deposit saturated with water	*Lim 2* – Boundary between unit 2 and 3 is < 2 mm & > 1 mm	*7* – Strong decompo sition

Table 2.1: Troels-Smith and Von Post classification of the first core taken at Flow Moss. Location of core shown by yellow dot in Figure 2.1

Core 2: 161cm deep						
Depth (cm)	**Code**	**Darkness**	**Stratification**	**Dryness**	**Joint between units**	**Von Post**
0 – 52 (unit 1)	*Th 4* – 100% ‘Roots, stems and rhizomes of herbaceous plants’	*Nig 4* – Black peat	*Strf 0* – No stratification	*Sicc 3* – Deposit not saturated with water		*7* – Strong decomposition
52 – 79 (unit 2)	*Tb 3, Th 1* – 75% ‘Protonema, rhizods, stems, leaves etc. of mosses’. 25% ‘Roots, stems and rhizomes of herbaceous plants’	*Nig 3* – Brown peat with dark shades	*Strf 0* – No stratification	*Sicc 3* – Deposit not saturated with water	*Lim 0* – Boundary between unit 1 and 2 is > 1 cm	*7* – Strong decomposition
79 – 82 (unit 3)	*Th 4* – 100% ‘Roots, stems and rhizomes of herbaceous plants’	*Nig 4* – Black peat	*Strf 0* – No stratification	*Sicc 3* – Deposit not saturated with water	*Lim 2* - Boundary between unit 2 and 3 is < 2 mm & > 1 mm	*7* – Strong decomposition
82 – 132 (unit 4)	*Tb 3, Th 1* – 75% ‘Protonema, rhizods, stems, leaves etc. of mosses’. 25% ‘Roots, stems and rhizomes of herbaceous plants’	*Nig 3* – Brown peat with dark shades	*Strf 0* – No stratification	*Sicc 3* – Deposit not saturated with water	*Lim 2* - Boundary between unit 3 and 4 is < 2 mm & > 1 mm	*7* – Strong decomposition
132 – 161 (unit 5)	*Dg 2, Tb 2* – 50% ‘Woody and herbaceous hunified plant remains <2mm >0.1mm that cannot be separated’. 50% ‘Protonema, rhizods, stems, leaves etc. of mosses’	*Nig 3* – Brown peat with dark shades	*Strf 0* – No stratification	*Sicc 3* – Deposit not saturated with water	*Lim 0* – Boundary between unit 4 and 5 is > 1 cm	*7* – Strong decomposition

Table 2.2: Troels-Smith and Von Post classification of the second core taken at Flow Moss. Location of core shown by yellow dot in Figure 2.1

The second core is obviously deeper than the first but they both identify the same 3 key units in the peat. Just beneath the surface is a dark peat unit that contains herbaceous plant material while the peat unit below this is slightly lighter in colour and contains root and stem material from mosses. At the bottom of the peat there is another unit of darker peat that similar to the peat near the top of the core. A section of peat that contains woody material was identified below this third unit in the longer core but it was not preserved in the first core. Both cores identified a sandy and gravel layer below the peat. There was no variability in the degree of decomposition or the amount of stratification between the units within the cores and also between the cores, although the second core was drier. This is possibly because it was located in a slightly higher part of the site and is less likely to be an area of water ponding.

2.7 Restoration practices employed by Peatscapes at Flow Moss

The 7 hectare area is undergoing restoration as part of the North Pennines AONB's Peatscapes project which was established in 2006 to conserve and enhance the functionality and resource of peatlands (Section 1.4). The Peatscapes project has previously focussed on the blocking of drainage ditches or 'grips' to restore the hydrological conditions of peatlands and aims to block 1000 km of these drains by 2012 (Peatscapes, 2011). Across the North Pennines, it is estimated there is 20 km^2 of bare blanket bog that is experiencing extensive erosion and using techniques developed by the Moors for the Future project in the South Pennines; the project is starting to restore these areas (Peatscapes, 2011).

Flow Moss is the first such area of bare peat to undergo restoration as part of the Peatscapes project and restoration began at the site in April 2010 when a fence was constructed to remove the grazing pressure from sheep from the area. Work began in November and December 2010 to actively restore the vegetation coverage by the cutting and spreading of *Calluna Vulgaris* (heather brash) over the site using a spreading machine (Figure 2.2). More recently in November 2011 the perimeter fence at the site was upgraded to exclude rabbits. Flow Moss is typical of other peatlands in the North Pennines and UK upland environments.

Figure 2.2: The machine used to spread the heather brash across the bare peat surface. For scale the machine is approximately 1.5 m wide. *Source: Peatscapes*

Data collection began at Flow Moss in October 2011, approximately 6 months after the perimeter fence was constructed and shortly before the heather brash was spread over the surface. The restoration impact of the brash is not instantaneous as it takes time for the heather to colonise the peat surface; however, immediately after brash spreading surface sediment flux will be less because the peat surface is less exposed to direct erosive agents such as rainfall impact. It is clear, compared to a fully exposed bare peat surface, that the peat surface after brash spreading is more shielded from erosive processes (Figure 2.3). It is not, however, fully protected as some areas of peat are still exposed. Therefore during the initial stages of data collection, including the period just after brash spreading, Flow Moss was actively eroding as the restoration measures had not yet taken effect. Hence, monitoring at Flow Moss provides a unique opportunity to observe directly the effect of restoration techniques on active physical processes.

Figure 2.3: The peat surface shortly after the heather brash had been spread. Brash coverage is not 100% over the whole surface so some areas of the surface would still be exposed to erosion by processes such as raindrop impact.

Chapter 3. Methodology

An extensive monitoring framework designed with respect to the research objectives (Section 1.5) using a range of field instrumentation was installed at the restoration site. These techniques ranged from established methods used in previous studies (e.g. Warburton, 2003; Foulds and Warburton, 2007a; 2007b) to innovative solutions specifically designed for this project. This chapter describes the methods used to address each of the research questions and provides a spatial context for the siting of the equipment in the study site. A detailed description of methods is important so that techniques can be duplicated in other studies, this research can be compared to previous studies and that the limitations of the techniques are documented. A full map of the monitoring equipment (Figure 3.19) can be found at the end of the chapter.

The first research objective is addressed using the methods described in sections 3.1 to 3.4. The development of the sediment budget to achieve the second research objective uses data collected using methods in 3.1 to 3.3 combined with the peat area surveys described in 3.5.1. Section 3.5.2 assesses the effectiveness of the restoration measures. The volume of peat and terrestrial carbon store at the site is quantified using the methodology described in 3.5.3 and 3.4.2 and links to the final research objective.

The monitoring of the field equipment took place between 14th October 2010 and 7th July 2011 and site visits were made every two weeks during this period, except when visits were logistically impossible due to heavy snow between 19th November 2010 and 19th January 2011.

3.1 Quantifying erosion and transfer of peat at Flow Moss

3.1.1 Techniques to monitor sediment transfer by aeolian processes

Two methods were used to measure the amount of peat eroded by aeolian processes. Both methods have been previously used in studies of wind eroded peat and have useful reliable results. Warburton (2003) first used the vertical array of Big Spring Number Eight (BSNE) mass flux samplers (Fryear, 1986; Stout and Fryear, 1989) at Moss Flats, Moor House, to monitor the amount of peat eroded at different heights (Figure 3.1). The local topography of Moss Flats is similar to the Flow Moss study site as it is dominated by isolated peat haggs and residual peat mounds that stand ca. 0.2 – 1.5 m above the surface (Foulds and Warburton, 2007a). The BSNE apparatus is comprised of five samplers at heights of 0.145 m, 0.405 m, 0.665 m, 0.90 m and 1.165 m above the ground. Each sampler has a pivoting wind vane and is free to rotate around the central pole. The samplers are therefore always facing into the wind and will collect all transported material at these heights. Warburton (2003) suggested that sampling efficiencies vary between 70 and 120% depending on sediment size and wind speed.

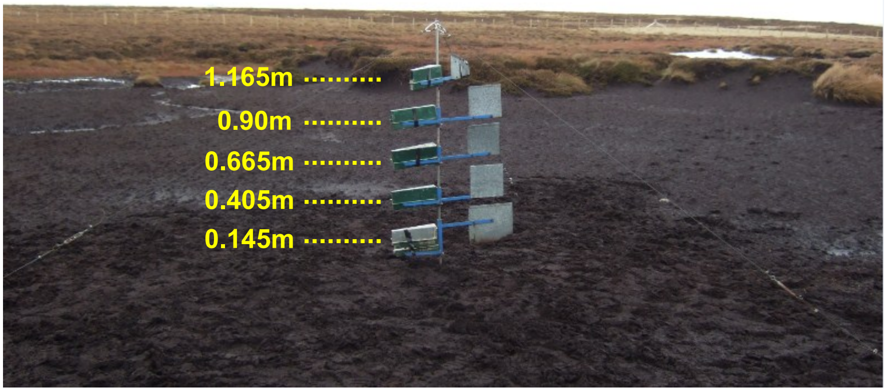


Figure 3.1: The Big Spring Number Eight (BSNE) mass flux sampler used to collect wind eroded peat at 5 heights.

The BSNE samplers were located in a large area of bare peat which is exposed to a higher proportion of wind erosion than vegetated areas (Figure 3.4). It was also positioned in this area so that there are no landforms nearby that could directly disturb (shadow) the transport of eroded material through the air. The samplers were emptied during regular site visits at approximately fortnightly intervals except during a period from the 19th November 2010 to 19th January 2011 when extreme weather, snow cover and logistics prevented site access. The material collected in the samplers was taken to the laboratory where the dry mass of eroded material was measured by drying the samples at 105 °C.

The study during 2004 by Foulds and Warburton (2007a; 2007b) measured the amount of wind erosion at Moss Flats but using fixed mass flux samplers. This type of samplers was also used in this study (Figure 3.2). The cardinal array of sampling tubes was arranged in a 5 m radius circle (Figure 3.3) shown on Figure 3.4. The 12 samplers collect peat eroded by dry blow and wind-driven rainfall processes through 360° as they are positioned at 30 degree intervals around the circle (Foulds and Warburton 2007a). Each of the mass flux samplers is 600 mm long with a slot of 250 x 10 mm installed 10 mm above the surface to avoid the effects of localised surface wash (Foulds and Warburton 2007b). In order that the tubes remain stable, the lower half of the sampler (approximately 300 mm) is inserted beneath the peat. The samplers were located in the centre of a large area of bare peat so any peat transported by the wind is not influenced by nearby landforms that may block the wind or prevent the transport of eroded peat. Therefore the peat collected in the samplers will be a good representation of wind erosion processes at Flow Moss.

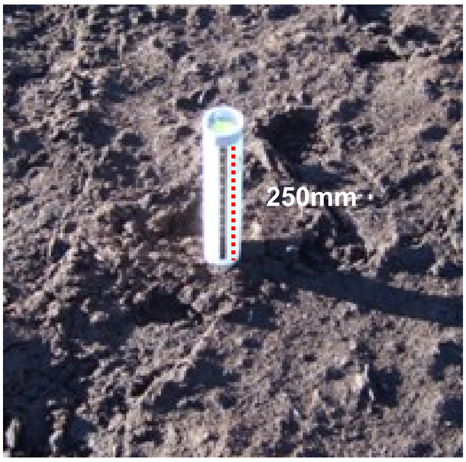


Figure 3.2: A passive mass flux sampler to collect wind eroded peat. 12 such samplers are located in a circle with a radius of 5 metres.

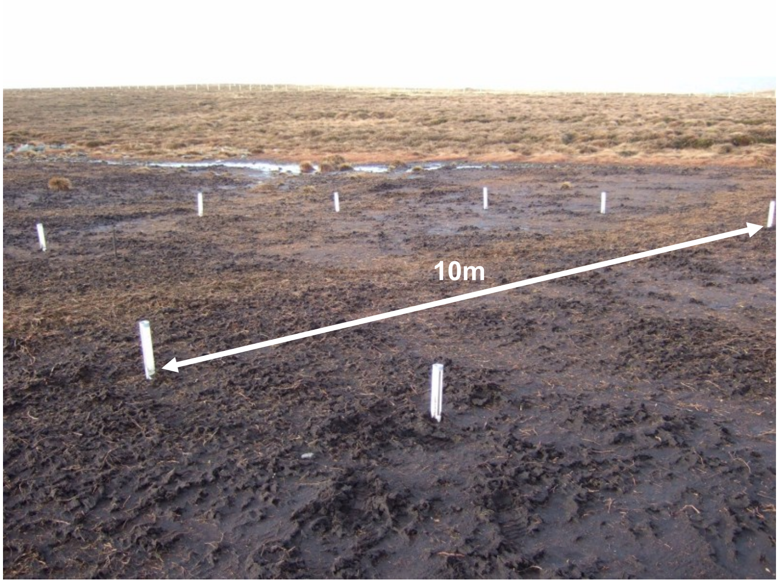


Figure 3.3: The circular array of mass flux samplers arranged in a circle with diameter of 10m at 30 degree intervals.

A significant limitation with these samplers identified by Foulds and Warburton (2007b) was that circulation cells can develop through flow separation within the samplers and these increase with wind-speed (Hall *et al.,* 1994). During conditions when the peat is dry and therefore very light these circulation cells could cause small quantities of material to be lost due to bounce-out. Small holes were drilled into the back of the samplers to aid air flow to try and limit this effect. The second limitation of this apparatus is the inability to collect large peat particles such as dried pieces of peat crust, eroded after surface desiccation, due to the size of the intake area of the samplers (Foulds and Warburton, 2007a). All of the samplers were emptied during the regular site visits at approximately fortnightly intervals and the material that was collected in the samplers was returned to the laboratory. The dry mass of the samples was determined in the same manner as the material collected in the BSNE sampler.

The BSNE samplers and the circular array of tube mass flux samplers monitor the wind erosion of peat during the study period but it is also useful to understand the longer term impact of aeolian processes on the evolution of the degraded peatland landscape. This was carried out through analysis of the form of peat haggs and mounds located in the bare peat area of the site. Analysis of these streamlined landforms in a similar location at Moss Flats has found these to be strongly oriented in the direction of the prevailing wind due to the greater erosion potential on the windward facing slope (Evans and Warburton, 2007). This relationship was tested at Flow Moss by measuring the angle of the long-axis of 79 peat haggs using a compass and comparing the distribution of landform orientations with measured wind direction during the study period.

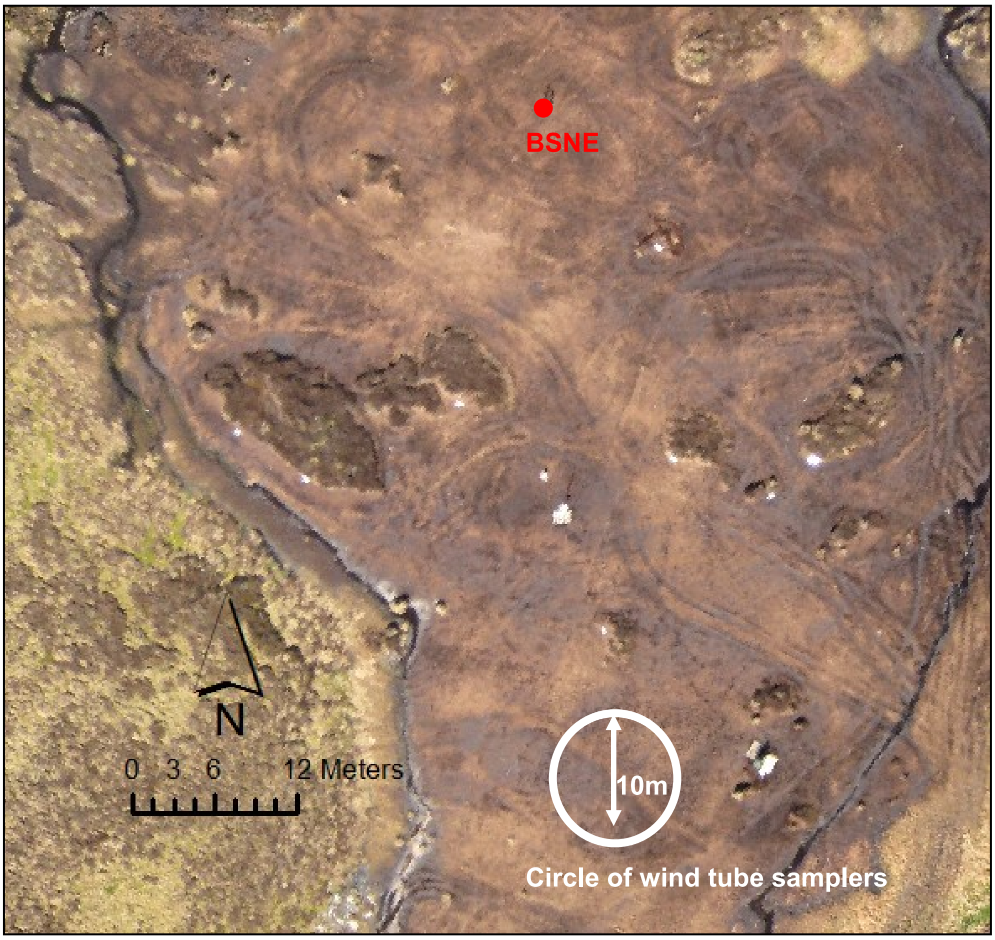


Figure 3.4: The red point indicates the location of the BSNE sampler and the white circle shows the location of the tube traps. Tracks from the brash spreading are clearly visible on the bare peat areas.

3.1.2 Quantifying the amount of peat transported from Flow Moss by fluvial (hydraulic) processes

The amount of material removed from the site by flowing water was monitored using a series of sediment traps located on the perimeter fence at the lower edge of the site along the natural catchment outlet from the site. These traps were designed specifically for this study using sacks made from weaved polypropolene strips (width 2.3 mm) (Figure 3.5). This design was constructed to allow water to flow through the sack but any peat that is transported in suspension is collected in the sack. The interlocking weave was effective in trapping the majority of the peat which was transported in aggregate clumps (0.5 – 2 mm) and small peat blocks (2 – 30 mm) which were far larger than the texture of the weave (approximate gap size 0.2 – 0.3 mm).

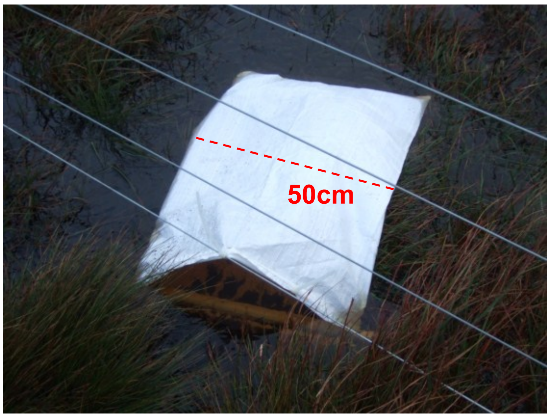


Figure 3.5: An example of the sack trap designed to collect peat transported in suspension. The traps were fixed to the fence at the bottom of the site and pegged down so they remained in position.

Four of these sack traps (blue numbers 2, 3, 5 and 6 in Figure 3.6) were positioned in locations along the fenceline at the north-western edge of the site where it was expected that peat is lost from the site in drainage channels. For comparison, three sacks (black numbers 1, 4 and 7 in Figure 3.6) were positioned in areas where there is little or no flow during normal hydrological conditions.

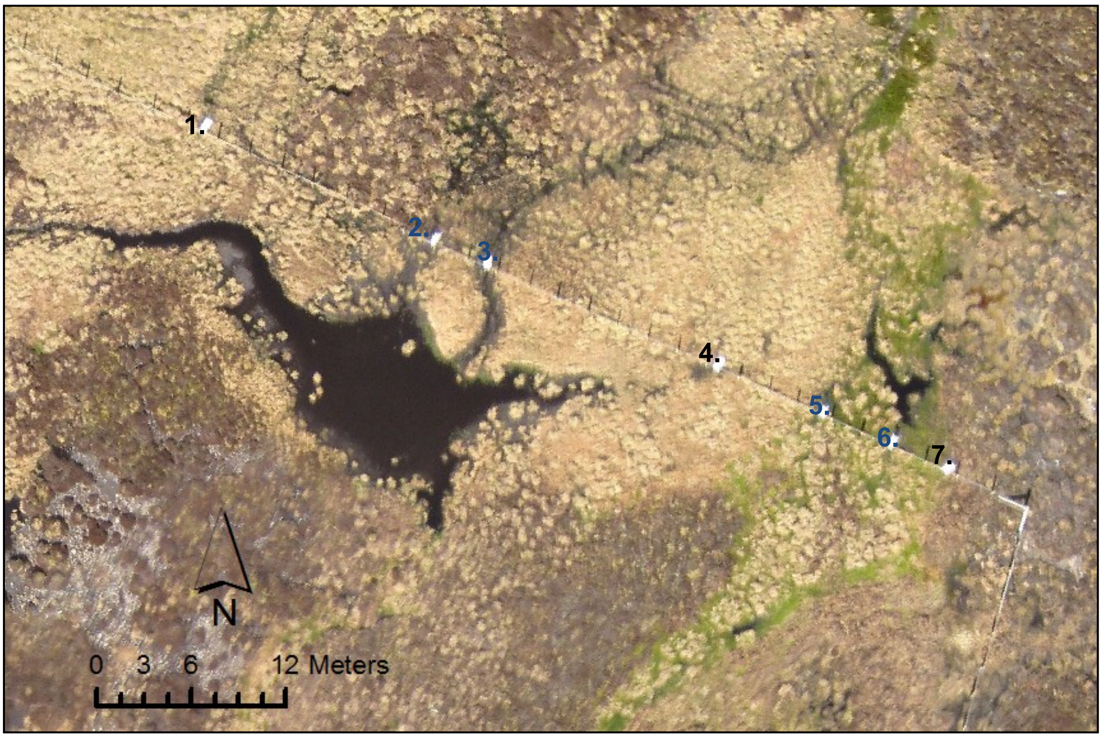


Figure 3.6: Location of white sack traps along the fenceline. Some are located in clear drainage channels (blue numbers).

3.1.3 Peat loss and transfer from peat hagg slopes

Across the site, peat haggs of different size stand above the surrounding bare peat. It has been previously suggested that the transfer of material from hagg or gully slopes can be a significant process in the sediment budget (Evans and Warburton, 2005). To understand the processes of slope recession and the delivery of the eroded material from these slopes to the rest of the peat flat system, Gerlach trough sediment traps were installed at the base of 10 slopes (Figure 3.8). These are dug into the ground so that the entrance to the trough is contiguous with the slope and are designed so that any material that is transported down the slope is washed directly into the trough (Figure 3.7). Sites for the sediment troughs were selected so that a range of slope lengths (365 to 630 mm) and slope angles (12 to 75^{o}) would be measured so that a range of sediment transfer conditions could be examined. The troughs were emptied during the regular site visits at approximately fortnightly intervals when the exposures of the erosion pins (discussed below in Section 3.2.1) were also measured. The dry mass of the sediment collected was measured in the laboratory using the same method as previously used for the BSNE sampler and the wind tubes.

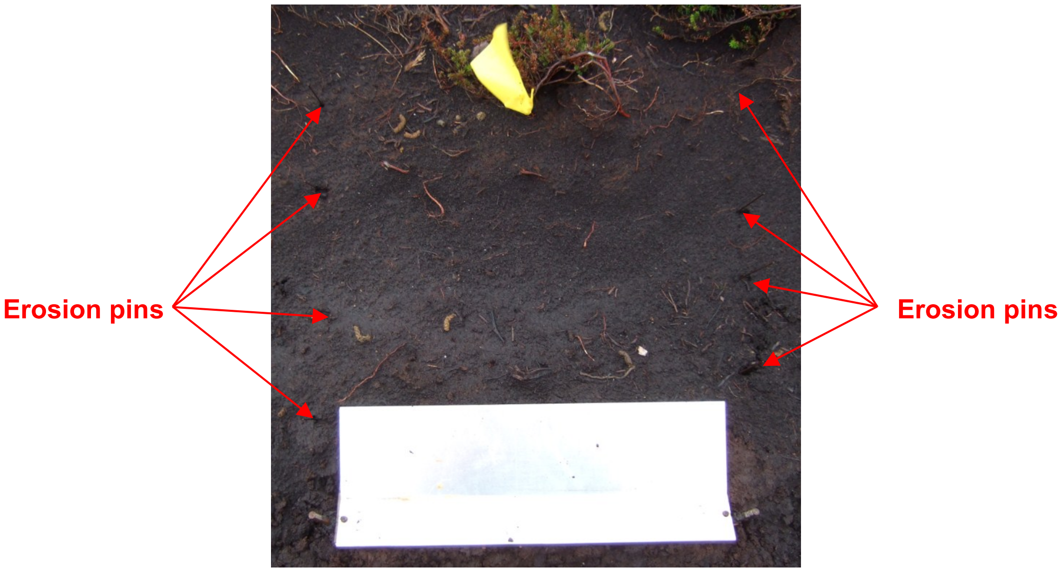


Figure 3.7: The set-up of a monitoring framework to assess the sediment transfer from slopes. The Gerlach trough is located at the foot of the slope while the arrangement of 8 erosion pins (two sets of 4 pins in a vertical array) is also visible. The width of the trough is 0.5 m.

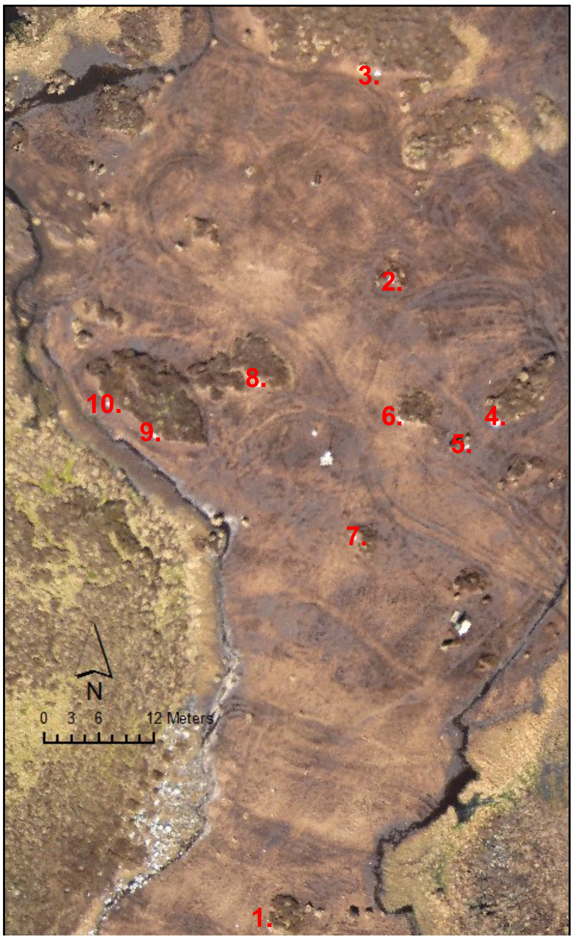


Figure 3.8: Location of Gerlach trough and erosion pin sites. The red numbers refers to the site number.

3.2 Measuring changes in the peat surfaces

3.2.1 Monitoring the peat hagg slope surfaces

The Gerlach sediment troughs collect material that is lost from the slope, it is also important to monitor any change in the retreat of the slope surface. In order to do this, an established method was adopted that has been used extensively to measure gully wall erosion (e.g. Evans and Warburton, 2005). Erosion pins were inserted into the slopes to measure the changes in height of the peat surface and the exposure of the pins were measured during the regular site visits. Eight erosion pins were installed into the slopes above each of the Gerlach troughs previously discussed in section 3.1.3 and were arranged in two vertical lines of four pins (Figure 3.7). This arrangement assesses both the vertical and horizontal variability in sediment transfer across the slope. However, there are some limitations associated with erosion pins as the pins may undergo frost-heave during the winter and also may be affected by the dynamic response of peat in response to wetting and drying. Evans and Warburton (2005) overcame this issue by extending the period between measurements so that the signal to noise ratio is improved. However, this was not possible due to the short nature of the study period but measurements were taken throughout different seasons so a range of conditions were monitored. Anderson *et al.* (1997) suggest results from the summer are more accurate as the surface of the peat is dry and not affected by frost action.

3.2.2 Monitoring the surface changes across the bare peat flats

A key part of understanding the dynamics of the physical processes acting on the peat surface requires the measurement of how the surface of the bare peat changes with time. This was carried out by installing poles of 1.5 m into the peat and measuring the exposure of the poles during the regular site visits. The poles were driven into the peat until they reached the mineral layer approximately 1 – 1.2 m depth, so that any changes in the exposure of the poles could be directly related to changes in the peat depth. Some of the poles were cut once they had been installed if the initial exposure was > 30cm to prevent the poles being affected by strong winds. The poles were installed in transects across key locations with short transects across the depositional pool located in the lower area of the site; to record changes in peat deposited in the pool (Figure 3.9 and 3.10). The number, and spacing, of the poles is shown on Figure 3.10. It could be expected that the exposure of these poles would be quite dynamic as it is controlled by the active deposition of peat in the pool. As the flow of water across peatlands is ‘flashy’ (Holden and Burt, 2003), the deposition or removal of peat from the pool may occur in high-magnitude low-frequency events rather than as a continuous process which would cause the changes in the pole exposure to be erratic. The measurement of the exposure of the poles in these transects may therefore be dependent on the timing of the site visit and the antecedent environmental conditions.

Figure 3.9: The depositional pool in the lower area of the site. The pole transects that monitor changes in the height of the peat are clearly visible.

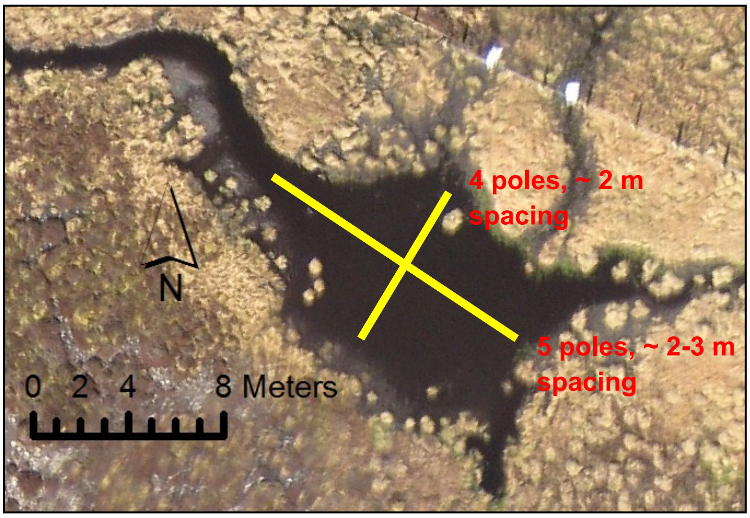


Figure 3.10: Yellow lines indicated the pole transects across the depositional pool.

Monitoring of the surface changes across the large area of bare peat was carried out with two lateral transects across the peat and one single longer transect that covers the length of this area (Figure 3.11). The number, and spacing, of the poles is shown on Figure 3.11. The analysis of the transects also allows a spatial understanding of the peat surface to be developed as areas of intense deposition or erosion can be identified from the individual pole data and the location of the pole within the field site. Measurement error was determined by repeat measurements as factors such as which side of the pole the measurement is taken can change the value of pole exposure significantly (although this was standardised in the measurements taken here).

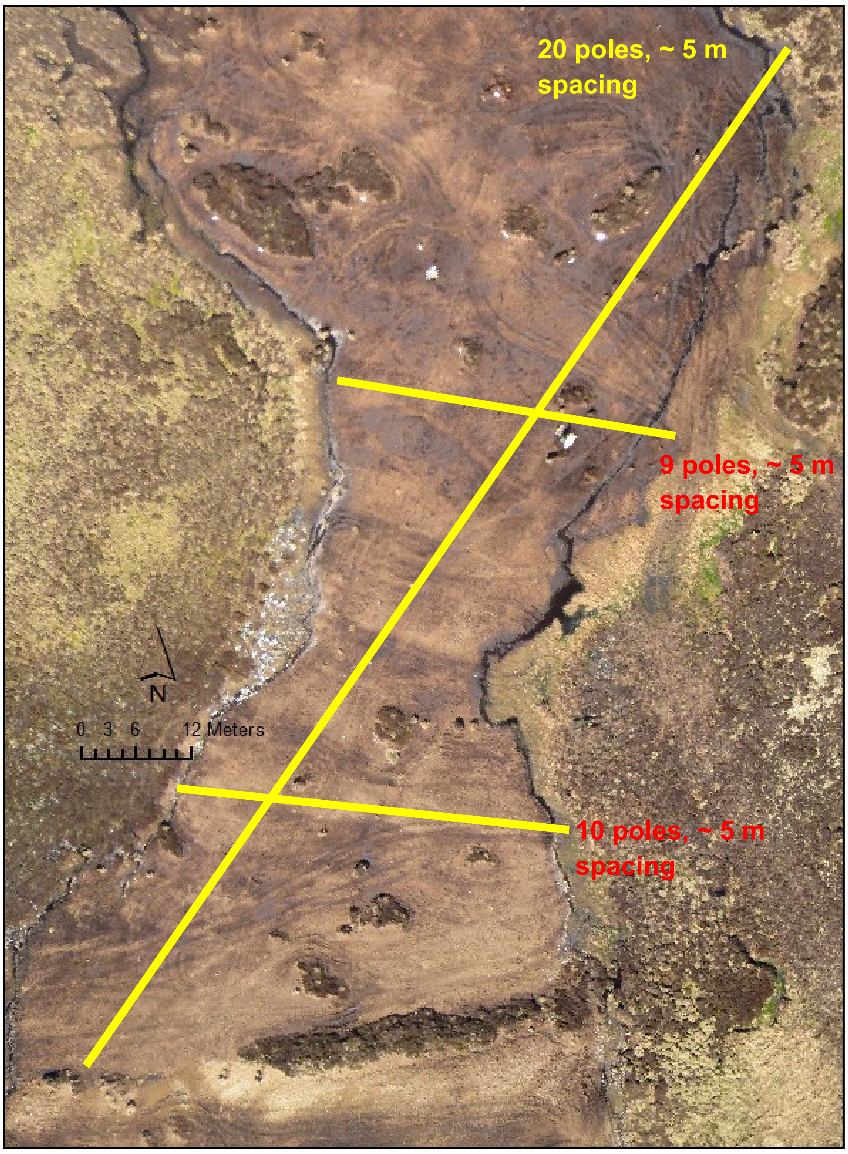


Figure 3.11: Yellow lines indicate the pole transects across the bare area of peat

3.3 Environmental conditions at Flow Moss

3.3.1 Monitoring the climate

In order to improve the understanding of the dynamics of the processes acting on the bare peat at Flow Moss, it is useful to try and identify the causes of some of these processes measured in sections 3.1 to 3.2. It is widely thought that the amount of sediment supply is important in controlling the timing of peatland sediment flux (Evans and Warburton, 2007) and that widespread weathering of bare peat surfaces prior to stormflow episodes is probably more important than direct fluvial erosion. The two key factors influencing sediment production from the slopes and peat flats are through freeze-thaw action and surface drying and desiccation (Evans and Warburton, 2007). To indirectly assess these conditions an Automatic Weather Station (AWS) (Figure 3.12) was installed at the site and this monitored a range of environmental parameters at 30 minute intervals. These parameters were air and soil temperature (depth 150 mm), wind speed, wind direction, rainfall and soil tension. The air and soil temperature measured by the AWS were valuable in defining periods of freeze-thaw activity. If a large amount of material was collected in the mass flux samplers between site visits and this time period was characterised by a prolonged period of freeze-thaw action, then it could be concluded that freeze-thaw weathering is an important process in producing sediment for erosion.

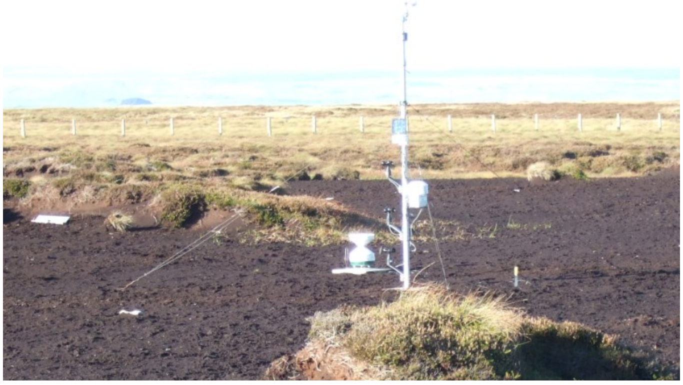


Figure 3.12: The Automatic Weather Station measuring wind speed at 4 heights, wind direction, air temperature, soil tension and temperature and precipitation. One of the erosion pin and sediment trough sites is visible in the background.

Wind speed was measured at 4 heights: 0.37 m, 0.755 m, 1.20 m and 2.34 m above the ground which enabled a velocity profile and the wind shear velocity to be calculated using equation 3.1 (Evans and Warburton, 2007):

$$\frac{u_z}{u_*} = \frac{1}{k ln(\frac{z}{z_o})} \tag{3.1}$$

Where u_z = wind velocity at height z (m), u_* = friction velocity (m s^{-1}), k = von Karman's constant (0.4), z = height (m), z_o = roughness length (m) (determined by regression of measured wind velocity and heights of anemometers).

The wind shear velocity can be compared with the results from the BSNE sampler described in section 3.1.1 to see if there is a relationship between wind velocity and the entrainment of surface peat. The wind direction is also measured which can be related to the circular array of tube mass flux samplers to identify whether the relationship determined by Warburton (2003) and Foulds and Warburton (2007b) between wind direction and the ratio of material in windward and leeward facing traps is also valid for Flow Moss. Foulds and Warburton (2007b) found that wind-driven rain and the resultant wind splash was a significant process controlling blanket peat geomorphology. The presence of the rain gauge as part of the AWS enabled this issue to be investigated further by determining whether periods of high rainfall intensity corresponded with more peat collected in the mass flux samplers.

3.3.2 Monitoring variability in the local water table

Due to the very high water content of blanket peat, it is important to investigate the impact of environmental conditions on peatland hydrology. In order to do this, a pressure transducer, connected to a Campbell CR10X data-logger, was installed in a dipwell excavated in the peat (Figure 3.13). The transducer monitors the height of the water table at 15 minute intervals and can be compared directly to the rainfall data collected by the AWS to see if there is a lag between precipitation and hydrological response. The dipwell was located in the middle of the large bare peat area, near the cardinal of wind sediment traps and is therefore only a local measure of the water table in this area. The approximate local depth of peat in this area is 1 – 1.25 m.

Figure 3.13: The Automatic Pressure Transducer installed in a well to measure the hydrological response of the blanket peat.

3.4 Determining peat characteristics

3.4.1 Peat particle size and shape

Peat particle form is influenced by a range of factors including degree of decomposition and the different processes under which the peat is eroded and transported (Warburton, 2003). Traditional methods of deriving particle size characteristics such as laser diffraction (e.g. Wilson *et al*., 2000) are very time consuming, both in sample preparation and analysis and can produce subjective results that are not statistically reliable (Tysmans *et al.*, 2006). Automated Dynamic Image Analysis (ADIA) can be applied to define the characteristics of a sample of small particles quickly and efficiently; producing statistically representative size and shape data for thousands of particles that is completely devoid of operator bias (Tysmans *et al*., 2006). ADIA was applied in this study using a Beckman Coulter RapidVUE particle size and shape analyser. The RapidVUE instrument has been used for shape and size analysis of a wide range of particles: sedimentary grains (e.g. Tysmans *et al*., 2006) and particulate debris in human veins after stenting (Rogers *et al.*, 2004).

The machine carries out automated image analysis at a rate of 20-30 images per second taken in a reservoir containing the sample. Images were analysed continuously over a 60 second period while a pump in the instrument creates a turbulent circulation. This keeps the particles in suspension which negates the effect of particle orientation on the analysis. However, this results in the possible limitation that some particles may be analysed several times during the measurement period (Xu and Di Guida, 2003). Each image that is analysed is composed of shapes that represent the two-dimensional projections of particles and the instrument measures the area and perimeter of each particle which are then converted to a range of size and shape parameters (e.g. Figure 3.14 and corresponding Table 3.1). The variable lens system allows a resolution of 1.5 µm/pixel enabling the detection and analysis of particles with a lower limit of 3.4 µm diameter (Tysmans *et al*., 2006). Size parameters calculated include the Equivalent Circular Area Diameter (ECAD) and the Fibre Length. The instrument produces a size-independent parameter to determine the particle shape called the ‘Sphericity’, calculated on the basis of area (A) and perimeter (p) and is calculated in the same way as Cox’s ‘circularity’ (C) parameter (Equation 3.2) (Cox, 1927):

$$C = 4\pi \frac{A}{p^2} \tag{3.2}$$

This dimensionless number between 0 and 1 defines the boundary irregularity of particles and will be equal to 1 for a perfect circle (Hentschel and Page, 2003). It has been found particle shape is dependent on particle size (Tysmans et al., 2006) so therefore, parameters of particle shape based on perimeter are useful when particles are of a similar size and when they are represented at the same scale (Hentschel and Page, 2003). As all of the samples that are analysed will be similar, the ‘Sphericity’ parameter is a useful measure of the shape of the peat particles.

These particle size and shape parameters were found using the RapidVUE instrument for a range of samples, including the material collected in the wind tubes. A sub-sample of peat was taken from each tube before the samples were dried and placed in de-ionised water. The samples were then run through the instrument twice to get a better representation of the particle size and shape distributions. This process should help in understanding the dynamics of the physical processes as it is expected that larger particles will be transported from the dominant wind direction. The BSNE sampler collects peat transported at different heights and the particle size and shape may be an important factor controlling at what height the particle is entrained by the wind. The results of the RapidVUE particle size and shape analysis should allow conclusions to be drawn about the sediment transport and erosion processes acting on the bare peat.

As an example, Table 3.1 presents the particle size and shape parameters calculated by RapidVUE for the particles shown in the image in Figure 3.14. A comparison between the meteorological data collected by the AWS and the particle size parameters may identify empirical evidence that larger peat particles are eroded during rainfall events because more energy is available for sediment transport through rainfall impact (Section 4.2.1.2). The particle shape parameters also provide useful information regarding the processes of peat transport as less rounded particles are likely to have freshly weathered from the peat surface whereas more rounded particles are more likely to already have been transported, possibly through saltation, which would smooth the edges of the particles.

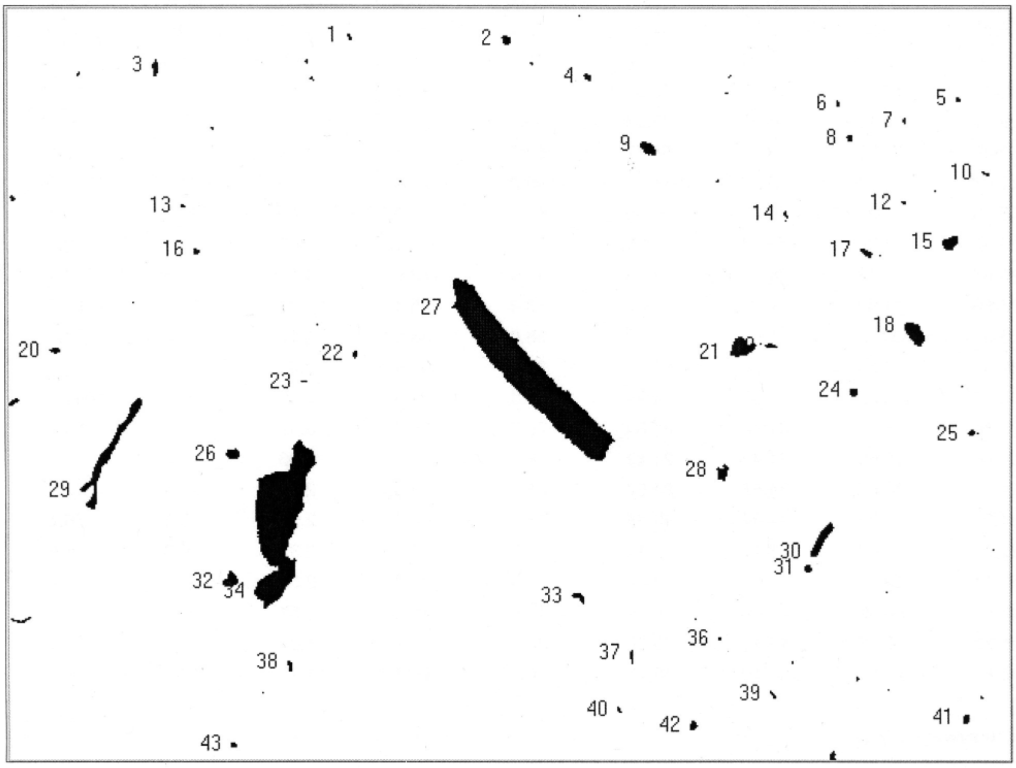


Figure 3.14: An example of the image taken by RapidVUE. The size and shape parameters of each numbered particle are calculated and the results are shown in Table 3.1. The instrument measures 20-30 images per second for a period of 60 seconds. N.B. Some smaller particles (< 10 μm) are not numbered, and therefore not analysed, due to the resolution of the instrument.

Table 3.1: The particle size and shape characteristics for the particles identified in the image shown in Figure 3.14.

Particle number	Particle size parameters									Particle Shape parameters	
	Equivalent Circular Area Diameter (microns)	Least Bounding Circular Diameter (microns)	Feret Width (microns)	Feret Length (microns)	Least Bounding Rectangle Width (microns)	Least Bounding Rectangle Length (microns)	Least Bounding Rectangle Aspect Ratio	Fibre Width (microns)	Fibre Length (microns)	Fibre Aspect Ratio	Sphericity
1	22.07	22.07	31.12	31.12	13.8	24.8	1.79	9.1	55.3	6.11	0.64
2	40.54	40.54	49.49	49.49	36.8	39.6	1.08	21.8	69.1	3.18	0.82
3	41.28	41.28	20.74	89.88	28.8	69.9	2.43	19	89.9	4.72	0.62
4	32.17	32.17	41.46	41.46	27.6	34	1.23	14.8	62.2	4.2	0.73
5	22.07	22.07	28.44	28.44	15.4	24.9	1.61	13.3	48.4	3.63	0.79
6	19.11	19.11	27.24	27.24	13	23.9	1.84	10.9	48.4	4.43	0.75
7	15.6	15.6	24.17	24.17	14.3	14.3	1	12.2	41.5	3.39	0.79
8	28.13	28.13	35.25	35.25	22.1	27.2	1.23	16.5	55.3	3.34	0.77
9	60.93	78.93	36.36	46.85	43.3	82.2	1.9	29.7	98.6	3.32	0.78
10	22.07	22.07	26.18	26.18	10.9	31.6	2.91	6.8	50	7.37	0.53
11	22.07	22.07	26.61	26.61	18.6	28.1	1.51	9.1	48.4	5.35	0.72
12	17.44	17.44	22.82	22.82	11.1	18.9	1.71	9.2	41.5	4.52	0.73
13	17.44	17.44	22.32	22.32	10.1	27.1	2.69	9.2	41.5	4.52	0.73
14	19.11	19.11	29.87	29.87	18.3	35	1.91	7.8	48.4	6.23	0.68
15	63.38	64.39	46.17	57.58	53.1	73.8	1.39	34	94.3	2.77	0.8
16	28.13	28.13	36.95	36.95	25.7	27.6	1.07	16.5	55.3	3.34	0.77
17	39.78	39.78	18.39	70.85	25.3	59.9	2.37	14.7	81.2	5.53	0.67
18	87.57	111.39	58.54	75.04	65.6	117.2	1.79	41.4	145.4	3.51	0.78
19	32.17	32.17	42.04	42.04	23.2	51.7	2.23	12.1	69.1	5.71	0.59
20	34.01	34.01	40.91	40.91	26.5	44.1	1.66	14.4	62.2	4.31	0.71

21	89.97	110.57	82.97	101.96	92.2	124.8	1.35	43.4	146.6	3.38	0.81
22	25.87	25.87	34.57	34.57	22.1	29	1.31	20	55.3	2.77	0.78
23	15.6	15.6	21.64	21.64	8.7	24.9	2.86	5.6	41.5	7.35	0.5
24	37.41	37.41	42.87	42.87	30.4	41.7	1.37	28.4	62.2	2.19	0.84
25	29.19	29.19	36.03	36.03	23.7	31.9	1.35	13.5	55.3	4.09	0.85
26	53.48	62.88	58.77	58.77	51.9	56.8	1.09	35.3	76.1	2.15	0.85
27	412.67	871.91	192.27	1021.4	199.2	1021.9	5.13	97.2	1244.5	12.8	0.34
28	55.16	76.91	46.05	96.8	53	76.9	1.45	22	106.4	4.84	0.58
29	151.48	538.96	89	532.05	95.9	539	5.62	22.4	742.8	33.14	0.15
30	83.66	139.43	36.11	172.85	43	173.9	4.04	24.4	214.4	8.78	0.47
31	34.89	34.89	49.22	49.22	33.4	35.4	1.06	20.4	62.2	3.05	0.86
32	63.38	103.51	51.06	65.83	58	64.9	1.12	30.2	104.6	3.46	0.78
33	40.54	40.54	20.89	69.14	27.8	62.4	2.24	15.5	80.3	5.18	0.61
34	356.32	672.54	269.65	754.24	297.3	739.8	2.49	94.3	1041.4	11.04	0.34
35	34.89	34.89	61.84	61.84	26.9	89.3	3.32	7.7	104.3	13.48	0.34
36	15.6	15.6	21.42	21.42	8.3	17	2.06	6.2	41.5	6.7	0.79
37	24.67	24.67	34.57	34.57	21.7	44.6	2.05	14.4	62.2	4.32	0.64
38	31.21	31.21	44.94	44.94	23.5	52.3	2.23	13.4	76.1	5.69	0.58
39	22.07	22.07	31.11	31.11	13.8	32	2.32	6.8	55.3	8.14	0.59
40	19.11	19.11	28.44	28.44	15.4	31.8	2.06	7.8	48.4	6.23	0.68
41	36.59	36.59	44.94	44.94	29.4	46.3	1.57	28.3	69.1	2.44	0.8
42	35.75	35.75	48.4	48.4	35	35.7	1.02	17.1	69.1	4.04	0.78
43	25.87	25.87	30.16	30.16	18.8	26.7	1.42	16.8	48.4	2.89	0.78

3.4.2 Total carbon content of the peat

An important factor driving peatland restoration is the loss of carbon from the terrestrial carbon store (Wheeler *et al.,* 1995). It is therefore important to know the total carbon content of the peat that is being eroded and transported at the site. The Total Carbon (TC) content for sub-samples collected in the tube sediment traps was found using a TOC1200 Carbon Analyser. The instrument was calibrated using prepared standards of different concentrations of potassium hydrogen phthalate before the samples were analysed. Dried peat samples were placed in a quartz boat and then inserted into a furnace at 1000 ^{o}C where the sample was combusted with a constant stream of oxygen. This converts any carbon compounds present in the sample to carbon dioxide which is conditioned when passing through a copper oxide scrubber, a Perma-pure dryer, and a particle filter. Through monitoring the amount of carbon dioxide given off during the combustion process the total carbon content was calculated as a percentage of material content. This was carried out using samples collected in the Gerlach troughs and the wind tubes and an average value of carbon content calculated. The carbon content was found for the peat that had been eroded, rather than from a core from the peat, because the carbon content, when combined with the sediment yield, provides an accurate representation of the Particulate Organic Carbon (POC) flux rate from the site.

3.5 Quantifying the spatial area and volume of peat at Flow Moss

3.5.1 Determining the total area of bare peat

High resolution aerial imagery was obtained of the site using an Unmanned Aerial Vehicle (UAV) (Figures 3.15 and 3.16) on 8th April 2011. UAVs are an alternative to traditional field survey techniques such as using GPS and can be advantageous because they can image large areas in a relatively short period of time (Breckenridge and Dakins, 2011). Recent scientific uses of UAVs include the assessment of the ecological condition of rangelands in the USA by the mapping of bare ground (Breckenridge and Dakins, 2011), the detection of weeds in agricultural land to allow for site-specific weed management (Lopez-Granados, 2011) and the identification of the distribution of geological hazards in the Beichuan area following the Wenchuan earthquake (Gong *et al.*, 2010).

The UAV was programmed to undertake an aerial survey of Flow Moss by creating a flight plan over the site with the on-board digital camera taking pictures with 80% overlap. This allowed the entire area of the site to be imaged several times and enabled the production of a single image mosaic of the bare peat and the surrounding area. The UAV flew at an altitude of 110m which produced pixel resolution in the images of 3.7cm. The image mosaic was then geo-referenced using differential GPS survey control points and the bare peat areas digitised in Arc-GIS.

Figure 3.15: The Unmanned Aerial Vehicle (UAV) used to obtain high resolution aerial imagery of the site.

Figure 3.16: The UAV in flight over the study area.

3.5.2 Assessing the degree of brash cover

In June 2011, a survey was carried out to determine the extent of the heather brash that had been spread in November and December 2010 as part of the restoration process. Differential GPS was used to assess the extent to which the brash had been blown or washed away from the bare peat surfaces since it was applied. This would be a useful indicator of the likely effectiveness of this key restoration measure. Four areas of 15m by 15m were surveyed across the study site with the areas selected so that a good representation of the different surface conditions were captured e.g. an area of bare peat, an area containing one of the channels, an area of bare peat that contains some haggs and an area within the ‘gully section’ (Figure 3.17). Peat haggs, vegetation cover and areas of bare peat within each sample site were surveyed and the extent of brash loss was quantified as a percentage of the original brash coverage assuming that every bare peat surface was covered in brash equally during the restoration process (Figure 3.18).

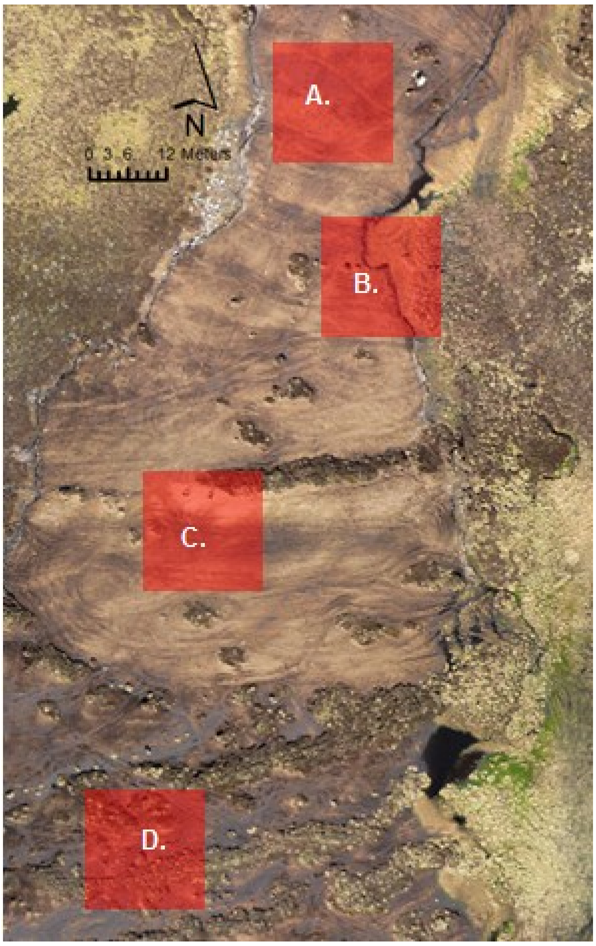


Figure 3.17: The four 15m by 15m areas surveyed in June 2011 to assess the loss of brash since it was spread as part of the restoration measures in November and December 2010.

Figure 3.18: Survey area B from Figure 3.17. An area where the brash has been washed away by the stream is clearly visible. The photo taken when site conditions were very dry, during 'wet' conditions water flows through this small channel.

3.5.3 Quantifying the depth of peat

Traditional techniques for measuring peat depth involve point measurements using coring or probes but they are destructive and provide an incomplete characterisation of the subsurface (Holden *et al.*, 2002). Here Ground Penetrating Radar (GPR) was used as an alternative method as it has been found to produce more detailed results of peat depth than those obtained by point measurements (Sass *et al.*, 2010). GPR surveys can also be used to identify peat structure and stratigraphy (Plado *et al.*, 2011), the identification and hydraulic conductivity of soil pipes within peat (Holden *et al.,* 2002; Holden, 2004), the boundary between peat and lake sediments (Slater and Reeve, 2002), sub-surface postglacial landforms such as eskers (Comas *et al.*, 2011) and ecological aspects by determining temporal changes in biogenic gas content in peat soils (Comas *et al.*, 2008).

GPR works by using a transmitting antenna that generates a high-frequency electromagnetic wave that penetrates through the soil. Antennas with a lower frequency penetrate further into the soil due to the longer wavelength. Features such as changing water content can influence the relative dielectric permittivity of the soil which in turn changes the return signal that the antenna receives (Comas e*t al*., 2005). The changing return signal is monitored by the antenna and can be used to identify sub-surface characteristics such as the boundary between soil and the underlying mineral layer. GPR is particularly effective in determining the boundary between blanket peat and the mineral layer beneath because of the significant drop in water content in the mineral layer. This causes large amplitude reflections in the radar signal which are clearly identified by the GPR antenna (Comas e*t al*., 2005). Rosa *et al.* (2009) evaluated the mean absolute error (MAE) between GPR and manually estimated peat depth to be approximately 0.27 m. This value is within the same order of magnitude as the variability of manual measurements estimated from repeated coring on a 1 m^2 area of peat and is therefore within an acceptable range for use in this study (Rosa *et al.,* 2009).

The GPR survey of Flow Moss was carried out using a shielded antenna of 500 MHz run over 9 cross profiles approximately 50 metres apart extending across the entirety of the site from the South-East fence to the North-West fence. The

GPR signal was triggered at a constant spacing of 5cm measured using a hip-chain fastened to fence at the end of the profile. Sub-surface features such as the boundary between the peat and the mineral layer below can be identified once the GPR data has been post-processed. The raw GPR data does not take into account the surface topography and plots the return signal relative to the surface. A realistic sub-surface profile therefore requires an accurate topographic profile which was measured using differential GPS. Each of the 9 GPR profiles was surveyed using the differential GPS and the resulting topographic profiles integrated with the GPR signal.

After the 9 profiles had been run with the GPR, repeat measurements were taken for profile no. 5. At strategic positions along the profile, estimates of peat depth from the raw GPR data were made and a gouge corer used to manually calibrate these estimated depths. Calibration of the GPR signal with manual depth measurements not only correlates the signal with the stratigraphy but also allows the adjustment of the estimated signal velocity which enables the conversion of the signal return travel time into a depth scale (Plado *et al.,* 2011) The gouge was driven into the surface until it reached the base of the peat and the length of the gouge that was beneath the surface at this point was measured (Section 4.2.1.1).

3.6 Summary of methods

Figure 3.19 summarises the field monitoring framework used in this study. The related methods used in this study have been designed to achieve the three research objectives through the combination of three types of findings; understanding the processes of erosion at Flow Moss, the study site morphology and the characteristics of the peat. Most of the methods described in this chapter were used to understand how the erosional processes acting at Flow Moss occur and possible causal mechanisms for the extent and rate of erosion. These methods are described in sections 3.1 and 3.2 with possible causal mechanisms monitored by methods from section 3.3. The morphology of the study area has been found using the methods described in section 3.5 although changes in the morphology of the surface peat are measured using section 3.2.2. The peat characteristics were found using methods from section 3.4 as well as the Troels-Smith and Von Post classification from section 2.6. It is suggested that a complete methodology for measuring the dynamics of the peat area has been devised which will enable the research questions developed in Chapter 1 to be answered.

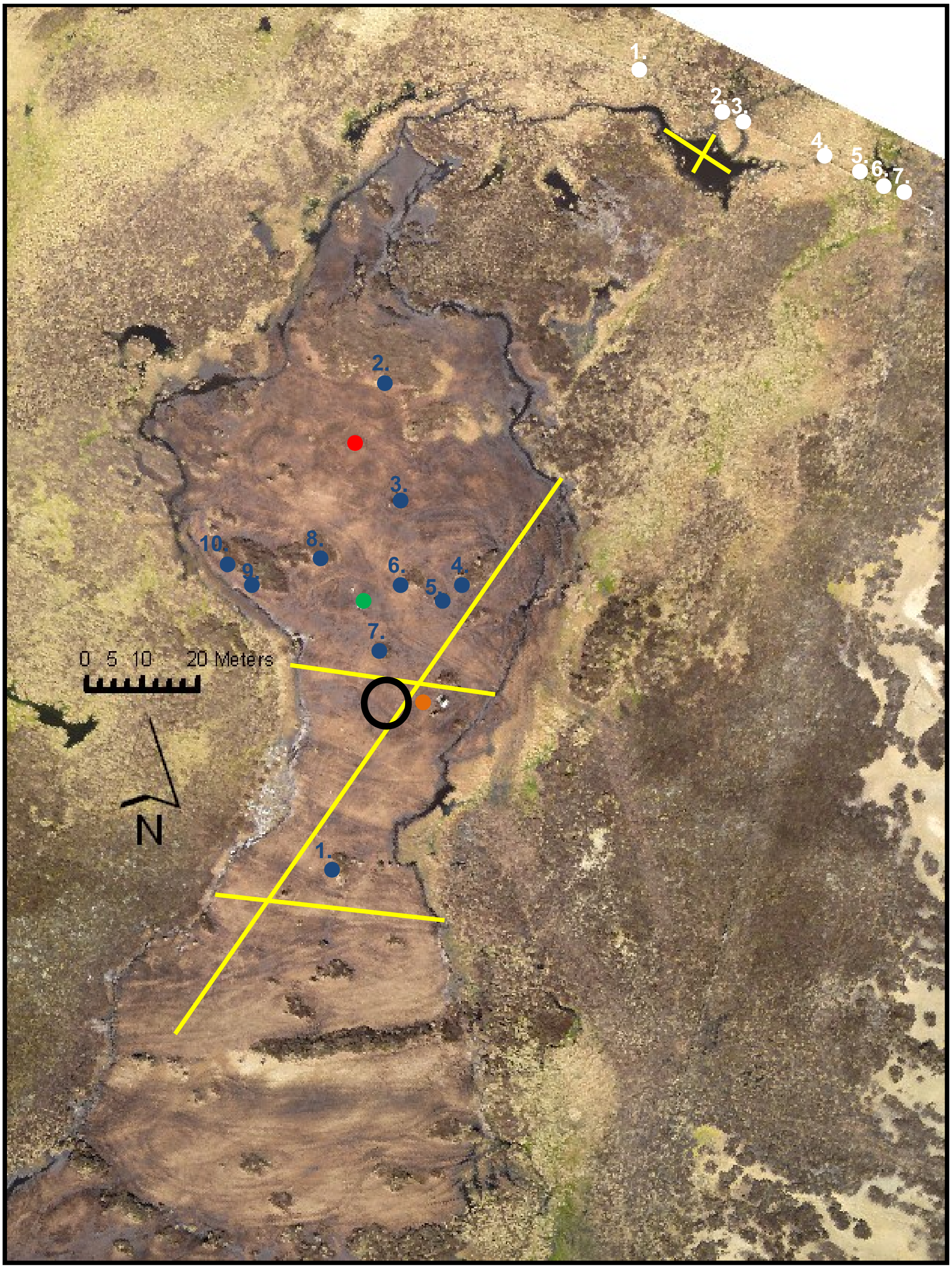


Figure 3.19: Map of all equipment in study area. Red = BSNE sampler. Black = Wind tube samplers. White = Sack traps. Blue = Gerlach trough/Erosion pin sites. Yellow = Pole transects. Green = Automatic Weather Station. Orange = Automatic Pressure Transducer

Chapter 4. Results

In this chapter, the results of the field monitoring between 14th October 2010 and 7th July 2011 are presented. Firstly, the environmental conditions during this period are discussed as a basis for examining the relationship between the process drivers and meteorological events. Next the field results of sediment collection are presented and comparisons made to the weather data to identify causal relationships between wind erosion, hydraulic parameters and diffusive erosion on slopes and weather. Thirdly, the morphological surveys to determine the surface area of bare peat and peat volume are presented along with results from the assessment of brash cover. Finally, these results are used to construct a preliminary sediment budget which is developed in Chapter 5.

4.1 Variability in the Environmental conditions at Flow Moss over the monitoring period

The range of environmental conditions discussed in this section identifies key factors that may be important when considering the processes of erosion in the following sections. For example, potential erosion events identified within the records may be important in controlling the extent of wind-driven rain due to the high energy available for particle detachment and entrainment and the number frost days identified within the temperature record are important when considering the availability of sediment for transfer as a result of freeze-thaw weathering (Evans and Warburton, 2007).

4.1.1 Climate conditions

The climate data presented here were collected at 30 minute intervals by the Automatic Weather Station (AWS) as described in section 3.3.1. The start of the climate record began on the installation date of the AWS at the site on 19th November 2010 and continued until 14th April 2011. The climate series ended on the 14th April 2011 because of a malfunction with the AWS that caused unreliable data to be recorded. This problem was resolved on the 26th May 2011 but the air temperature data during the 42 intervening days could not be recovered. In an attempt to maintain a continuous record over the study period, data was obtained from the UK Environmental Change Network weather station at Moor House (550 m.a.s.l), approximately 20km to the south of Flow Moss but this was not available for 2011. When the 2011 dataset becomes available, it will provide a useful comparison with the Flow Moss weather record.

4.1.1.1 Rainfall

Figure 4.1 shows the rainfall record for Flow Moss between 19th November 2011 and 7th July 2011 (excluding the period of 14th April – 26th May 2011). The rain gauge is a tipping-bucket device (tip increment 0.202 mm) and the AWS records the number of 'tips' in each 30 minute measurement period. The total rainfall during the 200 days of the measurement study period was 414 mm. During this period there was a prolonged period of snowfall from the end of November 2010 until January 2011 when access to the site was impossible. Although the AWS did not directly record days of snow cover, it was observed through a remote web-cam located near to Flow Moss that the area was covered in quite deep snow for a long period of time. If the rainfall collected during this period is assumed to be representative of the whole year, it can be extrapolated to give an annual precipitation of 756 mm. However, as the study period did not cover the summer months, July to September, which are typically drier, this is likely to be an overestimate. Compared to the average annual precipitation at Moor House (Section 2.3) the study period was very dry. For example, the Environmental Change Network data from the Moor House weather station indicates there was 1374 mm of rainfall at Moor House during 2010 which is approximately two-thirds of the annual average of 1982 mm. Furthermore, it is expected that Flow Moss would experience a lower amount of rainfall because of its lower altitude (~100 m) and more easterly location. This suggests that the study was carried out in a drier than average year which should be borne in mind when considering the results from this study.

Four events with rainfall intensity of greater than 5 mm hr^{-1} occurred in a two month period between mid-January and mid-March. Figure 4.1 also shows the dates that the sediment traps were emptied. Each of four highest peaks in precipitation occurred in an individual monitoring period so the effects of these rainfall events can be evaluated in the sediment yields from the traps.

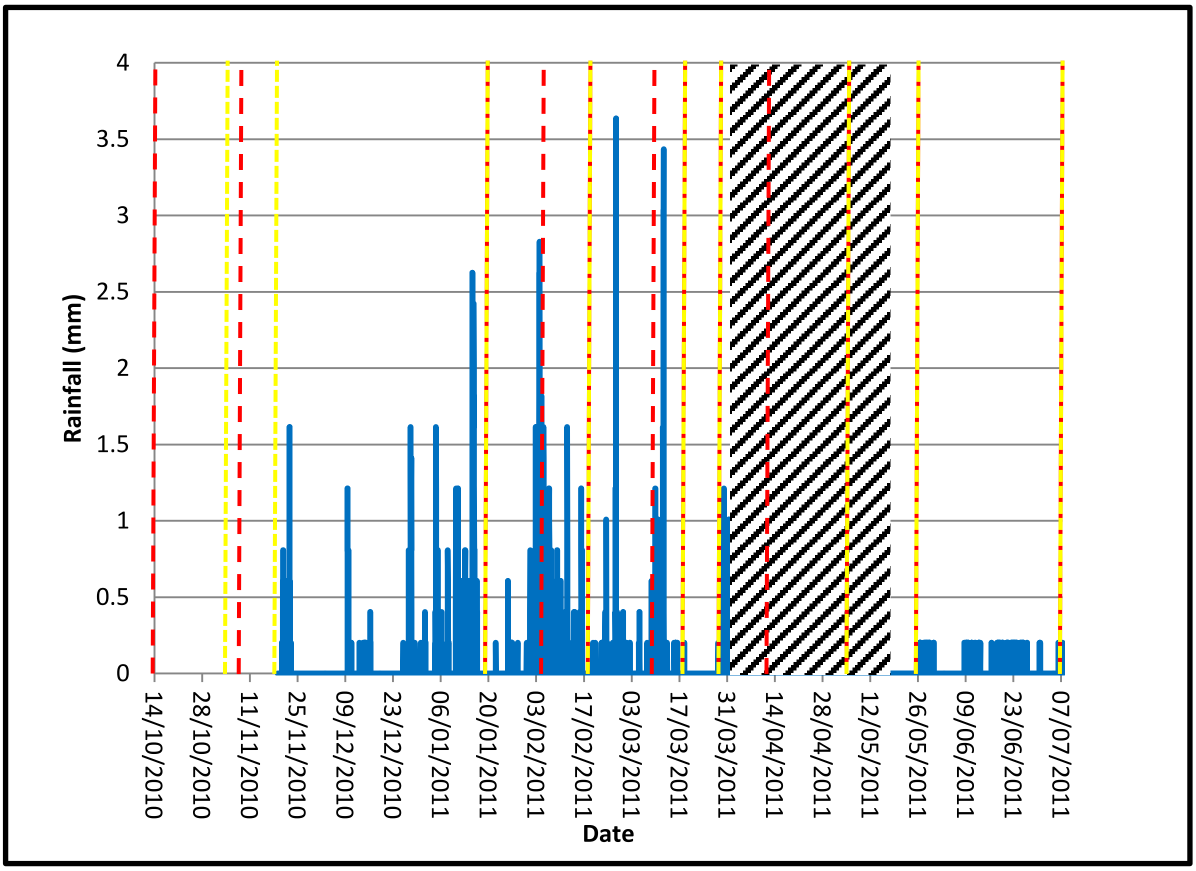


Figure 4.1: Rainfall collected by the AWS at Flow Moss at 30 minute intervals between 19/11/10 and 7/7/11. The four highest peaks identify rainfall events where rainfall intensity was greater than 5mm hr^{-1}. The black and white hatched area indicates the period when the AWS was not collecting data. The red dashed lines indicate the dates when the wind tubes samplers were emptied. The yellow dashed line shows when the BSNE and troughs were emptied. The yellow and red dashed line indicates the date when the wind tubes, the BSNE and the Gerlach troughs were all emptied.

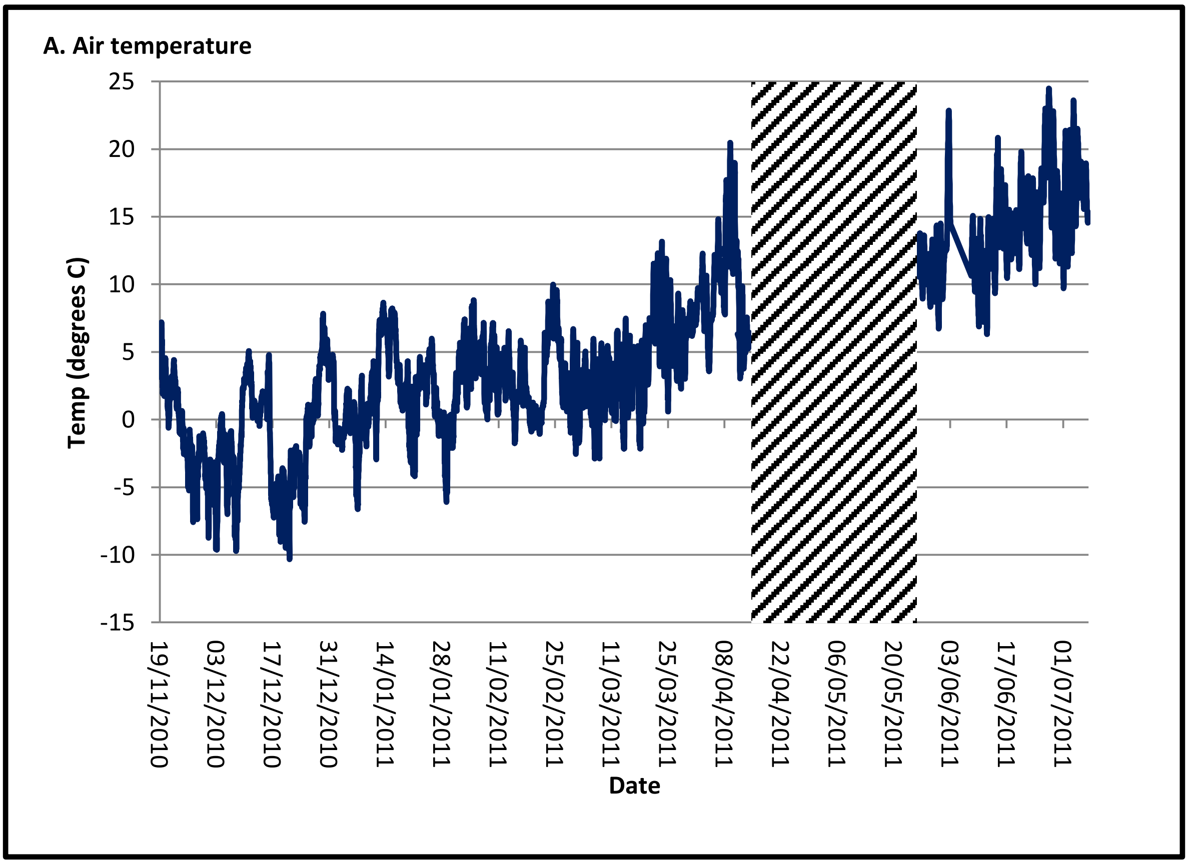
4.1.1.2 Temperature

Figure 4.2 shows the temperature record for both the air (A) and the soil (B) over the study period. There is a break in the air temperature record because of technical issues with the AWS. The two measurement periods of air temperature therefore cover the 19th November 2010 to 25th March 2011 and from 8th April 2011 to 14th April 2011. The technical issues after 14th April 2011 were resolved for the soil temperature sensor after 26th May 2011 but the air temperature sensor continued to give incorrect values. This was solved using a regression equation that was calculated between the soil and air temperature datasets (y = 1.4275x - 2.1089) and this was used to generate the air temperature record for the period after 26th May 2011

The observed air temperature range was 30.8°C with a minimum value of -10.3°C occurring on 21st December 2010 and the maximum temperature of

20.5°C occurring on the 9th April 2011. The average temperature across the two periods of measurement was 1.8°C. A frost day is defined as a day when the night-time minimum temperature is below 0°C (Meehl *et al.*, 2004). For this study period 69 frost days were calculated at Flow Moss which is less than the 105 day average for the higher Moor House site (Section 2.3). The AWS at Flow Moss was not able to directly measure the number of days when snow was lying on the ground but the first snow of the study period occurred on the 25th November 2010 and remained for a prolonged period, with snow still visible in sheltered areas on the field visit on 19th January 2011. During this period of snow cover, it is important to notice that the soil temperature record does not indicate any soil freezing despite the very low air temperatures. It is likely that the winter snow cover may have prevented frost penetration into the soil due to an insulating effect.

The ECN data for Moor House is only available for 2010 so a comparison was made between the two datasets for November and December 2010. At Flow Moss the average temperature during this period was -1.2 °C and at Moor House it was -3.04 °C. This is similar to the comparison made in section 4.1.1.1 where the weather conditions at Moor House are more extreme.



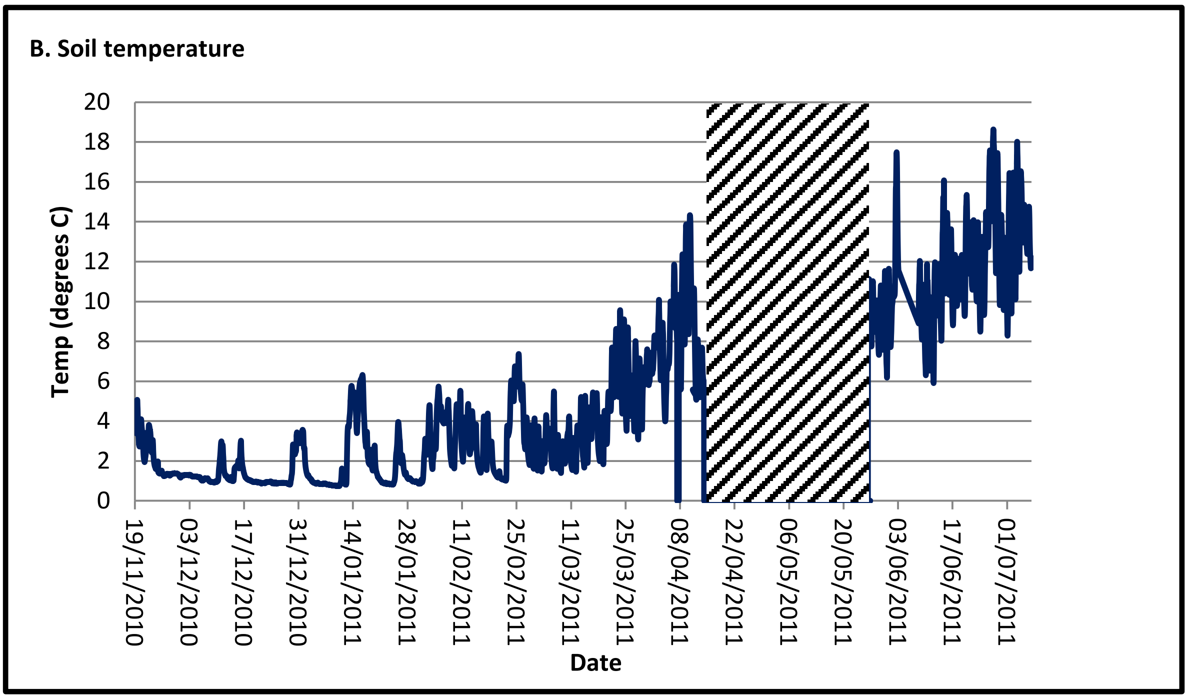


Figure 4.2: **A:** The air temperature and **B.** soil temperature recorded by the AWS at Flow Moss at 30 minutes intervals between 19/11/10 and 7/7/11. The hatched areas indicate periods when data was unavailable. The air temperature record after 26th May 2011 was generated using a regression based on the relationship between the soil and temperature records between 19th November 2010 and 14th April 2011

4.1.1.3 Wind

Other important environmental controls that could potentially affect erosion are the wind-speed and the wind-direction. The wind friction velocity was calculated using Equation 3.1 for the anemometer 2.34 m above the peat with the roughness length calculated using a regression between wind velocity and anemometer height. Figure 4.3 shows the calculated friction velocity during the study period with a ‘daily’ running mean fitted to the 30 minute time series. There are three high-speed events with have a peak friction velocity above 20 m s^{-1}.

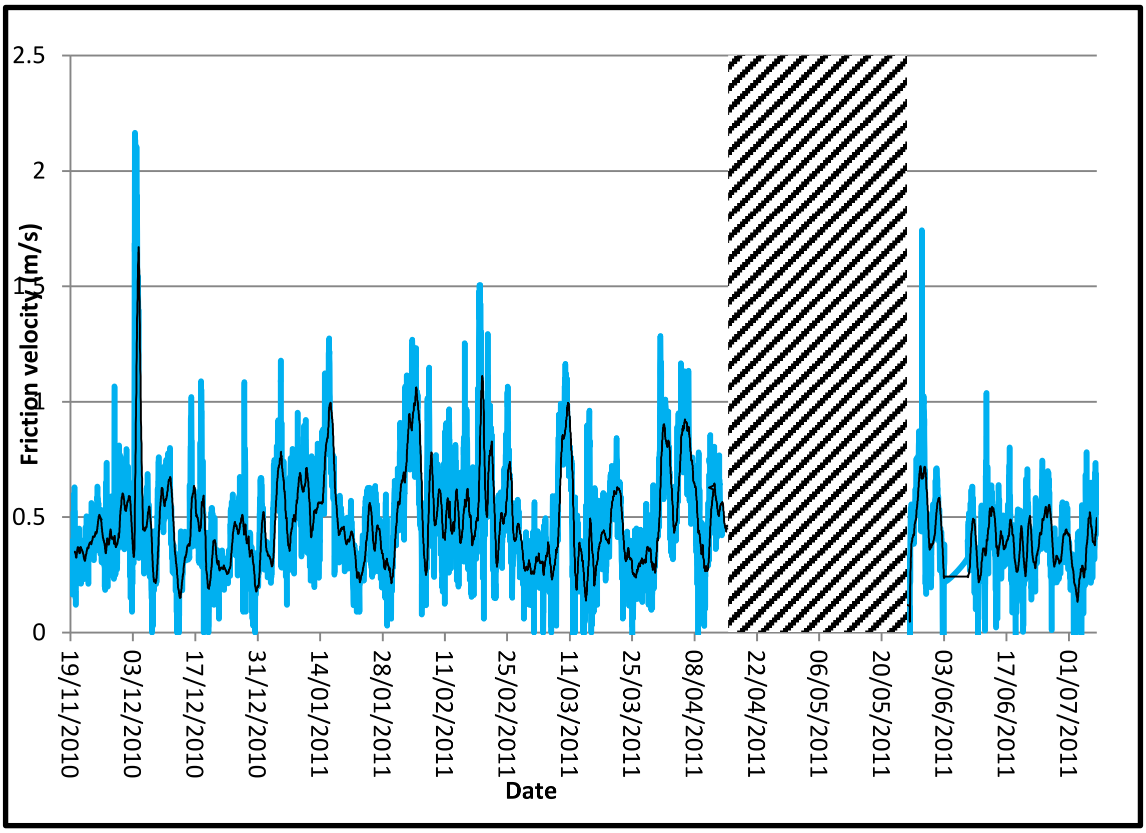


Figure 4.3: Wind friction velocity between 19/11/10 and 7/7/11 calculated from the AWS wind-speed data. The black line is a daily running mean fitted to the 30-minute time series. The hatched area indicates a period when no data is available.

When heavy rainfall combines with high wind-speeds there is a greater potential for erosion through the process of wind-splash because there is more energy available for both particle detachment (by rain) and particle transport (by wind) (Warburton, 2003). The identification of periods when heavy rainfall and high wind-speeds occur together represents times when there is the greatest potential for erosion. A comparison of the friction velocity and the precipitation pattern is shown in Figure 4.4. Four potential erosion events were identified when high rainfall intensities (> 4 mm hr^{-1}) combined with high wind-speeds (friction velocity > 1 m s^{-1}). These four events occurred on 15th January, 3rd February, 26th February and 12th March and are identified by red circles on Figure 4.4.

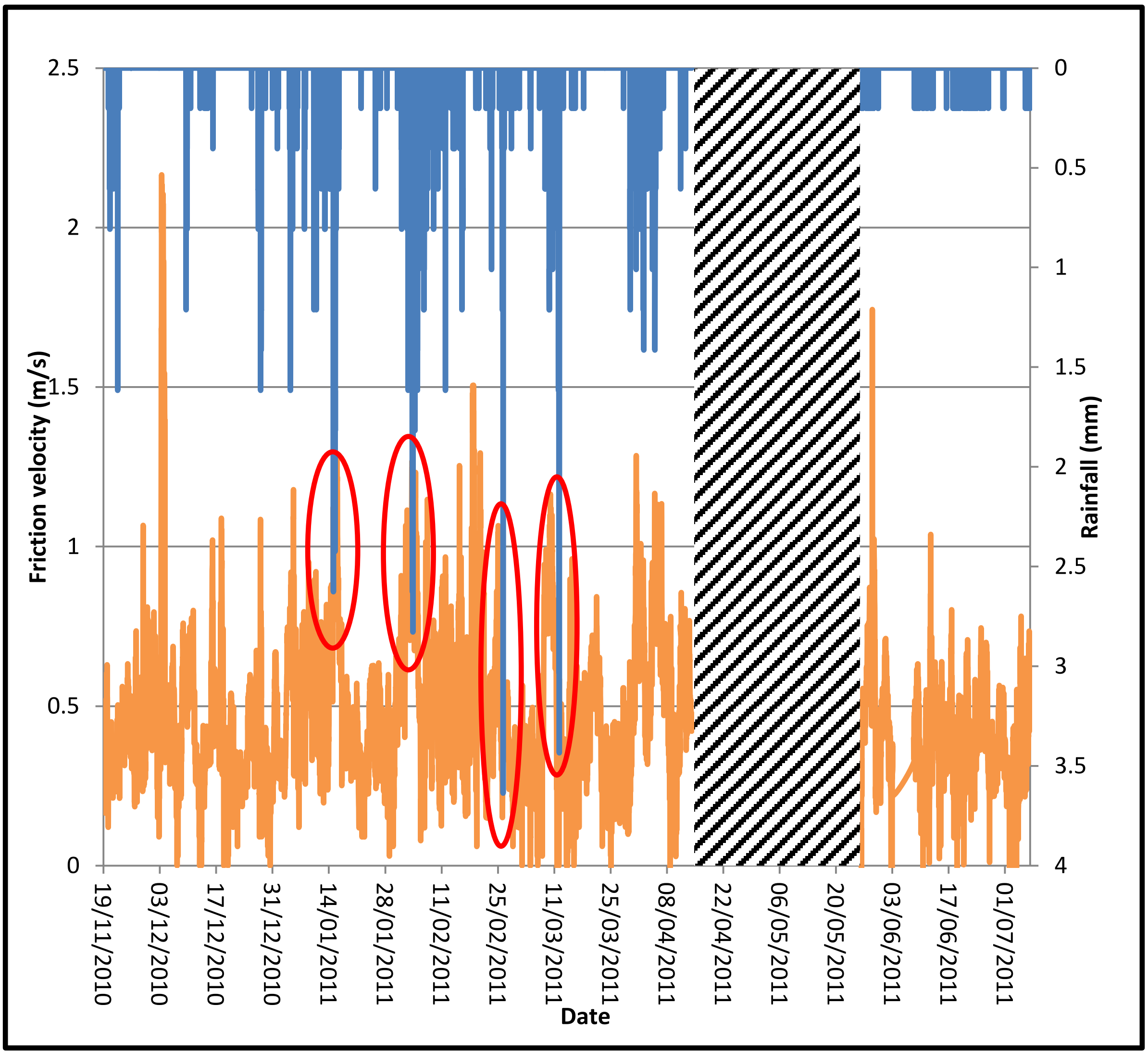


Figure 4.4: Comparison of rainfall (blue) and wind friction velocity (orange) allows the identification of four potential erosion events (red) in the record where heavy rainfall is combined with high wind-speed.

Warburton (2003) demonstrated that wind direction is also important in controlling the erosion of bare peat through aeolian processes because the erosive energy is focussed from the prevailing wind direction. Figure 4.5 shows the distribution of wind direction during the entire study period (19/11/10 to 7/7/11, except between 14/4/11 to 26/5/11). At low wind speeds, increased friction on the wind vane between 0 – 10 degrees reduced the ease of rotation over this angular range and produced a bias in the results towards these directions. The measurements from this range have been removed to allow an unbiased view of the record. The mean wind direction was 224.5^{o} with vector strength of 0.508.

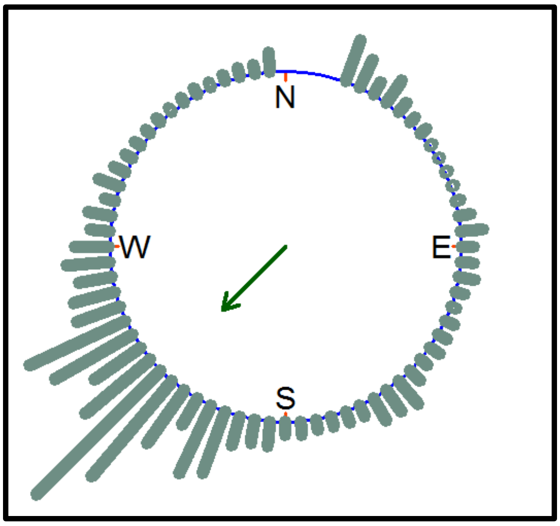


Figure 4.5: Wind direction distribution at Flow Moss between 19/11/10 and 7/7/11. Mean wind direction = 224.5° with vector strength of 0.508

The distribution of wind direction at Flow Moss clearly shows that the prevailing wind direction is from the South West with the other directions experiencing a similar amount of wind, with the exception of less from the North East. Flow Moss is quite exposed to the wind from the North, South and West but is protected to the East by a small ridge approximately 10 m higher in altitude. This may act to protect the monitoring site from wind from the East but this is unlikely to have a significant overall impact because the predominant wind direction across the UK is from the South West.

4.1.1.4 Summary of weather conditions

On the whole, the weather conditions monitored at Flow Moss are typical of a UK upland environment with very cold temperatures during the winter and periods of heavy rainfall although the winter of 2010-2011 experienced an unusually large amount of snowfall. The study period experienced less rainfall than average but four significant rainfall events (> 4 mm hr^{-1}) occurred with high wind friction velocities (> 1 m s^{-1}) which had high energy available to cause erosion. The dry periods in the spring and the 69 frost days during the winter may have generated sediment on the peat surfaces through desiccation and freeze-thaw weathering. Flow Moss experiences wind from all directions but the most common wind direction was from the South-West and matches the prevailing wind across the rest of the UK.

4.1.2 Variations in the local water table

Water table was measured at 15 minute intervals by an automatic pressure transducer and the time series is shown in Figure 4.6 plotted alongside the rainfall record.

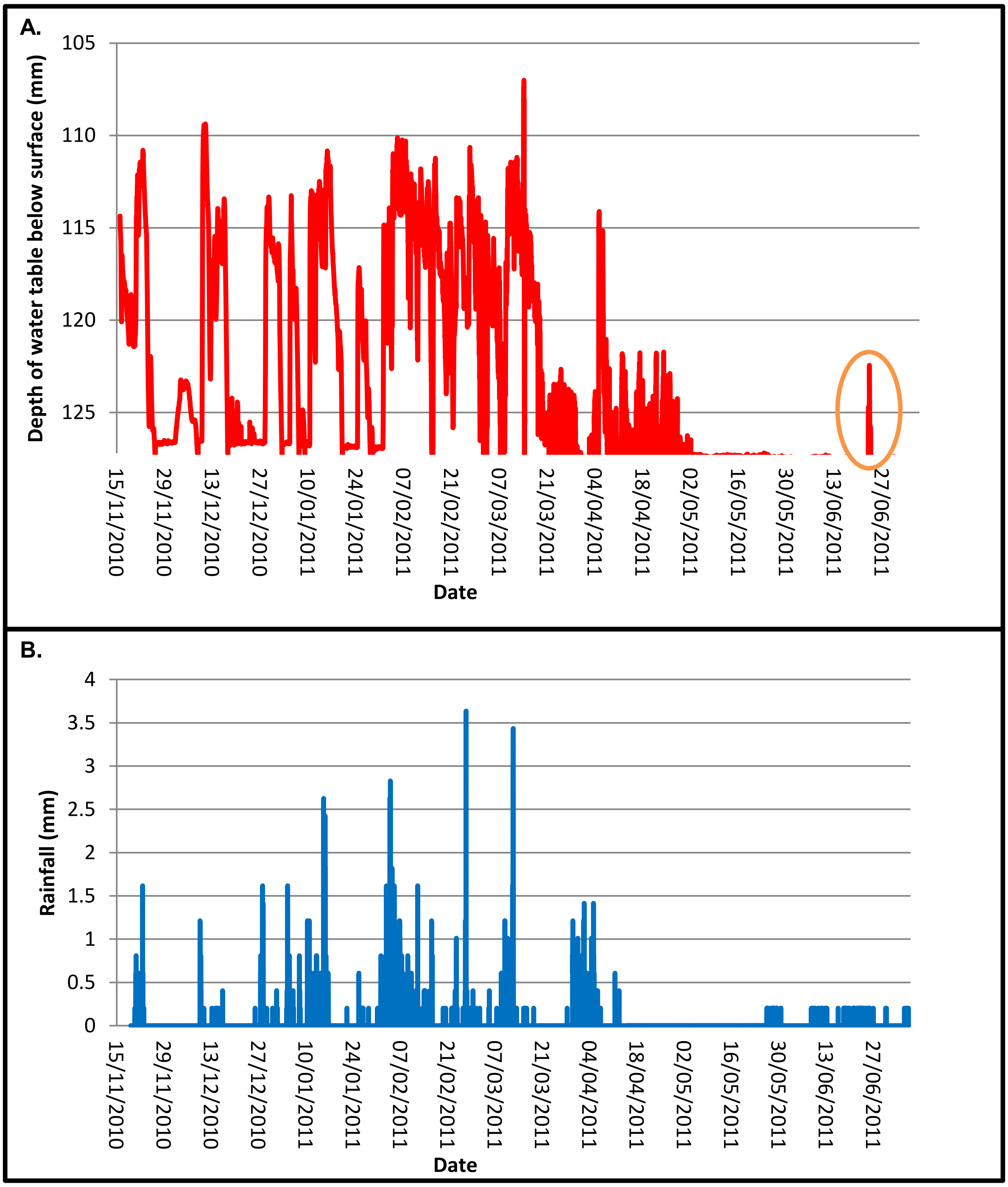


Figure 4.6: Fluctuations in depth of water table (**A**) compared to the rainfall record (**B**). The water table height responds rapidly to rainfall, characteristic of a ‘flashy’ peatland regime.

The bottom of the pressure transducer was located 127.2 mm beneath the surface of the peat and the raw data of water height above that point was converted into depth of the water table. Readings of water table depth beneath 127.2 mm are not available, but Figure 4.6 shows that during most of the winter and spring months, the water table is less than 127.2 mm from the surface. Comparison of the water table fluctuations and the rainfall record shows that the water table rises rapidly in response to rainfall but also falls again quite rapidly after the rainfall event. This suggests that the amount and duration of rainfall is very important in raising the water table near to the surface of the peat and follows previous work that describes the hydrological regime of peatlands as 'flashy' (Holden and Burt, 2003). Figure 4.7 shows the section of Figure 4.6 between 12.00 on 20th November until 09.00 on 21st November where the rapid response of the water table to rainfall can be seen. The water table rose rapidly in response to the start of the rainfall event and continued to rise with prolonged rainfall. The rainfall stopped at 04.00 am and the water table began to drop immediately before stabilising and rising in response to more rainfall after 09.00 on the 21st November 2010.

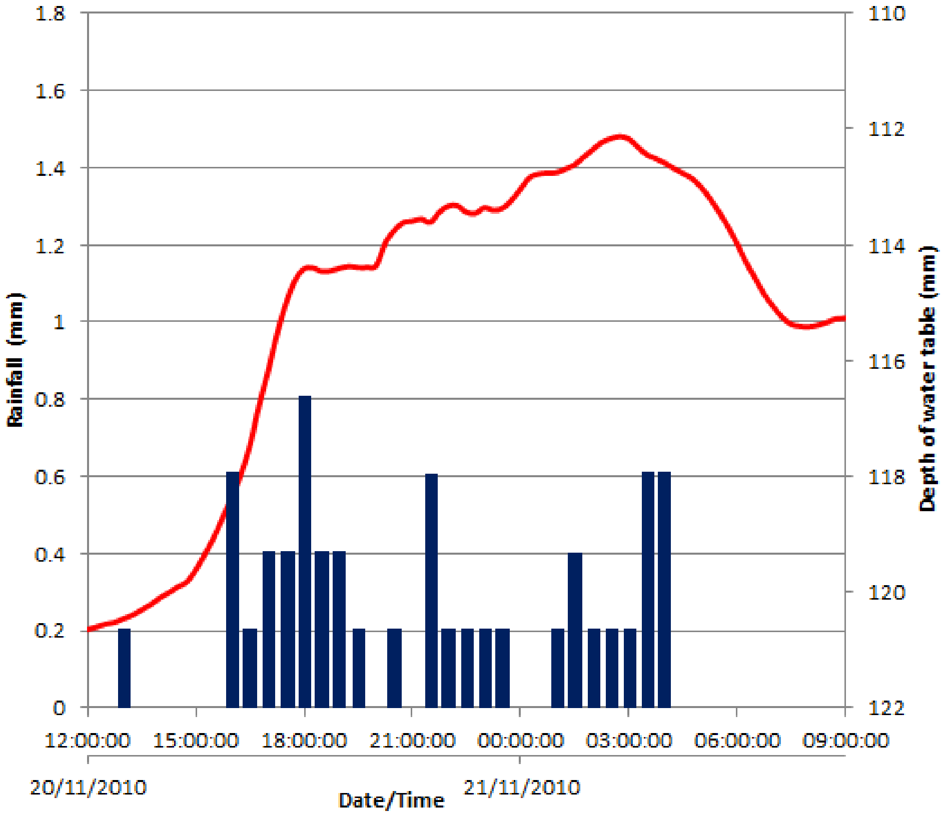


Figure 4.7: Rainfall and water table between 12pm on 20th November 2010 and 9am on 21st November 2010. It shows the rapid response in water table to a rainfall event.

While the pressure transducer does not measure below 127.2 mm, it can be concluded that the water table does not drop far below this depth as it can be seen to rise back above the depth of the transducer after some rainfall (e.g. during mid-June 2011, identified with the orange circle in Figure 4.6). Periods when the water table is low identify possible periods of surface desiccation as the surface of the peat can dry out and crack and are therefore important in identifying possible periods of erosive potential.

4.2 Quantification of erosion rates at Flow Moss

4.2.1 The nature and amount of erosion by aeolian processes

To fully understand the role of wind in the erosion of peatlands, it is important to examine both the nature of the process and to quantify the amount of peat eroded through aeolian processes. The following three sections present results collected using methods described in sections 3.1.1 which allow the quantification of wind erosion rates as well as improving our understanding of these processes.

4.2.1.1 The nature of peat erosion by wind and the important roles of rainfall intensity, wind-speed and wind direction in controlling the process

The Big Spring Number Eight (BSNE) sampler measures the amount of peat erosion by aeolian processes at different heights above the ground (Section 3.1.1). Figure 4.8 shows the dry mass of peat collected in the individual samplers during each measurement period. In every sampling period, the largest amount of peat is transported close to the ground with a general pattern of the quantity of peat reducing with increased height. This pattern does not hold in every case as from 4/11/10 to 19/1/11, 18/2/11 to 18/3/11 and 18/3/11 to 29/3/11, there was more peat collected at 1.165 m than at 0.9 m, identified with the blue circles in Figure 4.8. However, the variability at higher levels is not particularly significant due to the small quantities of sediment collected (Warburton, 2003). From 29/3/11 to 5/5/11, proportionately more peat was collected at 0.405 m than during the other time periods.

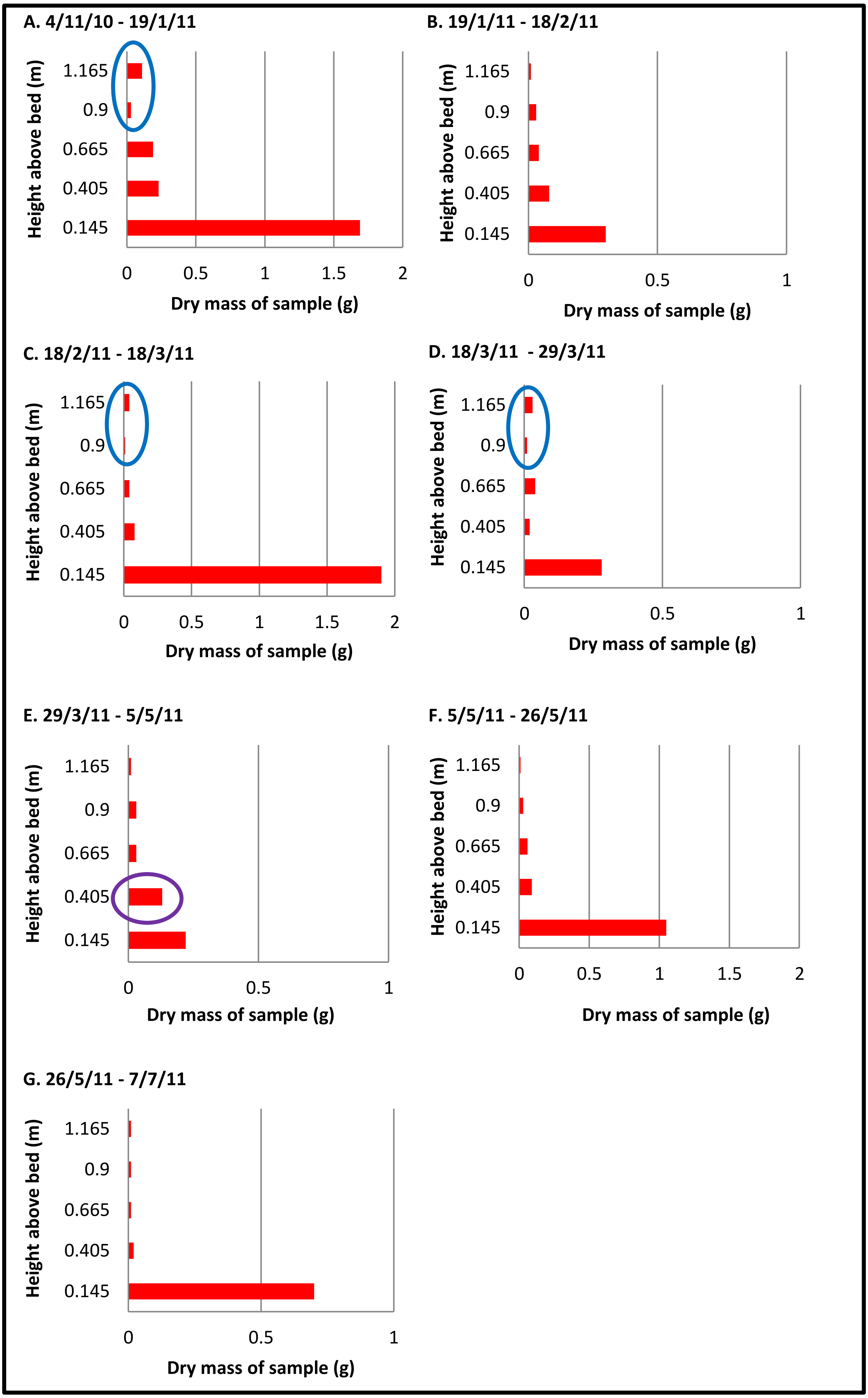


Figure 4.8: The dry mass of peat collected in the BSNE sampler during each of the measurement periods. In **A**, **C** and **D**, the amount collected at 1.165m is greater than the amount at 0.9m (blue circles). Also, the period E, there is proportionately more peat collected at 0.405m than in the other periods (purple circle).

More peat was possibly collected at 0.405 m from 29/3/11 to 5/5/11 because this time period coincides with a dry period with very little rain (purple circle in Figure 4.8). During the field visits, the peat surface was noticeably drier and this can lead to surface desiccation. Foulds and Warburton (2007a) found that rates of wind erosion of dry peat dust were up to two orders of magnitude lower than rates recorded during wet conditions, but the dust was observed to be blowing up to 1.87 m above the surface. The distribution of material collected between 29/3/11 and 5/5/11 matches what would be expected during dry conditions as the peat has been transported at higher altitudes and the overall total of peat collected (0.42 g) is lower than during period C (2.07 g) which experienced wet conditions.

Figure 4.9 shows the distribution of peat in each sampler as a percentage of total peat collected during the whole study period. The sampler closest to the surface collected 81.1% of the total with gradually lower proportions of peat with increasing height, with the exception at 0.9 m. The pattern appears to fit an exponential decay. An exponential decay trend-line was fitted through all five heights and gave the equation $y = 84.309\ e^{-0.812x}$ where y is the height above the bed and x is the percentage of total peat collected. The R^2 value for this trend-line was 0.78. If the 1.165 m value is removed from the trend-line so that it is only fitted through the lower four data points, the equation is $y = 168.84\ e^{-1.16\ x}$ and the R^2 value increases to 0.91. This suggests that the exponential decay of peat collection with height fits until 0.9 m but above this another process, or sampling error, is occurring. As discussed above, Foulds and Warburton (2007a) observed peat dust being blown at heights up to 1.87 m so it is possible that the sampler at 1.165 m is disproportionately collecting material transported at the highest altitudes. As can be seen by Figure 4.8, the mass of peat collected in the higher samplers is very low and due to the accuracy of the balance used in the laboratory (to two decimal places), and the difficulty in transferring all of the material from the sampler to the sample bag in the field may have led to some error in the peat masses measured. However, all of the samplers were emptied in the same way which would lead to random error rather than the systematic increase in peat collected at the higher altitude.

The BSNE sampler results clearly show that the majority of peat is transported by the wind close to the peat surface, implying that the erosion is as a result of wind-driven rain detaching the peat and transporting it over short distances. During dry conditions (e.g. period E, 29/3/11 to 5/5/11), peat is still eroded by wind but the total amount is less and is as a result of the desiccated peat surface being dislodged and blown as dust. Therefore some peat is transported at a higher height.

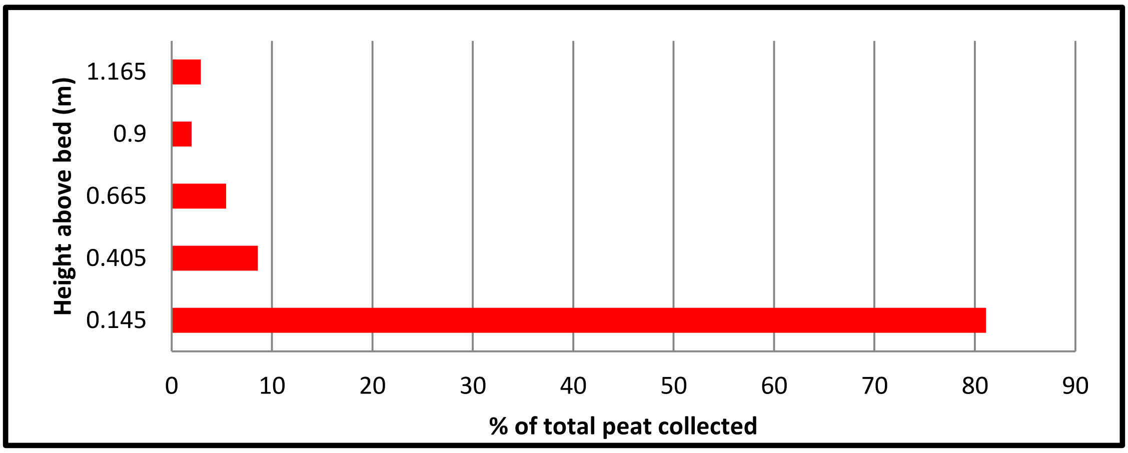


Figure 4.9: Percentage of peat collected in each sampler over the whole study period.

The studies by Warburton (2003) and Foulds and Warburton (2007a; 2007b) identify the climatic conditions as a very important factor in controlling the nature of wind erosion. This importance has already been identified from Figure 4.8E from the BSNE results but the issue was investigated further using the circle of tubes samplers described in section 3.1.1. The total mass of peat collected in the circle of tube samplers during a period of ‘wet’ conditions (4/2/11 - 18/2/11) and a period of ‘dry’ conditions (18/3/11 - 29/3/11) was compared (Figure 4.10A). Figure 4.10B shows the variations in the wind velocity with height monitored by the AWS during these same periods and it shows that in addition to the period from 4/2/11 to 18/2/11 being wetter than the period from 18/3/11 to 29/3/1, it also experienced higher wind velocities. During the first period (4/2/11 to 18/2/11), the rainfall intensity was an order of magnitude greater than during the dry conditions and the rate of sediment collection in the traps was also an order of magnitude greater. Therefore, rainfall in association with high wind velocities is very important in controlling the rate of erosion.

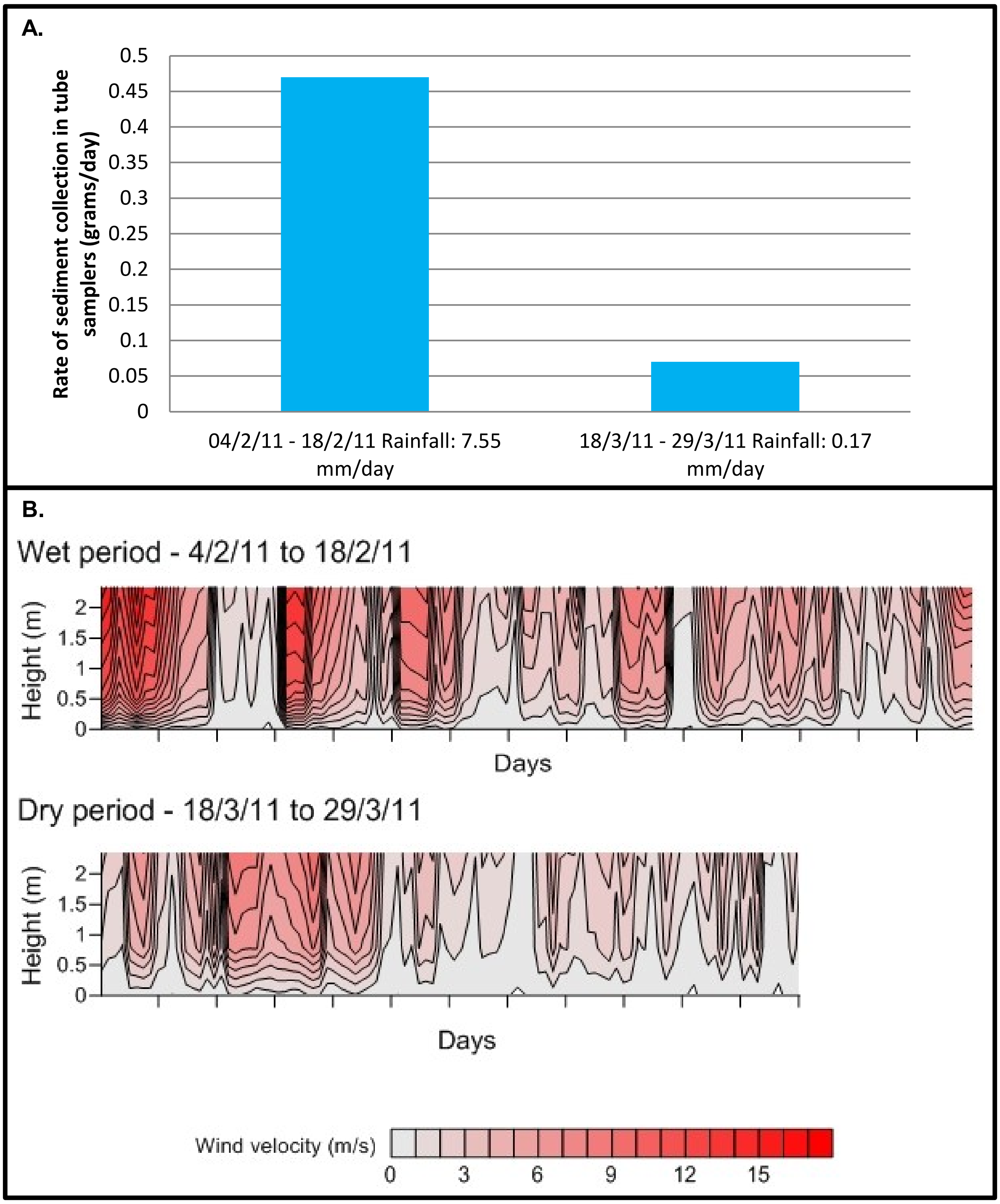
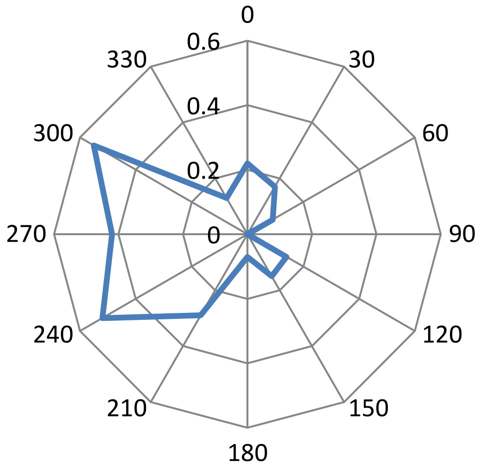


Figure 4.10: Comparison between rates of peat collection in the tube samplers during two monitoring periods: 4/2/11 – 18/2/11 and 18/3/11 – 29/3/11. **A.** The rate of sediment collection and rainfall intensity. **B.** The variations in wind velocity during these same periods.

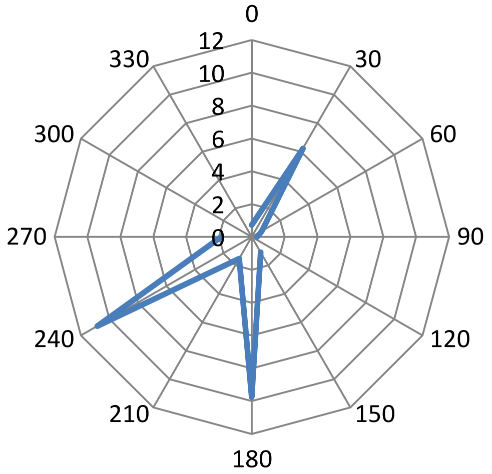
At Moss Flats, Moor House, Warburton (2003) observed that windward facing samplers had a peat flux rate between 3 and 12 times greater than leeward facing samplers. This clearly identifies that wind direction is important in controlling peat erosion by aeolian processes and was investigated further in this study. The wind direction across the whole study period has already been presented in Figure 4.5 but Figure 4.11 shows the amount of peat collected in the circle of tubes samplers with the wind direction measured for each of the measurement periods. The total peat collected during each study period is shown in Table 4.1.

A. 14/10/10 - 9/11/10. Total sediment collected = 2.75 g

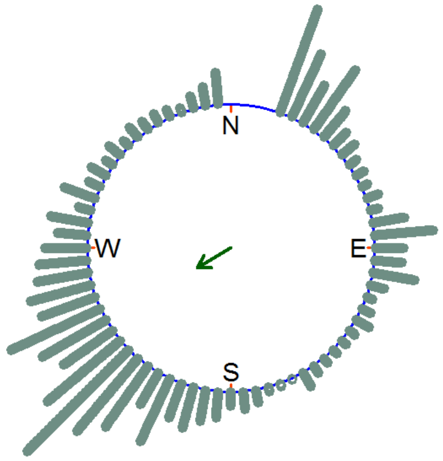


No wind direction data available for period A as AWS had not been installed.

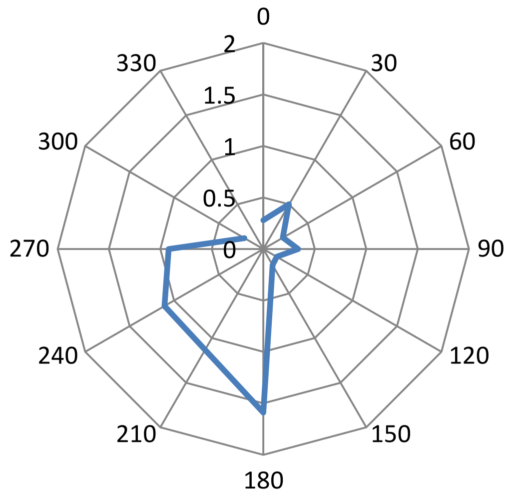
B. 9/11/10 - 19/1/11. Total sediment collected = 33.04 g



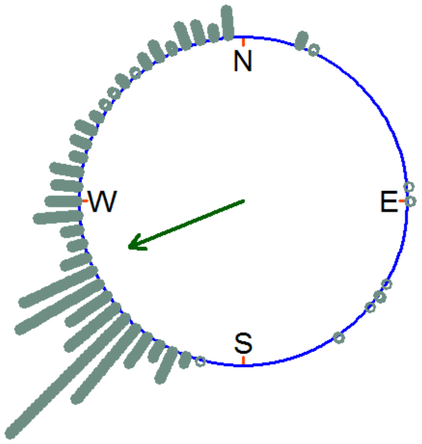
Mean wind direction = 239.6°. Vector strength = 0.272



C. 19/1/11 - 4/2/11. Total sediment collected = 6.63 g

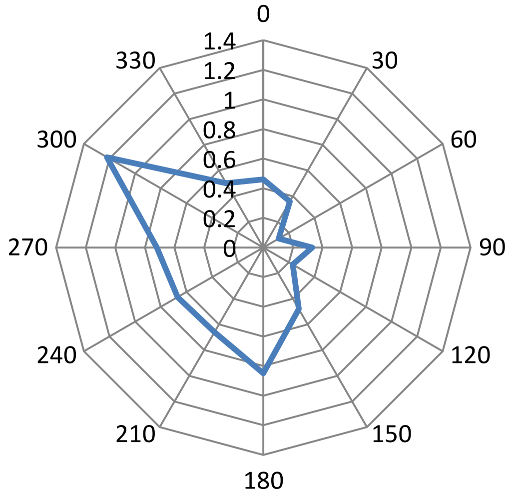


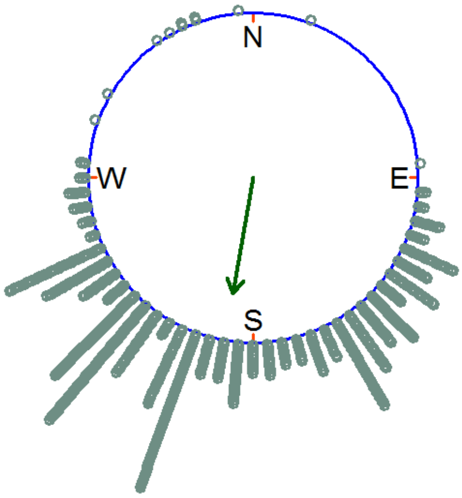
Mean wind direction = 248.1°. Vector strength = 0.747



D. 4/2/11 - 18/2/11. Total sediment collected = 6.6 g

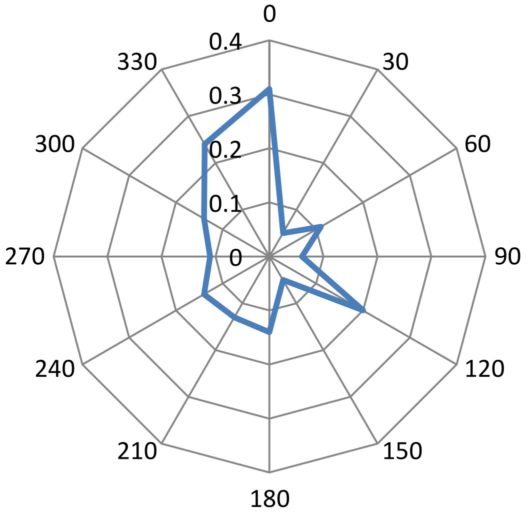
Mean wind direction = 189.9°. Vector strength = 0.711

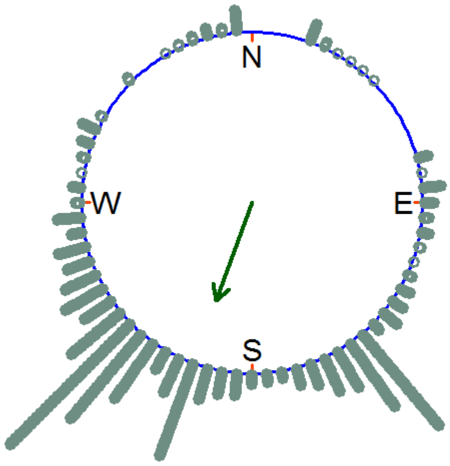




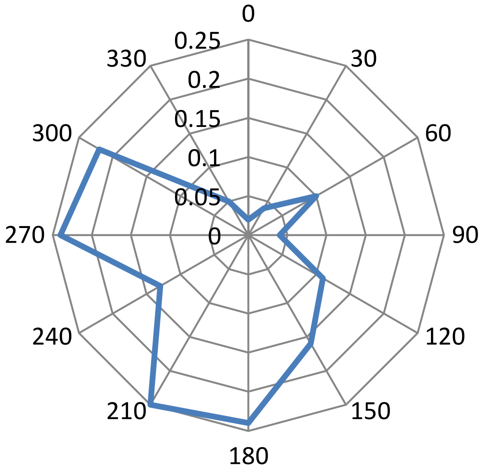
E. 18/2/11 - 9/3/11. Total sediment collected = 1.68 g

Mean wind direction = 200.4°. Vector strength = 0.609

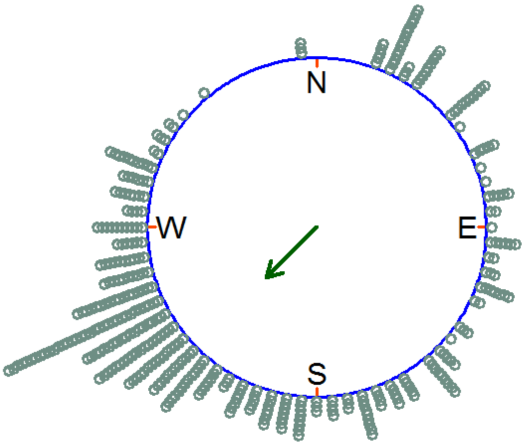




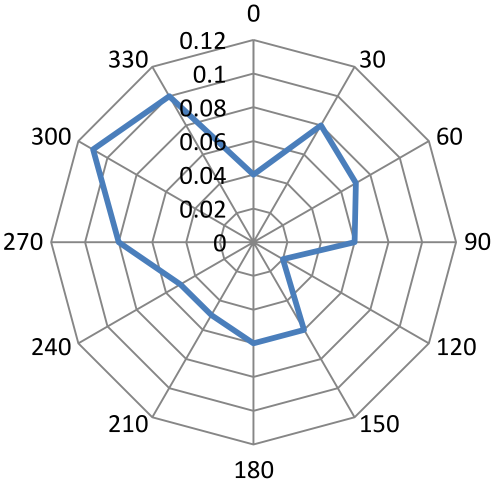
F. 9/3/11 - 18/3/11. Total sediment collected = 1.6 g



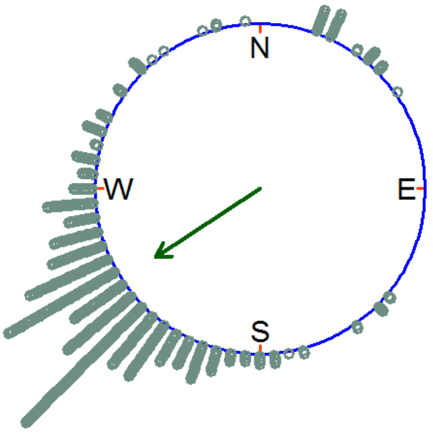
Mean wind direction = 225.3°. Vector strength = 0.420



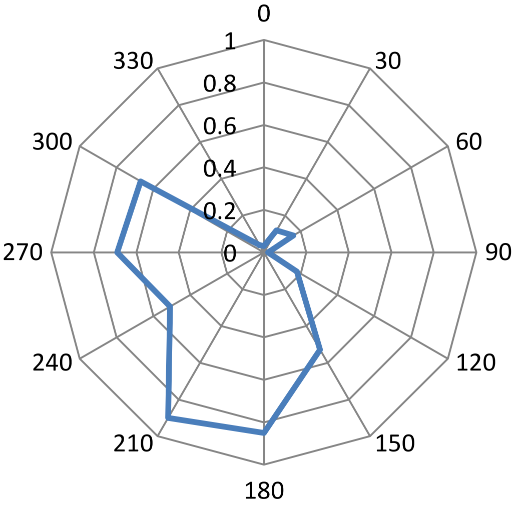
G. 18/3/11 - 29/3/11. Total sediment collected = 0.78 g



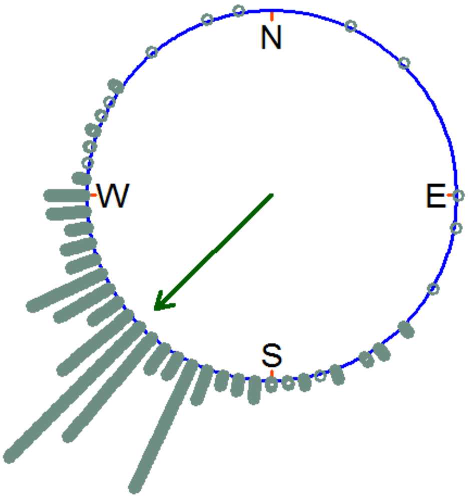
Mean wind direction = 236.8°. Vector strength = 0.756

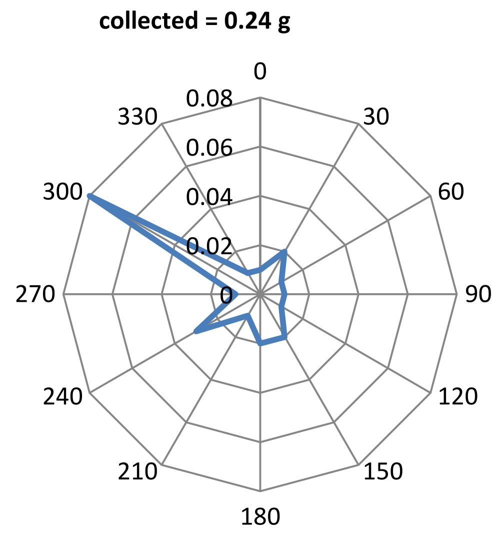


H. 29/3/11 - 12/4/11. Total sediment collected = 4.7 g



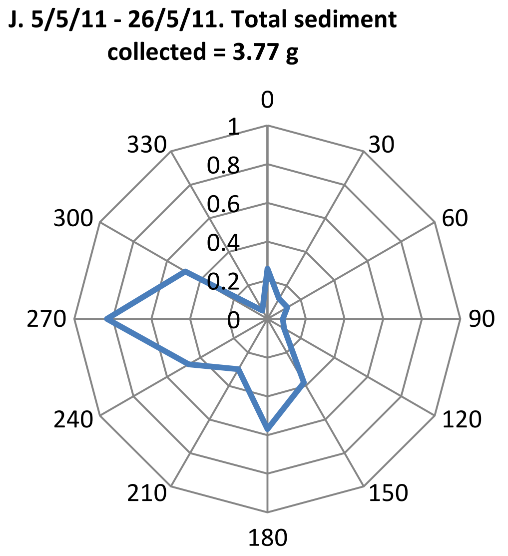
Mean wind direction = 225.5°. Vector strength = 0.876





I. 12/4/11 - 5/5/11. Total sediment collected = 0.24 g

No wind data available for period I as AWS was not collecting data.



J. 5/5/11 - 26/5/11. Total sediment collected = 3.77 g

No wind data available for period J as AWS was not collecting data.

K. 26/5/11 - 7/7/11. Total sediment collected = 0.99 g

Mean wind direction = 229.1°. Vector strength = 0.538

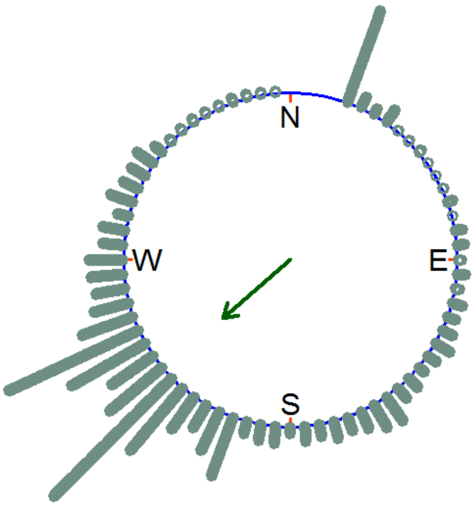


Figure 4.11: Dry mass of peat collected in the circle of tube samplers, and the wind direction from each measurement period.

Time period	Total peat collected (g)
14/10/10 – 9/11/10	2.75
9/11/10 – 19/1/11	33.04
19/1/11 – 4/2/11	6.63
4/2/11 – 18/2/11	6.60
18/2/11 – 9/3/11	1.68
9/3/11 – 18/3/11	1.60
18/3/11 – 29/3/11	0.78
29/3/11 – 12/4/11	4.7
12/4/11 – 5/5/11	0.24
5/5/11 – 26/5/11	3.77
26/5/11 – 7/7/11	0.99

Table 4.1: Total peat collected during each study period (grams) in the circle of tube samplers.

The distribution of peat collected in the tube samplers from to 9/11/10 to 19/1/11, 19/1/11 to 4/2/11, 9/3/11 to 18/3/11, 18/3/11 to 29/3/11 and 29/3/11 to 12/4/11 match the distribution of wind directions measured during those study periods. To a lesser extent the peat collected from 4/2/11 to 18/2/11 and 18/2/11 to 9/3/11 also match the wind record while the peat collected from 26/5/11 to 7/7/11 appears to follow a more random distribution than the other study periods. While there is no wind direction data available for the 14/10/10 to 9/11/10, 12/4/11 to 5/5/11 and 5/5/11 to 26/5/11 periods, the distributions of dry mass are similar to the others, with the exception of the spike at 300^{o} in the 12/4/11 to 5/5/11 data, so it is likely that these periods also match the wind direction record.

The total peat collected in the samplers facing 30^{o} (North-North-East), 240^{o} (West-South-West) and 180^{o} (South) between 9/11/10 and 19/1/11 are significantly greater than during the other time periods. This is possibly a result of processes other than wind erosion as the prolonged period of snowfall occurred during this time period. Due to the snow coverage, it is unlikely that the peat recorded in the samplers has been collected as a result of wind-driven rain detaching and blowing peat directly into the samplers. The data from 9/11/10 to 19/1/11 has therefore been removed from Figure 4.12 as the large totals for the three aspects discussed above will skew the overall data and will not allow the true identification of the effect of aeolian processes acting at Flow Moss.

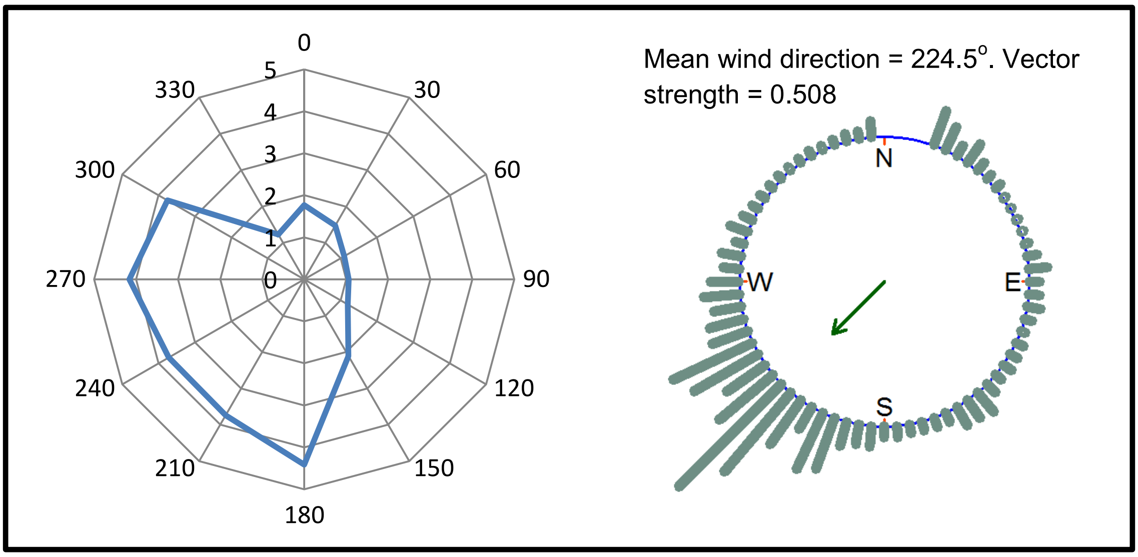
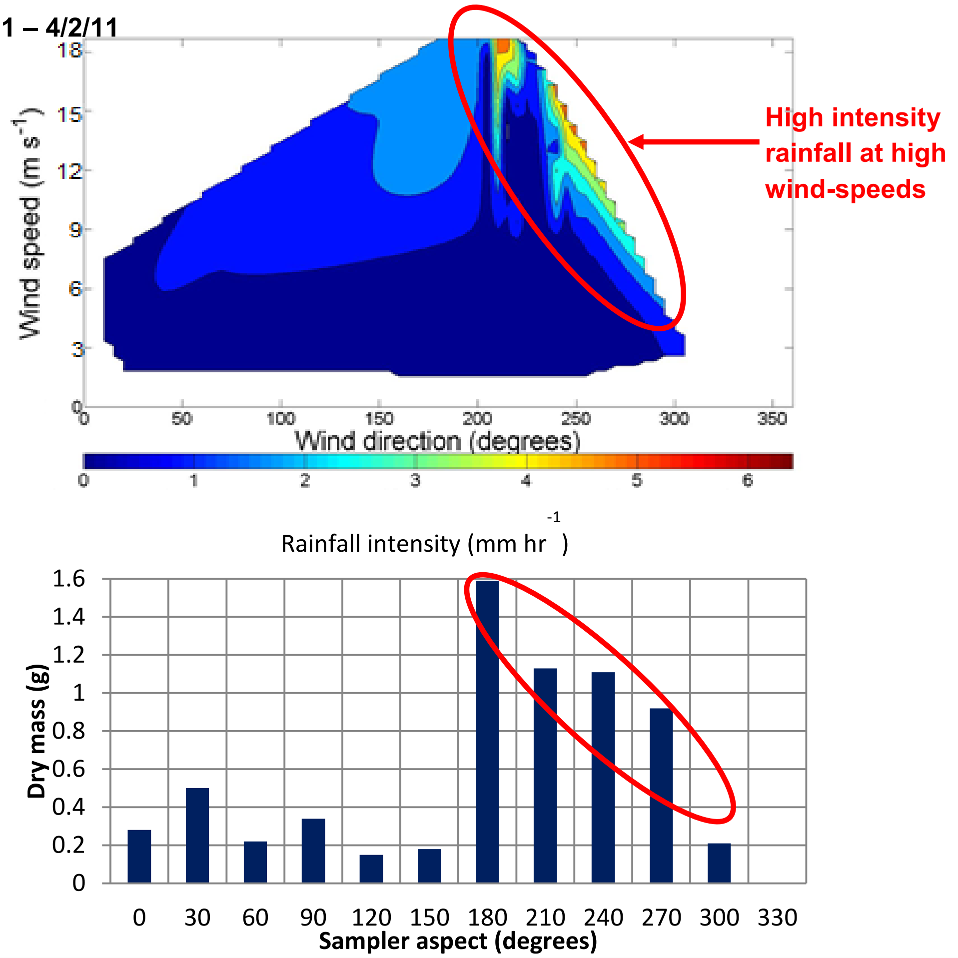


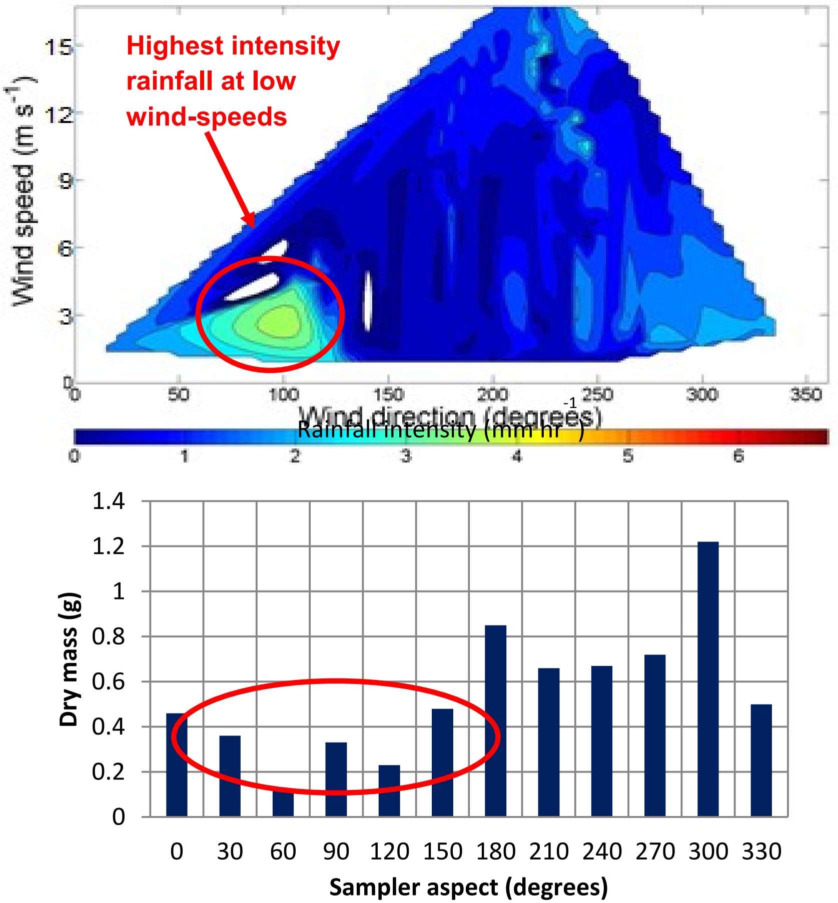
Figure 4.12: Distribution of peat collected in the wind tubes during the entire study period (excluding period B from Figure 4.10) compared to the wind direction measured by the AWS (from Figure 4.5). The distribution of sediment clearly matches the wind directions.

Figures 4.11 and 4.12 clearly identify that wind direction is an important control on the wind erosion of bare peat. However, the BSNE sampler data identifies that most of the peat is transported close to the surface as a result of peat detachment and transportation by wind-driven rain. To investigate this further, relationships between wind direction, wind-speed, rainfall intensity and peat erosion were investigated and results are presented in Figure 4.13. The results from 3 time periods (19/1/11 to 4/2/11, 4/2/11 to 18/2/11 and 9/3/11 to 18/3/11) because they occurred under different conditions and important patterns are identified from each (red circles). Rainfall intensity is plotted as contours against the wind speed and wind direction that was recorded by the AWS. The contours were drawn using a cubic interpolation.

A. 19/1/11 – 4/2/11



B. 4/2/11 – 18/2/11



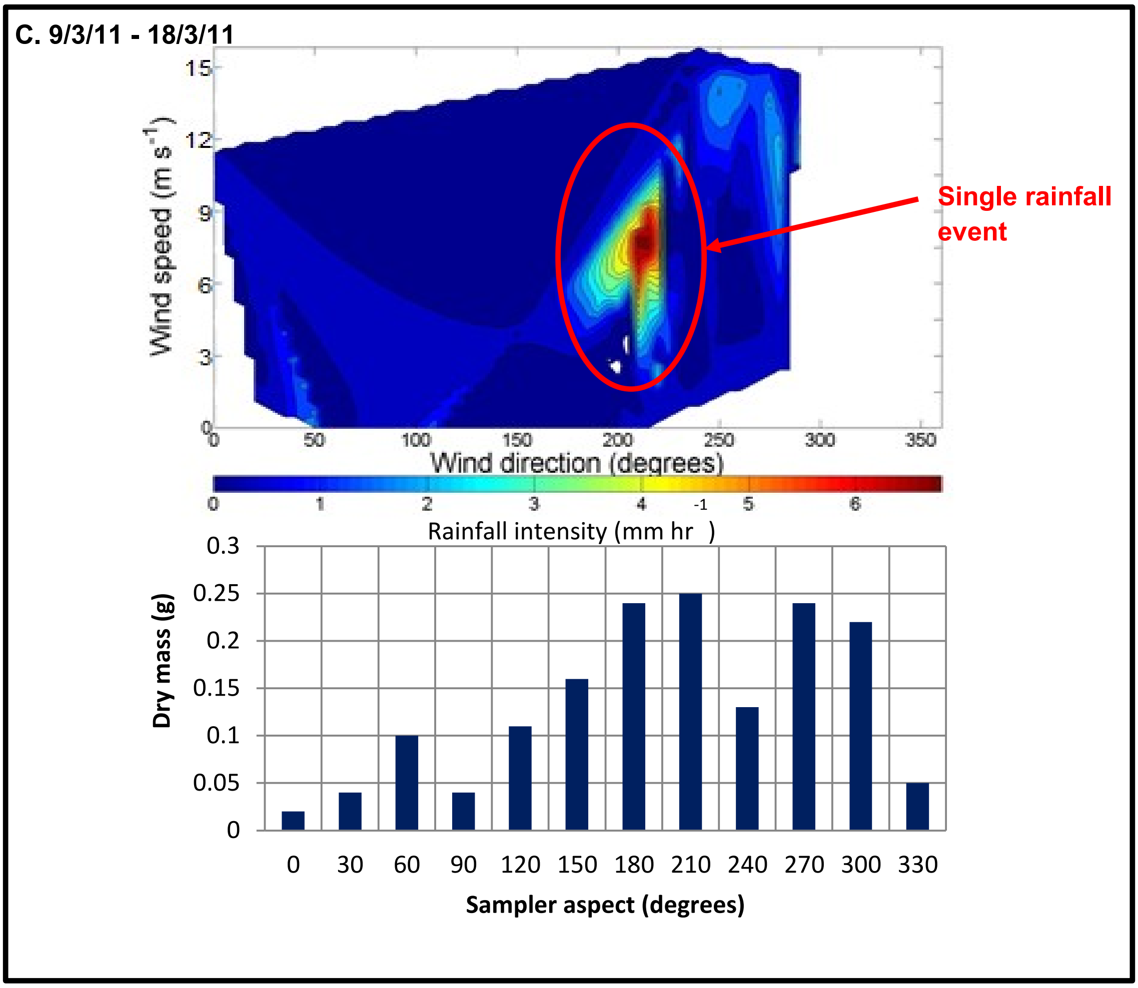


Figure 4.13: Contour plots of rainfall intensity with cubic interpolation plotted against wind direction and wind-speed. The graphs of peat dry mass are the same as in Figure 4.10 but plotted as bar charts to allow easy identification of patterns.

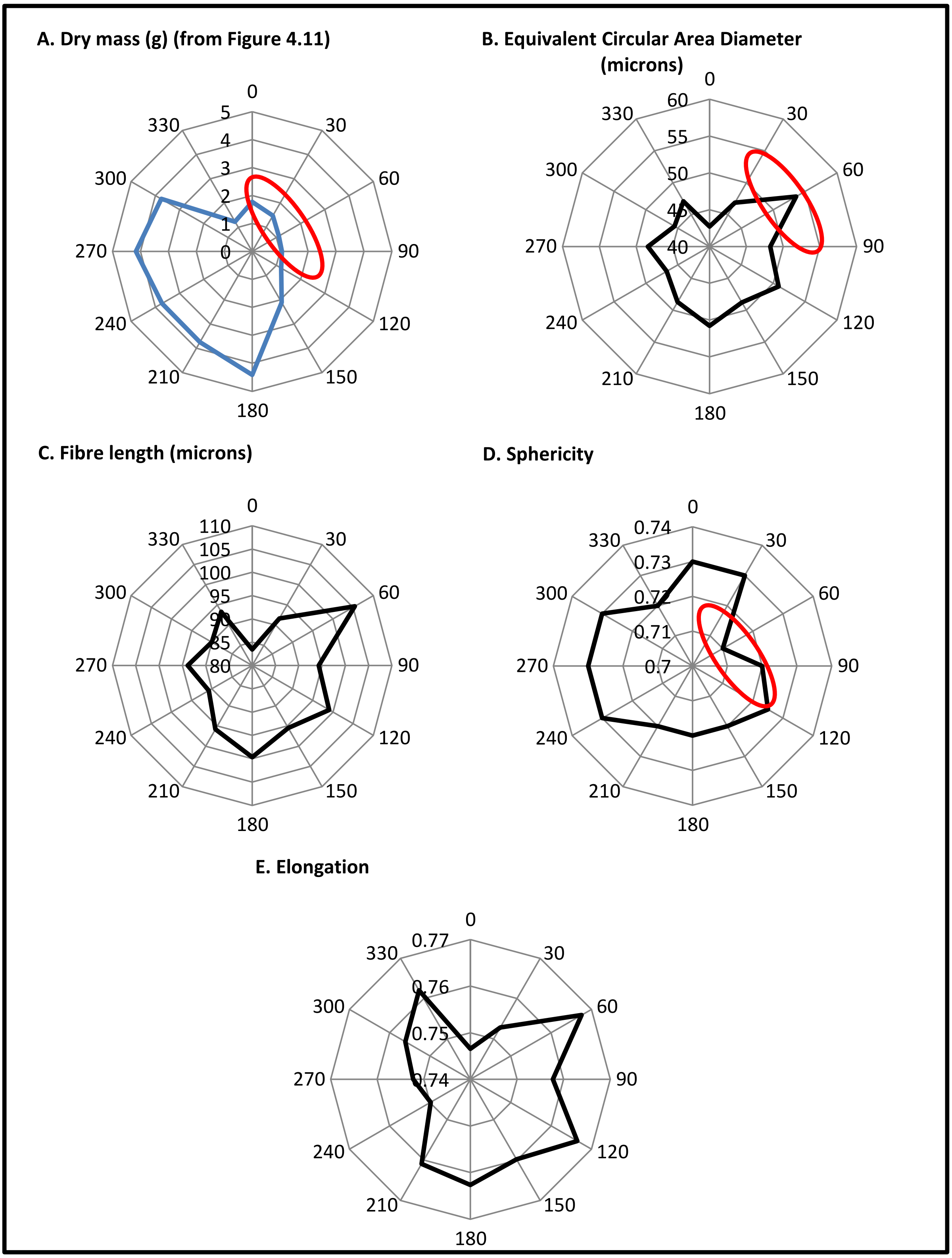
Figure 4.1 shows that there were two significant rainfall events between 9/1/11 and 4/2/11 while Figure 4.13A shows that the highest rainfall intensity during these events occurred at the high wind-speeds (> 12 m s^{-1}) and from the prevailing wind direction (South-West) (identified by a the red circle in Figure 4.13). Importantly, the amount of peat collected in the tubes during this period closely matches this pattern, with the highest amount of peat in the tube facing the direction that experienced high rainfall intensities at high wind-speeds (identified by a red circle in Figure 4.13). One of the potential erosion events identified from Figure 4.4 occurred during this period which may also be a reason why a higher mass of peat was collected during this period. The total amount of peat collected from 4/2/11 to 18/2/11 was less than between 19/1/11 to 4/2/11 because the highest rainfall intensities occurred with a low wind-speed (identified with a red circle in Figure 4.13). Therefore, while the peat may have been detached from the surface by the heavy rainfall, the transport component of the wind-splash process did not have a lot of energy thus creating lower rates of sediment transfer. The general distribution in the tubes is more varied than between 19/1/11 to 4/2/11 which matches the more varied wind direction experienced during this period (Vector strength = 0.711 for A, 0.747 for B as shown in Figure 4.11).

The time period 9/3/11 to 18/3/11 contained the potential erosion event on the 12th March (identified in Figure 4.4) which is clearly identified in the rainfall intensity contour plot. This potential erosion event was the only rainfall event to occur between 9/3/11 and 18/3/11 and as Figure 4.13F shows, the highest rainfall intensities do not correlate with the highest wind-speeds (identified with a red circle in Figure 4.13) so the amount of wind-splash erosion would be expected to be lower as the potential for erosion during the time period is lower. The potential erosion event of 3rd February had both higher winds than the potential erosion event in between 9/3/11 and 18/3/11 (Figure 4.4) which is why the total amount of peat collected in the tubes is lower in this time period.

Figures 4.11 and 4.12 clearly identify that wind-direction affects the amount of peat eroded by aeolian processes and Figure 4.13 shows that rainfall intensity and wind-speed are important controls on the process. The highest rates of erosion occur when the highest rainfall intensities combine with high-speeds and the wind-direction has implications for where the erosion will occur.

4.2.1.2 Characterisation of peat eroded by aeolian processes

To further understand the nature of aeolian erosion of bare peat requires an understanding of the size and shape of the particles being eroded. This was undertaken using the RapidVUE particle size and shape analyser (Section 3.4.1). Figure 4.14 shows graphs of Equivalent Circular Area Diameter (ECAD) and Fibre length used to investigate particle size and the Sphericity and Elongation (1-fibre width/fibre length) to investigate particle shape from peat collected in the tubes during from 4/2/11 to 18/2/11 (Figure 4.11). They are compared to the distribution of total peat collected in the tube samplers (Figure 4.12).


A. Dry mass (g) (from Figure 4.11)

B. Equivalent Circular Area Diameter (microns)

C. Fibre length (microns)

D. Sphericity

E. Elongation

Figure 4.14: A. Dry mass of peat collected in tube samplers (from Figure 4.11). **B.** Equivalent Circular Area Diameter (ECAD) of peat collected in tube sampler (microns). **C.** Fibre length (microns). **D.** Sphericity (no units). **E.** Elongation (1 – (width/length)) (no dimensions). The direction with the smallest sediment collected had the largest particles size and the least circular (red circle).

Figure 4.14 shows that the highest masses of eroded peat correspond with smaller particle sizes and the largest particles are found in the sediment traps with the lowest volume of eroded peat (Figure 4.14B&C) (identified with the red circle in Figure 4.14A&B). The largest peat particles, for example at 60°, are also the least spherical (Figure 4.14D) and the most elongate (Figure 4.14E). A possible explanation for this is that the erosion process of bare peat by wind-driven rain occurs in two phases and the suggested process is shown in the schematic diagram in Figure 4.15. During the first phase (Phase 1) of this erosion process, large loose particles present on the peat surface, generated by frost action or surface desiccation, are set in motion by ballistic raindrop impact and transported by the wind. The removal of this layer exposes the intact peat surface to raindrop impact which erodes smaller particles from the peat surface (Phase 2).

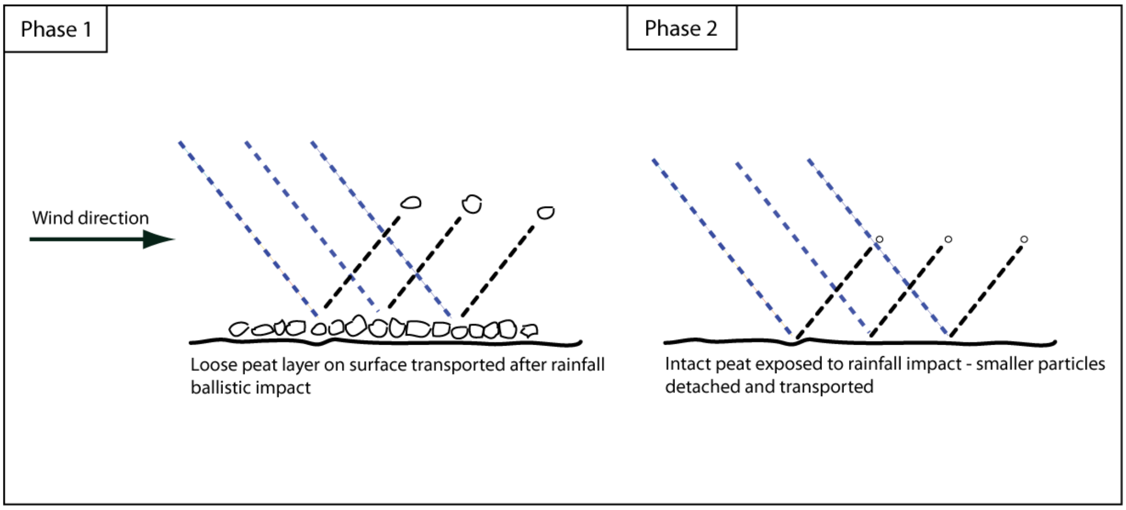


Figure 4.15: A proposed conceptual diagram showing the proposed two-phase mechanism of bare peat erosion by wind-driven rain, deduced from the particle size and shape

These two phases of erosion explain the patterns shown in Figure 4.14 as where there has been more peat collected, both phase 1 (larger particles) and phase 2 (smaller particles) erosion has occurred resulting in the average particle size being smaller (e.g. 240° in Figure 4.14). Where a smaller amount of peat has been collected, only the first phase of erosion has occurred, resulting in less particles of a larger size being present in the sediment traps (e.g. 60° in Figure 4.14).

4.2.1.3 Sediment yield from aeolian processes at Flow Moss

The sediment yield was calculated using the same method as that used in the study by Evans and Warburton (2005) for the sediment budget at Rough Sike, Moor House NNR (Section 1.7). The simple method involves scaling up the sediment collected in the tube mass flux samplers so it is representative of the whole bare peat area. Therefore an assumption is made that the processes of erosion resulting in peat collected in the samplers occur uniformly across the bare peat at Flow Moss. Warburton (2003) suggests that, under certain conditions, the sampling efficiency of the wind tubes can be as low as 70%. This value is used to generate the worst case scenario error bars for the sediment yield and mass of peat eroded.

The sediment yield from aeolian processes was calculated to be 1.84 ± 0.55 t ha^{-1} a^{-1}. The total area of bare peat at Flow Moss was found by digitising the areas of bare peat in the UAV image mosaic and was measured at 1.755 hectares. Therefore during one year, assuming that the processes occur uniformly across the bare peat surface and that the short period of study is representative of ‘annual’ conditions, approximately 3.2 ± 0.97 tonnes of peat is eroded at Flow Moss by aeolian processes.

4.2.1.4 Long term control of landform evolution at Flow Moss by the wind

Evans and Warburton (2007) found that there was a strong association between the prevailing wind direction (mean direction: 240^{o}, vector strength: 0.356) and the dominant orientation of streamlined hagg (mean direction: 240^{o}, vector strength: 0.963) at Moss Flats at Moor House. These results contradict Tufnell (1969) who stated that wind erosion has no long lasting control on the geomorphological development of landscapes. The same method as Evans and Warburton (2007) was carried out at Flow Moss to determine the orientation of the landforms at the site and was compared to the measured wind direction by the Automatic Weather Station (AWS) during the study period (Figure 4.16).

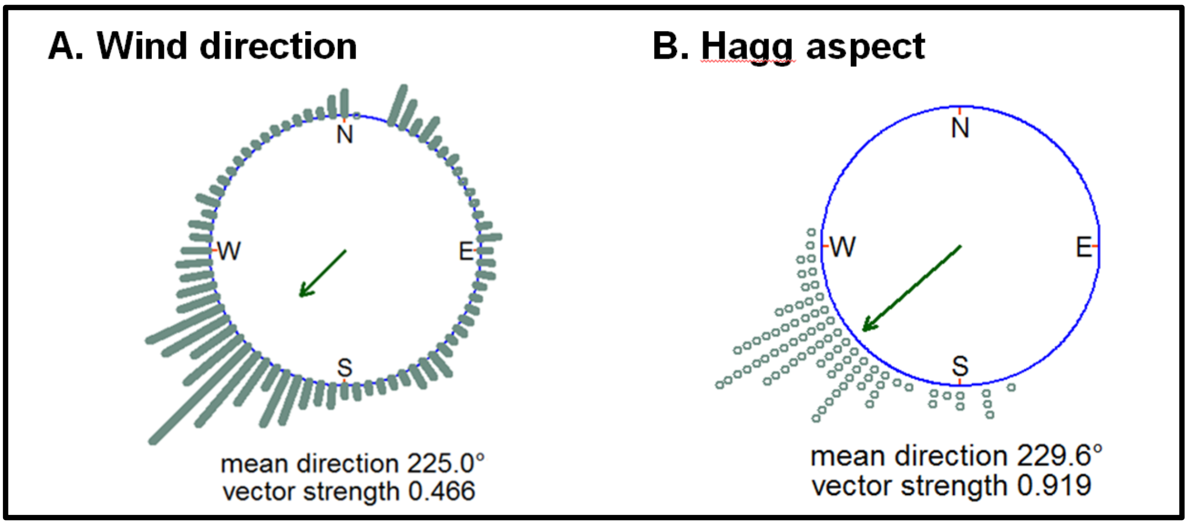


Figure 4.16: Comparison between measured wind direction and peat hagg orientation. The distributions are similar suggesting that wind direction has a long term on geomorphological development of Flow Moss.

The results from Flow Moss are very similar to those from Moss Flats and suggest that haggs on peat flats are preferentially oriented towards the prevailing wind, due to erosive power of the wind erosion process. Producing this comparison provides a useful method for identifying whether the evolution of landforms in the area is controlled by aeolian processes.

Figures 4.11 to 4.13 and 4.16 all clearly show that the climate is an important control on the nature and amount erosion of bare peat with wind direction being particularly important in the long term landscape development of the area. In the short term, the amount of erosion is controlled by a complex interaction between a range of climatic factors including rainfall intensity, wind-speed and wind direction. It is hypothesised that the relative importance of Phase 1 and Phase 2 erosion (Figure 4.15) depends on the extent of loose particles present across the peat surface. If there has been an extensive period of frost action or prolonged dry climatic conditions that causes lots of surface desiccation, there will be more loose material on the surface so Phase 1 erosion will dominate the process. If the rainfall event occurs shortly after another event there would be less opportunity for weathered material to be produced on the surface so Phase 2 erosion of smaller particles will dominate the process.

4.2.2 The spatial distribution and amount of peat removed from Flow Moss by hydraulic (fluvial) processes

4.2.2.1 Locations where peat is lost by hydraulic processes

The hydraulic transport of peat from Flow Moss was monitored using the sack traps (Section 3.1.2) installed along the boundary (fenceline) at the lower end of the site (Figure 3.6). The aim was to collect any sediment leaving the site by fluvial processes. The traps were installed on 4th November 2010 and emptied on three occasions during the study period, on the 12th April 2011 (A), 8th June 2011 (B) and 7th July 2011 (C). Figure 4.17 shows the location of the traps and the mass of material collected in each trap (during period A - 4/11/10 to 12/4/11). The marked contrast in material yield between the traps allows the identification of 'active' drainage channels where peat is lost from the site through fluvial transport (red arrows in Figure 4.17).

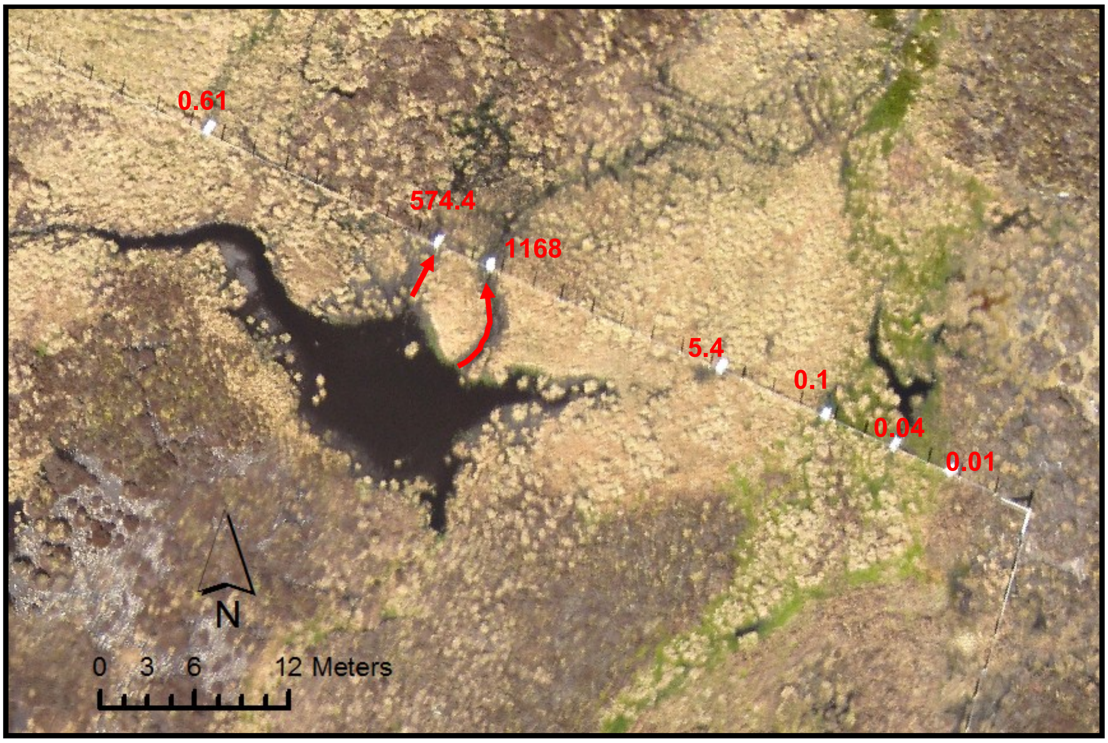
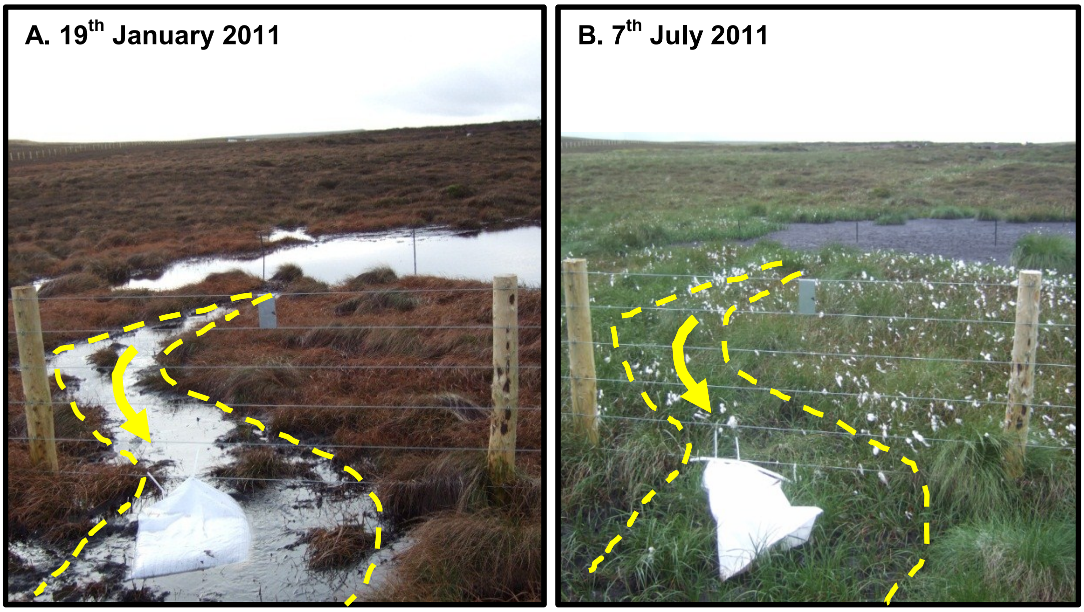


Figure 4.17: Mass of material in sack traps collected on 12th April 2011 (grams). The two main 'active' flows of peat from the depositional pool are identified in red.

The rate of peat deposition in the traps between 4/11/10 and 12/4/11 was 10.9 g day^{-1}, from 12/4/11 to 8/6/11 the rate was 1.2 g day^{-1} and between 8/6/11 and 7/7/11 the rate was 0.97 g day^{-1}. The rate from 4/11/10 to 12/4/11 is an order of magnitude higher because this was a much wetter period so the flow in the channels both into and out of the depositional pool was greater. Also, due to the sustained cold during this time period (Figure 4.2A), a lot of sediment would have been available for transport as a result of freeze-thaw weathering and this period also experienced a lot of snowmelt which would have transported loose peat from the surface into the channels and away from the site.

During the spring and summer, vegetation grew in the channels draining the depositional pool (Figure 4.18) which trapped material in the channel before it reached the traps, thus reducing the rate of peat collection. Figure 4.18A was taken on 19th January 2011 and Figure 4.18B was taken from the same location on 7th July 2011. The difference between the images is apparent as it is difficult to identify the course of the channel in Figure 4.18B due to the vegetation coverage and lower water table.


A. 19th January 2011

B. 7th July 2011

Figure 4.18: Channel draining depositional pool monitored by sack trap number 3 **A.** Photo taken on 19th January 2011 **B.** 7th July 2011. By July, vegetation has grown in the channel, trapping sediment and preventing the loss of peat from the site.

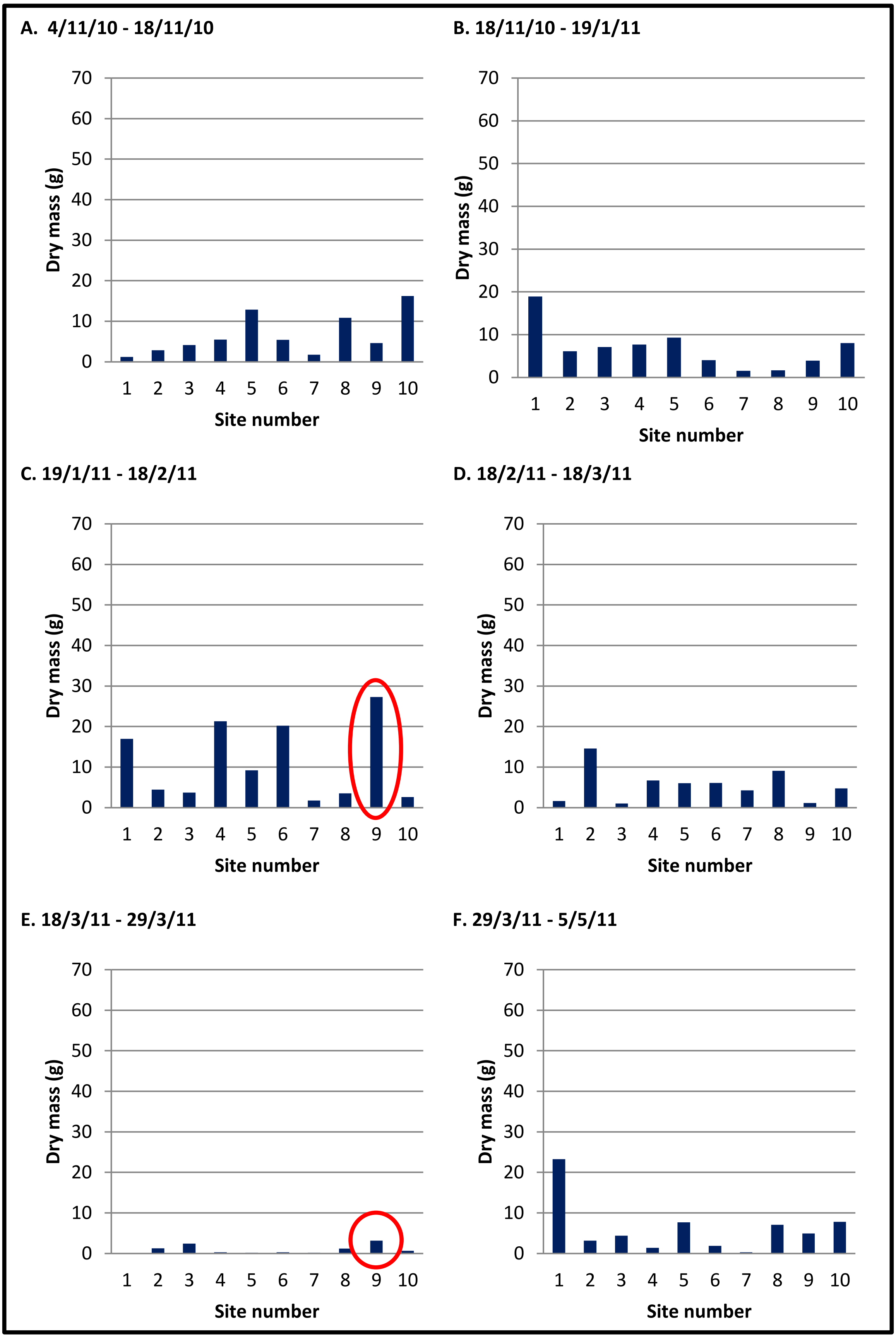
4.2.2.2 Rate of removal of peat by hydraulic processes at Flow Moss

In order to calculate the rate of removal of peat by hydraulic processes, several assumptions have been made. These include; i) the distribution of suspended peat is uniform within the channels and; ii) the peat collected in the traps is representative of the actual rate of peat transport. As discussed in section 4.2.2.1, the rate of peat loss varies throughout the year but the frequency of the monitoring means that it is not possible to fully evaluate the seasonal variability in peat transport rates. A daily average rate of peat collected in the traps was calculated using the total peat collected (1847 g) over the study period of 248 days. This provides an average rate of 7.45 g day^{-1} which corresponds to 2.72 kg a^{-1}. It is suggested that this is an underestimate of the annual yield as the study period covered a longer period of ‘dry conditions’ than ‘wet conditions’, although the annual dynamics of the process have not been fully characterised. In addition there is also likely to be a small underestimate of the yield due to the sampling efficiency of the traps. The weave of the sacks allowed water to pass through and this could also result in a loss of a small amount of fine sediment load.

The yield of 2.72 kg a^{-1} represents the rate of collection in the traps so therefore has to be scaled up to cover the all of the channels draining the site for a catchment-wide yield of peat transported by hydraulic processes. Figure 4.17 identifies the two ‘active’ channels where peat is transported from the site. The traps monitoring the other channels collected just 0.35% of the total sample during monitoring period A so the catchment yield is calculated from the two active channels. The traps in the active channels sample approximately half the maximum channel width (seen in Figure 4.18A and Figure 4.17). Assuming that this remains constant so that the traps monitor 50% of the flow from the site throughout the year and increasing the yield by 0.35% to take into account the loss from the ‘inactive’ channels, the rate of peat loss through hydraulic transport is 5.46 kg a^{-1}, approximately 500 times lower than the rate of loss by aeolian processes. This implies that while large amounts of material is actively being transferred across the bare peat surface it is not washed into the channels or, if it does reach the channels, it is deposited in pools or trapped by vegetation, before it reaches the bottom of the site.

4.2.3 The dynamics of and rate of erosion of peat hagg slopes inferred from the Gerlach troughs

The Gerlach troughs monitor the loss of peat material from the slopes of the peat haggs and the locations of the ten sites are described in section 3.1.3. Figure 4.19 shows the dry mass collected in each trough during the measurement periods.



A. 4/11/10 - 18/11/10

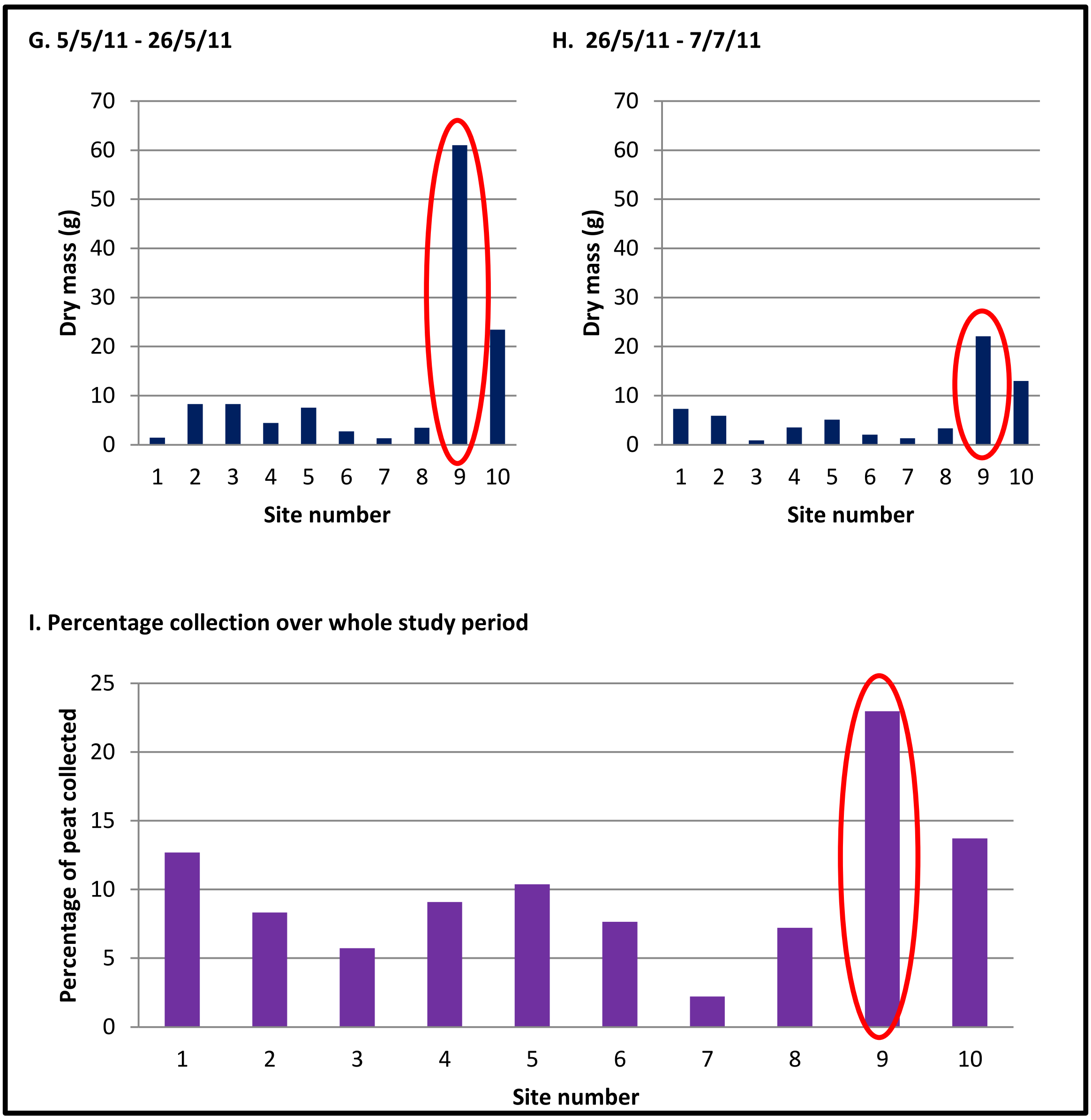
B. 18/11/10 - 19/1/11

C. 19/1/11 - 18/2/11

D. 18/2/11 - 18/3/11

E. 18/3/11 - 29/3/11

F. 29/3/11 - 5/5/11



G. 5/5/11 - 26/5/11

H. 26/5/11 - 7/7/11

I. Percentage collection over whole study period

Figure 4.19: A-H: The amount of peat collected in the Gerlach troughs during each time period. **I:** The percentage of total peat collected in each trough over the whole study period.

In half of the measurement periods; 19/1/11 to 18/2/11, 18/3/11 to 29/3/11, 5/5/11 to 26/5/11 and 26/5/11 to 7/7/11; there is a large amount of peat collected at site number 9 and this is shown in Figure 4.19I as site 9 has collected over 20% of the total peat over the whole study period. Figure 4.20 investigates the role of slope angle (A) and slope size (B) in determining the amount of peat collected in the troughs. There is no distinct relationship between either of the two variables and percentage peat collected as the Pearson correlation coefficient between the percentage of peat and slope angle is low at 0.132 (3.sf) and between slope size and percentage of peat is -0.111 (3.sf)

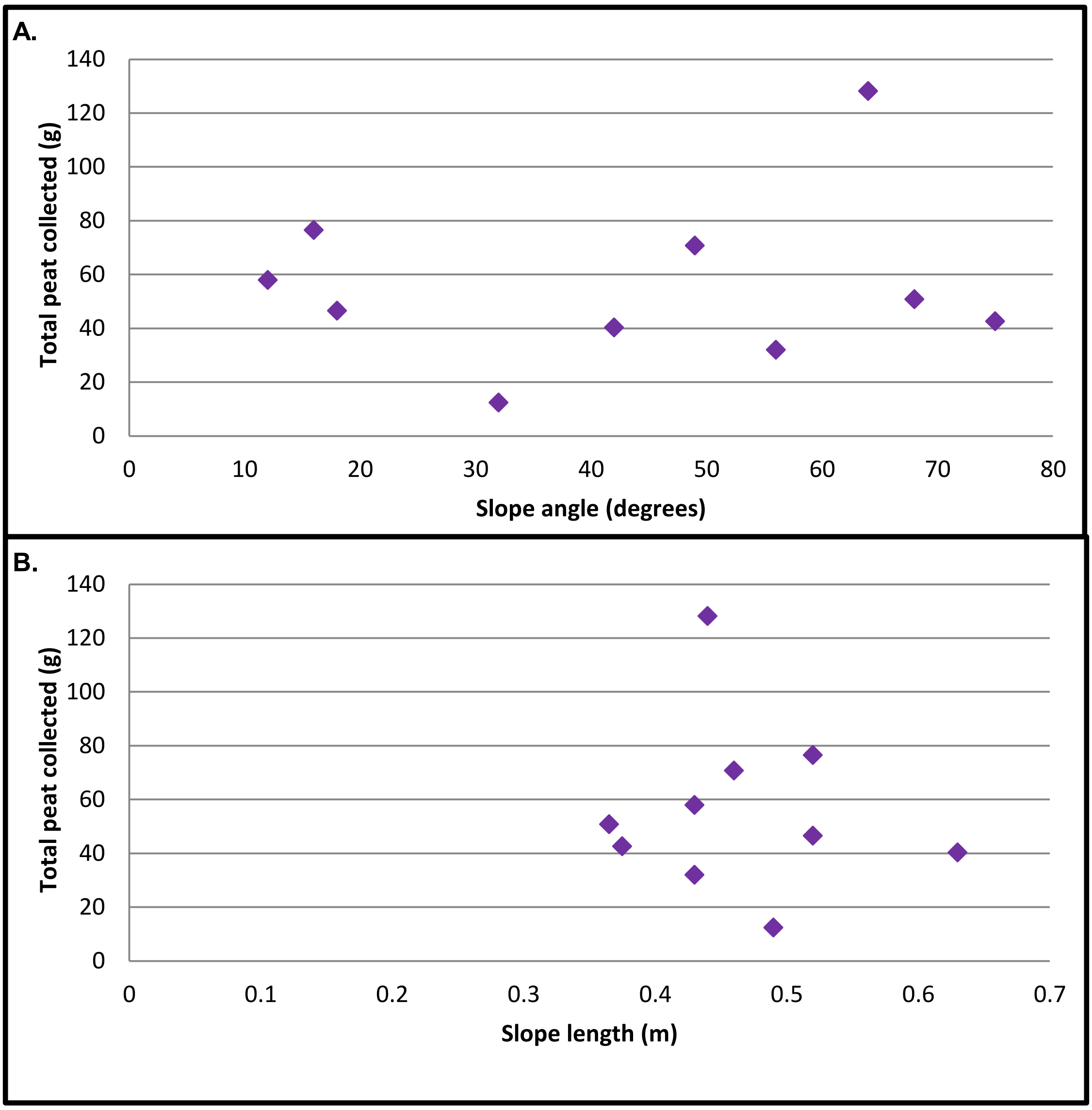


Figure 4.20: Relationships between total peat collected in the Gerlach troughs and the features of the slope they monitor. **A.** Slope angle (Pearson correlation coefficient = 0.132) **B.** Slope length (Pearson correlation coefficient = 0.111).

The lack of a relationship between either variable suggests that there is no simple process that transfers peat into the Gerlach troughs and it is probably a result of a more complex diffusive transport mechanism including gravitational processes, particle saltation and local wind. Under certain conditions, peat will move upslope. If the wind is the control, it could be possible that smaller slopes could produce more sediment if they are exposed to a gust or are oriented directly in the vector direction of the wind-driven rain. Given the variability in the wind-direction exemplified in section 4.2.1, peat slopes orientated into the prevailing wind may have a different yield from those facing in other directions. This is also noticed qualitatively through analysis of the form of peat haggs as they are stream-lined towards the prevailing wind direction. Trough number 9 faces South-West and is one of the sites most exposed to the wind and rain which is possibly why it contributes the most to peat transfer from slopes. Figure 4.21 plots slope aspect against the total peat collected and, again, fails to identify a clear pattern between the amount of peat collected in the Gerlach troughs and an environmental variable.

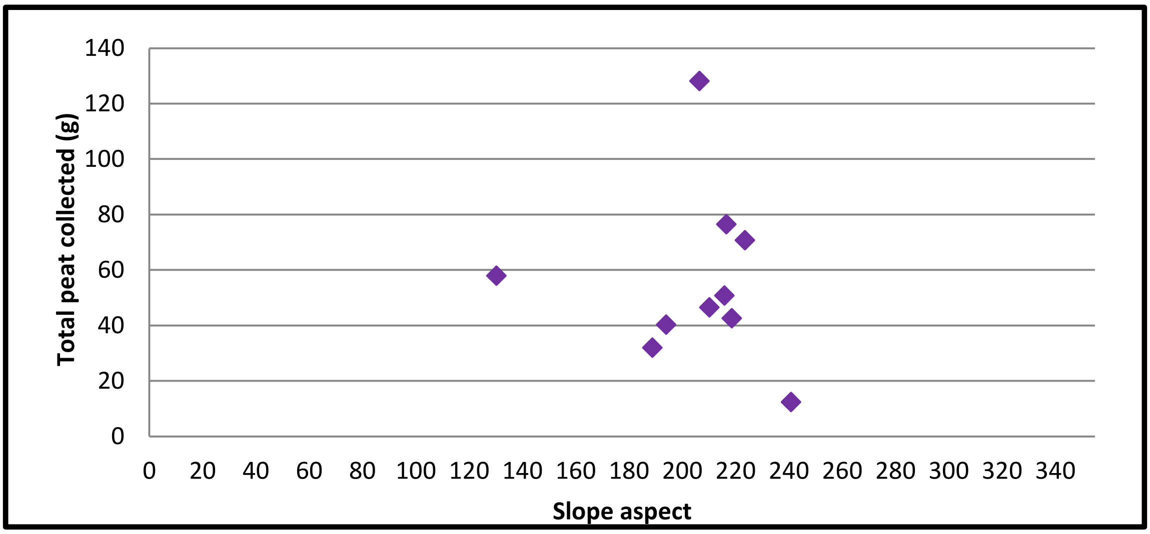


Figure 4.21: Total peat collected in the Gerlach trough plotted against slope aspect. There does not appear to be a clear relationship other than the highest rate is collected in a trough facing South-West, towards the prevailing wind (Figure 4.5). Pearson correlation coefficient = -0.0960

The four periods that collected the most peat were from 19/1/11 to 18/2/11, 29/3/11 to 5/5/11, 5/5/11 to 26/5/11 and 26/5/11 to 7/7/11, which also suggests that it may be processes other than hydraulic action on the slopes that causes the sediment transfer. With the exception of from 19/1/11 to 18/2/11, the other periods all occurred during dry conditions which led to the drying out and desiccation of the peat surface. Figure 4.22 shows a photograph taken on 5th May 2011 of one of the peat hagg slopes close to trough site 4. The surface of the peat is very light in colour because of the dryness and has cracked into loose sections approximately 4 mm thick. The cracked surface is extremely susceptible to wind erosion and can easily be transferred down the slope, leading to high sediment yields during these dry periods (Figure 4.19).

Figure 4.22: A peat hagg slope during dry conditions. The section of peat surface being held is approximately 4 mm thick. Photo taken on 5th May 2011.

Assuming that the 10 Gerlach trough sites are representative of all the exposed slopes at Flow Moss, it is possible to calculate the amount of peat transferred from all the hagg slopes, using a similar method to the aeolian processes in section 4.2.1.2. The yield from the peat hagg slopes is 3.55 t ha^{-1} a^{-1}. The length of peat hagg slopes was digitised using the UAV image and the area of exposed slopes at Flow Moss was calculated to be 2040 m^2 by multiplying the length of haggs from the average slope length of the 10 monitored sites. Using this slope area, the total mass of peat lost from hagg slopes at Flow Moss during one year is 0.72 tonnes. The error in these calculations is not fully quantifiable but several possible factors could lead to error and these include; the efficiency of the traps in collecting all of the sediment transported down the slope and; losses of sediment during the trap emptying process. Therefore values for catchment sediment yield are likely to be underestimated using the Gerlach trough data alone.

4.3 Quantified changes in the surfaces of peat hagg slopes and bare peat flats

Variability in the peat surfaces was measured using erosion pins (Section 3.2.1) and transects of poles across the bare peat (Section 3.2.2). The following section presents the results from these methods.

4.3.1 The erosion rates and processes acting on peat hagg slopes

4.3.1.1 The processes acting to erode peat hagg slopes

At each Gerlach trough site, eight erosion pins were inserted in a cross pattern to measure the variability of slope surface changes across the 0.5 m width section of monitored slope (Section 3.2.1). Figure 4.23 shows the mean erosion pin exposure change over the whole study period at all of the sites with the standard deviation plotted as error bars.

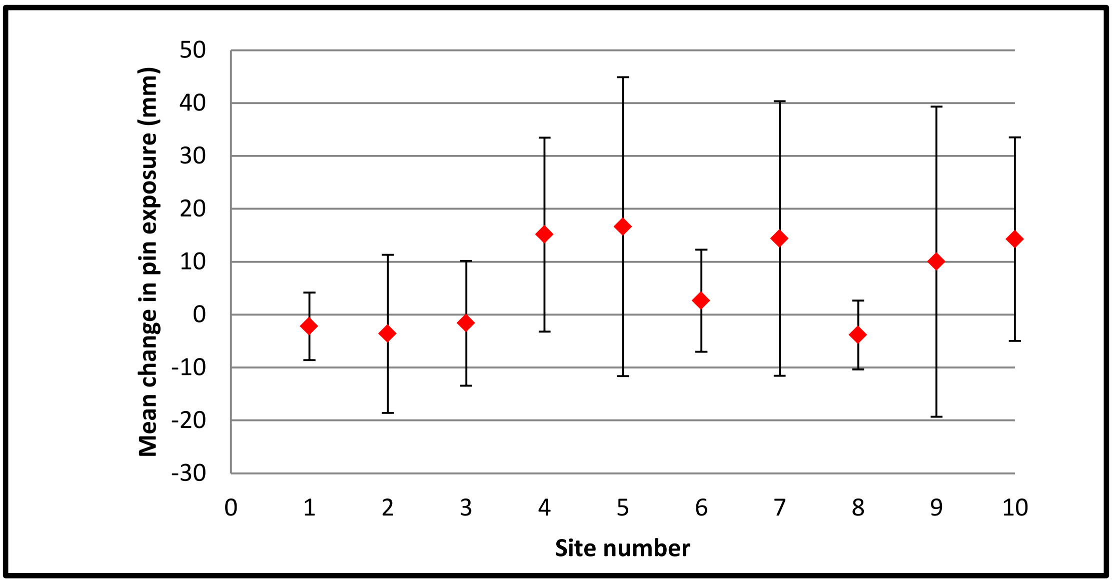


Figure 4.23: Mean exposure change at the erosion pin sites over the whole study period. Error bars are plotted using the standard deviation. Positive values represent erosion.

The erosion pins were positioned in the slopes monitored by the Gerlach trough measurements and Figure 4.24 shows a comparison between mean erosion pin exposure change and total peat collected in the corresponding Gerlach troughs. There does not appear to be a clear trend between the two datasets (pearson correlation coefficient of 0.17) which may be the result of the large error bars associated with the erosion pin exposure measurements. Possible reasons for the large errors in the pin measurements are possibly due to the short length of time after pin installation and are discussed further in Section 4.3.1.2.

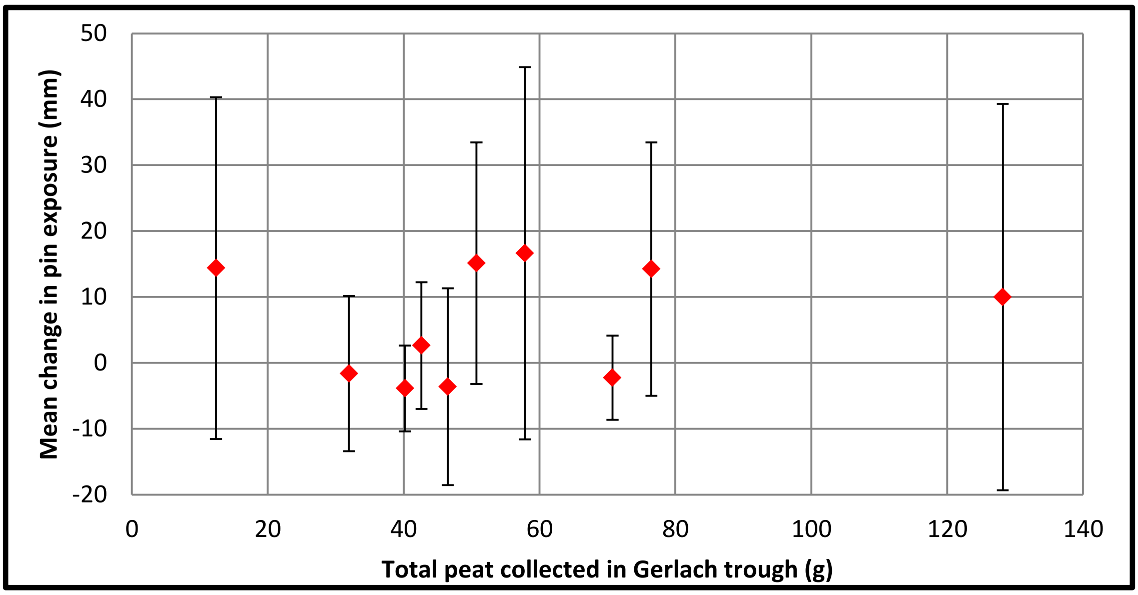


Figure 4.24: Comparison between mean exposure change in erosion pins and the total peat collected in the Gerlach troughs. Pearson correlation coefficient = 0.17. Positive values represent erosion

Analysis of the variability in the erosion pin exposures allows the nature of the erosion processes to be inferred. If there is a clear pattern of more erosion at the bottom of the slope than at the top it is likely that the erosion is being caused by surface wash acting uniformly across the slope. If the pattern is more random and has, for example, horizontal variability between pin exposures, the erosion is more likely to be diffusive; as a result of wind erosion or the impact of individual raindrops.

Figure 4.25 shows the spatial variability in the erosion pin measurements at each site across the whole study period and Figure 4.26 shows a selection of erosion pin exposure changes from some of the sites during specific time periods. Due to the lack of a consistent pattern in the erosion pin exposures, it can be concluded that surface wash is not the only process controlling the downslope movement of peat on hagg surfaces. The random pattern suggests that diffusive processes such as saltation by wind-driven rain or, during dry conditions, the removal of dry peat dust by high wind-speeds cause the erosion of peat from the slopes.

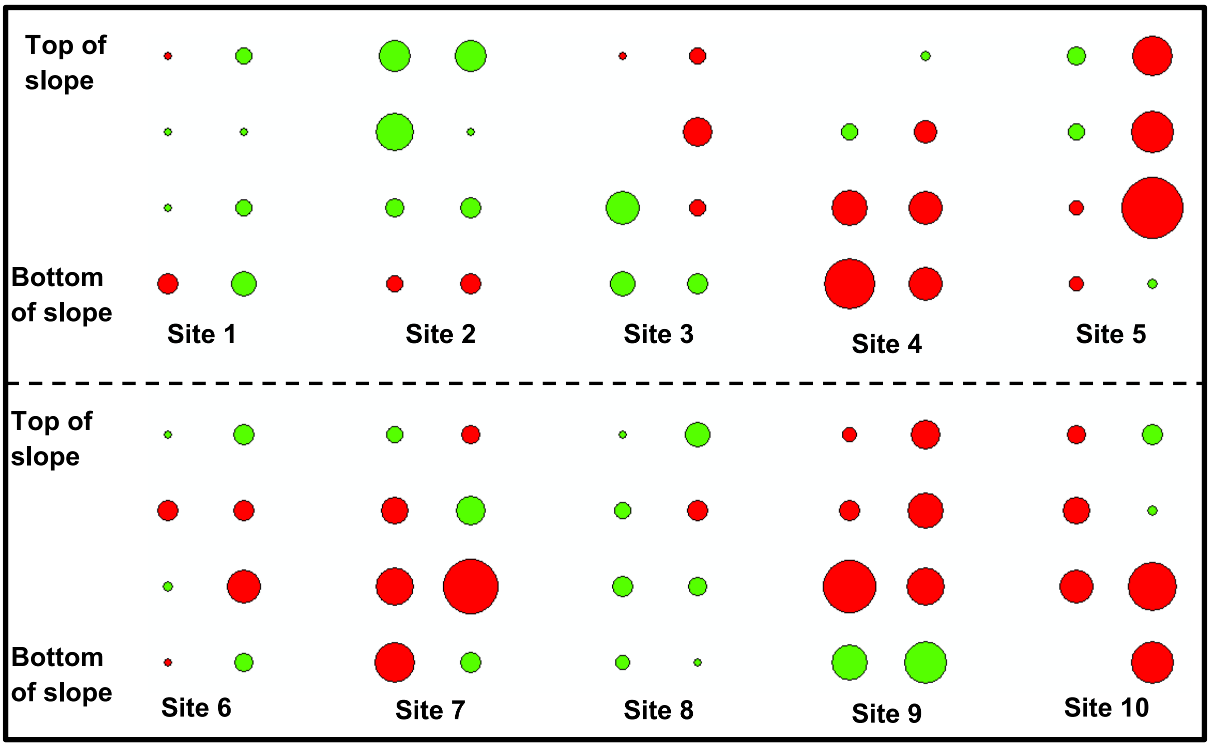
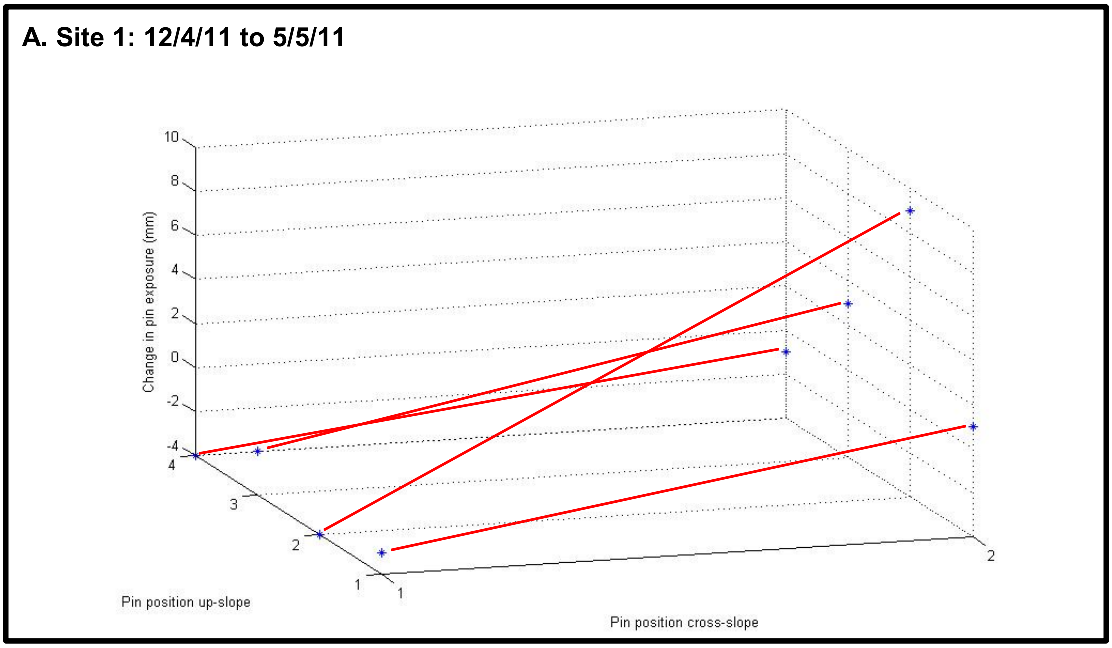
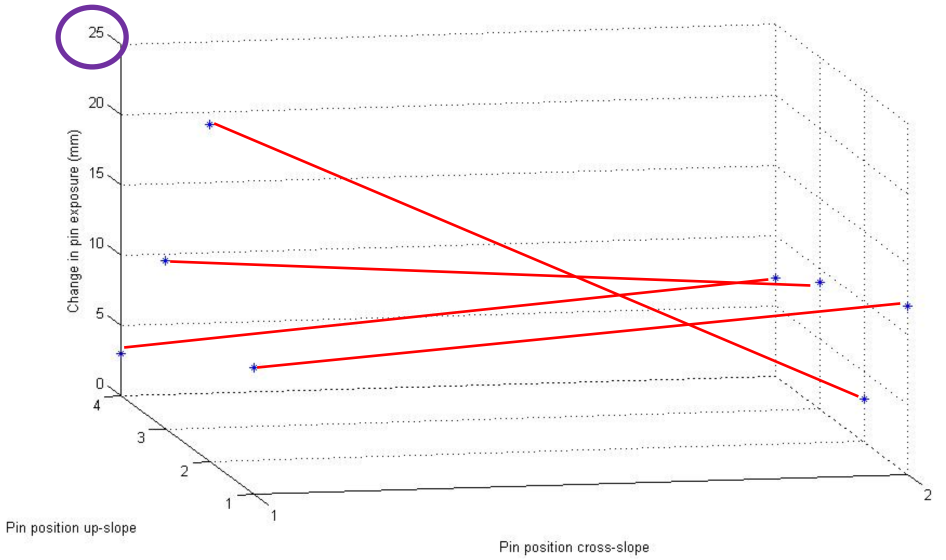


Figure 4.25: Spatial variability in erosion pin exposure change at each site across the whole study period. The green points indicate deposition (decreases in erosion pin exposure) and red points indicate erosion (increases in erosion pin exposure). The points at Site 3, 5 and 10 where there is no data are pins that have not recorded any change. Point size is proportional to amount of change in exposure.

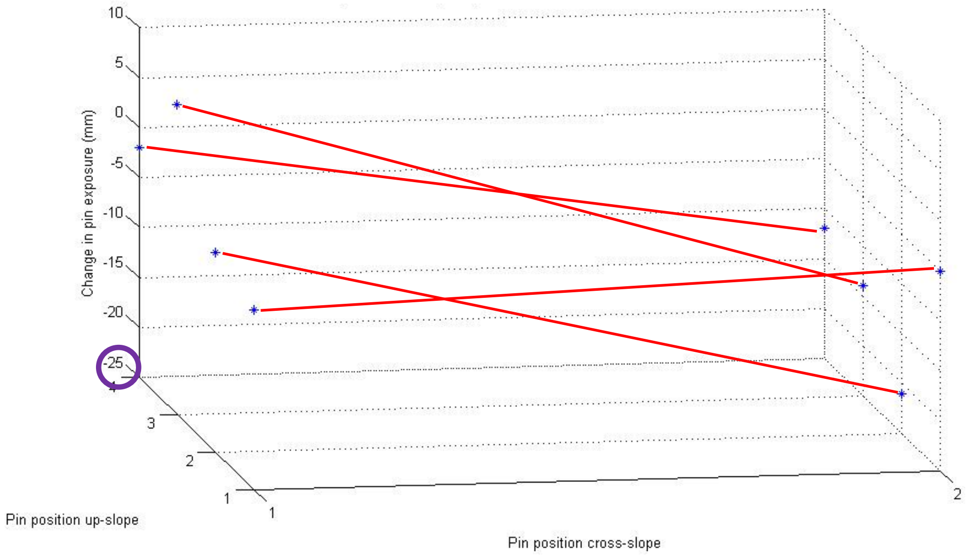


A. Site 1: 12/4/11 to 5/5/11

B. Site 3: 29/3/11 to 12/4/11



C. Site 5: 18/11/10 to 19/1/11



D. Site 8: 5/5/11 to 26/5/11

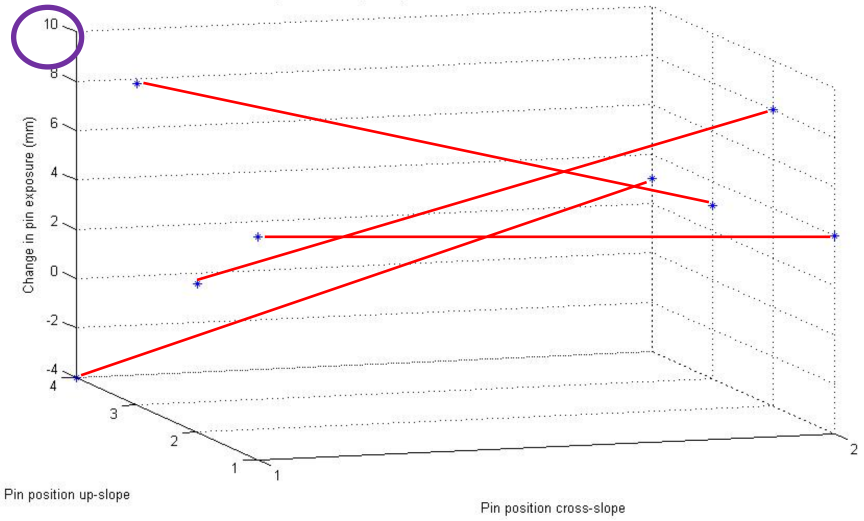


Figure 4.26: 4 sets of erosion pin exposure measurements. The red lines join pins on the same horizontal level, to aid the identification of patterns. Positive values of exposure change indicate erosion while negative values are deposition. The size of the monitored slope is approximately 0.5 m by 1 m.

Figure 4.26B & D contain some pin exposure change measurements that are very large. There are two possible causes for this; the environmental conditions caused a lot of erosion during these periods or they are a result of measurement error. The results in Figure 4.26B (Site 3, 29/3/11 to 12/4/11) and Figure 4.26D (Site 8, 5/5/11 to 26/5/11) both occurred when the environmental conditions were dry which can lead to surface drying and cracking as shown previously in Figure 4.22. Therefore it is possible that these large measurements of erosion are accurate. The result shown in Figure 4.26C (Site 5, 18/11/10 to 19/1/11) suggests that a large amount of deposition occurred as some of the results are highly negative. During period C (Site 5, 18/11/10 to 19/1/11), the site experienced heavy snowfall which may have affected the pins due to freeze-thaw heaving during this period (Evans and Warburton, 2005). It is also possible that the sites were disturbed during the restoration process. The spreading of the heather brash by the machine (Figure 2.1) occurred during this measurement period and while attempts were made to limit the impact on the monitoring equipment, some of the erosion pin and Gerlach trough sites were disturbed during this process. Therefore some of the exposure changes should be treated with caution during this period. Additionally the human measurement error was quantified by repeat measurements at ± 2 mm. Possible causes of this error are differences in judging where to measure the top of the slope surface as the brash layer covered the peat by up to 2 mm in some cases. Although this error is relatively large compared to the measurements of pin exposure change, it is unlikely to alter the random pattern of the data so it can be concluded that complex diffusive erosional processes are at work on the peat hagg slopes. Over a longer period of monitoring, different patterns may be observed

4.3.1.2 The erosion rate of peat hagg slopes inferred from the erosion pins

In the study of Rough Sike, Evans and Warburton (2005) used the erosion pin exposure changes to calculate the erosion of gully walls and to scale up the monitoring sites so a sediment yield for the whole catchment could be quantified. A similar method for the erosion pins is used here although an important factor to note is the use of negative pin exposure values in the calculations. Couper *et al.* (2002) discuss the correct use of negative erosion pin measurements, either the assumption that they indicate local deposition or that they are considered local error. Evans and Warburton (2005) treat the negative pin values as random error as the downslope flux of weathered material is assumed to be constant across the face. This is possible because they measured the pin exposures on five occasions over four years whereas this study has nine measurements over a study period of eight months.

Table 4.2 compares the surface retreat rate inferred from the erosion pins at Flow Moss to previous studies listed in ascending order. The results from this study are at the lower end of the range but are a similar order of magnitude to the other studies. It is to be expected that the average retreat, when including negative values, is lower than others as measurements of local deposition are also taken into account. As this study is relatively short compared to the others and was undertaken on hagg faces rather than gully walls, where erosion rates are expected to be higher due to fluvial action, care should be taken when comparing the results to other locations such as the actively eroding South Pennines.

Location	Context	Period (years)	Surface retreat rate (mm a^{-1})	Source
Flow Moss, North Pennines	**Hagg faces (including negative values)**	**0.67**	**1.03**	**This study**
Snake Pass, South Pennines	Peat margin	1	5.4	Philips *et al.,* 1981
Flow Moss, North Pennines	**Hagg faces (excluding negative values)**	**0.67**	**7.34**	**This study**
Snake Pass, South Pennines	Gully walls	1	7.8	Philips *et al.*, 1981
Doctors Gate, South Pennines	Low angled eroded face	2	9.6	Tallis and Yalden, 1983
Shetland Islands	Summit peat	5	10 - 40	Birnie, 1993
Moor House, North Pennines	Gully walls	1	10.5	Philips *et al.,* 1981
Harrop Moss, Pennines	Bare peat surface	7	13.2	Anderson *et al.,* 1997
Upper North Grain, South Pennines	Gully walls	3	14	Unpublished data
Plynlimon, Wales	Peat faces	2	16	Francis, 1990
Cabin Clough, South Pennines	Low angled eroded face	2	18.5	Tallis and Yalden, 1983
South Pennines	Low angled flats	1	18.4 – 24.2	Anderson, 1986
Moor House, North Pennines	Gully walls	4	19.3	Evans and Warburton, 2005
Mid-Wales	Ditch walls	1.4	23.4	Francis and Taylor, 1989
Holme Moss, South Pennines	Low angled peat margin	2	33.5	Tallis and Yalden, 1983
North York Moors	Low angled bare peat surfaces	2	40.9	Imeson, 1974
Macquarie Island, Tasmania	Low angled peat surface	3.3	43	Selkirk and Saffigna, 1999
Holme Moss, South Pennines	Peat Margin	1	73.8	Philips *et al.,* 1981

Table 4.2: Comparison of surface retreat rates using erosion pins in ascending order. Values from this study are highlighted in bold. Many of the studies have been previously listed in Table 1.2. The rate of erosion at Flow Moss is lower than most of the previous studies. *Adapted from Evans and Warburton (2007).*

Over the course of the whole study period at Rough Sike, only 0.3% of the erosion pin measurements were negative but during the first year of study 40% of measurements were negative (Evans and Warburton, 2005). This value is very similar to results from the Flow Moss erosion pin measurements as during the first 8 months since installation 39.7% of the measurements are negative. A possible explanation for these initial negative values is due to the time required for the pins to ‘settle’ into the slope surface. The initial disturbance of the peat caused by pin insertion may create sub-surface cracks that are makes the monitoring areas more responsive to freeze-thaw weathering and desiccation. This increased movement of the slope surface is likely to be the cause of the negative values. It is expected that the proportion of these negative values will decrease in the future but for this study the negative values are important in determining the amount of peat lost from slope surfaces. Therefore the calculations of sediment yield from the erosion pin data is presented twice, once using all of the pin measurements both positive and negative and once with the negative values ignored to be consistent with the Evans and Warburton (2005) Rough Sike study.

The measurements of slope change are multiplied by the area of the monitored slopes to get the volume of peat lost (assuming the process occurs uniformly across the surface) and then is scaled up using the total area of exposed slopes in the study area digitised using the UAV image. This volume of peat is converted to mass by multiplying by the density of peat (value used is 100 kg m^{-3} to be consistent with Evans and Warburton, 2005). When the negative values of pin exposure change are included, the sediment yield is 8.42 ± 2.97 t ha^{-1} a^{-1}. If the negative values are considered as random error, the yield is 24.1 ± 2.97 t ha^{-1} a^{-1}. The sediment yield when the negative values are included is approximately twice the sediment yield calculated by the Gerlach troughs which implies that a significant amount of peat that is lost from the slopes does not reach the troughs. Possible mechanisms for this are through peat wastage by the oxidation of peat and by the wind removing material from the peat surface. If all of the difference between the troughs and the pins is assumed to be as a result of oxidation and using the error bars from the erosion pin data, oxidation makes up 35% to 69% of the peat lost from the hagg faces. Values for the significance of oxidation are similar to previous studies with peat wastage calculated to be 30% at Rough Sike (Evans and Warburton, 2005) and 46% at Upper North Grain (Evans *et al.*, 2006). However, as discussed above, the erosion pins are still ‘settling’ into the slope surfaces during this course of this study so the results should be treated with some caution.

4.3.2 Surface changes across bare peat surfaces

4.3.2.1 The dynamics of deposition in the peat pool

The different sediment yields discussed in sections 4.2.1.2 and 4.2.2.2 suggest that there is a large difference between the sediment production on the bare peat areas and the rate of sediment loss from the site in the exit channels. While some of this sediment remains on the bare peat or is entrained by the wind, the rest enters the channel system but does not reach the boundary of the site. This peat must, therefore, be deposited somewhere in the catchment and the most likely place is in vegetation or depositional pools. A photograph taken on 25th February 2011 clearly shows deposition of peat within the pool located at the boundary of the site which was monitored using transects of poles (Figure 4.27).

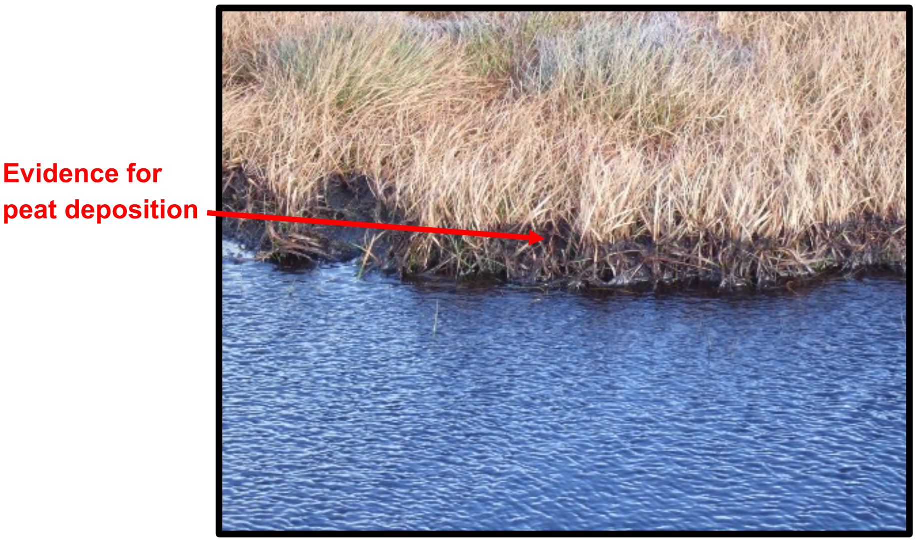


Figure 4.27: Photo taken on 25th February 2011 showing clear evidence for deposition of peat within the pool located at the boundary of Flow Moss.

It can be seen in Figure 2.1 that there is one pool at the lower boundary of the site into which all of the active drainage channels feed into. Analysis of the pole transects (Section 3.2.2) located across this pool shows that the average deposition during the study period was 11.6 ± 6.4 mm, which assuming a constant rate corresponds to 15.9 ± 6.4 mm a^{-1}. The human error was quantified using repeat measurements and found to be 6.4 mm. Variability in deposition and the consistency of the peat around the poles made repeat measurements very difficult. Using the UAV image, the area of the monitored pool is 114 m^2 so the volume of peat deposited in the pool over one year would be 1.813 ± 0.73 m^3, assuming that the rate of deposition measured during the study period is uniform over the course of the year.

The total area of pools within the Flow Moss restoration area is 471 m^2 so in order to calculate the total volume of material deposited in all of the pools, the rate of deposition in the monitored pool needs to be scaled up by 4.13; giving 7.49 ± 3.01 m^3 a^{-1} which is a dry mass of 0.749 ± 0.3 t a^{-1} assuming a density of 0.1 t m^{-3}. Additional, but unquantifiable, error arises from the digitisation of the pools using the UAV image. The UAV was flown in April 2011 during dry conditions and it was observed that the pools were larger during the winter months so the calculations of pool area, and thus mass of peat deposited, may be underestimated.

Figure 4.28 shows the variation in pole exposure over the whole study period and it shows that the largest amount of deposition occurs at the edges of the pool while some erosion occurred in the centre. The pole nearest the drainage channel recorded one of the highest rates of deposition because during the spring and summer the drainage channels become vegetated and less peat is lost from the channel (Figure 4.18).

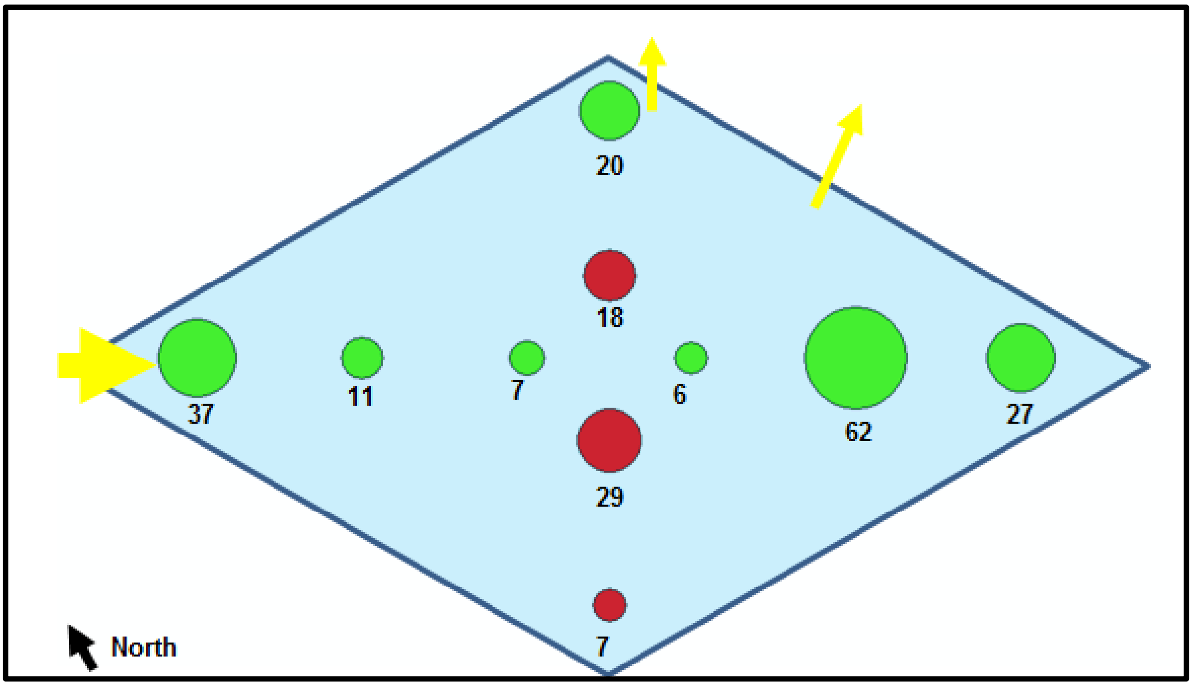


Figure 4.28: Conceptual aerial view of the depositional pool showing proportional variations in deposition (green) and erosion (red) monitored by the pole transects The yellow arrows indicate the in-flow and out-flows from the pool. Error is ± 6.4 mm. Depositions occurred at the edges of the pool, with some apparent erosion in the centre.

Figure 4.29 shows the temporal variability in the heights of the poles in the South-West to North-East transect. The poles are labelled 1 to 4 with pole no. 1 at the South-West end of the transect.

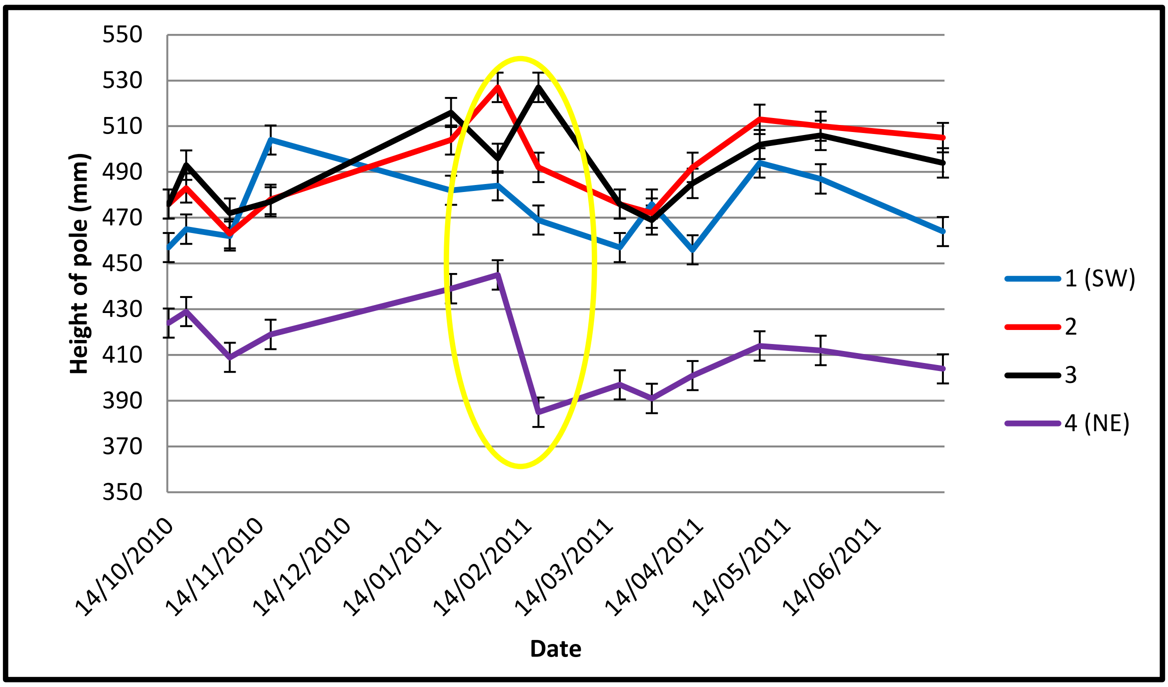


Figure 4.29: Temporal variability in the height of the poles across the depositional pool. Negative gradients indicate deposition, positive gradients indicate erosion. Error bars = 6.4 mm.

A key feature of this graph is the decrease in all of the pole heights in February 2011, indicating deposition across the pool surface (yellow circle). The environmental conditions during this period were wet and there was a lot of water flowing through the channels and into the pool. During these high flow conditions there would have been large quantities of suspended sediment which was deposited in the pool. A pattern suggesting erosion then occurred during April and May 2011 during a period of dry conditions when at times the amount of water on the pool surface was reduced (Figure 4.30).

Figure 4.30: The depositional pool during dry conditions. During wet conditions, water is present across the whole peat surface. Photo taken: June 2011.

The reduction of water on the surface makes the peat in the pond susceptible to aeolian erosion, shown to be an important process acting on bare peat in section 4.2.1.2. This could be an explanation for the pattern of erosion shown in Figure 4.29 although it is unlikely that aeolian processes will have caused all of the erosion. Alternative explanations for this is that these are not actually measuring peat erosion but either the rate of peat compaction due to the reduction of the water content during the dry conditions as the peat settles or as a result of a varying peat bulk density due to changes in the environmental conditions.

4.3.2.2 Changes in the peat flats surface

Across the bare peat flats, the average total difference in pole exposure between the start and end of the study period was 6.0 ± 6.4 mm which suggests that the surface of the peat flats is relatively stable. Figure 4.31 shows the spatial variability in the changes in pole exposure over the whole study period. It appears that erosion has occurred both in the middle of the peat flats and at the edges near the channels. The northern lateral transect appears to show that more erosion occurs at the eastern edge of the peat flats but this pattern is not replicated in the southern lateral transect.

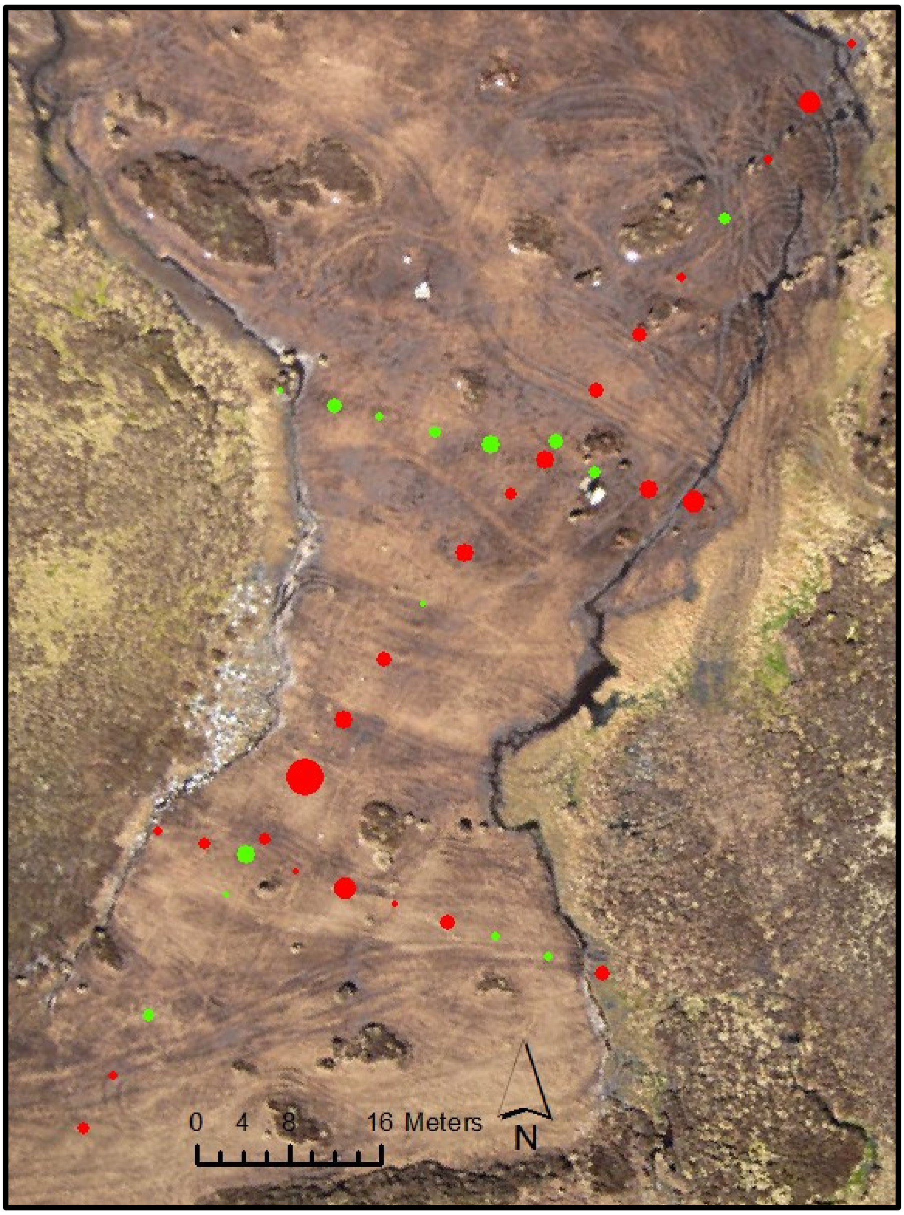
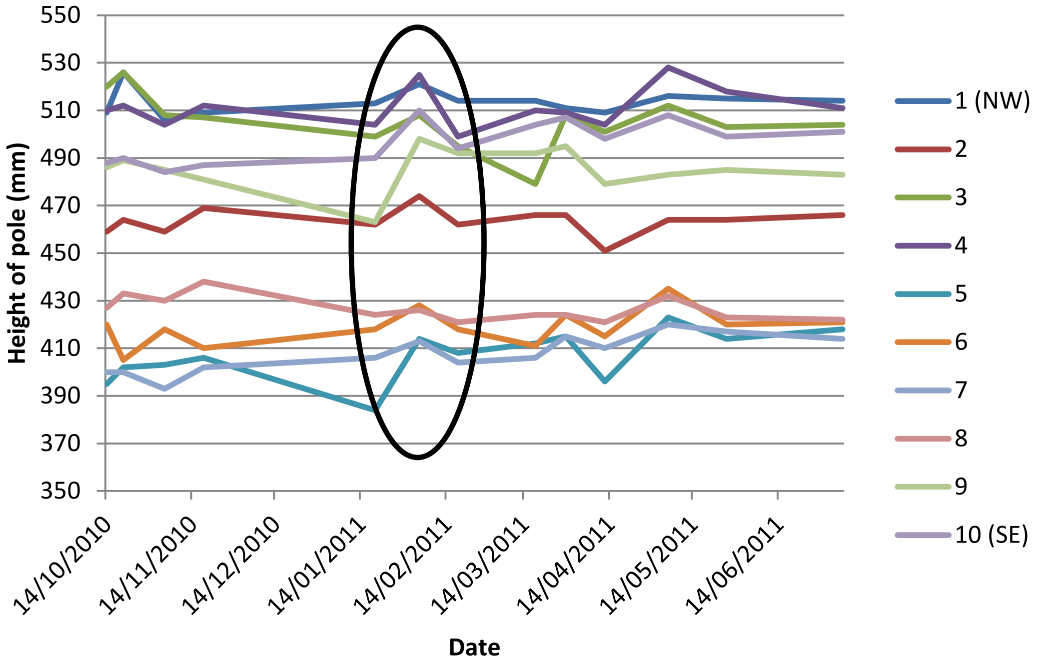


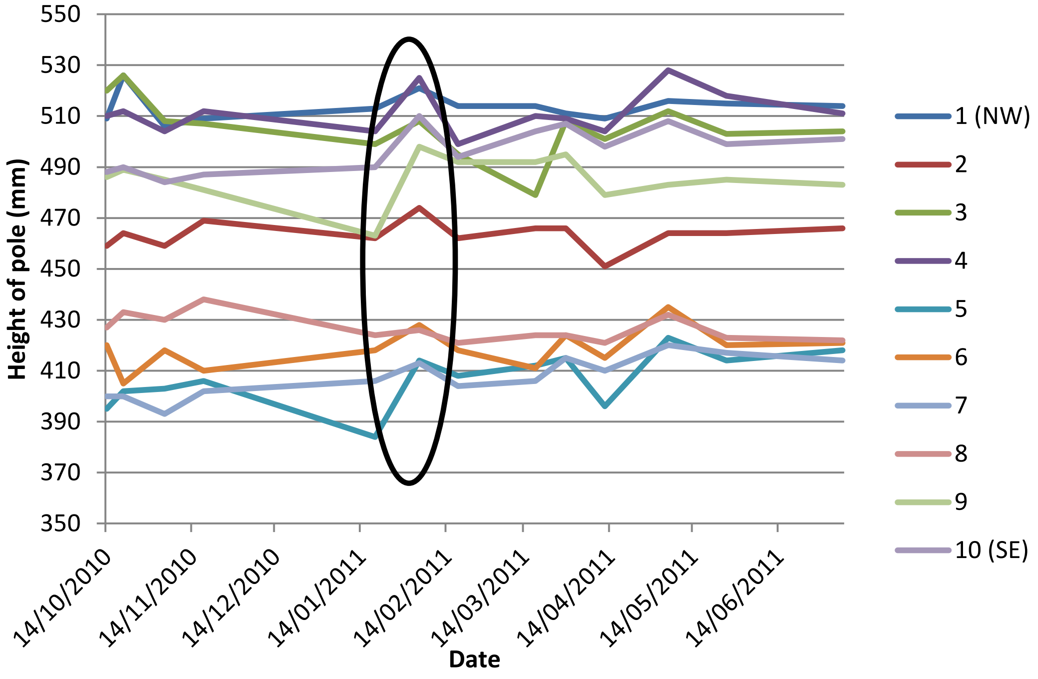
Figure 4.31: The spatial variability in erosion (red) and deposition (green) across the bare peat area measured by the pole transects during the whole study period.

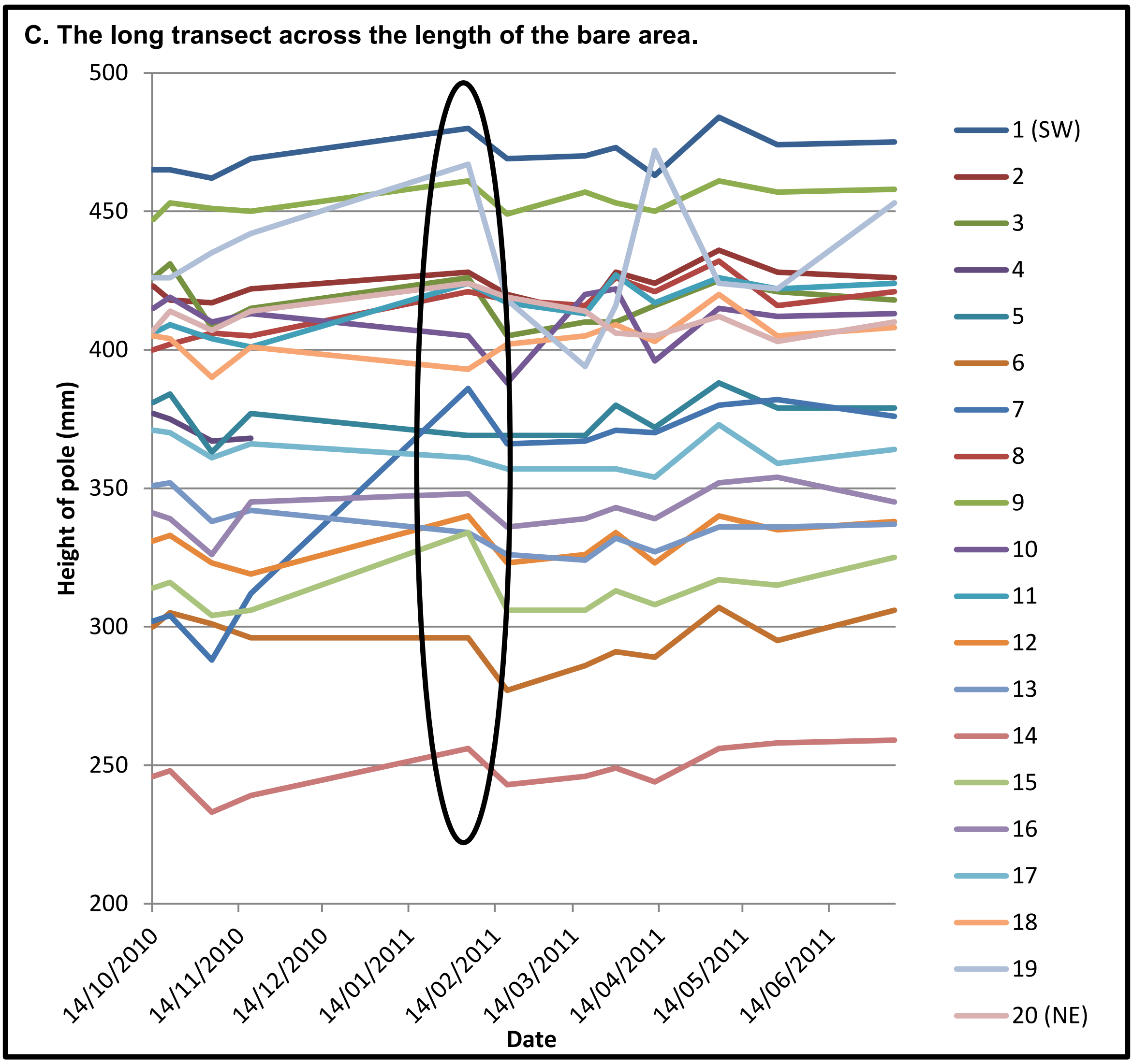
Analysis of the temporal variability in the pole measurements (Figure 4.32) shows that the poles experienced both erosion (sections of positive gradient) and deposition (sections of negative gradient) during the study period. Figures 4.32A and 4.32B show the temporal variability of the two lateral transects and Figure 4.32C shows the data from the long transect shown in Figure 3.11. Although the general pattern of the graphs demonstrate dynamic variability around a mean exposure, a brief period of erosion and then deposition during January and February 2011 stands out. This corresponds to when the ‘storms’ occurred (identified in Figure 4.4) suggesting that the surface of the peat flats responded dynamically to increased erosive potential of high wind-speed and intense rainfall. Some very large localised changes are visible in the record (at site 7 in Figure 4.32C) but this occurred during the period of snow cover and when the brash was spread. It is possible that this large variation in pole exposure is due to interference from the brash-spreading machine (Figure 2.2) and not the result of extreme localised erosion.

A. The upper lateral transect



B. The lower lateral transect





C. The long transect across the length of the bare area.

Figure 4.32: The temporal variability of the pole measurements. **A.** The upper lateral transect nearest the ‘gully section’ **B.** The lower lateral transect nearest the depositional pool **C.** The long transect along the length of the bare peat are. **Error** is 6.4mm but error bars are not plotted so the variation in pole height can be easily seen.

4.4 The areal extent and volume of peat at Flow Moss

4.4.1 The spatial distribution of bare peat at Flow Moss

The bare peat areas were digitised from the UAV image (Figure 4.33) that was geo-referenced using differential GPS data. The total area of bare peat was found to be 1.755 hectares (17550 m^2) (green shape-file in Figure 4.33, while the total fenced off area was 7.8 hectares. The majority of the bare peat is found in one contiguous area but there are smaller areas of bare peat between the haggs in the ‘gully section’ described in section 2.5. The erosion dynamics within the ‘gully section’ were not directly monitored but are likely to be different from the erosion dynamics in the main bare peat area due to the factors such as peat haggs sheltering bare peat areas from the wind.

Figure 4.33: Digitised areas of bare peat (green) overlain onto the UAV image mosaic.

4.4.2 Peat depth and calculated volume of peat and the terrestrial carbon store

4.4.2.1 Peat depth and volume

Ground Penetrating Radar (GPR) was used to produce nine profiles of sub-surface topography across Flow Moss which allow the determination of peat depth (Figure 4.35). Interpolation between the profiles allows an estimation of the total volume of peat at Flow Moss. This is important for understanding the peatland resource of Flow Moss and for quantifying the terrestrial carbon store in the surface layer. GPR raw data consist of the travel time of the electromagnetic wave between the transmitter and receiver. This can be converted to a distance by estimating the velocity of the electromagnetic wave. Calibration of the GPR data with peat depths measured by coring allows the calculation of the electromagnetic wave velocity through the peat. Seven peat cores of varying depths were taken along profile 5 and were used to calculate the electromagnetic wave velocity through the peat (Figure 4.34).

Profile 5. Length of transect: 171.1 m. Vertical scale = 1.27 m

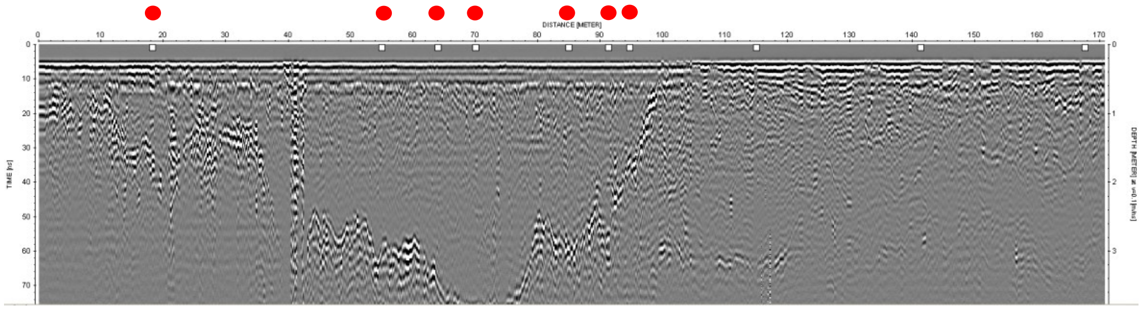


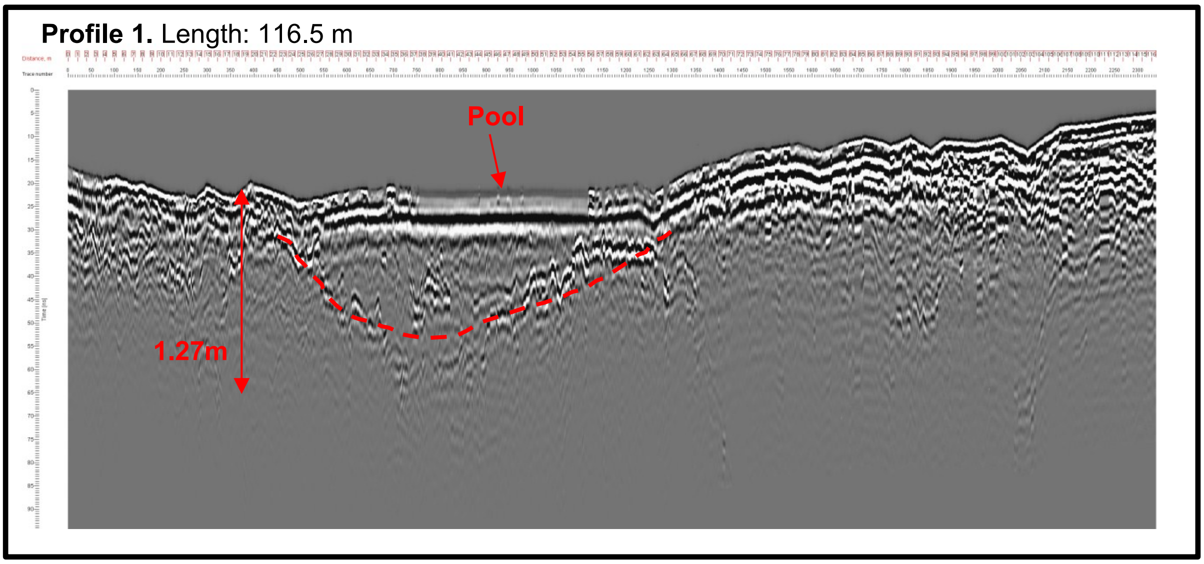
Figure 4.34: GPR transect used to calculate the electromagnetic wave velocity. Cores used in the validation were taken at the sites marked with the red dots.

Table 4.3 shows the raw GPR data of time taken for signal to reach the bottom of the profile and the uncalibrated raw GPR depths for each of the cores. Also included in Table 4.3 is the electromagnetic wave velocity at each point calculated using the raw time and depth measurements.

Distance of core along transect (m)	Time (ns)	Depth (m)	Velocity (m ns^{-1}
18	23.4	1.16	0.04957
55	56.5	2.75	0.04867
64	64.14	3.19	0.04977
70	70.11	3.49	0.04981
85	51.15	2.59	0.05067
91	39.92	1.98	0.04965
95	28	1.39	0.04971

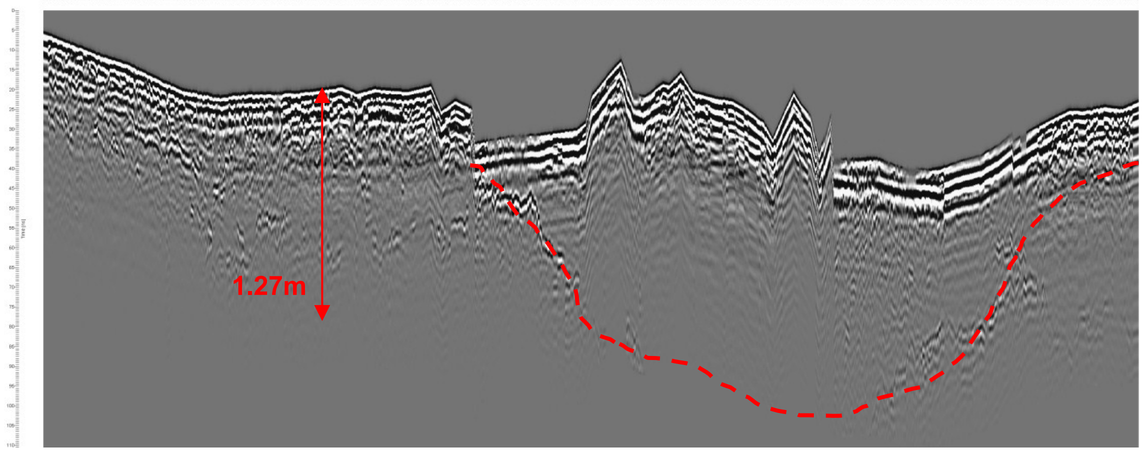
Table 4.3: Calculation of the electromagnetic wave velocity through the peat.

The mean calculated electromagnetic wave velocity is 0.0497 m ns^{-1} with a standard deviation of 0.000583. This velocity is similar to previous studies using GPR to survey peat as the calculated range of electromagnetic wave velocities given by Sass *et al.* (2010) is 0.033 to 0.063 m ns^{-1} for an Austrian peatland while Plado *et al.* (2011) uses a velocity of 0.036 m ns^{-1} for a bog in Estonia and Lowry *et al.*, (2009) use a velocity of 0.035 m ns^{-1} for a peat layer in USA.

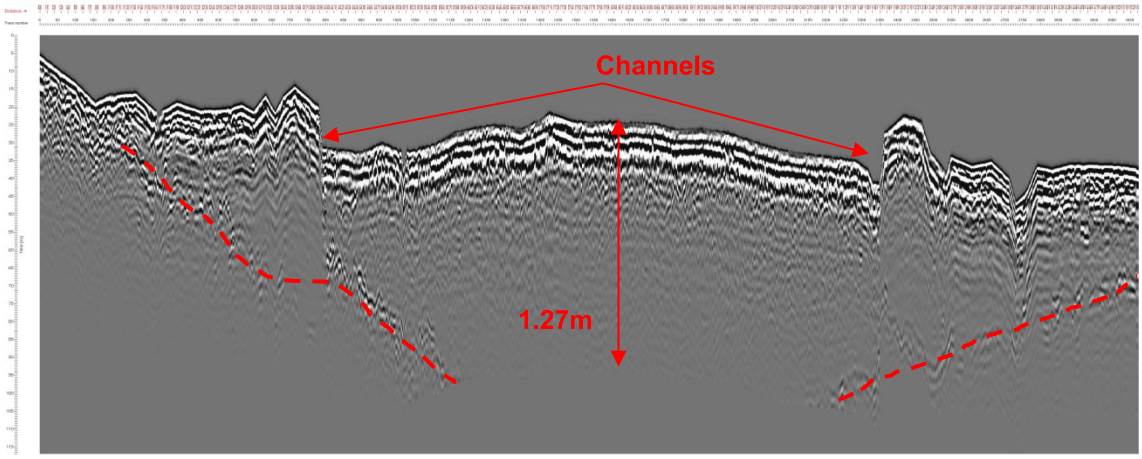


Profile 1. Length: 116.5 m

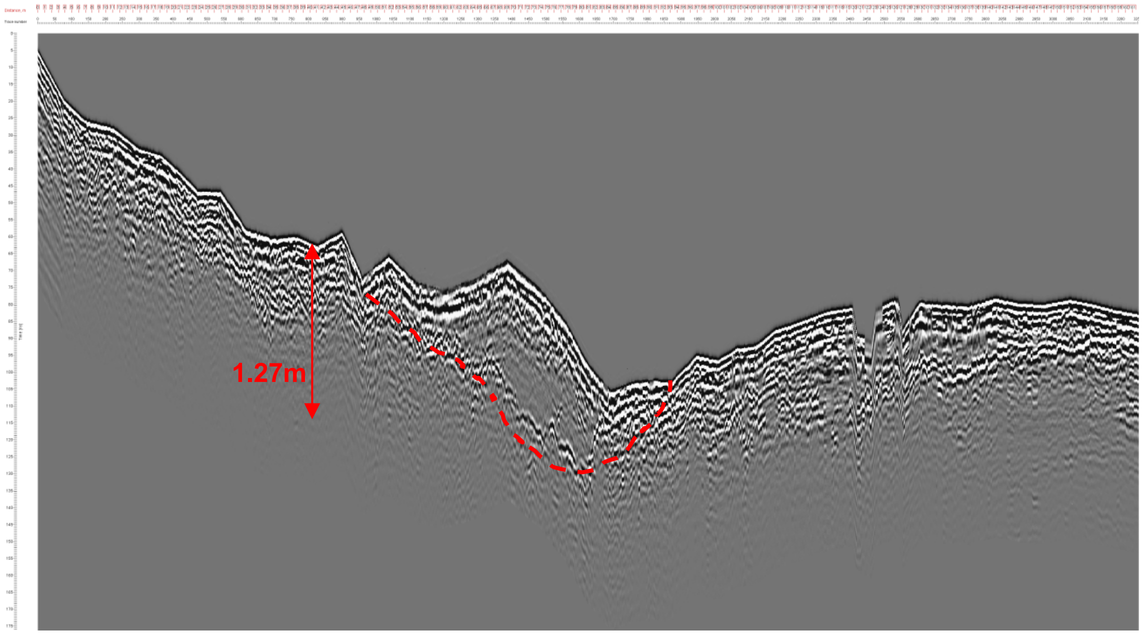
Profile 2. Length: 138.4 m



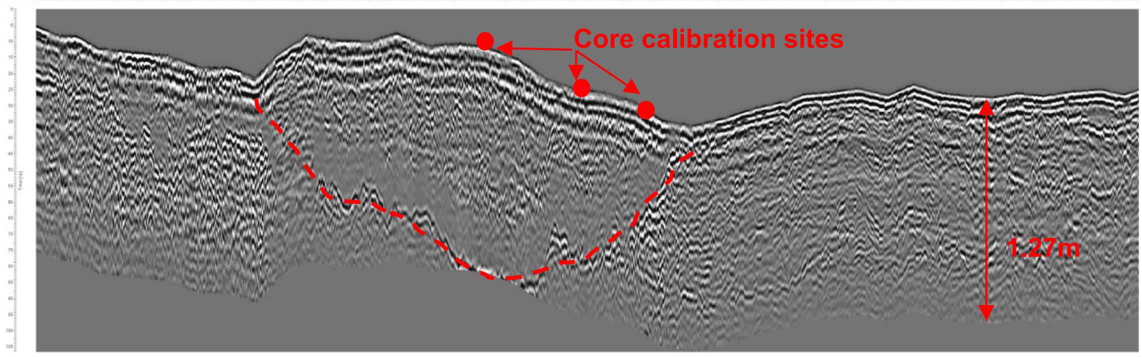
Profile 3. Length: 153.1 m



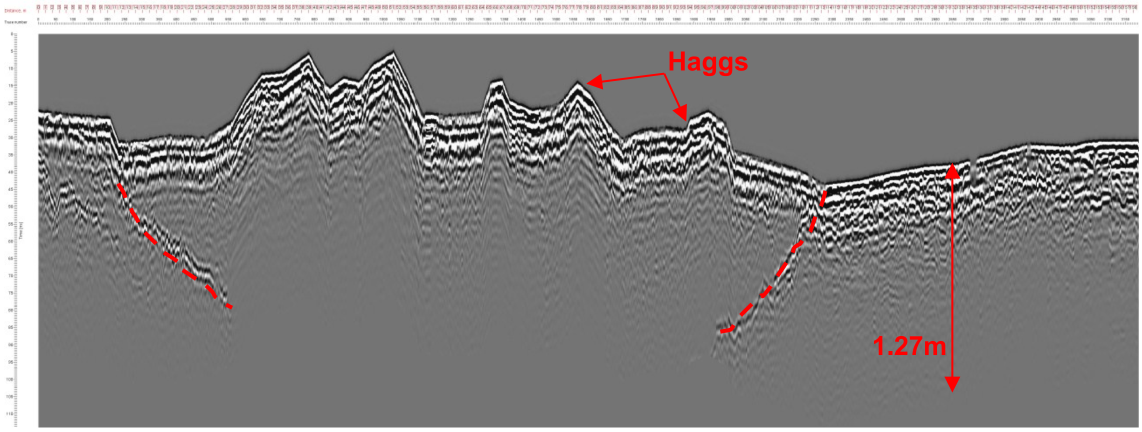
Profile 4. Length: 162.0 m



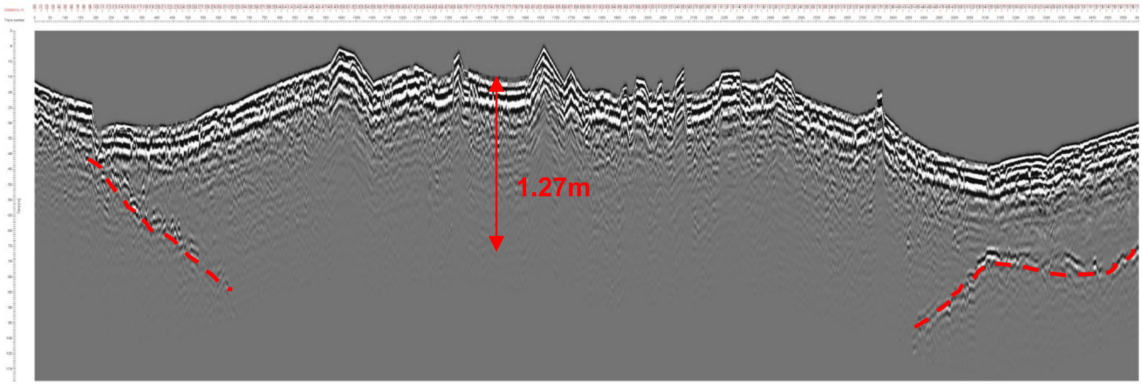
Profile 5. Length: 171.1 m



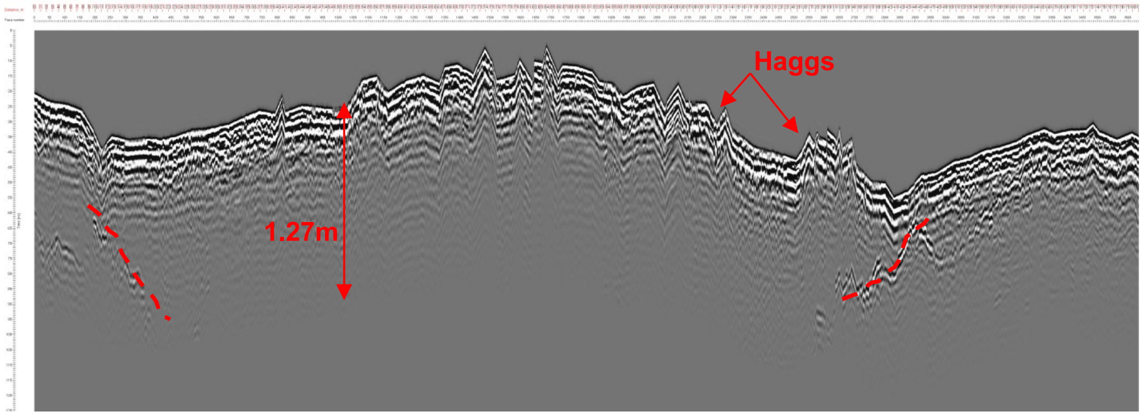
Profile 6. Length 158.8 m



Profile 7. Length 179.3 m



Profile 8. Length: 181.1 m



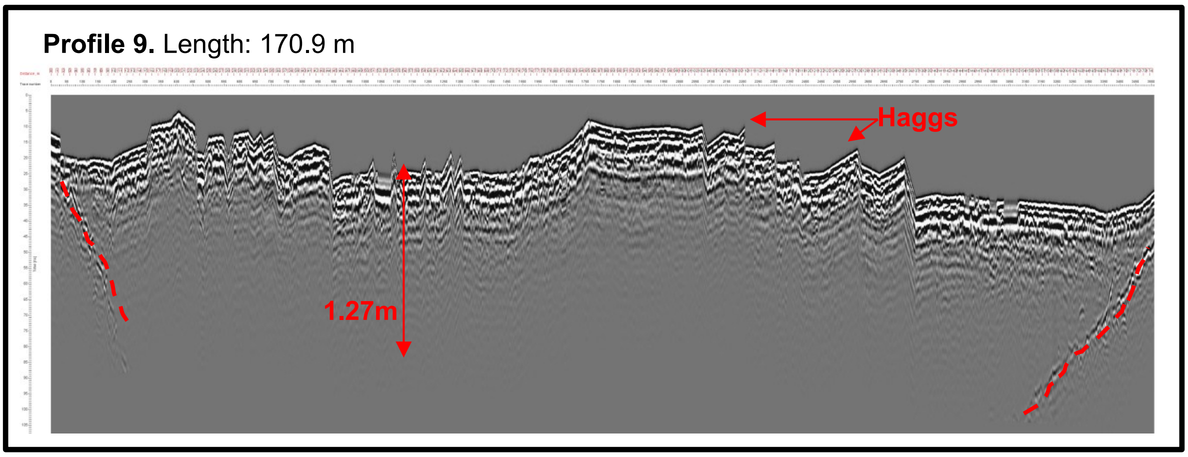
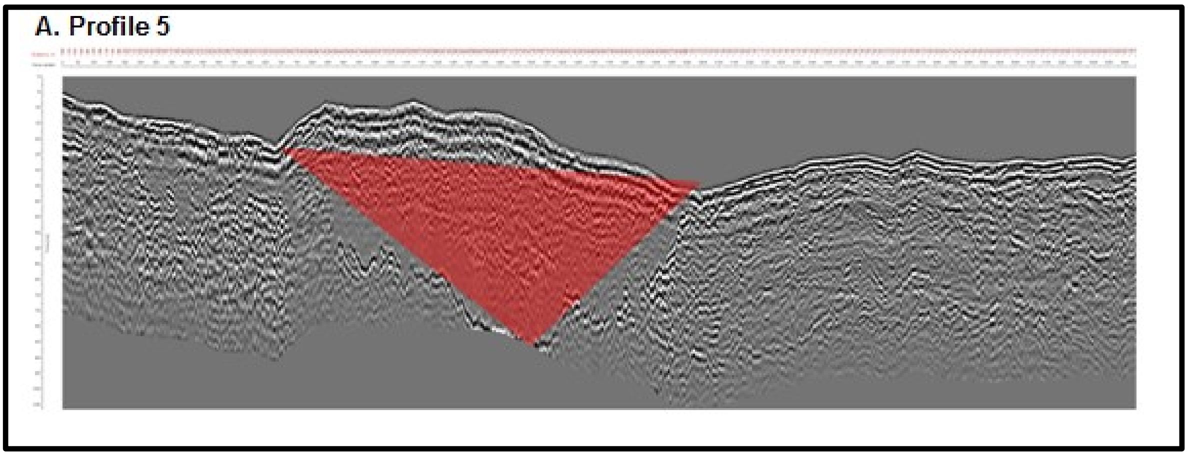

Profile 9. Length: 170.9 m

Figure 4.35: Sub-surface profiles of the peat from the GPR survey. Boundary between peat and mineral layer highlighted in red. For vertical scale, the distance between the peat surface and the base of the signal is 1.27 m, labelled in each cross-section.

The peat depths calculated from the GPR data were used to approximate the volume of peat stored at Flow Moss. The cross-sectional area of peat along each of the profiles was estimated by assuming the boundary between the peat mass and the mineral layer was triangular in shape (Figure 4.36A). However, this would lead to a gross-underestimation of the cross-sectional area for the profiles where the maximum peat depth was not recorded (profiles 3, 6, 7, 8 and 9). In these cases, the cross-sectional area of the peat mass was calculated using a trapezium (Figure 4.36B). The depth value used to find the cross-sectional area for these profiles was the maximum depth of measured by the instrument (1.27 m) rather than attempting to extrapolate the peat depth beyond the resolution of the instrument. Therefore, the cross-sectional areas presented in Table 4.3 are still a slight under-estimate of the total amount of peat.


A. Profile 5

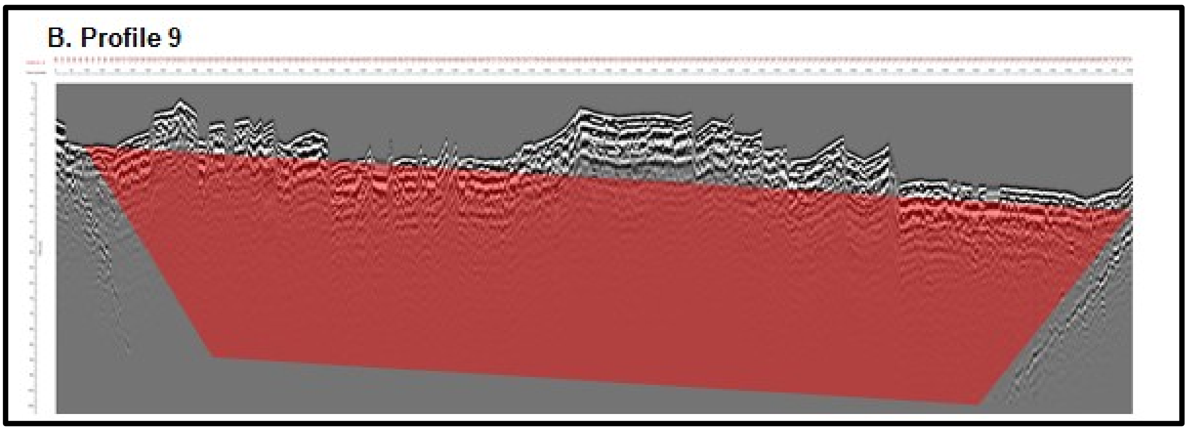


Figure 4.36: Examples of the method used to calculate the cross-sectional area of the peat mass at each profile. Where the maximum peat depth was recorded, a triangle was used **(A. Profile 5)**. Where the maximum peat depth was not recorded, a trapezium of depth 1.27m was used **(B. Profile 9).** Scale is the same as in Fig 4.34.

Profile number	Cross-sectional area of peat (m^2)
1	15.8
2	49.2
3	125.7
4	12.7
5	64.8
6	110.8
7	179.5
8	158.8
9	201.5

Table 4.4: Cross sectional area of peat at each profile.

Table 4.4 gives the cross-sectional area of peat at each of the nine profiles but in order to get a total volume of peat, the cross-sectional areas were interpolated across the site to get the total peat volume. The total peat volume stored at the site was calculated to be 41,200 m^3 which, assuming a dry density of 100 kg m^{-3}, means that there is at least 4120 tonnes of peat stored within the restoration area at Flow Moss. As discussed previously, this represents an underestimate of the total peat stored due to the resolution of the GPR antenna. A more accurate peat depth survey could be carried out using a GPR antenna of a lower frequency, which would penetrate deeper beneath the peat surface.

4.4.2.2 Terrestrial carbon store

Twenty three sub-samples collected in the wind tubes and Gerlach troughs were analysed using a TOC1200 carbon analyser. The values for total carbon content of the samples ranged from 25.4% to 68.4% with an average value of 51.8% and a standard deviation of 8.94%. The large range is due to the sensitivity of the machine as it is not usually calibrated to analyse materials with carbon content as high as peat. This is the reason why a large number of samples were analysed so that the mean value is as accurate as possible. The histogram of the total carbon values is shown in Figure 4.37. For ease of calculating the total carbon stored at Flow Moss, a value of 50% is used as the largest frequency density is between 50 and 55% and is close to mean value of 51.8%

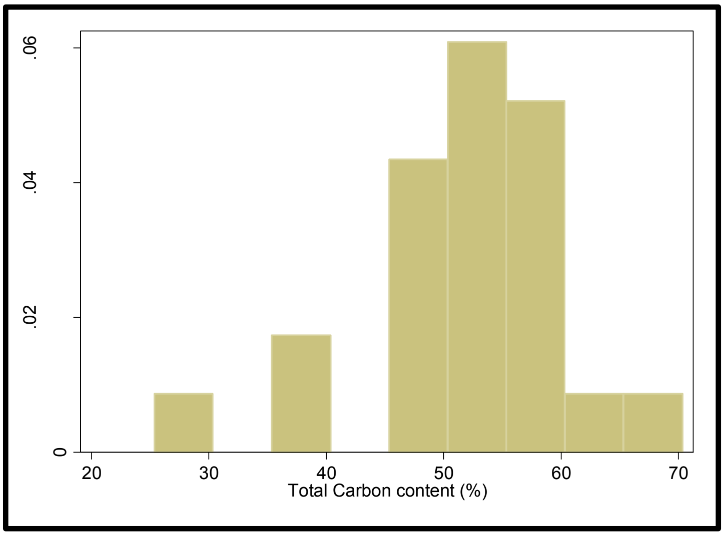


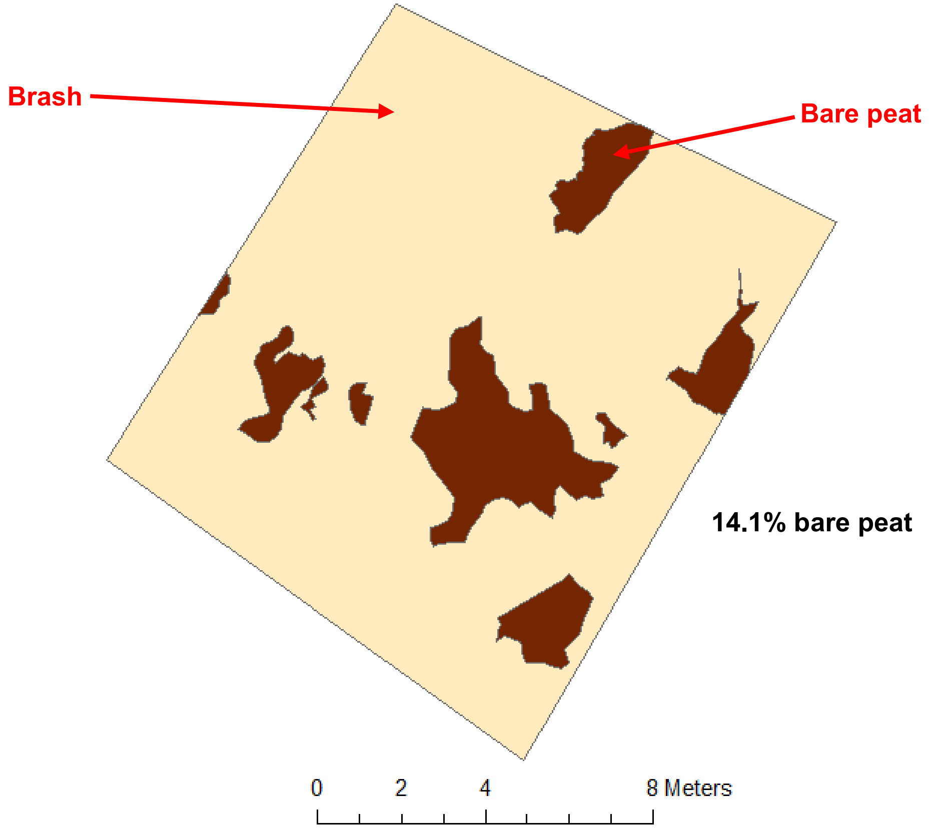
Figure 4.37: Histogram of the measured Total Carbon content of the 23 samples measured. Highest frequency is between 50 and 55%.

The estimated peat mass stored at Flow Moss is at least 4120 tonnes (Section 4.4.2.1) and using a carbon content of 50% there is at least 2060 tonnes of carbon stored in the peat at Flow Moss.

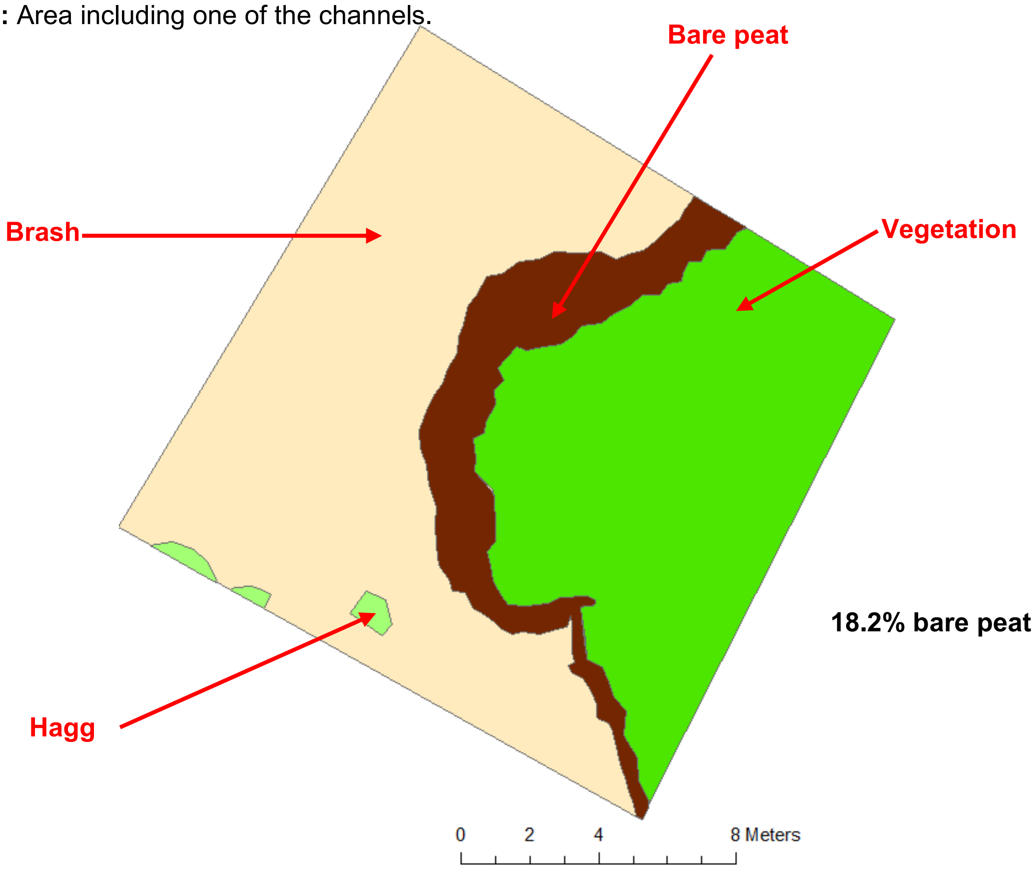
4.5 The area of bare peat that was covered by heather brash

As one of the main restoration measures at the site, heather brash was spread over the surface of the peat in December 2010, just after the main snowfall. A survey was undertaken on 8th June 2011 to assess the amount of this brash that has been lost from the peat surface (Section 3.5.2). The areas of bare peat identified in the survey (Figure 4.38) are areas where the brash has been washed or blown from the surface. If the mapping was extended to all areas in the future, this could be used to map process regime areas and identify areas more at risk from erosion.

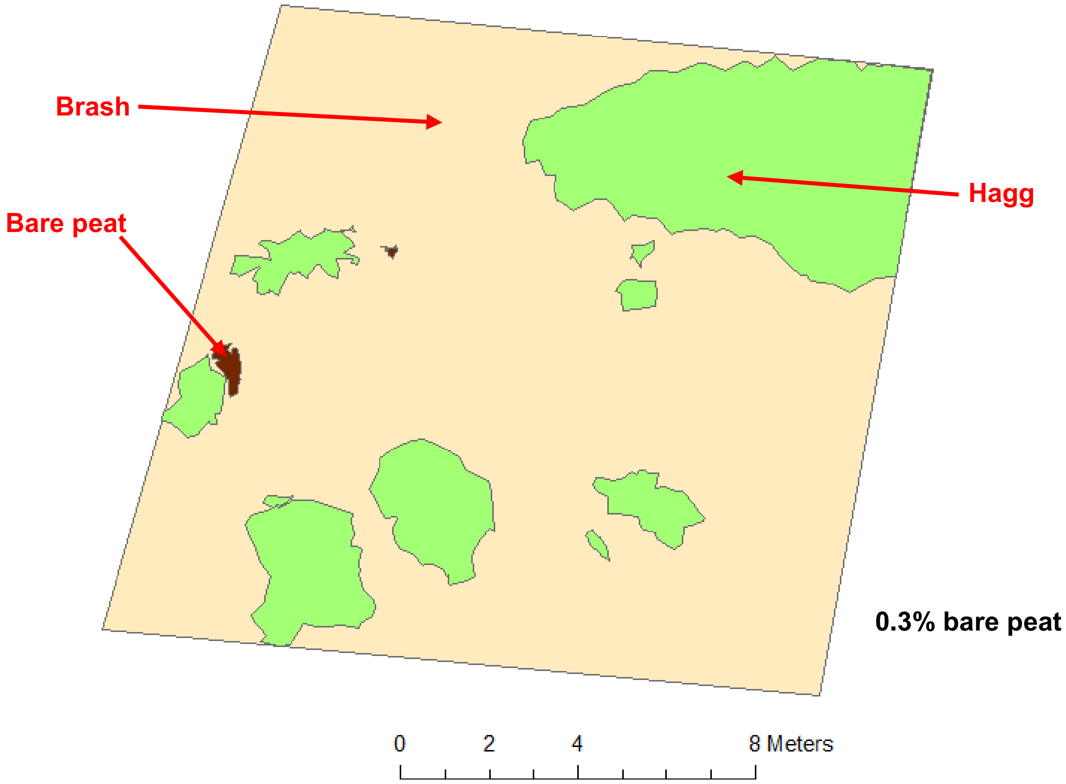
A: Bare peat area



B: Area including one of the channels.



C: Bare peat area with some peat haggs



D: The ‘gully’ section

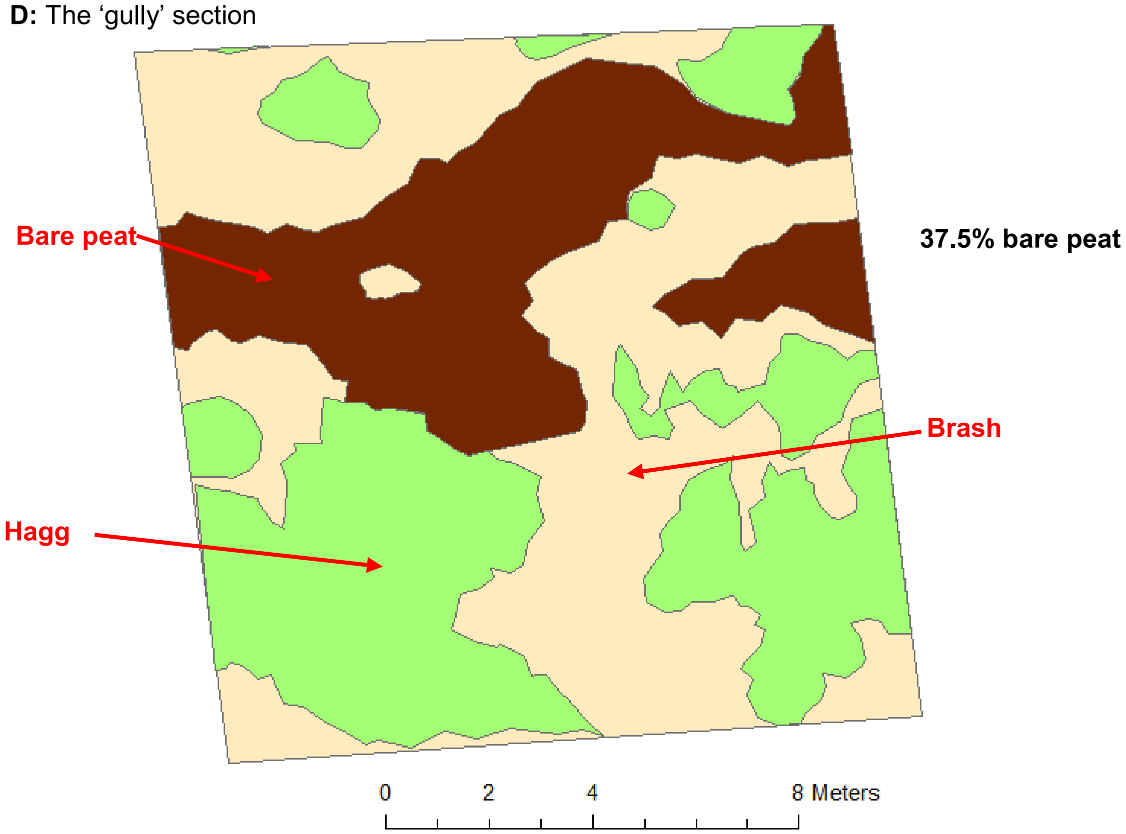


Figure 4.38: The maps of the survey areas to quantify brash and bare peat coverage.

Within each of the survey areas, the initial area of bare peat was quantified by subtracting the areas of haggs and vegetation from the total survey area. The coverage of heather brash remaining over these areas was calculated by subtracting the areas of visible peat from the total area. The maps generated from the mapping are presented in Figure 4.38 and include the outline of peat haggs that stand ~ 0.5 to 1 m above the surrounding peat, and in survey area B, an area of peat flats that is vegetated. The survey areas were chosen because they cover the different characteristics of the site; an exposed area of bare peat (A), the effect of the drainage channels (B), a sheltered area of bare peat (C) and the rough ground of gullies and haggs to the south of bare area (D).

It was assumed that during the restoration process heather brash was consistently spread over all of the bare peat areas (with 100% coverage of the bare peat). The average bare peat exposure over the four survey areas was 17.5% but the values range from 0.3% to 37.5%. Therefore the erosive processes are not acting uniformly at Flow Moss and this implies that some areas are more under threat to the erosion than others. This is expected because the geomorphological features at Flow Moss are varied and as shown in Figure 2.2, the site is split into two distinct areas; the bare peat flats and the area of ‘type 1’ gullies to the south characterised by rough ground and large peat haggs.

Survey area D was located in the small-gully system where the greater slope angle ensures that hydraulic flows dominate the erosive processes. There is more likely to be surface runoff in this area than the bare peat flats which is a possible reason why 37.5% of the heather brash has been lost from the survey area. Survey area A, on the other hand, was located in the middle of the large area of bare peat flats where most of the other monitoring equipment was located. This survey area is very exposed to wind and rain (Section 4.2.1.2) and erosion by the aeolian processes is significant on the bare peat flats at Flow Moss. It is, therefore, not surprising that 14.1% of the brash has been blown from this area as the small cuttings of brash can easily be entrained by high-intensity rainfall impacts combined with high wind-speeds. Survey areas A and D capture the effect of two important erosive processes acting at Flow Moss and indicate that erosion by water flowing over the peat surface is more effective in removing the brash from the surface than by raindrop impact. Therefore, during the restoration process, it is suggested that extra brash is spread over bare peat in gully systems than bare peat flats as it is more likely to be lost before the seeds can colonise the surface.

Survey area C was also located across a sheltered area of the bare peat flats because it is surrounded by peat haggs whereas survey area A was much more exposed. These haggs stand approximately 0.5 – 1 m above the bare peat flats and act to shelter the surface by diverting the wind and, depending on the size of the hagg, by shielding the downwind areas of the surface from raindrop impact. These are possible reasons why survey area C has the smallest percentage of brash loss at 0.3%. In these sheltered areas, less brash is therefore required during the restoration process to enable the seeds to re-colonise the peat surface. Survey area B covers one of the two main drainage channels that cross the bare peat flats and is therefore, during wet hydrological conditions, likely to wash away brash that is spread over the nearby area. An example of this is shown in Figure 4.39 as brash has been washed away from the areas that the channel covers during wet hydrological conditions.

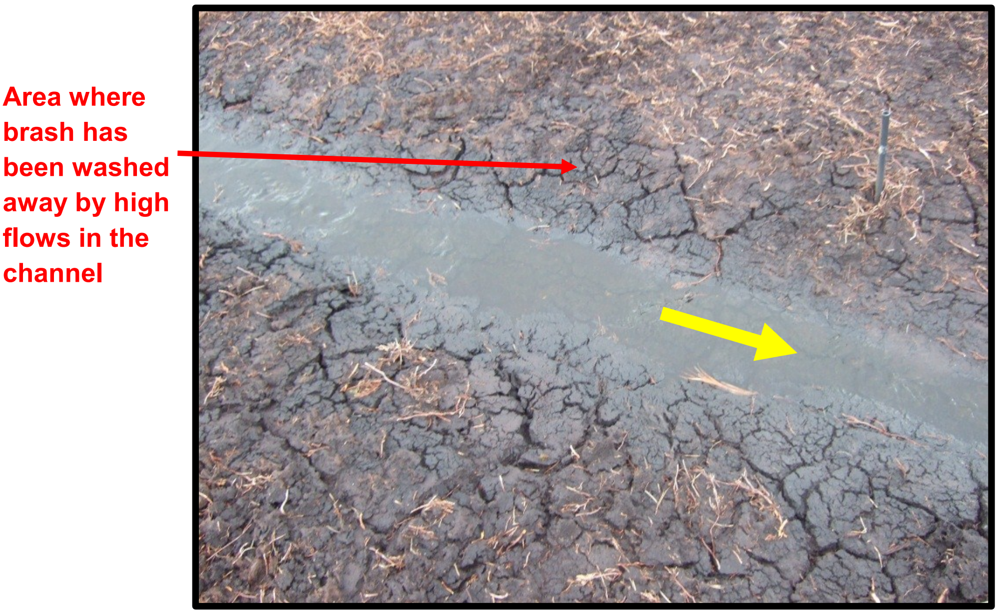


Figure 4.39: Example of the effect of the drainage channel in washing away brash from the peat surface. Yellow arrow indicates flow direction.

When the survey was undertaken, in June 2011, the hydrological conditions were dry so the channel had a limited flow but the maximum width of the channel could be clearly identified from the distinct edge of the brash coverage and the start of the bare peat areas at the channel edge. On the other side of the channel was a large area of vegetation over a relatively flat area. This suggests that the course of the channel is important in restricting the colonisation of the bare peat area and adds to the observation in Figure 2.2 that the bare peat flats are surrounded by two channels that flow either side of the peat flats. This leads to the conclusion that in order to fully restore the vegetation coverage over the bare peat flats, the flow in the channels must be reduced so that colonising seeds are not washed away and the margins of the bare area are not eroded to such an extent.

The surveys of brash coverage have identified the importance of surface processes in eroding the surface as both hydraulic and aeolian processes have removed significant amounts of brash from the surface in the six months since it was spread. Also, the impact of the peat hagg landforms in sheltering the bare peat is very important as much less brash lost was lost from this area. Therefore, it is likely, that if the restoration measures are successful in sheltering the bare peat from wind and rain, the amount of sediment transfer across the bare peat flats will be significantly reduced.

4.6 Summary of results

The results presented in this chapter cover a range of geomorphological processes and provide insight into the erosion dynamics acting at Flow Moss. The study period was drier than average but there were five occasions when heavy rainfall was combined with high wind-speeds when large amounts of erosion could potentially occur.

Sediment transfer is active on the bare peat flats controlled primarily by aeolian processes. The vast majority of peat transported by the wind occurs close to the peat surface and controls on the amount of erosion are dependent on complex relationships between wind direction, wind-speed and rainfall intensity. A two-phase mechanism of erosion by wind-driven rain is proposed where loose peat particles, generated by freeze-thaw weathering or surface desiccation, are put into motion by rainfall impact before smaller particles are detached from the intact peat surface. This two-phase model of erosion is dependent on the amount of surface weathering prior to the rainfall event. Erosion of the slopes at Flow Moss occurs at a slower rate than the rates determined by previous studies at other sites but this is possibly due to the initial settling in of the erosion pins into the surface which artificially disturbs the slope surface creating. The total volume of peat stored at Flow Moss is approximately 41,200 m^3 which contains approximately 2060 tonnes of Carbon. Sediment fluxes were calculated for aeolian processes, slope processes, hydraulic transport and pool deposition and are shown in Table 4.5.

Process	**Sediment flux (t a^{-1})**	**Quantified error (t a^{-1})**	**Catchment wide sediment yield (g m^{-2} a^{-1})**
Wind erosion of peat flats	3.2	0.97	41.0
Peat loss from hagg slopes	0.72	-	9.23
Hydraulic peat transport	0.00546	-	0.07
Deposition in pools	0.749	0.3	9.60

Table 4.5: Sediment fluxes for different processes at Flow Moss calculated using the sediment yields monitored between October 2010 and July 2011.

The nature of the physical processes and the sediment fluxes presented in Table 4.5 are discussed further in Chapter 5 and are used to construct a sediment budget that allows the aim of this research to be achieved.

Chapter 5. Discussion

The purpose of this chapter is to discuss the results presented in Chapter 4 and to discuss how these results achieve the research objectives outlined in Chapter 1. Comparisons are made between the data presented in Chapter 4 and previous work published in the literature. A preliminary sediment budget for Flow Moss is constructed using the data and this is compared to other peatland catchments. Finally, an assessment is made of the successfulness of the restoration measures carried out as part of the *Peatscapes* project.

5.1 Physical processes and erosion dynamics acting at Flow Moss

The field monitoring provides a detailed description of the processes acting at Flow Moss and addresses the first research objective of this study (Section 1.5). The results improve the understanding of aeolian processes acting on the bare peat flats, the sediment transfer from the peat hagg slopes to the peat flats and the importance of peat deposition in pools within the channel network.

5.1.1 Comparison with previous studies of aeolian processes

5.1.1.1 Previous studies of aeolian processes on peatlands

The results of the aeolian erosion and sediment transfer monitoring (Section 4.2.1) can only be directly compared to two previous field studies of the wind erosion of bare peat at Moss Flats, also in the North Pennines (Warburton, 2003; Foulds and Warburton, 2007a&b). The results agree with these studies as they also found the highest peat flux rates occur in the direction of the most common wind direction. The flux of peat recorded in the windward facing traps in this study ranged between 1 to 8 times the flux of peat recorded in the leeward facing traps, with the windward flux ratio reported by Warburton (2003) ranged between 3 to 12 and the windward flux ratio reported by Foulds and Warburton (2007b) ranged between 2 to 13. The flux ratios during dry periods differ between the previous studies as Warburton (2003) reports that the greatest difference between windward and leeward fluxes (8 times greater) occurred during dry conditions whereas Foulds and Warburton (2007b) report the lowest difference during dry conditions (only 2 times greater). The results from Flow Moss support the findings of Foulds and Warburton (2007b) as during dry conditions, the flux of peat in the windward facing traps is similar to the flux of peat in the leeward facing traps. It is suggested here that this is because during dry conditions the wind erosion is not controlled by rainfall events and, therefore, the variability in the direction of eroded particle transport is directly controlled by the variability of the wind direction with particles entrained by the shear stress generated by the wind rather than by the ballistic impact of raindrops.

5.1.1.2 Previous studies of aeolian processes in coastal dune systems

Pye (1983) reviewed the aeolian processes controlling the geomorphological development of coastal dunes and some of the observations made for dune systems appear relevant to the observations made in peatlands. There is limited cohesion between dry sand particles which is similar to loose peat particles that have been detached from the peat surface by freeze-thaw weathering or surface desiccation. Therefore comparisons can be made between the processes of aeolian sand transport and the aeolian transport of dry peat. Aeolian transport occurs through two processes; the result of ballistic impact by rainfall or other particles and; by the shear velocity of the wind at the surface that lifts the particles from the surface (Pye, 1983; Figure 5.1).

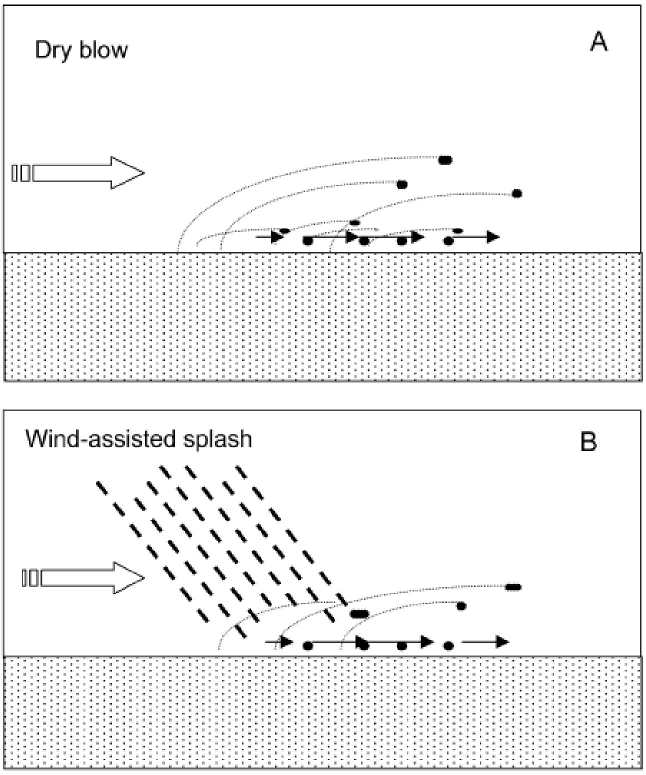


Figure 5.1: Schematic diagrams showing the two main forms of wind erosion observed on bare peat. **A.** Aeolian transport of dry peat particles and crust and **B.** wind-assisted splash transport under oblique rain (*Source: Warburton, 2003)*

The wind velocity required to generate the necessary stress to cause these two processes is different as the velocity required to produce the stress to maintain movement by ballistic impact (the impact threshold velocity) is lower than the velocity required to initiate particle movement by lift or shear (the fluid threshold velocity) (Pye, 1983). The results from this study show that the difference between the threshold velocities is also relevant in peatlands because during a dry period (Figure 4.11I) as the rate of peat collection in the sediment traps is lower than during a wet period (Figure 4.11D). Aeolian erosion during a wet period is dominated by the effect of raindrop impact whereas during a dry period, the particles on the peat surface are set in motion through wind shear. The lower rate of peat erosion during a dry period implies that a higher stress is required to initiate motion through lift or shear than the stress required to entrain particles by ballistic impact. Aeolian geomorphology literature that focuses on coastal dune systems (e.g. Pye, 1983) is therefore relevant for peatlands especially when there is a weathered layer of loose particles on the surface. Coastal dune systems are more relevant than desert dune systems because the coastal dune vegetation gives some cohesion to the sand through the roots. Intact peat, prior to weathering by freeze-thaw processes or surface desiccation, has a similar erodibility (the susceptibility of the surface to erosion, Livingstone and Warren, (1996)) to coastal dune systems as the surface is also cohesive.

Pye (1983) also argues that aeolian transport rates are highest in exposed dune systems characterised by wide, low-angle dissipative beaches and lowest on sheltered, narrow, steep reflective beaches. The results of the brash coverage surveys also match this notion as the exposed area of bare peat has lost a larger amount of brash (14.1%) than the bare peat area that is sheltered by peat haggs (0.3%). Therefore the amount of aeolian erosion of an area of bare peat is dependent on the sheltering effect of surrounding landforms. In addition to the exposure of the surface, Pye (1983) states that the density of vegetation, as well as the vegetation height, is important in reducing the amount of peat erosion by aeolian processes. Increased vegetation density at the surface decreases the slope of the wind velocity profile as the roughness height increases (described in section 3.3.1) and therefore the wind shear at the soil surface, reducing the energy available to erode the surface (Bressolier and Thomas, 1977). Therefore in terms of peatland restoration, it is very important that vegetation coverage is increased over the bare peat area as this will reduce the overall sediment flux by aeolian processes.

5.1.2 The role of climate and weather

Climatic and weather conditions have been identified as an important control on the amount of erosion through the relationships between rainfall intensity, wind-speed and wind-direction and the difference between rates of sediment supply during wet and dry conditions (Figure 4.10). Experimental studies by Erpul *et al.* (2002; 2004) of sand erosion by wind-driven rain demonstrated that very high rainfall intensities can lead to net downwind sediment transport. These rainfall intensities (> 92 mm hr^{-1}) are unrealistic in a UK context but the results are still relevant. While the rainfall intensities experienced in the UK are lower, peat has a lower density than sand so requires lower energy to be detached and transported across the peat surface.

Over the longer term, these relationships combine to affect the longer term development of landforms (Figure 4.16) and suggest that in upland peatland environments in the UK, wind and rain are very important in the development of the upland landscape. The mean orientation of smallscale landforms (haggs and mounds) at Flow Moss was 230^{o} while at Moss Flats the mean direction was 240^{o} (Evans and Warburton, 2007). As Flow Moss and Moss Flats are ~20 km apart and located in different catchments, this similarity suggests that wind erosion produces a significant geomorphological imprint on the North Pennines upland landscape. This is at odds with the traditional view of Tufnell (1969) who suggested that wind erosion has no lasting control on landscape evolution. In the early 1960's, there was disagreement in the literature surrounding the importance of wind erosion as Radley (1962) believed that aeolian processes were the most significant agent of erosion in summit locations whereas Bower (1961) viewed hydraulic action as the most significant. Neither study had direct evidence of rates of wind erosion but the more recent studies, and the evidence from Flow Moss, suggest that the view of Radley (1962) is correct for summit and flat locations. Bower's suggestion is not incorrect as even on low-angle slopes, surface wash becomes more important than aeolian processes in eroding the peat surface. However, the detailed evidence of aeolian processes has only been collected at two locations in the North Pennines so evidence should be collected at additional locations in the UK uplands. If the patterns observed at Flow Moss and those observed by Warburton (2003) and Foulds and Warburton (2007a&b) are consistent with other locations then there would be unequivocal evidence that wind erosion is a significant geomorphological process in summit locations and flat areas in UK upland environments. This would also support the view of Radley (1962) that when slope angle and hydraulic processes are insignificant, aeolian processes dominate the geomorphological development of the landscape

5.1.3 The importance of sediment production and availability for aeolian processes

The degree of weathering and production of sediment available for transfer by aeolian processes is important in controlling the sediment flux during subsequent rainfall events (Warburton, 2003). The loose sediment on the peat flats comes from two main sources; the weathering on the intact peat mass by freeze-thaw weathering or desiccation and; material that has been transferred from the slopes of the peat haggs. Section 4.3.1.1 shows that material is lost from the slopes through complex, diffusive, processes that are probably the result of raindrop impact and/or the lift of particles by wind shear.

The two-phase hypothesis of erosion by wind-driven rain (Figure 4.15) supports the conclusion that the amount of weathered material available on the surface is very important in controlling the dynamics and amount of erosion over short timescales (Labadz *et al.*, 1991). The relative importance of each phase in the erosion model is dependent on the degree of sediment production by weathering processes as the transportation of the weathered material occurs in the first phase. The maximum time over which Phase 1 erosion occurs is controlled by the length of time it takes to flush all the loose weathered sediment from the surface as well as the time period before the erosion event when sediment is produced on the surface. The length of the subsequent Phase 2 erosion is more directly controlled by climate as if the rainfall event is longer, there is more opportunity for rainfall impacts to erode the freshly exposed peat surface after the weathered sediment has been removed.

The bare peat flats are particularly susceptible to aeolian processes and respond dynamically to the changing environmental conditions (Figure 4.26). The low degree of coupling between the peat flats and the channel system implies that the two systems are disconnected (Evans and Warburton, 2007). While active sediment transfer is taking place across the peat flats, the majority of the sediment is not transferred into the channel system suggesting that most of the eroded peat is deposited elsewhere on the bare peat flats.

5.1.4 Hydrological and hydraulic processes at Flow Moss

Many studies have found that climate is an important control on the height of the water table and the hydrological conditions in peatlands with typical conditions described as 'flashy' (Holden and Burt, 2003). Figure 4.6 shows the water table at Flow Moss also responds rapidly to rainfall and is close to the surface reaching a maximum height of just 107 mm from the surface at the monitoring location in the centre of the peat flats. This is consistent with other peatlands as Daniels *et al.* (2008) found that the water table can be as high as 50 mm from the surface for prolonged periods of time and a study by Jauhiainen *et al.* (2002) at a restored peatland found that the water table was never lower than 200 mm from the surface. The climatic conditions are an important factor controlling the height of the water table (Figure 4.6) and, in turn, the hydrological conditions are very important in controlling the sediment flux in the ephemeral channel and pool system. During dry conditions, the channel flow is reduced so suspended sediment settles and is deposited in the pools. During wet conditions, higher flows in the channels transport more peat and therefore more peat exits the pools and is lost from the site (Figure 4.18). There is also evidence for compaction of deposited sediments as during dry conditions the water content in the pool reduces markedly and the pole transects across the pool increase in exposure. It is unlikely that this increase in exposure is as a result of wind erosion of the exposed peat which suggests that the depth of the deposited peat is being lowered through compaction and consolidation. Meckel *et al.* (2007) found that peat compaction rates can be as high as several mm a^{-1} and this order of magnitude is similar to the apparent compaction rates at Flow Moss. Therefore, during dry conditions, when the water level drops in the pools, the peat that been deposited consolidates slightly to give the apparent measure of erosion by the pole transects.

5.1.5 Summary of physical process dynamics at Flow Moss

The first research objective of this study was to improve the understanding of the dynamics of erosion and sediment transfer acting at Flow Moss. Monitoring has demonstrated that the prevailing meteorological conditions provide the driver that determines the dominant process regime (and process rate) which in turn determines the peatland morphology. Wind erosion has a strong control on the geomorphological development of Flow Moss over a long timescale but the intensity of the process varies in the short term dependent on meteorological factors such as rainfall intensity. Different processes occur during wet and dry regimes due to the importance of rainfall impact on the peat surface and the antecedent sediment production on the surface before each erosion event is significant in determining the volume of peat transfer.

Climate is indirectly important in controlling the sediment flux in the channels and the rate of deposition in the pools, through the effect of the hydrological conditions on channel flow and peat compaction in the pools during dry periods. This study has contributed to the understanding of wind erosion of bare peat building on the work of Warburton (2003) and Foulds and Warburton (2007a; 2007b). However, further work is required (discussed below in Section 5.5) as in-depth studies of wind erosion have only taken place at two locations; Moss Flats at Moor House and Flow Moss.

5.2 A Sediment budget for Flow Moss

5.2.1 Construction of sediment budget

The measurement of key sediment fluxes and the identification of the linkages between the different components of the geomorphological system enable the construction of a sediment budget (Dietrich *et al.*, 1982). Sediment budgets assess the catchment sediment balance by evaluating the total sediment inputs and the change in storage of sediment within the catchment (Evans and Warburton, 2005) and therefore allow the identification of the relative importance of key processes at the catchment scale. Table 5.1 lists the key fluxes of the sediment budget at Flow Moss (Chapter 4) and Figure 5.2 demonstrates these fluxes and the linkages between the systems in diagrammatic form.

Physical Process	Sediment flux (t a^{-1})	Quantified error (t a^{-1})	Sources of unquantified error
Wind erosion of peat flats	3.2	0.97	Assumption that the data from this study period is representative of annual rate. Assumption that the monitoring area is representative of the whole bare peat area.
Peat loss from hagg slopes	0.72	-	The study slopes are representative of the rest of the study area
Hydraulic peat transport (at catchment outlet)	0.00546	-	Loss of fine suspended sediment through sack traps. Assumption that rates of peat collection are consistent throughout the year.
Deposition in pools	0.749	0.3	The monitored pool is representative of other pools.

Table 5.1: Table of calculated sediment fluxes for Flow Moss between 19/11/10 & 7/7/11.

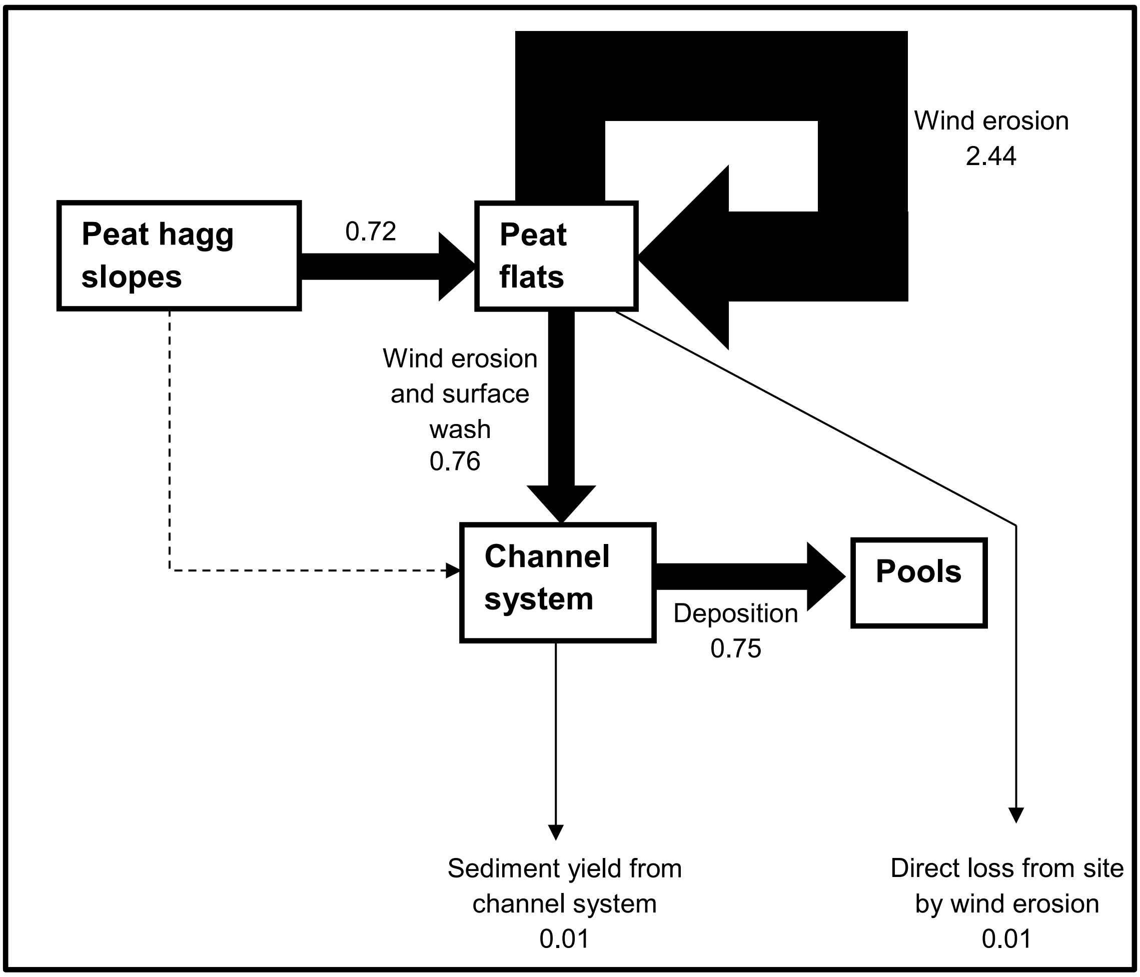


Figure 5.2: Diagrammatic representation of the annual Flow Moss sediment budget. All values in tonnes. Arrows are proportional.

The sediment budget diagram identifies two important features that characterise the processes that occurred at Flow Moss during the study period; the highly active bare peat flats and; the very low overall sediment yield. A relatively large amount of sediment is transferred across the bare peat flats by wind erosion but the majority of this sediment remains on the peat flats and does not enter the channel system. Warburton (2003) suggests that particles eroded by wind-splash generally travel distances between 1 and 10 m once they have been put into transport and up to and in excess of 50 m when dry dust is blown. These distances are short relative to the size of the bare peat area at Flow Moss so it appears that during each wind-erosion event; most of the peat will be transported to another area of the peat flats, rather than lost from system. The length of the bare peat area at Flow Moss is approximately 200 m long with the width ranging from 16 m to 76 m (Figure 2.2). Five potentially large erosion events were identified during the study period (Figure 4.4) and if particles are only transported distances of up to 10 m, it will take a long time for the weathered material to be transferred from the peat flats. Therefore the active peat flats are disconnected from the rest of the system because the weathered material from the intact peat mass is transferred and deposited within the peat flat system (mainly in vegetation and pools). Therefore, material transfer from the peat flats to the channel system in a single rainfall erosion event is likely to exploit sediment already located close to the margin of the channels rather than sediment stored in the middle of the peat flats. However, some material will be lost from the site through wind erosion but given the size of the vegetated area between the bare peat flats and the site boundary (fenceline) (Figure 2.1), it will be a small amount. It is assumed that only the peat transported at the highest altitude above the peat surface would be lost from the site and this makes up < 3% of the total transported by the wind (Figure 4.9). Using this value of 3%, give a total loss of peat from the site through aeolian processes of 0.01 tonnes.

Peat is transferred from the slopes of the peat haggs directly to the peat flats and where these slopes are close to the channels, some peat will be lost directly to the channel system (dotted line in Figure 5.2). This was not directly measured in this study, as all the monitoring sites were located on haggs within the bare peat area (Figure 3.19), but it is unlikely that the volume of peat transferred in this manner will significantly alter the sediment budget. Therefore, the majority of material that enters the channels is eroded from the peat flats but once in the ephemeral channel system, most of the material is trapped by vegetation or deposited in pools. Only a very small volume of peat is lost from the site. The bare peat flats are inefficiently coupled to the channel system and while erosion and sediment transfer are very active on the flats, the nature of the channel and pool system prevents this eroded material from being lost from the site. However, the degree of connectivity between peat flats and channels depends on the season. Wetter conditions occur in the winter and this has been shown to affect the volume of peat removed from the site (section 4.2.2 and 5.1.4). Therefore due to the dynamic nature of the processes, the relative importance of the linkages and sediment fluxes in the sediment budget will vary between winter and summer, however over an annual timescale Figure 5.2 provides a useful estimate of the catchment sediment budget.

In addition to intra-annual variability in the sediment budget, there will also be inter-annual variability. Results from section 4.1.1 show that the study period experienced lower than average rainfall which is important as the amount of rainfall is significant in controlling the export of material from the channel system. The relatively dry conditions allowed vegetation to establish in the channels which acted to trap sediment and reduce the sediment yield (Figure 4.18). If the study period had occurred during a wetter year, high flow in the channels would occur for a longer period, thus increasing the overall sediment yield for the catchment and increasing the connectivity between the systems. The amount of wind erosion is also controlled to some extent by rainfall so during a wetter year it is also expected that more erosion would occur on the bare peat flats providing a greater flux to the channel system.

Initially it was planned to produce a preliminary sediment budget for Flow Moss at the start and end of the monitoring period to assess the effectiveness of reducing peat flux. Unfortunately, due to the length of the study period relative to the length of time required for the restoration measures to take effect this was not possible so differences between pre- and post-restoration processes could not be determined. Therefore the sediment budget presented here is representative of a catchment that has undergone recent brash spreading, but the measures are yet to fully take effect so it can be assumed that the nature of the sediment fluxes in the catchment are still in their most active state. However, it is important to note that the brash spreading may have already affected the peat surface but it is suggested that this would not significantly alter the results. Figure 4.37 indicates that some of the brash has been lost from the surface since spreading which would have increased the organic sediment yield during the study period. If the original spreading mass of the brash was known, it would be possible to use Figure 4.37 to calculate the loss if organic material during the study period simply through brash removal. In order to assess the effectiveness of the restoration measures, the monitoring of the processes must continue in the future so the overall period of study is increased and the heather brash has a chance to re-vegetate and reduce the amount of sediment transfer across the bare peat flats.

5.2.2 Implications of sediment budget

5.2.2.1 The terrestrial carbon store

5.2.2.1.1 Calculation of the carbon balance at Flow Moss

Section 4.4.2 estimated the volume of peat stored within the 7 hectare restoration site at Flow Moss and calculated from this an estimate of the amount of carbon stored in the peat mass. As the peat depth measurements are an under-estimate, there is at least 2060 tonnes of carbon stored in the peat mass inside the fenced off restoration area. This value does not represent a carbon budget for Flow Moss (e.g. Worrall *et al.*, 2009a; Gibson *et al.*, 2009) but rather the total carbon stored within the peatland resource. In order to find whether Flow Moss is currently a net carbon sink or a net carbon source, a budget was developed using a simple model that assessed the relative importance of carbon loss from areas of bare peat and carbon drawdown by areas of vegetated peat within the catchment. This study did not directly measure the gaseous fluxes from the peat, or the quantity of dissolved organic carbon (DOC) lost from the site but an estimation of the carbon budget can be made using values from previous studies and the knowledge of the areas of bare peat and vegetated peat within the catchment.

Evans and Lindsay (2010) found that an intact peatland in the South Pennines fixes carbon into terrestrial store at a rate of 20.3 ± 4.0 gC m^{-2} yr^{-1} and this is similar to rates from other studies as Roulet *et al.* (2007) monitored the rate to be 21 gC m^{-2} yr^{-1} and Nilsson *et al.* (2008) found the rate to be between 20 – 27 gC m^{-2} yr^{-1}. Therefore, this study uses the value of 20.3 ± 4.0 gC m^{-2} yr^{-1} as it was monitored at a site similar to Flow Moss. There remains debate over the rate that carbon is lost from areas of bare peat and Evans and Lindsay (2010) use a value of 56 gC m^{-2} yr^{-1} in carbon budget calculations while Worrall *et al.* (2011) claim that the carbon flux from bare peat areas ranges from 272 ± 15 to 522 ± 59 gC m^{-2} yr^{-1}. Within the 78,000 m^2 fenced off restoration area, there is currently 17,550 m^2 of bare peat and 60,450 m^2 of vegetated peat. Using these areas and the carbon fluxes listed above, Table 5.2 shows the calculations for the carbon budget of Flow Moss. As the flux of carbon from bare peat areas is still debated, two scenarios are presented in Table 5.2; the first uses the value of 56 gC m^{-2} yr^{-1} and the second can be treated as a 'worst case' of carbon loss as it uses the maximum value from the range of Worrall *et al.* (2011); 591 gC m^{-2} yr^{-1}.

Surface cover	Carbon flux rate (gC m^{-2} yr^{-1})	Area (m^2)	Total carbon stored/lost per year (tC yr^{-1})
Vegetated peat	20.3	60450	1.22
Bare peat (1)	-56	17550	-0.98
Bare peat (2)	-591	17550	-10.37
Flow Moss Carbon budget (1)	+3.13	78000	0.24
Flow Moss Carbon budget (2)	-117.243	78000	-9.15

Table 5.2: Table showing calculations of the carbon budget at Flow Moss under two scenarios

Table 2 clearly shows that the rate at which carbon is lost from bare peat can have a major impact on whether an area is a net source or a net sink of carbon. In scenario 1, using a peat flux of 56 gC m^{-2} yr^{-1}, the fenced off restoration area at Flow Moss is at present a slight sink of carbon with 0.24 tonnes of carbon stored across the site per year. However, in scenario 2, the restoration area is a large net source of carbon with 9.15 tonnes of carbon lost across the site per year.

5.2.2.1.2 Implications of carbon balance for the carbon store

Section 4.2.2.2 estimated the total carbon currently stored at Flow Moss to be 2060 tonnes. Therefore, at present, using scenario 1, the total carbon stored at Flow Moss is increasing by 0.01% per year. Using scenario 2, the total carbon store at Flow Moss is decreasing by 0.4% per year. These low values, for both scenarios, suggest that the terrestrial carbon store at Flow Moss is relatively stable when other processes, such as POC loss during gully erosion or peat slides, are not significant contributors to the carbon budget. Neither of these processes is likely to occur at Flow Moss due to the low slope angle across most of the site.

5.2.2.1.3 Projections of future carbon balance due to restoration measures

It is also possible to use the carbon budget model from Table 5.2 to project the impact of the restoration measures at Flow Moss on the carbon store. The main aim of the restoration is to re-vegetate the bare areas of peat and thus varying the bare peat extent in the model changes the relative importance of the two flux rates. For example, using the flux rates from scenario 1, but assuming a full vegetation cover; the total carbon stored at Flow Moss would increase to 1.58 tonnes of carbon per year. It would require a 90% decrease in bare peat cover under scenario 2 before Flow Moss would stop being a source of carbon and would become a net sink. Therefore, assuming the worst case in flux rates; while bare peat areas persist within the area, there would be an ongoing net loss of carbon. In order to achieve the restoration aim of preventing carbon loss from the site, it is very important that the re-vegetation of all the bare areas is successful.

With full vegetation coverage within the restoration area, the model predicts that 1.58 tonnes of carbon would be stored at Flow Moss each year. However the model used to generate Table 5.2 does not take into account the loss of particulate organic carbon (POC) through fluvial processes. While the sediment budget suggests that very little peat (containing 50% carbon) is lost from the site through these processes, it would require an increase in peat flux of 3.16 tonnes per year to offset the carbon balance; a 586 times increase on the present day rate (0.054 tonnes per year). While it is unlikely that the loss of POC will increase sufficiently in the future to completely offset the carbon balance under fully vegetated conditions, it is possible that it will reduce the net carbon sink slightly.

5.2.2.2 Comparison with sediment budgets from other peatlands

There have been two studies in the past that have constructed sediment budgets for peat catchments at different levels of degradation; at Rough Sike, North Pennines, by Evans and Warburton (2005) and; at Upper North Grain, South Pennines, by Evans *et al.* (2006). The sediment budget diagrams for these catchments are shown in Figure 5.3 and can be compared to the budget at Flow Moss in Figure 5.2.

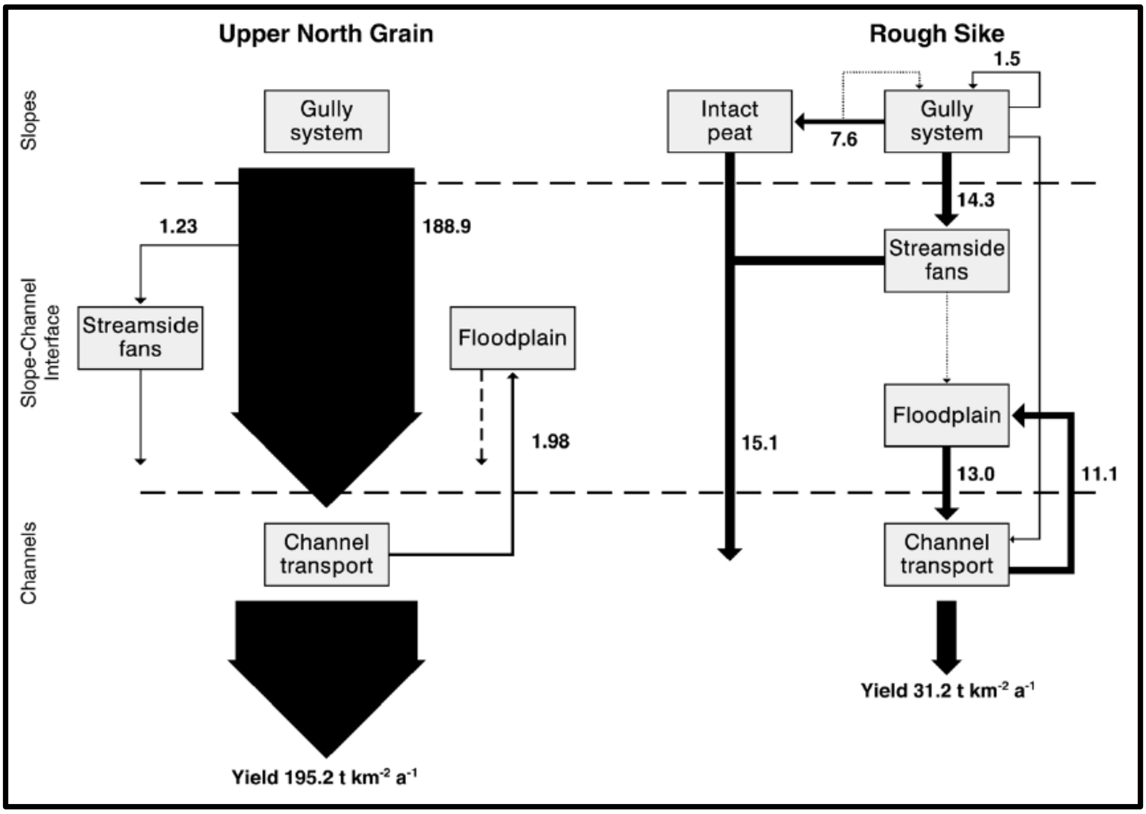


Figure 5.3: Sediment budgets for Upper North Grain, an actively eroding and highly connected catchment in the South Pennines and Rough Sike, a naturally re-vegetating catchment in the North Pennines.

Upper North Grain is characterised by an actively eroding gully system that is highly connected to the channel system. Most of the eroded material in the gullies is lost from the catchment in the channel system and very little is stored within the catchment once it has been eroded (Evans *et al.*, 2006). At Rough Sike, on the other hand, the gully system is disconnected from the channel system because the gully floors have begun to recently re-vegetate (Evans and Warburton, 2005). The roots and leaves of the vegetation not only trap eroded sediment but also bind the gully floors together making it harder to erode them. This is similar to the drainage channels at Flow Moss which have been vegetated grows during the spring and summer months of 2011 (Figure 4.17B). It is not known whether the vegetation growth at Flow Moss is a natural trend that occurs every year or is an early response to the restoration measures.

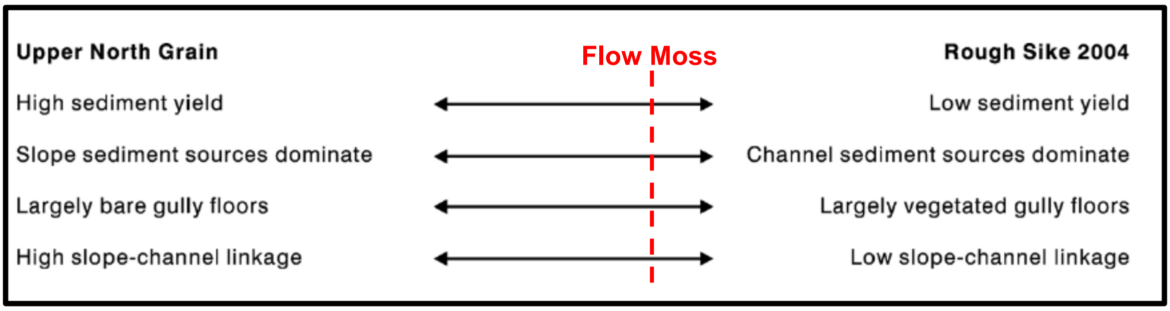


Figure 5.4: Spectrum of eroding peat catchments. Red line indicates approximate location of Flow Moss. Adapted from Evans *et al.* (2006).

Evans *et al.,* (2006) claim that these catchments represent the two extremes on a spectrum of eroded peat catchments (Figure 5.4). It is difficult to locate Flow Moss on the spectrum but a possible position is suggested by the red line on Figure 5.4. Flow Moss has characteristics of both of the extreme catchments; a very low sediment yield similar to Rough Sike and active erosion across bare areas similar to Upper North Grain. The red line is closer to the less actively eroding end of the spectrum due to very low overall sediment yield but the catchment is different to Rough Sike because the bare peat flats are very active but, during the dry conditions of this study period, are not connected to the channel system particularly well. Under wetter conditions, it is more likely that the peat flats and the channel system at Flow Moss will become better connected with less peat deposited in the pools, therefore moving towards the more actively eroding end of the spectrum. However, Flow Moss will never be characterised by similar processes to Upper North Grain as the erosion/sediment transfer potential at Flow Moss is low due to the low relative relief and shallow channel gradients. These macroscale controls (Evans and Warburton, 2007) are important in controlling the geomorphic activity of upland peatland systems.

5.2.2.3 Possible threats to Flow Moss in the future

An understanding of the processes operating at Flow Moss through the sediment budget framework provides a basis for predicting how the system will respond to climate change (Evans and Warburton, 2007). Ombrotrophic peatlands exist because of the maintenance of a positive water balance through the complex interaction of different climatic factors such as rainfall and evapo-transpiration (Evans and Warburton, 2007). As demonstrated in this study, climatic and weather conditions are important in controlling the type and magnitude of peat erosion. Therefore, future changes in the climate could be important in altering the balance of peat growth/erosion and could become a significant threat to the UK uplands. There is a large body of work that has studied the historical onset to peat erosion, mostly by Tallis in the South Pennines (summarised in Tallis, 1997b; 1997c), and this palaeo-ecological (pollen and macrofossil) evidence identified climate change as an important triggering factor. A significant period of peat erosion occurred between 1250 and 1450 AD which coincides with the early Medieval Warm Period when climate conditions were slightly warmer than present. This suggests that peatland degradation can be more severe during warmer conditions and/or increased rainfall (Evans and Warburton, 2007). Under warmer and drier conditions, peatlands are more likely to experience lower hydrological conditions for longer periods making them more susceptible to degradation and environmental change. It has been identified in this study that more peat is eroded during rainfall events that combine high rainfall intensities with high wind-speeds (Figure 4.13). If there is an increase in the occurrence of these most extreme events (five were identified during this 8 month study period), it is likely peatlands will be under a greater threat of degradation in the future.

Table 5.3 gives the projections for future climate in the UKCP09 report for the North-East England during 2080s. The table can be summarised by the winters becoming warmer and wetter and the summer becoming warmer and drier relative to the 1961-1990 baseline. The impact that these conditions can have on UK peatlands is presented in Table 5.4 and the possible impact on Flow Moss is discussed below.

		2080s		
		Low emissions	**Medium emissions**	**High emissions**
Summer	**Temperature (^{O}C)**	+2.8	+3.7	+4.7
	Precipitation (%)	-13	-18	-23
Winter	**Temperature (^{O}C)**	+2.4	+2.6	+3.2
	Precipitation (%)	12	+14	+19

Table 5.3: Climate projections for North-East England for the 2080s relative to the 1961-1990 baseline. *Source: UKCP09.*

Climatic change	**Hydrological change**	**Erosional impact**
Increased summer and autumn drought	Lower water tables (greater acrotelm depth)	Peat shrinkage and desiccation Increased aeolian erosion
Increased summer and winter rainfall intensity	Increased peak storm runoff	Accelerated erosion of bare peat areas (rainsplash and wash) and increased channel erosion and gullying Less deposition in pools
Extended growing season	Greater evapotranspiration (minor)	Reduced erosion due to re-vegetation of bare peat areas and more mature vegetation blanket
Reduced frost frequency	Reduced impact of snowmelt events	Less frost-heave disturbance Less disruption to newly established vegetation

Table 5.4: Hydrological and erosional consequences of climate changes on upland peat in Britain. Climate change scenarios from Hulme *et al.* (2002). *Adapted from Evans and Warburton (2007).*

Each of the possible outcomes listed in Table 5.4 has the ability to threaten the peat at Flow Moss in terms of increasing erosion and sediment transfer. With an increase in annual rainfall and the frequency of extreme events, there is a higher erosive potential as there is more energy for erosion to occur through rainfall ballistic impact and transfer by higher velocity winds. Increased rainfall will also prolong the period when the water table is close to the surface of the peat and thus increase the connectivity between the peat flats and the channel system, resulting in a greater sediment yield. Figure 4.16 identifies the long term impact of wind direction on the geomorphological development at Flow Moss and, under the predicted changing climate; this relationship between wind and landscape is likely to strengthen further.

It is also likely that there will be an increase in the amount of weathering and sediment production on the peat surface in the future as a result of climate change. A decrease in the number of frost days will generate less sediment through freeze-thaw weathering but there will be longer periods of dry and warm conditions in the summer months which will generate more sediment through surface desiccation and cracking. Therefore there will be more sediment available and more energy available through wind and rain to transport the sediment from the bare peat flats. If the site was not undergoing restoration or if the measures were to be unsuccessful, it would be expected that both the sediment yield and the connectivity in the system would increase. One possible positive outcome of predicted climate change is the extended growing season which may benefit the re-vegetation of the bare areas as there is more opportunity for heather seeds to colonise the bare peat. The extended growing season would also increase the uptake of carbon in the peat store by increasing the amount of primary productivity but it is unlikely that this will stop Flow Moss from being a net carbon source. Freeman *et al.* (2001) suggested that longer periods with a lower water table will increase the export of carbon as increased rates of aerobic respiration near will occur at the peat surface. The balance of the carbon cycle may change slightly, but without successful restoration measures, Flow Moss will continue to suffer a net loss of carbon from the terrestrial peatland store.

Widespread regional scale peat erosion occurs almost uniquely in the UK (Evans and Warburton, 2007) but under a warming climate, the threats to other, currently stable, peatlands across the Northern Hemisphere will increase. Therefore an understanding of the response in UK upland peatlands could be extrapolated to help understand and predict how other peatlands across the globe will respond. Through study of restoration techniques carried out in the UK, the widespread degradation of the other peatlands could be prevented before it begins. Despite restoration strategies, it may be impossible to return a degraded peatland to a fully natural state and structure and is only possible to restore the function of a peatland (Dobson *et al.*, 1997). Therefore, it is important that degradation of natural peatlands is prevented in the future before it can occur as the natural peatland system could be lost.

5.3 Quantitative assessment of effectiveness of peatland restoration measures at Flow Moss

The third research objective outlined in chapter 1 was to provide a quantitative assessment of the effectiveness of the restoration measures in terms of reducing erosion and sediment transfer. An assessment of the heather brash coverage was carried out in June 2011 to assess how successful the measures had been. Section 4.5 describes areas of the bare peat where brash has been blown from the surface leaving exposed bare peat which shows that on average 17.5% of the brash has been lost. The two main aims of spreading the brash over the peat surface are to shelter the bare peat from wind and rain and for seeds contained in the cuttings to colonise the bare areas of peat. At the end of the study period (7th July 2011), approximately seven months after the brash had been spread, there was no noticeable sign that the seeds contained in the brash had begun to grow on the peat.

There are two possible reasons why this may be the case and both are related to the climate. The brash was spread in December 2010 which was characterised by a prolonged period of sub-zero temperatures (Figure 4.2) which meant that the brash was being spread onto frozen ground and a loose layer of peat generated by freeze-thaw weathering. It is possible that these antecedent conditions may have prevented the fertilisation of the heather seeds during the spring months of 2011. The other possible climatic cause is due to the below average rainfall that the site received during the study period. This has led to a low water table which dried out the peat surface which may also not be ideal conditions for heather growth. The publication of the *Moors for the Future* five year report on the nature and rates of Sphagnum recovery in 2012 will provide valuable information for assessing the time frame for the recovery of the Flow Moss peat flats following restoration measures.

5.3.1 Implications of research for peatland restoration techniques

Peat erosion is potentially a reversible process, either through natural re-vegetation or with the benefit of restoration measures (Evans and Warburton, 2007) but the degree of recovery varies spatially across regions. Evans and Warburton (2007) state that further research is required on the interaction of ecological and geomorphological processes to promote the re-vegetation of eroded landscapes and this study is one of a growing number of investigations that attempts to quantify the effectiveness of restoration measures. The sediment budget identifies the effect of wind erosion as being several times greater than the other sediment fluxes but monitoring of the initial phase following the restoration measures suggests they not been entirely successful as the brash as not ‘taken’ on the peat surface during the study period. Despite the monitoring occurring in a dry year relative to normal conditions, the bare peat flats are poorly connected to the channel system. Over time the loose material dislodged by rainfall impact will eventually reach the channel system where the vast majority is deposited in pools or trapped by vegetation. It is therefore very important, in terms of reducing erosion and sediment transfer, that the restoration measures are successful but in order to achieve this, additional measures may need to be carried out. The monitoring of the brash and re-colonisation should continue to identify whether there is a significant time delay between the brash spreading and the re-colonisation of the bare peat surface.

If the initial spreading of the brash is proved not to have been successful, more heather brash should be spread over the bare peat areas, targeting exposed areas where the original brash layer has been blown or washed from the surface. As it appears that the heather seeds had not colonised the bare peat during the spring of 2011, a re-application of brash may be necessary. From October 2010 to July 2011, Flow Moss experienced below average rainfall which led to a drying out of the peat surface, a potential factor preventing seed germination. In the South Pennines, bare peat restoration is carried out under the 'Moors for the Future' project which uses other restoration measures in addition to the spreading of heather brash. These include 'geo-textiles', a bio-degradable netting that is spread over areas where heather brash can be lost from the surface such as on steep slopes. The geo-textiles act to reduce erosion and trap the brash seeds on the bare peat surface (Moors for the Future, 2011).

Section 4.5 demonstrated that some of the brash has been lost from the peat surface due to the wind and the channels washing the brash away. A solution to this could be the spreading of geo-textiles over the bare peat surface, especially in the margins of the peat flats close to the channels so that the brash and the heather seeds are protected from the wind and rain. Although a more expensive measure, it could accelerate the rate of re-colonisation of the bare peat areas so that Flow Moss returns to a 'natural' state over a shorter timescale.

5.4 Important issues for future study

With any monitoring study, the dataset is limited by both spatial and temporal constraints. This study details the erosion and sediment transfer at one site; Flow Moss; for a relatively short 8 month period covering the period of time just before, and the period after, the initial application of the restoration measures. The easiest way to improve this study is by extending the monitoring period. This study does not have any data for the late summer and early autumn months which may be important as increased rates of surface desiccation may occur during August and September. The increased length of the dataset would provide a better understanding of the physical processes, and also a more accurate sediment budget for the site would be able to be constructed.

Also, this phase of the study has ended before the restoration measures have fully taken effect. Therefore, the monitoring should be continued so that the dataset covers the impact of the restoration measures on the site. If, for example, 2012 is a wetter than average year then the processes acting at Flow Moss will be different to those monitored during 2010-2011 and will add to the understanding of the dynamics of peatland erosion and restoration. In addition to the field equipment remaining in place over a longer period, repeat surveys using the UAV should be carried out at regular intervals. The UAV images allow the efficient assessment of the total area of bare peat so a dataset of images built up over time will show how the area of bare peat is reduced as a result of the restoration. The field equipment has remained at the site at Flow Moss so in the future; the detailed monitoring of processes will be continued.

In addition to Flow Moss, detailed studies of erosional, especially aeolian, processes have only occurred at Moor House, also located in the North Pennines by Warburton (2003), Foulds and Warburton (2007a & b) and Evans and Warburton (2005). To allow a fuller understanding of the mechanical processes acting on bare peat, the findings from these studies should be compared to findings that have been generated from a wide variety of studies from different contexts such as the very actively eroding South Pennines or lowland peatland environments where weather conditions are not as extreme. It may be the case that the processes acting at Flow Moss and Moss Flats are isolated to the North Pennines and may not be representative of other peatland systems. Therefore, where possible, a study of aeolian erosion processes should be carried out across a variety of locations that complement this study at Flow Moss and those carried out at Moor House.

A significant limitation of this study is the lack of baseline monitoring of erosive processes before the restoration measures were implemented. This study, into the effect of peatland restoration on erosion and sediment transfer has the potential to apply a Before-After-Control-Impact experimental approach (discussed in Section 1.7). The monitoring framework at Flow Moss began just before the start of the intervention, rather than several years before which would have been ideal in accurately determining the background rates of erosion and sediment transfer. However, this problem is not likely to be significant because of the time taken for the heather brash to colonise the areas of bare peat. The initial sediment budget calculated here can therefore be used as the baseline to monitor any impact the restoration measures may have on sediment transfer and erosion rates at the site. There is not, however, a similar ‘control’ site nearby that has not experienced restoration which could be compared to the Flow Moss data. A solution to this is to compare some of the data to work that has been carried out on similar processes at Moor House, 22 km from Flow Moss, also located in the North Pennines. Moor House is an area of blanket bog which experiences similar meteorological conditions to Flow Moss although it is approximately 100m higher in altitude. These comparable studies include the work on aeolian processes on the Moss Flats peat flats by Warburton (2003) and Foulds and Warburton (2007a, 2007b) and the calculation of the sediment budget for Rough Sike by Evans and Warburton (2005). As both Flow Moss and Moor House experience similar environmental conditions and the studies were carried out using similar methods, a comparison can be made between the datasets to try and isolate the impact of peatland restoration from background noise. However, due to the distance between the sites and the changeable nature of the upland climate across small spatial and temporal scales (Burt and Holden, 2010); any conclusions drawn from the comparison between the two sites should be taken with a degree of caution as the sites do not allow the construction of a full BACI investigation.

Chapter 6. Conclusions

This chapter provides a brief synthesis of the findings discussed in Chapter 5 and outlines the main conclusions from the research. The chapter ends with suggestions for further work.

6.1 Synthesis of findings

The first part of Chapter 5 discussed the mechanics and dynamics of the physical processes acting on the bare peat at Flow Moss. Processes of aeolian erosion differ during dry and wet conditions due to the ballistic impact of rainfall detaching particles from the peat surface (Section 4.2.1). This leads to a larger amount of erosion by wind during wet periods than under dry conditions (Figures 4.10, 4.13). Wind-speed is also an important meteorological control on peat erosion, because peat once detached, is transported further by higher wind-speeds. Wind direction is significant in controlling geomorphological processes over both short and long timescales. Up to eight times more peat was collected in the windward facing traps than the leeward facing traps during rainfall events and peat haggs are oriented dominantly in the same direction as the prevailing wind (Figures 4.12, 4.16 and Section 5.1.1.1).

Antecedent meteorological conditions prior to an erosion event, leading to freeze-thaw weathering or desiccation, are vital in preparing loose material on the bare peat surface. The erosion of this material occurs in two phases, with the loose material eroded first before the intact peat surface layer (Figure 4.15). The sediment yield is therefore supply-limited and dependent on the degree of sediment production that occurs prior to the erosion event.

The preliminary sediment budget constructed for Flow Moss (Figure 5.2) shows that while the bare peat flats are being actively eroded, they are not well connected to the channel/pool drainage system so most of the material is reworked or deposited elsewhere on the peat flats. However, during wet conditions the peat flats are more highly connected to the channels. Thus, because this research was carried out under drier than average conditions, it would be expected that the sediment yield would be greater under more ‘normal’ wetter conditions, when the water table is higher for longer and the ephemeral channels more active. The vast majority of material that is transferred from the peat flats to the channel system is deposited in the peat pool system. These pools are therefore highlighted as a very important part of the budget as they act as a significant store for the eroded and transferred peat.

At present, the fluvial export of peat from Flow Moss is very low (< 0.1 tonnes per year) because of the effective trapping of eroded peat in the drainage network and pools. These pools, especially the pool located near the catchment outlet of Flow Moss, are very important sites of deposition and prevent large volumes of peat from being lost from the site. However, given the current rate of erosion processes acting at the site (e.g. wind erosion: 3.2 tonnes per year), an increase in the fluvial export by only a few tonnes would be enough to offset the balance of these processes. An increase in fluvial erosion (peat export) could be caused by increased rainfall in the future or if the depositional capacity of the pools were to become exhausted (Section 5.2.2.3)

Section 5.2.2.1 discussed the calculation of the carbon balance (Table 5.2) and it was found that the terrestrial store of carbon at Flow Moss (2060 tonnes) is relatively stable at present. Even under the worst case scenario of carbon flux rates, it is only decreasing in total size by 0.4% (9.15 tonnes) per year (due to physical processes). It is nevertheless still important that the restoration measures are successful because the carbon balance calculations demonstrate that the site will stop being a ‘source’ of carbon and become a ‘sink’ when approximately 90% of the current extent of bare peat has been re-vegetated.

6.2 Main conclusions of the research

- The amount, type and timing of erosion of bare peat at Flow Moss is closely controlled by the environmental conditions both before and during an erosion event.
- Rainfall influences the amount and dynamics of aeolian processes on the bare peat flats as well as the hydrological conditions across the catchment which affect the connectivity of the bare peat flats to the channel/pool system.

- Fluvial export of peat from Flow Moss is very low due to the active deposition of transported peat in the pools and ephemeral nature of the channel system.
- The total terrestrial carbon store at Flow Moss is currently relatively stable but could potentially be under threat in the future from increased fluvial export of peat (POC).
- Successful restoration of full vegetation cover is essential to reduce erosion rates through aeolian processes, mitigate the potential impact of enhanced fluvial erosion and to ensure Flow Moss returns to a positive net carbon store.

6.3 Suggestions for further work

Section 5.4 discussed recommendations made for future research based on the experience of study. Firstly, it is important that the monitoring at Flow Moss is extended to provide further evidence of the dynamics and relative importance of the physical processes acting at the site. An extended period of monitoring would help further understand the effectiveness of the restoration measures in terms of reducing erosion rates and should ideally be continued for a minimum of two additional years. Secondly, similar studies should be carried out at other locations and should be combined with local weather monitoring so the conclusions regarding the dynamics and mechanics of the physical processes can be built on and tested further. In particular, real-time monitoring of aeolian peat transport and channel system sediment flux would be highly desirable.

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