# Modelling blanket peat erosion under environmental change

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#### **Abstract**

Many peatlands across the world are suffering from degradation and erosion exacerbated by human influences. Blanket peat erosion has adverse impacts on terrestrial and aquatic habitats, reservoir capacity and water quality. It also leads to accelerated carbon release. Bioclimatic modelling suggests that some areas, which are suitable for active peat growth currently, may be no longer under a climate supporting the accumulation of peat by the end of the century. Erosion in these marginal regions is thus more likely. However, there have been no attempts to date, to model blanket peat erosion mechanisms and rates and how they might respond to different climate scenarios and land management drivers.

The PESERA-GRID model was chosen as a basis for modelling blanket peat erosion as it had a number of suitable properties such as its applicability in various spatial scales, and hydrological module is theoretically suitable for blanket peatlands. The model was modified to incorporate freeze-thaw and desiccation processes and typical land management practices (artificial drainage and burning) in blanket peatlands. This resulted in a modified model called PESERA-PEAT. In PESERA-PEAT, blanket peat erosion is determined by both sediment supply through weathering and the transport capacity of overland flow. A novel sediment supply index was defined and employed to parameterize the sediment supply from blanket peatlands. Land management practices were parameterized for their influence on vegetation cover and biomass and soil moisture condition. Potential wildfire severity was estimated with a previously developed ignition model. The PESERA-PEAT model was calibrated and validated with field data from previous publications and data from three blanket peat-covered catchments. Model testing suggested that PESERA-PEAT was robust for modelling blanket peat vegetation, runoff and erosion.

Climate change scenarios were established and climate data were compiled to 2100. The PESERA-PEAT model was applied at a regional scale for the blanket peatlands of the North Pennines and at a smaller scale for ten sites across Great Britain to examine the response of blanket peat erosion to possible changes in climate and land management practices. Modelling results suggested that the response of blanket peat

erosion to climate change was highly variable across space both within regions and across Great Britain with some sites experiencing reduced erosion under some climate scenarios with most experiencing increased erosion. The model suggested that peat erosion change would be generally higher in southern and eastern areas than in western and northern parts of Great Britain. Predicted erosion change was particularly high in the North York Moors where lower rainfall and higher temperatures suppressed the water table, and led the predicted future erosion to be usually transport limited. It was suggested that summer desiccation may become a more important sediment source for British blanket peat erosion in the future, leading to more sediment erosion released from blanket peatlands during subsequent rainstorms. Erosion change with climate change to 2100 was predicted to be smaller in wetter and colder locations. As climate changes, rainfall was shown to be more important than temperature in shaping long-term changes in runoff production while temperature was generally more dominant than rainfall in controlling long-term erosion change. However, in the North York Moors rainfall appeared to be more dominant in long-term erosion change. Overall, the modelling work suggested that land management may have a greater impact on blanket peat erosion than on runoff, while climate plays a more important role in runoff production rather than in blanket peat erosion. It was suggested that adjusting land management practices may be appropriate in order to buffer the impacts of future climate change on blanket peat erosion. However, when blanket peatlands were managed to protect them from soil erosion through ensuring a thriving vegetation biomass cover, then wildfireawareness and precautionary fire measures would be required as the wildfire risk increased substantially with climate change and may also increase with such land management strategies.

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# **Chapter 1**

## Introduction

#### 1.1 Background

Peat is an organic-rich soil resulting from very slow vegetation decomposition under a water-logged environment. Approximately 4 million km<sup>2</sup> of peatlands exist across the world, storing 33 % to 50 % of the world's soil carbon (Charman 2002; Holden 2005c). Being an important subset of peatlands, blanket peat mainly occurs within the hyper-oceanic climate areas such as the British Isles, Newfoundland, Alaska, Iceland, Norway, New Zealand, Falkland Islands and Japan etc. Many peatlands globally occur on rather gentle terrain or infill the topography of an underlying basin. However, blanket peatlands tend to occur in a deposit that follows the underlying topography (Lindsay 1995) and can occur on slopes up to 30 degrees in steepness (Nature Conservancy Council 1989). Blanket peat deposits often tend to occur over depths of one metre or more, sometimes exceeding 6 m of thickness (Charman 2002). They are in contact with the underlying mineral horizon at their base, but gain almost all of their water and nutrient supply from precipitation.

Where blanket peatlands form on a slope, they can be susceptible to rapid erosion if they become degraded because flowing water over hillslope gradients can act to entrain and transport peat particles to river channels. If peatlands degrade and become badly eroded then this means that i) they are no longer acting as good sequestration sites for carbon as the surface vegetation becomes less widespread and ii) the carbon once stored in the system is being lost from the site. Peatlands have a large potential to become net carbon sources when degraded, rather than good carbon sinks when intact (Evans, Stimson et al. 2012; Grayson, Holden et al. 2012; Pawson, Evans et al. 2012). At the same time, blanket peat erosion also has negative impacts on terrestrial and aquatic habitats (Ramchunder, Brown et al. 2009), reservoir capacity (Labadz, Burt et al. 1991) and water quality (Pattinson, Butcher et al. 1994).

Soil erosion is a process of detachment and transportation of soil materials by erosive agents, which can be wind, rainfall and runoff. In blanket peatlands, freezethaw and desiccation are commonly cited mechanisms to produce erodible materials (Tallis 1973; Francis 1990), which are vulnerable to the erosive agents. Many blanket peatlands globally have suffered from severe erosion over the past 60 years or so mainly because of land management drivers (Holden, Shotbolt et al. 2007) and atmospheric pollution (Evans and Warburton 2007) particularly in parts of the British Isles (Evans, Allott et al. 2005; Evans, Warburton et al. 2006; Cummins, Donnelly et al. 2011), Falkland Islands (Wilson, Clark et al. 1993), Sweden (Foster, Wright et al. 1988) and Australian Alps (Victoria National Park Association 2005). Several studies have also shown that some historical erosion in blanket peatlands has been driven by climatic change (Tallis, Meade et al. 1997; Tallis 1998). "Climate envelope analysis" for blanket peat-covered areas suggests that in many areas where there are currently blanket peatlands, these areas may no longer be under a climate suitable for active peat growth as the climate shifts over the coming century (Clark, Gallego-Sala et al. 2010; Gallego-Sala, Clark et al. 2010; Gallego-Sala and Prentice 2012). There may therefore be a possibility of enhanced degradation and erosion as favourable zones for peat formation shift towards being marginal climate zones for blanket peatlands, although the exact fate of the blanket peat in these marginal areas is uncertain given the unknown resilience of blanket peat to climate change. Furthermore, the interactions between land management and climate change may lead the change of blanket peat erosion to be more complicated in the future.

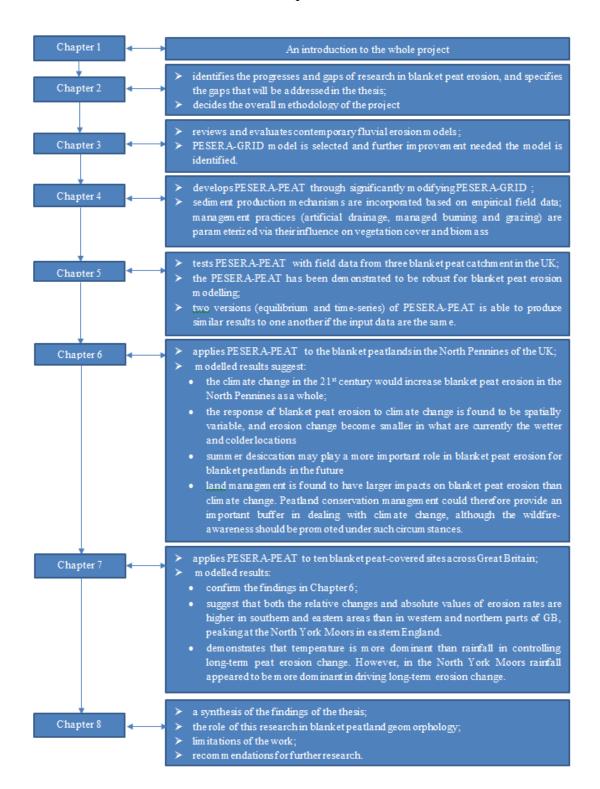
Often, research is carried out through field observation and experimental manipulation (Wainwright and Mulligan 2013). Hypotheses can be generated upon the observations from fieldwork and experiments to explain the structure and function of natural phenomena. These hypotheses can be tested and refined against new observations, and may eventually gain recognition as tested theory or general law. A model is an abstraction of reality, representing a complex reality in the simplest way that is adequate for the purpose of the modelling. Modelling is not an alternative to observations but, under certain circumstances, can be a powerful tool in understanding observations and in developing and testing theory. In environmental science, modelling has already become one of the most powerful tools in understanding of the interactions between the environment, ecosystems and

the populations of humans and other animals (Wainwright and Mulligan 2013). This understanding is increasingly important in sustainable management of the environment under possible changes in driving forces such as human activities and climate and so on. Being an important part of environmental modelling, there have already been many erosion models established over the last several decades (Merritt, Letcher et al. 2003; Aksoy and Kavvas 2005). Existing erosion models usually take account of hydrology, topography, land use / cover and soil properties as controlling factors of erosion, although each model tends to have a different emphasis related to the research purposes they were originally developed to address. Some of the erosion models (e.g. USLE and its modifications) have been widely applied and recognised as powerful tools in predicting soil erosion (Renard, Foster et al. 1991; Stone and Hilborn 2000; Tiwari, Risse et al. 2000; Onori, De Bonis et al. 2006; Meusburger, Konz et al. 2010). The possible reaction of soil erosion to changes in environmental factors involved in these models can be investigated and predicted without having to undertake large scale field trials for each scenario. The advances in erosion modelling and the scientific understanding of erosion processes in blanket peatlands facilitate a prediction of blanket peat erosion using a modelling approach. However, to the author's knowledge there has not been a blanket peat erosion model published. It is therefore important to develop a model to link blanket peat erosion with various driving forces to support environmental planning and protection. Given there are many erosion models established over last several decades, some of them may already be suitable or partly suitable for blanket peatlands. It may be more advisable to model blanket peat erosion with an existing model in order to avoid repeating the work that has been done previously.

#### 1.2 Research aim and objectives

Given the sensitivity of peatlands, the major aim of the project is to establish how fluvial blanket peat erosion mechanisms and rates may change under climate and management practices through the 21<sup>st</sup> century, and modify a preferred model to explicitly consider such mechanisms. In order to accomplish this aim, the project focuses on the case study of the UK and the following research objectives have been defined:

- to select and modify an erosion model for blanket peat capable of addressing the overall aim of this project;
- 2) to produce a spatially distributed climate and land management dataset to drive the modified peat erosion model for the 21<sup>st</sup> century, based on UKCP09 and combined upland management data resources;
- 3) to apply the modified model to determine the envelope of erosion risk under climate and management scenarios to the end of the 21<sup>st</sup> century for a case study region North Pennines, UK;
- 4) to explore national variations in climate-driven erosion risk predictions for Great Britain (GB).



**Figure 1.1** A flow chart of chapters and what they mainly achieve.

#### 1.3 Thesis structure

A flow chart of chapters and what they mainly achieve are presented in Figure 1.1. In order to investigate the response of fluvial blanket peat erosion to possible changes in climate and land management over the 21st century, it is necessary to understand the erosion processes operating in blanket peatlands and their contributing factors. A synthesis is provided in Chapter 2. The overall approach of the project is also presented in Chapter 2 related to the research gaps identified by the synthesis. Chapter 3 reviews and evaluates contemporary erosion models to find out which one is potentially suitable for further development and use in blanket peat environments. The grid version of Pan-European Soil Erosion Risk Assessment (PESERA-GRID) model is selected for the project. Significant adaptations are considered based on literature and field data to modify the PESERA-GRID model in Chapter 4 in order to include observed sediment production processes in blanket peatlands, and to aggregate typical land management practices into the model. The updated PESERA-GRID model (termed PESERA-PEAT in the thesis) is then numerically evaluated in Chapter 5 where different components of the model are tested against field measurements and previously published data. The PESERA-PEAT model has two modes: equilibrium and time-series. They have exactly the same physical processes but different manners of operation. The equilibrium model iterates sufficient times with monthly average climatic inputs over the study period to determine the equilibrium status of hydrology and erosion, while the time-series model runs only once through the whole study period with continuous monthly climate variables as inputs. The robustness of these two versions of PESERA-PEAT is demonstrated. It is also shown in Chapter 5 that the equilibrium and time-series PESERA-PEAT models are able to produce similar results to one another if the input data are the same. This provides more flexibility in applying PESERA-PEAT, as the equilibrium model needs relatively less input data, and is therefore easier to be applied over a large area. In contrast, much higher input requirements limit the application of the time-series model over a large space. However, the time series model is able to produce continuous monthly results within the study periods, and is therefore more suitable to capture extreme events at case study sites. The two versions of PESERA-PEAT are then used in Chapter 6 and Chapter 7 respectively. In Chapter 6, the equilibrium PESERA-PEAT model is applied based on spatially distributed input data to look at the development of blanket peat erosion in the North Pennines under projected climate change and possible land management scenarios. Spatially distributed results allow investigation of the impact of environmental change on both the magnitude and pattern of blanket peat erosion. In Chapter 7, the time-series PESERA-PEAT model is used to investigate the change of blanket peat erosion with environmental shifts at a GB national scale. Ten sites are selected to represent major blanket peat-covered areas in the GB. The spatial pattern of blanket peat erosion change with environmental variation is examined. The climatic drivers of the changes in blanket peat erosion are analysed. The implications for management of blanket peatlands in GB are discussed. A synthesis of the work (including research conclusions) in the project and its contribution to the geomorphology of blanket peatlands are presented in Chapter 8. Limitations of the work and areas for further research are identified in the chapter including discussion of the utility of the model internationally.

## Chapter 2

# Understanding blanket peat erosion

#### 2.1 Introduction

In order to investigate the development of blanket peat erosion under environmental change, it is necessary to understand erosion processes in blanket peatlands and their contributing factors. The main purpose of this chapter is to review what is known about processes of sediment production and transport in blanket peatlands and their relationship with different external forces.

The structure of this chapter is as follows. An introduction to peatlands is presented in section 2.2. Sections 2.3 and 2.4 concentrate on current knowledge of hydrology and erosional processes in blanket peatlands while drivers of change in blanket peat erosion are outlined in section 2.5. Section 2.6 summarizes the chapter by prioritising key research needs. The overall methodological approach for the rest of the thesis is presented in section 2.7.

## 2.2 Peatland classification and global distribution

Peat is not the same over the world and there are different characteristics which peat may have depending on its environmental setting. Charman (2002) categorized peat into four classifications which are moss, herbaceous, wood and detrital or humified peat. Moss peat could be further divided into *Sphagnum* (i.e. Sphagnaceae) and brown moss (i.e. Amblystegiaceae) which are common peat formers. Herbaceous peat often forms from the seed parts, leaves, stems, roots of sedges, grasses and rushes while woody peats are common in forested and shrub-dominated peatlands. Detrital or humified peat means that disarticulation and decomposition make the bulk of the plant remains hardly identifiable. As peat accumulates through time, peatlands are formed, but they also vary spatially across an individual site. As well as classification of peat, there is a long history of classification of peatlands (Moore 1984; Lindsay and Heritage 1995; Dykes and Kirk 2006; Boylan, Jennings et al. 2008). The source of water and nutrients are usually adopted to categorize peatlands into fens and bogs. The former are minerotrophic (groundwater-fed), receive water

and nutrients from outside their confines and tend to be nutrient-rich and alkaline. The latter are ombrotrophic (rainfall-fed), obtain water and nutrients only from the atmosphere and thus are acid and nutrient-poor. Moreover, a hydro-morphological peatland classification system (Table 2.1) was proposed by Charman (2002). In this system, the overall shape of the peat deposit and the underlying ground together with the hydrology of site are employed to determine the basic site types, which are then further subdivided by vegetation, water chemistry and peat stratigraphy.

**Table 2.1** Hydro-morphological classification system (summarized from Charman 2002)

First class	Second class	Definition
Ombrotrophic	Raised bog	Peatlands with domes and receiving water and nutrient only from atmosphere
	Blanket bog	A type of mire complex, made up of various ombrotophic peatlands
	Intermediate	An individual mire unit linked to another peatland type or extends beyond the usual definition of peatlands
Minerotrophic	Topogenous fens	Basin fens: form in basin situation where topographic depression is confined and no main inlet or outlet
		Floodplain fens: form along river system, receive much water from floods, sometimes including mineral soils
	Soligenous peatlands	Valley mires: form along the floors an lower slopes of valley that have dispersed flow of water through them
		Sloping fens: form on sloping terrain, receive water from runoff and groundwater maybe in the form of spring
Others	Other fens	Boreal and subartic peatlands, patterned fens and aapa mire: characterized by complex patterning on surfaces by the arrangement of pools, hollows and hummocks
	Mire complex	Complexes containing a variety of peat landforms and types

Peatlands have wide distribution around the world. However, neither the precise amount nor the exact extent of peat is well known mainly because criterion used to classify peat varies between countries (Immirzi, Maltby et al. 1992) and there are difficulties in determining peat depths. Even in Europe and North America, only the

approximate extent and distribution of peat can be determined (Gorham 1991). For the whole world, it is estimated that 4.4 million km<sup>2</sup> of peatlands exist (Yu, Loisel et al. 2010). Figure 2.1 shows the global distribution of peatlands. High latitudes of North America and Eurasia are important regions for peat accumulation and this is because of wet, cool climatic conditions. Peat accumulation increases northwards and peaks at around 60°N. Further north the low temperatures inhibit plant growth and hence active peat formation decreases (Zoltai, Taylor et al. 1988). Tropical areas also have large quantities of peatlands. High temperatures encourage decomposition, but anaerobic conditions in areas of plentiful water supply will, nevertheless, inhibit decomposition. Vegetation growth rates will also be fast in tropical peatlands so that organic matter accumulation is large. In Southeast Asia, peatlands may cover more than 10 % of the land area in many regions. In the Southern Hemisphere, peat is less of a feature than in the Northern Hemisphere because there is less land at latitudes suitable for its formation. However, peatlands can be found in large quantities in many parts of Southern America, Tasmania, New Zealand, Africa and islands of the South Atlantic.

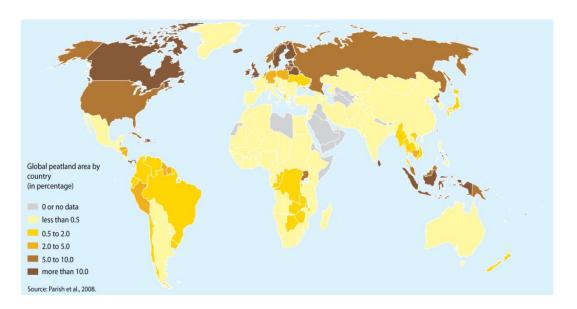
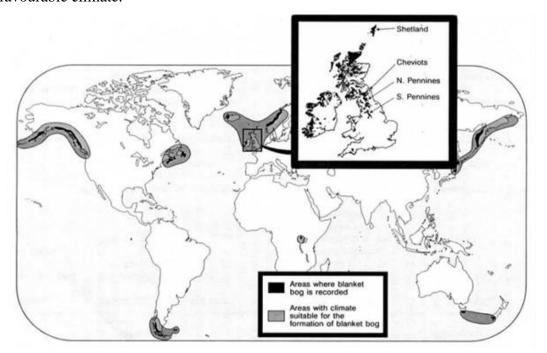


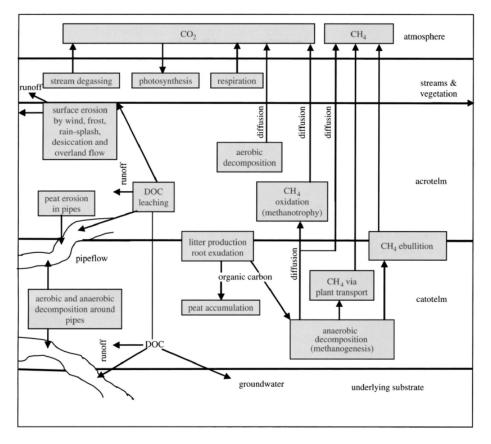
Figure 2.1 Global distribution of peatlands (from Parish, Sirin et al. 2008)

Blanket peat is the focus of this thesis. It is an ombrotrophic (rain-fed) peat system, occurring mainly on gently-sloping terrain (Taylor 1983; Shotyk 2002; Warburton 2003). Certain climate is required for blanket peat growth, resulting in blanket peat having a restricted but global distribution (Figure 2.2) (Conaghan 1995). Linsday

(1988) suggested four criteria for blanket bog growth: 1) annual precipitation above 1,000 mm; 2) more than 160 rainy days each year; 3) the warmest month having an average temperature lower than 15 °C and 4) limited seasonal temperature variability. The global distribution (Figure 2.2) of areas suitable for blanket peatlands can be determined from the above conditions. Blanket peatlands are mainly restricted to hyper-oceanic regions such as north-western Europe, the eastern coast of Canada, the North American Pacific coast, the north-eastern coast of Asia, the tip of South America, mountainous regions of central Africa, New Zealand and other Southern Pacific islands. Blanket peat has been found within all these areas, although in some of these regions blanket bog formation still remains debatable and uncertain (Conaghan 1995). In addition, future climatic change may put more pressure on blanket peatlands. Gallego-Sala and Prentice (2012) suggested via a modelling exercise that shrinkage of the zone suitable for blanket peatlands would occur under future climate change, although there would be some small areas that were more suitable for blanket peat formation. During this process, erosion of blanket peat is more likely where the peatland system is no longer in a zone of favourable climate.



**Figure 2.2** Global distribution of blanket peatlands (from Evans and Warburton 2007, page 13)



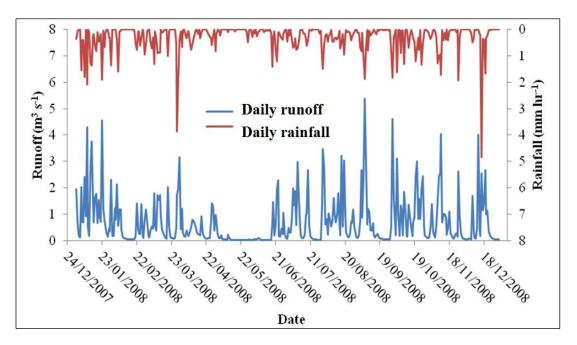
**Figure 2.3** Carbon exchanges between blanket bog and the atmosphere (from Holden 2005c)

Peatlands play an important role in global carbon cycling (Limpens, Berendse et al. 2008). As the rate of decay is less than the rate of production, many peatlands are significant carbon sinks. Globally, peatlands were estimated to contain 33 % to 50 % of the world's soil carbon (Holden 2005c). Yu et al. (2010) estimated that over 600 Gt C have been stored as peat since the last glacial maximum with 547 Gt C for northern peatlands, 50 Gt C for tropical peatlands and 15 Gt C for southern peatlands, and this is large enough to seriously impact the global carbon budget. A conceptual model shown in Figure 2.3 outlines carbon cycling for blanket peatlands (Holden 2005c). Photosynthesis provides the main carbon input. Losses from respiration and mineralization (CO2) and methane (CH4) production from anaerobic decay occur from the peat mass. Additionally, water-borne losses occur via dissolved gases, aqueous carbon and particulate carbon (Holden, Smart et al. 2012a). There can also be wind-borne losses of particulates from a peatland site. Disturbance of peatlands could alter the balance of the parts of the carbon cycle and transform a

peatland into a net source of carbon rather than a net sink (Moore and Knowles 1989; Evans, Stimson et al. 2012).

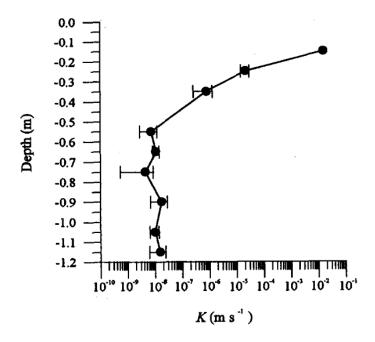
### 2.3 Blanket peat hydrology

Blanket peat stream regimes are very flashy. Figure 2.4 shows water discharge from Trout Beck catchment, a typical blanket peat-covered catchment in the North Pennines, UK. The hydrograph is quite spiky with very low baseflow, illustrating quick response of runoff to rainfall.



**Figure 2.4** Daily rainfall and daily runoff from the Trout Beck catchment, North Pennines, UK in 2008 (Source data were provided by the ECN).

It is necessary to understand runoff generating mechanisms in blanket peatlands in order to explain the above streamflow regime. Runoff production in actively forming blanket peat is often dominated by saturation processes. Evans, Burt et al. (1999) found a strong negative linkage between water discharge and water-table depth. At a mid-slope point in the Trout Beck catchment water tables were within 5 cm of the surface during 83 % of the time. Therefore when it rains the water table quickly rises to the surface and the peat is saturated, generating saturation-excess overland flow. This flow can move quickly over the peat surface or through the shallow vegetation that forms the uppermost peat into stream systems (Holden and Burt 2003c).

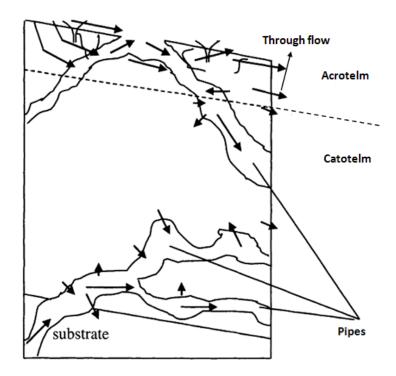


**Figure 2.5** Vertical variation in hydraulic conductivity in blanket bog at Cape Race, Newfoundland, Canada (from Hoag and Price 1995)

The hydraulic conductivity is one of the most important hydrological parameters of peatlands (Evans and Warburton 2007), and usually thought to become rapidly smaller with slight increase in depth from the surface in the peat profile (Figure 2.5). One model, developed by Russian scientists (Ivanov 1981), is usually employed to describe the vertical changes in peat properties. In the model, peat is divided into an upper acrotelm layer and a lower catotelm layer. In the upper acrotelm layer, litter is rapidly decomposed due to the access of air through the pores during water-table oscillations. The abundance of fresh litter (from bog vegetation) and relatively undecomposed nature of the upper layers mean that the density of the acrotelm peat is relatively low and the hydraulic conductivity is relatively high. However, the hydraulic conductivity declines and density increases rapidly with depth due to compression of the peat. In the catotelm layer, microbial activity and decomposition are suppressed because of permanent saturation in this zone. The hydraulic conductivity in the catotelm could be 3 to 5 orders of magnitude lower than in acrotelm (Figure 2.5). Consequently, most matrix flow is generated within upper peat layers, while matrix throughflow decreases quickly with depth within the acrotelm layer. The matrix throughflow in catotelm peat is very restricted (Evans, Burt et al. 1999; Holden and Burt 2002a; Holden and Burt 2003b; Holden 2005c). The low hydraulic conductivity in the catotelm peat means that once water tables drop by a few cm the lateral flows from the peat are restricted and streamflow quickly reduces. Further water-table declines are often only due to evapotranspiration and during summer months diurnal steps in water table can often be seen associated with day-night transpiration differences (Boatman and Tomlinson 1973; Ingram 1983).

The acrotelm-catotelm model has been widely adopted to account for peatland hydrology but suffers from some major flaws because of over-simplification of processes. For example: 1) hydraulic conductivity is anisotropic and hillslope-scale runoff production varies spatially and over time and this is often ignored (Holden and Burt 2003b; Morris, Waddington et al. 2011); 2) natural soil pipes and macropores, that may operate within the catotelm, are not taken into account and may interfere with the simple model structure in terms of water flow paths and sources as shown in Figure 2.6 (Holden 2005c); 3) the acrotelm-catotelm model often means researchers in blanket peat systems have mistakenly played down the role of topography on runoff production mechanisms (Holden 2005c).

Holden and Burt (2003c) gave the contributions of each layer of peat to runoff production in the Moor House site, North Pennines as 81.5 % at the peat surface, 17.7 % between the surface and 5 cm depth, 0.7 % between 5 and 10 cm depth, and less than 0.1 % from below 10 cm depth despite the depth of peat deposit. However, subsurface pipes (Figure 2.6) in blanket peatlands have started to receive much attention in the past decade. Pipe flow has been found to account for about 10-14 % of catchment streamflow (Holden and Burt 2002b; Smart, Holden et al. 2012). More about pipes is provided in section 2.4.3.1.



**Figure 2.6** Acrotelm-catotelm model rendered less useful due to pipe flow (redrawn from Holden 2005c)

## 2.4 Blanket peat erosion

#### 2.4.1 Overview

Soil erosion is the process of weathering, transporting and depositing soil and its parent materials through external forces such as running water, wind and gravity etc. Soil erosion is widespread globally, with approximately 10.5 million km<sup>2</sup> of land being eroded, of which 7.5 million km<sup>2</sup> suffer from water erosion while another 3 million km<sup>2</sup> are impacted by wind erosion. Moreover, Yang, Kanae et al. (2003) suggested that nearly 30 % of the world's arable lands were eroded during the second half of the 20th century, so that soil erosion is a major threat to the sustainability and productivity of agriculture (Stone, Cassel et al. 1985; Verity and Anderson 1990; Bakker, Govers et al. 2005).

Inside the British Isles, there may be as much as 3,500 km<sup>2</sup> of blanket peat eroded (Stevenson, Jones et al. 1990; Tallis 1998). Blanket peat is extensively eroded in British uplands (Tallis 1997; Grayson, Holden et al. 2013). Twenty six percent of Irish blanket bog has been exploited or disturbed by land management practices

(Hammond 1979); many of these bogs have since been degraded through erosion (Bowler and Bradshaw 1985; Bradshaw and McGee 1988). Blanket peat erosion is extensive in the uplands of western Ireland (Leira, Cole et al. 2007). Although severe and extensive erosion of blanket peat is a phenomenon which is almost unique to British Isles, blanket peat erosion has also been reported in other parts of the word such as the Falkland Islands (Wilson, Clark et al. 1993), Sweden (Foster, Wright et al. 1988) and Austrian Alps (Victoria National Park Association 2005). Table 2.2 demonstrates that erosion rates from eroding blanket peatlands in the UK could reach over 200 ton km<sup>-2</sup> yr<sup>-1</sup> but it is usually modest in global terms. Even so, because of the low dry bulk density of peat (often approximating 0.1 g cm<sup>-3</sup>), large volumetric landform change caused by erosion may happen (i.e > 90 % of the peat mass is water, but bulk densities are measured on dry weight soils). Land cover may be related to the rate of erosion in blanket peatlands (Table 2.2). In addition, blanket peat erosion could lead to a series of ecological and economic problems (Yeloff, Labadz et al. 2006), which includes loss of terrestrial and aquatic habitats (Ramchunder, Brown et al. 2009), loss of grazing land, reduction of reservoir capacity (Labadz, Burt et al. 1991) and discoloration of water (Pattinson, Butcher et al. 1994). As shown in Figure 2.3, erosion also results in more carbon export from blanket peatlands. Therefore blanket peat erosion could cause considerable landform change and various environmental issues.

As blanket bog can occur on sloping terrain, it could be subject to rapid erosion once degradation is initiated. Blanket peat erosion is a three-stage process: 1) the disruption and removal of vegetation cover by external forces; 2) the formation of an easily eroded surface layer by frost or drought; 3) the transport of erodible materials by wind and / or water (Tallis 1998). Water is seen as the main agent of blanket peat erosion, while wind is sometimes a very important force, for example, in sheet erosion (Bower 1961) or through wind-assisted splash (Foulds and Warburton 2007b).

Table 2.2 Erosion rates of blanket peat catchments in the UK

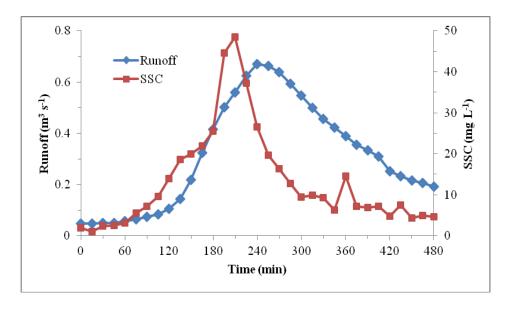
Site	Region	Erosion rates (ton km <sup>-2</sup> yr <sup>-1</sup> )	Catchment size (km²)	Year	Cover	Source
Monachyle	Central Scotland	38	7.7	1984-1985	Moorland	Stott et al. (1997)
Hopes Reservoir	SE Scotland	25	5	1935-1970	Eroding moorland	Ledger, Lovell et al. (1974)
North Esk Reservoir	SE Scotland	26	7	1850-1971	Eroding moorland	Ledger, Lovell et al. (1974)
Cyff	Mid Wales	6	3.1	unknown	Grassland	Moore and Newson (1986)
Tanllwyth	Mid Wales	38	0.9	unknown	forest	Moore and Newson (1986)
<b>Upper Severn</b>	Mid Wales	66	0.94	1982-1984	Blanket peat moorland	Francis (1990)
CeunantDdu	Mid Wales	3.7	0.34	1982-1983	Blanket peat moorland	Francis and Taylor (1989)
CeunantDdu	Mid Wales	9	0.34	1982-1983	Ploughed	Francis and Taylor (1989)
Nant Ysguthan	Mid Wales	0.7	0.14	1982-1983	Blanket peat moorland	Francis and Taylor (1989)
Nant Ysguthan	Mid Wales	3	0.14	1982-1983	Ploughed	Francis and Taylor (1989)
Rough Sike	North England	112	0.83	1960	Eroded blanket peat	Crisp (1966)
Rough Sike	North England	44.34	0.83	1998-2001	Re-vegetated blanket peat	Evans and Warburton (2005)
<b>Upper North Grain</b>	North England	267	0.38	2001-2002	Eroding blanket peat	Evans, Warburton et al. (2006)
Gt. Eggleshope Beck	North England	12.1	11.68	1980	Uneroded blanket peat	Carling (1983)
Burnhope Reservoir	North England	33.3	17.8	1936-1998	Eroding peat moorland	Holliday (2003)
Trout Beck	North England	10.5	12	1997-2009	Re-vegetated blanket peat	ECN sampling data

Table 2.2 Continued

Location	Region	Erosion rates (ton km <sup>-2</sup> yr <sup>-1</sup> )	Catchment size (km²)	Year	Cover	Source
Cottage Hill Sike	North England	2.8	0.17	2008-2009	Re-vegetated blanket peat	Holden, Smart et al. (2012a)
Coalburn	North England	3	3.1	1972-1973	Uneroded peat moorland	Robinson and Blyth (1982)
Coalburn	North England	25	3.1	1972-1973	Ploughed	Robinson and Blyth (1982)
Coalburn	North England	13	3.1	1972-1973	Planted	Robinson and Blyth (1982)
Wessenden Moor	North England	55	0.0042	1984-1986	Eroding blanket peat	Labadz (1988)
Shiny Brook	North England	203.69	2.4	1881-1986	Eroding blanket peat	Labadz, Burt et al. (1991)
<b>Featherbed Moss</b>	North England	12-40	0.03	1970	Eroding blanket peat	Tallis (1973)
Howden Reservoir	North England	128	32	1912-1987	Eroding peat moorland	Hutchinson (1995)

# 2.4.2 Sediment production

Supply-limited processes are dominant in blanket peat erosion so there is a positive hysteresis relationship (Figure 2.7) between suspended sediment concentration and runoff (Labadz, Burt et al. 1991). This implies that freshly exposed peat may need a period of weathering driven by external forces to become loose and consequently is then transported. However, transport-limited erosion may occur sometimes when sediment supply exceeds the transporting capacity of water flow, which can be determined by the runoff, local topography and soil properties (Musgrave 1947).



**Figure 2.7** A storm event from Rough Sike, North Pennines, UK on 19/11/1998, showing the positive hysteresis between runoff and suspended sediment concentration (SSC) (Source data were provided by Martin Evans, the University of Manchester)

Freeze-thaw and desiccation are commonly cited as key sediment production mechanisms in blanket peatlands (Tallis 1973; Francis 1990). Frost is common in cool, wet upland climates coinciding with peat deposits (Evans and Warburton 2007). Because of the high volumetric heat capacity, low heat conductivity and thermal difference from wet to dry (Fitzgibbon 1981), strong temperature gradients are thus present on the peat surface, which, in addition to a sufficient moisture supply, provides essential conditions to the development of needle ice (Outcalt 1971). The growth of needle ice may then lead to a 'fluffy' peat surface (Figure 2.8), which is loose and granular and is usually transported to the stream as particles or

small aggregates of particles. Needle ice may also make the surface peat layer desiccated (Burt and Gardiner 1984; Evans and Warburton 2007). However, the development of desiccated surface layers usually spans a long-term dry period, leading to platy aggregates. These aggregates are much lower in density than the material produced by frost action and are hydrophobic (Ingram 1983) Therefore they are transported as large floating particles when overland flow occurs.

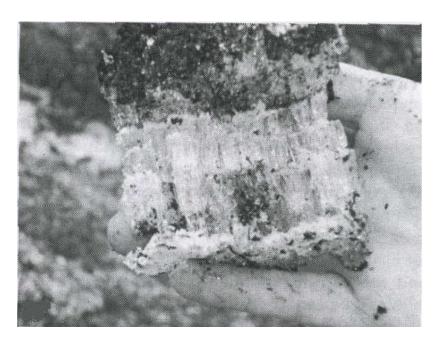


Figure 2.8 Illustration of needle ice (from Evans and Warburton 2007, page 63)

Two classic studies about blanket peat erosion were conducted in the Upper Severn catchment in mid Wales and the Shiny Brook catchment in the South Pennines (Francis 1990; Labadz, Burt et al. 1991). Sediment production from Plynlimon was dominated by summer desiccation, while winter frost heave was more important in sediment supply at Shiny Brook. The contrasting findings were interpreted as the result of climatic difference in the catchments during the study periods (Evans and Warburton 2007). In addition, trap results from Rough Sike, North Pennines, UK suggested that total rainfall and soil moisture were the most related parameters to sediment flux, and erosion pin results from this catchment demonstrated that bigger surface advance was consistent with soil temperature below freezing (Evans and Warburton 2007). Therefore sediment supply in peat catchments is much to do with climatic conditions. In line with this idea, Yang (2005) has demonstrated that the

slope of best fitted lines through measured discharge-sediment concentration relations for individual storm events in Upper North Grain, are controlled by sediment supply from eroding gully walls. This regression slope is highly sensitive to climatic variability and connectivity within catchments (Evans and Warburton 2007). Such an indicator could potentially be applied widely to account for variations in sediment supply with climate, and therefore provide a good basis for predicting sediment production from blanket peatlands. However, Yang's work is at storm and small catchment scale. Whether such an indicator works at other spatial and temporal scales (e.g. plot scale, hillslope scale) is unclear. Thus more work may be needed to test or improve the indicator proposed by Yang (2005) before it could be applied broadly.

## 2.4.3 Sediment transport

#### 2.4.3.1 Water related processes

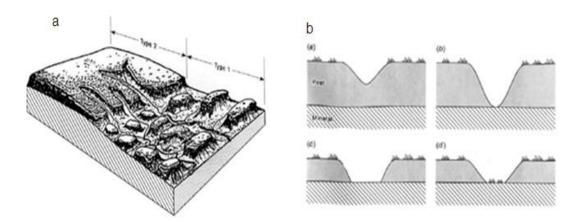
Fluvial erosion is the dominant process controlling sediment delivery from eroding peatlands. Bower (1960a; 1960b; 1961; 1962) gave an extensive review on the distribution, causes and classification of peat erosion in the Pennines, UK. According to morphology and pattern, Bower suggested that water erosion in peatlands existed in the forms of dissection systems, sheet erosion, and marginal faces. The description of these processes are provided below as the work was influential, but proceeding sections will include more up to date studies.

### a) Classic description of water erosion

#### 1) Dissection system

Bower (1960a; 1961) suggested that there were two types of dissection systems which were usually referred to: type 1 and 2 (Figure 2.9a). The dissection systems are different in pattern but may be both initiated by seepage along horizontal or vertical lines of weakness within the peat, runnels on the peat surface and headward erosion from the margin of the peat mass. She considered the development of gully cross-sections as occurring through four stages (Figure 2.9b). The gullies are widely variable in the process of development, eroding headwards, laterally and eventually incise to the peat base. During the early stages, gullies are V-shaped with a different extent of vertical and lateral incision. For the first stage, gullies are shallow and contained within the peat, while the second stage contains narrow gullies which

have already eroded into the peat base. Late stages of gullies show a U-shaped cross section. In the third stage, the rate of lateral erosion into peat exceeds that of vertical erosion into mineral substrate, leading to the formation of gullies with a flat-floored profile. Separate peat islands (Figure 2.9a) are therefore formed between gullies, firstly having the same height as the original peat mass then lowered by either peat shrinkage or further erosion. In the fourth stage, eroded gullies are re-vegetated artificially or naturally. The above process could also be observed along a single dissection system. From head to foot of the system, the gully could develop from the V-shaped shallow narrow system to the U-shaped wider deeper gully.



**Figure 2.9** a) Type 1 and type 2 gully systems (from Evans and Warburton 2007, page 80); b) Evolvement of gully system (from Evans and Warburton 2007, page 78).

Empirically, Bower (1961) examined factors associated with the distribution of these two types of gully distribution. Type 1 is often present on sites where the slope is less than 5 degrees and the depth of peat is 1.5-2.1 m, especially where hummock-pool complexes used to occur. In type 1, the peat is intensively dissected by a close network of intricately branching gullies. Type 2 takes place more extensively than type 1 because there is no restriction in peat depth and slopes for it to occur. In type 2 gullies Bower suggested that the gullies become more open, that is to say, their frequency is low, mainly due to individual gullies which rarely branch (Bower 1961). Islands will be generated in the process of formation of both dissection systems. In type 1, the gullies tend to incise to the peat base and the peat mass is reduced to small islands of a height equal to the original peat depth. Laterally, the

islands will be lowered either by peat shrinkage or by erosion. In type 2, islands between gullies are larger and more angular due to the low frequency of gullies (Bower 1960a).

## 2) Sheet erosion

Sheet erosion takes place on the surface of the peat mass; water and wind are the major agents of sheet erosion (Bower 1961). Sometimes sheet erosion may occur during the development of dissection systems, especially on high, exposed summit sites and on the highest moors. On high, exposed summit sites, the vegetation cover is broken up by the early stage of dissection, which provides large areas of bare peat, then sheet erosion may become dominant (Bower 1960b). On the highest moors, sometimes the development of type 1 dissection slows down at the early stage, but lateral erosion continues and bare peat flats are then produced and sheet erosion occurs.

#### 3) Marginal faces

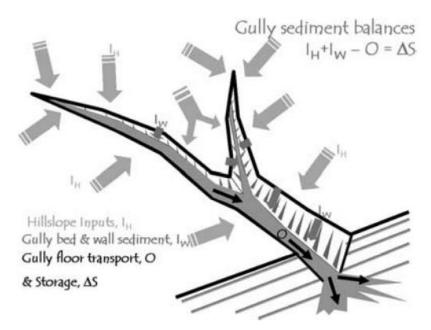
Marginal faces often occur on the edge of the peat mass. It is particularly common when the peat mass is thinned to the feather edge lying on suddenly increased slopes, leading to the whole chunk of the peat mass move downslope, and resulting in erosion scars without vegetation cover. Such faces are often present on the edge of grit-stone plateau and benches. Marginal face erosion begins on the peat edge and often results in gullies, which usually erode back into peat mass because of headward erosion (Bower 1960a; Bower 1960b; Bower 1961). Frost and desiccation action can occur on exposed marginal faces.

### b) Recent advances in peatland water erosion

#### 1) Fluvial processes

Recent work on fluvial erosion of peatlands has focussed on the upper reaches of the fluvial system (Rothwell, Evans et al. 2007; Kirkby and Bracken 2009; Evans and Lindsay 2010; Evans and Lindsay 2010), particularly on hillslope gullies (Stott 2010). Gullies are an effective way of delivering eroded materials. Generally, a gully is defined as a deep channel generated by running water on a hillslope. Additionally, classical gullies are linear channels, which are too large to be reshaped or obliterated by farming equipment or operations so that they have a serious impact

on the landform and surface soil by transporting considerable quantities of upland soil and parent material to main stream channels (Kirkby and Bracken 2009).



**Figure 2.10** Gully sediment balance:  $l_H + l_W - O = \Delta S l_H l_W$  are hillside and gully wall sediment inputs, O is channel sediment transport and  $\Delta S$  is the change in channel sediment storage,  $l_H$  is the sediment inputs from hillsopes,  $l_W$  is gully bed and wall sediment load (redrawn from Kirkby and Bracken 2009)

Figure 2.10 illustrates the sediment balance and components of sediment transport within gully systems. Sediment transport following weathering of bare peat is usually divided into three parts including sediment input from hillsides to gullies, flux from gully walls to the stream channel and flux within stream channels. Sediment derived from outside of the gullies is one important source of transported material. For example, some peat islands between severely eroded gullies are bare because of the early incision of gullies, then later erosion on these islands results in available sediment for transport to the adjacent gullies (Bower 1960a). The delivery of sediment to stream channels is as important as sediment production for the sediment supply (Trimble 1981; Chamberlain 1983; Phillips 1989; Walling, Owens et al. 1999). However, sediment delivery from hillslope gullies to stream channels may vary dramatically among different catchments. Evans, Warburton et al. (2006) took two eroded catchments called Upper North Grain and Rough Sike as examples

to examine the sediment budget in blanket peatlands. In the Upper North Grain catchment, storage of the sediment from eroding faces by overbank deposition and deposition at the interface of hillslope gullies and the floodplain tended to be insignificant as the sediment production measured by erosion pins is the approximately same as the measured sediment flux from the catchment. That is to say, most of the sediment produced at hillslope gullies was transported into the channels. A different situation occurred in the Rough Sike catchment where sediment delivery to stream channels was sharply reduced by the vegetation at the end of gullies trapping the sediment. Instead, the main sources of sediment for the main channel sediment load were lateral floodplain erosion and localized sources where the stream cuts into the intact blanket peat. Direct comparison of sediment budgets in Upper North Grain and Rough Sike emphasised the importance of vegetation cover in sediment transport from eroding hillslopes of blanket peatlands (Evans, Warburton et al. 2006). Low sediment flux from the Rough Sike catchment was mainly attributed to re-vegetation of the slope-channel interface. However, more work is desirable to evaluate the impact of vegetation cover on blanket peat erosion at different scales more comprehensively. For example, the influence of vegetation covers on sediment production and sediment transport along hillslopes and so on require study.

The above also demonstrates that peat erosion is a natural and expected process within peatlands. Rivers and streams will often migrate and incise into surrounding peat deposits. A well-vegetated peat system could therefore still have a large sediment load if the stream systems are dynamic.

The process of both fine and coarse sediment transport in stream channels is complicated. In channel systems, there are two types of peat sediment: peat blocks and fine peat sediment. Peat blocks occur when peat banks are directly undercut by stream systems. A large number of peat blocks stored on the river bed, may either change the plan form of the channel in larger peatland catchments or lead to the upstream accumulation of bed material and stepped river beds in smaller catchments. The removal of peat blocks by a large flood will cause the reorganization of the stream system. Transport of peat blocks in stream channels is in the form of rolling and then floating as the flow depth increases, leads to an

important in-channel source of the fine sediment (Evans and Warburton 2001). Suspension and floating are the major form of fine sediment delivery in channels. However, floodplain deposition happens together with the overbank flow (Klove 1997; 1998). Warburton's work in a small North Pennine blanket peat catchment showed overbank deposition could be as much as 36 % of catchment sediment yield (Warburton, Holden et al. 2004).

#### 2) Mass movement

Mass movement of peat usually occurs on slopes, having been well recorded over the last few hundred years (Warburton, Holden et al. 2004). Eighty percent of peat mass movements have been reported in the UK (Boylan, Jennings et al. 2008), although examples have been recorded around the world including in Germany (Vidal 1966), Switzerland (Feldmeyer-Christe and Mulhauser 2011), and Canada (Hungr and Evans 1985).

Mass movement often takes place on slopes and may take the form of a sliding of the peat mass or a bog burst (Dykes and Kirk 2006). Peat slides and bog bursts are important mainly due to their capacity to move large amount of surface peat, significantly affecting the stream ecosystem (McCahon, Carling et al. 1987). However, Statham (1977) thought that creep might be another important type of mass movement on peat which occurs very slowly compared to peat slides and bog bursts. Peat slides and bog bursts can be triggered by heavy or prolonged rainfall, and involve instability of peat overburden above mineral substrate (Carling 1986). Peat slides occur when a whole part of the peat mass moves down-slope due to the previous shear failure at or just below the peat-substrate interface. Bog bursts are the consequence of considerable quantities of near-fluid basal peat flowing down-slope through existing surface water channels. The basal peat usually comes to the peat surface through the peat tears or margins, which results in the let-down of the peat surface. Peat slides are dominant on areas of blanket bogs while bog bursts usually occur at sites where raised bog dominates (Dykes and Kirk 2001). In terms of the analysis of peat mass movements in the British Isles by Mills (2003), the distribution of bog bursts tends to occur at lower slope angles than peat slides; bog bursts generally have a larger volume of failure than peat slides, which means that sites where bog bursts occur have a deeper peat mass than slides sites, and therefore this has an implication that there is a link between peat depth and the type of peat mass movement. Given the apparently increasing frequency of peat failures in the British Isles and the possibility of more peat failures elsewhere in the world as a consequence of climate change, it is necessary to improve the reliability of hazard assessment of peat failures (Dykes and Jennings 2011). In line with such requirement, Dykes and Warburton (2007) proposed a new precisely defined classification scheme for peat landslides (i.e. excluding creep), using type of peat deposit and failure morphology as the key criteria. Such a classification scheme enables a systematic approach to the identification and recording of peat failures, and improves peat instability hazard assessment.

### 3) Pipe erosion

The above types of erosion occur on the surface of peatlands. There is subsurface erosion called pipe erosion (Figure 2.3 and Figure 2.6). Pipes are found in all continents around the world and are natural conduits through soils often many centimetres in diameter and several hundred meters in length. The shape of pipes is complicated, fluctuating not only horizontally but also vertically: Studies on natural pipes have been conducted in tropical forests, collapsible loess soils, boreal forests, subarctic hillslopes and dispersive semi-arid soils. However, most attention has been paid to soil pipes through peatlands although even here there is still rather limited research (Holden, Smart et al. 2009) (Figure 2.11).



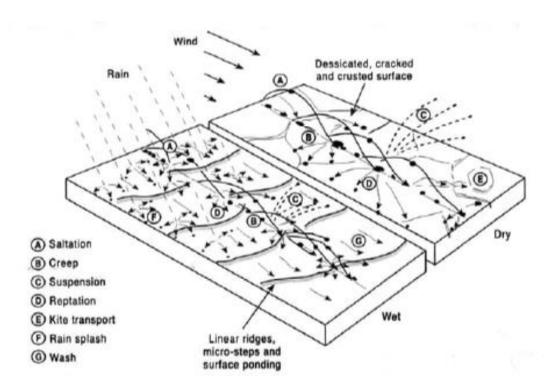
Figure 2.11 A soil pipe in blanket peat

Pipes have been reported in many types of peatlands (Ingram 1983; Woo and DiCenzo 1988; Holden, Smart et al. 2009), but appear common in blanket peat (Holden 2005a; Holden 2006; Smart, Holden et al. 2012; Holden, Smart et al. 2012a; Holden, Smart et al. 2012b). The initiation of pipes in peatlands is subject to the inherent properties of peat and external forces. With regard to the internal properties, peatlands are prone to pipe formation mainly because of plentiful water supply and the high gradients in horizontal and vertical hydraulic conductivity (Rosa and Larocque 2008). Outside, the drag force triggered by the water flow through the soils could lead to the conduit eroding back into the peat mass from outlets. In addition, root channels, desiccation cracks and faunal burrows are also commonly cited pipe initiation mechanisms (Holden, Smart et al. 2009) but the reality is that pipe formation is still not fully understood (Holden, Smart et al. 2012b).

Soil pipes often transport water, sediment and solute from the soil profile to the stream channels and may play an important role in water and carbon transfer in peatlands (Smart, Holden et al. 2012; Holden, Smart et al. 2012a). In blanket peatlands, soil pipe density peaks at topslopes and footslopes which may be related to peat properties at different parts of the slope and how the peat has developed through time (Holden 2005a). Holden (2006) demonstrated that pipe density could double 35 years after beginning of open cut drainage. He also estimated that there could be an extra 5.8×10<sup>3</sup> kg C km<sup>-2</sup> yr<sup>-1</sup> exported from pipe erosion alone for slopes where drainage is 40 years old. More complete measurements by Holden, Smart et al. (2012a) from selected pipes in Cottage Hill Sike, North England, suggested that pipe outlets produced 14 % of discharge to the stream and sediment equivalent to 62 % of the annual stream POC flux. The morphology of pipe outlets has been shown change over time, further demonstrating that pipes are not benign geomorphological features of peatlands. A survey of natural pipe outlets in the Cottage Hill Sike (Holden, Smart et al. 2012b) between 2007 and 2010, showed that the cross-sectional area of most pipe outlets changed and potentially responded to changes in weather condition. In addition, pipes may also contribute to the development of gullies, and pipe collapse is more likely to generate type 2 gullies; pipes can often be found at the head of gullies (Holden and Burt 2002b; Evans and Warburton 2007).

### 2.4.3.2 Wind-related processes

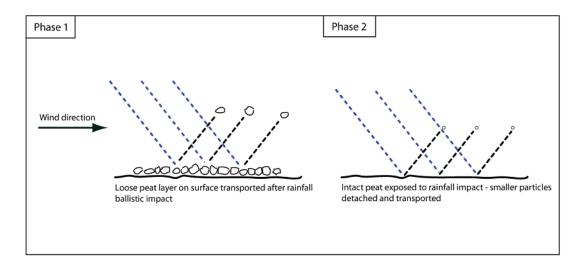
Wind is a marked feature in the UK uplands and has long been considered as an important agent of peat erosion (Warburton 2003). Wind erosion is the process by which weathered peat is picked up and transported by wind. Because of low density, dry peat is very susceptible to wind erosion (Evans and Warburton 2007). The wind erosion and transport processes in peatland environments are different between dry and wet conditions (Figure 2.12).



**Figure 2.12** The processes of wind erosion under dry and wet conditions (from Evans and Warburton 2007, page 143)

In dry conditions, the peat surface is often desiccated, crusted and cracked. Saltation, suspension and creep are the dominant processes of aeolian transport and sometimes reptation might occur due to the collisions of saltating particles with the surface dislodge particles (Nickling 1988). Occasionally, dry surface peat crusts (Figure 2.12) may be entrained by the process named kite transport, which means that a whole chunk of peat between the cracks is blown off from the cracked peat surface. Under wet periods, the normal aeolian processes including saltation, suspension and

creep still occur. However, rainsplash and surface wash are also very important. Wind-driven rain is a common phenomenon in wet and windy conditions of upland Britain. Dry blow processes were directly measured by Foulds and Warburton (2007a) at Moss Flats, North Pennines, UK during a dry summer period, the rate was two order of magnitude less than wind-driven rain erosion monitored by Warburton (2003), who also suggested that the ratio of windward to leeward sediment flux is 2-12. However, dry blow processes may become more important in terms if climate change promotes more summer desiccation. A strong association between prevailing wind direction and the dominant orientation of streamlined haggs has been found by Evans and Warburton (2007). Wind-splash erosion is mainly controlled by climate characteristics such as rainfall intensity, wind speed and wind direction. A two-phase conceptual model was proposed by Edwin and Crews (2012) to describe wind erosion. 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 events occur 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 (Figure 2.13). Overall, there are relatively less studies on wind erosion than fluvial erosion in blanket peatlands. Detailed studies of aeolian processes of blanket peat have only occurred at Flow Moss (Baynes 2012) and Moor House (Warburton 2003; Foulds and Warburton 2007a; Foulds and Warburton 2007b), which are both in the North Pennines, UK. The observation durations of these projects are usually quite short (less than two years). Studies on wind erosion could be enhanced in two aspects to help further understand the processes involved: 1) detailed studies of aeolian processes should be conducted at other locations; 2) extended periods of field monitoring should also be done.



**Figure 2.13** The conceptual model of the wind-driven rain (from Baynes 2012)

# 2.5 Contributing factors to blanket peat erosion

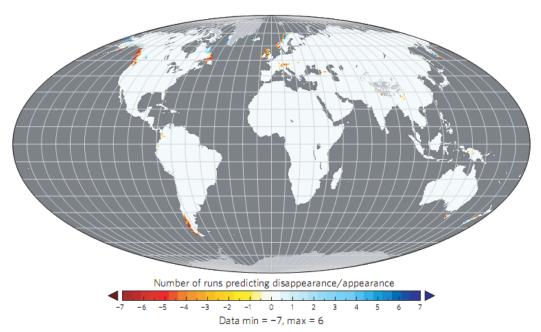
As noted above, peat erosion is a natural process, part of a cycle of landscape change along with re-vegetation. However, erosion will also be impacted by environmental disturbance such as climate change and land management. These disturbances alter the balance between the forces of erosion (frost, desiccation, wind, and runoff) and the ability of vegetation to retain peat, eventually leading to the initiation and / or acceleration of erosion (Evans and Warburton 2007). On the one hand, climate shifts impact the weathering (freeze-thaw and desiccation) and transport (runoff, wind) of peat, contributing to peat erosion. On the other hand, peat erosion is viewed as an artificial product of human action via disturbance through artificial drainage, grazing and trampling, air pollution, and prescribed or accidental fire (Phillips, Yalden et al. 1981).

## **2.5.1 Climate**

Climate change has already been recognized as a global phenomenon (Harrison, Harrison et al. 2010), and blanket peat is sensitive to climate change (Tallis 1998; Ellis and Tallis 2000; Ellis and Tallis 2001). Evidence has suggested that some eroded peat systems pre-date intensive human disturbance (Bragg and Tallis 2001), and climate shifts were responsible for the initiation of these erosion processes. The early Medieval (ca. AD 1100-1250) Warm Period has been suggested as playing a role in priming the peat surface for any subsequent erosion (gullies) in the South

Pennines, UK (Tallis 1995; Tallis 1997; Bragg and Tallis 2001). Rhodes and Stevenson (1997) found the Little Ice Age (ca. 1500-1850) was associated with increased peat erosion at six of seven small lake sites with extensive peat-covered catchments in Scotland, Ireland and Wales. Similar findings were also found in the sub-Antarctic region, where Van der Putten, Hlbrard et al. (2008) suggested that drier climate between AD 1150 and 1300 caused weathering of the peat surface. Therefore, it was suggested that erosion risk was largely increased during the following Little Ice Age, with colder winters and wetter summers leading to larger volume of runoff.

Future climate change scenarios indicate that the UK will experience warmer, drier summers and warmer, stormier winters during the 21st century (UKCP09 2009). In order to predict the impacts of future climate change on the existing blanket peatlands, bioclimatic envelope modelling has been adopted, which is widely used to study the current distribution of species and to project potential changes under future climate scenarios (Sykes, Prentice et al. 1996; Berry, Dawson et al. 2002). In these models, bioclimatic space is usually characterized by the climatic thresholds expressed as one or several climate variables. There are two types of bioclimatic envelope modelling: 1) statistical and 2) process-based (Gallego-Sala, Clark et al. 2010). Both could be applied to ecosystems and species. With well-defined climatic thresholds (Wieder and Vitt 2006), the distribution of peatlands could be described by bioclimatic envelope models. Clark, Gallege-Sala et al (2010) used eight statistical bioclimatic envelope models to examine the vulnerability of blanket peat within the UK to climate change. Seven out of eight models showed a decline in bioclimatic space associated with blanket peat, with no increase in the bioclimatic space even in the north of Scotland or at high altitudes, using UKCIP02. Peat in eastern and southern regions was predicted to be more vulnerable to climate change than in western and northern areas and high-altitudes in the UK. The decrease in peatland bioclimatic envelope could lead to changes in peatlands, although the rate of change is not known. For process-based bioclimatic envelope modelling, the PeatStash model was applied in the UK and across the world to predict the response of blanket peatlands to climate shifts (Gallego-Sala, Clark et al. 2010; Gallego-Sala and Prentice 2012). In the UK, blanket peatlands were predicted to retreat towards the north and west between 2011 and 2100. This is consistent with the results from studies based on statistical models (Clark, Gallego-Sala et al. 2010). Globally, the distribution of suitable regions for blanket peat is also predicted to be subject to change under climate scenarios from UKCP09 (Figure 2.14), with the appearance and disappearance of areas suitable for blanket peat growth occurring simultaneously. During these phases, the degradation of peatlands is much more likely, providing conditions for erosion to originate and evolve. However, no research has been done to directly test the response of blanket peat erosion to future climate change. It is therefore important to examine how blanket peat erosion develops with climate in the future so that the fate of blanket peat in the enlarged marginal areas could be assessed.



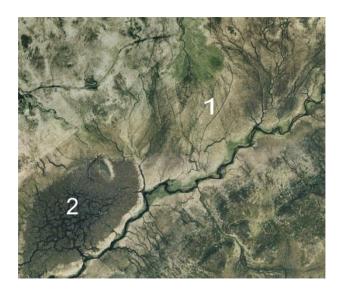
**Figure 2.14** Projected changes to blanket bog potential area for climate change scenarios compared with standard period. The colour scale represents the number of climate models predicting new appearance (blue) or disappearance (red) of blanket bog potential are. Ice caps and areas where no climate data are available are shown in light grey (from Gallego-Sala and Prentice 2012).

# 2.5.2 Anthropogenic effects

Human activities including artificial drainage, prescribed burning, grazing and pollution also are factors important to blanket peat erosion as they could result in changes to vegetation cover or its complete removal and soil properties, so enhance sediment production (desiccation) and transport (gullies and pipes) (Holden 2005b).

### 2.5.2.1 Artificial drainage

Drainage of peatlands has been widespread for several centuries (Holden, Chapman et al. 2004; Holden, Wallage et al. 2011) for agriculture, forestry, horticulture and flood risk alleviation (Holden, Gascoign et al. 2007b; Holden, Wallage et al. 2011). New drainage in UK upland peat peaked between the 1940s and 1970s (Holden 2006; Ballard, McIntyre et al. 2011). However, problems associated with drainage of blanket peat are frequently reported including increased flooding, peat erosion, decrease of water quality and ecosystem destruction (Ramchunder, Brown et al. 2009). Artificial drainage could change the hydrological properties of blanket peatlands such as water-table depths and fluctuations (Holden, Wallage et al. 2011), hydraulic conductivity (Wallage and Holden 2011), water storage capacity and runoff coefficient (Holden, Chapman et al. 2004). Attempts have been made to incorporate drainage into hydrological modelling. Ballard, McIntyre et al. (2011) proposed a simplified physics-based model that allowed the associated hydrological processes and flow responses to be explored. A drainage model has also been developed to account for the impact of drainage on soil moisture deficit during a project funded by Yorkshire water and conducted by the University of Leeds (Beharry-Borg, Hubacek et al. 2009). The model was incorporated into the point version Pan-European Soil Erosion Assessment (PESERA-POINT) model to assess the socio-economic implications of land management policies in Yorkshire's catchments. Drains often incise rapidly both vertically and horizontally (Mayfield and Pearson 1972) especially on steeper slopes. In addition, the vertical incision is often associated with the undercutting of ditch sides and occasional block failure (Holden, Gascoign et al. 2007b), probably because the bare peat on the sides is subject to frost heave and desiccation and transported by flowing water. The above processes may lead small peat drains to form large gullies.



**Figure 2.15** Land drainage on peatlands in Northern Scotland (from Google maps)

Figure 2.15 shows a drainage system in northern Scotland. In area 1 the land drains are in the relatively earlier stage while in area 2 large gullies and separate islands have been formed. Pipe density is known to increase around drainage networks (Holden, Evans et al. 2006), and sometimes rapid mass movements may occur in association with peatland drainage due to peat failure along the artificial drainage line (Holden, Chapman et al. 2004). Holden, Gascoign et al. (2007b) presented a survey of peat erosion in drains from four blanket peat catchments in northern UK. They suggested that slope and catchment area may be the most important factors determining the extent of peat erosion in drains; slopes less than 2 degrees are rarely eroded, slopes greater than 4 degrees have drains that are rarely naturally infilled and the erosion tends to be more severe with slope. The correlation between drain erosion and catchment area was significantly positive with a coefficient of 0.43. With regard to suspended sediment production, the unblocked drains produced significantly more sediment per unit area (more than one order of magnitude) than the blocked drains (using periodic dams) and intact peat subcatchments, which means drain blocking is an effective way to reduce the sediment production from land drains (Wilson, Wilson et al. 2011). Measured data from Upper Wharfedale also supported the idea that the peatland drains were an important suspended sediment source for the catchment as 18.3 % of the catchment sediment yield came from unblocked drains which only cover 7.3 % of the catchment (Holden, Gascoign et al. 2007b).

#### **2.5.2.2 Burning**

A wide range of studies have shown that prescribed burning affects the structural diversity of peat ecosystems (Gimingham 1972; Lance 1983; Norton and De Lange 2003). Grouse management for shooting involves rotational burning to encourage a mosaic of old and new vegetation stands thought to favour the grouse life cycle (Holden, Chapman et al. 2012). However, this burning cycle may result in time periods and spatial plots for which there is a relatively bare surface and hence may change the hydrological regime and accelerate the potential for sediment release (Bower 1960a; Hough, Towers et al. 2010). However, this may depend on the connectivity of bare (recently burnt) patches and the stream system, and buffers are supposed to be left between burnt areas and watercourses (Defra 2007). The UK guidance restricts the timing, frequency and size of burning to ensure sufficient soil moisture and reduce the burning damage to underlying soil and peat (Worrall and Adamson 2008). There is quite limited data on the roles of burning in sediment production in peatlands. Prescribed burning is usually associated with fine sediment in the streams which affects macro-invertebrate communities (Ramchunder, Brown et al. 2013). During some very dry periods, wildfire could have severe sediment production consequences since the size and severity of the fire may be more intense (McMorrow, Lindley et al. 2009; Esteves, Kirkby et al. 2012), with a destruction of the seed stock and subsequent generation of rapid connectivity (e.g. gullies, sheet erosion) to stream networks (Bower 1962; Stevenson, Jones et al. 1990; Rothwell, Evans et al. 2007). Several models have already been developed to predict the wildfire risk and potential wildfire severity (Venevsky, Thonicke et al. 2002; McMorrow, Lindley et al. 2009). Esteves and Kirkby et al. (2012) demonstrated infrequent wildfire may result in more soil erosion than frequent managed burning in two catchments of central Portugal. McMorrow (2011) suggested, that in the UK, management for multiple land uses requires wildfire-aware management of ecosystem services and ecosystem service-aware management of wildfire. So there are interactions between wildfire and land management since the fuel load may be greater without land management making the potential impact of a wildfire worse. However, this is a contentious issue since there are a large number of process interactions (Holden, Chapman et al. 2007a).

#### **2.5.2.3 Grazing**

It is widely acknowledged that overgrazing is a significant factor in degradation of upland peat (Evans 1977; 2005; Holden, Chapman et al. 2007a; Worrall and Adamson 2008). The carrying capacity of peatlands is so low that it only takes a few additional sheep to cause severe degradation. Peat erosion can be initiated or exacerbated by grazing, and such erosion is then difficult to control even if the animals are excluded from the area by fencing (Evans 1997).

Grazing may act to trigger blanket peat erosion. When stocking density is greater than carrying capacity of land, the vegetation cover tends to be eaten and / or trampled by sheep, and therefore produces bare soils, which are vulnerable to weathering processes. The situation could be enhanced in poorly drained peat on flat or gentle slopes (Evans 1997). Grazing may also be responsible for maintaining a bare peat surface from erosion initiated by other factors such as burning, drainage and mass movements etc. (Rawes and Hobbs 1979). Through investigating the causes of erosion and degradation of the March Haigh catchment, Yeloff, Labadz et al. (2006) suggested that bare peat surfaces exposed by the accidental fire in 1959 were maintained by highly intensive sheep grazing leading to severe erosion. Decreased soil infiltration caused by overgrazing may result in more surface flow (Burt and Gardiner 1984), and changed water table. Meyles, Williams et al. (2006) reported that more intensive grazing caused conditions suitable for the increased delivery of soil water to rapid flowpaths such as sheep tracks and other rapid routes which connect the source of hillslope water to channels during large floods. This means that a rapid connectivity is formed between hillslopes and main channels, and may lead to increased flooding, which transports more sediment into stream networks. In addition, the changed hydrological properties may also lead to varied soil moisture conditions, resulting in variation in sediment produced by desiccation. Overall, grazing may play a more important role in maintaining erosion than runoff (NSRI 2002). However, the exact influence of sheep grazing upon upland environments is still uncertain as there is a lack of quantitative information on variation of sediment production and transport caused by overgrazing.

### 2.5.2.4 Atmospheric pollution

"On a global scale the impact of pollution on mire surfaces is very localized" (Evans and Warburton 2007). In the Southern Pennines, UK, several studies have shown that serious atmospheric pollution from adjacent industrial and urban areas may have very adverse effects on the vegetation cover, especially Sphagnum (Bower 1962; Tallis 1997; Charman 2002). However, recently the emission of many atmospheric pollutants has undergone a reduction due to statutory limitation in the UK (Skeffington, Wilson et al. 1997) with a significant reduction in emissions and deposition of sulphate in last 25 years. However, globally, nitrogen emission has increased significantly during the 20<sup>th</sup> century (Terry, Ashmore et al. 2004). In Europe, the main increase of nitrogen oxide emissions resulting from car travel occurred between 1950 and 1990. Recently, although a decline of emissions has occurred since 1990, the concentration of nitrate-nitrogen and ammonium-nitrogen in precipitation and atmosphere is still beyond natural levels (Cundill, Chapman et al. 2007). In upland environments, atmospheric deposition usually acts as the major nitrogen input to the ecosystem (Chapman, Edwards et al. 2001). Experience from Europe and North America suggests that increased concentration of N species could lead to changes in vegetation community structure (Kirkham 2001; Terry, Ashmore et al. 2004). That is to say, the soil environment may become unsuitable for some plants because of the increase of N deposition, which may cause temporal changes or reductions of vegetation cover and consequently increase the risk of erosion although other plant species might invade and take over eventually.

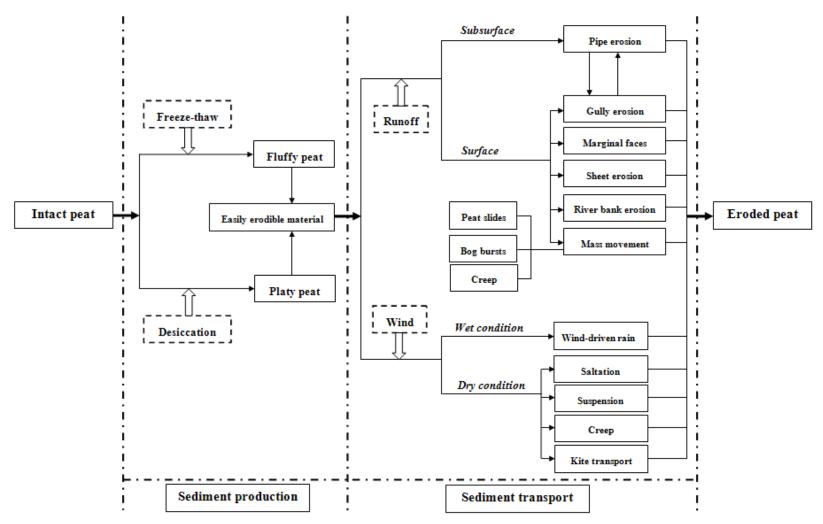
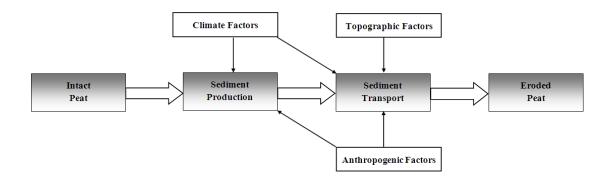


Figure 2.16 A conceptual model of blanket peat erosion

# 2.6 Summary and discussion

Peat is weathered through sediment production mechanisms (freeze-thaw and desiccation) and then transported by water and wind. A conceptual model of the peat erosion system, which attempts to summarise the processes described in the review above, is shown in Figure 2.16. Blanket peat erosion is a natural process and inevitable even without external disturbances (Bragg and Tallis 2001). However, climate change and human activities can accelerate degradation of blanket peatlands. A simplified form the impacts of environmental factors on blanket peat erosion are shown in Figure 2.17. Climate and human factors can influence surface conditions, most notably through directly altering the vegetation cover. In turn a change in vegetation cover will influence production and transport of sediment. Subsurface processes such as pipe development may also respond relatively quickly to climate change and land management (Holden, Smart et al. 2009; Holden, Smart et al. 2012b). Climate and human factors also influence the hydrological properties of the peat system (Holden, Evans et al. 2006; Worrall, Armstrong et al. 2007; Kay and Davies 2008; Ballard, McIntyre et al. 2011; Holden, Wallage et al. 2011). Consequently, as the climate changes in the future some peatlands may become subject to more severe stresses which encourage degradation and erosion, despite our best efforts to conserve and restore peatlands. It will be important to anticipate such change so that we can mitigate and adapt and also account for such changes in our carbon store and release calculations.



**Figure 2.17** A simplified conceptual model of blanket peat erosion and its relationship with environmental factors

Based on the review above, a synthesis of recent advances and gaps in understanding blanket peat erosion is discussed as follows:

# 2.6.1 Sediment production

The importance and mechanisms of freeze-thaw and desiccation in blanket peatlands have been highlighted recent years (Holden and Burt 2002a; Yang 2005; Evans and Warburton 2007). The slope of sediment rating curves has been demonstrated to be a good indicator of sediment supply in blanket peatlands at catchment scale based on individual storms (Yang 2005; Evans and Warburton 2007), providing a good way of predicting sediment production with climatic and soil moisture conditions. More work is desirable to extend the application of this indicator at other spatial and temporal scales.

#### 2.6.2 Sediment transport

There are relatively few studies on wind erosion in blanket peatlands (Warburton 2003; Foulds and Warburton 2007a; Foulds and Warburton 2007b; Baynes 2012) and more long-term observations are required at a wider range of sites. With regard to fluvial erosion of blanket peatlands, recent studies have particularly concentrated on hillslope gullies. Sediment budget studies on some typical blanket peat-covered catchments offer good understanding of the transport and deposition of erodible materials from hillslopes to catchment outlets (Evans and Warburton 2005; Evans, Warburton et al. 2006). However, the impacts of vegetation cover on blanket peat erosion should be identified more explicitly. Recent studies on mass movement have

concentrated on improved understanding of mechanisms behind different types of peat failures in order to achieve more reliable hazard assessment of peat deposits. The contributions of pipes to runoff production, sediment yield and carbon export have been shown to be important in blanket peatlands (Holden and Burt 2002b; Holden 2005a; Holden 2006; Holden, Smart et al. 2009; Smart, Holden et al. 2012; Holden, Smart et al. 2012a). However, more process-based investigation is needed to more thoroughly understand the controls on morphology of pipes in blanket peatlands (Holden, Smart et al. 2012b).

## 2.6.3 Contributing factors

Climate change and human activities have been recognised as an important reason for initiation and acceleration of peat erosion. Bioclimatic modelling suggested that many blanket peatlands will be under a climate unsuitable for active peat accumulation by the end of the century (Clark, Gallego-Sala et al. 2010; Gallego-Sala, Clark et al. 2010; Gallego-Sala and Prentice 2012). Blanket peat degradation and erosion may be more likely as climate changes in the future. However, the eventual fate of existing blanket peat outside the bioclimatic space remains uncertain because of the unknown resilience of peat to climate change (Clark, Gallego-Sala et al. 2010). It would be meaningful to examine how blanket peat erosion evolves with possible changes in future climate as this could help to identify the fate of blanket peatlands in the vulnerable areas predicted by bioclimatic modelling.

It is now widely accepted that land management is a key factor promoting blanket peat erosion. Artificial drainage, burning and grazing are commonly cited land management options in blanket peatlands. For drainage, some models have already been developed to account for the impact of drainage on peat hydrology (Beharry-Borg, Hubacek et al. 2009; Ballard, McIntyre et al. 2011). For burning and grazing, there are still a dearth of data to support a good understanding of their influence on hydrology and erosion of blanket peatlands (Worrall, Armstrong et al. 2007; Worrall and Adamson 2008; Esteves, Kirkby et al. 2012; Ramchunder, Brown et al. 2012; Holden, Wearing et al. 2013). Modelling results in other (non-peat) environments suggest that wildfire may have more adverse impact on soil erosion than prescribed burning, and there are interactions between wildfire and land management

(McMorrow 2011; Esteves, Kirkby et al. 2012). More research effort is therefore desirable to better understand these interactions.

Most studies looking at the impacts of environmental change on peatland erosion processes have focused on the relationship between peat erosion and individual factors rather than combinations of climatic and anthropogenic forces (Stevenson, Jones et al. 1990; Tallis, Meade et al. 1997; Ellis and Tallis 2001; Yeloff, Labadz et al. 2006). Little effort has been made to date to explore the combined impacts of climate change and land management on blanket peat erosion.

#### 2.6.4 Overview

There is some good understanding of hydrology and erosion processes (especially fluvial processes) in blanket peatlands, and their relationships with external forces. However, bioclimatic modelling results emphasise the necessity of investigating the development of blanket peat erosion through time. Long-term observational data from field and experimental manipulations could be helpful. However, given the complexity of relationships between peat erosion and environmental factors, uncertainties in future environmental change, and the expense of such projects, an alternative approach via modelling is sought. Models are usually established based on existing knowledge, and operate with different possible inputs to account for uncertainties in future change. Although modelling results are not alternatives to observations, they are powerful tools in interpreting observations, and in testing and developing theories (Wainwright and Mulligan 2013). Current knowledge of the hydrology and erosion processes in blanket peatlands (and it is accepted that there are still knowledge gaps as identified above) provides a good basis to establish, calibrate and validate a model. Erosion models not only provide information on the stage of erosion but also link varied erosion-causing factors usually including climate and land use / management conditions (Licciardello, Govers et al. 2009). Scenario analysis based on erosion modelling offers a good way of investigating the evolvement of sediment erosion under possible changes in climate, land use / management and their interactions over time. In addition, recent advances in modelling theory such as distributed physically-based models and other technologies such as Geographic Information Systems and Remote Sensing also facilitate the application of a modelling approach. However, modelling all types of peat erosion would need large quantities of work and would not be possible given the lack of measurements on some peat erosion processes such as sheet erosion, river bank erosion or wind-driven rainsplash etc. This project will, therefore, mainly concentrate on the modelling of fluvial erosion in blanket peatlands because of its high significance and data availability (Baynes 2012; Clay, Dixon et al. 2012). Evans and Warburton (2007) demonstrated that the relative importance of fluvial erosion is usually higher than wind erosion through comparing the amount of peat loss from several catchments via fluvial erosion, wind erosion and peat shrinkage in the UK.

# 2.7 Overall methodology for the thesis

As noted above, it is possible to develop a new model for this project based on previous research results on the hydrology and erosion in blanket peatlands. However, many models looking at hydrological and erosion processes for other soil systems have already been developed and tested independently in recent decades (Aksoy and Kavvas 2005; Stott 2010), and some of them may already be capable of simulating all or some of the hydrological and / or erosion processes in blanket peatlands. This is to say, it may be more advisable to model blanket peat erosion with an existing model in order to avoid repeating the work that has been done previously. Given this consideration, three major steps, which are model selection, model development and model application, will be involved in this project. A flowchart for this project is shown in Figure 2.18.

#### 2.7.1 Model selection

In this step, firstly candidate models will be reviewed from current existing erosion models based on the basic characteristics of them such as model type, model structure etc. Secondly, candidate models will be evaluated based on current knowledge of blanket peat erosion and the purposes of this project, to decide whether any are suitable for blanket peatlands. The most promising model will then be tested against field data to decide whether improvements are needed. This first step will be undertaken in Chapter 3.

## 2.7.2 Model development

There would be no need to modify the selected model if it is perfectly suitable for blanket peatlands. However, this is unlikely. Therefore, two major tasks are involved in model development: modifying the selected model and testing the modified model. The former will be done mainly based on analysis of secondary field data, and previous publications. Then the modified model will be evaluated systematically with more field data. The final model will be obtained if the modified model behaves robustly in blanket peatlands. This second step will be completed in Chapters 4 and 5.

## 2.7.3 Model application

After model development, the final model will be applied to investigate the reaction of blanket peat erosion to possible changes in climate and land management. The model will firstly be applied in the North Pennines and then in ten blanket peat-covered sites across the Great Britain (GB). It is expected that modelling results will be useful to inform long-term land management strategies in GB peatlands. This third step will be accomplished in Chapters 6 and 7.

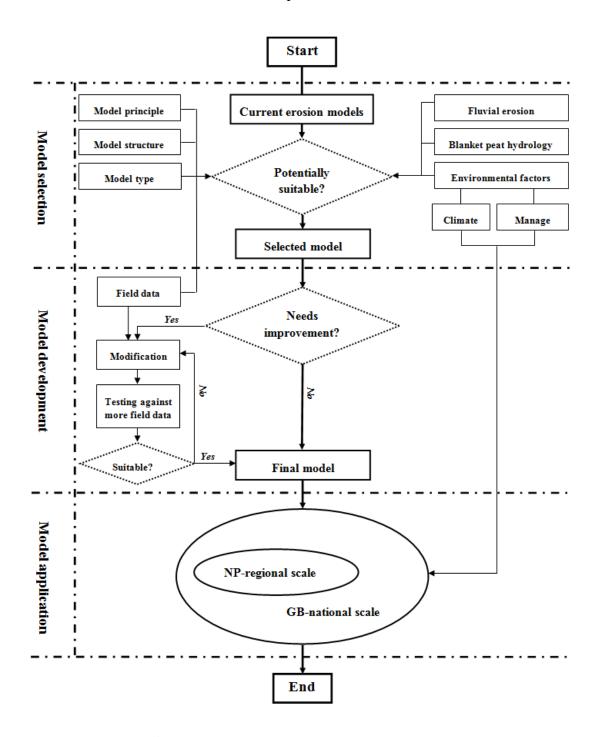


Figure 2.18 Overall flowchart of the project

# **Chapter 3**

# **Evaluation of contemporary erosion models**

### 3.1 Introduction

In Chapter 2, it was suggested that this project included three major steps, which were model selection, model development and model application. Model selection will be undertaken in this chapter by reviewing and evaluating existing erosion models.

The structure of this chapter is as follows: Section 3.2 focuses on the theoretical development of erosion modelling and review of existing erosion models, especially candidate models for the project. Section 3.3 concentrates on theoretical assessment of candidate models to support the choice of the promising model for the project. Numerical evaluation of the selected model is then undertaken in section 3.4. Section 3.5 is a summary of the chapter. The improvements that are needed for the selected model to fit the blanket peat case are also discussed.

# 3.2 Development of erosion modelling

## 3.2.1 Theoretical advances in erosion modelling

Models are simplified representations of reality. In general, three broad types of model are frequently used in erosion modelling: empirical, physically-based, and conceptual models.

In empirical models, statistical techniques (e.g. regression) are employed to generate the relationships between different components of studied systems (Gobin and Govers 2003). Empirical models are able to provide very accurate results after parameterization and optimization. However, empirical-statistical models are not able to explain how or why inputs are transformed into outputs. Therefore, two issues often emerge after parameterization and optimization of empirical-statistical models. First, the calibration of parameters may result in the model getting the right answer in the sense of matching observations but for the wrong reason (i.e.

physically unrealistic parameter values). Second, empirical models often perform very poorly if generalized because the relationships between input and output variables are only reliable for certain place and time.

Process / physically-based models can avoid the disadvantages of empirical models. Physically-based models consist of mathematical equations derived from theoretical principles for interaction within a system in order to explain and predict the dynamic behaviour of the system as a whole (Wiltshire 1983). Theoretically the actual processes could be perfectly reproduced by physically-based models, while all parameters in the model could be measured in the field and so are 'known'. While it would be nice if physical models involved all physical processes in reality, it is not possible for models to incorporate so many processes because: 1) more complex models may require too much computing time to run and may not necessarily yield better predictions than simpler models (Beven and Binley 1992) and 2) field data supporting the establishment or testing of models typically has not covered all of the processes. This is to say, knowledge of some processes may be lacking and more field work is still needed to obtain process-based data.

Conceptual models are an abstract representation of actual processes (Child and Rodrigues 2005), typically representing a catchment as series of internal storages (Merritt, Letcher et al. 2003). The work of conceptual models is to make theory more explicit and applicable, and experimental, in order to test the correspondence between theory and reality. However, they only include a general description of catchment processes rather than details of process interactions. Whilst they tend to be aggregated they still reflect the hypothesis about the processes governing system behaviour (Merritt, Letcher et al. 2003). Therefore, they usually play an intermediary role between empirical and physically-based models.

Moreover, erosion models are usually built in two structures: lumped and distributed (Aksoy and Kavvas 2005). In lumped models, contributing factors of erosion are represented by a constant value over the whole study area. However, factors that influence erosion significantly vary over space even within areas as small as one field such as soil properties or topography. This variability cannot be represented by the average value. Recent advances in Geographic Information Systems and Remote

Sensing support better representations of this spatial variability. As a result, spatially distributed models may provide an improvement over the performance of traditional lumped models (Aksoy and Kavvas 2005). In spatially-distributed models, a large area is divided into small sub-units, which have uniform characteristics such as climate, land use and topography etc. Models then run in each of the sub-units to calculate soil loss (Morgan, Quinton et al. 1998a). There are two types of distributed models: fully-distributed and semi-distributed models. In fully-distributed models small sub-units are usually grid cells, while in semi-distributed models small sub-units are defined as sub-catchments which models work on.

It is clear that the variability, nonlinearity and the interacting nature of erosion and deposition processes over various scales significantly influence the mechanics of surface runoff generation and soil erosion (Kirkby 1999a; 1999b). In particular, the important temporal dynamics of precipitation and surface characteristics (e.g. vegetation cover), which also vary spatially, have strong controls on surface runoff generation and the resulting soil erosion (Saavedra 2005). So an erosion model usually could only focus on the soil erosion and transport at specific spatial and temporal scales. The time scale of a model is commonly known as the "time-step". Typically modelling scales are plot / local (1 m<sup>2</sup>), hillslope (10000 m<sup>2</sup>), catchment (100 km<sup>2</sup>) and regional (> 1000 km<sup>2</sup>) in space; and event (~1 day), seasonal (~1 year), and long-term (~100 years) in time (Saavedra 2005). Erosion and sediment transport models tend to have been developed from two points of view. Event-based models are developed to look at the response of the modelled area to single storm events. For each event, the model time step is in the order of minutes to hours. The model algorithms are often developed for application to small plots or grid cells in a catchment (Merritt, Letcher et al. 2003; Aksoy and Kavvas 2005). Alternatively, a larger temporal resolution is used in models that explore general trends over time with respect to changes in rainfall, vegetation or land management (Renschler and Flanagan 2002). This approach is usually to use a continuous time step, usually daily / monthly, that is responsive to, for example, the development and recession of saturated zones or other processes that can be captured at this time step (Merritt, Letcher et al. 2003).

## 3.2.2 Existing erosion models

Along with the development of modelling theory, various soil erosion models have been established over the past few decades such as the Universal Soil Loss Equation and its modifications (USLE / RUSLE / MUSLE) (Wischmeier and Smith 1965; Wischmeier and Smith 1978; Renard, Foster et al. 1991), Chemical, Runoff and Erosion from Agriculture Management System (CREAMS) (Knisel 1980), Water Erosion Prediction Project (WEPP) (Laflen, Lane et al. 1991), European Soil Erosion Model (EUROSEM) (Morgan, Quinton et al. 1998b), Soil and Water Assessment Tool (SWAT) (Neitsch, Arnold et al. 2005), Pan-European Soil Erosion Risk Assessment (PESERA) (Govers, Gobin et al. 2003), Limburg Soil Erosion Risk Model (LISEM) (De Roo 1996) and Cellular Automaton Evolutionary Slope And River model (CAESAR) (Coulthard, Macklin et al. 2002; Coulthard 2010). A summary of the basic characteristics of existing erosion models is provided in Table 3.1. Each type of model serves a purpose, and a particular model type may not categorically be considered more appropriate than others in all situations (Merritt, Letcher et al. 2003). Choice of a suitable model relies heavily on the function that the model needs to serve. In this project, the chosen model will be applied at regional and national scales; therefore physically-based models are preferred mainly because of higher transferability. There are 15 physically-based erosion models in Table 3.1, and they are considered as candidate models for the project.

**Table 3.1** Basic characteristics of existing soil erosion models (summarised from Merritt, Letcher et al. 2003; Aksoy and Kavvas 2005)

Name	Туре	Temporal scale	Spatial scale
AGNPS	Conceptual	Event/continuous	Small catchment
EMSS	Conceptual	Continuous	Catchment
HSPF	Conceptual	Continuous	Catchment
IQQM	Conceptual	Continuous	Catchment
LASCAM	Conceptual	Continuous	Catchment
AGWA	Conceptual	Continuous	Catchment
WATEM	Conceptual	Annual	Catchment
SEDNET	Conceptual	Annual/continuous	Catchment
SEDNET	Conceptual/empirical	Continuous	Catchment
SWAT	Conceptual	Continuous	Catchment
USLE	Empirical	Annual	Hillslope
RUSLE	Empirical	Annual	Hillslope
MUSLE	Empirical	Annual	Hillslope
IHACRES-WQ	Empirical/conceptual	Continuous	Catchment
USPED	Empirical/conceptual	Event/annual	Catchment
MMMF	Empirical/conceptual	Annual	Hillslope/catchment
SEAGIS	Empirical/conceptual	Annual	Catchment
SPL	Empirical/conceptual	Annual	Catchment
ANSWERS	Physically-based	Event/continuous	Small catchment
GUEST	Physically-based	Continuous	Plot/field
CREAMS	Physically-based	Event/continuous	Plot/field
PERFECT	Physically-based	Continuous	Plot/field
EPIC	Physically-based	Continuous	Hillslope/catchment
WEPP	Physically-based	Event/continuous	Hillslope/catchment
MIKE-II	Physically-based	Continuous	Catchment
SHETRAN	Physically-based	Event	Catchment
EROSION-3D	Physically-based	Event	Small catchment
CASC2D-SED	Physically-based	Event	Catchment
KINEROS	Physically-based	Event	Hillslope/small catchment
EUROSEM	Physically-based	Event	Field/small catchment
LISEM	Physically-based	Event	Small catchment
PESERA	Physically-based	Continuous	Hillslope/regional
CAESAR	Physically-based	Event/continuous	Catchment

#### 3.2.3 Candidate models

The 15 candidate models are briefly introduced and discussed in this section before any further assessment is implemented. USLE has been extensively applied in predicting water erosion and supporting soil conservation measures around the world (Yang, Liu et al. 2005). USLE and its modifications have been used as a core for some of the other physically-based erosion models listed such as CREAMS, PERFECT and EPIC. So USLE and its variants are also introduced in this section.

#### 3.2.3.1 USLE and its modifications

The Universal Soil Loss Equation (USLE) model was developed by the US Department of Agriculture (USDA) for sheet and rill erosion based on experimental data from 10,000 agricultural plots and is only valid for a field area up to 1 ha (Wischmeier and Smith 1978). The model estimates average annual water erosion as a function of six factors:

$$A = R K L S C P$$

Equation 3.1

where, A is the estimated soil loss per unit area; R is the rainfall erosivity factor, K is the soil erodibility factor, L is the slope length factor, S is the slope steepness factor, C is the crop management factor, and P is the erosion control practice / support practice factor (Wischmeier and Smith 1978).

A number of modifications have been made to the model to take into account of additional information, resulting in some derivatives of USLE such as MUSLE and RUSLE. The MUSLE has been an attempt to estimate stream sediment yield for individual storms by replacing the rainfall factor with a runoff factor, based on 778 storm-runoff events collected from 18 small watersheds (Aksoy and Kavvas 2005; Sadeghi, Gholami et al. 2013). The RUSLE is a systematic improvement of USLE based on an extensive review of the USLE and its data base, analysis of data not previously included in the USLE, and theory describing fundamental hydrologic erosion processes (Renard, Foster et al. 1991; 1994).

#### **3.2.3.2 ANSWERS**

The Areal Non-point Source Watershed Environment Response Simulation (ANWERS) model was developed by Beasley, Huggins et al. (1980). It is one of the first operational, fully spatially distributed, catchment erosion and sediment yield models, including a water erosion and sediment transport model. The main component of the model is the sediment continuity equation proposed by Foster and Meyer (1977). Runoff modelling in the ANSWERS model considers runoff as occurring only where rainfall intensity exceeds the infiltration capacity. Detachment of soil particles is calculated using an empirical function of soil properties, soil cover conditions, raindrop impact and overland flow (Bouraoui and Dillaha 1996). Dillaha, Wolfe et al. (1998) noted that plans exist to replace the existing empirical sediment detachment component with a reliable and robust physically-based sediment detachment sub-model. ANSWERS uses a form of the Yalins' (1963) bedload transport equation to predict the transport of cohesionless gains over a movable bed for steady uniform flow of a viscous fluid (Loch, Maroulis et al. 1989).

#### **3.2.3.3 GUEST**

The Griffith University Erosion System Template (GUEST) is a steady-state, process-based model developed to interpret temporal fluctuations in sediment concentration from bare soil in single erosion events (Hairsine and Rose 1992a; Hairsine and Rose 1992b; Misra and Rose 1996). The model relates measured runoff and rainfall rates, soil characteristics and plot geometry of uniform slope to the concentration of eroded sediment, defined as dry mass of sediment per unit of runoff (including sediment volume) (Misra and Rose 1996). The hydrology component of the GUEST model requires measured rainfall rates and the runoff rate per unit area for a bare plot of known area and downslope length. These inputs are used to obtain the volumetric flux of water per unit width of plot and from these discharge-depth relationships to obtain an estimate of the depth of the water produced. GUEST allows for the consideration of sheet erosion and rill erosion. Discharge-depth relationships are used to calculate shear stress on the soil or sediment surface associated with runoff water. Shear stress and the velocity of flow are then used to estimate stream power. Whether or not an erosion event leads to differences in sediment concentration from the equilibrium conditions is assumed to be controlled by the stream power and the threshold stream power (Misra and Rose 1996). Entrainment and re-entrainment are considered to occur only the stream power exceeds the threshold stream power.

#### **3.2.3.4 CREAMS**

The Chemical Runoff and Erosion from Agricultural Management System (CREAMS) model was developed by Knisel (1980a) as a tool to predict runoff, erosion and chemical transport from agricultural areas. The model operates in both single storm events or in a long-term average (continuous) mode. Algorithms in CREAMS have been used in numerous other models of erosion and water quality (e.g. PERFECT, WEPP). Runoff production in the CREAMS model is simulated with the empirical SCS curve number approach (USDA 1972), which is capable of estimating saturation-excess overland flow. Alternatively, a Green-Ampt approach for infiltration excess can be used. The CREAMS model uses a physically-based approach to erosion and sediment transport. The erosion estimated by the CREAMS is determined by the sediment supply and sediment transport capacity for overland flow. Sediment supply is predicted by the USLE, while transport capacity, as with the ANSWERS model, is calculated using Yalin's equation (Yalin 1963).

#### **3.2.3.5 PERFECT**

The Productivity, Erosion and Runoff, Functions to Evaluate Conservation Techniques (PERFECT) model was developed by the Queensland Department of Primary Industies and the QDPI / CSIRO Agricultural Production System Research Unit (Littleboy, Silburn et al. 1992) to provide long-term predictions of runoff, soil erosion, soil water, drainage, crop growth and yield at plot and field scales. The model is comprised of six modules: data input, water balance, crop growth, crop residue, erosion and model output. Runoff depth is predicted using a modified form of the SCS curve number technical (Knisel 1980a). So a larger volume of runoff occurs at a low soil water deficit and little runoff occurs at a high soil moisture deficit. Predicted runoff will equal the daily rainfall when the soil is fully saturated. Partial area runoff processes and subsurface flow are not considered (Home 1997). Sediment yield is simulated in the model using MUSLE.

#### 3.2.3.6 EPIC

The Erosion Productivity Impact Calculator (EPIC) model was developed by Williams, Jones et al. (1984) to assess the effect of soil erosion on soil productivity. It is a continuous simulation model that can be used to determine the effect of management strategies on agricultural production and soil and water resources. The drainage area considered by EPIC is generally field-sized up to 100 ha. The major components in EPIC are weather simulation, hydrology, erosion-sedimentation, nutrient cycling, pesticide fate, plant growth, soil temperature, tillage, economics, and plant environment control. The EPIC model simulates surface runoff volumes and peak runoff rates, given daily rainfall amounts. Runoff volume is estimated with a modification of the SCS curve number approach (USDA 1972). The water erosion is simulated with the MUSLE.

## 3.2.3.7 WEPP

The Watershed Erosion Prediction Project (WEPP) is a physically-based model, which was developed by an interagency team of scientists in United States to replace the USLE family models and expand the capabilities for erosion prediction in a variety of landscapes and settings (Laflen, Lane et al. 1991; Flanagan and Livingston 1995). The model can be used in either a single event or continuous time scale and calculates erosion from rills and inter-rills at hillslope and catchment scales. Runoff is predicted with the a solution of the Green-Ampt equation developed by (Chu 1978). The peak runoff rate can be simulated using either kinematic wave overland flow routing or simplified regression equations. WEPP divides runoff between rills and interrill areas. The steady-state sediment continuity equation is used to predict rill and interrill processes (Nearing, Foster et al. 1989). Rill erosion occurs if the shear stress exerted by flow exceeds the critical shear stress while sediment load in the flow is smaller than the transport capacity of flow. Interrill erosion is considered to be proportional to the square of the rainfall intensity. Interrill area delivers sediment to rills (Tiwari, Risse et al. 2000).

## 3.2.3.8 MIKE-II

The MIKE-II model is a one-dimensional dynamic model consisting of a number of modules (Hanley, Faichney et al. 1998), operating on a number of timescales from single storm events to monthly water balance at catchment scale. The basic modules

are a rainfall-runoff component, a hydrodynamic module, a water quality module, and a sediment transport module. The model contains a mix of conceptual and physically-based modules. The runoff components are relatively simple conceptual models (Madsen 2000) although flow routing is described using physically-based St Venant's equations (Hanley, Faichney et al. 1998). The erosion and transport of water flow module includes a description of the erosion and deposition of both cohesive and non-cohesive sediments. Erosion and deposition are modelled as source or sink terms in an advection-dispersion equation.

#### **3.2.3.9 SHETRAN**

The SHETRAN model is physically-based, spatially distributed, erosion and sediment yield component of the existing European distributed hydrological modelling system SHE and is for use at catchment scale (Ewen, Parkin et al. 2000). Three main components in SHETRAN are water flow, sediment transport and solute transport. Surface water flow is determined from the net rainfall and evaporation rates supplied by the interception / evapotranspiration component and from the soil infiltration rate of unsaturated zones (Abbott, Bathurst et al. 1986). The model simulates the erosion, transport and deposition of sediments at the ground surface and along the channel network and is divided into two subcomponents: hillslope and channel. For hillslopes, SHETRAN simulates soil erosion by raindrop impact, leaf drip and sheet overland flow, and the transport of eroded material by overland flow. For channels, the component simulates the erosion of the bed material and the downstream transport of this material, together with that supplied by overland flow (Ewen, Parkin et al. 2000).

## 3.2.3.10 EROSION-3D

The EROSION-3D model is a physically-based model based on physical principles for forecasting the soil erosion in water catchment areas caused by naturally occurring single rain-storm or by a series of such precipitation events (Schmidt, Werner et al. 1999). Runoff is calculated as infiltration-excess mechanisms, which is simulated by the Green-Ampt approach. The erosion component is based on calculating the detachment of soil particles caused by overland flow and falling raindrops, the transport of particles including deposition depending upon the transporting capacity of surface runoff (Schmidt and Werner 2000). On the basis of

individual rainfall events, detachment, deposition and net erosion for each grid cell of a catchment area are computed. In addition, the amount of runoff, sediment concentration, and the grain size distribution are calculated.

#### 3.2.3.11 CASC2D-SED

The CASCade 2 Dimensional SEDiment (CASC2D-SED) model was developed at the Colorado State University (CSU), is a distributed physically-based, hydrological and soil erosion model that simulates the hydrological response of a catchment subject to a given storm event (Julien and Saghafian 1991; Julien, Saghafian et al. 1995; Johnson and Julien 2000). For a given rainfall event, once the initial losses have been subtracted from rainfall, water begins to infiltrate. The Green-Ampt infiltration equation accommodates spatial and temporal variability due to changes in the rainfall and / or soil properties. When the precipitation rate exceeds the infiltration rate, the excess rainfall runs off as Hortonian overland flow. The final sediment yield is estimated based on the availability of sediment in the watershed and the transport capacity of the stream. The available sediment is calculated as a function of the hydraulic properties of the flow, the physical properties of the soil and the surface characteristics. Transport capacity of overland flow is estimated using the modified kilinc (1973) transport capacity equation, which depends on flow discharge, terrain slope and soil and land use characteristics.

#### **3.2.3.12 KINEROS**

The KINEmatic runoff and eROSion (KINEROS) model is an event oriented physically- based model describing the processes of interception, infiltration, surface runoff and erosion from small agricultural and urban watersheds (Smith, Goodrich et al. 1995). The catchment is represented by a cascade of planes and channels. It uses the Smith / Parlange infiltration model and the kinematic wave approximation to route overland flow and sediments (Julien, Saghafian et al. 1995). Only Hortonian overland flow is considered in KINEROS. The model can account separately for the erosion caused by raindrop energy and flowing water. The movement of eroded soil along with the movement of surface water is also considered (Woolhiser, Smith et al. 1990).

#### **3.2.3.13 EUROSEM**

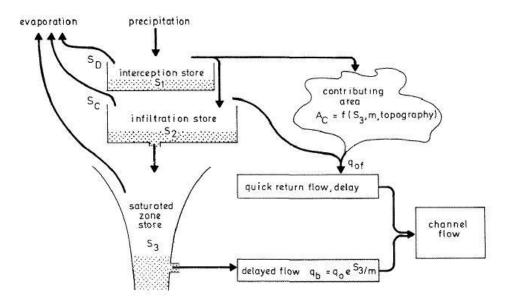
The European Soil Erosion Model (EUROSEM) was developed by European Commission funded research involving scientists from Europe and the USA between 1989 and 1992 (Morgan, Quinton et al. 1998a). The model simulates erosion on an event basis for fields and small catchments, adopting physically distributed descriptions to describe the process of soil erosion and is fully dynamic (Morgan, Quinton et al. 1998b). EUROSEM is based on the KINEROS (Woolhiser, Smith et al. 1990) model to predict infiltration-excess overland flow. Water transport in EUROSEM involves interception by vegetation, soil infiltration, depression storage and flow in channels. Erosion is triggered by raindrop splash and surface runoff and then transported through hillslopes and channels to catchment outlet (Morgan, Quinton et al. 1998a). With regard to the output, the model produces total runoff and soil loss as well as the hydrograph and sediment graphs, which leads EUROSEM to be able to model peak sediment discharge during single events.

#### 3.2.3.14 LISEM

The LImburg Soil Erosion Model (LISEM) is a fully dynamic, physically-based, single event based soil erosion model developed during the LISEM project in the loess area of the Netherlands on the basis of experiences with ANSWERS (Beasley, Huggins et al. 1980) and SWATRE (Belmans, Wesseling et al. 1983). The hydrological and erosion processes of LISEM include rainfall, interception, depression storage, infiltration, overland flow, channel flow, detachment by leaves, drainage and throughfall, detachment by overland flow and transport capacity of flow. In addition to the above, tractor wheelings, small roads and surface sealing could also be included if needed (Hessel, Jetten et al. 2003). Saturation-excess overland flow is simulated with the Richards equation based sub-model (SWATRE) when detailed soil information is known. Otherwise, only infiltration-excess overland flow can be simulated using the empirical Holtan / Overton infiltration equation. Erosion and transport processes involved in LISEM are raindrop splash, rill / interrill erosion, and channel erosion. Splash detachment is estimated using an empirical function derived from unpublished data based on soil aggregate stability, rainfall kinematic energy and the depth of the surface water layer (De Roo, Wesseling et al. 1996a; De Roo, Jetten et al. 1996b). The approaches to estimate flow detachment and deposition are from EUROSEM, comparing the sediment concentration in flow and transport capacity of the flow, which is previously calculated using slope gradient and mean flow velocity, to determine detachment or deposition occurs and then calculate the rates with related equations (Morgan, Quinton et al. 1998a).

#### **3.2.3.15 PESERA**

The Pan-European Soil Erosion Risk Assessment (PESERA) model is a physically based, spatially distributed long-term soil erosion model. It was developed as a diagnostic tool of regional and / or European scale to predict soil erosion rates under various land use types, soil and landscape characteristics (Tsara, Kosmas et al. 2005), based on earlier models (Kirkby and Neale 1987; Kirkby and Cox 1995). PESERA models water erosion processes occurring on hillslopes such as rill erosion and sheet erosion, not including channel erosion, rainsplash and river bank erosion etc. Nevertheless, PESERA may be used to assess sensitivity to changed climate and land use scenarios as land use (e.g. vegetation cover) and climate (e.g. rainfall) are key drivers in the model. Daily sediment yield is calculated based on soil erodibility, local gradient and overland flow. Long-term average erosion rate is obtained from daily erosion through summing over the frequency distribution of daily rainfalls for each month. Soil erodibility is mainly controlled by soil properties, especially soil texture. The value is highest for fine sand and silt soils with low clay content (Kirkby, Irvine et al. 2008). In addition, vegetation cover also plays an important role in resisting soil erosion by improving surface roughness and binding soil together with shallow root mats. Local gradient is usually extracted from a digital elevation model (Oldeman). The overland flow runoff is estimated with a storage model in the PESERA model. Runoff is a certain percentage of rainfall minus the threshold storage, which is dependent on various factors relating to soil, vegetation cover, tillage and soil moisture status (Kirkby 2003). PESERA is able to reproduce both saturation-excess and infiltration overland flow (Tsara, Kosmas et al. 2005).



**Figure 3.1** Hydrological processes within TOPMODEL (from Beven and Kirkby 1979)

In the PESERA, the TOPography based hydrological Model (TOPMODEL) is incorporated to update the soil moisture content, which is crucial for reproducing runoff, especially for saturation-excess overland flow and subsurface flow (Govers, Gobin et al. 2003; Kirkby, Jones et al. 2004; Kirkby, Irvine et al. 2008). TOPMODEL was developed by Beven and Kirkby (1977) to predict the hydrological responses of ungauged catchments of up to 500 km<sup>2</sup> within humidtemperate zones (Beven, Kirkby et al. 1984). The model is physically based and was originally semi-distributed, with assumptions and process representations of TOPMODEL being suitable for blanket peat-covered catchments. The applicability of the model in blanket peatlands has been numerically tested since 1984 (Beven, Kirkby et al. 1984). The hydrological processes within the TOPMODEL are illustrated in Figure 3.1. Interception by vegetation cover and / or depression is considered as the interception store, meanwhile evaporation is allowed in this layer. The infiltration store will not receive water from the interception store until the interception store is fully filled. In the infiltration store layer, infiltration-excess overland flow occurs when rainfall intensity from the interception store exceeds the rate of infiltration from the infiltration store to saturated zone. Saturation-excess overland flow occurs when the infiltration store reaches its capacity. Evaporation is also present in the layer of the infiltration store. With regard to the layer of the saturated zone store, it is significant in generating the subsurface flow, which plays a crucial role in providing the hydrograph tail and low flows (Knisel 1973) and sometimes return to flow over the surface (return flow). Spatially variable contributing areas are related to subsurface soil water storage. For a given storage level, the related source areas could be determined. Any rain falling on contributing areas will immediately become overland flow. The overland flow and subsurface flow resulting from the above processes are merged into the channel flow and eventually routed to the catchment outlet.

#### **3.2.3.16 CAESAR**

The Cellular Automaton Evolutionary Slope And River (CAESAR) model was developed based on a cellular automaton model of river catchment evolution of Coulthard, Kirkby et al. (1996; 1998). It was initially used to simulate the influence of changes in climate and land use on the geomorphic processes of UK rivers on a flood event basis over the Holocene (Coulthard, Macklin et al. 2002; Coulthard 2010). CAESAR is a cellular model using a regular mesh of grid cells to represent the river catchment studied. Both fluvial erosion and deposition are calculated as a balance between forces moving and restraining the soil particles (Coulthard, Macklin et al. 2002). Slope process such as mass movement and soil creep are taken into account in CAESAR (Coulthard, Macklin et al. 2002). The CAESAR model can run in catchment mode or reach mode. For catchments under study, the description of hydrological process based on the input rainfall data in the model is derived from the TOPMODEL. Saturation-excess overland flow is therefore considered. The output from the hydrological model is then routed through the catchment using a scanning multiple flow algorithm (Coulthard, Macklin et al. 2002) that sweeps across the catchment in four directions (from north to south, east to west, west to east and south to north). For the reach mode, the input discharge is also routed using the scanning algorithm (Van De Wiel, Coulthard et al. 2007). In each scan, flow is routed to three down slope neighbours, but if the total flow is greater than the subsurface flow, the excess is treated as surface runoff and flow depth is calculated using Manning's equation (Van De Wiel, Coulthard et al. 2007).

## 3.3 Model selection

In order to determine the promising model for the project, five criteria (Table 3.2) were set up with reference to the basic characteristics of hydrology and erosion in blanket peatlands, and the objectives of this project. In terms of the introduction to contemporary erosion models in section 3.2.3, some of the models are theoretically capable of simulating saturation-excess overland flow such as CREAMS, PERFECT, EPIC, MIKE-II, LISEM, PESERA and CAESAR. However, there was no existing erosion model considering freeze-thaw and desiccation as the sediment production mechanism. So none of the candidate models listed in section 3.2.3 was fully suitable for blanket peat erosion simulation. A model was then selected if it met more criteria in Table 3.2 than others. The PESERA was the only model appropriate to work at a long-term, large spatial scale. The large spatial scale allows the simplification of some of the detailed processes observed but retains key drivers and parameters. However, the PESERA model can be implemented in two modes (Kirkby, Irvine et al. 2008). Firstly, to provide an estimate of sediment yield at a point, which is carried out in Excel, supported by Visual Basic Macros (PESERA-POINT), and secondly to produce a distributed estimate of erosion risk over a large spatial area, which is achieved in FORTRAN90 (PESERA-GRID), operating on data extracted from ArcGIS grids. Therefore, the PESERA-GRID model was chosen as a basis for the project. Furthermore, PESERA is theoretically able to simulate saturation-excess runoff generation which is crucial for blanket peatlands (Evans, Burt et al. 1999; Holden and Burt 2002a). The climate variables used in the PESERA model could be derived from UKCP09 predictions. With regard to land management practices, grazing has already been represented in both versions of the PESERA model by vegetation cover and biomass removed (Kirkby, Irvine et al. 2008). A drainage model has been developed and incorporated into the PESERA-POINT model the account for the impact of drainage on vegetation and soil moisture content (Beharry-Borg, Hubacek et al. 2009). The PESERA-POINT model was also extended to evaluate the impact of managed burning and wildfire on soil erosion based on a previous developed ignition model and experiments in central Portugal (Esteves, Kirkby et al. 2012).

**Table 3.2** Criteria used for evaluation of candidate models

No.	Criteria
1	Is the model able to simulate saturation-excess overland flow?
2	Is the model capable of describing typical fluvial erosion processes in blanket peatlands?
3	Is the model suitable to work at a long-term, large spatial scale?
4	Does the model include climate variables? If yes, are these variables available for future climate?
5	Does the model consider typical land management practices in blanket peatlands such as grazing, burning and drainage?

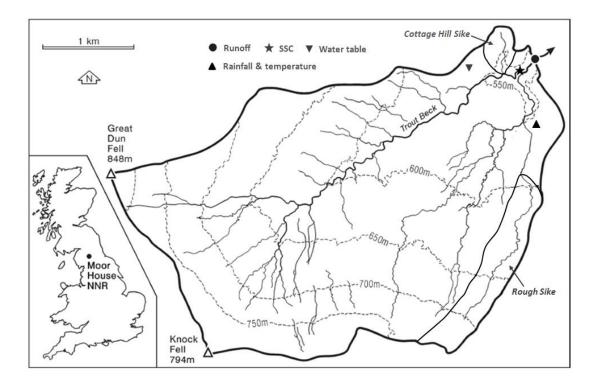
## 3.4 Numerical evaluation of the PESERA-GRID

The PESERA-GRID model was recognized as the promising model for this project in terms of the analysis in section 3.3, although not fully theoretically ready for blanket peat erosion modelling. In this section, PESERA-GRID is further evaluated with field data to investigate its applicability and potential improvements needed for the blanket peat use more explicitly.

## 3.4.2 Study site

The site chosen to test PESERA-GRID is Trout Beck catchment (Figure 3.2). One of the key reasons for choosing this site was the availability of field data as Chapter 2 showed this was lacking from blanket peat sites more generally (Table 2.2). It lies within the Moor House National Nature Reserve (NNR), UK. The area is 11.4 km<sup>2</sup> with elevation ranging from 532 m to 845 m. The geology here is alternating strata of Carboniferous limestones, sandstone and shales. Over most of the catchment, the bedrock is mantled with a soliflucted till deposit dating from the end of the last glaciations (Johnson and Dunham 1963). Such a clay-rich deposit provides an impermeable base, which has allowed the formation of blanket peats. Additionally, the climate of the catchment is sub-arctic oceanic (Manley 1936) with 2012 mm of mean annual rainfall and 244 precipitation days per year (Holden and Rose 2011), which meets requirements necessary for blanket peat formation (Lindsay, Charman et al. 1988). Trout Beck is over 90 % covered by blanket peat, of which 18 % was classified as eroded peat (Evans, Burt et al. 1999). Blanket peat depths are typically 1-2 m (Holden and Burt 2003a). However, mineral soils and soil complexes are distributed towards fell tops and along main stream channels. Vegetation cover is

dominated by the association of ling heather, cotton grass and *Sphagnum*. However, above 630 m cotton grass alone becomes dominant (Evans, Burt et al. 1999). Two important tributaries of Trout Beck named Cottage Hill Sike and Rough Sike have previously been studied for hydrological and erosion research (Evans and Warburton 2005; 2006; 2007; Smart, Holden et al. 2012; Holden, Smart et al. 2012b).



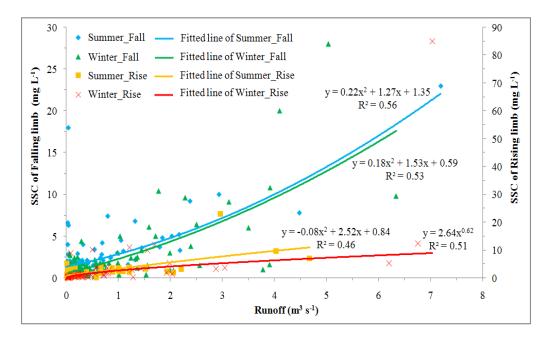
**Figure 3.2** Trout Beck, Cottage Hill Sike, Rough Sike and gauges within Trout Beck catchment to measure runoff, suspended sediment concentration water table, rainfall and temperature (redrawn from Evans, Burt et al. 1999).

## 3.4.3 Model evaluation

## 3.4.3.1 Reconstruction of sediment flux

Water discharge (1993-2009), suspended sediment concentration (1997-2009), rainfall (1991-2010) and temperature (1991-2010) of the Trout Beck catchment are available from Environmental Change Network (ECN) gauging stations (Figure 3.2). Mean monthly potential evapotranspiration (PET) between 1993 and 2002 were estimated by Clark (2005) with a Penman-Monteith equation, and the mean annual total was 677 mm.

Suspended sediment concentration data are monthly before 2004 and weekly during and after 2004. PESERA provides monthly sediment flux. Therefore, interpolation of the original suspended sediment concentration data is needed in order to obtain sediment flux datasets appropriate for PESERA-GRID testing. A sediment rating curve was adopted for interpolation of suspended sediment concentration. Best fitted lines were achieved when taking into consideration of seasonal (summer or winter half year) and hydrograph characteristics (rising or falling limb of hydrograph) of sampling points. Figure 3.3 shows the resulting sediment rating curves. Continuous suspended sediment concentration and monthly sediment flux was then calculated based on these equations and the 15-min measured runoff. Total sediment flux from Trout Beck catchment between 1997 and 2009 was estimated to be 1557 ton. This is similar to the value of 1531 ton calculated with an equation proposed by Verhoff, Melfi et al. (1980) and Walling and Webb (1985) (method 5), demonstrating the reliability of the fitted sediment rating curves.



**Figure 3.3** Sediment rating curves of the Trout Beck catchment between 1997 and 2009

#### 3.4.3.2 Evaluation method

With regard to model output assessment, the Nash-Sutcliffe model efficiency (E) was employed to assess predictive power over the whole modelling period. Although initially developed to evaluate the performance of hydrologic modelling, it has been reported for model simulations of water quality constituents such as sediment, nitrogen, and phosphorus loadings (Schoenberger 1991). It is calculated as:

$$E = 1 - \frac{\sum_{t=0}^{T} (Q_0^t - Q_m^t)^2}{\sum_{t=0}^{T} (Q_0^t - \overline{Q_0})^2}$$
 Equation 3.2

where, T is the time period for modelled and observed data;  $Q_o^t$  is the observed value at time t;  $Q_m^t$  is modelled value at time t;  $\overline{Q_o}$  is the average of observed value across the whole time period T. The Nash-Sutcliffe efficiency could range from  $-\infty$  to 1. Essentially, the closer the model efficiency is to 1, the more accurate the model is. An efficiency of 1 means a perfect match of modelled data and field measurements. An efficiency of 0 means indicates the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero occurs when the observed mean is a better predictor than the model outputs (Maguire, Batty et al. 2005).

In addition, modelling results and observed results will be compared visually through plotting them together. Attention will mainly be paid to the magnitude of values and shape of the plots. This work is conducted to capture more details of differences between modelled and observed data.

## 3.4.4 Testing of PESERA-GRID

PESERA-GRID consists of three modules: hydrology, erosion and vegetation growth (Figure 3.4). The hydrological sub-model is centred on a water balance, and able to simulate saturation-excess overland flow generation which is crucial for blanket peatlands (Evans et al., 1999). In PESERA-GRID, total erosion is estimated as the transporting capacity of overland flow driven by soil property-derived erodibility, overland flow and local relief, and it is assessed at the slope base to

estimate total loss from the land, and delivered to stream channels. Many eroded blanket peatlands have been partly re-vegetated, with weathered peat often trapped before entering stream channels (Evans et al., 2006). Investigation of blanket peat erosion at a hillslope scale is therefore meaningful in evaluating blanket peat erosion systems. Vegetation growth is considered in the model based on a biomass carbon balance for both living vegetation and soil organic matter. This provides a good way of describing the interactions between land management and vegetation cover and biomass.

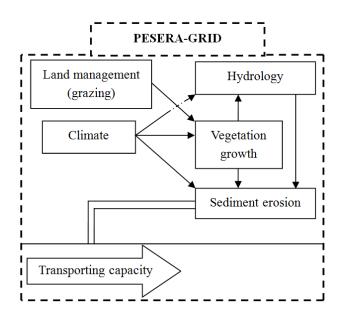


Figure 3.4 The conceptual framework of PESERA-GRID

The PESERA-GRID model treats the study area as a cascade of hillslopes. However, it usually requires 128 input grid layers to parameterize climate, land cover and use, topography and soil. Table 3.3 presents the parameters required by the PESERA-GRID model. Large amounts of input data require much data processing and it takes much time, when PESERA-GRID is running for a spatial area. So in order to determine whether the theoretical framework of PESERA-GRID is suitable for blanket peatlands or not, PESERA-GRID was initially tested at a hillslope represented by a 100-m grid cell, with input parameters (i.e. climate, vegetation, soil and topographic characteristics) the same as typical / average values for the Trout Beck catchment. This point could thus be viewed as an average hillslope in the Trout Beck catchment.

Table 3.3 The input parameters required by the PESERA-GRID model

Parameters	Units	Description
meanrf130	mm	Mean monthly rainfall
meanrf2	mm	Mean monthly rainfall per rainy day
cvrf2	-	Coefficient of variation of monthly rainfall per rainy day
mtmean	°C	Mean monthly temperature
mtrange	°C	Monthly temperature range
meanpet30	mm	Mean monthly PET
newtemp	°C	Predicted future temperature
newrf130	mm	Predicted future rainfall
use	-	Land cover type
eu12crop1	-	Dominant arable crop
maize_210c	-	Maize crop
eu12crop2	-	Second dominant arable crop
itill_crop1	-	Planting month: dominant arable crop
itill_maize	-	Planting month: maize
itill_crop2	-	Planting month: second dominant arable crop
mitill_1	-	Planting marker: dominant arable crop
mitill_m	-	Planting marker: maize
mitill_2	-	Planting marker: second dominant arable crop
cov	%	Initial ground cover
rough0	mm	Initial surface storage
rough_red	%	Surface roughness reduction per month
rootdepth	mm	Root depth
crusting	mm	Crust storage
erodibility	mm	Sensitivity to erosion
swsc_eff_2	mm	Effective soil water storage capacity
p1xswap1	mm	Soil water available to plants in top 300 mm
p2xswap2	mm	Soil water available to plants between 300 and 1000 mm
m	mm	Scale depth (TOPMODEL)
std_eudem2	mm	Standard deviation of elevation for all points within a certain radius

## 3.4.4.1 Model inputs

## a) Climate inputs

**Table 3.4** Climate inputs of PESERA-GRID

Month	meanrf130 (mm)	meanrf2 (mm)	cvrf2 (Unitless)	mtmean (°C)	mtrange (°C)	meanpet30 (mm)
1	232	10.56	1.39	1.49	3.83	10
2	184	9.77	1.51	1.33	4.41	12
3	194	8.88	1.58	2.39	5.22	40
4	138	6.43	1.15	4.25	6.76	60
5	119	5.85	1.15	7.59	7.74	100
6	107	5.57	1.08	10.15	6.79	105
7	125	6.13	1.51	11.99	6.92	110
8	139	5.89	1.53	12.09	6.75	97
9	148	6.92	1.31	10.13	6.35	70
10	195	7.43	1.30	6.82	4.83	45
11	205	8.87	1.18	3.93	4.05	20
12	228	11.69	1.33	1.47	4.16	8

Climate inputs include mean monthly rainfall (meanrf130), mean monthly rainfall per rainday (meanrf2), coefficient of variation of monthly rainfall per rain day (cvrf2), mean monthly temperature (mtmean), mean monthly temperature range (mtrange), mean monthly potential evapotranspiration (meanpet30). Input values for the Trout Beck catchment between 1997 and 2009 were calculated from ECN station data while potential evapotranspiration data were obtained from the estimation of Clark (2005). The values of newtemp and newrf130 were the same as meanrf130 and mtmean as future climate scenarios are not considered in this initial testing.

## b) Topography

Slope length and relief are required to define a slope profile. In this test the length of slope is 100 m while relief is 20 m, which is average value for the Trout Beck catchment using a 100-m DEM. So the slope profile shown in Figure 3.5 is able to show the basic topographic characteristic of the Trout Beck catchment.

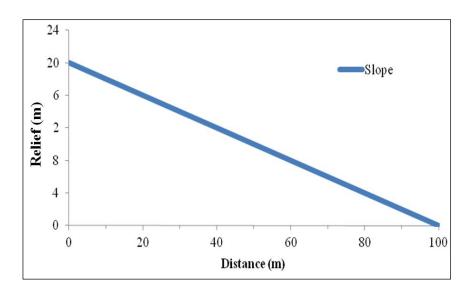


Figure 3.5 Profile of the testing grid cell

### c) Land cover / use

Land cover parameters used in this test are based on the major land cover in the Trout Beck as described in section 3.4.2. Land cover code (code), initial land cover (cov), root depth (rootdepth), initial roughness storage (rough0) and reduction of roughness storage per month (rough\_red) are required to operate PESERA-GRID. As no croplands were found in the Trout Beck catchment, parameters about crops and planting dates are not provided here. Values of land cover related parameters are presented in Table 3.5. Detailed description of vegetation growth model and parameterization of land cover / use is provided in section 4.5.2.2 of Chapter 4 and section 5.3.2.2 of Chapter 5.

**Table 3.5** Land cover parameters

Parameters	Value
code	334
cov (%)	100
rootdepth (mm)	100
rough0 (mm)	5
rough_red (%)	0

## d) Soil

Six soil parameters are required by PESERA-GRID. Values of soil parameters for blanket peatlands are based on the pedo-transfer functions and PESERA manual (Irvine and Kosmas 2003). The resulting values for the soil parameters are shown in Table 3.6. The "erodibility" and "crusting" describe the vulnerability of soil to

erosion and surface crusting. "p1xswap1" and "p2xswap2" are soil water available to plants in the top 300 mm and between 300 and 1000 mm respectively. "swsc\_eff\_2" represents the effective soil water storage capacity. "zm" is the TOPMODEL soil parameter, which impacts the soil water moisture and subsurface flow (Beven and Kirkby 1979; Beven, Kirkby et al. 1984).

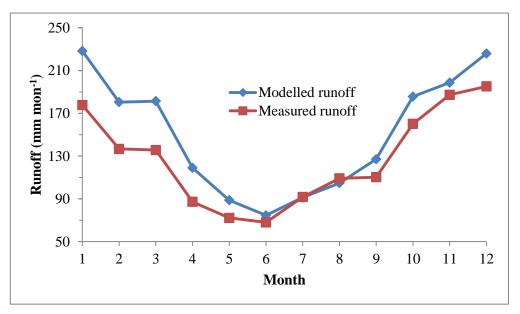
**Table 3.6** Soil parameters

Parameters	Value
erodibility (mm)	1.16
crusting (mm)	1.16
p1xswap1	130
p2xswap2	21
swsc_eff_2 (mm)	114
m (mm)	5

## 3.4.4.2 Evaluation of modelling results

#### a) Runoff

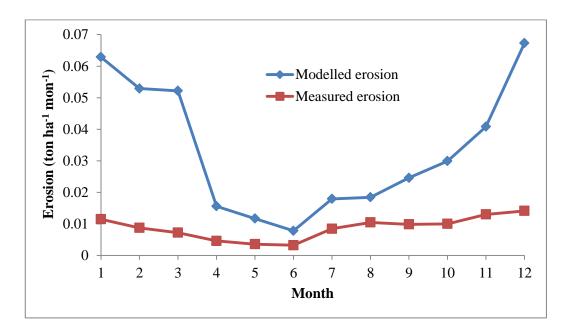
A comparison between the modelled and measured runoff is shown in Figure 3.6. The Nash-Sutcliffe coefficient is 0.55. The shape of the modelled and measured runoff is very similar, confirming that the hydrology sub-model of PESERA-GRID can capture the changes in runoff generating of blanket peatlands. However, the modelled annual runoff is apparently higher than the measured annual runoff, with the difference between them being 18 % of measured annual runoff. This may be caused by the scaling difference between measured (catchment scale) and modelled (hillslope) runoff, given the runoff coefficient is usually observed to decrease with distance or area downslope (Kirkby, Irvine et al. 2008; Bracken, Wainwright et al. 2013). The difference between modelled and measured runoff is lower in summer than in winter, this may be because the water use efficiency (WUE), which impacts the amount of water being lost as evapotranspiration, was set to a constant through the whole year.



**Figure 3.6** Comparison of measured runoff at catchment outlet and runoff at hillslope scale predicted by PESERA-GRID.

## b) Erosion

Modelled erosion is systematically higher than measured erosion (Figure 3.7), with the Nash-Sutcliffe coefficient being -80.68. It seems that PESERA-GRID overestimates the sediment yield for blanket peatlands. However, it should be noted that measured erosion is at a catchment scale while the PESERA model only considers erosion transported to the bottoms of hillslopes. Sediment budget studies (e.g. Evans and Warburton 2005; Baynes 2012) demonstrated that vegetation cover significantly reduced the soil erosion produced on hillslopes reaching catchment outlets through decoupling the slope-channel linkage. This is considered as a scaling component and should be considered during interpolation of the model outputs. More significantly t is also noted that both the modelled and measured monthly erosion are higher in winter months, peaking in December and bottoming out in June. However, modelled erosion tends to be more sensitive than measured erosion to changes in runoff conditions. For example, the change of modelled erosion from February to March is about same as the change of runoff between these months. However, the change of measured erosion does not follow runoff variation in these two months. This phenomenon may be mainly due to unreasonable sediment-supply mechanisms in PESERA. Freshly exposed peat is often fibrous and thus resistant to erosive forces. Therefore, a period of weathering is needed to produce loose materials for subsequent flow wash. This mechanism drives the erosion in blanket peatlands to be supply-limited in general (Evans and Warburton 2007). However, in the current version of PESERA model, runoff shear stress is considered to be the only agent for erosion, assuming that the erodible material is always enough for runoff wash (transport limited erosion), and freeze-thaw and desiccation are not considered. This could inevitably add inaccuracy to the PESERA-GRID sediment outputs and lead modelled erosion to be over-sensitive to runoff production.



**Figure 3.7** Comparison of measured erosion at catchment outlet and hillslopes against erosion at hillslope scale predicted by PESERA-GRID. The measured erosion data are the monthly average for the period of 1997-2009 based on the re-constructed sediment flux, which was produced with the method shown in section 3.4.3.1.

# 3.5 Summary and discussion

Recent developments of modelling theory, computing power and spatial data have led to the development of many erosion models over the past several decades (Merritt, Letcher et al. 2003; Aksoy and Kavvas 2005). It seems possible that modification of an existing model might be appropriate for simulation of fluvial blanket peat erosion based on current understanding of peat erosion processes. Given this context, this chapter reviewed and evaluated contemporary erosion models, which are possibly aligned for simulation of blanket peat hydrology and erosion. Fifteen physically-based erosion models were firstly selected as candidate models. Through theoretical assessment of candidate models with criteria defined in

terms of current knowledge on the objectives of the project and current understanding of hydrology and erosion processes of blanket peatlands, PESERA-GRID seemed to be most theoretically ready for blanket peat erosion modelling. The PESERA-GRID model then underwent some preliminarily tests with historical data from the Trout Beck catchment of northern England.

According to the theoretical and numerical evaluation, there are still three key things to be done before PESERA-GRID could be applied to blanket peat erosion modelling:

- 1) Sediment production mechanisms of blanket peatlands need to be incorporated into PESERA-GRID for better representation of physical processes of blanket peat erosion;
- 2) As described in section 3.3, only grazing has been considered in the PESERA-GRID model at the moment. More effort is thus needed to incorporate other land management practices such as burning and artificial drainage into the PESERA-GRID model.
- 3) Most measured erosion data from blanket peat-covered areas are at the catchment scale (Table 2.2 of Chapter 2), which is different from the scale PESERA works on. Therefore, a better method, which eliminates the scaling difference between modelling results from PESERA-GRID and field measurement, is needed in order to evaluate the model at different blanket peat-covered sites.

These three tasks will be undertaken in Chapter 4.

# **Chapter 4**

# **Development of PESERA-PEAT**

## 4.1 Introduction

Chapter 3 evaluated contemporary erosion models and concluded that PESERA-GRID was promising for this project. Three aspects of work were required before the model could be applied in blanket bog simulation:

- 1) Currently PESERA only considers transport-limited erosion, assuming that erodible material is ample for flow transport (Kirkby, Irvine et al. 2008). However, supply-limited erosion is most prevalent in blanket peatlands (Evans and Warburton 2005; Evans, Warburton et al. 2006; Holden, Gascoign et al. 2007b), although transport-limited erosion might happen more in the summer half year (Holden and Burt 2002a). Therefore, sediment production mechanisms in blanket peatlands should be incorporated into PESERA-GRID model so that more reasonable treatment of peat erosion can be achieved. Freeze-thaw and desiccation are common in northern blanket peatlands, and are mainly controlled by climate and soil moisture conditions (Francis 1990; Holden and Burt 2002a; Evans and Warburton 2007). Therefore, summer and winter weathering processes will be built into PESERA-GRID model through linking sediment supply with the driving factors.
- 2) Grazing has already been incorporated into PESERA-GRID. However, drainage and burning have not been considered with PESERA-GRID and so work is required to incorporate the impacts of artificial drainage and managed burn into the model.
- 3) Table 2.2 of Chapter 2 showed measured erosion from blanket peatlands around the UK, implying that most of the erosion measurements reported previously were at catchment scales. However, only hillslope hydrology and erosion are considered in PESERA (Kirkby, Irvine et al. 2008; Meusburger, Konz et al. 2010; Esteves, Kirkby et al. 2012), and channel processes are neglected. Therefore, understanding scaling impacts on hydrology and erosion from blanket peatlands is crucial for this project as it is significant for interpreting and evaluating the modelling results.

Consequently the aims of this chapter are as follows

- to understand the impacts of scales on runoff and sediment flux in blanket peatlands;
- 2) to investigate and quantify the relationships between sediment production and freeze-thaw and desiccation in blanket peatlands;
- 3) to parameterize land management options suitable for running scenario modelling in PESERA-GRID;
- 4) to provide an updated PESERA-GRID framework (PESERA-PEAT) with newly established outputs from 2-3 above including sediment production regressions and parameterized land management options, and a description of processes within PESERA-PEAT.

The structure of this chapter is as follows. Data sources and processing of the data are stated in section 4.2; the emphasis of this section will be on understanding the general characteristics of erosion catchments with good data availability and changes in sediment flux and runoff production from blanket peatlands with catchment size. Section 4.3 focuses on establishing numerical relationships linking sediment supply with freeze-thaw and desiccation. Parameterization of land management practices will be discussed in section 4.4. Section 4.5 gives an updated PESERA-GRID framework (PESERA-PEAT) with the established sediment production relationship and parameterized land management options derived from sections 4.3 and 4.4. The processes within PESERA-PEAT are also described in detail. Section 4.6 is a summary and discussion of the chapter.

# 4.2 Data sources, processing and preliminary results

Data employed in this chapter came from the River Tees and River Ashop. Their locations are shown in Figure 4.1. In this section, data available at these two sites from previous publications and field measurements are presented and used to: 1) obtain a preliminary understanding of blanket peat erosion, providing a basis to predict sediment production; 2) build up relationships between runoff efficiency and sediment from blanket peatlands with catchment size, providing evidence of how runoff and erosion change between different scales.

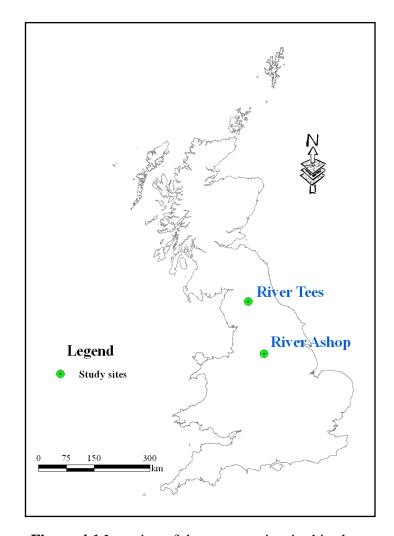


Figure 4.1 Location of data source sites in this chapter.

## 1) River Tees

Three tributaries of the River Tees were involved: Trout Beck, Rough Sike, and Little Dodgen Pot Sike. Detailed information on the Trout Beck catchment including geology, vegetation, soil cover and climate was provided in section 3.4.2 of Chapter 3. Rough Sike is a tributary of Trout Beck, draining 0.83 km² of typical blanket peatlands (Evans and Warburton 2005; Evans, Warburton et al. 2006). Little Dodgen Pot Sike drains 0.44 km² of intact blanket peat, and flows into the Tees downstream of the Trout Beck catchment (Holden and Burt 2003c). Lower Carboniferous sequences of interbedded limestone, sandstone and shale in the Little Dodgen Pot Sike provide a base for a glacial till. The glacial clay in the Little Dodgen Pot Sike catchment is usually around 30 cm deep although it can contain coarse clasts resulting in a clayey diamict. The overlying clay has resulted in poor drainage, which has led to the development of blanket bog. Peat formation began in the late

Boreal as bog communities began to replace a birch forest, macroremains of which are commonly found at the base of the peat. The vegetation is dominated by *Eriophorum sp.* (cotton grass), *Calluna vulgaris* (heather) and *Sphagnum sp.* (moss) (Holden and Burt 2002b).

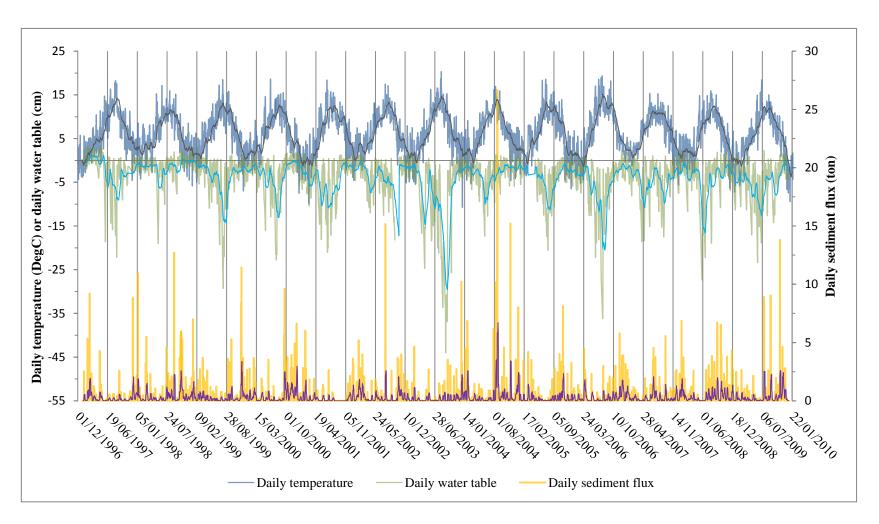
As shown in Table 4.1, the sediment concentration, runoff, temperature and water-table data from the Trout Beck catchment between 1997 and 2009 were available from the Environmental Change Network (ECN). Sediment fluxes from the Trout Beck catchment between 1997 and 2009 were re-constructed with sediment rating curves, and the detailed procedures and evaluations for reconstructed erosion were presented in section 3.4.3.1 of chapter 3. Runoff efficiency reported by Holden and Burt (2003c) and (Holden 2000) for Trout Beck, Rough Sike and Little Dodgen Pot Sike are 72 %, 77 % and 80 % respectively.

**Table 4.1** Data available for tributaries of the River Tees.

Catchment	Size (km²)	Data available	Periods	Data source
	11.4	Sediment		
		Runoff	Jan/1997- Dec/2009	ECN
Trout Beck		Rainfall		ECN
110ut Deck		Temperature		
		Runoff efficiency	Oct/1994-	Holden 2003c
			Dec/1999	
Rough Sike	0.83	Runoff efficiency	Oct/1994-	Holden 2003c
			Dec/1999	
Little Dodgen Pot Sike	0.44	Runoff efficiency	Jul/1999-	Holden 2000
			Dec/1999	

Figure 4.2 plots daily sediment flux, daily temperature and daily water table for the Trout Beck catchment between 1997 and 2009, offering an opportunity to achieve an overall feeling about the relationship between peat erosion and dry periods and freezing temperatures. Peak sediment flux usually happens after deep water table and during freezing periods. This confirms the importance of freeze-thaw and desiccation in blanket peat erosion (Evans and Warburton 2007). The delay between deep water table and peak sediment flux may imply that peat erosion is transport limited in dry periods sometimes, especially in summer months (Francis 1990; Holden and Burt 2002a). In this case surplus erodible material is firstly stored, and then washed away in following periods, which have sufficient rainfall. In addition,

there is no delay between peak sediment fluxes and freezing periods, demonstrating that peat erosion is supply limited and all erodible material is washed off. Figure 4.2 confirms present understanding about blanket peat erosion and shows that the actual pattern and magnitude of blanket peat erosion is dependent upon both the sediment production and transport. Therefore both sediment production and transport should be considered in this project so that more accurate descriptions of blanket peat erosion can be achieved.



**Figure 4.2** Time series of daily sediment flux, daily temperature and daily water table in the Trout Beck catchment between 1997 and 2009. The daily sediment flux, daily temperature and daily water table are smoothed using a 7-day moving average.

Runoff ratios of Trout Beck, Rough Sike and Little Dodgen Pot Sike are plotted against catchment size to evaluate scaling impacts on runoff production efficiency in blanket peat-covered catchments. As shown in Figure 4.3, a power relationship was found between runoff efficiency and catchment size, clearly demonstrating that the runoff efficiency decreases with catchment size.

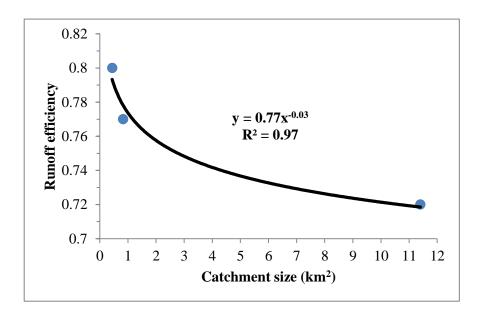
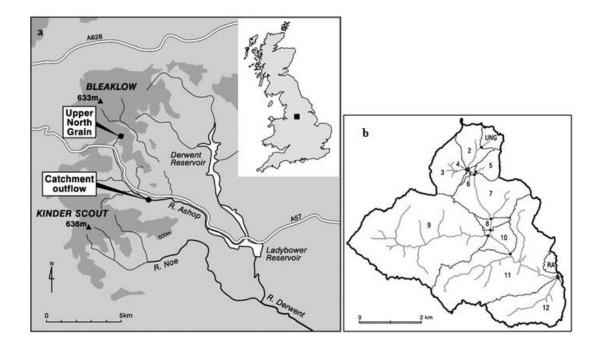


Figure 4.3 Relationship between annual runoff efficiency and catchment size.

## 2) River Ashop

The River Ashop (Figure 4.4a) lies within the English Peak District, in the Southern Pennines, UK. It drains the slopes of both Kinder Scout and Bleaklow upland plateaux which supports an extensive cover of blanket peat (Pawson, Evans et al. 2012). These systems are among the most severely eroded peatland sites in the UK (Evans, Warburton et al. 2006; Evans and Lindsay 2010). The catchment ranges in elevation from 631 m on the northern part to 253 m at the catchment outlet. Average annual rainfall is 1554 mm (Aksoy and Kavvas 2005). The catchment is underlain by interbedded sandstones and mudstones of the Carboniferous-age millstone grit series (Roering, Kirchner et al. 1999). Soils are dominated by deep peat, although other types of soil such as stagnopodzols and brown earths have developed on steeper valley sides and lower altitude areas respectively (Aksoy and Kavvas 2005). Vegetation cover is primarily a *Calluna*, *Vaccinium*, *Eriophorum* assemblage on the deep peat plateau, with acid grasslands on the steeper slopes and some limited

improved grassland on the floodplains of the main valley (Pawson, Evans et al. 2012).



**Figure 4.4** a) the location of River Ashop; b) the illustration of the 13 reaches chosen by Pawson and Evans et al (2012), the upper six reaches were used in this study (from Pawson and Evans et al. 2012).

Pawson and Evans et al. (2012) presented POC flux from 13 reaches (Figure 4.4b) spanning a 7-km headwater section of the River Ashop between December 2005 and January 2007. This provided a good opportunity to investigate how the magnitude of erosion varies with cumulative upper stream size. However, as stagnopodzols and brown earths become prevalent in low elevation areas, only the upper six sites, where peat coverage is more than 90 %, were selected. Information on the selected six sites is shown in Table 4.2.

**Table 4.2** Detailed information of the selected sites along the River Ashop (from Pawson, Evans et al. 2012).

Site	Catchment size (km²)	Peat coverage (%)	POC flux (ton ha <sup>-1</sup> yr <sup>-1</sup> )
1	0.43	98.8	0.74
2	1.49	94.7	0.79
3	1.54	95.9	0.45
4	3.03	95.2	0.35
5	0.57	94.4	0.54
6	3.69	94.4	0.38

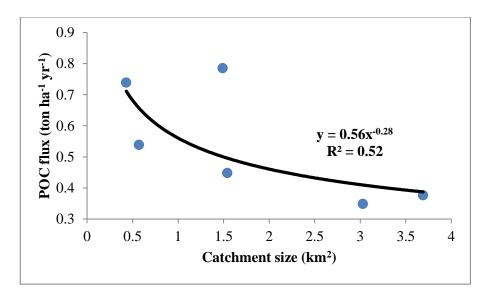


Figure 4.5 Relationship between annual POC flux and catchment size.

Figure 4.5 shows the relationship between annual POC flux and catchment size; POC flux declines with increased catchment size. Changes in POC flux were used to represent those of peat erosion mainly because: 1) there is a high organic content of blanket peat (Charman 2002) and 48 % of organic sediment is POC in the River Ashop (Pawson, Evans et al. 2012); 2) there were no more data suitable for establishing such a relationship for blanket peat erosion.

## 4.3 Prediction of sediment supply

Freshly exposed peat is quite resistant to water flow, and Carling, Glaister et al. (1997) suggested that 5.7 m s<sup>-1</sup> of overland flow is required to produce erosion on freshly exposed peat. Velocities of 5.7 m s<sup>-1</sup> are clearly beyond the likely runoff to be produced from relatively low gradient peatland surfaces (Evans and Warburton 2007). This is to say, sediment flux from peatlands tends to be close to zero after the surface erodible materials are all removed. It is therefore reasonable to view fluvial erosion in blanket peatlands as the result of the balance between sediment supply and the transporting capacity of runoff flow. In winter, erosion usually tends to be supply limited because of plenty of rainfall and a lack of evaporative drawdown of the water table, but in summer drying conditions may result in erodible material beyond the transporting capacity of water flow, so transport-limited erosion sometimes occurs (Francis 1990; Holden and Burt 2002a). Since the original PESERA model could only account for transport limited erosion (transporting

capacity of runoff) (Govers, Gobin et al. 2003; Kirkby, Irvine et al. 2008), it was necessary to incorporate sediment supply in order to describe the physical processes of blanket peat erosion more reasonably. Freeze-thaw and desiccation are major sediment production mechanisms in blanket peatlands, and therefore were employed for prediction of sediment supply. Parameterization of weathering mechanisms and sediment supply were conducted at a monthly scale in order to be consistent with the original PESERA-GRID model.

### 4.3.1 Parameterization of freeze-thaw and desiccation

Frost heave is characterized by formation of needle ice, which is supported by the abundant supply of moisture and a strong thermal gradient (Outcalt 1971; Albertson, Aylen et al. 2010). Desiccation is a result of drought and thus is closely related to soil moisture condition (Burt and Gardiner 1984; Francis 1990; Holden and Burt 2002a). Moreover, Figure 4.2 confirms the linkage between peak sediment flux and dry and freezing periods, indirectly demonstrating that temperature and soil moisture relevant parameters should be able to act as indicators of freeze-thaw and desiccation.

Several variables were derived from daily values in the Trout Beck catchment between 1997 and 2009 to represent the characteristics of temperature and soil moisture content at a monthly scale, which is consistent with the PESERA-GRID model. The names, units and definitions of these variables are shown in Table 4.3. It was assumed that soil surface freezing is more likely when the air temperature record drops below zero. Therefore, NDBF shown in Table 4.3 reflects the degree of freeze-thaw within a month. WNDBF and WNDBF2 were used to capture the impacts of different freezing levels with higher weights given to days with lower temperature. The basic characteristics of temperature such as Temp, MinTemp, MaxTemp and SDTemp were also used as potential indicators of freeze-thaw. Because soil moisture content time-series from the Trout Beck catchment were not available for the study period; in this study water table was chosen as a proxy of soil moisture content. It was hypothesized that desiccation is more likely when water table drops below -5 cm. Similar to NDBF, NDB5 is to parameterize the degree of desiccation within a month. WNDB5 and WNDB52 are variables reflecting the

impacts of different drought levels on desiccation. The basic characteristics of monthly water table such as WT, MinWT, MaxWT and SDWT were also involved. All these variables are plotted against sediment supply from the Trout Beck catchment to identify the potential relationship between sediment production and weathering process drivers. So, it is necessary to parameterize the sediment supply from the Trout Beck catchment for the same time periods before any relationship can be built. This is addressed in the following sections.

**Table 4.3** Potential indicators of freeze-thaw and desiccation.

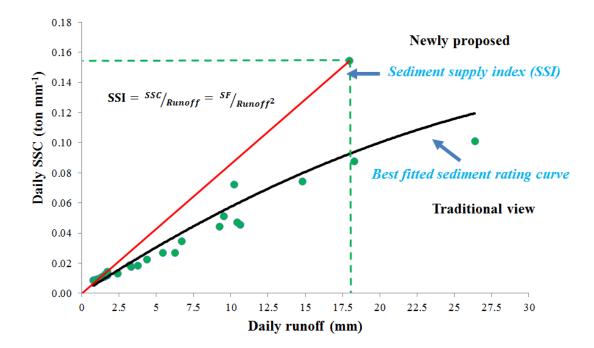
Name	Unit	Definition
Temp	°C	Average of daily average temperature over a specific month
MinTemp	°C	Minimum daily temperature over a specific month
MaxTemp	°C	Maximum daily temperature over a specific month
SDTemp	-	Standard deviation of daily average temperature over a specific month
NDBF	day	Number of days with temperature below freezing
WNDBF	-	NDBF with different weights for different temperature levels (°C)
		>= 0: 0; < 0  and  >= -5: 1; < -5  and  >= -10: 2; < -10: 3
WNDBF2	-	NDBF with different weights for different temperature levels (°C)
		>= 0: 0; < 0  and  >= -5: 1; < -5  and  >= -10: 4; < -10: 9
WT	cm	Average of daily average water table over a specific month
MinWT	cm	Minimum daily water table over a specific month
MaxWT	cm	Maximum daily water table over a specific month
SDWT	-	Standard deviation of daily average water table over a specific month
NDB5	day	Number of days with water table below -5 cm
WNDB5	-	NDB5 with different weights for different water table levels (cm)
		>= -5: 0; $< -5$ and $>= -10$ : 1; $< -10$ and $>= -20$ : 2; $< -20$ : 3
WNDB52	-	NDB5 with different weights for different water table levels (cm)
		>= -5: 0; < -5  and  >= -10: 1; < -10  and  >= -20: 4; < -20: 9

<sup>&</sup>quot;-" indicates the corresponding variable is unitless.

## **4.3.2** Parameterization of sediment supply

The slope of best-fitted sediment rating curves has been demonstrated as a good way of indicating sediment supply status in peatland catchments (Aksoy and Kavvas 2005; Yang 2005; Evans and Warburton 2007). Yang (2005) demonstrated that the slope of best-fitted sediment rating curve was highly sensitive to the climatic variability within a catchment, and the difference of sediment delivery and connectivity between catchments with various eroding conditions could also be reflected by sediment rating curves. Evans and Warburton (2007) also emphasized

the applicability of the sediment rating curve as an indicator of sediment supply status at a catchment scale. For example, in the Rough Sike catchment (a tributary of Trout Beck), the difference between slopes of sediment rating curves in 1960 and 2000 was attributed to the re-vegetation of gully floors so that the connectivity between hillslopes and channels was significantly reduced (Evans, Warburton et al. 2006; Evans and Warburton 2007). Therefore, the slope of best-fitted sediment rating curves was adopted to investigate the sediment supply status and its relationship with freeze-thaw and desiccation. However, there are common shortfalls with sediment rating curves, such as substantial scatter associated with the plots, which may cause a loss of crucial details on changes of sediment production which do not match a uniform equation (Walling and Webb 1988) (Figure 4.6).



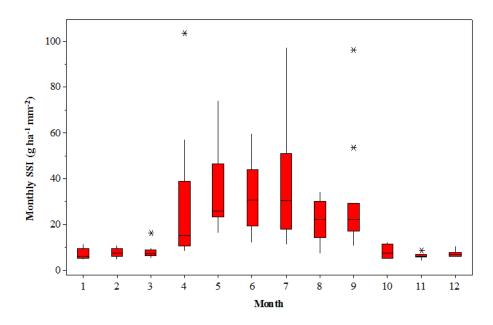
**Figure 4.6** The definition of sediment supply index (SSI), and the comparison between SSI and the best fitted sediment rating curve. The daily runoff and suspended sediment concentration (SSC) data for Trout Beck catchment for 01/2000 are used as an example in the figure.

In order to overcome the shortfalls with sediment rating curves, the slope of each point in the sediment rating curve, which is the sediment concentration per unit runoff, was defined as a sediment supply index to indicate the sediment supply capacity (Figure 4.6). So for every single point, the sediment supply index equals the

sediment flux divided by runoff squared. The sediment supply index for each point can be given by,

$$SSI = \frac{SSC}{Roff} = \frac{SF}{Roff^2}$$
 Equation 4.1

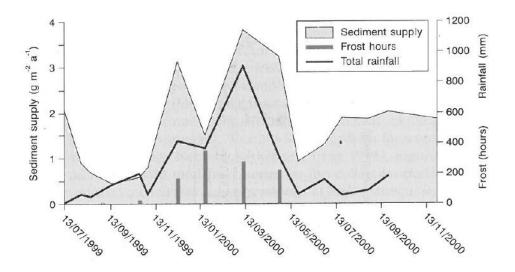
where, SSI is the sediment supply index; SSC is sediment concentration; Roff is the water discharge; SF is the sediment flux.



**Figure 4.7** Monthly sediment supply index of Trout Beck between 1997 and 2009.

Daily sediment concentration and water discharge from Trout Beck catchment between 1997 and 2009 were used as the basis for analysis because, while recognizing the limitations of these data, PESERA parameterizes storms with daily precipitation (Kirkby, Irvine et al. 2008). Therefore this makes aggregation of the results with PESERA-GRID theoretically reasonable. Monthly sediment supply index was used to describe the sediment supply status within a month quantitatively. It is defined as the mean of daily sediment supply index within a specific month. As data were available between 1997 and 2009 in the Trout Beck catchment, thirteen sediment supply indices were therefore achieved for each month and shown in Figure 4.7, where sediment supply index in the summer half year (Apr-Sep) is much higher than that for the winter half year (Oct-Mar). Figure 4.7 does not imply that

sediment production in winter is lower than in summer but reflects the idea that erosion in the summer half year is more likely to be transport-limited than in the winter half year as runoff in summer is significantly lower than in winter. Therefore, sediment supply index is theoretically available to represent the sediment supply status in blanket peatlands, and its change could serve as a proxy of variation in sediment supply. The monthly sediment supply index was then used to build up relationships with temperature and water-table relevant variables for each month for Trout Beck catchment between 1997 and 2009, and the results are shown and discussed in section 4.3.3.



**Figure 4.8** Sediment supply measured by traps at Rough Sike catchment between July 1999 and July 2000 (from Evans and Warburton 2007, page 65).

The sediment supply index is not numerically equal to the actual sediment supply in the Trout Beck catchment. Therefore, the actual sediment supply value is needed as the baseline, which changes at the same rate as the sediment supply index. Measured sediment supply from bare peat in the Rough Sike catchment between July 1999 and July 2000 was reported by Evans and Warburton (2007). In that study, nine sites with size ranging from 0.225 to 1.3 m<sup>2</sup> were selected for sediment traps. The average annual sediment supply from the nine sites between July 1999 and July 2000 was 6.89 ton ha<sup>-1</sup>. The monthly distribution of this sediment supply was firstly estimated based on Figure 4.8, and then adjusted during model calibration in Chapter 5. These values were employed as the actual sediment supply from bare

peat, which was the result of freeze-thaw and desiccation and so was linked with changes in sediment supply index to account for variations in sediment supply in blanket peatlands.

# 4.3.3 Linking sediment supply with climatic and soil moisture condition

Freeze-thaw, desiccation and sediment supply have been parameterized as various indicators in sections 4.3.1 and 4.3.2. Relationships between these variables and monthly sediment supply indices were examined to determine which of them was capable of accounting for the weathering processes in blanket peatlands. Table 4.4 and Table 4.5 show regressions between monthly sediment supply indices and variables related to freeze-thaw and desiccation respectively. In Table 4.4, MinTemp, MaxTemp and SDTemp have systematically lower R<sup>2</sup> in relationships with sediment supply indices than other variables, demonstrating that these three variables are not suitable to be adopted as indicator for freeze-thaw. NDBF, WNDBF and WNDBF2 mainly have positive relationships with sediment supply indices in the winter half year (Oct-Mar). In the summer half year (Apr-Sep), the relationships appear to be negative or with a much lower R<sup>2</sup> than those of the winter half year; especially in July and August there are no relationships found between NDBF, WNDBF, wNDBF2 and sediment supply indices as no days were below freezing. Temperature impacts sediment supply indices negatively in the winter half year and positively in the summer half year. This may imply that freeze-thaw contributes to sediment production in blanket peatlands mainly in the winter half year. However, the relationships between sediment supply indices and Temp, NDBF, WNDBF, WNDBF2 for March have lower R<sup>2</sup> than those for other months of winter half year. If compared to relationships between sediment supply indices and water-table related variables in Table 4.5, it is inferred that sediment production in March is dominated by desiccation. For the rest of the winter half year (Oct-Feb), the average R<sup>2</sup> given by Temp, NDBF, WNDBF and WNDBF2 is 0.34, 0.35, 0.37 and 0.36. The R<sup>2</sup> of NDBF, WNDBF and WNDBF2 is higher than that of Temp. This could be explained as the freeze thaw only occurs when the temperature falls below freezing. Moreover, R<sup>2</sup> of NDBF is lower than those of WNDBF and WNDBF2, possibly implying that freeze-thaw is not only impacted by the length of time below freezing but also influenced by the freezing level. Both a longer time below freezing and stronger freezing could result in more erodible material. In Table 4.5 the R<sup>2</sup> between sediment supply indices and water-table related variables is higher in the summer half year and lower in the winter half year. However, even in the winter half year the R<sup>2</sup> between water-table variables and sediment supply indices is considerably high, demonstrating that desiccation could happen in winter together with freeze-thaw. This may be partly because the formation of segregation ice at the peat surface has the effect of desiccating the surface layer (Evans and Warburton 2007). SDWT, NDB5, WNDB5 and WNDB52 impact the sediment production positively while WT, MinWT and MaxWT impact the sediment supply negatively. The average R<sup>2</sup> related to NDB5, WNDB5, and WNDB52 across the whole year is 0.56, 0.59 and 0.55 respectively, demonstrating that desiccation is possibly impacted by both length and strength of drought. The highest average R<sup>2</sup> across the whole year appears to be 0.64 in the relationship between WT and sediment supply indices.

**Table 4.4** Regressions between monthly sediment supply indices and temperature related variables.

N/ 41.	Temp		MinTem	p	MaxTem	p	SDTemp	)	NDBF		WNDBF	,	WNDBF2	2
Month	Regression	$\mathbb{R}^2$												
Jan	y = -2.05x +10.1	0.73	y = -0.48 x + 5.31	0.11	y = -0.77 x + 11.8	0.24	y = 0.09 x + 6.81	0.00	y = 0.31 x + 2.09	0.52	y = 0.25 x + 2.15	0.61	y = 0.15 x + 3.09	0.64
Feb	y = -0.67 x + 8.56	0.16	y = -0.39 x + 6.24	0.11	y = 0.30 x + 5.78	0.06	y = 1.03 x + 4.87	0.12	y = 0.23 x + 4.12	0.33	y = 0.13 x + 5.13	0.26	y = 0.04 x + 6.39	0.14
Mar	y = -0.08 x + 8.34	0.002	y = -0.03 x + 8.06	0.00	y = -0.26 + 9.94	0.02	y = -0.28 x + 8.84	0.01	y = 0.17 x + 5.70	0.14	y = 0.12 x + 6.08	0.14	y = 0.06 x + 6.71	0.12
Apr	y = 15.1  x - 35.2	0.39	y = 5.56 x + 31.4	0.18	y = 12.2  x - 82.9	0.44	y = -7.9 x + 48.5	0.02	y = -0.20 x + 30.8	0.00	y = -0.18 x + 31.1	0.00	y = -0.13 x + 30.8	0.00
May	y = 16.9 x - 93.0	0.30	y = 0.25 x + 34.3	0.00	y = -0.78 x + 45.5	0.01	y = 0.09 x + 34.9	0.00	y = 0.96 x + 30.8	0.03	y = 1.41 x + 28.5	0.07	y = 1.75 x + 26.1	0.14
Jun	y = 9.40  x-  62.4	0.34	y = 2.59 x + 17.6	0.11	y = -0.24 x + 36.7	0.00	y = -2.08 x + 38.0	0.01	y = -6.16 x + 39.2	0.14	y = -6.16 x + 39.2	0.14	y = -6.16 x + 39.2	0.14
Jul	y = 16.0 x- 154	0.62	y = 8.74  x - 36.1	0.12	y = 8.26  x - 99.6	0.42	y = 29.2 x - 24.7	0.47	-	-	-	-	-	-
Aug	y = 1.44 x + 5.2	0.02	y = -0.91 x + 30.1	0.01	y = 4.06 x - 43.7	0.32	y = 9.44 x + 3.80	0.27	-	-	-	-	-	-
Sep	y = -1.22 x + 42.1	0.004	y = -5.09 x + 58.9	0.14	y = -1.09 x + 45.5	0.01	y = 12.4 x + 3.3	0.07	y = 2.94 x + 27.4	0.02	y = 2.94 x + 27.4	0.02	y = 2.94 x + 27.4	0.02
Oct	y = -0.49 x + 11.3	0.30	y = -0.56 x + 9.12	0.25	y = 0.99 x - 3.10	0.22	y = 2.34 x + 2.36	0.38	y = 0.61 x + 5.23	0.52	y = 0.58 x + 5.23	0.56	y = 0.51 x + 5.31	0.61
Nov	y = -0.07 x + 5.85	0.20	y = -0.05 x + 6.02	0.02	y = 0.50 x + 1.38	0.22	y = 0.98 x + 3.47	0.32	y = 0.08 x + 5.58	0.12	y = 0.07 x + 5.50	0.18	y = 0.051 x + 5.51	0.23
Dec	y = -0.69 x + 8.27	0.29	y = -0.14 x + 6.44	0.06	y = -0.24 x + 8.91	0.03	y = 0.26 x + 6.43	0.02	y = 0.14 x + 5.11	0.28	y = 0.08 x + 5.59	0.26	y = 0.03 x + 6.19	0.18

y is monthly sediment supply index; x represents Temp, MinTemp, MaxTemp, SDTemp, NDBF, WNDBF and WNDBF2 respectively.

**Table 4.5** Regressions between monthly sediment supply sediment index and water-table related variables.

3.5 (3	WT		MinWT		MaxWT		SDWT		NDB5		WNDB5	5	WNDB5	2
Month	Regression	$\mathbb{R}^2$	Regression	$\mathbb{R}^2$	Regression	$\mathbb{R}^2$	Regression	$\mathbb{R}^2$	Regression	$\mathbb{R}^2$	Regression	$\mathbb{R}^2$	Regression	$\mathbb{R}^2$
Jan	y = -1.15 x + 5.06	0.26	y = -0.39 x + 5.14	0.16	y = -0.17 x + 7.31	0.00	y = 1.23 x + 4.92	0.15	y = 0.43 x + 5.90	0.41	y = 0.32 x + 6.06	0.38	y = 0.18 x + 6.34	0.29
Feb	y = -0.57 x + 6.39	0.25	y = -0.28 x + 5.96	0.20	y = -0.86 x + 8.66	0.11	y = 1.03 x + 5.63	0.23	y = 0.17 x + 6.78	0.25	y = 0.13 x + 6.91	0.21	y = 0.08 x + 7.10	0.15
Mar	y = -1.23 x + 4.80	0.73	y = -0.6 x + 3.83	0.74	y = -1.82 x + 10.2	0.31	y = 2.20 x + 3.11	0.88	y = 0.44 x + 5.23	0.79	y = 0.31 x + 5.67	0.91	y = 0.17 x + 6.28	0.92
Apr	y = -6.90  x - 2.40	0.86	y = -3.76 x - 11.0	0.83	y = -23.1 x + 37.2	0.42	y = 13.3 x - 12.0	0.82	y = 2.01 x + 3.50	0.56	y = 1.30 x + 3.33	0.74	y = 0.66 x + 5.39	0.82
May	y = -4.52 x + 8.87	0.78	y = -2.89 x - 8.36	0.73	y = -8.03 x + 36.9	0.37	y = 8.64  x - 3.3	0.53	$y = 2.10 \times 0.62$	0.64	y = 1.04 x + 7.87	0.78	y = 0.43 x + 14.9	0.79
Jun	y = -4.03 x + 8.05	0.85	y = -2.30 x - 1.84	0.71	y = -7.92 x + 31.0	0.36	y = 7.59 x + 1.10	0.61	y = 1.75 x + 2.93	0.85	y = 0.82 x + 10.5	0.85	y = 0.33 x + 16.3	0.78
Jul	y = -4.79 x + 0.57	0.87	y = -2.85 x - 12.7	0.76	y = -17.2 x + 41.2	0.57	y = 8.36 x - 6.04	0.72	y = 2.88 x - 20.3	0.70	y = 1.17 x - 2.68	0.81	y = 0.43 x + 7.75	0.81
Aug	y = -2.26 x + 9.55	0.64	y = -0.99 x + 8.80	0.58	y = -4.23 x + 22.1	0.21	y = 2.94 x + 11.0	0.56	y = 0.82 x + 9.38	0.65	y = 0.49 x + 10.5	0.70	y = 0.21 x + 13.4	0.63
Sep	y = -3.80 x + 6.59	0.92	y = -2.21 x - 0.99	0.91	y = -11.0 x + 34.5	0.38	y = 6.96 x + 0.25	0.92	y = 3.06 x - 16.0	0.71	y = 1.25 x + 0.31	0.83	y = 0.43 x + 10.4	0.83
Oct	y = -1.38 x + 4.88	0.53	y = -0.31 x + 5.68	0.54	y = -2.13 x + 9.30	0.42	y = 1.87 x + 4.32	0.56	y = 0.35 x + 6.00	0.42	y = 0.30 x + 6.05	0.40	y = 0.18 x + 6.44	0.34
Nov	y = -0.81 x + 4.95	0.32	y = -0.55 x + 3.74	0.28	y = -0.60x + 6.75	0.19	y = 2.80 x + 2.07	0.34	y = 0.36 x + 5.59	0.28	y = 0.25 x + 5.72	0.19	y = 0.08 x + 5.96	0.05
Dec	y = -1.18 x + 5.02	0.64	y = -0.57 x + 4.34	0.57	y = -0.03 x + 7.30	0.00	y = 1.57 x + 4.50	0.43	y = 0.22 x + 6.56	0.41	y = 0.19 x + 6.62	0.35	y = 0.11 x + 6.82	0.19

y is monthly sediment supply index; x represents WT, MinWT, MaxWT, SDWT, NDB5, WNDB5 and WNDB52 respectively.

**Table 4.6** Regression models for prediction of monthly sediment supply index.

Month	SSI-Temp & WT		SSI-WNDBF & WT	
	Regression	$\mathbb{R}^2$	Regression	$\mathbb{R}^2$
Jan	SSI = 9.28 - 1.88 Temp - 0.33 WT	0.74	SSI = 1.84 + 0.22  WNDBF - 0.53  WT	0.66
Feb	SSI = 7.11 - 0.36 Temp - 0.46 WT	0.29	SSI = 5.21 + 0.08WNDBF - 0.36 WT	0.33
Mar	SSI = 4.80 - 1.23  WT	0.73	SSI = 4.80 - 1.23  WT	0.73
Apr	SSI = -2.40 - 6.90 WT	0.86	SSI = -2.40 - 6.90 WT	0.86
May	SSI = 8.87 - 4.52 WT	0.78	SSI = 8.87 - 4.52  WT	0.78
Jun	SSI = 8.05 - 4.03 WT	0.85	SSI = 8.05 - 4.03  WT	0.85
Jul	SSI = 0.57 - 4.79 WT	0.87	SSI = 0.57 - 4.79  WT	0.87
Aug	SSI = 9.55 - 2.26 WT	0.64	SSI = 9.55 - 2.26 WT	0.64
Sep	SSI = 6.59 - 3.80 WT	0.92	SSI = 6.59 - 3.80  WT	0.92
Oct	SSI = 8.17 - 0.5  Temp - 1.39  WT	0.58	SSI = 4.21 + 0.39  WNDBF - 0.85  WT	0.7
Nov	SSI = 4.99 - 0.01 Temp - 0.82 WT	0.32	SSI = 4.62 + 0.06  WNDBF - 0.72  WT	0.42
Dec	SSI = 5.39 - 0.14 Temp - 1.09 WT	0.65	SSI = 4.83 + 0.02 WNDBF - 1.10 WT	0.65

As described above, WNDBF and WT could produce the best relationships with sediment supply indices individually. Therefore, they were selected to produce multiple regressions with sediment supply indices. However, NDBF, WNDBF and WNDBF2 were derived from time-series of daily minimum temperature, of which data availability was usually poorer than monthly temperature. Therefore, Temp and WT were also used to produce another group of relationships with sediment supply indices. Table 4.6 depicts the relationships linking sediment production with Temp, WNDBF and WT. In these regression equations WT has negative impacts on sediment supply indices across the whole year, and WNDBF and Temp are included in the equations for the winter half year except March. Equations based on Temp and WT (SSI-Temp & WT) were ultimately chosen for prediction of sediment supply indices in the project mainly because there was better data availability of monthly temperature. In addition, as mentioned above, sediment supply varies at the same rate as sediment supply indices, and the sediment production from bare peat between July 1999 and July 2000 has been obtained by Evans and Warburton (Evans and Warburton 2007) (Figure 4.8). Therefore, the final sediment production from bare peat for each month is estimated by Equation 4.2:

$$SS = SS_c (1 + \frac{(SSI - SSI_c)}{|SSI_c|})$$
 Equation 4.2

where SS is the predicted monthly sediment supply from bare peat;  $SS_c$  is the actual monthly sediment supply shown in Figure 4.8; SSI is the predicted monthly sediment supply indexes by equations in Table 4.6;  $SSI_c$  is the monthly SSI for  $SS_c$ ;  $|SSI_c|$  is the absolute value of  $SSI_c$ . In this project,  $SSI_c$  directly took values of monthly SSI for the whole Trout Beck catchment between July 1999 and July 2000 as monthly data of temperature and water table were not available for Rough Sike during this period.

# 4.4 Parameterization of land management

## 4.4.1 Artificial drainage

It has been demonstrated in section 2.5.2.1 of Chapter 2 that artificial drainage has effects of altering hydrological properties of blanket peat, and horizontal incision of ditch sides often results in more bare peat and thereafter erosion. The variation in soil properties could be attributed to changed water table, which is related to the density of ditches and the topographic location (Holden, Chapman et al. 2004; Ramchunder, Brown et al. 2009; Holden, Wallage et al. 2011). Holden, Wallage et al. (2011) demonstrated lower water table in drained blanket peat was detected than in nearby intact sites. Therefore, changes in water table caused by drainage management should be reflected in the model. In addition, a high density of artificial drainage also leads to considerable reduction of vegetation, which adds more impacts to the hydrology and erosion of blanket peatlands (Tallis 1998; Worrall, Armstrong et al. 2007). Consequently, drainage should be parameterized in two aspects: 1) fluctuations of water table; 2) vegetation removal. The PESERA-POINT drainage model meets the above requirements, and was therefore chosen for the project and aggregated into the PESERA-GRID model. It was developed and incorporated during a project, which was funded by Yorkshire Water and conducted by the University of Leeds, to evaluate the socio-economic implications of land management policies in Yorkshire's catchments (Beharry-Borg, Hubacek et al. 2009).

The PESERA-POINT drainage model is a conceptual model considering the impact of drainage on water table and vegetation cover and biomass. The conceptual diagram of this model is shown in Figure 4.9, where DS is the drain spacing in m; Z represents the depth of drainages in m, it was set to 0.5 in this project; W is the width of drainages in m, it was set to 1 in this project. In addition, it was assumed that all the drainages within each grid cell were evenly distributed.

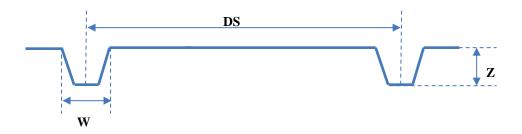


Figure 4.9 Conceptual diagram of the drainage model.

Vegetation cover and biomass removal is directly calculated as the percentage of area of each grid cell. It follows Equation 4.5:

$$\text{vcrop}_{\text{grip}} = \frac{\text{DD A W}}{\text{A}} = \text{DD W}$$
 Equation 4.3

where,  $vcrop_{grip}$  is the vegetation cover or biomass removed by drainage; DD is the drainage density (length of drainage / A); A is the area of the grid cell.

A "ditch level" value, which represents the drainage deficit, is adopted to account for the impact of the drainage on the soil moisture conditions. The ditch level increases with drainage depth and saturated conductivity, decreases with drain spacing. So,

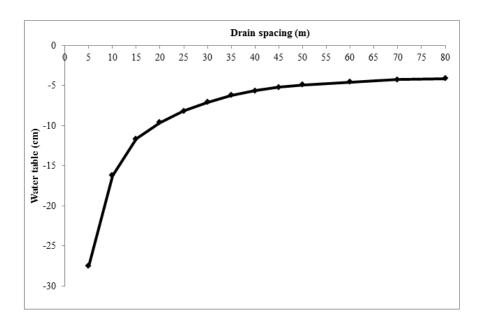
$$DL = \frac{\beta K_{sat} Z}{DS}$$
 Equation 4.4

where, DL is the ditch level representing the drainage deficit in mm;  $K_{sat}$  is the saturated conductivity;  $\beta$  is a scaling factor and was set to 5 in the project; DS is negatively related to drainage density, and given by,

$$DS = A/DD$$
 Equation 4.5

$$j_* = j_* \exp(-DL/m)$$
 Equation 4.6

The saturated runoff rate (j<sub>\*</sub> in Equations 4.12, 4.13 and 4.14), which is crucial for the speed of soil infiltrating into soil and soil moisture dynamics in PESERA-GRID, decreases exponentially with the ditch level in drained blanket peatlands (Beven 1997). Please refer to section 4.5.2.1 for more details about runoff production in PESERA-GRID. Sensitivity analysis of the drainage model is presented in Figure 4.10. The depth of modelled water table increases when the drains become denser, demonstrating the drainage model is capable of capturing the effect of drainages on water table.



**Figure 4.10** Sensitivity analysis of the drainage model based on the climatic conditions of the Trout Beck catchment between 1997 and 2009.

# 4.4.2 Burning and grazing

Through review of recent publications in section 2.5.2.2 and 2.5.2.3 of chapter 2, burning and grazing were known to impact surface conditions and soil properties at the same time, and therefore change the hydrological regime and increase peat erosion. However, there was a dearth of data on hydrology or impacts on peatland erosion following fire and grazing in peatlands (Worrall, Armstrong et al. 2007; Worrall and Adamson 2008; Esteves, Kirkby et al. 2012; Ramchunder, Brown et al. 2012; Holden, Wearing et al. 2013). However, Worrall, Armstrong et al (2007) suggested that land management controlled hydrology through influencing the development of vegetation in peatlands. Meanwhile, vegetation removal resulting from burning and grazing leads to more bare peat, which is vulnerable to erosive forces (Tallis 1998). It was therefore possible to hypothesize that changed hydrological regimes and increased sediment erosion after fire and grazing could be attributed to the removal of vegetation. This is to say, burning and grazing could be parameterized as a percentage of vegetation removed.

Managed burning is controlled to burn quickly in small patches without getting out of control. Vegetation cover and biomass were considered to be fully removed within the area burnt. In this project, the length of managed burning rotations was used to estimate the area under prescribed burning as it could be represented by the reciprocal of the area burnt i.e. 1 / 20th of the land burnt = 20-year rotation (Defra 2007). Therefore, for each grid cell, the proportion of vegetation cover and biomass removed by managed burning is estimated as shown in Equation 4.7:

$$vcrop_{burn} = \frac{1}{rotation}$$
 Equation 4.7

where, vcrop<sub>burn</sub> is proportion of vegetation cover or biomass removed by managed burning; rotation is the rotational years of managed burning.

**Table 4.7** Legal burning seasons and legislation in the UK.

Country	Upland	Lowland	Principal legislation
England	1 <sup>st</sup> Oct- 15 <sup>th</sup> Apr	1 <sup>st</sup> Nov - 31 <sup>st</sup> Mar	The Heather and Grass etc. Burning (England) Regulations 2007
Wales	1 <sup>st</sup> Oct - 31 <sup>st</sup> Mar	1 <sup>st</sup> Nov - 15 <sup>th</sup> Mar	The Heather and Grass etc. Burning (Wales) Regulations 2008
Scotland	1 <sup>st</sup> Oct - 30 <sup>th</sup> Apr (above 450 m)	1 <sup>st</sup> Oct - 15 <sup>th</sup> Apr (below 450 m)	Hill Farming Act 1946
Northern Ireland	1 <sup>st</sup> Sep- 14 <sup>th</sup> Apr		Game Preservation Act (N. I.) 1928, Chapter 25 as amended by the Game Law Amendment Act 1951, Chapter 4

Managed burning is restricted to the winter months by the government in the UK in order to minimize the damage to peatlands (Table 4.7). Therefore, managed burning was turned on only in the periods shown in Table 4.7 for different regions of the UK.

Wildfires could extend across a large area (McMorrow, Lindley et al. 2009). Vegetation removed by wildfire is usually greater across a catchment in which it occurs than that removed by managed burn. In this project, an ignition model derived from algorithms, which were developed and tested by Venevsky, Thonicke et al. (2002) independently for the Iberian Peninsula, has been incorporated into PESERA-GRID to estimate the potential wildfire severity. This model has been incorporated into the PESERA-POINT model by Esteves, Kirkby et al. (2012) to account for the reaction of soil erosion to managed burn and wildfire in central Portugal. The formula of the model is shown as Equation 4.8:

PFS = VEGTN 
$$(1 + 5 \left(1 - \sqrt{\frac{AET}{PET}}\right))$$
 Equation 4.8

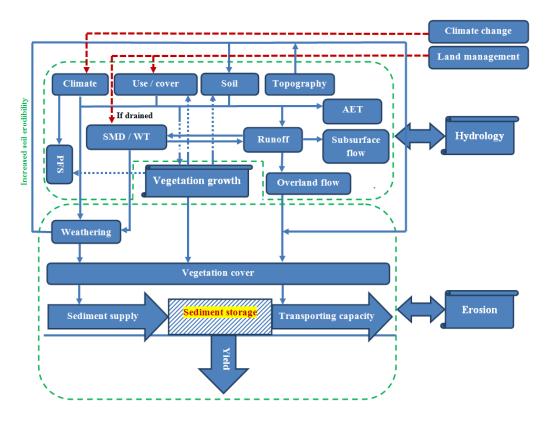
where, PFS is unitless potential wildfire severity; VEGTN represents the vegetation biomass in kg m<sup>-2</sup>; AET and PET are actual and potential evapotranspiration in mm.

The predicted potential wildfire severity was used to evaluate how serious the wildfire could be under certain climate and land management practices. Therefore it offers an opportunity to assess the impact of environmental changes on peat erosion more comprehensively. For example, land management practices which reduce erosion in blanket peatlands may increase potential wildfire severity at the same time. Wildfire under such conditions may cause more damage to blanket peat systems and result in more erosion.

Grazing was also parameterized as a percentage of vegetation cover and biomass removed. Two levels of grazing were considered in this project: light grazing and overgrazing, which were assumed to reduce vegetation cover and biomass by 15 % and 30 % respectively. These values were estimated based on the work of Chapman, Termansen et al. (2009) on the response of upland vegetation to low and high stocking densities of 0.5 and 3 ha<sup>-1</sup> respectively, based on field investigations undertaken in upland areas of the UK (Peak District). Grazing was assumed to occur though the whole year as the periods, when sheep were taken off, were not officially regulated.

## 4.5 Modified PESERA-GRID - PESERA-PEAT

# 4.5.1 Updated PESERA-GRID framework



**Figure 4.11** Updated framework of the PESERA-GRID model. Dashed lines indicate there are no intersections between crossed lines.

An updated conceptual framework of the PESERA-GRID model is given in Figure 4.11. Climate, land use / cover and soil properties are used to derive the runoff, which is composed of overland flow and subsurface flow (Beven and Kirkby 1977; Beven and Kirkby 1979; Kirkby, Irvine et al. 2008). PESERA-GRID also calculates the soil moisture deficit, which is closely related to water table. The sediment yield in the modified PESERA-GRID is determined as a balance of sediment supply and transporting capacity. Both sediment supply and transport are considered to be impacted by vegetation cover, given erosion normally occurs on bare ground (Tallis 1998). The soil erodibility increases when weathered, and is used to determine the transporting capacity with overland flow and topographic factors. The vegetation growth model in PESERA-GRID can update vegetation cover, biomass, humus etc. (Licciardello, Govers et al. 2009). In the updated PESERA-GRID framework, climate change impacts hydrology and erosion outputs by altering the runoff output,

water table, vegetation growth, temperature and evapotranspiration. Reduced vegetation cover and biomass and changed water table resulting from land management interventions work on the hydrology, vegetation growth, sediment production and transport. In order to be distinguishable from the original PESERA-GRID model, the updated one shown in Figure 4.11 is named as PESERA-PEAT.

# 4.5.2 Detailed description of processes incorporated in PESERA-PEAT

The overall conceptual framework of PESERA-PEAT has already been stated above. In this section processes involved in PESERA-PEAT are described in more detail. Modules of runoff production, vegetation growth and transporting capacity of overland flow are directly inherited from the original PESERA-GRID model. Sediment supply and storage are also incorporated to improve the erosion processes of PESERA-GRID for blanket bog.

## 4.5.2.1 Runoff production

This module is directly inherited from the original PESERA-GRID model, which is built based on water balance with precipitation divided into three components: overland flow, evapotranspiration and changes in soil moisture storage.

The overland flow is estimated as:

$$r = p (R - R_0)$$
 Equation 4.9

where R is the total rainfall,  $R_0$  is the runoff threshold, p is the proportion of subsequent rainfall that runs off when runoff threshold is exceeded. They are all expressed in mm.

Evapotranspiration is partitioned between the vegetated and unvegetated fractions of the surface. Final evapotranspiration is calculated as a sum of the partitions weighted for the fractional plant cover. Interception is calculated as a fraction of rainfall, and this fraction increases with vegetation biomass, and is given by,

$$xint = \frac{1 - e^{-VEGTN}/5}{5 + (R/PET)}$$
 Equation 4.10

where, xint is the proportion of rainfall intercepted by the plant cover.

For each component, potential evapotranspiration, after subtraction of interception, is then reduced exponentially with rooting depth to an actual rate of:

$$AET = WUE PET e^{-D/h_R}$$
 Equation 4.11

where AET is the actual evapotranspiration in mm, WUE is dimensionless water use efficiency for storage of plant growth, PET is the potential evapotranspiration in mm, D is the saturated subsurface deficit in mm and  $h_R$  is the rooting depth for the vegetated or unvegetated partition in mm.

Soil moisture deficit is updated monthly with the TOPMODEL expressions of Equations 4.12 and 4.13, and subsurface flow is estimated as monthly change of soil moisture deficit as shown in Equation 4.14:

$$\begin{split} D &= D_0 + \ m \ \ln \left\{ \frac{j_*}{i} \, e^{^{-D_0}/m} + \left[ 1 - \frac{j_*}{i} \, e^{^{-D_0}/m} \right] e^{^{-it}/m} \right\} \ \text{for} \ i \ \neq 0 \quad \text{Equation 4.12} \\ D &= \ D_0 + \ m \ \ln \left[ 1 + \frac{j_*t}{m} \, e^{^{-D_0}/m} \right] \text{for} \ i = 0 \qquad \quad \text{Equation 4.13} \\ D &- D_0 + \ it = m \ \ln \left[ 1 - \frac{j_*}{i} \, e^{^{-D_0}/m} + \frac{j_*}{i} \, e^{^{(it-D_0)}/m} \right] \quad \text{Equation 4.14} \end{split}$$

where D is the deficit after time t,  $D_0$  is the initial deficit (mm), i is the net rainfall intensity (mm mon<sup>-1</sup>), which is calculated as the total rainfall plus snowmelt minus overland flow and evapotransporation (including vegetation interception), m is the TOPMODEL soil parameter (mm), and  $j_*$  is the average saturated runoff rate (mm mon<sup>-1</sup>), and calculated as a function of saturated hydraulic conductivity and m, increasing with both saturated hydraulic conductivity and m.

The soil moisture deficit predicted by the PESERA-PEAT is then used to calculate water table, which is employed for sediment supply prediction, using the

relationship between PESERA-PEAT modelled soil moisture deficit and measured water table for the Trout Beck catchment. The relationship is established and presented in Figure 5.9 of Chapter 5.

The hydrological model also responds to snow and frozen soil conditions. The range of monthly temperatures is used to estimate the proportional time below freezing (Kirkby, Irvine et al. 2008), when rainfall is assumed to fall as snow, and lying snow is accumulated and melted according to a linear degree-day model (Hock 2003). Soil freezing depth is estimated based on a constant thermal conductivity for soil with a simple physical conductivity model (Wiltshire 1983), and the thermal conductivity of the snow pack is assumed to be 20 % of that of the soil (Kirkby, Irvine et al. 2008). The effective soil storage capacity is then decreased exponentially with the freezing depth, resulting in the increased overland flow.

Given the mechanism shown above, PESERA-PEAT is able to simulate both Hortonian and saturation-excess overland flow through comparing soil moisture deficit and available near-surface water storage capacity, which depends on land cover, organic matter and soil properties (Kirkby, Irvine et al. 2008). The detailed processes are as follows. If the soil is dry and far from saturation, the available near-surface water storage capacity is lower than the soil moisture deficit. The runoff threshold takes the value of the available near-surface water storage capacity, and Hortonian overland flow occurs when rainfall intensity is over the runoff threshold (Equation 4.9). On the other hand, if the soil is near to saturation, the available near-surface water storage capacity is higher than the soil moisture deficit. The runoff threshold takes the value of the soil moisture deficit so that saturation-excess overland flow could be generated if the soil is fully saturated (Equation 4.9).

In the project, p value in Equation 4.9 was set to 1 due to the "spiky" characteristic of runoff production in blanket peatlands (Evans, Burt et al. 1999; Holden and Burt 2002a). WUE in Equation 4.11 was set to 1 for bare ground and 0.3 for natural vegetation in terms of PESERA manual (Irvine and Kosmas 2003).

## 4.5.2.2 Vegetation growth

The vegetation growth model of the PESERA-PEAT is exactly the same as that within the original PESERA-GRID model. It is built upon a biomass carbon balance for both living vegetation and soil organic matter (Kirkby, Irvine et al. 2008). The generic vegetation growth model primarily estimates gross primary productivity, soil organic matter and vegetation cover. Gross primary productivity is calculated as a proportion of the actual transpiration from the plant. The estimated gross primary productivity is offset by respiration at a rate increasing exponentially with temperature and proportional to biomass. Soil organic matters increases with leaf fall, and decompose at a rate increasing with temperature. Leaf fall fraction is a decreasing function of biomass, to allow for a larger structural component in large plants. Additional leaf fall is achieved for deciduous plants at a rate that increases with temperature if respiration is greater than gross primary productivity. Cover converges on an equilibrium value, which is defined as the ratio of plant transpiration to potential evapotranspiration, at a rate that is larger where biomass is small. In PESERA-PEAT, vegetation cover and biomass predicted by the vegetation growth model decrease at the same rate when blanket peatlands are managed.

The original PESERA-GRID model also has a crop growth model, which is a variant of this generic model (Kirkby, Irvine et al. 2008). However, given UK blanket peatlands usually do not have croplands, the crop growth model is not incorporated into PESERA-PEAT currently, and so is not described here although it could be quite useful in future applications of PESERA-PEAT in blanket peat-covered areas which are used or planned to be used for arable agriculture.

### **4.5.2.3 Erosion**

## a) Sediment supply

This is a newly added module in the PESERA-PEAT model. Monthly sediment supply is estimated with the equations shown in Table 4.6, which link sediment supply indices with temperature and water table, and Equation 4.2. However, Equation 4.2 produces the sediment supply from bare peat as the base erosion data measured by Evans and Warburton (2007) were mainly from bare peat on gully sides. Therefore, in the model, sediment supply is partitioned for bare soil and

vegetated areas, and it is assumed to decrease linearly with vegetation coverage. Therefore, the final sediment supply for each month could be expressed as:

$$TSS = SS (1 - cov) + \frac{SS}{X} cov$$
 Equation 4.15

where TSS is the total sediment supply resulted from freeze-thaw and desiccation for a month in ton ha<sup>-1</sup>; SS is the erodible material produced by freeze-thaw and desiccation on bare peat for a month in ton ha<sup>-1</sup>; cov is the vegetation coverage for the month; x is the rate at which sediment supply decreases with vegetation coverage.

## b) Sediment transport

Transporting capacity of overland flow is estimated based on soil erodibility, water discharge and local relief (Musgrave 1947; Kirkby, Irvine et al. 2008). This is exactly the same as the equation for sediment yield calculation in the original PESERA-GRID.

It takes the form of:

$$C = k \Delta \sum r^2$$
 Equation 4.16

where C is transporting capacity of overland flow for a month in ton ha<sup>-1</sup>; k is soil erodibility in mm;  $\Delta$  is local relief in m;  $r^2$  is the squared daily runoff summed over a month, so the unit is mm<sup>2</sup>.

With regard to the calculation of the parameters in Equation 4.16, k is derived from the soil texture with pedotransfer functions in the original PESERA-GRID. However, in PESERA-PEAT k is set to the value of erodibility of weathered peat so that C is the transporting capacity of overland flow for erodible material produced by freeze-thaw and desiccation rather than fresh peat;  $\Delta$  is calculated as the standard deviation of elevation within a certain radius. In order to calculate  $r^2$ , storm rainfall is needed. Daily rainfall is used to stand for independent storm events (Kirkby,

Irvine et al. 2008). A gamma function is used to fit monthly rainfall distribution, based on monthly total precipitation, mean rainfall per rainy day and standard deviation of rainfall on rainy days, and the probability density function of daily rainfall and squared daily runoff over the month could then be achieved.

pd (R) = 
$$\frac{\alpha}{\overline{R}} \frac{\alpha R / \overline{R}}{\tau_{\alpha}} e^{-\alpha R / \overline{R}}$$
 Equation 4.17

$$\sum r^2 = \int_{R_0}^{\infty} (R - R_0)^2 \frac{\alpha}{\overline{R}} \frac{(\alpha R/\overline{R})^{\alpha - 1}}{\tau_{\alpha}} e^{-\alpha R/\overline{R}} \cdot dR \qquad \text{Equation 4.18}$$

where pd (R) is the rainfall distribution over the month in mm;  $\overline{R}$  is the mean rain per rainy day in mm,  $\alpha$  is the squared reciprocal of standard deviation of rainfall on rainy days, and it is unitless.

In PESERA-PEAT, transporting capacity is partitioned for bare soil and vegetated areas, with the transporting capacity being higher on bare ground than on vegetated areas. Therefore, the final form of the transporting capacity equation is:

$$TC = C (1 - cov) + \frac{C}{x} cov$$
 Equation 4.19

where TC is the final transporting capacity of overland flow for a month in ton ha<sup>-1</sup>; C is estimated with Equation 4.16; x is the rate at which transporting capacity decreases with vegetation coverage (cov), and this rate was assumed to be the same as the rate at which sediment supply decreased with vegetation coverage mainly because there were no data to support the difference between them. In addition, x was originally set to 90 % empirically and then adjusted during model calibration in Chapter 5.

## c) Sediment yield

In blanket peatlands, erosion usually tends to be supply limited (Evans and Warburton 2005; Evans, Warburton et al. 2006). However, transport-limited erosion happens sometimes (Holden and Burt 2002a), and surplus sediment will be

accumulated on the land surface as sediment storage. Thus it was necessary to create a sediment storage component for PESERA-PEAT. The sediment storage for each month is calculated through comparing the sediment availability and transporting capacity (Equation 4.20). Sediment availability is defined as a sum of the total sediment production by freeze-thaw and desiccation in the month and the sediment storage from previous months (Equation 4.21). If the sediment availability is more than the transporting capacity, the erosion would be transporting capacity for that month. If the sediment availability is less than the transporting capacity, the erosion would be supply limited, and sediment storage for the month is zero. Final sediment yield is calculated with Equation 4.22.

$$\begin{aligned} \text{Storage}_{c} &= \text{Sedi}_{av} - \text{TC} & \text{Equation 4.20} \\ \text{Sedi}_{av} &= \text{TSS} + \text{Storage}_{p} & \text{Equation 4.21} \\ \text{SY} &= \begin{cases} \text{Sedi}_{av}; & \text{if Sedi}_{av} < \text{TC} \\ \text{TC}; & \text{if Sedi}_{av} > \text{TC} \\ \text{Sedi}_{av} \text{ or TC}; & \text{if Sedi}_{av} = \text{TC} \end{cases} \end{aligned} \end{aligned} \quad \text{Equation 4.22}$$

where, Sedi<sub>av</sub> is the sediment availability for the current month; TSS is the total sediment production through freeze-thaw and desiccation for the current month in ton ha<sup>-1</sup>; Storage<sub>p</sub> is the sediment storage from previous months; Storage<sub>c</sub> is the sediment storage for the current month; TC is the transporting capacity of overland flow for the current month; SY is the final sediment yield. All values are in ton ha<sup>-1</sup>.

# 4.6 Summary and discussion

Time-series analysis of sediment flux, water table and temperature in the Trout Beck catchment between 1997 and 2009 confirmed the dominance of freeze-thaw and desiccation in sediment supply (Evans and Warburton 2007). In order to overcome the shortage of sediment rating curves a new indicator of sediment supply (termed the sediment supply index) was proposed and used to relate sediment supply with various temperature and soil moisture relevant variables, which were thought to be indicative of freeze thaw and desiccation (Francis 1990; Albertson, Aylen et al.

2010). In terms of these relationships, sediment supply is a result of combined freeze-thaw and desiccation in the winter half year (except March) while desiccation becomes dominant in other months. Monthly temperature and water table were then chosen for final regression equations with sediment supply indexes for each month (Table 4.6). Water table was included in the equations for all months while temperature was only considered between October and February. Freeze-thaw that happens between March and September is not taken into account by these equations. Therefore, these equations may encounter challenges when applied in colder places, where freeze-thaw may be an important source of sediment in summer. However, the following three points make the application of these equations across the UK acceptable: 1) the Trout Beck catchment is a relatively cold site in the UK due to its high elevation (Manley 1936), so freeze-thaw in summer months is unlikely to become dominant in sediment supply across the UK blanket peatlands; 2) climate projections suggest that the UK will experience warming in the next 100 years (UKCP09 2009), so freeze-thaw may become less and less important in the sediment supply of blanket peatlands; 3) there were not enough data from other sites to improve the equations established based on data from the Trout Beck catchment. On top of quantifying the linkage between sediment supply indices and weathering mechanisms, the final equations were aggregated into PESERA-GRID to account for sediment production by freeze-thaw and desiccation with the actual sediment supply measured at Rough Sike as a base. Land management practices were also parameterized: drainage, burning and grazing. Changed vegetation cover and biomass and water table resulting from land management shifts are linked with hydrology and erosion processes in the model. This enables PESERA-GRID to be applied to investigate the linkage between blanket peat erosion and land management in a more physically reasonable way. By doing so, an updated PESERA-GRID framework named PESERA-PEAT was developed.

In Figure 4.3 and Figure 4.5 decreased runoff efficiency and blanket peat erosion with catchment size imply that peat erosion and runoff data from catchment outlets may be not sufficient to indicate erosion and runoff production within catchments. This might be because the erosion and runoff produced on hillslopes is trapped by vegetation cover or deposited again before reaching catchment outlets. Given many eroded blanket peatlands have been partly re-vegetated, more and more weathered

peat is stored on hillslopes without entering stream channels (Evans, Warburton et al. 2006). Therefore, it is advisable to study the hydrological and erosion processes in blanket peatlands at hillslope scales. Investigation of blanket peat erosion at a hillslope scale and its reaction to climatic change and typical land management is meaningful in evaluating the erosion risk more specifically, therefore making conservation practices more effective and straightforward. The necessity of looking at peat erosion at a hillslope scale supports the selection of PESERA-GRID as a basis to address the research questions in this thesis. Lastly, understanding the impact of spatial scales on runoff and erosion in blanket peat-covered areas facilitates the application of the PESERA-PEAT model. This is mainly because most field erosion data in blanket peatlands was collected at catchment outlets, and Figure 4.3 and Figure 4.5 provide a way of downscaling measured runoff and sediment flux at the catchment outlet to hillslopes. The relationships identified in Figure 4.3 and Figure 4.5 can act as a linkage between PESERA-PEAT modelling results and measured data, and play an important role in numerically evaluating PESERA-PEAT, which will be completed in Chapter 5.

# Chapter 5

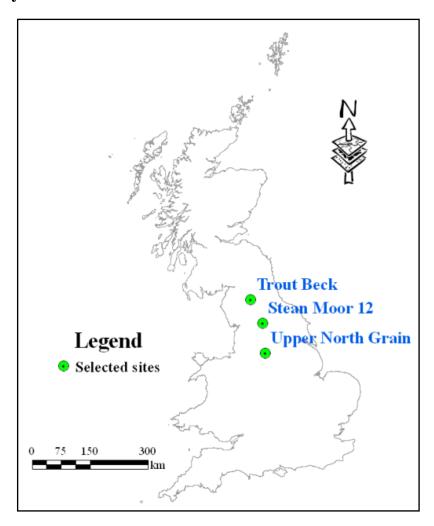
# **Evaluation of PESERA-PEAT**

## 5.1 Introduction

In Chapter 4 PESERA-GRID was modified for application to blanket peatlands based on analysis of field data and a review of previous literature. The major aim of this chapter is to calibrate and validate PESERA-PEAT at several blanket peat catchments under different erosion conditions, in order to confirm the applicability of PESERA-PEAT for regional or national blanket peatland use.

The structure of this chapter is as follows: Section 5.2 introduces blanket peat sites chosen for the calibration and evaluation of PESERA-PEAT. Section 5.3 concentrates on the data sources and methodology adopted for processing of model inputs and evaluation of model outputs. In section 5.4 PESERA-PEAT is operated and tested at three blanket peat catchments suffering from different eroding conditions. Key components such as evapotranspiration, runoff, vegetation biomass, sediment flux etc. are tested against field data and previous publications. The relationship between two versions of PESERA-PEAT (equilibrium and time-series) is also discussed in this section. Section 5.5 provides a summary outlining the reliability of PESERA-PEAT in blanket peat erosion modelling. Advantages and disadvantages of the equilibrium and time-series are discussed with reference to their utility at regional and national scales.

# 5.2 Study sites



**Figure 5.1** Location of sites chosen for calibration and evaluation of the PESERA-PEAT.

In order to demonstrate the reliability of PESERA-PEAT, it is necessary to test the model outputs with field data. However, there are few sites with good long-term field data on stream or hillslope sediment fluxes or concentrations. Three catchments were found where field data was available as shown in Figure 5.1and these were therefore used in this study. Trout Beck and Upper North Grain represent two extremes of a spectrum of eroded peat catchments in the UK (Evans and Warburton 2005; Evans, Warburton et al. 2006). Stean Moor is an area more eroded than Trout Beck and less eroded than Upper North Grain. Therefore, it represents a middle erosion condition. A general introduction to these sites is provided below:

### 1) Trout Beck

An overview of the Trout Beck catchment is presented in section 3.4.2 of Chapter 3. The aerial photograph of the Trout Beck catchment is shown in Figure 5.2. The percentage of bare peat in Trout Beck has changed with time. Grayson and Holden et al. (2010) digitized the bare peat of this catchment based on four sets of aerial photographs, which were taken in 1950, 1975, 1995 and 2000. The highest percentage of bare peat was found in 1975 at 9.2 %, with the remaining three sets of aerial photographs exhibiting smaller percentages of bare peat, which are between 2.3 % and 4.6 %. There is a small amount of experimental burning and one hillslope has experimental drainage (Holden, Evans et al. 2006; Holden, Chapman et al. 2012). The total area with experimental burn patches and drainage covered 0.7 % and 0.01 % of the catchment respectively. Most of the catchment has been left to naturally re-vegetate with low intensity grazing of 0.15 sheep ha<sup>-1</sup> (Grayson, Holden et al. 2010). Therefore, in this study, the Trout Beck catchment is considered at the relatively 'intact' end of the blanket peat erosion spectrum (Pawson 2008).

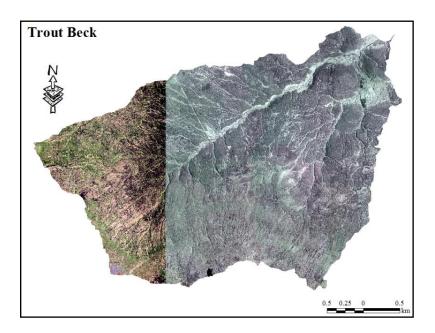
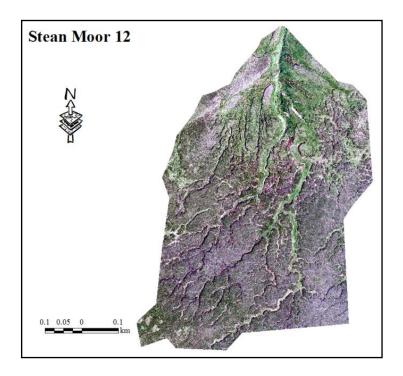


Figure 5.2 Aerial photograph of Trout Beck catchment (from Google map).

#### 2) SteanMoor 12

Stean Moor is located in Upper Nidderdale, North Yorkshire, UK and is part of the Nidd Comm Inlet at Chellow Heights water treatment works. There are twelve subcatchments in Stean Moor. They are named as Stean Moor 1 to 12. This name and

number code is used because the sub-catchments have been given this nomenclature over the past 30 years by Yorkshire Water, and this aids any future comparison with historical data from this site. Stean Moor 1 to 11 are heavily drained; most of drains in these catchments were blocked in the winters of 2009/10 and 2010/11 (Grayson and Holden 2012). In Stean Moor 12 (Figure 5.3), total length of ditches was considered to be close to zero, and no blocking was implemented (Grayson and Holden 2012). Therefore, sediment data from Stean Moor 12 should better reflect erosion on hillslopes. Hence this catchment was selected to assess PESERA-PEAT. Stean Moor 12 drains an area of 0.38 km² with sheep grazing as a management option. The altitude range is 494-558 m. Vegetation is dominated by *Calluna* and *Eriophorum*. The dominant soil in this catchment is deep peat.

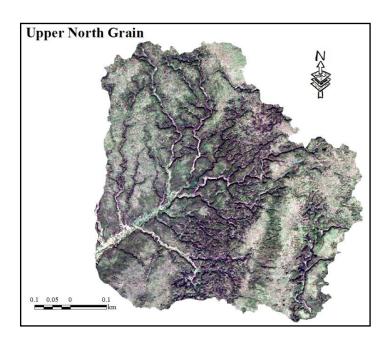


**Figure 5.3** Aerial photograph of Stean Moor 12 (from Google map).

### 3) Upper North Grain

Upper North Grain is a small headwater catchment of the River Ashop. It is a part of the National Trust High Peak Estate, situated in the Peak District, Southern Pennines, UK. Located at altitudes between 490 and 541 m, the catchment is dominated by blanket bog. It drains an area of 0.38 km<sup>2</sup>, with rough grazing by sheep as the dominant land use (Rothwell, Robinson et al. 2005). It is heavily eroded

with Bower Type I peat gullies (Bower 1961), which in the upper reaches occur solely in a peat stratigraphy which often reach several metres in depth. The lower reaches of the gullies cut into the underlying bedrock, which is dominated by sandstones of the Millstone Grit Series (Cope 1976). An aerial photograph of the Upper North Grain catchment is shown in Figure 5.4, where the dendritic gully networks are clearly visible. (Pawson, Lord et al. 2008). Extensive gully systems and grazing result in considerable bare peat and drainage density of around 60 km km<sup>-2</sup> in this catchment (Figure 5.4).



**Figure 5.4** Aerial photograph of the Upper North Grain catchment (from Google map).

# 5.3 Methodology

### 5.3.1 Model evaluation method

As stated in section 4.5 of Chapter 4, the PESERA-PEAT model includes three major modules: hydrology, erosion, and vegetation growth. In order to evaluate the model performance, modelling results from these three modules should be evaluated. Vegetation biomass was used to assess the vegetation growth model. Evapotranspiration, runoff and soil moisture deficit were used for evaluation of the hydrology module, and the erosion sub-model was assessed with comparison between modelled and measured sediment flux.

The modelled vegetation biomass and evapotranspiration were evaluated with data from previous publications to identify whether their magnitudes were reasonable. The predicted soil moisture deficit was compared with measured water table to see if PESERA-PEAT could reflect changes in soil moisture condition. The predicted runoff and sediment yield were compared with field data and previously published data in two aspects: shape and magnitude. Because the modelling results are at hillslope scales, and field data are at catchment scales, field data should be downscaled to hillslopes before being compared with modelling outputs. The regression equations shown in Figure 4.3 and Figure 4.4 of Chapter 4 were adopted for downscaling measured runoff ratios and sediment yields respectively. Detailed evaluation strategies for modelled runoff and erosion are shown below:

Firstly, the modelled monthly results were plotted against downscaled measured monthly data to see if their shapes fitted. Linear regression between downscaled field and modelled monthly data was also undertaken to evaluate how well model data could reproduce the changes in field data. A higher R<sup>2</sup> of the linear regression indicates better fit between modelled and field data.

Secondly, comparisons were also conducted between annual modelling results and downscaled annual field data to assess if the model could produce a reasonable magnitude of runoff and erosion. The difference between modelled and downscaled data was calculated as:

$$Dif = \frac{Mod - Mea_d}{Mea_d} * 100 \%$$
 Equation 5.1

In Equation 5.1, Dif represents the difference between modelled and downscaled measured data; Mod and Mea<sub>d</sub> are modelled and downscaled actual data respectively.

Lastly, the Nash-Sutcliffe coefficient (*E*) was employed to assess the overall accuracy of the modelling results based on modelled and downscaled measured data. This is mainly because the Nash-Sutcliffe coefficient is capable of assessing the

shape and magnitude simultaneously. A general introduction to the Nash-Sutcliffe coefficient was provided in section 3.4.3.2 of Chapter 3. There is debate about what represents a satisfactory performance of models base on the Nash-Sutcliffe value. Santhi, Arnold et al. (2000) concluded that a model is acceptable when it obtains a Nash-Sutcliffe coefficient  $\geq 0.5$  and the  $R^2 \geq 0.6$ . Saleh et al. (2001) stated that model performance was adequate and very good when the model obtained the Nash-Sutcliffe coefficient of 0.54-0.65 and > 0.65 respectively.

## 5.3.2 Data sources and processing

### 5.3.2.1 Model evaluation data

**Table 5.1** The sources of data used for evaluation of modelling results.

Item	Site	Time period	Source
Vegetation biomass	Moor House	1971, 1975	Smith and Forrest (1978)
Evapotranspiration	North Yorkshire	Unknown	Wallace, Roberts et al. (1982)
Water table	Trout Beck	1997-2009	ECN
Runoff	Trout Beck	1997-2009	ECN
	Stean Moor 12	2010-2011	Unpublished data,
			University of Leeds
Erosion	Trout Beck	1997-2009	ECN
	Stean Moor 12	2010-2011	Unpublished data,
			University of Leeds
	Upper North Grain	2005-2007	Pawson, Evans et al. (2012)
		2001-2002	Evans, Warburton et al. (2006)

Table 5.1 shows data employed to assess different components of the PESERA-PEAT model. Details of measured vegetation biomass and evapotranspiration will be presented during model evaluation. The monthly water table (Table 5.2), runoff and sediment flux data of the Trout Beck catchment between 1997 and 2009 were calculated based on the dataset collected by ECN. A detailed description of the dataset has been provided in section 3.4.3.1 of Chapter 3.

The time-series of runoff and erosion of Stean Moor 12 between 2010 and 2011 were extracted from an unpublished dataset collected by the University of Leeds. In the dataset, the water discharge was estimated based on a rating curve between flow rates and stages of water surface. The original estimated runoff of Stean Moor 12 between 2010 and 2011 was subject to a systematic overestimation, with resulting mean annual runoff of 1407 mm being higher than the average measured rainfall of

1191 mm. This is mainly because the rating curve employed to estimate the water discharge for the twelve sub-catchments of the Stean Moor is well populated at the bottom end but not at the high end of the stage. Hence as an alternative, the magnitude of annual runoff of Stean Moor 12 was estimated based on that of Stean Moor 3, whose rating curve was considered very reliable, using the downscaling equation shown in Figure 4.3 of Chapter 4. Meanwhile, the monthly distribution of the estimated annual runoff from Sean Moor 12was the same as that of the original runoff estimated with the rating curve. The resulting runoff was then considered as the actual measured runoff of Stean Moor 12 between 2010 and 2011. In 01/2010 and 09/2011, around twenty days of suspended sediment concentration were missing for each of these two months. In order to avoid the possible impacts of the missing suspended sediment concentration on calculating the sediment flux in these two months, the suspended sediment concentrations of 01/2011 and 09/2010 were used to substitute those of 01/2010 and 09/2011 respectively. Such an adjustment was also done for the actual runoff data as well for calculation of the adjusted sediment flux. In this chapter, the adjusted sediment flux and runoff were employed as the base for assessment of the sediment flux and runoff predicted by the equilibrium and time-series versions of PESERA-PEAT for Stean Moor 12 between 2010 and 2011.

Time-series of measured sediment data for Upper North Grain was not available. Average annual sediment flux from the Upper North Grain between 2005 and 2007 was estimated based on the field measurements reported by Pawson, Evans et al. (2012) and Evans, Warburton et al. (2006). Pawson, Evans et al. (2012) demonstrated that the mean annual POC flux from the Upper North Grain was about 0.73 ton ha<sup>-1</sup> between 2005 and 2007, and 48 % of organic sediment flux in this site was POC. In addition, Evans, Warburton et al. (2006) built up the sediment budget for the Upper North Grain and showed that about 70 % of total sediment yield was organic sediment. So the mean annual sediment flux from the Upper North Grain between 2005 and 2007 was estimated to be 2.17 ton ha<sup>-1</sup>.

The measured runoff and sediment flux for the selected catchments were downscaled from a catchment scale to a 1-ha scale, which PESERA-PEAT works on in this project, with the equations shown in Figure 4.3 and Figure 4.4 of Chapter 4. The downscaling results are shown in Table 5.2. The model was calibrated based on

the downscaled sediment flux from Trout Beck catchment and validated with datasets from other sites.

**Table 5.2** The downscaled monthly / annual average measured runoff and erosion, and water table used for model evaluation. TB\_97-09, SM12\_10-11 and UNG\_05-07 represent Trout Beck between 1997 and 2009, Stean Moor 12 between 2010 and 2011 and Upper North Grain between 2005 and 2007.

	Runo	ff (mm)	E	rosion (ton h	a <sup>-1</sup> )	Water table (cm)
Month	TB_	SM12_	TB_	SM12_	UNG_	TB_
	97-09	10-11	97-09	10-11	05-07	97-09
1	218	97	0.08	0.19	N/A	-1.72
2	168	102	0.06	0.10	N/A	-2.27
3	167	53	0.05	0.02	N/A	-2.66
4	107	49	0.03	0.01	N/A	-4.11
5	89	32	0.03	0.01	N/A	-5.81
6	83	38	0.02	0.01	N/A	-6.19
7	113	69	0.06	0.06	N/A	-7.71
8	134	92	0.08	0.08	N/A	-6.57
9	135	123	0.07	0.12	N/A	-5.87
10	197	132	0.07	0.10	N/A	-2.32
11	230	144	0.10	0.32	N/A	-1.43
12	240	123	0.10	0.12	N/A	-1.89
Annual	1880	1053	0.77	1.14	6.01	-4.05

## 5.3.2.2 Model input data

## a) Climate

**Table 5.3** The sources of climate data for the selected sites.

Site	Time (year)	Rainfall (mm)	Temperature (°C)
Trout Beck	1997-2009	ECN station	ECN station
Stean Moor12	2010-2011	Unpublished data, University of Leeds	Met Office gridded dataset
Upper North Grain	2005-2007	MIDAS station	Met Office gridded dataset

Table 5.3 shows the sources of base climate data, from which climatic inputs for PESERA-PEAT were derived. The time periods of employed climate data for the three sites were chosen mainly dependent upon the availability of field runoff and erosion data. For the Trout Beck catchment, climate data between 1997 and 2009 were used, collected by the ECN meteorological station (Grid Ref: NY758335) within the catchment. For Stean Moor 12, rainfall data between 2010 and 2011 were obtained from an unpublished tipping bucket raingauge dataset collected by the

University of Leeds, while temperature data were downloaded from Met Office gridded datasets. For Upper North Grain, rainfall data from the nearest MIDAS station (ID: 3257; Grid ref: SK 128895) were used as there was no measured rainfall available within this site, while temperature data were extracted from Met Office gridded datasets. Climatic inputs of PESERA-PEAT are the same as those of PESERA-GRID. Detailed description of the climate inputs was shown in section 3.4.4.1 of Chapter 3. In the project, the PESERA-PEAT operated at a spatial scale of 100 m, but temperature layers from Met Office gridded datasets are at 5-km spatial resolution. Therefore, these temperature data were downscaled from 5 km to 100 m assuming that the temperature decreases by 6.5 °C with elevation increasing by 1 km. More specifically, the downscaling equation is as below:

$$Temp_{100} = \{Resample [(Temp_{5000} + 0.0065 Elevation_{5000}), 100, BILINEAR]\} - 0.0065 Elevation_{100}$$

Equation 5.2

where,  $Temp_{100}$  Temp<sub>100</sub> is the temperature (°C) at 100-m resolution; Temp<sub>5000</sub>  $Temp_{5000}$  is the temperature (°C) at 5-km resolution; Elevation<sub>5000</sub>  $Elevation_{5000}$  is the altitude (m) at 5-km resolution; Elevation<sub>100</sub>  $Elevation_{100}$  is the altitude (m) at 100-m resolution, and the bilinear resampling method was taken to interpolate the temperature surface from 5 km to 100 m.

Potential evapotranspiration (PET) was derived directly from a modified temperature-based model which was originally proposed by Oudin, Hervieu et al. (2005). In the project the original model was revised to include wind speed and vegetation height, which are also considered to be important for PET (Chiew and McMahon 1991), as used in the PET estimation by Clark (2005) at the Trout Beck catchment. The final model is as below:

$$PET = 1000 \ N\left(\frac{R_e}{\lambda \rho_w} \frac{T_a + 5}{100}\right) - \ 11.1 \ WS - 8.6 \ VH + 106 \quad Equation \ 5.3$$

where, N is the number of days in the month;  $R_e$  is the extraterrestrial radiation in MJ m<sup>-2</sup> day<sup>-1</sup>;  $\lambda$  is the latent heat flux in MJ kg<sup>-1</sup> (taken as 2.45 MJ kg<sup>-1</sup>);  $\rho_w$  is the density of water in kg m<sup>-3</sup> (taken as 1000 kg m<sup>-3</sup>);  $T_a$  is the mean air temperature in °C, derived from long-term average; WS is the wind speed in m s<sup>-1</sup>; VH is the vegetation height in m; PET is the total potential evapotranspiration per month in mm.

For Trout Beck and Upper North Grain, the climatic inputs were directly derived from the above data sources (Table 5.3) and methodologies. For the Stean Moor 12, the climatic inputs of 01/2010 and 09/2011 were replaced by that of 01/2011 and 09/2010 because such adjustment had been done for the runoff and sediment flux. The resulting monthly/annual average rainfall and temperature for the three sites during the chosen periods are presented in Table 5.4.

**Table 5.4** The monthly / annual average rainfall and temperature used for model evaluation. TB\_97-09, SM12\_10-11 and UNG\_05-07 represent the Trout Beck between 1997 and 2009, Stean Moor 12 between 2010 and 2011 and Upper North Grain between 2005 and 2007.

	R	ainfall (m	ım)	Ten	nperatur	e(°C)
Month	TB_	SM12_	UNG_	TB_	SM12_	UNG_
	97-09	10-11	05-07	97-09	10-11	05-07
1	232	127	155	1.49	0.75	2.67
2	184	135	122	1.33	1.12	1.54
3	194	68	106	2.39	3.07	2.88
4	138	25	76	4.25	6.99	6
5	119	69	107	7.59	8.06	8.43
6	107	64	159	10.15	11.36	12.19
7	125	101	131	11.99	12.57	13.75
8	139	104	104	12.09	11.92	12.61
9	148	124	111	10.13	10.97	11.84
10	195	109	114	6.82	8.08	9.15
11	205	154	118	3.93	4.43	4.31
12	228	136	179	1.47	-0.19	2.5
Annual	2014	1216	1482	6.14	6.59	7.32

### b) Land use /cover

Croplands are not likely to exist in the UK blanket peatlands. Therefore, parameterization of croplands is not provided here. However, PESERA-PEAT can

be applied to blanket peatlands with croplands if needed as growth of crops is included in the original PESERA-GRID model (Kirkby 2003; Kirkby, Jones et al. 2004; Kirkby, Irvine et al. 2008; Esteves, Kirkby et al. 2012). Given the above description, the PESERA-PEAT model has to date included land use codes (code), initial ground coverage for each month (cov), initial surface storage (rough0), surface roughness reduction per month (rough\_red), and root depth (rootdepth) as the input to define the initial land use / cover condition. In PESERA-PEAT seven land use codes are employed in order for the vegetation growth model to recognise different vegetation types, and allow them to grow in different manners. The codes and corresponding land uses are provided in Table 5.5.

**Table 5.5** Land use codes used in PESERA-PEAT and corresponding land uses.

Code	Definition
100	Artificial land
231	Grassland or pasture
310	Woodland
320	Scrub
330	Bare land
334	Degraded natural land
400	Water surface or undifferentiated bog

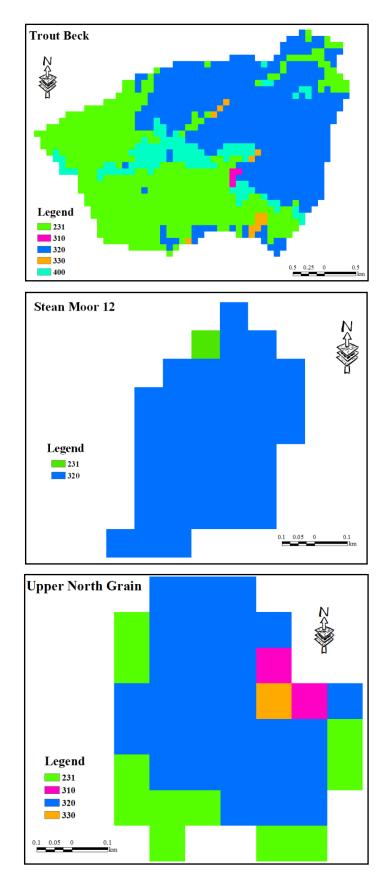
Water surfaces and artificial lands are masked out and so not engaged in calculations during model implementation given no erosion is considered to occur in these areas. The vegetation growth model works to update the vegetation coverage on "231", "320" and "334". Ground coverage for "310", "330" and "400" (undifferentiated bog) is always kept as initial input values. Vegetation biomass and soil organic matter are updated by the vegetation growth model for all land use types other than "330", where they are kept as zero. In the project land management practices were considered to only work on "231", "320" and "334" to impact the soil moisture content (drainage only), vegetation cover, biomass and thus soil organic matter. Land use / cover information was mainly derived from LCM2000, so LCM2000 use codes needed to be translated into land use codes in the PESERA-PEAT. Such translation is shown in Table 5.6. Initial ground cover, initial surface storage, surface roughness reduction per month and root depth for each land use type of LCM2000 are shown in Table 5.6 with reference to the values provided in the user manual of the PESERA (Irvine and Kosmas 2003).

Table 5.6 Linkage between LCM2000 land use type and PESERA-PEAT land use code, and parameters related to each land use type.

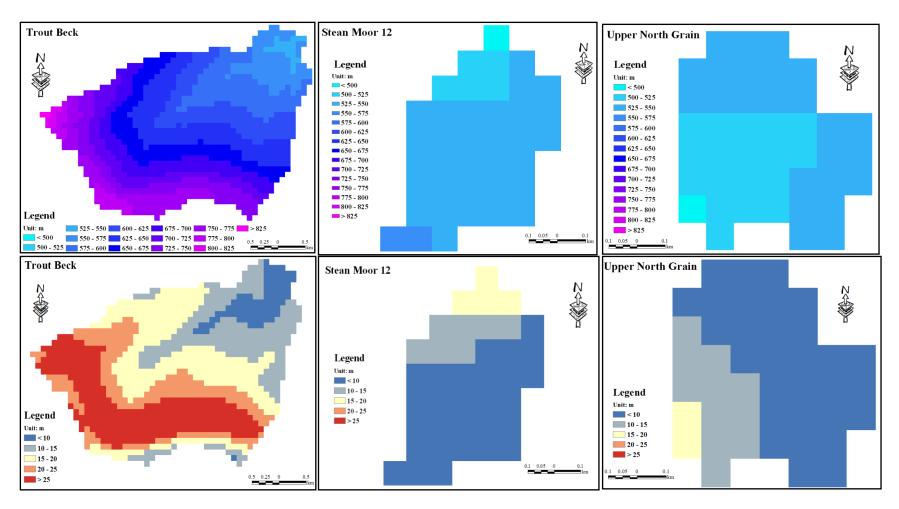
LCM2000 category	LCM2000 type	LCM2000 code	PESERA-PEAT code	cov (%)	rough0 (mm)	rough_red (%)	rootdepth (mm)
	Deciduous	1.1.1	310	100	5	0	1000
1. Broad-leaved woodland	Mixed	1.1.2	310	100	5	0	1000
1. Broad-leaved woodland	open birch	1.1.3	320	100	5	0	600
	Scrub	1.1.4	320	100	5	0	600
	Conifers	2.1.1	310	100	5	0	1000
2. Coniferous woodland	Felled	2.1.2	310	100	5	0	1000
	new plantation	2.1.3	310	100	5	0	1000
4. Arable & horticulture	setaside (bare)	4.3.3	334	0	5	0	200
	setaside (undifferentiated)	4.3.4	334	100	5	0	200
	Intensive	5.1.1	231	100	5	0	300
5. Improved grassland	grass (hay/ silage cut)	5.1.2	231	100	5	0	300
	grazing marsh	5.1.3	231	100	5	0	300
	grass setaside	5.2.1	231	100	5	0	300
	rough grass (unmanaged)	6.1.1	231	100	5	0	300
6. Neutral	grass (neutral / unimproved)	6.1.2	231	100	5	0	300
7. Calcareous	calcareous (managed)	7.1.1	231	100	5	0	300
7. Calcal cous	calcareous (rough)	7.1.2	231	100	5	0	300
	Acid	8.1.1	231	100	5	0	300
0 4 11	acid (rough)	8.1.2	231	100	5	0	300
8. Acid	acid with Juncus	8.1.3	231	100	5	0	300
	acid Nardus/Festuca/Molinia	8.1.4	231	100	5	0	300
9. Bracken	Bracken	9.1.1	320	100	5	0	300
	dense (ericaceous)	10.1.1	320	100	5	0	300
10. Dwarf shrub heath	Gorse	10.1.2	320	100	5	0	300
	open	10.2.1	320	100	5	0	300

Table 5.6 continued

LCM2000 category	LCM2000 type	LCM2000 code	PESERA-PEAT code	cov (%)	rough0 (mm)	rough_red (%)	rootdepth (mm)
12. Bog	bog (shrub)	12.1.1	320	100	5	0	300
	bog (grass/shrub)	12.1.2	320	100	5	0	300
	bog (grass/herb)	12.1.3	231	100	5	0	300
	bog (undifferentiated)	12.1.4	400	100	5	0	300
13. Standing water/canals	water (inland)	13.1.1	400	0	0	0	10
15. Montane habitats	Montane	15.1.1	320	100	5	0	600
16. Inland rock	Despoiled	16.1.1	330	0	5	0	10
	semi-natural	16.1.2	330	0	5	0	10
17. Built up areas, gardens	suburban/rural developed	17.1.1	100	100	0	0	10
	urban residential/commercial	17.2.1	100	100	0	0	10
	urban industrial	17.2.2	100	100	0	0	10
18. Supra-littoral rock	Rock	18.1.1	330	0	5	0	10
19. Supra-littoral sediment	shingle (vegetated)	19.1.1	330	0	5	0	10
	Shingle	19.1.2	330	0	5	0	10
	Dune	19.1.3	330	0	5	0	10
	dune shrubs	19.1.4	330	0	5	0	10
20. Littoral rock	Rock	20.1.1	330	0	5	0	10
	rock with algae	20.1.2	330	0	5	0	10
21. Littoral sediment	Mud	21.1.1	330	0	5	0	10
	Sand	21.1.2	330	0	5	0	10
	sand with algae	21.1.3	330	0	5	0	10
	Saltmarsh	21.2.1	231	100	5	0	300
	saltmarsh (grazed)	21.2.2	231	100	5	0	300



**Figure 5.5** Spatial distribution of land use for the Trout Beck, Stean Moor 12 and Upper North Grain catchments. Colour scales are the same for the three sites.



**Figure 5.6** 100-m DEM (first row) and relief (second row) for Trout beck, Stean Moor 12 and Upper North Grain. Classification and colour scales for each similar variable plotted are the same between the catchments for ease of comparison.

## c) Topography

The topographic input for the PESERA-PEAT is relief, which is defined as the standard deviation of elevation for all points within a certain radius. The radius was set to 500 m in the study. The base DEM was downloaded from Digimap and resampled to 100-m spatial resolution with the bilinear resampling method. The relief for Trout Beck, Stean Moor 12 and Upper North Grain is shown in Figure 5.6.

#### d) Soil data

The input soil properties were the same as values shown in Table 3.5 of Chapter 3 except for the soil erodibility. In PESERA-PEAT, the soil erodibility of blanket peat stands for the erodibility after weathering processes rather than erodibility of fresh peat. It was estimated that weathered peat had erodibility about 2-3 times higher than that of intact peat based on the erodibility index calculated by Mulquee, Rodgers et al.(2006) based on *in situ* peat collected from four sites, which were under different weathering conditions. Therefore, the input erodibility was changed from 1.16 to 2.5 mm for the erodible materials generated by freeze-thaw and desiccation.

### e) Land management condition

The Trout Beck catchment has re-vegetated in recent years with very low grazing intensity (Grayson, Holden et al. 2010). Managed burning and land drainage only occur in very small areas (Holden, Evans et al. 2006; Holden, Chapman et al. 2012). So the Trout Beck catchment was considered as "no land management" during model implementation. In Stean Moor 12, artificial drainage density is close to zero (Grayson and Holden 2012). In terms of the peat status map provided by Natural England (Longden 2009), there is no managed burning and no overgrazing within Stean Moor 12. However, there is active sheep grazing practices. Hence, the management option for this catchment was considered as light grazing during model runs. In Upper North Grain, rough grazing is the dominant management practice (Rothwell, Robinson et al. 2005). In terms of the peat status map provided by Natural England (Longden 2009), there is no managed burning or artificial drainage in Upper North Grain. However, extensive active gullies in this catchment results in a particularly high sediment erosion (Evans, Warburton et al. 2006; Pawson, Evans et al. 2012). It was thus necessary to take into account of the impacts of gullies when modelling the sediment yield from the Upper North Grain. The incision of deep gully systems into the peat surface causes local peatland drainages (Evans and Lindsay 2010), which influence both the soil moisture deficit and vegetation. So overgrazing and drainages caused by the gully system were considered for this catchment during model implementation.

# 5.4 Model implementation and evaluation

# 5.4.1 Model implementation

The PESERA-PEAT model has two modes: equilibrium and time-series. The physical processes incorporated into them are exactly the same and described in section 4.5 of Chapter 4. Different manners of operation are adopted in equilibrium and time-series versions of PESERA-PEAT in order to predict the average and continuous monthly values of long-term erosion respectively. In equilibrium mode, the model iterates sufficient times to determine the equilibrium status of hydrology and erosion. A convergence threshold of 0.01 is defined to determine if the model reaches equilibrium status. Average monthly climate data over the study period are required as input values. Therefore, modelling outputs are average monthly data as well. In time-series mode, the model runs only once through the whole time period. Climatic conditions of every single month are required by the time-series model over the whole study period, while other input parameters are currently the same as those for the equilibrium model. The outputs from the time-series model are continuous monthly data for the whole study time. The time-series model usually needs a period of time (1 year in this study) to warm up, making initial conditions of the model parameters more realistic.

# 5.4.1.1 Equilibrium modelling

Compared to the original PESERA-GRID, there are three more input layers required by PESERA-PEAT to indicate the land management conditions. They are spatial patterns of drainage density, grazing and prescribed burning. As a result, one hundred and thirty one grid layers are required as input data for the equilibrium PESERA-PEAT model at the moment. Please see section 3.4.4.1 of Chapter 3 for more details of the other 128 input layers. All the input data for the chosen sites were obtained based on data sources and methods described in section 5.3.2.2. Land management condition for the three sites was parameterized with the method provided in section 4.4 of Chapter 4. The spatial pattern of management practices

was not considered. If a catchment has more than one management option, total vegetation cover and biomass removal is the sum of vegetation cover and biomass reduced by separate management practices. For the Upper North Grain, it was considered that the drainages caused by the gully system existed across the whole catchment. During model operation, they were parameterized in the same way as the artificial drainage.

# 5.4.1.2 Time-series modelling

The time-series model operated with data from the Stean Moor 12 catchment between 2010 and 2011 at one grid cell. The time-series of monthly climatic inputs between 2010 and 2011 were derived from the data source shown in Table 5.4. Land use code was set to "334", and related parameters were set in terms of Table 5.6. The input topographic relief (8.5 m) was the average value for Stean Moor 12. The soil erodibility was set to 2.5 mm, which was the same as for the equilibrium model. The other soil parameters were the same as those in Table 3.5 of Chapter 3. Management option was set to light grazing, which was parameterized with the method in section 4.4.2 of Chapter 4.

#### 5.4.1.3 Model calibration and validation

PESERA-PEAT was calibrated in equilibrium mode with the downscaled measured data from the Trout Beck catchment between 1997 and 2009. Model calibration was erosion orientated and included two aspects: 1) adjusting the rate at which sediment erosion decreased with vegetation cover (x in Equations 4.12 and 4.16) to achieve a reasonable magnitude of modelled erosion; 2) changing the monthly distribution of base sediment supply derived from Figure 4.7 of Chapter 4 to obtain a good fit of measured and modelled erosion in shape. The above two steps were repeated manually until the calibrated modelling results were of reasonable magnitude and shape compared to the downscaled measured ones. The calibrated base sediment supply is displayed in Figure 5.7, and the calibrated x is 20. It should be noted that, at present, in the PESERA-PEAT x and base sediment supply only work on erosion prediction. This means that changes in x and base sediment supply have no influence on hydrology and vegetation growth, given the modelled erosion does not feedback to these processes. The calibrated equilibrium model was then applied to the other two sites. The calibrated x and base monthly sediment supply were directly used in

the time-series model, which was validated with the time-series of monthly sediment yield from Stean Moor 12 between 2010 and 2011.

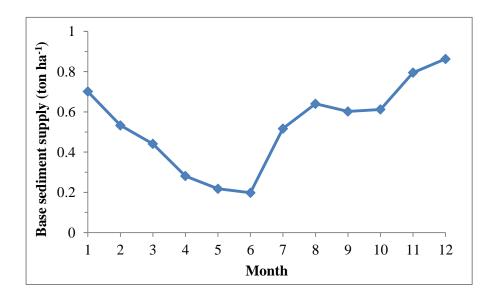


Figure 5.7 The distribution of calibrated base sediment supply for each month

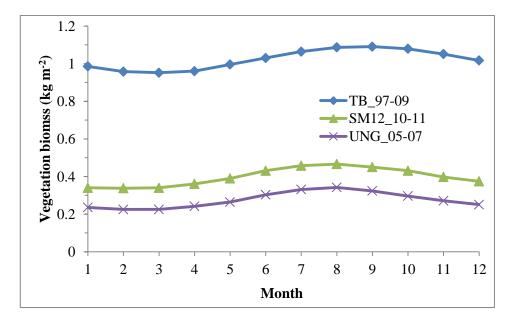
# 5.4.2 Evaluation of equilibrium modelling results

In this section, the calibration and validation results based on the equilibrium model are presented and compared with measured and previously published data to test how reasonable the modelling results are. Since the calibration of PESERA-PEAT only impacts the erosion outputs and has no effects on hydrology and vegetation growth, so only modelled erosion is split into calibration and validation results in the following paragraphs, while all other modelling results are validation results.

### **5.4.2.1 Vegetation biomass**

Figure 5.8 presents the modelled average vegetation biomass for the selected sites during the corresponding periods. Vegetation biomass is lower in winter and higher in summer. Smith and Forrest (1978) reported the vegetation biomass for a *Calluneto-Eriophoretum* blanket bog in Moor House National Nature Reserve (within which Trout Beck sits) under different grazing conditions. Vegetation biomass was demonstrated to be  $0.78 \pm 0.053$  and  $0.43 \pm 0.24$  kg m<sup>-2</sup> in August when grazing density was 0.02 and 0.04 sheep ha<sup>-1</sup> respectively. In terms of Figure 5.8, the modelled vegetation biomass in August is 1.09, 0.47, and 0.34 kg m<sup>-2</sup> in Trout Beck, Stean Moor 12 and Upper North Grain. They are close to Smith and

Forrest's results, demonstrating the reliability of the vegetation growth model. The predicted vegetation biomass in the Trout Beck catchment is much higher than in the Stean Moor 12 and Upper North Grain possibly because the Trout Beck catchment is well vegetated while the other two catchments have relatively more intensive management practices.



**Figure 5.8** Monthly average vegetation biomass for Trout Beck between 1997 and 2009 (TB\_97-09), Stean Moor 12 between 2010 and 2011 (SM12\_10-11) and Upper North Grain between 2005 and 2007 (UNG\_05-07).

### **5.4.2.2** Evapotranspiration

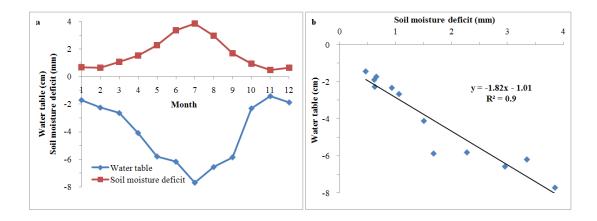
Evapotranspiration rates, which are ratios between actual and potential evapotransporation, for Trout Beck, Stean Moor 12and Upper North Grain during the corresponding periods are 30.8 %, 30.1 % and 29.6 % respectively. Wallace, Roberts et al. (1982) reported the evapotranspiration rates from heather moorland in North Yorkshire, suggesting that evapotranspiration rates could be as low as 25 – 50 % of potential evapotranspiration. This supports the feasibility of the modelled evapotranspiration rates. Mean annual evapotranspiration values for the Trout Beck, Stean Moor 12and Upper North Grain are predicted to be 217, 242 and 259 mm respectively for the chosen periods, with monthly evapotranspiration higher in summer months and lower in winter months (Table 5.7).

**Table 5.7** Monthly distribution of evapotranspiration (% of annual total) and average annual total evapotranspiration (mm) for Trout Beck between 1997 and 2009 (TB\_97-09), Stean Moor12 between 2010 and 2011 (SM12\_10-11) and Upper North Grain between 2005 and 2007 (UNG\_05-07).

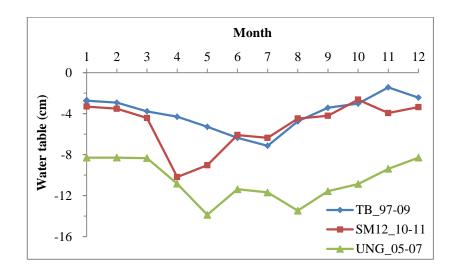
Month	TB_97-09	SM12_10-11	UNG_05-07
1	1.6	2.5	0.9
2	1.9	3.6	4.1
3	6.1	5.0	4.8
4	8.9	8.8	8.4
5	14.4	12.5	11.3
6	15.0	14.9	15.6
7	15.8	16.4	15.6
8	14.3	14.1	13.9
9	10.5	9.7	9.9
10	7.0	6.5	8.0
11	3.2	3.5	3.9
12	1.3	2.3	3.7
Annual total	217	242	259

#### 5.4.2.3 Soil moisture deficit

In PESERA-PEAT, sediment supply is determined by the contemporary temperature and water table. Temperature can be directly obtained from measured data. Water table is calculated from the soil moisture deficit predicted by the model as discussed in section 4.5.2.1 of Chapter 4. It was thus necessary to confirm the accuracy of the soil moisture deficit against the field data on water tables. Figure 5.9 depicts the field water table and predicted soil moisture deficit for the Trout Beck catchment. The shape of modelled soil moisture deficit is quite similar to that of measured water-table depth with R2 of correlation between soil moisture deficit and water table being 0.9, demonstrating that PESERA-PEAT is capable of predicting water table in blanket peatlands. In addition, the relationship shown in Figure 5.9b was adopted to predict water table in other blanket peatlands based on soil moisture deficit predicted by the model mainly due to Stean Moor 12 and Upper North Grain having not measured water table available. The predicted water table for the Trout Beck, Stean Moor 12 and Upper North Grain in the chosen periods is shown in Figure 5.10. The predicted annual average water table for TB\_97-09, SM12\_10-11 and UNG\_05-07 are -3.97, -5.13 and -10.53 cm respectively.



**Figure 5.9** a) The comparison between measured water table and modelled soil moisture deficit and for the Trout Beck catchment between 1997 and 2009; b) The relationship between measured water table and modelled soil moisture deficit for Trout Beck catchment between 1997 and 2009.



**Figure 5.10** The predicted water table for the Trout Beck between 1997 and 2009 (TB\_97-09), Stean Moor 12 between 2010 and 2011 (SM12\_10-11) and Upper North Grain between 2005 and 2007 (UNG\_05-07).

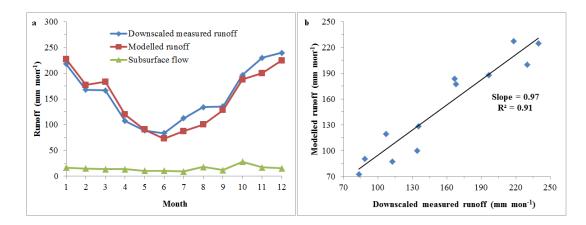
## 5.4.2.4 Runoff production

Both the modelled overland flow and subsurface flow were tested against data available from gauging stations and previous publications. Since the time-series of water discharge was only available for Trout Beck and Stean Moor 12, the monthly distribution of the runoff outputs was tested for these two catchments. Subsurface flow was tested against previously published data from the Trout Beck catchment.

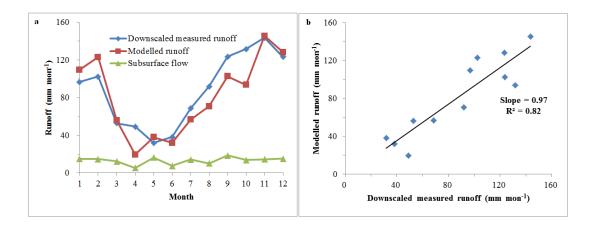
**Table 5.8** The comparison of downscaled measured and modelled runoff ratios, and contribution of subsurface flow to total runoff for the Trout Beck between 1997 and 2009 (TB\_97-09), Stean Moor 12 between 2010 and 2011 (SM12\_10-11) and Upper North Grain between 2005 and 2007 (UNG\_05-07). Dif and Nash-Sutcliffe coefficient were calculated with Equation 5.1 based on downscaled measured and mean modelled runoff; Sub/Total means the percentage of subsurface flow in total runoff.

Site	Annual runoff ratio (%)		I 11T		Sub / Total	
	Downscaled	Modelled	(%)	Sutcliffe	(%)	
TB_97-09	93.3	89.3	-4.3	0.89	9.9	
SM12_10-11	86.6	80.2	-7.4	0.76	16.1	
UNG_05-07	N/A	82.5	N/A	N/A	4.3	

The difference between downscaled and modelled annual runoff ratios of the Trout Beck and Stean Moor 12 are -4.3 % and -7.4 % of the downscaled field measurements. This demonstrates that the model can predict the magnitude of runoff production from blanket peatlands reasonably, given climate data for these catchments are partly / fully represented by point data and the coarse spatial resolution (100 m) employed during model implementation. The contribution of subsurface flow to total annual flow predicted by the model is shown in Table 5.8. Previous studies have demonstrated that subsurface flow contributes about 10 % -14 % of total runoff in the Trout Beck catchment (Holden and Burt 2002b; Holden, Smart et al. 2009). Therefore, modelled subsurface flow is consistent with results from the Trout Beck catchment, although there are no field data of subsurface flow available for the other two sites. In terms of Figure 5.11 and Figure 5.12, the shapes of predicted monthly runoff are close to the downscaled measured monthly data with the R<sup>2</sup> of the fitted line between measured and modelled runoff being 0.91 and 0.82 respectively. This suggests that the model could capture the monthly change of the runoff in blanket peatlands well. Overall the Nash-Sutcliffe coefficient between downscaled measured and modelled runoff for the Trout Beck and Stean Moor 12 are 0.89 and 0.76 respectively (Table 5.8).



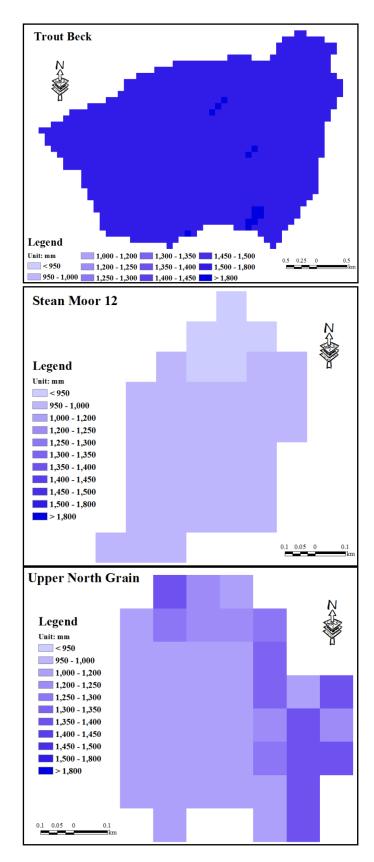
**Figure 5.11** a) The comparison between downscaled measured runoff and modelled runoff and subsurface flow for the Trout Beck catchment between 1997 and 2009; b) The correlation between downscaled measured and modelled runoff for the Trout Beck catchment between 1997 and 2009.



**Figure 5.12** a) The comparison between downscaled measured runoff and modelled runoff and subsurface flow for the Stean Moor 12 catchment between 2010 and 2011; b) The correlation between downscaled measured and modelled runoff for the Stean Moor 12 catchment between 2010 and 2011.

Figure 5.13 displays the spatial pattern of modelled runoff production from the three sites during the corresponding periods. In the Trout Beck catchment, the spatial distribution of runoff production is mainly controlled by vegetation as the climate inputs (both rainfall and temperature) were derived from point data. Runoff production on bare ground (PESERA-PEAT code: 330) is higher than other areas. This is mainly because during model running lower vegetation coverage and biomass on bare areas result in less rainfall lost as evapotranspiration (including interception). In Stean Moor 12 and Upper North Grain, the rainfall input was

derived from point data while temperature inputs were spatially distributed. So, higher runoff is achieved in higher elevation areas of these two catchments mainly because lower temperature leads to less water flow being lost as evapotranspiration. Overall, runoff production with climate and land cover follows current understanding of hydrology in blanket peatlands. The impacts of the land management practices on the spatial pattern of runoff production were not discussed, given that the detailed spatial pattern of the management options within the selected sites were not considered.



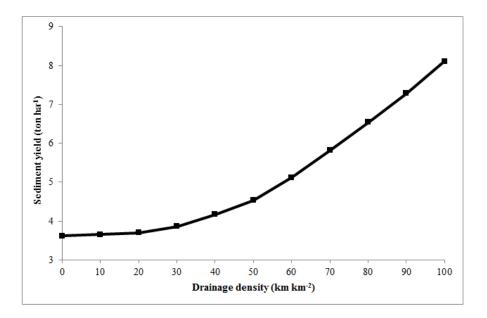
**Figure 5.13** Spatial pattern of average annual runoff production for the three sites during corresponding periods. Classification and colour scale are the same for the three sites.

#### 5.4.2.5 Sediment flux

The downscaled measured and modelled average annual erosion for the three selected sites during the chosen periods are shown in Table 5.9. The differences between downscaled and modelled erosion are 5.2 %, 12.3 % and -14.8 % for the Trout Beck, Stean Moor 12 and Upper North Grain respectively. The very low difference between downscaled field data and modelled results for the Trout Beck catchment is mainly because the model was calibrated with the downscaled sediment data from this catchment. On the other hand, relatively higher differences emerge when the model was validated in Stean Moor 12 and Upper North Grain. Given the rainfall for these two sites is represented by point data, and 100 m is quite a coarse scale for such small catchments, such differences between modelled and downscaled erosion are acceptable. It is therefore considered that the model can produce a reasonable magnitude of erosion for blanket peatlands. In terms of modelling results shown in Figure 5.14, the drainages (60 km km<sup>-2</sup>) caused by gully systems in the Upper North Grain (Pawson, Evans et al. 2012) leads the modelled erosion to be 5.12 ton ha<sup>-1</sup> yr<sup>-1</sup>, which is around 1.4 times the modelled erosion if drainages are completely removed (drainage density = 0). The increased erosion is mainly attributed to the lower water table and more bare ground, which is caused by the drainages (Figure 4.10), resulting in more erodible materials being produced.

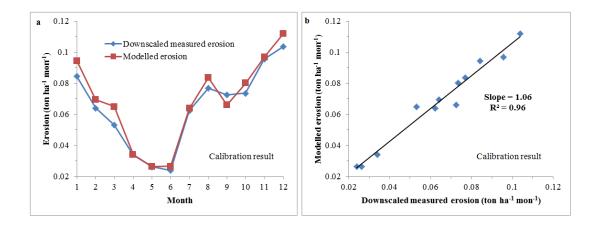
**Table 5.9** The comparison of downscaled measured and modelled erosion for Trout Beck between 1997 and 2009 (TB\_97-09), Stean Moor 12 between 2010 and 2011 (SM12\_10-11) and Upper North Grain between 2005 and 2007 (UNG\_05-07). Dif and Nash-Sutcliffe coefficient were calculated with Equation 5.1 based on downscaled measured and mean modelled erosion.

Sites	Annual erosion (ton ha <sup>-1</sup> )		<b>Dif</b> (%)	Nash-	
	Downscaled	Modelled		Sutcliffe	
TB_97-09	0.77	0.81	5.2	0.94	
SM12_10-11	1.14	1.28	12.3	0.86	
UNG_05-07	6.01	5.12	-14.8	N/A	

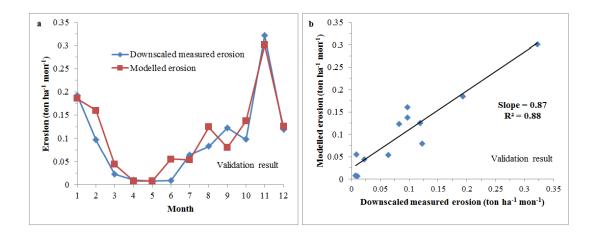


**Figure 5.14** Sensitivity of the PESERA-PEAT model to drainage density based on the environmental conditions of the Upper North Grain between 2005 and 2007.

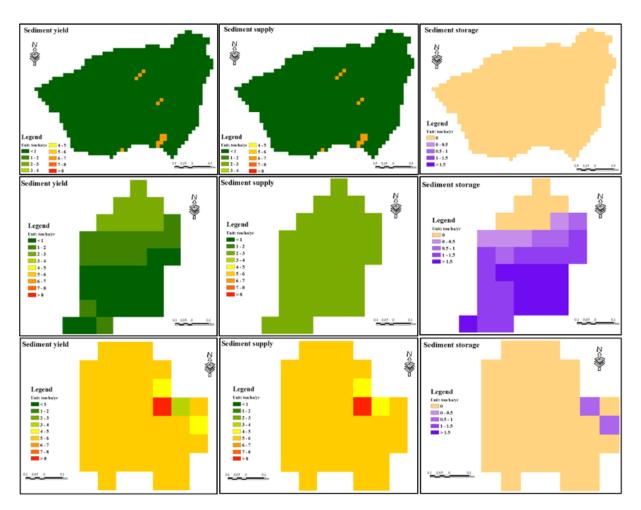
Monthly measured sediment flux was only available for Trout Beck and Stean Moor 12. Therefore, only comparison of downscaled measured and modelled monthly sediment flux for those catchments are evaluated and presented in Figure 5.15 and Figure 5.16. Good fit ( $R^2 = 0.96$  and 0.88) in shape demonstrates that the model is capable of predicting monthly sediment flux change. Relatively higher  $R^2$  for the Trout Beck catchment is because the model was calibrated with the sediment data from this catchment. Overall, the Nash-Sutcliffe coefficients between downscaled and measured monthly sediment flux are high (Table 5.9).



**Figure 5.15** a) Comparison of downscaled measured and modelled erosion for the Trout Beck catchment between 1997 and 2009; b) Correlation between downscaled measured and modelled erosion for the Trout Beck catchment between 1997 and 2009.



**Figure 5.16** a) The comparison of downscaled measured and modelled erosion for the Stean Moor 12 catchment between 2010 and 2011; b) The correlation between downscaled measured and modelled erosion for the Stean Moor 12 catchment between 2010 and 2011.

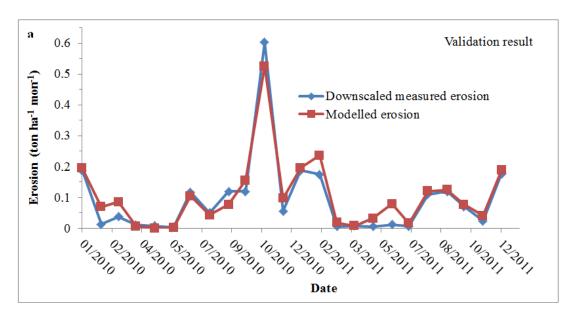


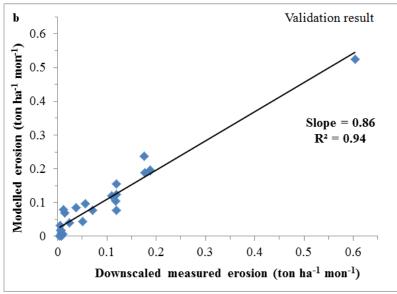
**Figure 5.17** Sediment budget (ton ha<sup>-1</sup> yr<sup>-1</sup>) for Trout Beck between 1997 and 2009 (TB\_97-09), Stean Moor 12 between 2010 and 2011 (SM12\_10-11) and Upper North Grain between 2005 and 2007 (UNG\_05-07). Classification and colour scales for each similar variable plotted are the same between the catchments for ease of comparison.

Figure 5.17 shows the spatially distributed sediment budget of the chosen sites during the study periods predicted by the equilibrium version of PESERA-PEAT. Modelled average annual erosion peaks in bare areas and becomes lower at locations with higher vegetation cover in these catchments as vegetation cover impacts both sediment supply and transport in the model. In terms of Figure 5.17, average annual erosion in the Trout Beck catchment is fully supply-limited based on the average climate inputs between 1997 and 2009. Therefore the final erosion is equal to sediment supply, and transporting capacity is always higher than sediment supply. In Stean Moor 12 and Upper North Grain, average annual erosion tends to be transport limited in drier or gently sloping areas during the chosen study periods. Overall sediment supply driven by freeze-thaw and desiccation seems dominant in controlling the final erosion since both sediment yield and sediment supply are highest in UNG\_05-07, medium in SM12\_10-11 and lowest in TB\_97-09. So the impacts of climate, vegetation cover and topography on final erosion could be reflected by the model. Land management practices have impacts on both vegetation cover and biomass and soil moisture condition (for drainage only) in PESERA-PEAT, so they influence the final sediment yield through working on both the sediment supply and transport. However, since the spatial pattern of the land management practices in the study sites were not considered, their impacts on the spatial pattern of the erosion were not discussed. Besides, the coarse scale (100 m) of land-use data (Figure 5.5) may be of limited accuracy, adding inaccuracy to the spatial pattern of modelling results.

In summary, the applicability of PESERA-PEAT in blanket peatlands was tested with monthly average measurements. The results suggest that PESERA-PEAT could reasonably reproduce runoff and erosion processes in blanket peatlands. PESERA-PEAT theoretically considers the soil loss driven by overland flow on hillslopes such as rill and sheet erosion. However, the field runoff and sediment data adopted for development and evaluation of PESERA-PEAT were originally collected at catchment outlets. This means the sediment budget predicted by PESERA-PEAT is actually a lumped version of erosion caused by both hillslope and channel fluvial processes. This was a compromise during model development mainly because there were no enough data to support the process-based descriptions of more erosion processes such as river bank erosion, pipe erosion and mass movement etc. In

addition, wind erosion, which is a component of blanket peat erosion in some locations (Foulds and Warburton, 2007), is not considered in PESERA-PEAT at present.



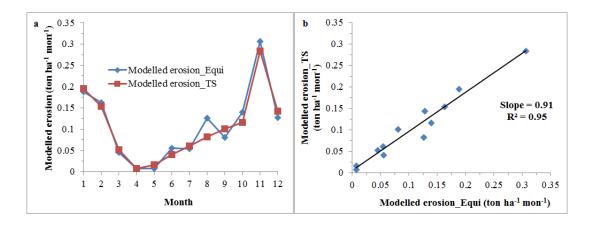


**Figure 5.18** a) The comparison of measured erosion and modelled erosion from time-series modelling for Stean Moor 12 between 2010 and 2011; b) The correlation between measured erosion and modelled erosion from time-series modelling for the Stean Moor 12 between 2010 and 2011.

# 5.4.3 Evaluation of time-series modelling results

As the major components of the PESERA-PEAT have been evaluated in section 5.4.2, only the sediment flux is presented in this section against the time-series of measured sediment flux from the Stean Moor 12 catchment between 2010 and 2011. Figure 5.18 shows the time-series plot of downscaled measured sediment flux, which was calculated with the equation shown Figure 4.4 of Chapter 4, and modelled sediment flux from the Stean Moor 12 between 2010 and 2011. Overall, PESERA-PEAT is able to capture the changes in monthly erosion, with R<sup>2</sup> and a Nash-Sutcliffe coefficient between modelled and downscaled measured erosion being 0.94 and 0.93 respectively. Average annual modelled sediment flux between 2010 and 2011 is 1.25 ton ha<sup>-1</sup>, which is close to mean downscaled average annual measured erosion of 1.14 ton ta<sup>-1</sup>.

# 5.4.4 Comparison of equilibrium and time-series model



**Figure 5.19** Comparison of erosion predicted by the equilibrium and time-series versions of PESERA-PEAT for Stean Moor 12 at one grid cell between 2010 and 2011: a) modelled erosion; b) correlation between equilibrium and time-series predictions.

It is noted that the sediment yield of Stean Moor 12 between 2010 and 2011 predicted by the time-series model (1.25 ton ha<sup>-1</sup> yr<sup>-1</sup>) is close to the one predicted by the equilibrium model (1.28 ton ha<sup>-1</sup> yr<sup>-1</sup>). However, the equilibrium model was operated with spatially distributed topography and land use / cover data, while in time-series modelling they were both represented by point data. In order to examine if these two versions of the model work in the same way, the equilibrium model was also operated at one grid cell with input parameters exactly the same as for the time-

series model. The comparison of equilibrium and time-series modelled erosion at one grid cell is shown in Figure 5.19, in which the shape of monthly average erosion is very similar between equilibrium and time-series erosion prediction ( $R^2 = 0.95$ ) (Figure 5.19b). Average annual erosion modelled by the equilibrium and time-series model is 1.3 and 1.25 ton ha<sup>-1</sup> respectively (Figure 5.19a). This suggests that the equilibrium and time-series model work in the same way. However, differences between these two versions of the model still exist (Figure 5.19a). This is because the time-series model is able to reflect erosion change with climate in more detail, while such detailed information is lost in the equilibrium model as all climate inputs are the average values over the study period.

# **5.5 Summary**

In this chapter, the PESERA-PEAT model was evaluated with field data from several blanket peat-coved sites. Evaluation of modelling results demonstrated that three major modules of the model worked well in blanket peatlands with consideration of the scaling difference between the measured (catchment scale) and modelled (hillslope scale) runoff and sediment flux. Parameterization of management options were considered reliable in relation to the literature (Beharry-Borg, Hubacek et al. 2009; Chapman, Termansen et al. 2009; Defra 2007). Modelling results thus demonstrated that the sediment supply index is a useful tool for indicating sediment supply from blanket peatlands, and quantitatively linking the sediment production with climatic and soil moisture conditions. Modelling results also confirmed the reliability of the drainage model and the values employed for the vegetation removed by grazing, although it was not possible to numerically test the parameterization of managed burning against field data as these were not available.

PESERA-PEAT can now be applied to examine the response of blanket peat erosion to environmental changes at regional, national and global scales. Such applications will be beneficial for planning of land-use strategies in blanket peatlands. The structure of PESERA-PEAT means that climate scenarios based on the outputs of global and regional climate models can be used to drive PESERA-PEAT to investigate the impact of climate change on peat erosion. In addition, the impact of changing management scenarios (e.g. drainage density, burning frequency or

grazing intensity) can be investigated by using PESERA-PEAT and comparisons or interactions between climate change impacts and management impacts on peat erosion could be studied in the future using the model.

Two versions of the model gave similar results under the same environmental conditions. The average monthly values of climate variables during the study period are required by the equilibrium model, while a time-series of monthly climate conditions over the whole time period studied is needed to drive the time-series model. This provides more flexibility in applying PESERA-PEAT as equilibrium and time-series models could serve different research purposes. The equilibrium model is easier to apply to assess average peat erosion over a large space and long time period given its relatively smaller data requirements. The time-series model is able to test the reaction of erosion to more detailed changes of environmental conditions, and therefore could capture extreme conditions during the study periods. However, its application over a large region is restricted by its much bigger data requirement. In the following chapters, these two versions of PESERA-PEAT will be applied to understand the reaction of fluvial blanket peat erosion under possible future environmental change at regional and national scales. The equilibrium model will be employed in Chapter 6 to examine potential blanket peat erosion change spatially in the North Pennines, and then the time-series model will be used in Chapter 7 to examine the potential changes and differences in fluvial blanket peat erosion across Great Britain, selecting 10 blanket peat-covered sites.

# Chapter 6

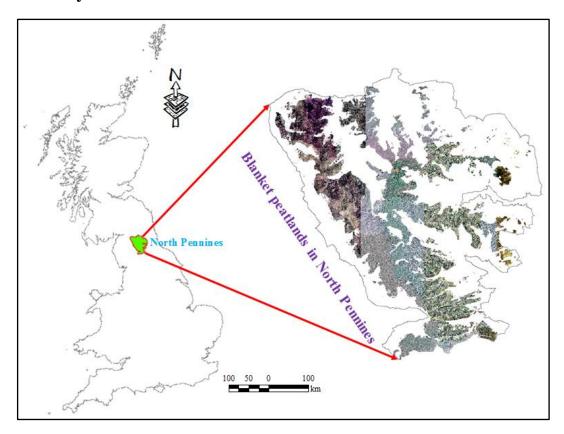
# Prediction of fluvial blanket peat erosion in the North Pennines under environmental change

### 6.1 Introduction

It has been demonstrated in Chapter 5 that PESERA-PEAT is suited to fluvial blanket peat erosion modelling. The major aim of this chapter is to explore water erosion of blanket peatlands in the North Pennines, UK subject to scenarios of climate change and possible land management shifts using the equilibrium version of PESERA-PEAT. Spatially distributed climate and land management scenarios were set up to represent different combinations of possible future environmental change. Modelling results from these scenarios were used to examine the impact of climate change, land management variations and their interactions.

The structure of this chapter is as follows: Section 6.2 is an introduction to the blanket peatlands in the North Pennines. Data sources of climate scenarios, land management, and other input data for the equilibrium version of PESERA-PEAT are presented in section 6.3. Combinations of climate and land management scenarios are selected in section 6.4 based on an analysis of future climate change and adopted land management practices. In section 6.5 the chosen scenarios are used as input for the model to predict changes in fluvial blanket peat erosion while section 6.6 discusses key findings.

# 6.2 Study site



**Figure 6.1** Blanket peatlands in the North Pennines, and their location.

The North Pennines (Figure 6.1) is the northernmost section of the Pennine range of hills which runs north-south through northern England. The North Pennines was designated as an Area of Outstanding Natural Beauty (AONB) in 1988 and currently is the second largest of the 49 AONBs in the UK, covering an area of approximately 2000 km². It lies between the National Parks of the Lake District, the Yorkshire Dales and Northumberland with the urban centres in County Durham away to the east. Twenty seven percent of England's blanket peatlands are distributed over the North Pennines. The classification of blanket peatlands is not the same in different countries (Charman 2002), nor between different institutes in the UK. In this study, the extent of blanket peatlands in the North Pennines was determined by peat depth (provided by Natural England) and the organic content of various types of peat (provided by the Land Information System) (Table 6.1). Accordingly, blanket peatlands had peat with depths of > 40 cm and an organic content of > 45 % in (Table 6.1), covering about 43 % of the whole of the North Pennines (Figure 6.1).

There are no fens in the North Pennines according to the Natural England base maps. Bower (1961) suggested that peat erosion at that time in the English Pennines was common and extensive at higher altitudes where it was common on flat ground as well as on slopes. More recent investigation suggested that around 20 % of blanket peatlands in the North Pennines were in an eroding state (Longden 2009).

**Table 6.1** Peat depth and organic content of various peat types defined by Natural England and Land Information System.

Peat types	Natural England	<b>Land Information System</b>	
Blanket bog	Peat depth > 40 cm	Organic content > 45 %	
Raised bog	Peat depth > 40 cm	Organic content < 45 %	
Rich fens / reedbeds	Peat depth > 40 cm	N/A	
Wet heath	10 cm < Peat depth < 40 cm	Organic content < 45 %	
Dry heath	10 cm < Peat depth < 40 cm	Organic content < 45 %	

# 6.3 Data sources, processing and climate downscaling

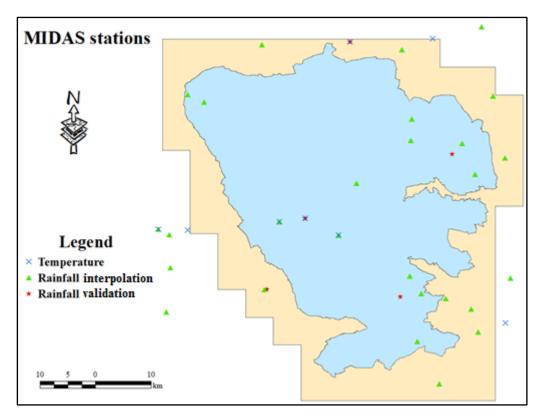
#### **6.3.1** Climate

Four time periods of climate data were chosen to account for climate shifts in the North Pennines in the future. They are "Baseline", "2020s", "2050s" and "2080s", coving 30-year periods of 1961-1990, 2010-2039, 2040-2069 and 2070-2099 respectively. Baseline climate data were derived from Met Office measured data and the other three periods were interpolated from UKCP09 climate projections.

## **6.3.1.1** Baseline climate

The stations chosen to produce the baseline climate of the North Pennines are shown in Figure 6.2. PESERA-PEAT requires six climate inputs which are: monthly total rainfall (meanrf130); mean rainfall per rainfall day (meanrf2); coefficient of variation of rainfall per rainfall day (cvrf2); monthly temperature range (mtrange); monthly temperature (mtmean); and monthly potential evapotranspiration (meanpet30). Rainfall related variables are monthly statistical results of daily meteorological data from 32 MIDAS stations. Twenty seven of them were selected for interpolation to create continuous surfaces for input parameters. The other five points were used for validation of the interpolated results. Monthly temperature and

monthly temperature range were obtained from 8 MIDAS stations within and around the North Pennines area. Since temperature data are only available for eight stations, it may be unreasonable to separate the dataset into training and validation subsets. So all eight stations were used for interpolation and interpolated results were evaluated with four of the stations within / close to the North Pennines.



**Figure 6.2** MIDAS stations for interpolation of baseline climate for the North Pennines

The methods employed for MIDAS baseline climate interpolation are presented in Table 6.2. Stepwise regression based on climatic variables, elevation, and coordinates (easting and northing) was the main method adopted. The resulting equations for January are shown in Table 6.2. The coefficient of variation of rainfall per rain day (cvrf2) was interpolated with the Inverse Distance Weighted (IDW) model rather than a regression model because no good relationship could be found between cvrf2, elevation and coordinates during winter months in both baseline and future periods. Potential evapotranspiration (PET) was derived from a modified temperature-based model shown in Equation 5.3 of Chapter 5. The validation of interpolated results for different variables is shown in Table 6.3.

**Table 6.2** Methods for baseline climate interpolation, taking January as an example.

January	Method	$\mathbb{R}^2$	n
meanrf130 (mm)	meanrf130 = $286 + 0.210 \text{ H} - 0.000576 \text{ E}$	0.70	27
meanrf2 (mm)	meanrf2 = 24.1 + 0.00693  H - 0.000026  E - 0.000019  N	0.75	27
cvrf2 (unitless)	IDW	-	27
mtmean (°C)	mtmean = 3.78 - 0.00635 H	0.88	8
mtrange (°C)	mtrange = $-6.79 - 0.00315 H + 0.000034 E$	0.87	8
meanpet30 (mm)	Equation 5.3 of Chapter 5	-	-

H, E and N represent elevation, easting and northing respectively; n means number of observations, this is the same as in Table 6.3.

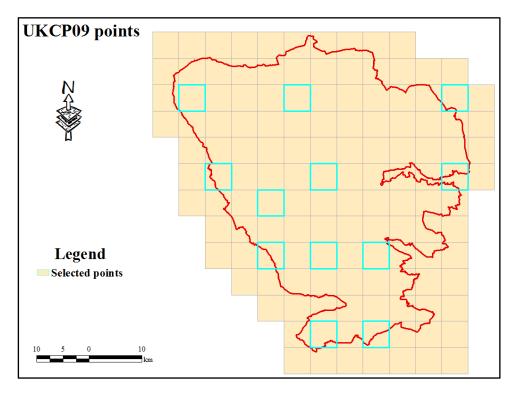
**Table 6.3** Validation of baseline climate variable interpolation

Variables	RMSE	RMSE / average	$\mathbb{R}^2$	n
meanrf130 (mm)	17.59	0.18	0.83	5
meanrf2 (mm)	0.76	0.15	0.78	5
cvrf2 (unitless)	0.13	0.10	0.46	5
mtmean (°C)	0.27	0.05	0.98	4
mtrange (°C)	0.54	0.09	0.92	4
meanpet30 (mm)	8.30	0.15	0.95	1

# **6.3.1.2** Future climate scenarios

Future climate change was derived from the United Kingdom Climate Projection 2009 (UKCP09) which developed probabilistic climate change projections resulting from an innovative modelling approach from the Met Office Hadley Centre's climate model HadCM3 (UKCP09 2009). UKCP09 projections are based on Met office meteorological data between 1961 and 1990. They predict future UK climate based on different carbon emission scenarios from the IPCC Special Report of Emission Scenarios (SRES). Future climate projections consider different emission probabilities as a fundamental factor. In UKCP09 three of the SRES scenarios were involved, which are high emission (A1F1), medium emission (A1B) and low emission (B1) so that climate change can be predicted with consideration of impacts of anthropogenic greenhouse gas emission. The medium emission scenario was selected as the context of climate change in this study.

The UKCP09 weather generator can produce daily climate projections over the 21<sup>st</sup> century with a spatial resolution of 5 km which is suitable for the establishment of climate scenarios for PESERA-PEAT. One hundred model realisations from UKCP09 were extracted randomly to obtain future climatic conditions. PESERA-PEAT-related climate variables could be calculated based on UKCP09 outputs. There are 100 possibilities for each variable. In this chapter, climatic variables take values of central estimates (50 % probability level) from UKCP09 for each month. This is because such scenario establishment is: 1) capable of capturing the likely change of each variable with time at a monthly scale; and 2) suitable for extrapolation across surfaces.



**Figure 6.3** The selected climate projection points for interpolation of future climate for the North Pennines. The squares with light blue outlines indicate the selected points.

In order to build up future climate for the whole of the North Pennines twelve points across the North Pennines were selected to create continuous surfaces with central estimates of variables derived from UKCP09 projections (Figure 6.3). Interpolation methods were the same as those for the MIDAS baseline climate data. However,

future climate projections from UKCP09 are based on the Met Office's historical gridded datasets which are different from the MIDAS climate data in the same period. Thus the UKCP09 climate projections needed to be transferred to be based on the MIDAS data. Furthermore, the resolution of the UKCP09 data is at 5 km which is too coarse to show the spatial distribution of climate and erosion across the North Pennine landscape. Hence the UKCP09 data should be downscaled from 5 km to a finer resolution. A 100-m spatial resolution is considered reasonable. Rainfall-relevant variables and temperature range were downscaled assuming that the ratio of each 100-m square to 5-km square remains stable from baseline to the future. Regression equations resulting from MIDAS baseline data were applied to produce surfaces with resolutions of 100 m and 5 km respectively (except cvrf2 which was interpolated by IDW). The resulting surfaces were then employed to identify the ratios for each square in blanket peatlands of the North Pennines. Temperature was downscaled with the assumption that temperature decreases by 6.5 °C when elevation increases by 1 km.

$$MIDASUKCP_{5000} = MIDASBASELINE_{5000} + (UKCP_{5000} - METBASELINE_{5000})$$
 Equation 6.1

$$\begin{split} \text{MIDASUKCP}_{100} &= \text{MIDASUKCP}_{5000} \left( \frac{\text{MIDASBASELINE}_{100}}{\text{MIDASBASELINE}_{5000}} \right) \\ &= \text{MIDASBASELINE}_{100} \left\{ \text{Resample} \left[ \left( \frac{\text{MIDASUKCP}_{5000}}{\text{MIDASBASELINE}_{5000}} \right) \right], 100, \text{BILINEAR} \right\} \quad \text{Equation } 6.2 \text{ } \\ \end{split}$$

$$MIDASUKCP_{100} =$$

{Resample [(MIDASUKCP
$$_{5000}$$
 + 0.0065 NPDEM $_{5000}$ ), 100, BILINEAR]}- 0.0065 DEM $_{100}$  Equation 6.3

In Equation 6.1 to Equation 6.3, MIDASBASELINE<sub>5000</sub> / MIDASBASELINE<sub>100</sub> is the 5-km / 100-mcontinuous surface of climate variables at the baseline period based on measurements from MIDAS stations; UKCP<sub>5000</sub> is the 5-km continuous surface of future climate variables derived from median estimates of UKCP09 projections; METBASELINE<sub>5000</sub> is the 5-km surface of baseline climate of UKCP09 provided by

the Met Office; MIDASUKCP<sub>5000</sub> / MIDASUKCP<sub>100</sub> is the 5-km / 100-m continuous surface of future climate based on baseline climate derived from MIDAS stations;  $DEM_{100}$  is the digital elevation model with spatial resolution of 100 m for blanket peat-covered areas of the North Pennines.

Equation 6.1 was employed to enable UKCP09 projections to be based on climatic data from MIDAS stations in the baseline period. Equations 6.2 and 6.3 were adopted to downscale the spatial resolution of climatic variables from 5 km to 100 m. The coefficient of variation of rainfall per rain day (cvrf2), rainfall per rain day (meanrf2) and potential evapotranspiration (meanpet30) are not available in the Met Office UKCP09 baseline dataset. It was therefore impossible to transfer these three variables directly with Met Office baseline values based on Equation 6.1, and as a result downscaling could not be done for them. Alternative methods were employed to achieve UKCP09 baseline cvrf2 and meanrf2. For baseline cvrf2, the average value derived from 100 UKCP09 model realisations on the selected 12 points was taken. Then these values were interpolated into a continuous surface with Inverse Distance Weight interpolation (IDW). Baseline meanrf2 was calculated as Met Office gridded monthly rainfall divided by rainy days per month. Rainy days per month was the average of values derived from 100 UKCP09 model realizations, and interpolated into surface based on its relationship with elevation and coordinates (easting and northing). In addition, the 100-m monthly potential evapotranspiration was directly calculated using the downscaled temperature surface (100 m), wind speed and vegetation height with Equation 5.3 of Chapter 5 without undergoing transfer and downscaling processes separately.

In this project, future climate conditions established in the above way are termed as median climate scenarios. In this chapter, median climate scenarios for the 2020s, 2050s and 2080s were utilized to indicate climate changeover the blanket peatlands of the North Pennines.

# 6.3.2 Land use / cover / management, topography and soil

Land use / cover/ management, topography and soil properties are also required by PESERA-PEAT as input data to set up initial conditions. land use / cover parameters were set according to Table 5.6 of Chapter 5. Topographic information (relief) was

calculated from 100-m DEM, The radius adopted for relief calculation was 500 m. The erodibility of weathered blanket peat was set to 2.5 mm (Mulqueen, Rodgers et al. 2006). Please refer to section 3.5.3.2 for values of other soil parameters. Land use, DEM and relief are shown in Figure 6.4. Three land management practices were taken into consideration in this chapter. They are artificial drainage, grazing and managed burning. The distribution of ditches in the North Pennines was supplied by the Peatland Programme. ArcGIS 10 was employed to calculate the drainage density based on the distribution of ditches. The extent of grazing and managed burning was determined based on the maps provided by the Natural England. *Potential* wildfire severity was also predicted to provide supplementary information on assessing the impact of climate change and land management on the blanket peat system.

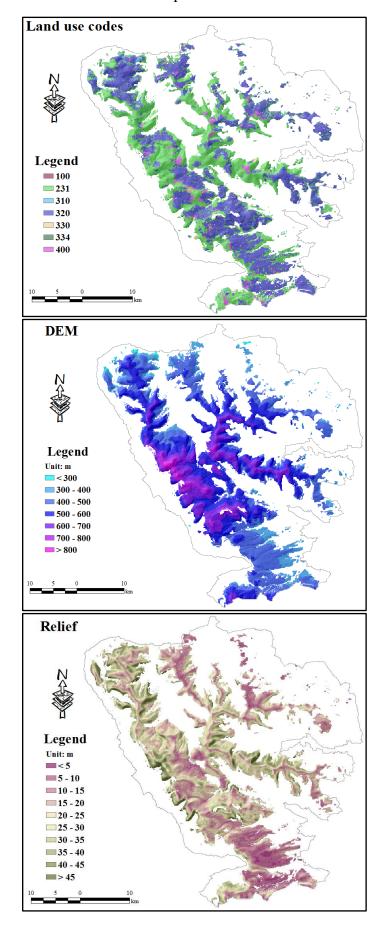
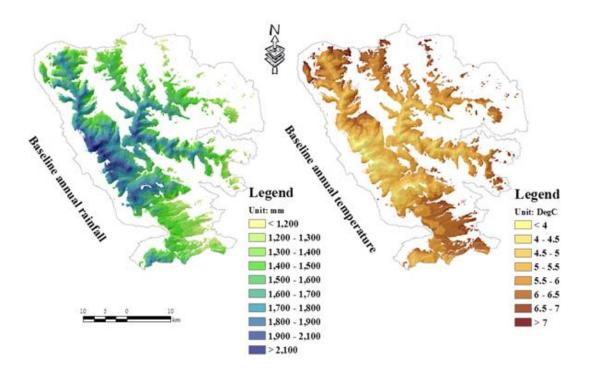


Figure 6.4 Land use, DEM and relief of blanket peatlands in the North Pennines.

### **6.4** Environmental conditions in the North Pennines

# **6.4.1** Climate change

As stated in section 6.3.3.1, the PESERA-PEAT model requires six inputs to define climatic conditions. Rainfall and temperature are important factors impacting sediment production in blanket peatlands as rainfall is closely related to water table (then desiccation) (Evans, Burt et al. 1999; Holden and Burt 2002a) and temperature is an important indicator of freeze-thaw as determined from field data from the Trout Beck catchment in section 4.3 of Chapter 4. Rainfall also drives processes leading to sediment transport. It is therefore vital to know how rainfall and temperature shift temporally and spatially over the blanket peatlands of the North Pennines so that better understanding of blanket peat erosion change can be achieved. Changes in the other four variables are also investigated to provide supplementary information on climate change for blanket peatlands in the North Pennines, and also to support a better understanding of modelling results.



**Figure 6.5** Spatial distribution of annual rainfall and temperature of the North Pennines in the baseline period of 1961-1990

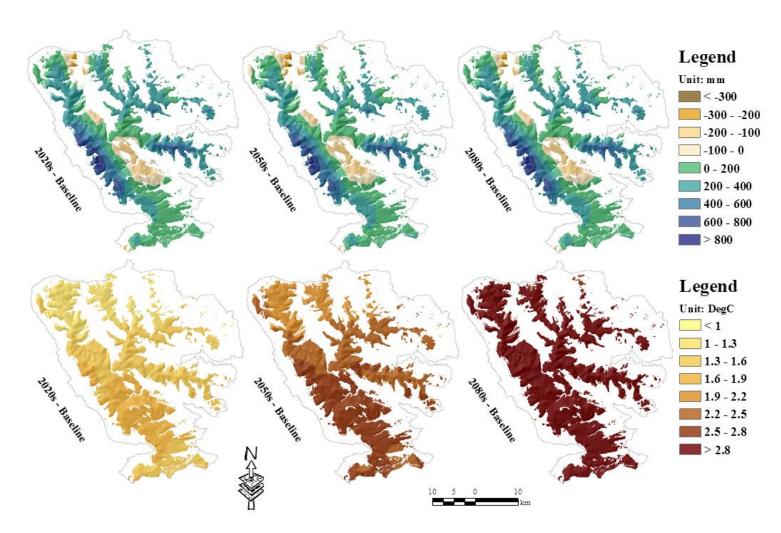
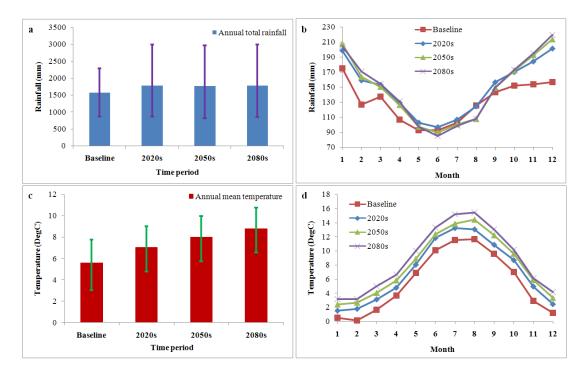
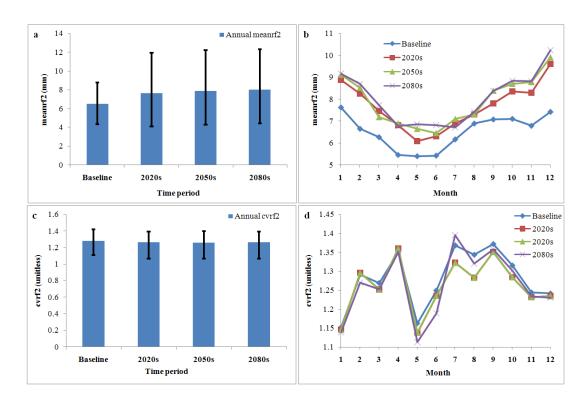


Figure 6.6 Spatial distribution of changes in annual rainfall and temperature between baseline and future time periods



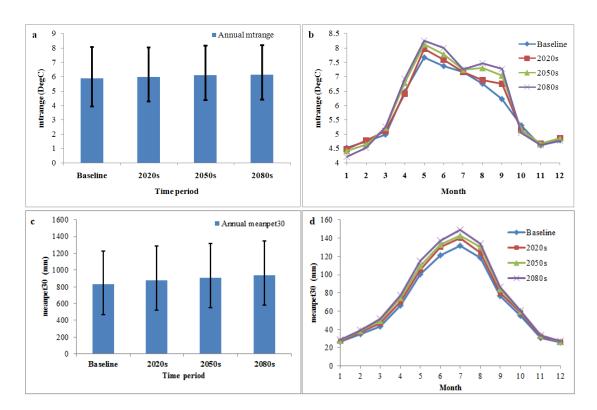
**Figure 6.7** Change of rainfall and temperature in the North Pennines in selected time periods. a) and b) show the annual total rainfall and monthly rainfall, while c) and d) indicate the annual mean temperature and monthly temperature respectively.

Figure 6.5 shows the spatial distribution of mean annual rainfall and temperature across the blanket peatlands of the North Pennines in the baseline period. Rainfall peaks in high-altitude areas and decreases to low areas while the temperature has an opposite trend. In terms of Figure 6.6, which displays change of mean annual rainfall and temperature spatially, the increase of rainfall peaks in the western and southeastern part of the North Pennines where annual rainfall increases by over 400 mm from baseline to future periods. In the central part and some of the northern parts of the North Pennines annual rainfall decreases from baseline to future time periods and sometimes the decrease of mean annual rainfall could be more than 300 mm. Change in temperature overtime shows a relatively simpler pattern. Mean annual temperature increases more quickly in the southern part than in the northern part of the North Pennines. In the 2080s most areas of the North Pennines will witness a warmer climate by about 3 °C. Predicted rainfall and temperature change for the whole North Pennines blanket peatlands is summarised in Figure 6.7. Both mean annual rainfall and temperature are increased between baseline and the future according to median climate scenarios (Figure 6.7a and Figure 6.7c). At the same time mean annual rainfall decreases slightly between the 2020s and 2050s, and then increases again between the 2050s and 2080s. Figure 6.7b and Figure 6.7d show the mean monthly rainfall and temperature of the North Pennines during the selected four time periods. The mean monthly temperature increases with time. Mean monthly rainfall in winter months increases significantly from the baseline to future periods. In the summer months, mean monthly rainfall firstly increases from the baseline to the 2020s and then decreases in the following time periods. Summer rainfall in the 2050s and 2080s is lower than in the baseline period. Based on the analysis of temperature and rainfall, blanket peatlands in the North Pennines will experience warmer, wetter winters and warmer, drier summers in the future in terms of central estimates from UKCP09. This is consistent with the general conclusion UKCP09 has made about the trend of climate change over the whole of the UK.



**Figure 6.8** Change of rainfall per rain day and coefficient of variation of rainfall per rain day in the North Pennines in selected time Periods. a) and b) show rainfall per rain day at annual and monthly scales, while c) and d) indicate the coefficient of variation of rainfall per rain day at annual and monthly scales respectively. "meanrf2" and "cvrf2" represent rainfall per rain day and coefficient of variation of rainfall per rain day respectively.

According to Figure 6.8a and Figure 6.8b, rainfall per rain day (meanrf2) is higher in winter months and lower in summer months in all time periods. This implies that winters of the North Pennines tend to be stormier than summers. Rainfall per rain day (meanrf2) in the baseline period is systematically lower than in other time periods and keeps relatively constant between the 2020s and 2080s. This demonstrates that blanket peatlands of the North Pennines are likely to suffer from bigger storms in the future in terms of the median estimate from UKCP09. Figure 6.8c and Figure 6.8d display the coefficient of variation of rainfall per rain day (cvrf2) at annual and monthly scales. Both the shapes of monthly distribution and annual mean cvrf2 are kept similar with the annual difference between future and baseline cvrf2 smaller than 2 %. Mathematically, cvrf2 is the standard deviation of meanrf2, and thus similar cvrf2 between periods demonstrates that the distribution of rainfall on rainy days does not change very much, although average rainfall intensity on rainy days is obviously increased from baseline to future.



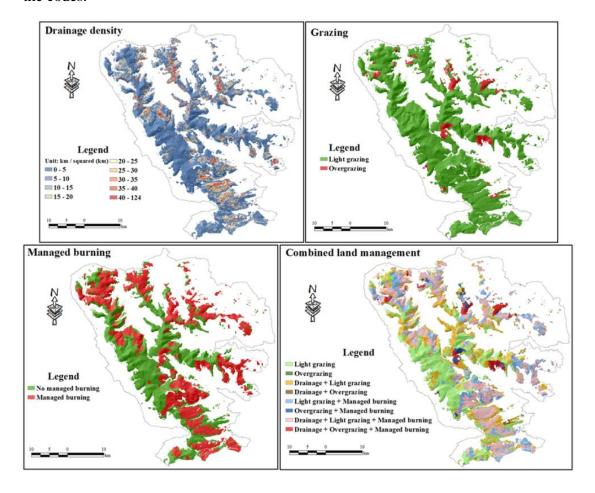
**Figure 6.9** Change of temperature range and potential evapotranspiration in the North Pennines in selected time periods. a) and b) show the temperature range at annual and monthly scales, while c) and d) indicate potential evapotranspiration at annual and monthly scales respectively. "mtrange" and "meanpet30" are employed to represent temperature range and potential evapotranspiration respectively.

In terms of Figure 6.9a, the annual temperature range is slightly increased from the baseline to the 2080s. However, Figure 6.9b shows that change of temperature range in summer months is higher than in winter months, except for July. Annual potential evapotranspiration is predicted to continuously increase from the baseline to the 2080s (Figure 6.9c) with summer months having more of a contribution on such increases than winter months (Figure 6.9d). Given the decreased summer rainfall and increased potential summer evapotranspiration in the blanket peatlands of the North Pennines in the future, peatlands are likely to be suffering from more serious desiccation. This may drive up soil erosion risk in blanket peatlands of the North Pennines. However, winter will become wetter and warmer in the future according to median climate scenarios based on UKCP09. It is thus logically reasonable to expect that sediment production caused by freeze-thaw will become weaker and peat erosion risk in winter is likely to be lower in the future. However, soil loss from hillslopes is not only dependent upon sediment production but also closely related to the transporting capacity of runoff (Julien and Simons 1985; Roering, Kirchner et al. 1999; Aksoy and Kavvas 2005), which is also responsive to climate change. The interaction between sediment supply and transporting capacity of runoff increases the complexity of the relationship between soil loss from blanket peatlands and climate drivers. It is therefore crucial to investigate the blanket peat erosion driven by both sediment production and transport under climate change in order to achieve more physically realistic predictions. The PESERA-PEAT model is suitable for such investigations.

### **6.4.2** Land management practices

Figure 6.10 shows the situation of drainage, grazing, managed burning, and their combination in blanket peatlands of the North Pennines. The drainage density in the North Pennines is between 0 and 124 km km<sup>-2</sup>. In maps of grazing and managed burning in Figure 6.10, overgrazing and managed burning are restricted to the red areas, and the dark green areas are designated as blanket peatlands in the North Pennines under light grazing or without managed burning. A combination of drainage, grazing and managed burning is displayed in the map of combined land management of Figure 6.10, showing that there are often overlaps between different management options. In overlap areas each land management practice is thought to work on vegetation cover and biomass separately, and total vegetation cover and

biomass removal is the sum of vegetation cover and biomass reduced by separate management practices. In this chapter each land management practice is represented by a code: "1" is drainage, "2" is light grazing, "3" is overgrazing and "4" is managed burning. So each management combination could be simply expressed by the codes.



**Figure 6.10** Spatial distribution of drainage, grazing, managed burning and their combination in blanket peatlands of the North Pennines under BAU condition.

Given that the aim of this chapter is to investigate the response of fluvial blanket peat erosion in the North Pennines to possible changes in climate and land management, it is necessary to build up environmental scenarios based on climate and management. As shown above, climate scenarios were mainly derived from MIDAS and UKCP09 data. With regard to management scenarios, the current land management situation was employed as the base condition for establishment of these scenarios. The baseline land management condition is termed the Business-As-Usual (BAU) land management scenario. Other land management scenarios were built up

based on BAU condition mainly through altering the intensity of management. Land management practices were parameterised with the method stated in section 4.4 of chapter 4. Specific values of parameters for BAU and other management scenarios are described in section 6.4.3 and shown in Table 6.4.

### **6.4.3** Environmental scenarios

Twelve environmental scenarios were set up to examine the impacts of changes in climate and land management practices on blanket peat erosion in the North Pennines. Interactions between climate change and land management variation were also investigated. Details of these combinations are displayed in Table 6.4. The "Base Condition" scenario was built on the baseline climate and BAU land management conditions. Modelling results from all other scenarios were compared with outputs based on the "Base Condition" scenario to test the response of blanket peatlands to corresponding shifts in climate and land management. The impact of climate change was investigated with a BAU land management scenario and climate conditions at the baseline, 2020s, 2050s and 2080s. Previous studies have already pointed out two major end-member directions of change in land management practices in British uplands. They are 1) "what if British hill farmers managed the land for wildlife and carbon?" and 2) "what would improving UK food security mean for our hills?"(Reed, Arblaster et al. 2009; Reed, Bonn et al. 2009; Reed, Hubacek et al. 2013). These are represented as "Carbon" and "Food" in Table 6.4. Reed, Hubacek et al. (2013) examined the possible influence of such land management change on ecosystem services in British uplands. To the author's knowledge no research has been done to investigate the response of blanket peat erosion to these likely variations in land management. Two more land management scenarios were therefore established in this chapter to quantify these two scenarios. The first one was represented by completely removing current land management practices and the second scenario was quantified by burning frequency and drainage density in the areas where there is currently burning and drainage. The intensity of overgrazing is unlikely to increase any more given its high impact on vegetation cover and biomass, and so areas that are currently grazed were moved to 'overgrazed' in this food security scenario rather than increasing the % vegetation cover and biomass removed by overgrazing. Both the removal of land management and the doubling of management intensity scenarios were applied with climate

conditions at baseline and future climate conditions to look at the impact of land management and interactions between land management practices and climate change.

Table 6.4 Combinations of scenarios employed and their function in assessing the impacts of climate change, land management variation

Category	Name	Climate	Land manag	ement		Back up
			Drainage	Grazing	Managed burning	
Base	Base Condition	Baseline	Current (X)	15 %, 30 % (Y1, Y2)	10 (Z)	Baseline climate and current land management practices (Business-As-Usual land management scenario)
Climate change	2020s_BAU	2020s	-	-	-	
	2050s_BAU	2050s	-	-	-	Investigating the impacts of climate changes, which are based on UKCP09.
	2080s_BAU	2080s	-	-	-	
Land	Baseline_Carbon	Baseline	0	0	0	
Management	Baseline_Food	Baseline	2X	2Y1, Y2	0.5Z	Investigating the impacts of land management practices.
	2020s_Carbon	2020s	0	0	0	1
	2020s_Food	2020s	2X	2Y1, Y2	0.5Z	
Interactions	2050s_Carbon	2050s	0	0	0	Investigating the interactions between climate
	2050s_Food	2050s	2X	2Y1, Y2	0.5Z	shifts and changes in land management.
	2080s_Carbon	2080s	0	0	0	
	2080s_Food	2080s	2X	2Y1, Y2	0.5Z	

X, Y1, Y2, and Z represent drainage density, vegetation cover and biomass removal by light grazing and overgrazing, and rotational years of managed burning respectively; 2X, 2Y1, 2Y2, 0.5Z indicate the intensity of related land management is doubled or halved."0" indicates the management practice is totally removed."-" indicates the land management intensity does not change.

# 6.5 Reaction of blanket peatlands to environmental change in the North Pennines

# 6.5.1 Runoff production

**Table 6.5** Seasonal distribution (% of annual total) and mean annual runoff production (mm) in the North Pennines under different scenarios.

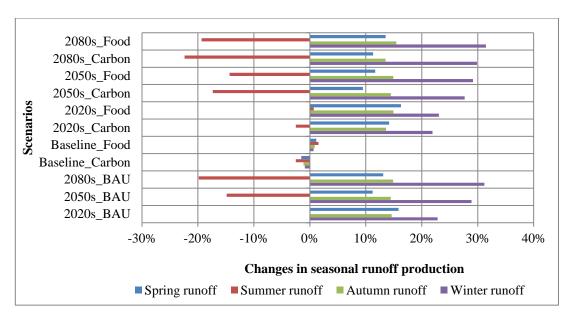
Categories	Base	2020s	2050s	2080s	Baseline	Baseline
	Condition	_BAU	_BAU	_BAU	_Carbon	_Food
Spring	20.95	21.05	20.45	20.71	20.91	20.99
Summer	15.72	13.65	11.75	11.01	15.54	15.82
Autumn	30.38	30.20	30.52	30.51	30.45	30.35
Winter	32.95	35.10	37.27	37.77	33.10	32.85
Annual total	1316.6	1518.1	1499.9	1506.4	1298.7	1329.3
Categories	2020s	2020s	2050s	2050s	2080s	2080s
	_Carbon	_Food	_Carbon	_Food	_Carbon	_Food
Spring	20.99	21.06	20.34	20.46	20.67	20.71
Summer	13.45	13.69	11.52	11.78	10.82	11.04
Autumn	30.30	30.19	30.84	30.54	30.58	30.54
Winter	35.25	35.06	37.29	37.22	37.93	37.71
Annual total	1500.0	1522.8	1484.6	1505.2	1485.2	1512.2

Table 6.5 shows the seasonal and annual total runoff production from the blanket peatlands of the North Pennines. Runoff production is generally highest in winters and lowest in summers. Runoff production in spring and autumn are in the middle with autumn flow being higher than spring flow. The distribution of annual runoff production from blanket peatlands of the North Pennines under different environmental scenarios is shown in Figure 6.13. High runoff production is mainly restricted to areas with high elevation and low runoff production primarily occurs in the central and southern parts of the North Pennines.

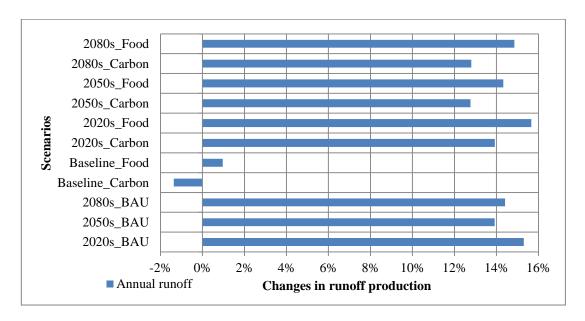
**Table 6.6** Percentage (%) of blanket peat-covered areas in the North Pennines with different classes of runoff production under various environmental scenarios.

Category	Base	2020s	2050s	2080s	Baseline	Baseline
	Condition	_BAU	_BAU	_BAU	_Carbon	_Food
<1000	5.68	3.26	3.65	3.61	7.17	5.31
1000-1300	42.96	24.85	25.11	25.39	44.62	42.56
1300-1600	42.40	36.52	38.71	37.14	40.18	42.94
1600-1900	8.60	22.50	20.61	21.59	7.74	8.82
>1900	0.36	12.87	11.91	12.27	0.30	0.37
Category	2020s	2020s	2050s	2050s	2080s	2080s
	_Carbon	_Food	_Carbon	_Food	_Carbon	_Food
<1000	4.02	3.09	4.10	3.42	4.44	3.38
1000-1300	26.50	24.37	26.84	24.56	27.50	24.70
1300-1600	35.89	36.71	38.14	38.98	36.34	37.55
1600-1900	21.32	22.80	19.37	20.97	20.00	21.95
>1900	12.27	13.02	11.56	12.06	11.71	12.41

In terms of Table 6.6, change of areas of different flow condition with environmental change could be detected. If only climate change is considered, low runoff areas are apparently decreased from the baseline to future periods and high flow areas are significantly increased during the same time periods. For each period of climate condition, low flow areas increase and high flow areas decrease from BAU to the carbon storage management scenario and low flow areas decrease and high flow areas increase from BAU to food security management scenario. Under interaction scenarios, changes in the area distribution of runoff are close to that under climate change scenarios. This is also supported by Figure 6.13, where the spatial pattern of runoff distribution is similar for each time period even if the land management practices are different. The biggest difference emerges between maps of baseline and future time periods under all management scenarios (BAU, carbon storage and food security). This is to say, climate change is likely to be more important than land management practices in influencing the spatial distribution of runoff in the North Pennines given the established environmental scenarios in this chapter.

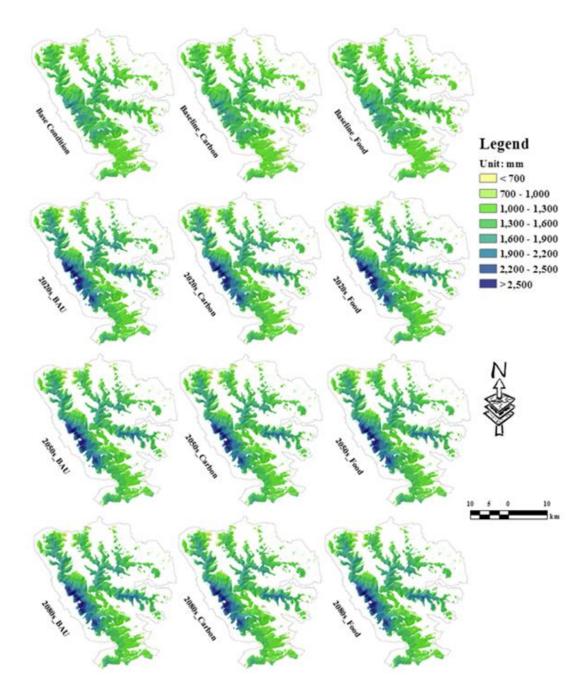


**Figure 6.11** Response of seasonal runoff production to change of climate and land management practices. All changes are calculated as difference of runoff production between specific scenarios and "Base Condition" divided by runoff under the "Base Condition" scenario.

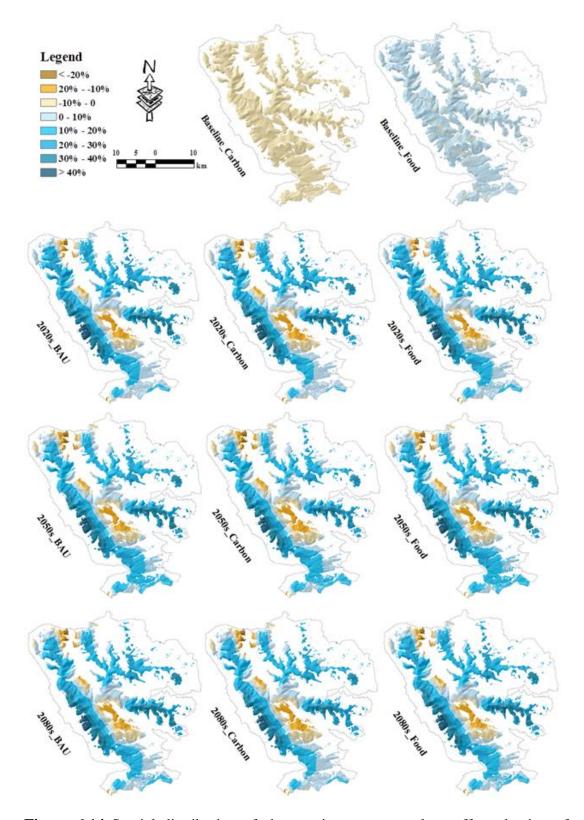


**Figure 6.12** Response of mean annual runoff production to change of climate and land management practices. All changes are calculated as difference of runoff production between specific scenarios and "Base Condition" divided by runoff under the "Base Condition" scenario.

Figure 6.11 and Figure 6.12 present the impact of environmental change on the seasonal and annual average runoff production from blanket bog of the North Pennines. In terms of Figure 6.11, as climate changes in the future, summer runoff decreases while runoff in other seasons increases, with most runoff increase occurring in winter. As a result, annual runoff is increased if climate change occurs in the future (Figure 6.12). With regard to the impact of land management, runoff production declines under carbon storage management and rises under food security management scenarios at both seasonal and annual scales. This is strongly supported by maps of "Baseline Carbon" and "Baseline Food" scenarios in Figure 6.14. Most areas produce less runoff under the "Baseline Carbon" scenario and more runoff under the "Baseline Food" scenario than under the "Base Condition" scenario. The impact of climate change on runoff production under carbon storage and food security management practices does not show much difference to that under the BAU condition. Consequently, climate change is more important than land management practices in influencing the amount of runoff production. This is also demonstrated by Figure 6.14 in which the pattern of maps shows a greater difference with climate change than with land management shifts.



**Figure 6.13** Spatial distribution of mean annual runoff production in the blanket peatlands of the North Pennines under different environmental scenarios



**Figure 6.14** Spatial distribution of changes in mean annual runoff production of blanket peatlands of the North Pennines under different environmental scenarios. The spatial distribution of land management is shown in Figure 6.10.

### 6.5.2 Erosion

**Table 6.7** Seasonal distribution (% of annual total) and mean annual sediment yield (ton ha<sup>-1</sup>) for the whole blanket peatlands of the North Pennines under different scenarios.

Category	Base	2020s	2050s	2080s	Baseline	Baseline
	Condition	_BAU	_BAU	_BAU	_Carbon	_Food
Spring	14.36	15.23	15.43	15.57	14.36	14.35
Summer	20.06	20.49	21.55	22.04	22.22	19.69
Autumn	30.22	30.71	32.57	33.64	29.88	30.38
Winter	35.36	33.57	30.44	28.75	33.53	35.57
Annual total	2.23	2.25	2.27	2.29	0.95	3.26
Category	2020s	2020s	2050s	2050s	2080s	2080s
	_Carbon	_Food	_Carbon	_Food	_Carbon	_Food
Spring	15.24	15.18	15.24	15.34	15.32	15.48
Summer	22.61	20.21	23.63	21.11	24.10	21.60
Autumn	30.27	30.55	32.55	32.63	33.57	33.67
Winter	31.88	34.05	28.58	30.92	27.01	29.26
Annual total	0.96	3.22	1.00	3.30	1.01	3.32

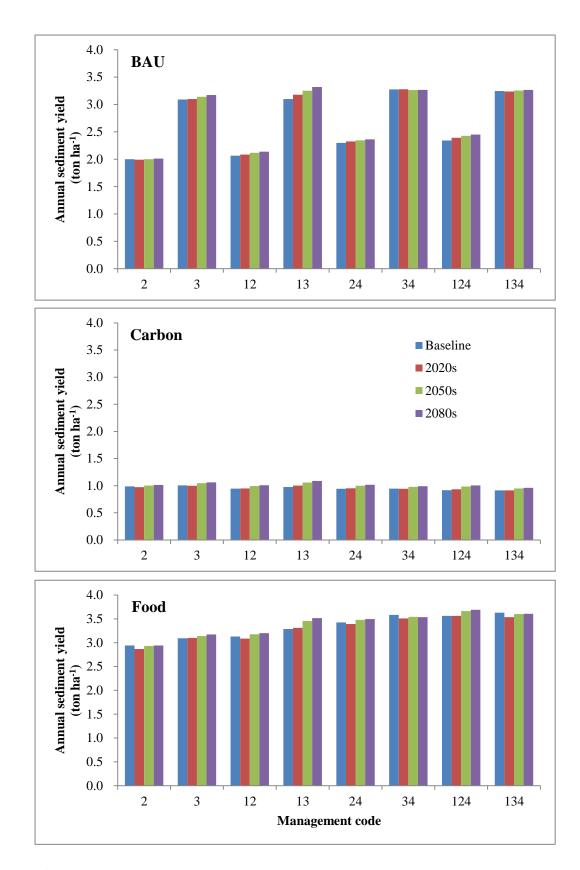
Seasonal and annual average soil loss from blanket peatlands over the North Pennines under established environmental scenarios are shown in Table 6.7. Under the "Base Condition" scenario, average sediment yield of the North Pennines blanket peatlands is highest in winter and lowest in spring with summer erosion and autumn erosion in the middle between spring and winter soil loss. As the climate progresses, the proportion of winter erosion declines while spring, summer and autumn, sediment yield contributes proportionally more to annual soil loss in future periods than in the baseline period. Autumn sediment becomes the biggest part of the annual soil loss in the 2050s and 2080s. Land management also alters the seasonal distribution of annual sediment yield. The proportion of spring and autumn erosion remains stable while the contribution of summer erosion declines and winter erosion rises with intensity of land management practices.

**Table 6.8** Percentage (%) of blanket peat-covered area in the North Pennines undergoing a different level of erosion under defined environmental scenarios.

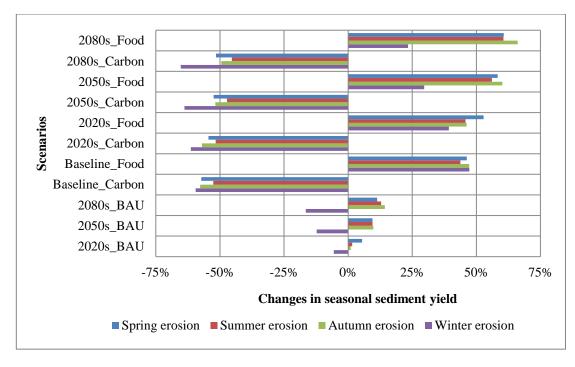
Category	Base Condition	2020s BAU	2050s BAU	2080s BAU	Baseline Carbon	Baseline Food
<1.5	6.86	5.44	5.19	5.16	98.95	4.83
1.5-2	21.20	27.16	18.62	18.44	0.02	1.13
2-2.5	48.88	50.80	50.74	48.06	0.04	2.03
2.5-3	16.36	10.03	18.62	21.45	0.01	18.36
>3	6.70	6.56	6.83	6.89	0.98	73.64
Category	2020s	2020s	2050s	2050s	2080s	2080s
	_Carbon	_Food	_Carbon	_Food	_Carbon	_Food
<1.5	98.95	4.60	98.95	4.57	98.94	4.57
1.5-2	0.01	0.43	0.01	0.31	0.03	0.29
2-2.5	0.05	1.01	0.04	0.83	0.04	0.78
2.5-3	0.01	26.60	0.01	18.77	0.02	18.94
>3	0.98	67.35	0.98	75.52	0.98	75.42

As shown in Table 6.8, under the "Base Condition" scenario, about half of blanket peatlands in the North Pennines produce an annual sediment yield of 2-2.5 ton ha<sup>-1</sup> and areas suffering from a higher and lower level of soil loss become smaller. The distribution of blanket peatlands with different amounts of erosion does not show much difference with climate change. In contrast, land management shifts appear to impact the spatial pattern of erosion to a greater degree. In BAU scenarios, the distribution of blanket peatlands in different erosion levels tends to be normally distributed. Carbon storage and food security scenarios add large skewness to the distribution. As a result, the majority of blanket peatlands tend to have low erosion in carbon storage scenarios while food security scenarios could result in much more areas suffering from more severe erosion. The above pattern is also demonstrated by maps in Figure 6.18, which outlines the spatial pattern of annual sediment yield from blanket peatlands of the North Pennines under possible environmental change as defined in section 6.4.3.

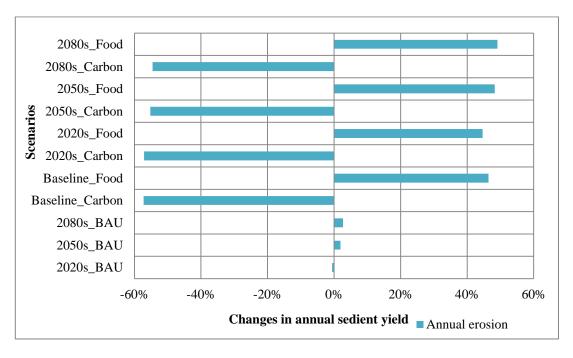
As shown in Figure 6.10, land management practices are spatially distributed and not uniform in blanket peatlands of the North Pennines. This results in the change of land management intensity and then its impacts on erosion being spatially variable given the method for scenario establishment shown in Table 6.4. Eight land management combinations have been identified in Figure 6.10. The pattern of changes in the land management intensity between different management scenarios is the same in areas covered by a management combination, so the spatial pattern of land management change and its impact on erosion could be explored based on these eight land management combinations. Figure 6.15 shows the annual sediment yield for each management combination under defined environmental changes. Under BAU condition annual erosion shows an apparent difference with management pattern, with the annual erosion being much higher in areas with overgrazing than in regions without overgrazing. In contrast, the change of annual erosion with management under carbon storage and food security scenarios is considerably small. Under carbon storage scenarios annual erosion is systematically lower than under BAU and food security scenarios. Given there are no active management practices under carbon storage scenarios, the difference of annual erosion among regions defined by management pattern under BAU condition are mainly driven by climatic variance. Under food security scenarios annual erosion is highest among the three management scenarios, and variation in annual erosion between different areas defined by management codes of the BAU condition is also smaller than that under BAU scenarios. This is because there is no light grazing under food security scenarios; all light grazing-covered areas are changed to be overgrazed, and a double intensity of managed burning and drainage lead to the impact of management being much higher than in the BAU condition, but the variance of management intensity among areas becomes smaller. The results confirm that the spatial pattern of erosion is closely related to the distribution of land management practices rather than climate conditions in blanket peatlands of the North Pennines.



**Figure 6.15** Mean annual sediment yield for regions defined by management code under established environmental scenarios. "1" is drainage; "2" is light grazing; "3" is overgrazing and "4" is managed burning.

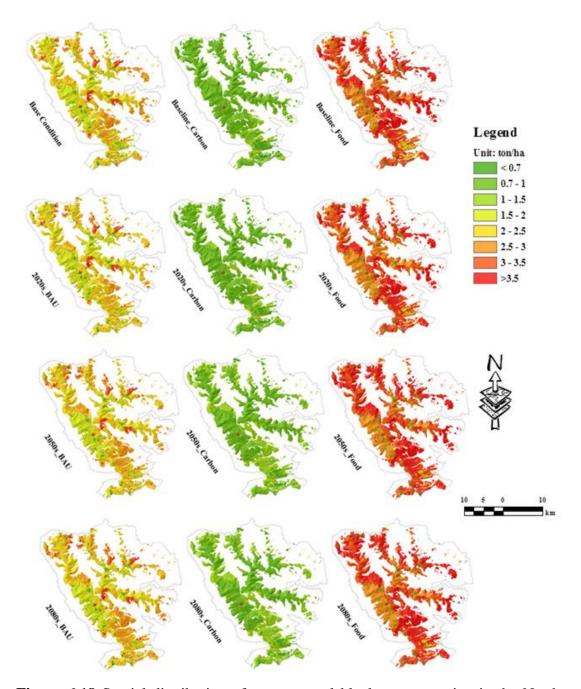


**Figure 6.16** Response of seasonal sediment yield to change of climate and land management practices. All changes are calculated as the difference of sediment yield between the specific scenarios and "Base Condition" divided by sediment yield under the "Base Condition" scenario.

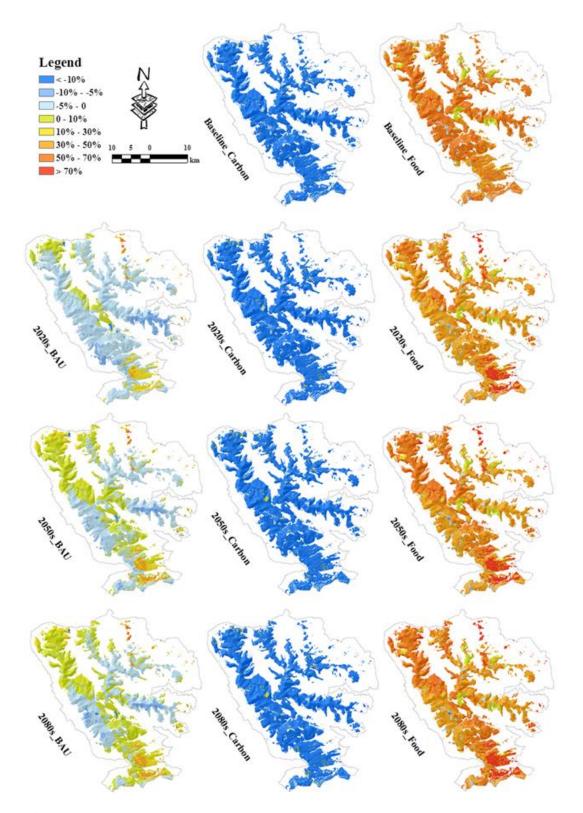


**Figure 6.17** Response of mean annual sediment yield to change of climate and land management practices. All changes are calculated as the difference of sediment yield between the specific scenarios and "Base Condition" divided by sediment yield under the "Base Condition" scenario.

Figure 6.16 and Figure 6.17 present the impact of various environmental changes on seasonal and annual sediment yield for the North Pennines blanket peatlands as a whole. As climate changes in the future, sediment yield decreases in winter while it increases in other seasons (Figure 6.16). As a result, annual sediment yield slightly increase from the baseline to future time periods (Figure 6.17). Under BAU scenarios, more and more blanket peatlands in the North Pennines appear to be under more severe erosion conditions with climate change from baseline to future (Figure 6.19). The biggest increase of annual sediment yield occurs in the southern part and northeastern part of the North Pennines. However, negative change of blanket peat erosion often occurs in high elevation regions. The areas with negative change retreat to higher areas from the 2020s to 2080s. With regard to land management change, sediment yield declines under carbon storage management scenarios and rises under food security management scenarios at both seasonal and annual scales compared to BAU management scenarios. Figure 6.19 also shows that in the majority of the North Pennines the change of annual sediment yield from the "Base Condition" scenario tends to be negative when land is managed for carbon storage and positive when lands is managed for food security although climate change is also a factor. Land management change may play a more important role in controlling the magnitude of blanket peat erosion rather than climate change in the future given the environmental scenarios defined in this chapter.



**Figure 6.18** Spatial distribution of mean annual blanket peat erosion in the North Pennines under different environmental scenarios



**Figure 6.19** The spatial distribution of changes in mean annual blanket peat erosion in the North Pennines under different environmental scenarios. The spatial distribution of land management is shown in Figure 6.10.

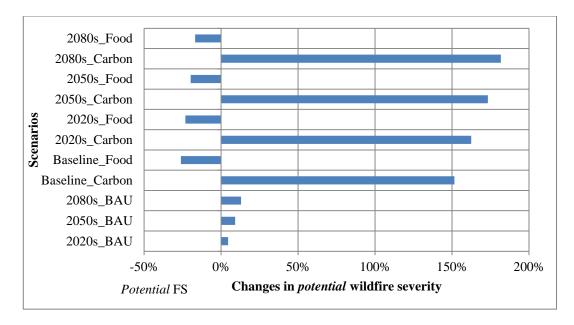
# 6.5.3 *Potential* wildfire severity

**Table 6.9** Mean *potential* wildfire severity for blanket peatlands in the North Pennines under different environmental scenarios. PFS represents unitless *potential* wildfire severity.

Category	Base	2020s	2050s	2080s	Baseline	Baseline
	Condition	_BAU	_BAU	_BAU	_Carbon	_Food
PFS	0.42	0.44	0.45	0.47	1.05	0.31
Category	2020s	2020s	2050s	2050s	2080s	2080s
	_Carbon	_Food	_Carbon	_Food	_Carbon	_Food
PFS	1.09	0.32	1.14	0.33	1.17	0.35

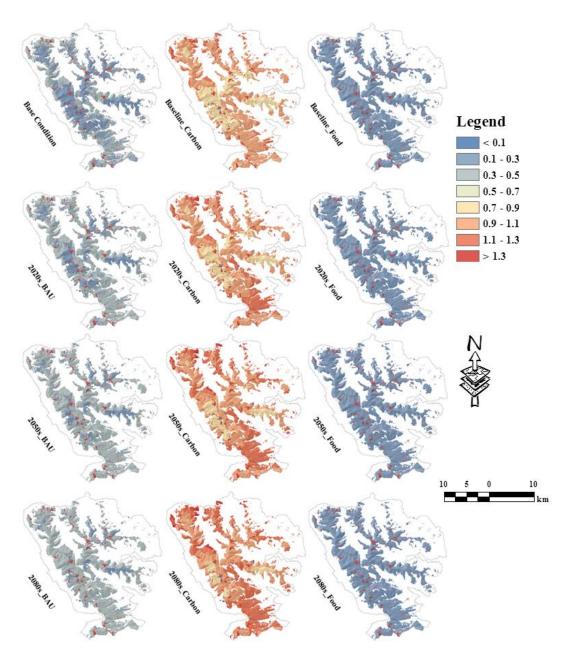
**Table 6.10** Percentage (%) of blanket peat-covered areas in the North Pennines with different levels of mean *potential* wildfire severity under established environmental scenarios; zero in the table indicates percentage of area is less than 0.005 %.

Category	Base	2020s	2050s	2080s	Baseline	Baseline
	Condition	_BAU	_BAU	_BAU	_Carbon	_Food
<0.3	47.84	26.70	17.40	11.49	0.98	95.44
0.3-0.5	47.60	68.74	78.03	83.93	0	0
>0.5	4.56	4.56	4.56	4.58	99.02	4.56
Category	2020s	2020s	2050s	2050s	2080s	2080s
	_Carbon	_Food	_Carbon	_Food	_Carbon	_Food
<0.3	0.98	95.44	0.98	95.44	0.98	95.44
0.3-0.5	0	0	0	0	0	0
>0.5	99.02	4.56	99.02	4.56	99.02	4.56

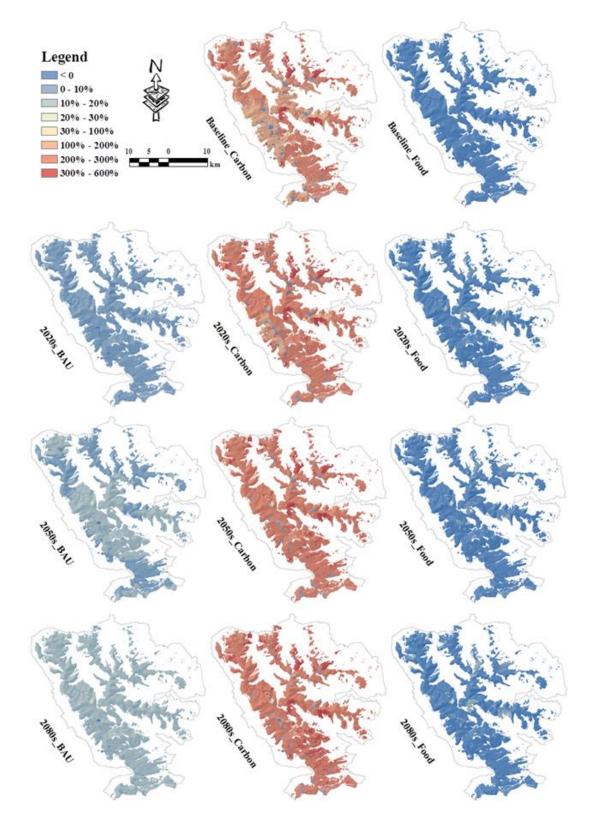


**Figure 6.20** Response of mean *potential* wildfire severity to change of climate and land management practices. All changes are calculated as difference of *potential* wildfire severity between a specific scenarios and "Base Condition" divided by *potential* wildfire severity under the "Base Condition" scenario. *Potential* FS represents unitless *potential* wildfire severity.

The highest monthly potential wildfire severity during the summer half year (Apr-Sep) was selected to stand for the potential severity of wildfire mainly because wildfire is more likely in the summer half year (Apr - Sep) than in the winter half year (Oct - Mar). Maps in Figure 6.21 display the spatial distribution of potential wildfire severity under each environmental scenario. Potential wildfire severity always peaks in areas with least intensity of land management practices. This is mainly because vegetation biomass could build up into a maximum in these areas, and so provides more fuel load to fire. The average values of the *potential* wildfire severity across the North Pennines blanket peatlands are shown in Table 6.9, and the change of potential wildfire severity from the "Base Condition" is illustrated in Figure 6.20. As climate changes, potential wildfire severity increases from baseline to future time periods. Potential wildfire severity increases by about 180 % when lands are managed for carbon storage, and decreases by about 26 % when lands are managed for food security. Variations of *potential* wildfire severity under interaction scenarios have the same direction as under the respective land management scenario, although the degree of change is adjusted by climate effects. Therefore, possible land management change may have more influence than climate change derived from median climate scenarios on *potential* wildfire severity of blanket peatlands in the North Pennines. This is also demonstrated by Table 6.10 and Figure 6.22, where the spatial distribution of *potential* wildfire severity is more severely altered by land management change than established climate variance.



**Figure 6.21** Spatial distribution of the mean *potential* wildfire severity (highest in any month of the summer half year) in blanket peatlands of the North Pennines under different environmental scenarios



**Figure 6.22** Spatial distribution of changes in mean *potential* wildfire severity (highest in any month of the summer half year) in blanket peatlands of the North Pennines under different environmental scenarios.

## 6.6 Summary and discussion

The equilibrium version of PESERA-PEAT was applied to blanket peatlands in the North Pennines, UK to consider how erosion may change in this area under possible future environmental change. Median climate scenarios were developed to account for possible climate change in this region. Drainage, grazing and burning were incorporated to reproduce possible future land management change (Reed, Hubacek et al. 2013). Twelve environmental scenarios were then set up to represent different combinations of possible variations in climate and land management practices. Runoff production and sediment yield under the 12 scenarios were reported. In addition, *potential* wildfire severity was also calculated to evaluate the possible influence of wild fire on the blanket peat ecosystem.

## 6.6.1 The impacts of climate change

Based on central estimates (50 % probability level) of UKCP09, the North Pennines will experience a warmer, wetter winter and a warmer, drier summer in the future. This is the same direction as the climate change for the whole of the UK predicted by UKCIP02 and UKCP09, although the magnitude of climate change varies for different regions of the UK (Hulme, Lu et al. 2002; UKCP09 2009). Annual rainfall and temperature for the North Pennines will increase from baseline to the 2080s.

At an annual scale, such climate change will accelerate runoff production and soil loss from blanket peat covered hillslopes in the North Pennines. Modelling results suggest that climate change has more impact on the magnitude and spatial pattern of runoff production rather than soil loss in blanket peatlands (Table 6.6, Figure 6.11 and Figure 6.12). In addition, increased annual sediment output confirms the inferences from previous bioclimatic envelope analyses on blanket peatlands (Clark, Gallego-Sala et al. 2010; Gallego-Sala, Clark et al. 2010; Gallego-Sala and Prentice 2012), which demonstrated shrinkage of suitable environments for blanket peatlands at both a UK and global scale and which had suggested that progressive peat erosion and vegetation cover change would be a direct consequence of climate change in the future. At a seasonal scale, sediment flux peaks in winter and bottoms in spring during the baseline period. In the future to the 2080s, increased evapotranspiration and lower rainfall aggravate desiccation in summer months. Therefore more erodible material is generated to be washed away by flow in the summer and autumn. Francis

(1990) also noted the significance of the summer desiccation as the source of the sediment erosion in Upper Severn catchment, mid Wales during two drought years in the 1980s. Increased temperature and more rainfall in winter months weaken the impact of freeze-thaw in peat, so sediment yields in winter will probably decline despite stormier weather providing a higher transporting capacity. As a result, the sediment flux peaks during autumn in the 2050s and 2080s.

As climate changes, the areas with negative change of blanket peat erosion were predicted to retreat towards higher areas under the BAU condition. This may be because in higher elevation areas there is usually more rainfall and lower temperature, which is the key condition for maintenance of blanket peatlands (Charman 2002).

### 6.6.2 Interactions between climate change and land management shifts

If rewilding (carbon storage scenario) takes place then the modelling for the North Pennines suggests that both river flow and sediment yield will decrease. On the other hand, if lands are managed for food security, both runoff production and soil erosion increase. However, the magnitude of erosion change is of a greater extent than for runoff change with land management shifts. Take the "2080s Cabon" and "Base Condition" scenarios as an example: sediment yield under "2080s Carbon" is less than half of soil loss from the "Base Condition". In contrast, runoff production under the "2080s Carbon" scenario is 13 % higher than under the "Base Condition" scenario, and only slightly smaller than the "2080s BAU" scenario. This demonstrates that different land management intensities are capable of influencing blanket peat erosion significantly without impacting the water supply function of blanket peatlands. This is important as 70 % of UK's drinking water is collected from upland areas, where blanket peatlands are widely distributed (Evans, Warburton et al. 2006; Reed, Bonn et al. 2009). The distribution of blanket peat erosion is also closely related to the spatial pattern of land management practices rather than climate change (Table 6.8 and Figure 6.15). It is thus concluded that land management practices are able to serve as a tool to mitigate peat erosion under future under climate change.

Potential wildfire severity responds to shifts in land management in an opposite way to runoff and erosion. Esteves, Kirkby et al. (2012) suggested that frequent managed burning was likely to reduce soil erosion relative to infrequent wildfires, although both types of fire could result in more soil loss when they studied a post-fire period in two semi-arid catchments in central Portugal. Wildfire adds uncertainty to changes in blanket peat erosion under environmental scenarios (McMorrow 2011). Further work is thus required to understand the interactions between management interventions (or the lack of them) and wildfire in upland blanket peatlands. This is particularly the case when trying to understand possible future erosion rates.

### 6.6.3 Limitations of the work

Climate change derived from median climate scenarios was found to play a less important role in influencing the magnitude and spatial pattern of fluvial blanket peat erosion than land management shifts between carbon storage, BAU and food security in the North Pennines. However, the magnitude of climate change is not the same in different regions of the UK (UKCP09 2009), nor is the current climate condition the same across all UK blanket peatlands. Hence the response of blanket peat erosion to climate change may vary across the UK. In addition, climate scenarios in this chapter were established based on central estimates of UKCP09 projections which inevitably reduce the variability of climate variables and only cover one possibility of future climate conditions. This is to say, the above conclusion may be challenged at a national scale and when other possibilities of future climate scenarios are employed. It is thus necessary to examine the response of blanket peat erosion to climate change and land management shifts at a national scale, and also climate change derived from other possible future climate conditions also needs to be assessed. These issues form the focus of work in Chapter 7.

The drainage networks caused by gully systems were not considered in the way as applied in Chapter 5. This is because 1) the method used for incorporation of gully system in Chapter 5 was actually a compromise given the actual spatial distribution of gullies, gully width and depth were not achieved; 2) the parameters (i.e. drainage density, drain depth and width) required by the drainage model for gullies are difficult to achieve. They were traditionally measured manually using field survey or

aerial photographs. These two methods are both time-consuming, labour intensive, and potential subjective. Evans and Lindsay (2010) proposed a novel approach to the automated detection of gullies from high resolution topographic data (LiDAR: 2 m resolution), providing a useful tool of parameterizing gullies. However, the DEM data available in the project was originally at 10-m resolution, which appeared too coarse for gully mapping. Nevertheless, if the gully-caused drainages were incorporated, the lowering of water table due to drainages enhances the sediment production, and decreases the runoff production and thus transporting capacity of water flow. Such two aspects of effects add uncertainties to the modelling results in this chapter, although more bare ground resulting from the gullies facilitates the development of erosion. The accurate incorporation of gullies is therefore desirable in the future model applications.

# **Chapter 7**

# Prediction of fluvial blanket peat erosion across Great Britain under environmental change

### 7.1 Introduction

In Chapter 6, the response of fluvial erosion in blanket peatlands of the North Pennines to possible changes in climate and land management practices has been examined with the equilibrium version of PESERA-PEAT. The work in Chapter 6 has two main weaknesses: 1) only one possibility of climate change derived from a median climate scenario was considered, and this may be not sufficient to indicate climate change in the future given future climate conditions have uncertainties (UKCP09 2009); 2) only one region of blanket peat was investigated. The magnitude of climate change is spatially variable (UKCP09 2009), meaning that blanket peat erosion response to climate change may vary in different regions. The major aims of this chapter are:

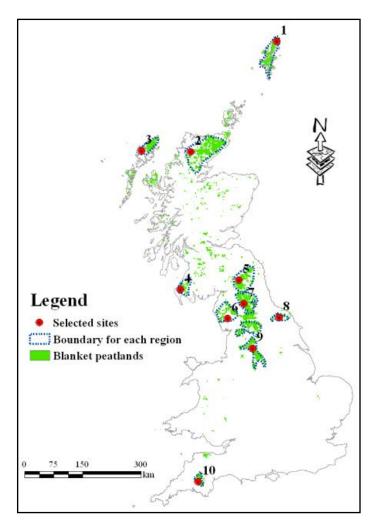
- 1) to investigate how fluvial blanket peat erosion reacts to different possibilities of future climate change, land management shifts, and their interactions;
- 2) to examine the reaction of fluvial blanket peat erosion to possible environmental changes at a national scale, taking Great Britain (GB) as a case study.

The time-series version of PESERA-PEAT was employed in this chapter. Compared to the equilibrium version of PESERA-PEAT, the time-series model is able to provide continuous monthly predictions rather than the monthly average values produced by the equilibrium PESERA-PEAT. Thus the time-series version can be used to investigate blanket peat erosion change over time in more detail. Time-series of monthly sediment outputs are good for exploring possible extreme erosion events under climate and land management change. Meanwhile the time-series model requires climatic information for every single month during the periods studied. Such large data requirements restrict its application over a large space, and so ten blanket peat-covered sites were sampled in different locations of GB. The time-

series model was operated at these sites with defined environmental scenarios to address the main purposes of this chapter.

The structure of this chapter is as follows: Section 7.2 is an introduction to the distribution of blanket peatlands and selection of study sites. Data sources and preparation for model inputs and scenario establishment are described in section 7.3. Section 7.4 concentrates on analysis of climate scenarios to understand possible future climate shifts within blanket peatlands in GB. This is then linked with modelling results to give an explanation of future change in fluvial blanket peat erosion. In section 7.5, blanket peat erosion, runoff production and *potential* wildfire severity under "Base Condition" are described. Section 7.6 concentrates on the analysis of modelling results to explore the impact of climate change and land management on blanket peatlands at a national scale. The summary and discussion are provided in section 7.7.

## 7.2 Study sites



**Figure 7.1** Spatial distribution of blanket peatlands across GB, with the chosen study sites and their corresponding regions examined in this chapter.

The spatial distribution of blanket peatlands over GB was compiled from results of blanket peat maps from Natural England and the No. 8 (bog (deep peat)) land cover type of the LCM2000 1-km map. The areas, which were covered by either Natural England-defined blanket bog or No. 8 of LCM2000, were classified as blanket peatlands. As a result, an area of 7359 km² was designated as being covered by blanket bog in GB, marked green in Figure 7.1. Ten blanket peat covered sites were selected to represent major regions with blanket peatlands in GB. Each study site is at a MIDAS weather station, where climatic conditions were available between 1961 and 1990 (baseline period). The major reason for this is to ensure baseline climate was based on actual measurements. Basic information for each site is shown in

Table 7.1. Site 3 is the lowest altitude site with lowest relief, while site 7, which is part of the Trout Beck catchment in the North Pennines, is highest, while site 6 has the largest relief.

**Table 7.1** Background information on the sites selected across GB in this chapter.

Site	Name		dinates al degree)	Elevation (m)	Relief (m)
		Latitude	Longitude		
1	Shetland	60.76	-0.89	24	18.70
2	Sutherland	58.17	-4.73	99	16.32
3	Ross-shire	58.13	-6.88	7	7.22
4	Wigtown-shire	54.98	-4.93	166	11.96
5	Northumberland	55.23	-2.58	201	19.87
6	Westmorland	54.34	-3.02	91	44.85
7	North Pennines	54.69	-2.38	556	22.01
8	North York Moors	54.37	-0.96	151	19.07
9	South Pennines	53.66	-2.03	387	23.97
10	Dartmoor	50.55	-4.00	453	18.59

## 7.3 Data source and processing

### **7.3.1** Climate

As in Chapter 6, four periods of climate were involved. They are "Baseline", "2020s", "2050s" and "2080s", coving 30-year periods of 1961-1990, 2010-2039, 2040-2069 and 2070-2099 respectively. The baseline climate was based on the MIDAS measurements, while future climate scenarios were established based on UKCP09 predictions and MIDAS baseline climate.

#### 7.3.1.1 Baseline climate

The climate variables input into the time-series version of PESERA-PEAT are the same as those for the equilibrium model. They are monthly total rainfall (meanrf130), mean rainfall per rainfall day (meanrf2), coefficient of variation of rainfall per rainy day (cvrf2), monthly temperature range (mtrange), monthly temperature (mtmean), and monthly potential evapotranspiration (meanpet30). As shown in section 6.3.1.1 of Chapter 6, climatic inputs are monthly statistics of daily measured data except potential evapotranspiraton (PET), which was calculated with a modified temperature-based model shown in Equation 5.3 of Chapter 5.

The only difference in processing of the climatic inputs between Chapter 6 and this chapter is that the time-series PESERA-PEAT model requires the climate inputs for every single month rather than monthly average values over each time period. This is to say, for a 30-year period 360 values are needed for each climate variable. Unfortunately, MIDAS measured data often have missing values between 1961 and 1990 for the sites selected. Hence the baseline climate predicted by the UKCP09 was used to produce the time-series for baseline periods, and the UKCP09 time-series was then adjusted using the monthly average of the MIDAS data in the baseline period to achieve a plausible time-series of MIDAS baseline climate.

#### 7.3.1.2 Future climate scenarios

The climate scenarios for future time periods were established based on the UKCP09 projections. Three carbon emission scenarios from the IPCC Special Report of Emissions Scenarios (SRES) are included in UKCP09 (UKCP09 2009). They are high emission (A1F1), medium emission (A1B) and low emission (B1). As in Chapter 6, the medium emission scenario was selected as the context of climate change in this chapter. The UKCP09 can produce a number of potential climate change projections, so different probabilities of projected climate conditions could be derived from these outputs. The weather generator in UKCP09 can generate daily climate projections over the 21<sup>st</sup> century. These outputs are suitable for calculation of climatic inputs for the time-series version of PESERA-PEAT.

One hundred model realizations randomly extracted from predictions of the UKCP09 weather generator were employed to build up climate scenarios for each time period between 2010 and 2099. In this case, there are 100 possibilities of climate for each time period, and so 100 projected values for each of climatic input variables for PESERA-PEAT can be achieved. Such 100 probabilistic climate projections were then used to develop seven climate scenarios at different probability levels. These scenarios are median climate scenario as well as the 10<sup>th</sup>, 50<sup>th</sup> and 90<sup>th</sup> percentile rainfall and temperature scenarios. Median climate scenarios were established through picking up median values of each climatic input variable of the PESEREA-PEAT from the 100 UKCP09 outputs for every single month over the corresponding 30-year period. The rainfall scenarios were composed of climate variables corresponding to a UKCP09 model realization, of which the average

rainfall is at the 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> position of that of 100 model realizations for each time period. Similar to rainfall scenarios, the 10<sup>th</sup>, 50<sup>th</sup> and 90<sup>th</sup> percentile temperature scenarios are the climate variables corresponding to a UKCP09 model realization, of which the average temperature is at the 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> position of that of the 100 UKCP09 model realizations for each time period. In this chapter, median climate scenarios are represented by 50 %. The 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentile rainfall / temperature scenarios are abbreviated as 10 %, 50 % and 90 % rf / tm scenarios. The seven climate scenarios established for future periods consist of a climatic envelope for the selected blanket bog sites through covering both median and extreme climate (10 %, 90 % rf / tm scenarios) conditions.

UKCP09 data are at a 5-km resolution while MIDAS measured data are at a point. PESERA-PEAT was operated at 100-m grid cells. So there were three spatial resolutions: 5 km for UKCP09, point for MIDAS data and 100-m for PESERA-PEAT inputs. Theoretically all base data should be transferred to a 100-m resolution before being assigned to the 100-m grid cells. In Chapter 6, interpolation and downscaling were conducted to offset the impacts of such scaling differences on the magnitude of climate data. In this chapter, the scale transfer of the UKCP09 and MIDAS data were not conducted mainly because there were not enough data to do so, given data from only one point was used in each region. This may lead the modelling results for site 7 to be different from predictions in Chapter 6, but such a difference would be systematic as all sites selected in this chapter were processed in the same way. In addition, results from site 7, which is located in the North Pennines, could serve as a link between Chapter 6 and Chapter 7 so that the findings of this chapter could be compared with those of Chapter 6. As a result, the time-series of climate input variables derived from UKCP09 outputs for each future time period were directly transferred with Equation 7.1 to base on MIDAS baseline climate. The resulting MIDASUKCP data were assigned to 100-m grid cells, without considering the scaling difference between different data sources.

MIDASUKCP = MIDASBASELINE + (UKCP - UKCPBASELINE) Equation 7.1

where, MIDASUKCP is the future climate variables based on MIDAS baseline climate; MIDASBASELINE is MIDAS baseline climate variables; UKCP is the future climate variables derived from UKCP09 projections; UKCPBASELINE is the baseline climate calculated from UKCP09 predictions.

### 7.3.2 Land use / cover / management, topography and soil

As shown in previous chapters, land use / cover / management, topography and soil properties are also required by PESERA-PEAT as input data to set up initial conditions. In this chapter, land cover type for all ten selected sites was considered to be natural vegetation, and land use code used in the model was "334" (Table 5.2), on which both the vegetation growth model and land management work. Other land use / cover parameters related to "334" were set according to Table 5.3 of Chapter 5. Parameterization of land management practices (drainage, grazing and prescribed burning) was conducted with the method provided in section 4.4 of Chapter 4, and specific values of management parameters are described in section 7.4.3 and shown in Table 7.4. Topographic information (relief) was calculated as the standard deviation of elevation for all points within a certain radius. The radius was set to 500 m in the study. The base digital elevation model was downloaded from Digimap and then resampled to a 100-m spatial resolution with a bilinear resampling method. As each site represented a blanket peat-covered region, the relief for a site was the average value for the blanket peatlands within the corresponding region rather than itself (Figure 7.1). The resulting relief and elevation of each site are shown in Table 7.1. The erodibility of weathered blanket peat was set to 2.5 mm (Mulqueen, Rodgers et al. 2006). Please refer to Table 3.5 of Chapter 3 for specific values of the other soil parameters.

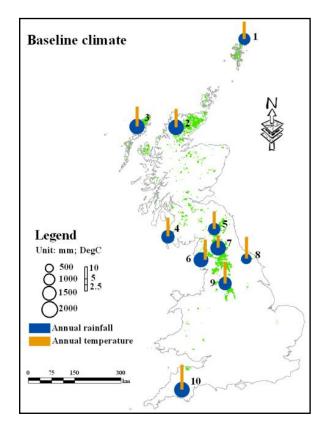
# 7.4 Outputs of environmental conditions in GB blanket peatlands

# 7.4.1 Climate change

In the baseline period, mean annual rainfall and temperature of the selected sites are shown in Table 7.2 and mapped in Figure 7.2.

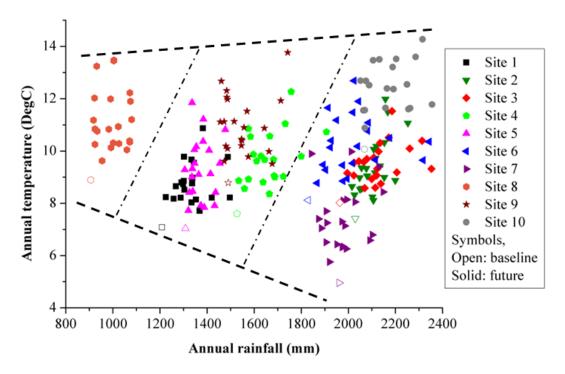
**Table 7.2** Mean annual rainfall and temperature of the selected sites in the baseline period.

Site	Rainfall (mm)	Temperature (°C)
1	1209	7.08
2	2029	7.42
3	1964	8.02
4	1527	7.60
5	1309	7.03
6	1829	8.12
7	1961	4.96
8	907	8.89
9	1490	8.78
10	2069	10.06



**Figure 7.2** Mean annual rainfall and temperature of the selected sites in the baseline period.

As described above, seven climate scenarios from UKCP09 between 2010 and 2099 were employed to represent the possible future climate conditions for the blanket peatlands in GB. Table 7.3 shows the position of average rainfall and temperature of each scenario in the whole 100 UKCP09 model realizations for the three future periods. In median climate scenarios, average rainfall appears to be always in the bottom end of the whole model realizations and average temperature tends to be in the middle. In some cases, average rainfall in median scenarios is even lower than in 10 % rf scenarios such as at sites 8 and 9. It would not be surprising if runoff production in median scenarios is less than in 10 % rf scenarios. Apart from median scenarios, variation of rainfall and temperature in the other six scenarios are much wider compared to that in median climate scenarios, giving a broad envelope to understand the reaction of blanket peat erosion to climate change. Figure 7.3 displays the clustering of climate for the selected sites based on average annual rainfall and temperature in baseline and future time periods. There are three future time periods, which are the 2020s, 2050s and 2080s, and a baseline period (1961-1990). Seven climate scenarios were built up for each future time period. For each site there should be 22 climate conditions over the four time periods. This means that there are 22 points for each site in Figure 7.3. Clustering results suggest that climate for the chosen sites could be divided into three groups. Site 8 is much drier than other sites and consists of a group on its own, sites 1, 4, 5 and 9 have similar rainfall and falls into another group, and sites 2, 3, 6, 7, 8, and 10 are categorised into a third group with high precipitation. The temperature declines and the temperature range becomes wider from dry to wet groups.



**Figure 7.3** Clustering of climate for the selected sites based on average annual rainfall and temperature over the baseline and future periods. For each site, an open symbol represents the baseline climate while a solid symbol stands for the future climate, which is derived from the seven future climate scenarios.

**Table 7.3** Probability level (%) of mean annual rainfall and temperature in the 100 UKCP09 model realizations for each site under the established climate scenarios; "rf" and "tm" represent mean annual rainfall and temperature respectively.

	Site	50	0%	10% rf	50% rf	90% rf	10% tm	50% tm	90% tm
		rf	tm	tm	tm	tm	rf	rf	rf
	1	28	47	53	92	42	93	44	53
	2	17	48	25	18	76	55	7	58
<b>7</b>	3	23	51	61	10	21	80	81	36
<b>50</b>	4	17	53	22	42	58	63	6	53
2020s	5	12	50	8	16	15	63	92	39
	6	17	51	8	17	65	41	36	20
	7	19	51	95	43	70	22	44	12
	8	9	48	88	54	34	20	76	68
	9	9	50	44	23	6	6	39	43
	10	10	48	48	56	55	9	89	51
	Site	50	%	10% rf	50% rf	90% rf	10% tm	50% tm	90% tm
		rf	Tm	tm	tm	tm	tm	tm	tm
	1	31	42	34	38	16	48	51	99
	2	16	41	42	70	67	8	62	73
70	3	22	44	35	65	72	33	38	71
2050s	4	16	52	56	14	50	52	90	6
90	5	10	51	34	99	64	14	3	49
(4	6	17	53	4	97	58	39	100	41
	7	19	52	69	84	28	38	19	99
	8	10	48	29	64	13	91	92	87
	9	12	51	49	14	4	52	34	20
	10	13	50	60	81	96	96	69	83
	Site	50	%	10% rf	50% rf	90% rf	10% tm	50% tm	90% tm
		rf	tm	tm	tm	tm	tm	tm	tm
	1	28	44	54	90	3	13	23	50
	2	22	44	14	98	82	4	31	55
<b>CO</b>	3	24	44	18	7rf	12	23	86	41
2080s	4	19	53	8	66	56	30	5	62
<b>2</b> 0	5	14	56	25	49	75	55	10	8
• •	6	19	57	67	35	4	37	52	30
	7	22	55	4	91	85	39	57	1
	8	9	53	85	89	43	35	38	51
	9	18	52	70	26	46	78	19	96
	10	17	50	18	51	96	37	19	52

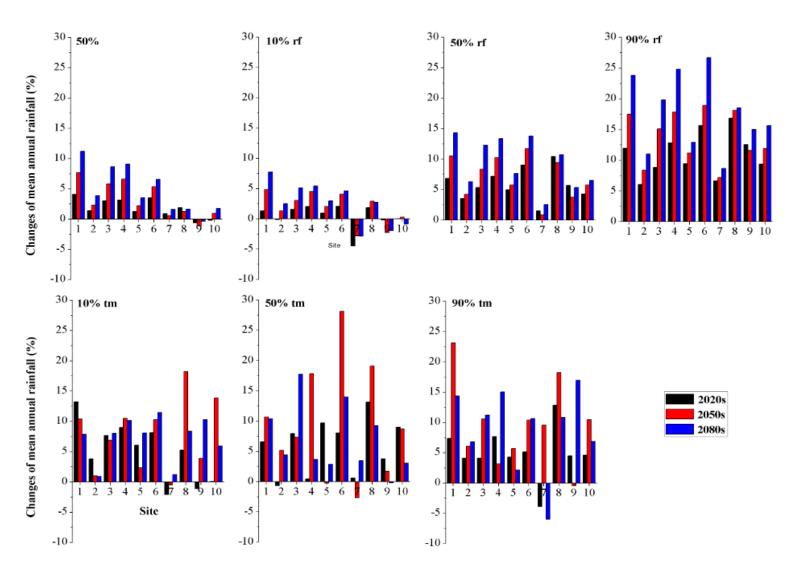


Figure 7.4 Changes of average annual rainfall in future time periods under different climate scenarios for each of the ten sites.

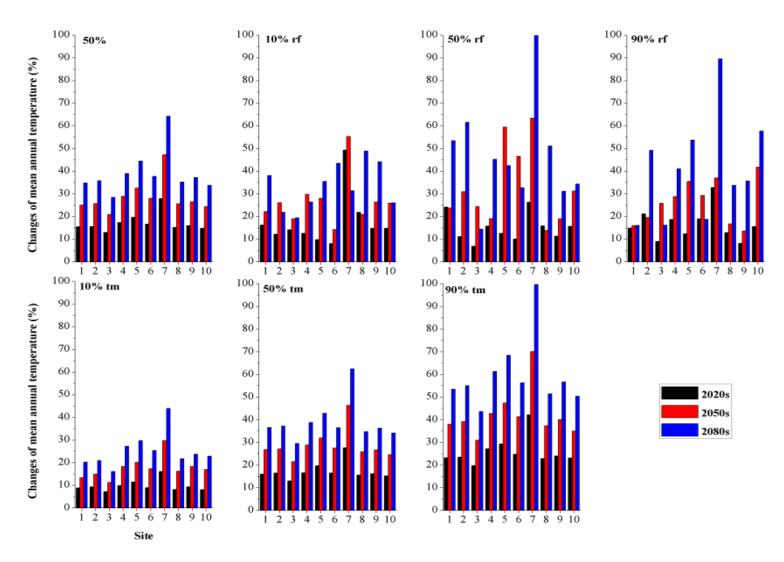


Figure 7.5 Changes of average annual temperature in future time periods under different climate scenarios for each of the ten sites.

Figure 7.4 and Figure 7.5 indicate climate change defined by the established climate scenarios for each selected site from baseline to future periods. In most cases, mean annual rainfall is increased between baseline and future periods and the largest relative increase emerges at site 6 under the 50 % tm scenarios. However, a decrease of mean annual rainfall happens sometimes between baseline and future time periods. For example, at sites 2, 7 and 9. At site 7, the overall change of annual rainfall for model runs appears to be smaller compared to other sites in most cases. Changes in mean annual temperature show a simpler pattern than that in mean annual rainfall as temperature always increases from baseline to future in all scenarios, although the magnitude of the increase varies among sites. The relative increase of mean annual temperature usually peaks at site 7 and appears to be smaller in other sites. Snow and ice cover are common in winter for site 7 (within Trout Beck, Beck North Pennines), temperature increase could be more enhanced where winter is closer to 0 °C due to reduced snow / ice cover and albedo feedbacks (Holden and Rose 2011).

#### 7.4.2 Environmental scenarios

For each climate scenario, eight environmental scenarios were established for each site to explore the response of blanket peatlands to corresponding environmental shifts. The combination of climate and land management strategies for each environmental scenario is shown in Table 7.4. As detailed information about the current land management condition is not available for sites other than site 7, two land management scenarios were adopted to account for the impact of possible changes in land management on blanket peatlands. One takes a carbon storage focus, while the other uses a food security scenario (Reed, Arblaster et al. 2009; Reed, Bonn et al. 2009; Reed, Hubacek et al. 2013). They are represented as "Carbon" and "Food" in Table 7.4. The carbon storage scenario is defined as no pro-active land management practices exist. In the food security scenario the land management intensity is the same as that in food security scenarios of Chapter 6 so overgrazing is represented by 30 % vegetation cover and biomass removal per month, the rotational period of managed burning is 5 years and the drainage density is 16 km km<sup>-2</sup>, which is the double the current average drainage density of the North Pennines blanket peatlands. This value was used mainly because the actual density of artificial drainage for sites other the North Pennines was unavailable. For each site, total vegetation cover and biomass removal is the sum of vegetation cover and biomass reduced by separate management practices. The "Base Condition" scenario was built upon baseline climate and carbon storage management conditions. Modelling results from all other scenarios were compared with outputs based on the "Base Condition" scenario. Climatic impact was investigated with the carbon storage scenario and climate conditions at baseline, 2020s, 2050s and 2080s. Then food security scenarios were applied with climate conditions in baseline and future time periods to examine the impact of land management shifts and interactions between climate and management change.

**Table 7.4** Environmental scenarios employed in this chapter.

		Land Mana	gement		
Name	Climate	Drainage (km km <sup>-2</sup> )	Grazing (%)	Managed burning (year)	Back up
<b>Base Condition</b>	Baseline	0	0	0	Baseline climate and carbon storage scenarios.
2020s_Carbon	2020s	0	0	0	Investigating the
2050s_Carbon	2050s	0	0	0	impacts of climate
2080s_Carbon	2080s	0	0	0	changes.
Baseline_Food	Baseline	16	30	5	Investigating the impacts of land management.
2020s_Food	2020s	16	30	5	Investigating the
2050s_Food	2050s	16	30	5	interactions between climate
2080s_Food	2080s	16	30	5	and land management change (interaction scenarios).

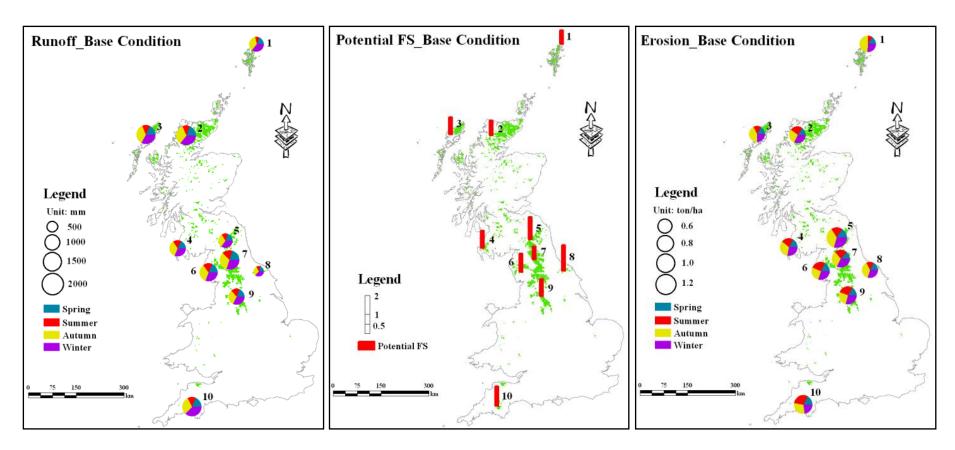
<sup>&</sup>quot;0" indicates the management practice is totally removed.

# 7.5 Runoff, erosion and *potential* wildfire severity in blanket peatlands of GB under the "Base Condition" scenario

**Table 7.5** Mean annual runoff, *potential* wildfire severity, sediment yield, and seasonal distribution of the mean annual sediment yield for the chosen sites under the "Base Condition" scenario. *Potential* FS represents *potential* wildfire severity, which is defined as the highest *potential* wildfire severity during any month of the summer half year (Apr-Sep).

Site	Annual runoff (mm)	Potential FS (unitless)	Annual erosion (ton ha <sup>-1</sup> )	Spring erosion (%)	Summer erosion (%)	Autumn erosion (%)	Winter erosion (%)
1	1005	0.81	0.78	15.46	9.41	48.81	26.32
2	1790	0.87	0.8	14.52	24.61	28.95	31.92
3	1666	0.99	0.73	16.82	15.77	41.70	25.70
4	1246	1.02	0.91	16.98	22.03	33.17	27.82
5	939	1.33	1.16	15.75	18.35	36.12	29.78
6	1522	1.07	0.93	16.89	26.59	26.82	29.70
7	1751	0.77	0.89	13.74	22.35	30.69	33.22
8	535	1.5	0.74	17.94	14.47	37.96	29.63
9	1213	1.02	0.92	16.42	27.49	26.94	29.15
10	1731	1.15	0.98	17.16	30.40	29.10	23.35

The mean annual runoff, *potential* wildfire severity, erosion and its seasonal distribution under the "Base Condition" scenario are displayed in Table 7.5 and mapped in Figure 7.6. The distribution of annual runoff is close to that of annual rainfall in the baseline period with the highest and lowest annual runoff of 1790 mm and 535 mm respectively occurring at sites 2 and 8. This is consistent with climate clustering results shown in Figure 7.3, where sites 2 and 8 fall into the wettest and driest groups respectively. Most runoff is produced in autumn and winter; while spring and summer contributes less to annual total runoff. Mean annual erosion varies between 0.73 and 1.16 ton ha<sup>-1</sup> at sites 3 and 5 respectively. Similar to annual runoff, sediment yield for the selected sites mainly comes from autumn and winter rather than summer and spring (Table 7.5 and Figure 7.6). *Potential* wildfire severity ranges between 0.76 and 1.32 at sites 7 and 5 respectively.



**Figure 7.6** Mean annual runoff, *potential* wildfire severity and sediment yield for the selected sites in the baseline period without management.

# 7.6 The impact of environmental change on runoff, erosion and potential wildfire severity in blanket peatlands of GB

#### **7.6.1 Runoff**

The impact of climate change and land management on mean annual runoff is illustrated in Figure 7.7. Mean annual runoff increases by less than 5 % with land management shifts from carbon storage to food security. The changes in average annual runoff with climate change show more variety, ranging between -8 % to 30 %, and the direction and magnitude of average annual runoff change are similar to those of mean annual rainfall.

Changes of average annual runoff production from the baseline period under the carbon storage scenarios for each site with rainfall and temperature are presented in Figure 7.8, where the x- and y-axes stand for the range of average annual rainfall and temperature for each time period. It is shown in Figure 7.8 that runoff increases with rainfall, and does not show a strong relationship with temperature. However, runoff bands curve to higher rainfall, implying that higher temperature results in less runoff when rainfall is constant. The impact of rainfall on long-term runoff production is much stronger than that of temperature across GB under baseline and future climatic conditions.

Descriptive statistics based on annual runoff from time series modelling are shown in Table 7.6. It shows that runoff production under food security scenarios is slightly higher than that under carbon storage scenarios. Such a difference is lower than the biggest difference in runoff production under the defined climate scenarios. The standard deviation of annual runoff production between 2010 and 2099 is about same under the carbon storage and food security scenarios. This confirms that the land management change has a smaller impact than climate variation on runoff production from blanket peatlands. The specific years with highest predicted annual runoff for each site are shown in Table 7.7. Sites 1, 2, 4, 5, 7, 8 and 9 have the highest predicted annual runoff production under the 90 % rf scenarios in 2063, 2083, 2086, 2070, 2094, 2013 and 2099 respectively. Sites 3 and 10 have the highest predicted annual runoff under 90 % tm scenarios in 2054 and 2044. Annual runoff for site 6 peaks in 2052 for the 50 % tm scenario. The highest predicted annual

runoff peaks at site 10 and bottoms at site 8. This is consistent with the result of climate clustering shown in Figure 7.3, where sites 10 and 8 appear to be wettest and driest among the sites involved.

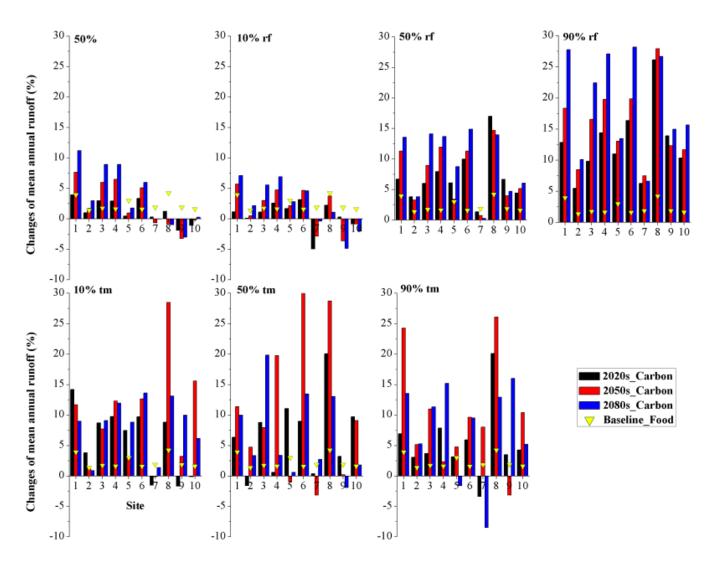
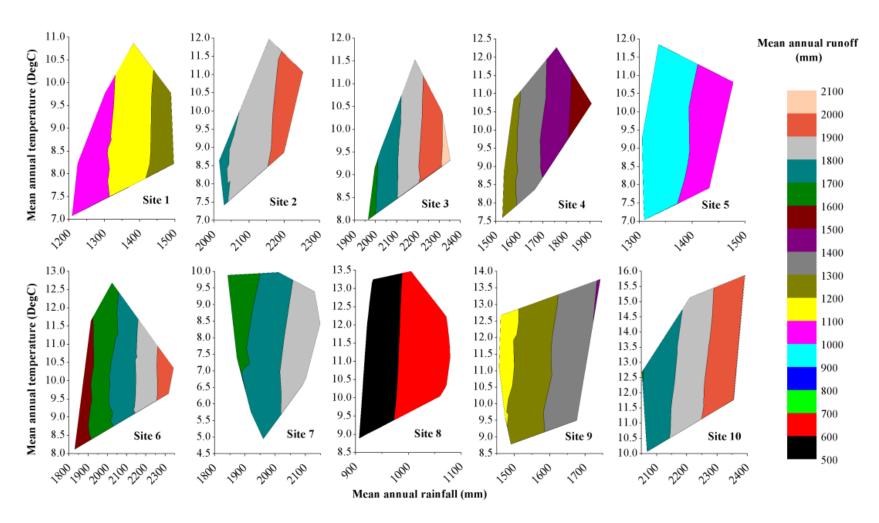


Figure 7.7 Changes in mean annual runoff for each site between future and baseline periods under variations in climate and land management.



**Figure 7.8** Mean annual runoff production for each site under the carbon storage scenarios against average annual temperature and rainfall between baseline and 2080s periods under carbon storage scenarios. The legend indicates the classification of mean annual runoff production.

**Table 7.6** Descriptive statistics based on time series of annual runoff (mm) between 2010 and 2099 under different environmental scenarios. The highlighted values represent the highest predicted annual runoff for each site under different land management scenarios.

		Site	1			Site	2			Site	3			Site	4			Site	5	
Scenarios	Mean	Min	Max	SD	Mean	Min	Max	SD												
50%_Carbon	1082	1013	1143	33	1824	1742	1914	34	1766	1661	1861	48	1323	1240	1400	38	949	850	1009	25
10%rf_Carbon	1052	844	1342	105	1806	1606	2030	91	1720	1341	2101	161	1306	977	1727	142	960	679	1245	106
50%rf_Carbon	1111	854	1350	95	1855	1561	2188	125	1828	1425	2240	163	1386	1013	1968	163	996	739	1326	118
90%rf_Carbon	1203	895	<mark>1470</mark>	116	1933	1683	<mark>2218</mark>	117	1938	1548	2358	179	1501	976	<mark>1989</mark>	190	1056	787	1429	113
10%tm_Carbon	1122	903	1397	105	1824	1579	2117	112	1808	1477	2183	152	1388	857	1762	158	999	757	1256	103
50%tm_Carbon	1098	829	1342	97	1828	1554	2199	125	1870	1481	2370	187	1345	962	1843	200	972	714	1353	126
90%tm_Carbon	1156	847	1441	121	1870	1550	2207	117	1811	1522	<mark>2452</mark>	178	1352	987	1824	180	958	673	1296	126
50%_Food	1106	1028	1175	32	1846	1775	1936	34	1795	1685	1891	49	1346	1264	1429	38	978	879	1037	26
10%rf_Food	1087	856	1387	109	1839	1629	2080	91	1748	1368	2131	163	1336	1018	1763	146	991	735	1284	107
50%rf_Food	1151	891	1418	105	1884	1590	2210	125	1856	1445	2273	165	1416	1029	1999	164	1027	762	1365	122
90%rf_Food	1235	915	1492	116	1957	1691	<mark>2240</mark>	118	1966	1581	2387	180	1529	1003	<mark>2024</mark>	192	1088	812	1440	115
10%tm_Food	1168	945	1449	115	1859	1601	2155	110	1838	1500	2212	153	1421	902	1800	155	1030	787	1295	105
50%tm_Food	1137	859	1403	102	1857	1571	2229	123	1899	1506	2400	189	1375	985	1875	203	1003	741	1392	129
90%tm_Food	1189	866	1484	121	1894	1578	2226	118	1840	1546	<mark>2490</mark>	180	1376	1008	1855	181	989	694	1336	128

**Table 7.6** Continued

		Site	6			Site	7			Site	8			Site	9			Site	10	
Scenarios	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD
50%_Carbon	1595	1529	1666	29	1749	1683	1815	26	534	469	582	22	1180	1143	1220	20	1725	1652	1817	34
10%rf_Carbon	1585	967	2292	271	1703	1355	2092	161	547	247	898	128	1180	815	1608	161	1709	1167	2377	223
50%rf_Carbon	1706	1159	2443	283	1765	1311	2273	195	616	322	1194	146	1275	828	1662	174	1821	994	2678	245
90%rf_Carbon	1849	1261	2443	270	1870	1576	<mark>2564</mark>	183	679	367	1262	163	1380	949	<mark>2107</mark>	196	1948	1296	2607	281
10%tm_Carbon	1705	955	2308	251	1750	1351	2249	184	625	269	1046	160	1260	767	1644	184	1856	1182	2810	275
50%tm_Carbon	1789	1105	<mark>2807</mark>	315	1751	1380	2423	188	645	385	990	133	1219	804	1684	206	1850	1324	2691	259
90%tm_Carbon	1650	1105	2542	275	1729	1169	2201	220	640	346	1043	154	1279	867	1795	185	1846	1296	<mark>2975</mark>	268
50%_Food	1621	1555	1695	30	1797	1724	1866	31	556	491	600	23	1206	1156	1249	21	1754	1682	1848	35
10%rf_Food	1620	980	2325	275	1728	1344	2114	165	570	262	928	132	1215	873	1615	162	1740	1190	2423	224
50%rf_Food	1740	1183	2483	284	1798	1375	2317	195	641	338	1241	150	1306	849	1669	175	1853	1016	2726	248
90%rf_Food	1881	1288	2473	274	1905	1581	<mark>2595</mark>	184	705	386	1302	167	1411	967	<mark>2138</mark>	196	1979	1319	2644	285
10%tm_Food	1738	964	2349	254	1780	1414	2286	185	649	282	1086	164	1293	803	1667	185	1889	1212	2855	277
50%tm_Food	1819	1123	2847	320	1780	1392	2451	188	670	404	1028	138	1252	845	1713	206	1883	1347	2740	263
90%tm_Food	1679	1117	2590	279	1764	1302	2221	215	665	366	1082	159	1310	897	1819	184	1877	1324	<mark>3017</mark>	270

**Table 7.7** The years with the highest predicted annual runoff, corresponding climate scenarios and the highest predicted annual runoff production for each site between 2010 and 2099 under established environmental scenarios. The years and climate scenarios with the highest predicted annual runoff are identical for each site under both carbon storage and food security scenarios; "Runoff\_Carbon" and "Runoff\_Food" represent the highest predicted annual runoff under carbon storage and food security scenarios respectively.

Site		Carbon sto	orage / food security sc	enario
	Year	Climate scenario	Runoff_Carbon (mm)	Runoff_Food (mm)
1	2063	90%_rf	1470	1492
2	2083	90%_rf	2218	2240
3	2054	90%_tm	2452	2490
4	2086	90%_rf	1989	2024
5	2070	90%_rf	1429	1440
6	2052	50%_tm	2807	2847
7	2094	90%_rf	2564	2595
8	2013	90%_rf	1262	2302
9	2099	90%_rf	2107	2138
10	2044	90%_tm	2975	3017

#### **7.6.2 Erosion**

Figure 7.9 shows the change of average annual erosion with climate change from baseline to future periods and the defined land management shifts. It is apparent that mean annual sediment yield change with land management shifts is much higher than the change associated with climate change. In terms of Figure 7.9, the reaction of blanket peat erosion to climate change is not constant across GB. Under climate change between baseline and 2080s periods, changes of mean annual sediment yield increase from site 1 to site 10 in general. Erosion change peaks at site 8 in five of the seven climate scenarios which are the 50 % rf, 90 % rf, 10 % tm, 50 % tm and 90 % tm scenarios. In the median climate scenario mean annual erosion change peaks at site 10, while in 10 % rf scenarios the highest mean annual erosion change emerges at site 6.

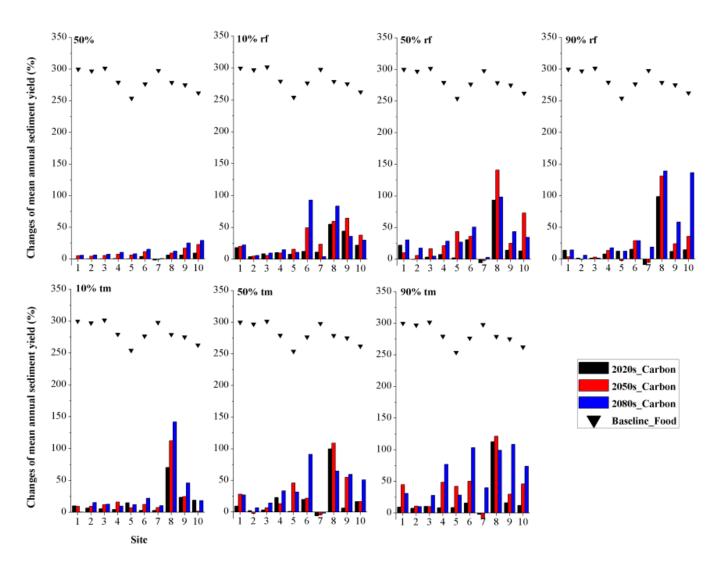
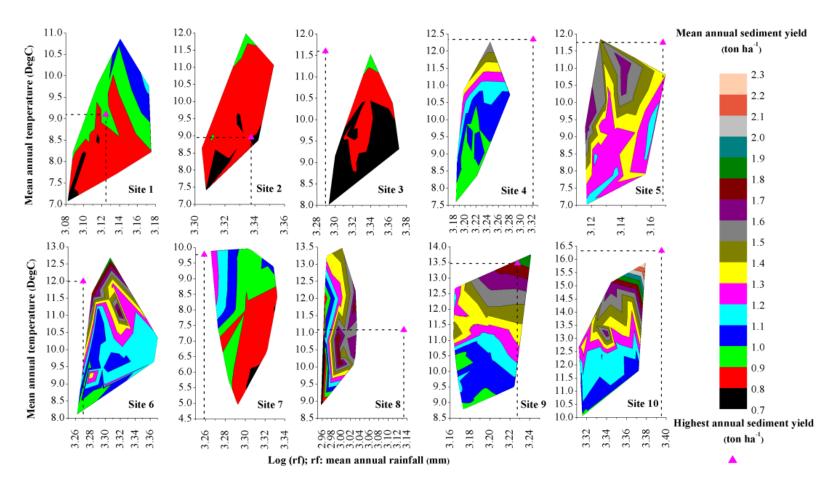


Figure 7.9 Changes in mean annual erosion for each site between future and baseline periods under climate and land management change.



**Figure 7.10** Mean annual sediment yield for each site under the carbon storage scenarios against average annual temperature and rainfall between baseline and 2080s. The highest predicted annual sediment yield for each site under the carbon storage scenario between 2010 and 2099 is also plotted against the annual rainfall and temperature associated with the highest annual erosion. The rectangular legend indicates the classification of average annual sediment yield. The pink triangle in each graph represents the highest predicted annual sediment yield between 2010 and 2099.

The average annual sediment yield for the selected sites under the carbon storage scenarios is plotted against the corresponding average annual rainfall and temperature in the baseline and future periods in Figure 7.10 where x- and y-axes stand for a range of mean annual rainfall and temperature for each time period. In terms of change of average annual sediment yield with average annual rainfall and temperature, the predicted erosion for sites 1 and 8 peaks for the wettest condition. At sites 2, 3, 4 and 6, the predicted erosion peaks at the warmest condition, and sites 9 and 10 have the highest erosion under the warmest and wettest condition. Erosion peaks at the warmest and driest condition in site 7. Site 5 has two peaks occurring with a middle warm, dry condition and a middle wet, warm condition. For each site a warmer temperature is always coincident with increased erosion while increased rainfall does not always do the same thing. For example, at sites 2, 3, 5 and 7, higher rainfall may produce less sediment yield (Figure 7.10). It is therefore inferred that temperature is more important than rainfall in impacting long-term change of blanket peat erosion across GB between 2010 and 2099.

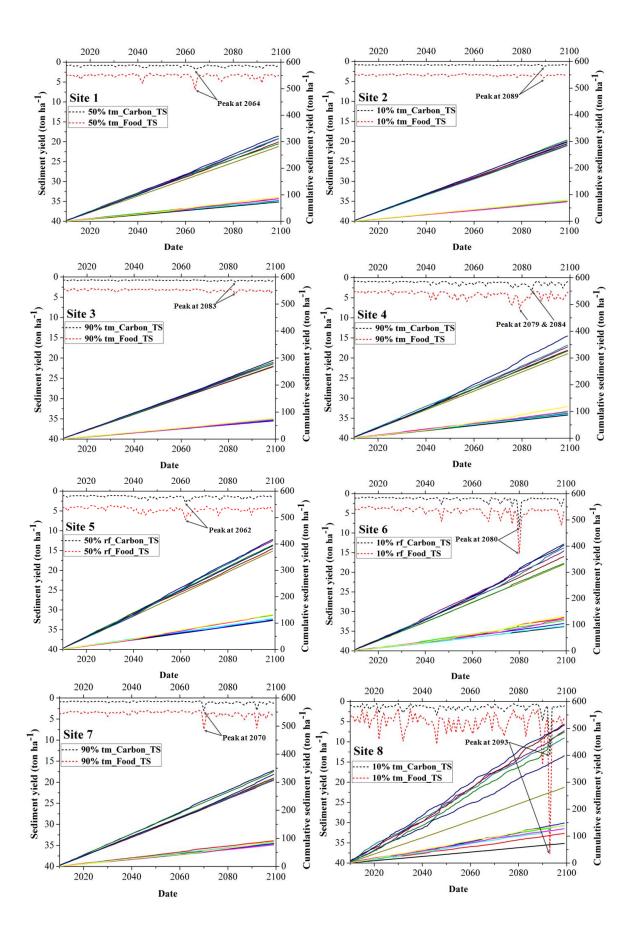
Descriptive statistics for the time series of annual sediment yield between 2010 and 2099 are provided in Table 7.8, while the cumulative sediment yield and time-series of annual erosion for scenarios with the highest predicted annual sediment yield are plotted in Figure 7.11. Cumulative sediment yield usually peaks in 90 % tm scenarios and drops in median climate scenarios. A higher standard deviation of annual erosion under food security scenarios demonstrates that more intensive land management could also make the sediment yield peakier. The change of cumulative sediment yield with land management intensity is apparently higher than that with climate change, confirming that land management shifts between carbon storage and food security usually have more impact on the total erosion between 2010 and 2099 than climate change (Figure 7.9). However, at site 8 the variation of cumulative sediment yield under different climate scenarios is closer to that with land management change than at other sites. In addition, the highest predicted annual erosion for site 8 is significantly higher than that for other sites (Table 7.8). This implies that blanket peat at site 8 is more vulnerable to climate change than at other sites. In Figure 7.11 the specific years with the highest predicted annual erosion are also marked out in the erosion time series of the corresponding scenarios. For most sites, annual sediment yield peaks simultaneously under both carbon storage and food security scenarios. However, annual erosion at sites 4 and 9 peak in different years when management conditions vary. Site 1 has the highest annual sediment yield in 2064 for the 50 % tm scenarios. The predicted annual erosion at sites 2 and 8 peaks at 10 % tm scenarios in 2089 and 2093 respectively, while sites 3, 4, 7 and 9 have the highest annual erosion under 90 % tm scenarios in 2083, 2084 (2079), 2070, 2097 (2070) respectively (the numbers outside the brackets indicate the year with the highest predicted annual erosion under carbon storage scenarios, while the number inside the brackets indicates the year with the highest predicted annual erosion under food security scenarios). Annual erosion at site 5 peaks in 2062 for the 50 % rf scenarios. Site 6 has the highest predicted annual erosion in 2080 for the 10 % tm scenarios, and predicted annual erosion of site 10 peaks in 2099 for the 90 % rf scenarios. The highest predicted annual sediment yield under the carbon storage scenarios for each site is also plotted in Figure 7.10 as a pink triangle to indicate the climate condition for the year with highest predicted annual sediment yield. Compared to average annual rainfall and temperature for the chosen time periods, the highest annual erosion at sites 1 and 2 occurs in years with medium rainfall and temperature. Sites 3, 4, 6 and 7 undergo highest annual erosion at dry and warm years. Annual sediment yield from sites 4, 5, 9 and 10 peaks in years with warm and wet climate, and site 8 has the highest sediment erosion in a quite wet year with medium temperature. Figure 7.12 illustrates the sediment yield and storage for the years with highest predicted annual sediment yield under corresponding scenarios (Table 7.8 and Figure 7.11). Sediment storage at all sites peaks during summer and then decreases in autumn and winter. It drives sediment yield to be "big event dominated" and usually peaks in autumn or winter. This means that transport limited processes are dominant in summer erosion, and stored erodible material is washed out in autumn and winter. So summer desiccation could be a major source of erodible material for future erosion, especially for the erosion with highest sediment output, although most sediment is still coming out of blanket peatlands in autumn and winter. The interaction between sediment yield and storage in Figure 7.12 also demonstrates that PESERA-PEAT works well under extreme erosion conditions.

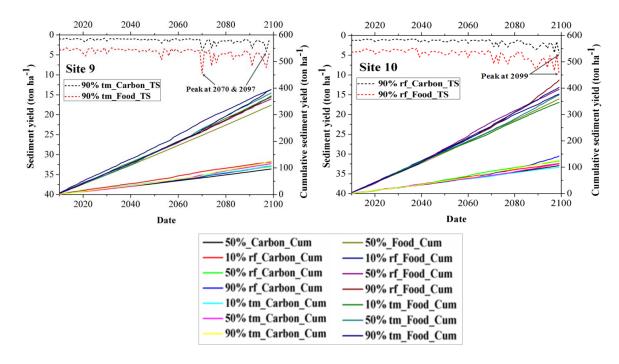
**Table 7.8** Descriptive statistics based on time series of annual erosion (ton ha<sup>-1</sup>) between 2010 and 2099 under environmental scenarios. The highlighted numbers indicate the highest predicted annual erosion for each site under carbon storage and food security scenarios.

inginighted it	imocro			111511	est pred			ii Ci Ob	1011 101			iuci c	di con s			1004	security			
		Site	1			Site	2			Site	3			Site	4			Site	5	
Scenarios	Sum	Min	Max	SD	Sum	Min	Max	SD	Sum	Min	Max	SD	Sum	Min	Max	SD	Sum	Min	Max	SD
50%_Carbon	72.87	0.73	0.91	0.04	74.21	0.73	0.94	0.04	69.03	0.66	0.84	0.04	86.82	0.85	1.08	0.05	109.90	1.08	1.36	0.07
10%rf_Carbon	84.72	0.60	1.45	0.20	75.25	0.72	1.16	0.07	71.42	0.65	1.06	0.08	91.37	0.79	1.76	0.15	116.69	1.00	2.07	0.20
50%rf_Carbon	85.20	0.67	1.67	0.19	77.10	0.68	1.12	0.09	71.39	0.64	1.02	0.08	97.38	0.76	1.88	0.22	129.89	0.98	2.88	0.36
90%rf_Carbon	77.73	0.63	1.52	0.13	73.16	0.68	1.15	0.08	67.21	0.65	0.93	0.06	92.27	0.72	1.63	0.18	112.35	0.96	2.13	0.19
10%tm_Carbon	75.20	0.57	1.24	0.12	79.14	0.71	1.20	0.08	72.79	0.69	1.11	0.07	90.13	0.66	2.02	0.20	116.58	1.01	1.88	0.17
50%tm_Carbon	85.58	0.67	1.78	0.24	73.11	0.64	1.03	0.07	71.34	0.65	1.06	0.07	100.82	0.76	2.74	0.28	131.95	0.90	2.68	0.38
90%tm_Carbon	90.35	0.60	1.70	0.25	78.29	0.71	1.08	0.07	76.77	0.66	1.19	0.11	118.32	0.78	<mark>3.26</mark>	0.48	132.20	0.82	2.75	0.35
50%_Food	282.07	2.93	3.43	0.10	290.01	2.82	3.53	0.13	270.51	2.78	3.19	0.09	315.95	3.23	3.77	0.11	372.86	3.77	4.55	0.20
10%rf_Food	311.30	2.31	4.84	0.49	291.40	2.87	3.92	0.18	278.50	2.70	3.75	0.21	328.79	3.07	5.24	0.36	392.81	3.65	5.72	0.40
50%rf_Food	312.05	2.60	5.00	0.44	296.73	2.88	3.89	0.19	279.56	2.64	3.67	0.20	341.44	3.02	5.66	0.51	412.45	3.58	<mark>7.19</mark>	0.67
90%rf_Food	299.53	2.69	4.79	0.34	285.28	2.80	3.80	0.21	268.02	2.68	3.44	0.15	328.66	2.77	4.98	0.39	382.55	3.66	5.75	0.44
10%tm_Food	291.76	2.52	4.12	0.34	304.68	2.85	<mark>4.09</mark>	0.21	284.41	2.84	3.86	0.18	325.93	2.74	6.77	0.49	396.14	3.59	5.68	0.43
50%tm_Food	311.84	2.74	<mark>6.88</mark>	0.60	283.81	2.70	3.63	0.17	278.79	2.72	3.75	0.18	347.81	2.99	6.55	0.61	417.19	3.30	6.74	0.71
90%tm_Food	321.35	2.49	5.79	0.58	299.34	2.90	3.74	0.19	291.71	2.71	<mark>4.14</mark>	0.27	382.26	3.06	<mark>7.62</mark>	0.91	416.61	3.00	6.40	0.71

**Table 7.8** Continued

		Site	e 6			Site	7			Site	8			Site	9			Site	10	
Scenarios	Sum	Min	Max	SD	Sum	Min	Max	SD	Sum	Min	Max	SD	Sum	Min	Max	SD	Sum	Min	Max	SD
50%_Carbon	92.43	0.90	1.14	0.06	79.99	0.80	0.96	0.04	72.87	0.66	0.92	0.05	95.90	0.88	1.25	0.08	106.19	0.99	1.44	0.10
10%rf_Carbon	126.90	0.86	<mark>8.48</mark>	0.89	91.15	0.73	2.65	0.25	110.63	0.46	2.87	0.48	122.26	0.86	2.85	0.42	114.41	0.90	2.30	0.26
50%rf_Carbon	116.64	0.83	3.41	0.49	79.19	0.71	1.74	0.14	140.51	0.48	7.50	0.91	105.35	0.83	2.74	0.33	123.47	0.83	3.15	0.41
90%rf_Carbon	104.06	0.81	2.88	0.28	81.52	0.70	2.01	0.21	148.52	0.63	4.45	0.72	108.49	0.88	2.43	0.31	142.84	0.88	<mark>4.41</mark>	0.73
10%tm_Carbon	94.22	0.75	4.03	0.36	86.25	0.74	1.95	0.20	138.73	0.46	13.35	1.42	108.56	0.82	2.41	0.32	99.72	0.83	1.77	0.19
50%tm_Carbon	120.86	0.82	5.49	0.62	77.09	0.68	1.47	0.10	127.35	0.70	3.65	0.53	115.79	0.65	2.64	0.41	112.64	0.89	2.32	0.29
90%tm_Carbon	130.97	0.75	5.93	0.77	88.33	0.69	3.01	0.36	140.65	0.63	3.48	0.60	125.11	0.81	<mark>4.17</mark>	0.63	126.85	0.86	3.09	0.43
50%_Food	330.26	3.36	3.95	0.13	310.52	3.10	3.76	0.14	281.04	2.60	3.54	0.20	335.72	3.21	4.17	0.19	359.28	3.55	4.61	0.23
10%rf_Food	402.90	3.19	15.23	1.49	342.27	3.12	6.83	0.53	398.86	1.67	10.49	1.72	394.79	3.21	9.16	0.92	378.04	3.39	6.12	0.52
50%rf_Food	381.84	3.28	7.94	0.95	307.11	2.86	4.81	0.31	491.53	1.33	26.53	3.04	359.44	3.12	6.80	0.65	395.44	3.17	8.22	0.82
90%rf_Food	360.25	3.11	7.06	0.58	314.69	2.87	5.61	0.44	516.03	2.45	14.60	2.35	367.57	3.27	7.04	0.71	431.12	3.21	<mark>9.67</mark>	1.34
10%tm_Food	333.71	3.05	8.52	0.63	338.34	3.15	5.48	0.43	485.61	1.74	<mark>37.69</mark>	4.09	370.67	2.95	6.48	0.71	346.20	3.16	5.14	0.44
50%tm_Food	392.80	3.24	11.19	1.14	308.91	2.86	4.89	0.27	464.01	2.53	13.60	1.86	381.25	2.49	7.43	0.89	374.56	3.40	6.29	0.61
90%tm_Food	407.82	3.00	12.31	1.40	327.99	2.88	<mark>7.43</mark>	0.70	511.79	2.24	11.24	2.13	394.84	3.15	<mark>9.54</mark>	1.14	403.40	3.24	7.77	0.89





**Figure 7.11** Cumulative sediment yield between 2010 and 2099 for each site under established environmental scenarios and time series of annual sediment yield for the scenarios with the highest predicted annual sediment yield. Two groups of cumulative-erosion lines relate to the carbon storage and food security scenarios respectively.

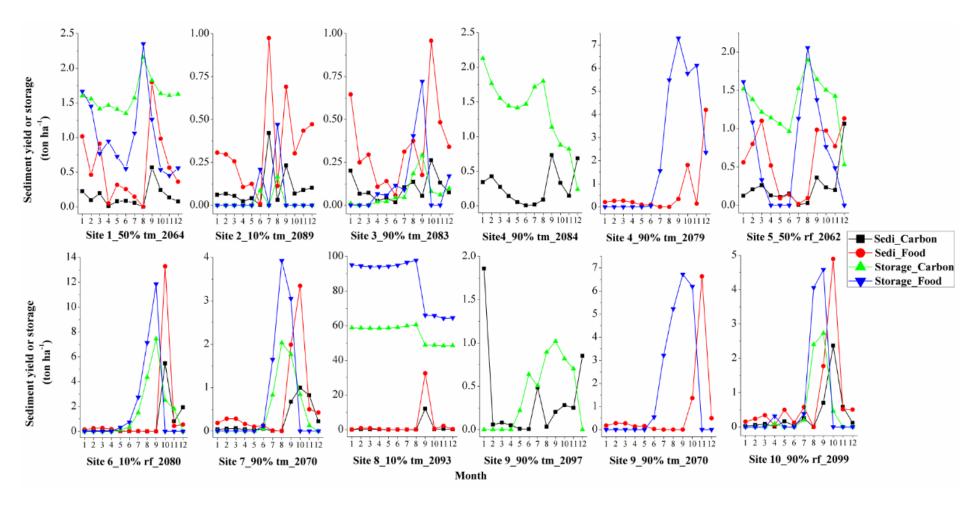


Figure 7.12 Monthly sediment yield and storage for each site in the years with the highest predicted annual sediment yield.

### 7.6.3 *Potential* wildfire severity

For each time period mean *potential* wildfire severity was calculated as the highest value of monthly average *potential* fire severity across thirty summer half years. Figure 7.13 shows the change of mean *potential* wildfire severity between baseline and future periods under climate and land management change. In most cases, mean *potential* fire severity increases between the baseline and future periods. However, some sites may experience decreased mean *potential* wildfire severity from the baseline to future periods such as site 5 in the 2020s for the 50 % rf scenarios, site 8 in the 2020s for the 90 % rf scenarios, site 9 in the 2020s for the 90 % rf and 50 % tm scenarios, site 6 in the 2020s for the 10 % tm scenarios, and site 10 in the 2050s for the 10 % tm scenarios. The largest increase of mean *potential* wildfire severity from baseline to future periods is less than 30 % which is much lower than the change of mean *potential* wildfire severity caused by land management shifts between carbon storage and food security.

The mean *potential* wildfire severity for the selected sites under the carbon storage scenario is plotted against the mean rainfall and temperature over the baseline and future periods in Figure 7.14, where x- and y-axes stand for the range of annual rainfall and temperature for each time period. In terms of Figure 7.14, the highest *potential* wildfire severity emerges at site 8. *Potential* wildfire severity always increases with temperature across the whole ten sites. Rainfall has a more complicated relationship with *potential* wildfire severity. For example, at sites 5, 7, 8 and 10, the lowest *potential* wildfire severity could emerge under a high-rainfall condition, while at sites 9 and 10 *potential* wildfire severity peaks in the wettest condition. The complex pattern between rainfall and *potential* wildfire severity is formed possibly because a wet condition could prevent the origin and spread of wildfire but produces a high fuel load at the same time (Esteves, Kirkby et al. 2012).

Time series modelling is able to produce the potential wildfire severity for every single month over the study period. Table 7.9 presents the descriptive statistics of the time-series of potential wildfire severity for each year, which is represented by the highest monthly potential wildfire severity during summer half year (Apr-Sep), between 2010 and 2099. It shows that potential wildfire severity is systematically

lower under food security than under carbon storage scenarios. This confirms the results shown in Figure 7.13. A lower standard deviation of annual potential wildfire severity under food security scenarios demonstrates that more intensive land management could also make the potential fire severity less peaked. The annual potential wildfire severity is highest at site 8. The specific years with highest predicted annual potential wildfire severity for each site under carbon storage and food security scenarios are presented in Table 7.10. The highest predicted annual potential wildfire severity for each of sites 1, 4, 5, 6, 7, 9 and 10 emerges simultaneously under carbon storage and food security scenarios, while the year with the highest predicted annual potential wildfire severity for each of the other sites (i.e. sites 2, 3 and 8) is different when management conditions change. Site 1 has the highest predicted potential wildfire severity in 2063 for the 50 % tm scenarios, while the predicted annual potential wild fire severity of sites 2 and 5 peaks under 50 % rf scenarios in 2077 (2094) and 2061. Sites 3, 4, 7 and 8 have the highest predicted annual potential wildfire severity under 90 % tm scenarios in 2032 (2098), 2079, 2092, 2083 (2095) respectively. The potential wildfire severity of sites 6 and 9 peaks in 2080 and 2058 under 10 % rf scenarios. Site 10 has the highest predicted annual potential wildfire severity in 2099 for the 90 % rf scenarios (for sites 2, 3 and 8, the number outside the brackets indicate the year with the highest predicted annual potential wildfire severity under the carbon storage scenarios, while the number inside the brackets indicates the year with the highest predicted annual potential wildfire severity under the food security scenarios). Therefore the wildfire may have the potential to become more serious in these years and could bring about more damage to blanket peatlands if it should occur (McMorrow, Lindley et al. 2009; Esteves, Kirkby et al. 2012).

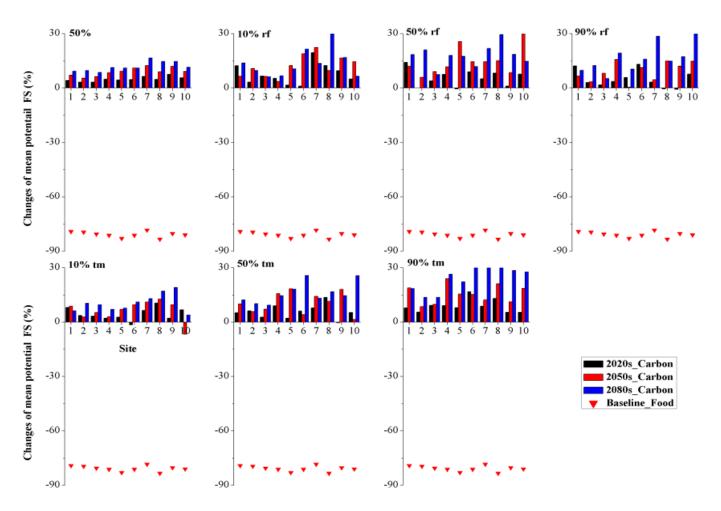
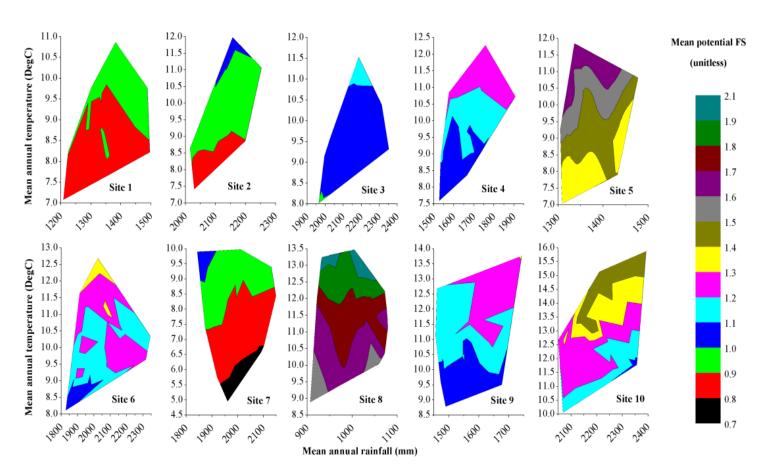


Figure 7.13 Changes in mean *potential* wildfire severity for each site from baseline to future periods under climate and management change.



**Figure 7.14** Mean *potential* wildfire severity under the carbon storage scenario against average annual temperature and rainfall for each site between baseline and 2080s. The legend indicates the classification of *potential* wildfire severity.

**Table 7.9** Descriptive statistics based on time series of annual *potential* wildfire severity between 2010 and 2099 under established environmental scenarios. The highlighted numbers indicate the highest predicted annual *potential* wildfire severity for each site under carbon storage and food security scenarios respectively.

		Site	e 1			Site	e 2			Site	e 3			Site	e <b>4</b>			Site	e <b>5</b>	
Scenarios	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD
50%_Carbon	0.87	0.72	0.96	0.04	0.94	0.77	1.02	0.05	1.08	0.90	1.17	0.05	1.12	0.88	1.24	0.06	1.47	1.18	1.63	0.08
10%rf_Carbon	0.93	0.72	1.24	0.09	0.96	0.73	1.14	0.07	1.12	0.83	1.29	0.08	1.16	0.87	1.55	0.12	1.52	1.08	2.03	0.16
50%rf_Carbon	0.97	0.71	1.21	0.09	0.99	0.73	<mark>1.19</mark>	0.10	1.13	0.82	1.33	0.09	1.21	0.86	1.58	0.14	1.59	1.11	<b>2.12</b>	0.20
90%rf_Carbon	0.90	0.68	1.16	0.07	0.96	0.73	1.15	0.07	1.10	0.88	1.25	0.07	1.20	0.87	1.54	0.14	1.50	1.09	1.92	0.14
10%tm_Carbon	0.90	0.70	1.06	0.06	0.95	0.73	1.11	0.07	1.12	0.85	1.33	0.08	1.15	0.85	1.61	0.12	1.51	1.15	1.88	0.15
50%tm_Carbon	0.93	0.69	1.38	0.10	0.97	0.76	1.14	0.06	1.12	0.86	1.29	0.08	1.22	0.85	1.67	0.15	1.59	1.11	2.08	0.18
90%tm_Carbon	0.97	0.73	1.26	0.10	1.00	0.81	1.13	0.06	1.17	0.88	1.43	0.09	1.29	0.94	<mark>2.09</mark>	0.19	1.63	1.19	2.09	0.18
50%_Food	0.18	0.17	0.21	0.01	0.20	0.17	0.22	0.01	0.21	0.19	0.23	0.01	0.21	0.19	0.24	0.01	0.25	0.22	0.28	0.01
10%rf_Food	0.19	0.17	0.22	0.01	0.20	0.18	0.22	0.01	0.20	0.19	0.22	0.01	0.21	0.19	0.25	0.01	0.25	0.22	0.29	0.01
50%rf_Food	0.20	0.18	0.24	0.01	0.21	0.18	0.25	0.02	0.21	0.19	0.23	0.01	0.22	0.19	0.26	0.02	0.27	0.22	0.33	0.03
90%rf_Food	0.18	0.17	0.21	0.01	0.20	0.18	0.23	0.01	0.20	0.18	0.23	0.01	0.22	0.19	0.26	0.02	0.25	0.22	0.30	0.01
10%tm_Food	0.18	0.17	0.20	0.01	0.19	0.17	0.22	0.01	0.20	0.19	0.22	0.01	0.21	0.19	0.26	0.01	0.25	0.23	0.29	0.01
50%tm_Food	0.19	0.17	0.25	0.01	0.20	0.18	0.22	0.01	0.21	0.19	0.23	0.01	0.22	0.19	0.27	0.02	0.26	0.22	0.32	0.02
90%tm_Food	0.20	0.17	0.24	0.02	0.20	0.19	0.22	0.01	0.22	0.19	0.25	0.01	0.24	0.20	0.34	0.03	0.27	0.23	0.33	0.02

**Table 7.9** Continued

		Site	6			Site	· 7			Site	e 8			Site	9			Site	10	
Scenarios	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD
50%_Carbon	1.19	0.96	1.30	0.06	0.87	0.71	0.97	0.05	1.66	1.36	1.89	0.11	1.14	0.89	1.27	0.07	1.29	1.02	1.46	0.08
10%rf_Carbon	1.34	0.96	2.21	0.19	0.96	0.66	1.39	0.12	1.98	1.42	2.68	0.30	1.25	0.89	1.86	0.17	1.40	1.01	1.82	0.15
50%rf_Carbon	1.33	0.94	2.04	0.20	0.94	0.72	1.36	0.11	1.96	1.16	3.05	0.38	1.19	0.91	1.78	0.15	1.42	1.05	2.04	0.17
90%rf_Carbon	1.30	0.91	1.77	0.16	0.92	0.66	1.38	0.12	1.85	1.23	2.74	0.29	1.19	0.82	1.79	0.16	1.46	1.10	2.12	0.19
10%tm_Carbon	1.24	0.88	2.04	0.15	0.91	0.68	1.26	0.11	1.91	1.42	2.77	0.27	1.18	0.83	1.65	0.16	1.31	0.95	1.73	0.14
50%tm_Carbon	1.36	0.95	2.00	0.20	0.91	0.68	1.19	0.09	1.89	1.31	2.65	0.31	1.23	0.86	1.66	0.16	1.38	0.99	1.78	0.15
90%tm_Carbon	1.42	0.96	2.05	0.20	0.99	0.73	<mark>1.49</mark>	0.13	2.01	1.40	3.26	0.35	1.27	0.91	1.71	0.16	1.44	1.05	1.95	0.16
50%_Food	0.23	0.20	0.26	0.01	0.19	0.16	0.21	0.01	0.28	0.25	0.33	0.02	0.23	0.20	0.26	0.01	0.25	0.22	0.29	0.02
10%rf_Food	0.24	0.19	0.34	0.03	0.19	0.16	0.25	0.01	0.31	0.26	0.41	0.04	0.24	0.20	0.32	0.02	0.26	0.22	0.31	0.02
50%rf_Food	0.24	0.19	0.31	0.02	0.19	0.16	0.24	0.02	0.30	0.24	0.43	0.04	0.22	0.19	0.28	0.02	0.26	0.23	0.35	0.02
90%rf_Food	0.23	0.20	0.30	0.02	0.19	0.16	0.25	0.02	0.29	0.25	0.38	0.03	0.23	0.20	0.31	0.02	0.28	0.22	0.40	0.04
10%tm_Food	0.22	0.20	0.30	0.02	0.18	0.16	0.22	0.01	0.30	0.24	0.38	0.03	0.22	0.19	0.28	0.02	0.24	0.21	0.30	0.02
50%tm_Food	0.24	0.20	0.33	0.03	0.18	0.16	0.21	0.01	0.30	0.25	0.38	0.03	0.24	0.20	0.28	0.02	0.26	0.22	0.33	0.02
90%tm_Food	0.24	0.21	0.33	0.03	0.20	0.17	0.27	0.02	0.33	0.26	0.44	0.04	0.25	0.21	0.31	0.03	0.27	0.22	0.35	0.03

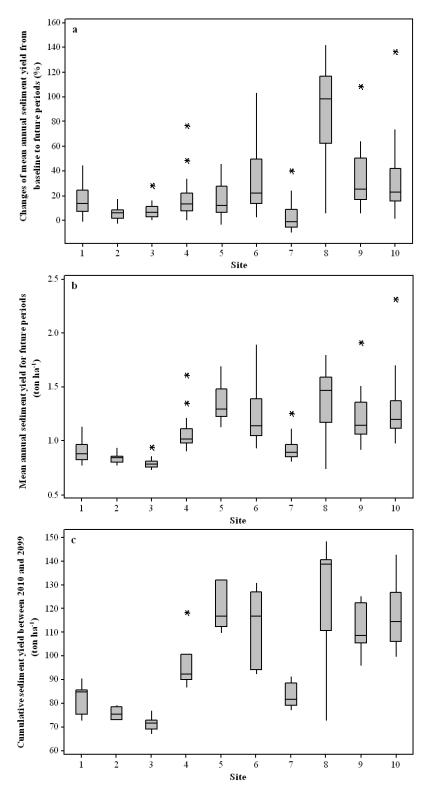
**Table 7.10** The years with the highest predicted annual wildfire severity, corresponding climate scenarios and the highest predicted annual *potential* wildfire severity for each site between 2010 and 2099 under established environmental scenarios.

Site		Carbon stor	age		Food securit	ty
	Year	Climate	Potential FS	Year	Climate	Potential FS
1	2063	50% tm	1.38	2063	50% tm	0.25
2	2077	50% rf	1.19	2094	50% rf	0.25
3	2032	90% tm	1.43	2098	90% tm	0.25
4	2079	90% tm	2.09	2079	90% tm	0.34
5	2061	50% rf	2.12	2061	50% rf	0.33
6	2080	10% rf	2.21	2080	10% rf	0.34
7	2092	90% tm	1.49	2092	90% tm	0.27
8	2083	90% tm	3.26	2095	90% tm	0.44
9	2058	10% rf	1.86	2058	10% rf	0.32
10	2099	90% rf	2.12	2099	90% rf	0.4

# 7.7 Summary and discussion

The time-series version of PESERA-PEAT was applied to ten selected blanket peatcovered sites across GB to explore changes in fluvial blanket peat erosion under
possible variation in climate and land management practices over the 21<sup>st</sup> century.

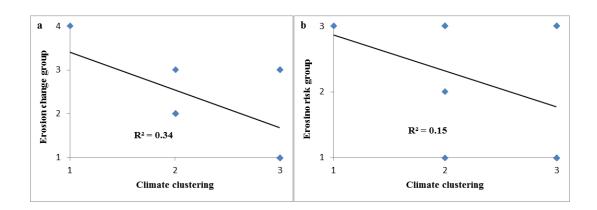
The time-series of monthly baseline climate conditions for each site were calculated
from UKCP09 outputs and then adjusted in terms of monthly statistics of measured
data from MIDAS stations. Seven future climate scenarios derived from UKCP09
median emission outputs were employed to account for the uncertainties in future
climate change. Drainage, grazing and prescribed burning were incorporated to
reproduce possible future land management change in blanket peatlands (Reed,
Hubacek et al. 2013). Eight environmental scenarios were then established for each
future climate scenario to stand for different combinations of possible variations in
climate and land management practices. Runoff production and sediment yield
under the eight scenarios were reported. In addition, *potential* wildfire severity was
also evaluated under the established environmental scenarios.



**Figure 7.15** The impact of climate change on fluvial blanket peat erosion. a) changes in annual sediment yield from baseline to future time periods under carbon storage scenarios shown in Figure 7.9; b) average annual sediment yield for future time periods under carbon storage scenarios shown in Figure 7.10; c) cumulative sediment yield between 2010 and 2099 under carbon storage scenarios presented in Table 7.8.

## 7.7.1 The future of blanket peat erosion in GB under climate change

A summary of erosion change for the ten sites with climate change is shown in Figure 7.15a, where erosion change at the selected sites could be roughly grouped into four classes. Erosion change at site 8 is systematically higher than at other sites, Sites 6, 9, and 10 have the second highest erosion change, sites 1, 4 and 5 have the third highest erosion change. Erosion change at sites 2, 3, and 7 are the lowest and close to zero. At sites 2 and 7, a negative change of erosion is sometimes found (Figure 7.9), implying that these wetter and colder areas are better suited for blanket peat. As a result, future erosion risk (Figure 7.15b and c) for the ten sites could be categorized into three groups: sediment yield from sites 5, 6, 8, 9 and 10 is obviously higher than from other sites; sites 1, 2, 3 and 7 have the lowest erosion risk, and sediment yield from site 4 falls in the middle. Overall, fluvial blanket peat erosion is likely to increase with climate change in most cases with increasing rates generally higher in the southern and eastern (e.g. Site 8) than in the northern and western parts of GB (except site 7).



**Figure 7.16** The relationship between climate clustering and grouping of erosion change and erosion risk. For the climate clustering, the number '1', '2', '3' represents the three climate zones from dry to wet in Figure 7.3; For erosion change / risk group the number '1', '2', '3' and / or '4' represent the groups with the erosion change or erosion risk from low to high as described above.

Figure 7.16 presents the relationship between climate difference and grouping of erosion change and risk described above. The relationship between climate clustering and relative erosion change is stronger than that between climate clustering and erosion risk. The relative erosion change is highest at driest locations,

and lowest at wettest locations. However, similar erosion change could occur even at locations in different climate zones (i.e. two points of erosion change group 3), at the same time, the highest absolute erosion (erosion risk) occurs at all climate conditions. This may be because the blanket peat erosion is impacted not only by the climate conditions but also by the local topography, although the land management was considered to be the same. Therefore, the future relative change and absolute rates of blanket peat erosion may not simply follow the pattern of climate distribution, even if the land management is not changed.

The general spatial pattern of erosion change with climate is consistent with the results from previous bioclimatic envelope modelling results for blanket peatlands using statistical and process-based (PeatStash) bioclimatic models (Gignac, Nicholson et al. 1998; Clark, Gallego-Sala et al. 2010; Gallego-Sala, Clark et al. 2010). Both Gallego-Sala, Clark et al (2010) and Clark, Gallego-Sala et al. (2010) demonstrated that the geographical distribution of climate suitable for blanket peatlands gradually retreats towards the north and west of GB. Model-based studies in Canada have suggested that peatlands in Canada may "migrate" northwards as a result of elevated temperatures and drought (Gignac, Nicholson et al. 1998). However, these bioclimatic modelling results do not determine the eventual fate of existing blanket peatlands left outside their bioclimatic space since the resilience of blanket peatlands to such climate change needs to be accounted for. Modelling results from this chapter may be able to help with assessment of the fate of blanket peatlands outside their suitable bioclimatic space. With climate change in the future, blanket peatlands within the marginal areas will be subject to more erosion and degradation.

The change of mean annual erosion at site 7 does not follow the general spatial pattern of blanket peat erosion change with climate across GB, and is lower than that of sites around it. It is noticeable that site 7 is located in the peak of the Pennines hills (Trout Beck) and has the highest elevation of all sites considered. As a result, it is subject to high rainfall and low temperature (Figure 7.3), which is fundamental for active peat growth (Charman 2002). Previous studies also suggest that peatland

ecosystems at higher latitudes may be less sensitive to a warmer climate in Europe and North America in the future (Meehl and Tebaldi 2004; Bragazza 2008).

### 7.7.2 Climatic drivers of changes in blanket peatlands

Modelling results demonstrate that runoff change is more related to rainfall variance rather than temperature across the ten sites between baseline and three future time periods. This is consistent with the results from previous studies at smaller temporal scales (Evans, Burt et al. 1999; Holden and Burt 2002a; Holden and Burt 2003c; Holden 2005c), which showed saturation-excess overland flow was commonly recognised as a dominant runoff generation mechanism in blanket peatlands, and quick response of runoff to rainfall is the major characteristic of blanket bog stream hydrology.

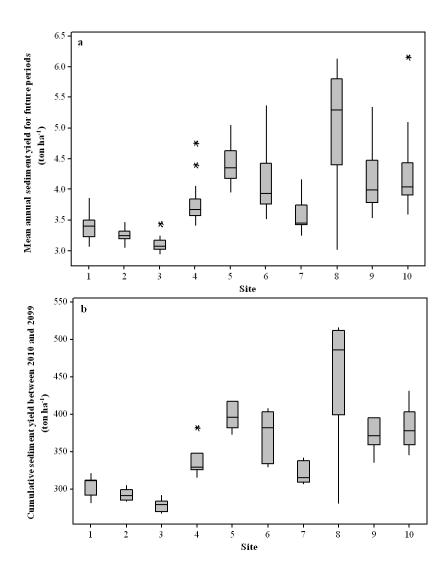
Temperature was demonstrated to be the main climate input variable driving the changes in fluvial blanket peat erosion under UKCP09 projected future climate for most sites (except site 8). Interestingly, Gallego-Sala, Clark et al (2010) found that temperature tended to be more important than rainfall and moisture index in variation of the areal extent of the peat bioclimatic envelope through sensitivity analysis of the PeatStash model dependent of climate scenarios.

The predicted change in sediment yield at site 8 is unusual in the context of the other sites where the increased erosion is the result of increased rainfall, and the highest predicted annual erosion is also coincident with high rainfall (Figure 7.10). This is possibly because the relatively dry and warm condition at this site leads the sediment yield to be transport limited (Figure 7.3). Similar field results were found by Francis (1990), who investigated blanket peat erosion in the Upper Severn catchment, mid Wales during two drought years in the 1980s. In that study, the eroding peat surfaces exhibited maximum recession during the summer, but the peat surface sediment trap indicated that the highest rates of sediment loss from peat faces was coincident with the high rainfall during autumn and early winter. Francis's results also imply that summer desiccation could be a major source of sediment erosion. This indirectly confirms the modelling results shown in Figure 7.12, where

summer desiccation is closely related to the highest predicted annual sediment yield for the selected sites.

# 7.7.3 Interactions between climate change and land management shifts

Modelling results suggest that runoff change with land management shifts (between carbon storage and food security) is smaller than with climate, while land management shifts is more influential than climate change in blanket peat erosion. This is consistent with the result for the North Pennines blanket peatlands presented in Chapter 6. Table 2.2 of Chapter 2 presented the measured blanket peat erosion from blanket peat-covered catchments around the UK. The spatial pattern of the measured erosion does not follow that suggested by the modelling results of this chapter or previous bioclimatic modelling results. This may be because the actual management conditions and gullies were not taken into account in this chapter, inevitably disturbing the climatic impacts on erosion. This may confirm the dominant role land cover play in controlling the magnitude and spatial pattern of blanket peat erosion. Field studies conducted by Ramchunder, Brown et al. (2013) demonstrated that rotational burning had more impact on suspended sediment concentration than on water discharge through comparing the field results from burnt and unburnt peatland sites in northern England. A significant decrease of blanket peat erosion in Rough Sike, northern England between 1960 and 2000 was attributed to re-vegetation of gullies (Evans, Warburton et al. 2006). This indicates the importance of land management and cover type in blanket peat erosion because management options usually impact vegetation cover and connectivity of sediment source areas to stream channels. It is acknowledged that only two extremes of land management scenarios have been examined in the study and that there may be many alternatives in between. Nevertheless, modelling results confirm that careful land management could be used to help partly mitigate the future impact of climatic change on blanket peat erosion, enhancing the resilience of these systems.



**Figure 7.17** Sediment yield from the selected sites under interaction scenarios.

a) boxplots represent average annual sediment yield for each site for future time periods under interaction scenarios; b) boxplots represent cumulative sediment yield for each site between 2010 and 2099 under interaction scenarios presented in Table 7.8.

Figure 7.17 presents a summary of the sediment yield from the chosen sites under interaction scenarios. Erosion risk for sites 5, 6, 8, 9 and 10 is systematically higher than that for other sites. Additionally site 8 has apparently higher erosion than sites 5, 6, 9, and 10. Sites 1, 2 and 3 have the lowest erosion compared to other sites. This may imply that under climate change in the future more careful and protective land management practices should be undertaken in GB blanket peatlands in order to

reduce erosion risk from climate change. However, the spatial distribution of erosion risk at the selected sites under different management conditions may also imply that sites 5, 6, 8, 9 and 10 may be more suitable for being managed for carbon storage compared to other sites. If there was a national food security disaster in the future then sites 1, 2 and 3 might be more suited for food security management if necessary. Site 4 could be managed for food or carbon according to the actual demand. Erosion at site 7 under carbon storage scenarios is lower than at site 4 and in the lowest group, while erosion at site 7 is about same as at site 4 and in the middle group under interaction scenarios. This demonstrates that site 7 is more suitable for carbon storage management.

The established land management changes have much more impact than predicted climate change on potential wildfire severity. Lower intensity of land management leads to enhanced potential wildfire severity, and such an impact is opposite to the impact of land management shifts on sediment yield. Modelling results from other soil system have suggested that infrequent wildfire could result in more sediment loss than frequent managed burning (Esteves, Kirkby et al. 2012). So wildfire-awareness should be taken when blanket pealtlands are managed (McMorrow 2011). More work is still desirable on the interactions between wildfire and land management practices.

#### 7.7.4 Limitation of the work

In this chapter, the gully-caused drainages were not incorporated in the "Base Condition" with the method employed for the Upper North Grain catchment in Chapter 5. This is because, as stated in Chapter 6, 1) the method used for incorporation of gully system in the Upper North Grain catchment was actually a compromise since the spatial distribution of gullies, gully width and gully depth were set to constants; 2) the parameters required by the drainage model for gullies are difficult to achieve. However, absence of natural gullies in the modelling work may add some uncertainties to the modelling results since lowered water table due to drainage will increase the sediment production, and restrict the transporting capacity

of water flow by decreasing the runoff production. Therefore, the natural gully systems should be incorporated accurately in the future application of the model.

# **Chapter 8**

# **Conclusions**

# 8.1 A synthesis of the findings of the thesis

The aim of this project was to understand "how fluvial blanket peat erosion mechanisms and rates may change under climate and management practices (artificial drainage, burning and grazing) through the 21<sup>st</sup> century". A modelling approach was used as it enables investigation of future scenarios of changes of climate and land management without impossibly laborious and expensive long-term field experiments (Chapter 2). In the project, the grid version of the PESERA model (PESERA-GRID) was chosen (Chapter 3) for further development to produce an erosion model for blanket peatlands (PESERA-PEAT). Figure 8.1 summarizes the modelling work that has been done in the project. The hydrology and vegetation growth modules of PESERA-PEAT are exactly the same as those of the PESERA-GRID model (Chapter 4), which have been shown in red in Figure 8.1, focused on two aspects: 1) incorporation of appropriate sediment production mechanisms that dominate in blanket peatlands (i.e. freeze-thaw and desiccation); 2) parameterization of typical land management practices in blanket peat-covered areas.

A novel sediment supply index, which is defined as sediment concentration per unit runoff, was used to relate freeze-thaw and desiccation with climatic and soil moisture conditions. The sediment supply index was based on a sediment rating curve, which had been demonstrated previously to be a good indicator of sediment production in blanket peat-covered catchments (Yang 2005; Evans and Warburton 2007). The resulting regression equations were then aggregated into the model to account for sediment production from blanket peatlands by examining actual sediment production measured at Rough Sike (a tributary of Trout Beck), northern England. The erodibility of weathered blanket peat was considered to be higher than that of freshly exposed blanket peat. As a result, the erosion processes in the

PESERA-PEAT model are composed of sediment supply, sediment transport and sediment storage. This is opposed to just a final sediment yield which, in the original PESERA-GRID model, is simply calculated as the transporting capacity of overland flow.

In the PESERA-GRID model, only grazing was originally considered via its impact on vegetation cover and biomass. In this thesis, artificial drainage and managed burning were incorporated into the model through the PESERA drainage model (Beharry-Borg, Hubacek et al. 2009) and vegetation cover and biomass were completely removed in the patches caused by rotational prescribed burning (Defra 2007). Potential wildfire severity was estimated by PESERA-PEAT with an ignition model based on the predicted vegetation biomass and climate conditions (Venevsky, Thonicke et al. 2002).

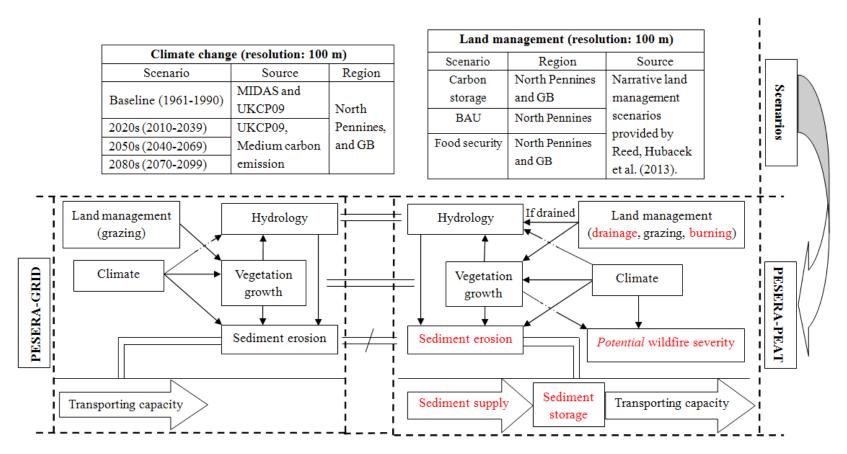
The PESERA-PEAT model was evaluated with field data from three blanket peat-covered catchments and previously published data, considering spatial scaling impacts on the magnitude of runoff and sediment measurements (Chapter 5). Model testing showed that the model could predict blanket peat erosion well. The verified PESERA-PEAT was then applied in blanket peatlands of the North Pennines, and ten blanket peat-covered sites across Great Britain (GB) (Chapters 6 and 7). Climate change to the end of the century was derived from the UKCP09 and Met Office's historical (1961-1990) meteorological data. A major undertaking for the project was to downscale climate data for use in the spatial model. Possible changes in land management practices were based on quantification of narrative land use scenarios resulting from previous investigations (Reed, Arblaster et al. 2009; Reed, Bonn et al. 2009; Reed, Hubacek et al. 2013).

Through model development and testing in Chapters 4 and 5, it has been demonstrated that:

- The PESERA-PEAT model is robust in blanket peat erosion modelling.
- > The sediment supply index is a useful tool for indicating the sediment supply capacity of blanket peatlands;

Through application of PESERA-PEAT in blanket peatlands of the North Pennines and over GB in Chapters 6 and 7, it has been demonstrated that:

- ➤ The response of blanket peat erosion to climate change is spatially very variable both within the North Pennines and across GB. Generally, changes in blanket peat erosion are predicted to be higher in southern and eastern areas than in western and northern parts of GB, peaking in eastern England (North York Moors), where relatively lower rainfall and higher temperatures under climate change leads the erosion to be transport limited.
- Change of blanket peat erosion with climate change becomes smaller in wetter and colder places;
- As climate changes, rainfall is more important than temperature in shaping longterm changes of runoff production while temperature appears to be more dominant than rainfall in controlling long-term peat erosion change. However, in the North York Moors rainfall appears to be more dominant in long-term erosion change;
- ➤ Summer desiccation may become a more important sediment source for GB blanket peat erosion in the future, leading to more sediment erosion released from blanket peatlands during subsequent rainstorms;
- ➤ Land management has stronger impacts on blanket peat erosion than on runoff, while climate plays a more important role in runoff production rather than in blanket peat erosion. Land management practices can act as a good tool in mitigating the impacts of climate change on blanket peat erosion, although wildfire-awareness should be promoted when blanket peatlands are rewilded.



**Figure 8.1** A synthesis of the modelling work in the project. Red indicates where significant modifications to the PESERA-GRID model have been undertaken. The top boxes indicate the scenarios that were modelled. Note that mixed climate and land management scenarios were also included.

# 8.2 The role of this research in blanket peatland geomorphology

The major contributions of this research to the geomorphology of blanket peatlands can be summarized through four components: 1) a quantitative description of sediment production mechanisms in blanket peatlands; 2) a first attempt in developing a model for blanket peat erosion; 3) determining implications for peatland management and restoration; 4) key implications for inference from site-based studies.

# 8.2.1 Sediment production

In this project, the sediment supply index has been successfully applied to parameterize the sediment supply from blanket peatlands at a monthly scale based on field data from the Trout Beck catchment, northern England between 1997 and 2009. Meanwhile, the sediment supply index could potentially be used for parameterization of sediment supply at an event scale as it is conceptually based on the slope of sediment rating curves, which is indicative of sediment supply status in small catchments based on data from individual storms (Yang 2005; Evans and Warburton 2007). This is to say, the sediment supply index could potentially be used to establish sediment supply modules for other existing erosion models which are hydrologically suitable for blanket peatlands such as LISEM and CAESAR etc.. Such an application could facilitate these models to capture blanket peat erosion processes (supply-limited and transport-limited) better, providing more flexibility in modelling them at various scales, both spatial and temporal.

### 8.2.2 Modelling approach

There has been little effort made, to date, to simulate blanket peat erosion. Only two studies were found: 1) May, Place et al. (2010) modelled soil erosion and transport in a typical blanket peat-covered catchment in County Mayo, on the northwest coast of the Republic of Ireland. In the model, USLE was employed for sediment production, while a delivery ratio determined the amount of eroded soil that entered the drainage network. 2) The CAESAR model has been applied to an upland catchment, which is partly covered by peat, to investigate the impacts of climate and land use change on sediment loss (Coulthard, Kirkby et al. 2000; Coulthard, Hicks et al. 2007). USLE only takes into account of detachment of soil by rainfall drops

(Stone and Hilborn 2000), while CAESAR considers the shear stress of overland flow as the major sediment production mechanisms (Coulthard, Kirkby et al. 2000). Therefore, these studies did not include the major sediment production mechanisms (freeze-thaw and desiccation) that occur in blanket peatlands. Moreover, none of the contemporary erosion models were capable of describing the sediment production mechanisms in blanket peatlands (Chapter 3).

This thesis provided the first attempt to build a model (PESERA-PEAT) for blanket peat erosion. In the model, erosion has been represented by two phases: 1) sediment production; and 2) sediment transport. Sediment production is driven by freeze-thaw and desiccation, which are described as a function of temperature and water table. Sediment transport is calculated as a function of overland flow, soil erodibility, and local relief. Both the sediment production and transport are heavily impacted by the vegetation cover. The major advantage of the PESERA-PEAT model is that all the erosion produced by PESERA-PEAT is originally generated by freeze-thaw and desiccation, which is not considered in any other existing erosion models. The model describes sediment supply and transport separately, and final sediment yield is calculated as the balance between sediment supply and transport. This characteristic enables the modelled erosion to be switched between supply-limited and transport-limited forms, better reproducing the erosion processes of blanket peatlands.

# 8.2.3 Peatland management and restoration

Modelling results have demonstrated that land management could be an effective way of mitigating the impact of climate change on blanket peat erosion. Peatland landscapes are sensitive to land management interventions, and erosion protection should focus on controlling management activities in climate areas that are marginal for peatlands over the next 100 years (Chapters 6 and 7). Less intensive management in the form of grazing, drainage and burning could help with the recovery of blanket peatland vegetation cover and water table (Grayson, Holden et al. 2010; Holden, Wallage et al. 2011) making sites more resilient to climate change influences on peat erosion. Peatland restoration techniques are often adopted to reduce peat erosion (Parry, Holden et al. 2014). Dams and re-vegetation are the most widely applied means of restoring eroded peat (Holden, Shotbolt et al. 2007). Such methods are

prevalent mainly because they break the connectivity between hillslopes and channels, so less sediment reaches the catchment outlet (Evans and Warburton 2007). However, they may not reduce erosion on hillslopes effectively, and less attention has been given to investigations of the change of peat erosion on hillslopes after the re-vegetation of gully floors and / or blocking the gullies with dams. The PESERA-PEAT model may offer an opportunity to implement such an investigation, promoting the effectiveness of peat restoration strategies and usage of the limited funding. The model is able to provide a sediment budget for blanket peat erosion on hillslopes. Such a budget is composed of three parts, which are the sediment production, sediment storage and sediment yield. So the impacts of peat restoration methods on each part of the sediment budget could be evaluated with the model. This is to say, the model could not only reflect the change of sediment yield at base of hillslopes after re-vegetation and blocking of gullies, but also link these restoration practices with sediment production in blanket peatlands. This is important as, in theory, sediment erosion in blanket peatlands comes from erodible materials produced by sediment production mechanisms.

# 8.2.4 Implications for inference from site-based studies

The impact of climate change on blanket peat erosion varies within the North Pennines (Chapter 6) and between different sites over GB (Chapter 7). For example, in terms of the modelling results, the erosion change in the North Pennines was negative (less erosion) under some climate change scenarios, while a 150 % increase of sediment yield could be detected in North York Moors under climate change scenarios. At the same time, the impact of land management practices on blanket peat erosion also showed difference among sites across GB (Figure 7.9). This result suggests that examining environmental change modelling results from one site or catchment area and assuming these findings may apply elsewhere would be a mistake. Trout Beck (within the North Pennines) appears to be least sensitive to potential climate change of the ten sites investigated. Notably it is also a site where there is a rich background of data. However, these findings warn against making broad assumptions from single-site-based modelling analyses of future environmental change impacts on peatland systems. It is thus suggested that such modelling needs to be conducted across different spatial regions nationally and internationally.

# 8.3 Limitations of the work

#### 8.3.1 Processes involved in the PESERA-PEAT

The PESERA-PEAT model treats the studied area as a cascade of hillslopes. Theoretically it only considers the soil loss driven by overland flow on hillslopes such as rill and sheet erosion, which are the dominant mechanisms controlling sediment flux from eroding peatland systems (Evans and Warburton 2007). However, the base sediment and runoff data used for establishing sediment supply indices were collected at the outlet of Trout Beck catchment between 1997 and 2009. The model was also evaluated with data originally collected at other catchment outlets. This means the sediment budget predicted by PESERA-PEAT is actually a lumped version of erosion caused by both hillslope and channel processes such as gully erosion, sheet erosion, pipe erosion, river bank erosion, and mass movement (if it happened in the Trout Beck catchment during the study period) etc. In fact, this was a compromise during model development mainly because data from the Trout Beck catchment were of best quality compared to other datasets available from UK sites, and there were no data to support incorporation of each erosion process into the model separately. In future studies, more process-based descriptions and datasets of mass movement, river bank erosion (especially the occurrence of peat blocks), and pipe erosion in the model is still needed. By doing so, a more detailed sediment budget in relation to separate processes could be derived.

The PESERA-PEAT model, at present, only accounts for the erosion driven by running water and so wind erosion processes are currently not included. However, wind erosion is an important component of blanket peat erosion in the UK (Warburton 2003; Evans and Warburton 2007) as strong winds are a characteristic feature of UK upland areas. Besides, wind-splash, which is usually highest when heavy rainfall is combined with high wind-speeds (Baynes 2012), may become more important in winter months in the future, given that the UK will experience wetter and stormier winter (UKCP09 2009). Meanwhile, future climate projections also suggested that more frequent dry weather would occur during the summer months over the next 100 years (UKCP09 2009), possibly leading to dry blow processes of erosion becoming more prevalent in UK upland areas (Foulds and Warburton 2007a). Hence a more comprehensive and accurate prediction of changes in blanket

peat erosion would be achieved if the wind erosion processes could be incorporated into the model in the future.

# 8.3.2 Parameterization of management practices and gullies

Currently burning and grazing have been parameterized as vegetation cover and biomass removal in the PESERA-PEAT model (Chapter 4). This method is subject to shortfalls as it does not directly consider the impacts of burning and grazing on the hydraulic properties of soil in blanket peatlands such as infiltration rates, soil moisture content, hydrological connectivity etc. (Worrall, Armstrong et al. 2007; Worrall and Adamson 2008). Unfortunately, however, results from previous studies were inconclusive for mathematical modelling of the reaction of peat properties to burning and grazing. Hence more research effort in this area is desirable.

Drainages driven by natural gullies were not considered in Chapters 6 and 7 mainly due to the parameters required by the drainage model were not achieved and the commonly used methods to achieve these parameters are unrealistic in terms of the scale of the project. However, absence of natural gullies negatively impacts the reasonability of the modelling results, and forms a limitation of this modelling approach. The accurate incorporation of gully systems is therefore expected in the future model application.

### 8.3.3 The impacts of vegetation on blanket peat erosion

In the project, model evaluation suggested that vegetation cover reduced sediment yield by 95 %, confirming that re-vegetation of bare ground is very clearly the most effective way of reducing blanket peat erosion (Evans, Warburton et al. 2006). However, the reliability of this result (95 %) was not validated with field data as there was no study directly investigating the impacts of vegetation cover on blanket peat erosion. Moreover, the value was obtained assuming that all vegetation types had the same impact on the transport capacity of overland flow if the vegetation cover was the same. However, this may be not the case given that the velocity of overland flow, which significantly affects the stream power of overland flow (Moore and Burch 1986), varies with vegetation cover types in peatlands (Holden, Kirkby et al. 2008). Moreover, in PESERA-PEAT, it is assumed that the impact of vegetation cover on sediment production and transport are the same. However, there is no

direct evidence to support whether this is reasonable as previous studies have usually focused on the impacts of vegetation cover on the final sediment yield rather than on the different phases of erosion processes (i.e. sediment production and transport) in blanket peatlands. More process-based research is thus needed to better understand blanket peat erosion under different vegetation cover types.

### 8.4 Recommendations for further research

In order to further investigate the change of blanket peat erosion under climate and management practices, there are a number of recommendations for future research. These may be divided into two sections: field investigations and modelling.

# 8.4.1 Field investigation

Future research on field investigations of blanket peat erosion should focus on:

### Improved understanding of erosion processes in blanket peatlands

To improve understanding of erosion processes in blanket peatlands, there should be process-based studies on different types of erosion and a greater body of work is required on understanding sediment production mechanisms more comprehensively. In order to fulfill the former, long-term observations on erosion processes of blanket peat-covered catchments are needed. The methods presented by Evans and Warburton (2005) and Evans, Warburton et al. (2006) for establishing a catchment sediment budget would be helpful. However, they need to be updated to include more erosion processes in blanket peatlands such as pipe erosion and mass movement. With regard to the latter, field data from more sites across the world are needed to assess the relationships between sediment production and climate and soil moisture content. Analysis of field measurements from the Trout Beck catchment between 1997 and 2009 demonstrated that freeze-thaw and desiccation are related to not only the length of temperature below freezing and drought, but also the freezing level and strength of drought. Attention should be paid to this point when establishing sediment production equations in the future.

### More field data collection to improve model evaluation

The available measured runoff and erosion data from blanket peatlands are usually at a catchment scale, so downscaling equations were employed to offset the scaling impact on the magnitude of field data during model calibration and validation.

However, long-term observational data on runoff and sediment flux from blanket peatlands at catchment scales are rare as well. So the available data were used and there was little choice in being able to select the best quality data. Therefore, more field observations on hillslope hydrology and erosion in blanket peatlands are urgently needed. These data would help to improve the accuracy of model calibration and validation.

➤ A better understanding of the impacts of burning and grazing on blanket peat ecosystems, and interactions between wildfire and land management strategies.

More research effort is needed to more thoroughly understand the impact of burning and grazing on soil properties of blanket peatlands. Modelling results in Chapters 6 and 7 also confirmed that more work is required to understand the interactions between wildfire and land management practices.

➤ More process-based field studies to understand the impacts of different vegetation types on the blanket peat erosion.

# 8.4.2 Modelling

- ➤ Operating the PESERA-PEAT model in different spatial regions of the UK and internationally;
- ➤ A better incorporation of peat erosion processes into the PESERA-PEAT model such as pipe erosion, mass movement, river bank erosion and wind erosion.
- ➤ Producing sediment production modules for erosion models at a smaller scale for modelling blanket peat erosion processes in more detail.

# 8.5 Overview of the project

This PhD project concentrated on modelling blanket peat erosion under environmental change. An erosion model for blanket peatlands (PESERA-PEAT) was established, being the first such model for peatlands to the author's knowledge. The model specifically incorporated freeze-thaw and desiccation processes. PESERA-PEAT was deemed to be suitable for investigating the potential response of blanket peat erosion to climate change and land management shifts. Such a model may be a useful tool, which can now be adopted by policy makers to support planning of land-use strategies in blanket peatlands of the UK. Application of PESERA-PEAT across the North Pennines and GB provided useful evidence of the

potential changes in erosion rates under climate and land use change scenarios. It also provided some useful lessons about the value of studying a wide range of sites and applying models across large areas rather than inferring future trajectories nationally based on results from single sites.

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