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PESERA-PEAT: a fluvial erosion model for blanket peatlands

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Abstract:

In peatlands, fluvial erosion can lead to a dramatic decline in hydrological function, major changes in the net carbon balance and loss of biodiversity. Climate and land management change are thought to be important influences on rates of peat erosion. However, sediment production in peatlands is different to that of other soils and no models of erosion specifically for peatlands currently exist. Hence, forecasting the influence of future climate or spatially-distributed management interventions on peat erosion is difficult. PESERA-GRID was substantially modified in this study to include dominant blanket peat erosion processes. In the resulting fluvial erosion model, PESERA-PEAT, freeze-thaw and desiccation processes were accounted for by a novel sediment supply index as key features of erosion. Land management practices were parameterized for their influence on vegetation cover, biomass and soil moisture condition. PESERA-PEAT was numerically evaluated using available field data from four blanket peat-covered catchments with different erosion conditions and management intensity. PESERA-PEAT was found to be robust in modelling fluvial erosion in blanket peat. A sensitivity analysis of PESERA-PEAT showed that modelled sediment yield was more sensitive to vegetation cover than other tested factors such as precipitation, temperature, drainage density and ditch/gully depth. Two versions of PESERA-PEAT, equilibrium and time-series, produced similar results under the same environmental conditions, facilitating the use of the model at different scales. The equilibrium model is suitable for assessing the high-resolution spatial variability of average monthly peat erosion over the study period across large areas (national or global assessments), while the time-series model is appropriate for investigating continuous monthly peat erosion throughout study periods across smaller areas or large regions using a coarser-spatial resolution. PESERA-PEAT will therefore support future investigations into the impact of climate change and management options on blanket peat erosion at various spatial and temporal scales.

Key words: freeze-thaw, desiccation, land use, climate change, wetlands, peat

1. Introduction

Peat is an organic-rich soil resulting from impeded vegetation decomposition under waterlogged conditions. Approximately 4 million km^2 of peatlands store one third to half of the world's soil carbon (Yu, 2012). Blanket peatlands are a type of bog (rainwater-fed peatland) which can occur on sloping terrain if there is sufficient rainfall and impeded subsurface drainage. They typically occur in hyper-oceanic regions (Charman, 2002; Gallego-Sala and Prentice, 2012). Erosion of blanket peat has been reported globally over the past 60 years but particularly in parts of Britain and Ireland (Evans and Warburton, 2005), the Falkland Islands (Wilson et al., 1993), and Sweden (Foster et al., 1988). In Britain and Ireland, the level of blanket peat erosion is high compared to some locations, which is thought to be driven by human disturbance combined with climatic drivers (Evans and Warburton 2007). Peat erosion has negative impacts on terrestrial and aquatic habitats (Ramchunder et al., 2009), reservoir capacity (Labadz et al., 1991), water quality (Rothwell et al., 2005) and carbon sequestration (Pawson et al., 2012).

Freeze-thaw and desiccation processes are dominant sediment production mechanisms in blanket peatlands (Francis, 1990; Labadz, 1991) while frequent and widespread occurrences of saturation-excess overland flow, strong winds and mass movement promote sediment transport (Evans and Warburton, 2007). Frost is common in cool, wet, upland climates coinciding with blanket peat deposits, providing conditions conducive to the development of needle ice (Evans and Warburton, 2007). The growth of needle ice can lead to a ‘fluffy’ peat surface, which is loose and granular and is usually transported to the stream as particles or small aggregates of particles. Desiccation usually occurs during dry periods of perhaps a week or more, leading to platy aggregates. These aggregates are hydrophobic and much lower in density than the material produced by frost action (Ingram, 1983). They are transported as large floating particles when overland flow occurs.

Vegetation cover is important to protect the peat surface from erosion. However, when surface vegetation is removed, weathering processes generate a greater volume of erodible materials (Holden et al., 2007a; 2007b; Shuttleworth et al., 2015), and high rates of connectivity can be established between sediment source zones and river channels in blanket peatlands (Evans et al., 2006; Evans and Warburton, 2007). Wind erosion usually takes the form of wind-driven rainsplash and dry blow processes (Warburton, 2003; Foulds and Warburton, 2007a; 2007b; Baynes, 2012). Vegetation cover may be influenced by environmental disturbances such as unsympathetic management and climate change (Evans and Warburton, 2007). Management practices include artificial drainage, prescribed burning and grazing, all of which can result in changes to vegetation cover and the hydraulic properties of the peat (Holden, 2008; Holden et al., 2014) altering rates and types of sediment production and transport (Holden et al., 2007a; 2007b).

Previous studies have shown that some historical phases of enhanced blanket peat erosion have been driven by climate change (Tallis, 1998; Tallis et al., 1997). Bioclimatic modelling for blanket peat-covered areas suggests that many may no longer be under a climate suitable for active peat growth by the end of 21st century (Gallego-Sala et al., 2010; Gallego-Sala and Prentice, 2012). Therefore, enhanced degradation and erosion may occur as currently favourable zones for peat formation shift towards being marginal for continued peat growth. Such degradation could be exacerbated or mitigated by peatland management practices including the alteration of grazing density, managed burning frequency or the creation or removal of artificial drainage. The outcomes of the bioclimatic modelling for blanket peatlands show that we urgently need to understand the long-term risk of blanket peat erosion to future environmental change. Such predictive information could support decision-making, facilitating national and regional policy to increase peatland resilience.

There has been a long history of soil erosion model development (Merritt et al., 2003; Aksoy and Kavvas, 2005). Existing erosion models usually take account of rainfall, hydrology, topography, land use / cover and soil properties as controlling factors of soil 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, such as Universal Soil Loss Equation (USLE) and its modifications (Wischmeier and Smith, 1965; 1978; Renard et al., 1991), have been widely applied to predict soil erosion. However, little effort has been made, to date, to simulate blanket peat erosion. We could only identify two modelling studies for blanket peat erosion (May et al., 2010; Coulthard et al. 2000). May et al. (2010) modelled soil erosion and transport in a typical blanket peat-covered catchment on the northwest coast of the Ireland. In that study, USLE was employed for sediment production, while a delivery ratio determined the amount of eroded soil that entered the drainage network. The Cellular Automaton Evolutionary Slope And River (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 et al. 2000). USLE only considers the detachment of soil by rain drops (Stone and Hilborn 2000), while CAESAR treats the shear stress of overland flow as the major sediment production mechanism (Coulthard et al. 2000). Neither of these studies took account of the dominant sediment production processes in blanket peatlands of freeze-thaw and desiccation.

In this paper, we use empirical data from the literature, and from our own field studies, to inform the development of a process-based model of peatland fluvial erosion. The model is based upon the grid version of the Pan-European Soil Erosion Assessment model (PESERA-GRID) (Kirkby et al., 2008), with which we have made substantial modifications to ensure its suitability for the blanket peatland case. We evaluate the new model (PESERA-PEAT) through a sensitivity analysis and by using field data from several blanket peat-covered sites under different erosion conditions and management intensities.

2. Model selection and proposed modifications

2.1 Model selection

Given that there are many established erosion models, some of them may already be partly suited to blanket peatland studies, subject to some modifications. This may be more efficient than developing a new model from scratch. In order to determine whether there was a promising model in the literature suitable for adaption to blanket peat erosion, six criteria were adopted. The model needed to: (i) be physically-based so that the new peat erosion model can be applied widely; (ii) be able to simulate saturation-excess overland flow, which is the dominant runoff-generating mechanism in blanket peatlands (Evans et al., 1999); (iii) be capable of describing typical sediment production (i.e. freeze-thaw and desiccation) and transport processes in blanket peatlands; (iv) be suitable for operation over long-term temporal scales and multiple spatial scales to capture climate change impacts among inter-annual variability and to ensure that land managers have access to catchment-scale, regional and national assessments from the same model; (v) use input climate variables which are readily available from climate model datasets so that climate change impacts on erosion processes such as freeze-thaw, desiccation and sediment transport can be studied based on credible climate model data; and vi) be suitable to include impacts of typical land management practices that occur in blanket peatlands such as grazing, prescribed burning and artificial drainage.

From a survey of the literature, including the models summarised by Merritt et al. (2003) and Aksoy and Kavvas (2005), no models met all of the above criteria (Table 1). In particular, there was a lack of models that explicitly considered freeze-thaw and desiccation processes. However, the grid version of the PESERA model (PESERA-GRID), developed by Kirkby et al. (2008), appeared to be more promising than other existing models as it met five of the six criteria. PESERA-GRID is process-based and capable of reproducing saturation-excess overland flow generation. Key process drivers and parameters have been retained within the model such as climate and vegetation, meaning there is good potential for modification for peatland water-related erosion. PESERA-GRID can operate over a range of spatial scales (i.e. hillslope, regional, national and global) and long time periods (i.e. months to centuries). The climate variables used in PESERA-GRID can be easily derived from outputs of global and regional climate models such as UKCP09 projections (UKCP09, 2009), facilitating an investigation of climatic impacts. Land management such as grazing has already been considered within PESERA-GRID (Kirkby et al., 2008). PESERA-GRID is also theoretically capable of addressing other management treatments if suitably modified. For example, the point version of the PESERA model (PESERA-POINT), which has the same conceptual framework as PESERA-GRID, has previously been modified to account for the impacts of artificial drainage (Beharry-Borg et al., 2009).

2.2 PESERA-GRID

PESERA-GRID consists of three modules: hydrology, erosion and vegetation growth. They will briefly be introduced here but note that their detailed description can be found in Kirkby et al. (2008).

2.2.1 Hydrology

The hydrological sub-model of PESERA_GRID is centred on a water balance, where the precipitation is divided into overland flow, evapotranspiration and changes in soil moisture storage. Overland flow was estimated as a proportion of rainfall exceeding the runoff threshold, which usually equals the soil moisture deficit when the model is applied to blanket peatlands. The proportion, which ranges between 0 and 1, was set to 1 in this study, representative of the quick response of runoff to rainfall in blanket peatlands (Evans et al., 1999). Interception of the vegetation canopy was estimated as a fraction of rainfall and this fraction increases with vegetation biomass. Evapotranspiration was partitioned into plant transpiration and bare-soil evaporation. For each component, potential evapotranspiration (PET) was firstly adjusted by a unitless water use efficiency index (WUE) ranging between 0 and 1, and then reduced exponentially at a rate of soil moisture deficit divided by rooting depth, to an actual rate. WUE was set to 0.3 for vegetated areas in our study since Wallace et al. (1982) demonstrated that plant transpiration could be 25-50 % of PET in heather moorland, and 1 for bare ground (Kirkby et al., 2008). Root depth, ranging between 10 and 1000 mm, was set according to land cover type for vegetated areas and 10 mm for bare ground (Kirkby et al., 2008). Soil moisture deficit was calculated monthly using TOPMODEL expressions, and subsurface flow was estimated as the monthly change of soil moisture deficit (Kirkby et al., 2008).

2.2.2 Vegetation growth

The vegetation growth model primarily estimates gross primary productivity, soil organic matter and vegetation cover based on the biomass carbon balance (Kirkby et al., 2008). In the model, gross primary productivity was estimated as a proportion of the actual transpiration from the plant, and then offset by respiration, which increases exponentially with temperature and proportional to vegetation biomass. Leaf fall fraction was a decreasing function of biomass, and for deciduous plants extra leaf fall was achieved at a rate that increases with temperature if respiration was greater than gross primary productivity. Soil organic matter increased with leaf fall, and decomposed at a rate increasing with temperature. Cover converged on an equilibrium value, which was defined as the ratio of plant transpiration to potential evapotranspiration, at a rate that was larger where biomass was small.

2.2.3 Sediment yield

In PESERA-GRID, sediment yield is interpreted as the erodible material transported to steam channels, while sediment delivery through the river system is explicitly not taken into account. Total sediment yield was estimated as the transporting capacity of overland flow, which was driven by erodibility, overland flow and local relief, weighted for fractional vegetation cover, assuming erodible materials were always ample for runoff wash.

2.3 Proposed modifications to PESERA-GRID

Blanket peat erosion is usually supply-limited since intact peat is fairly resistant to erosive agents (Evans and Warburton, 2007). For example, overland flow above 5.7 m s^{-1} is required to produce erosion on freshly exposed peat within channelized drainage ditches (Carling et al., 1997). Sediment flux from peatlands tends to be close to zero after the weathered surface is removed (Evans and Warburton, 2007). It may therefore be reasonable to view fluvial erosion in blanket peatlands as a result of the balance between sediment supply and the transporting capacity of runoff, and such a balance is often disturbed by high densities of gullies and channels. However, in PESERA-GRID only the transporting capacity is taken into account (Kirkby et al., 2008), and sediment production mechanisms in blanket peatlands are not included. Needle ice is supported by a strong thermal gradient between the cold surface and warmer peat at depth; the removal of vegetation may increase the thermal gradient during cold conditions (Brown et al., 2015) and thus make the soil surface susceptible to freeze-thaw action in winter. Desiccation results from warm conditions and a lack of rainfall over several days and may be enhanced by sparse vegetation cover which encourages significant warming and drying of the peat surface in summer (Francis, 1990; Brown et al., 2015). Hence, sediment production from blanket peatlands is closely related to temperature and soil moisture conditions (Evans and Warburton, 2007; Francis, 1990), which needed to be addressed in the modification of PESERA-GRID.

Management options including artificial drainage, prescribed burning and variations in grazing density may also be important factors influencing blanket peat erosion. Artificial drainage has the effect of lowering the water table (mainly downslope) within blanket peatlands (Holden et al., 2006), and vertical incision creates ditch sides which often result in more bare peat and thereafter erosion (Holden et al., 2007a). Prescribed burning (Brown et al., 2015; Holden, 2008; Holden et al., 2014; 2015) and grazing (Holden, 2008; Meyles et al., 2006) are also known to impact peat surface conditions and soil properties, although there is a dearth of data specifically on the impacts on peatland erosion. Therefore, the effects of management options should be accounted for when modifying PESERA-GRID.

Two types of modifications to PESERA-GRID were required before it can be applied to blanket peatlands: 1) incorporation of sediment production mechanisms in blanket peatlands; 2) parameterization of relevant land management practices. A modified PESERA model, PESERA-PEAT, which is theoretically capable of simulating blanket peat erosion, was proposed as shown in Figure 1. In PESERA-PEAT the hydrology and vegetation growth modules are directly inherited from PESERA-GRID. However, the sediment yield in PESERA-PEAT is dependent upon both sediment production and transport. Sediment production is a result of weathering processes, which are linked with climatic (i.e. temperature) and soil moisture conditions. The transporting capacity was estimated in the same way as in PESERA-GRID. Both sediment supply and transport are considered to be impacted by vegetation cover. A storage component was also defined to indicate surplus erodible materials when erodible materials exceed transporting capacity. The soil erodibility in PESERA-PEAT refers to the sensitivity of weathered peat to erosion. Reduced vegetation cover and biomass and changed water table resulting from land management interventions interact with the hydrology, vegetation growth, sediment production and transport processes. The parameterization of the new components that form PESERA-PEAT is described in section 4.

The PESERA-PEAT model can be implemented in two modes: equilibrium and time-series. In equilibrium mode, the model iterates sufficient times to determine the equilibrium status of hydrology and erosion. Average monthly climate data over the study period are required as input values. Therefore, modelling outputs are also average monthly data. In time-series mode, the model runs only once through the whole time period. Climatic conditions for each month are required over the whole study period. The outputs from the time-series model are continuous monthly data for the study period. Given its smaller data requirements, the equilibrium model is easier to apply to assess average peat erosion over a large spatial area at high resolution and for long-term periods than the time-series model. The time-series model can be used to test for changes in erosion under a continuous series of environmental conditions through time, and therefore can capture extreme conditions during the study period. However, the application of the time-series model over a large region at a high-spatial resolution is restricted by its much bigger data requirement.

3. Site descriptions and field data availability

Long-term peat erosion data were needed to develop and numerically evaluate PESERA-PEAT. However, few blanket peat sites with long-term stream or hillslope sediment fluxes or concentration data exist. Four blanket peat-covered catchments (Figure 2) were found where long-term (> 1 yr) sediment yield data were available. We therefore use all of these in our study. The characteristics and data availability for these sites are summarized in Tables 2 and 3.

3.1 Trout Beck

Most of the Trout Beck catchment is well vegetated, although there are some areas of bare peat and gullies, many of which are now revegetating, and there is a very low grazing intensity of 0.15 ewes ha^{-1} (Grayson et al., 2010). Managed burning and land drainage only occur on very small experimental areas (Holden et al., 2012a; Holden et al., 2006). Hence, Trout Beck is relatively 'intact' with 'no management interventions'. Suspended sediment concentration (SSC) records from Trout Beck between 1997 and 2009 represent the longest sequence of erosion measurements from a blanket peatland to date, facilitating analysis of erosion drivers.

Sediment rating curves were adopted for interpolation of SSC. Armstrong (2005) developed sediment rating curves for Trout Beck based on short-term data between October 2001 and November 2002. However, most samples employed in that study were taken on the rising limb of storm hydrographs, which would lead to an overestimation of SSC for a given runoff discharge since peatland streams typically exhibit positive hysteresis in their SSC-runoff relationship (Labadz et al. 1991; Evans and Warburton, 2007). Armstrong (2005) thus suggested that this might result in an overestimated sediment flux. Based on field measurements on suspended sediment from Burnhope Burn, Northern England and phosphorus transport by the Illinois River measured at Marseilles in the USA, Cox et al. (2008) demonstrated that generalized linear modelling can be used as a systematic and flexible way of fitting sediment rating curves, strongly implying that there are alternatives to power functions, which are the most widely adopted form of rating curves. Here we established sediment rating curves based on the fixed-interval (weekly and monthly) SSC and discharge provided by the UK Environmental Change Network (ECN) throughout 1997-2009. Trend lines are shown in Figure 3 and were derived after subdividing data to make allowance for two major influences on rating curve scatters, namely, seasonal effects (summer or winter half year) and hysteresis related to rising and falling state (Walling, 1977). Total sediment flux from Trout Beck between 1997 and 2009 was estimated to be 1557 t using the sediment rating curves developed here. This is slightly greater than the value of 1531 t calculated using the 'Method 5' flux equation proposed by Walling and Webb (1985).

3.2 Stean Moor 12

For Stean Moor 12, the artificial drainage density is close to zero (Grayson and Holden, 2012). There is light sheep grazing and no managed burning (Longden, 2009). Our site visits confirmed that any gullies in the catchment are well-vegetated and disconnected from stream channels. This means Stean Moor 12 is a relatively intact site.

We collected SSC data for Stean Moor 12 between 2010 and 2011 at 15-min intervals using a Greenspan TS3000 Turbidity probe. To convert measured nephelometric turbidity units (NTU) to SSC, grab samples were collected under various flow conditions with SSC determined using a gravimetric method in the laboratory. Around twenty days of SSC data were missing in each of January 2010 and September 2011, making the sediment yield in these two months unreasonably low (i.e. close to zero). In order to avoid the impacts of the missing SSC data on calculating the sediment flux in these two months, the SSCs of January 2011 and September 2010 were used to substitute those of January 2010 and September 2011 respectively. The climate conditions for January 2010 and September 2011 were comparable with January 2011 and September 2010 respectively, ensuring such a substitution did not significantly change the pattern of erosion processes between 2010 and 2011. Such an adjustment was also done for the runoff and climate data so that the correction for missing data was standardised. The adjusted data were employed as the actual field measurements for Stean Moor 12 between 2010 and 2011 and employed for validation of PESERA-PEAT.

3.3 Upper North Grain

In Upper North Grain, rough grazing is the dominant management practice (Rothwell et al., 2005), and the site is classified as ‘overgrazed’ by Natural Engalnd (Longden, 2009). There is no managed burning or artificial drainage (Longden, 2009). However, extensive active gullies in this catchment lead to a high drainage density (25 km km^{-2}), resulting in particularly high sediment erosion (Evans et al., 2006).

Particulate organic carbon (POC) is a large part of sediment yield from peatlands. Pawson et al. (2012) demonstrated that the mean annual POC flux was about 0.73 t ha^{-1} for Upper North Grain between December 2005 and January 2007 based on hourly stream discharge and sediment rating curves, and that 48 % of organic sediment flux in this site was POC. About 70 % of total sediment yield was organic sediment in Upper North Grain according to the field measurements of Evans et al., (2006). The average annual total erosion for Upper North Grain between 2005 and 2007 was estimated based on the above measurements and used to validate PESERA-PEAT.

3.4 Upper Severn

Between 1983 and 1984 the Upper Severn catchment was severely gullied (Francis, 1990), with a drainage density of 2.4 km km^{-2} (Kirby et al., 1991), and managed with low intensity grazing (Drupal Ecological Information System 2013). Francis (1990) examined the characteristics of sediment production and transport at sites in the Upper Severn during the 1983-1984 drought years. We used these historic data in our study for the validation of PESERA-PEAT.

4. Parameterization of sediment supply and land management practices

4.1 Linking sediment production with freeze-thaw and desiccation

Use of the gradient of sediment rating curves has been demonstrated as a good way of indicating the sediment supply status in small peatland catchments at the scale of storm events (Yang 2005; Evans and Warburton 2007). However, sediment rating curves can often be associated with substantial scatter of data. The scatter may result in large residuals between measurements and predictions (Figure 4), meaning that SSC predictions may be bereft of important detail on changes in sediment production (Walling and Webb, 1988). In order to overcome this shortfall, the gradient from the origin to each measured SSC-runoff point (essentially equivalent to SSC normalized by runoff) in the sediment rating plot (Figure 4), is proposed as a sediment supply index (SSI) to indicate the sediment supply capacity. The SSI considers the SSC-runoff ratio for each data collection point, and is therefore capable of capturing more detailed sediment supply changes which are normally lost by the smoothing effect of sediment rating curves. Daily SSC and runoff were employed to derive the SSI (i.e. daily sediment supply index) because PESERA-GRID is parameterized with daily precipitation (Kirkby et al., 2008). Monthly SSI ($\mathbf{SSI}_m$) is defined, in order to be consistent with the time step of PESERA-GRID, as the mean of the daily sediment supply index ($\mathbf{SSI}_d$) within a specific month. So $\mathbf{SSI}_d$ and $\mathbf{SSI}_m$ are given by,

$$SSI_d = \frac{SSC_d}{roff_d}$$ Equation 1

$$SSI_m = \frac{\sum_{i=1}^{i=n} SSI_i}{n}$$ Equation 2

where SSC_d means daily suspended sediment concentration, $roff_d$ is daily runoff, n is the total days in a given month, i means the i_{th} day in the month.

Temperature and water-table parameters can act as indicators of freeze-thaw and desiccation. Air temperature is commonly provided in historical datasets and climate projections and will be directly linked to ground surface temperatures. Soil moisture conditions will influence desiccation. Soil moisture in the upper peat is likely to be related to water-table depth in blanket peatlands, with deeper water tables associated with lower soil moisture content at the peat surface, particularly when the peat is bare. Water-table depth is a commonly measured parameter in peatlands. Therefore, temperature and water table were chosen as indicators of freeze-thaw and desiccation.

Multiple linear regressions between $\mathbf{SSI}_d$ and daily temperature and water table for the Trout Beck catchment between 1997 and 2009 were performed (Table 4). Water table is negatively related to $\mathbf{SSI}_d$ with this relationship being statistically significant ($p < 0.01$) for all twelve months of the year. This implies that desiccation, which is enhanced when water table moves downwards (Evans et al. 1999), plays a role in sediment production from blanket peatlands throughout the year. Temperature is negatively related to SSI_d and this relationship is statistically significant ($p < 0.01$) for October to February inclusive. It is inferred that in these months, in addition to desiccation, frost action, which is more prevalent under lower temperatures, also contributes to final sediment supply. Given PESERA-GRID estimates erosion at a monthly scale, the final equations linking sediment supply and weathering processes were established based on SSI_m and mean monthly temperature ($\mathbf{Temp}$) and water table ($\mathbf{WT}$):

$$SSI_m = \begin{cases} -a\,Temp - b\,WT + c & for\ Oct-Feb \\ -WT + c & for\ Mar-Sep \end{cases} \qquad \text{Equation 3}$$

where, a, b and c are constants for each month and R^2 ranged between 0.29 and 0.92.

In Equation 3, $\mathbf{WT}$ was a statistically significant factor ($p < 0.05$) in regression equations for Mar-Sep. For regressions for Oct-Feb, $\mathbf{Temp}$ and $\mathbf{WT}$ were not always statistically significant factors. However, $\mathbf{Temp}$ and $\mathbf{WT}$ were still used because: (1) they were reasonable in terms of the physical processes implied in Table 4 and (2) they were based on the longest data series available for blanket peat erosion (13 years) although this still provided a relatively small sample size (i.e. n = 13) for statistical analysis. The sample size was likely to be the major reason for the weaker statistical performance of variables in the regressions for Oct-Feb, given all predictors of regressions for these months based on SSI_d and daily temperature and water table were statistically significant ($p < 0.01$) (Table 4).

$\mathbf{SSI}_m$ is not numerically equal to the actual monthly sediment supply. However, since the $\mathbf{SSI}_m$ is based on established theory (Yang, 2005) and linked with temperature and water table (Equation 3), which vary spatially and temporally, $\mathbf{SSI}_m$ is an index of spatial and temporal changes in sediment supply driven by freeze-thaw and desiccation processes. For the model, the actual sediment supply value was needed to form a baseline, which changes at the same rate as the $\mathbf{SSI}_m$. Measured sediment supply reported by Evans and Warburton (2007) for bare peat in the Trout Beck catchment between July 1999 and July 2000 was employed as the baseline sediment supply ($\mathbf{SS}_m^c$). The $\mathbf{SSI}_m$ for $\mathbf{SS}_m^c$ ($\mathbf{SSI}_m^c$) was then estimated using equations 1 and 2. The difference in the nature of erodible materials produced by freeze-thaw and desiccation was not considered here as there was a lack of field data to separate these effects. The monthly sediment supply ($\mathbf{SS}_m$) from bare peat on other areas and for other times could be given by:

$$SS_m = SS_m^c + \Delta SS_m \qquad \text{Equation 4}$$

where $\Delta\mathbf{SS}_m$ is the variation of $\mathbf{SS}_m$ driven by changes in freeze-thaw and desiccation, estimated based on the $\mathbf{SS}_m^c$ and change of $\mathbf{SSI}_m$ from $\mathbf{SSI}_m^c$ (units for SSI_m and SSI_m^c cancel each other out):

$$\Delta SS_m = SS_m^c \frac{SSI_m - SSI_m^c}{SSI_m^c} \qquad \text{Equation 5}$$

so,

$$SS_m = SS_m^c + \Delta SS_m = SS_m^c + SS_m^c \frac{SSI_m - SSI_m^c}{SSI_m^c} = SS_m^c \left(1 + \frac{SSI_m - SSI_m^c}{SSI_m^c}\right) \qquad \text{Equation 6}$$

4.2 Parameterization of land management practices

The drainage model of PESERA-POINT was employed to parameterize drainage (Beharry-Borg et al., 2009). For the drainage model, vegetation removal, both cover and biomass, is estimated as a function of drainage density (m ha^{-1}) and drainage width (m). The width of artificial drainage was set to 1 m in this paper representing a typical field value for upland blanket peat systems with well developed ditch systems. However, this value can be changed to represent local field conditions. A “ditch level” value, which represents the drainage deficit, is adopted to account for the impact of the drainage on soil moisture. The ditch level increases with drainage depth and saturated hydraulic conductivity, and decreases with drain spacing. So,

$$DL = K_{sat} \frac{Z}{DS} \qquad \text{Equation 7}$$

where, DL is the ditch level representing the drainage deficit (mm); K_{sat} is the saturated hydraulic conductivity (mm month^{-1}); Z is the drainage depth (m) and set to 0.5 empirically for artificial drainage in our paper (but can be adjusted during the application of PESERA-PEAT). DS is the drain spacing (m), which is positively related to area (A , m^2) and negatively related to drainage density (DD), and given by,

$$DS = \frac{A}{DD} \qquad \text{Equation 8}$$

The saturated runoff rate ($\mathbf{z}_i$ in Equation 9, mm month^{-1}), which is crucial for the speed of infiltration into soil and soil moisture dynamics in PESERA-GRID (Kirkby et al., 2008), decreases exponentially with the ditch level in drained blanket peatlands (Beven, 1997):

$$z_j = z_j \exp\left(-DL/z_m\right) \qquad \text{Equation 9}$$

Managed burning is represented as vegetation removal. Vegetation is typically burned in patches in rotation with a typical frequency of burn for one patch of one in 7 years to one in 25 years (Holden et al., 2007b), with the proportion of burnt areas being usually estimated as the reciprocal of burning interval (Defra, 2007). Vegetation cover and biomass on the burnt areas were assumed to be completely removed in our paper for burning patches, growing back over time since burn. However, we recognise that in reality some unconsumed biomass (protruding stick) can remain after burning. In addition, two levels of grazing were considered: light grazing and overgrazing. They were considered to reduce vegetation cover and biomass by 15 % and 30 % respectively. These values were estimated based on the work of Chapman et al. (2009) on the response of upland vegetation to low and high stocking densities of 0.5 and 3 ewes ha^{-1} respectively, based on field investigations undertaken in upland areas of the UK (Peak District).

5. Detailed description of PESERA-PEAT

The hydrology and vegetation growth modules of PESERA-PEAT are directly inherited from the PESERA-GRID model, and a detailed description of them can be found in section 2.2 and in Kirkby et al. (2008). Here we describe the erosion processes in PESERA-PEAT.

5.1 Sediment supply

Sediment supply is partitioned for bare soil and vegetated areas, and assumed to decrease linearly with vegetation coverage since blanket peat erosion mainly occurs on bare ground (Shuttleworth et al., 2015). The monthly sediment supply is expressed as:

$$TSS_m = SS_m\,(1 - cov) + \frac{SS_m}{x}\,cov \qquad \text{Equation 10}$$

where, TSS_m is the total sediment supply (t ha^{-1}) for a month; SS_m is the erodible material (t ha^{-1}) on bare peat, and estimated by Equation 6; cov is the unitless vegetation coverage for the month; x is the unitless rate at which sediment supply decreases with vegetation coverage.

5.2 Sediment transport

As there is limited field data to differentiate transport rates for sediment produced by freeze-thaw compared to sediment produced by desiccation we estimated the sediment transport capacity in the same way for both cases. The transport capacity was partitioned for bare soil and vegetated areas, and given by,

$$TC = C\,(1 - cov) + \frac{C}{x}\,cov \qquad \text{Equation 11}$$

where TC is the transport capacity of overland flow (t ha^{-1}) for a month and C is the transport capacity of overland flow on bare ground (t ha^{-1}) for a month estimated in the same way as in PESERA-GRID.

5.3 Sediment yield

Sediment availability is defined as a sum of the sediment production in a month and sediment storage from previous months (Equation 12). Sediment storage is determined as the difference between sediment availability and transport capacity (Equation 13). If sediment availability is less than transport capacity, sediment storage is zero. The final sediment yield is calculated with Equation 14,

$$Sedi_{av} = TSS_m + Storage_p \qquad \text{Equation 12}$$

$$Storage_c = Sedi_{av} - TC \qquad \text{Equation 13}$$

$$SY = \begin{cases} Sedi_{av}; & if\ Sedi_{av} < TC \\ TC; & if\ Sedi_{av} > TC \\ Sedi_{av}\ or\ TC; & if\ Sedi_{av} = TC \end{cases}$$ Equation 14

where, $Sedi_{av}$ is the sediment availability (t ha^{-1}) for the current month; $Storage_p$ is the sediment storage (t ha^{-1}) from previous months; $Storage_c$ is the sediment storage (t ha^{-1}) for the current month; and SY is the final sediment yield (t ha^{-1}).

5.4 Gullies

In PESERA-PEAT, gullies are parameterized with the drainage model developed by Beharry-Borg et al. (2009) as for artificial drainage, which means ditch level and vegetation removal are adopted to account for the impact of gullies on hydrology and surface condition. However, unlike for artificial drainage, actual gully width and depth are used to derive ditch level and vegetation removal for gullies.

6. Numerical testing of PESERA-PEAT

6.1 Model evaluation method

The hydrology, vegetation growth and new erosion modules were evaluated separately with field data from the chosen study sites. The vegetation growth model was evaluated with the measured vegetation biomass of Trout Beck (Smith and Forrest, 1978). Measured runoff from Trout Beck and Stean Moor 12 catchments and measured water table for Trout Beck were compared with modelled runoff and soil moisture deficit to evaluate the performance of the hydrology module. Measured sediment yield from Stean Moor 12, Upper North Grain and the Upper Severn was employed to evaluate the erosion module. The comparison of modelled and measured runoff/sediment yield included two aspects: pattern and magnitude. Because the modelling results of PESERA-PEAT are at a 100-m scale and field data are at catchment scales, field data need to be downscaled to the 100-m scale before being compared with modelling outputs. Downscaling of runoff efficiency and sediment flux was based on equations shown in Figure 5a and b respectively. The equation in Figure 5a was derived from the runoff efficiency reported by Holden and Burt (2003) for Trout Beck, Rough Sike and Little Dodgen Pot Sike between January 1997 and December 1999 which are all nearby catchments in the Upper Tees at Moor House National Nature Reserve, and represent the best dataset available, to date, to account for the scaling impact on runoff production. Pawson et al. (2012) presented POC flux from 13 reaches spanning a 7-km headwater section of the River Ashop between December 2005 and January 2007. The upper six reaches, where peat coverage is more than 90 %, were selected to establish the relationship between erosion and catchment size (Figure 5b).

The modelled monthly results were plotted against downscaled measured monthly data to visually determine if their patterns fitted well. Linear regression between downscaled field and modelled monthly data was also undertaken to examine their relationships. Comparisons were conducted to assess if the model could produce a reasonable magnitude of runoff and erosion. The Nash-Sutcliffe coefficient (Nash and Sutcliffe, 1970) was employed to assess the overall accuracy of the modelling results as it is capable of evaluating both pattern and magnitude simultaneously.

6.2 Model implementation

6.2.1 Equilibrium modelling

Compared to PESERA-GRID, there are three more input layers required by PESERA-PEAT to indicate land management conditions. They are spatial patterns of drainage density, grazing and prescribed burning. Kirkby et al. (2008) and the PESERA manual (Irvine and Kosmas, 2003) provide details of the other input layers.

Climate inputs (i.e. rainfall, rainfall per rainy day (when rainfall is >0 mm for a day), coefficient of variation of rainfall per rainy day, temperature, temperature range and potential evapotranspiration (PET)) were derived from the datasets presented in Table 3. PESERA-PEAT operated at a 100-m grid cell scale, 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 a standard lapse rate (Brunt, 1933). PET was derived from a temperature-based model which was originally proposed by Oudin et al. (2005), and modified to include wind speed and vegetation height, as used in the PET estimation by Clark (2005) for Trout Beck. Land use was extracted from Land Cover Map 2000 (Fuller et al., 2002). Local relief was calculated based on a 10-m DEM downloaded from Digimap (Digimap, 2012). The input soil parameters were set according to the PESERA manual (Irvine and Kosmas, 2003). However, the soil erodibility in PESERA-PEAT represents the erodibility of erodible materials generated by freeze-thaw and desiccation, which was demonstrated to be 2-3 times that of intact peat (Mulqueen et al., 2006). The erodibility of fresh peat is estimated to be 1.16 mm through the pedo-transfer function presented in the PESERA manual. Therefore, the input erodibility was set to 2.5 mm.

Management and gullying conditions for the study sites were set as outlined in Table 2. For Upper North Grain, the depth of gullies was set to 1.95 m (Evans et al., 2006), and the width of gullies was set to 10 m according to gully widths reported by Evans and Lindsay (2010) for two test areas on Bleaklow Plateau, in the vicinity of Upper North Grain. The width and depth of gullies in the Upper Severn were unavailable; they were therefore set to 10 m and 1 m respectively representative of empirical data from UK upland peat gully systems (Evans et al., 2005; Evans and Lindsay, 2010).

Land-cover types for the chosen sites are presented in Figure 2. The processes operating within PESERA-PEAT mean that the trajectory of vegetation growth and accumulation of soil organic matter on different land-cover types are not considered to be the same. Vegetation coverage was calculated on a monthly basis for “Pasture” and “Scrub” and kept constant for “Woodland”, “Bare land”, and “Undifferentiated bog”. Vegetation biomass and soil organic matter were accumulated through time for all land-use types other than “Bare land”, where they were kept as zero. Land management practices were considered to only occur on “Pasture or grassland” and “Scrub”, while gullies were thought to occur across the whole area studied. In areas with multiple management practices, total vegetation cover and biomass removal was the sum of those reduced by each management practice.

6.2.2 Time-series modelling

The time-series model of PESERA-PEAT operated at one grid cell using data from Stean Moor 12 and the Upper Severn during the chosen periods. Climatic inputs were derived from the data sources shown in Table 3. Land use was set to natural vegetation, on which both the vegetation growth model and management options acted. The management option was set according to Table 2. The drainage density, gully width and gully depth employed for the Upper Severn were the same as those used by the equilibrium model. The input topographic relief was calculated from the DEMs for Stean Moor 12 and the Upper Severn, with an average value of 8.5 m and 11.5 m respectively. The soil parameters were also the same as those used in the equilibrium model described above.

6.2.3 Model calibration and validation

PESERA-PEAT was calibrated in the equilibrium mode with the downscaled measured erosion from the Trout Beck catchment, including two aspects: i) adjusting the rate at which sediment erosion decreased with vegetation cover (x in Equations 10 and 11) to achieve a reasonable magnitude of modelled erosion; ii) changing the monthly distribution of the baseline sediment supply (SS_m^c in Equation 4) to obtain a good fit of measured and modelled erosion. The calibrated equilibrium model was then applied to Stean Moor 12 and Upper North Grain. The calibrated x and baseline monthly sediment supply were directly used in the time-series model, which was validated with sediment yield from Stean Moor 12 and the Upper Severn.

6.3 Modelling results and discussion

6.3.1 Calibration results

The downscaled and modelled sediment yields for the Trout Beck catchment were close, being 0.77 and 0.81 t ha^{-1} yr^{-1} respectively (Figure 6). The R^2 of the linear regression between modelled and downscaled (based on field data) sediment yield was 0.96, and Nash-Sutcliffe coefficient was 0.94, suggesting that there was a good fit between the measured and calibrated erosion for the Trout Beck catchment. Parameters used for model calibration (x in Equations 10 and 11 and SS_m^c in Equation 4) only impact erosion processes, without influencing hydrology and vegetation growth in PESERA-PEAT. Hence, hydrological and vegetation outputs for the Trout Beck catchment were used for the validation of the model and presented in section 6.3.2.

6.3.2 Validation of equilibrium modelling results

<u>Vegetation biomass</u>

Modelled vegetation biomass for the chosen sites was lower in winter and higher in summer (Figure 7), being consistent with the general trend of measured and modelled vegetation biomass reported by Armstrong et al. (1997) for hill vegetation in the UK. Smith and Forrest (1978) reported that the vegetation biomass for a *Calluneto-Eriophoretum* blanket bog in the Trout Beck catchment was 0.78 ± 0.053 and 0.43 ± 0.24 kg m^{-2} in August under a grazing density of 0.02 and 0.04 sheep ha^{-1} respectively. The modelled vegetation biomass in August was 1.09 kg m^{-2} for Trout Beck without management options, 0.47 kg m^{-2} for Stean Moor 12 managed by light grazing, and 0.12 kg m^{-2} for Upper North Grain under a condition of overgrazing and dense gullies. These values were of the same order of magnitude as those of Smith and Forrest (1978), demonstrating that the vegetation growth model was reasonable. However, it should be noted that their measured vegetation biomass was from the 1970s. When all management options including gullies (in Upper North Grain) were removed, the predicted vegetation biomass was 1.02 kg m^{-2} for Trout Beck, 1.19 kg m^{-2} for Stean Moor 12 and 1.32 kg m^{-2} for Upper North Grain.

Soil moisture deficit

The pattern of modelled soil moisture deficit mirrors that of measured water-table depth (Figure 8a), demonstrating that PESERA-PEAT is capable of predicting water table in blanket peatlands. As water-table data were not available for Stean Moor 12 and Upper North Grain the relationship shown in Figure 8b was adopted to predict water table for these blanket peatlands based on the soil moisture deficit predicted by the model. The predicted annual average water table for Trout Beck, Stean Moor 12 and Upper North Grain during the corresponding study periods was -4.0, -5.1 and -11.8 cm respectively. These are consistent with the long-term (18 months) mean water-table depths measured by Holden et al. (2011) for intact (-5.8 cm), restored (-8.9 cm) and drained (-11.5 cm) blanket peat sites on Oughtershaw Moss, Northern England between January 2005 and June 2006. Daniels et al. (2008) found that water-table drawdown is a feature of peat sites subject to gullying, supporting the considerably deeper modelled water table for Upper North Grain (with extensive gullies) compared to that of the other two sites (without gullies) during the study periods.

Runoff production

Since discharge for Upper North Grain was unavailable, the predicted runoff was tested for Trout Beck and Stean Moor 12, where the modelled annual runoff ratios were 4.3 % and 7.4 % less than those of the downscaled measured runoff based on field data (Table 5). Given climate inputs for these catchments were fully (Trout Beck) or partly (Stean Moor 12 and Upper North Grain) represented by point data and the coarse spatial resolution (100 m) employed for model runs, the above errors were acceptable. It is therefore thought that PESERA-PEAT is capable of predicting the amount of runoff production from blanket peatlands. Modelled subsurface flow contributed 9.9 %, 16.1 % and 4.5 % of modelled total runoff from Trout Beck, Stean Moor 12 and Upper North Grain respectively. Field data of subsurface flow for Stean Moor 12 and Upper North Grain were not reported in the literature. However, modelled subsurface flow contribution is supported by previous studies (e.g. Holden and Burt 2003; Holden et al., 2009; Holden et al., 2012b), which demonstrated that 10-14 % of total runoff in the Trout Beck catchment is subsurface flow. The R^2 of linear regressions between modelled and measured runoff were 0.91 and 0.82 for Trout Beck and Stean Moor respectively suggesting that the model can viably predict monthly runoff changes in blanket peatlands (Figure 9). The Nash-Sutcliffe coefficients between downscaled measured and modelled runoff for the Trout Beck and Stean Moor 12 were 0.89 and 0.76 respectively (Table 5), demonstrating that the model sufficiently reproduces saturation-excess runoff-generating mechanisms in blanket peat.

For Trout Beck, the spatial pattern of modelled runoff is mainly controlled by vegetation cover as the climate inputs (both rainfall and temperature) were derived from point data and were therefore constant across the catchment (Table 3). Modelled runoff (Figure 10) on bare ground was higher than for other areas (Figure 2). This is because in the model, lower vegetation coverage and shallower root depth on bare areas results in less rainfall lost as evapotranspiration or vegetation interception. For Stean Moor 12 and Upper North Grain, the rainfall input was derived from point data while temperature inputs were spatially distributed (Table 3). Larger runoff values (Figure 10) were predicted for higher elevation areas (Figure 2) mainly because the lower temperature in these areas leads to less water being lost as evapotranspiration. In the model, less evapotranspiration or interception leads to more water being available for infiltration, resulting in higher runoff production when peat is saturated (Kirkby et al., 2008). These processes are consistent with previous hydrological studies on blanket peatlands (Evans et al., 1999; Holden and Burt, 2002; 2003; Holden 2005; 2008).

<u>Erosion</u>

The modelled erosion was 12.3 % and 13.3 % more than the downscaled measured erosion (based on empirical field data) for Stean Moor 12 and Upper North Grain respectively (Table 6). Given that the rainfall for these two sites was represented by point data, and 100 m was quite a coarse scale for such small catchments, such differences between modelled and downscaled erosion are acceptable and suggests that the model is able to simulate the amount of blanket peat erosion well. Measured sediment supply from blanket peatlands is rarely reported in the literature. The most widely used data are those reported by Evans and Warburton (2007) for Trout Beck (i.e. SS_m^C in Equation 4) and Yang (2005) for Upper North Grain. The modelled sediment production on bare ground for Upper North Grain is 11.3 t ha^{-1} yr^{-1}, which is close to the sediment supply of 13.0 t ha^{-1} yr^{-1} from bare peat in the catchment (Yang 2005). This demonstrates that the sediment supply index and regressions developed in Equation 3 are a robust way of parameterizing sediment supply from blanket peatlands. The large modelled sediment production for Upper North Grain (compared to the sediment supply of 6.9 t ha^{-1} yr^{-1} for Trout Beck, where the gully systems are well vegetated) is mainly a result of lower water table resulting from extensive gullying; a factor which has been previously recognized (e.g. Evans et al., 2006, Pawson et al., 2008; 2012).

Modelled monthly erosion for the equilibrium version of PESERA-PEAT was tested with the erosion measurements from Stean Moor 12. The similar pattern between modelled and measured erosion demonstrates that the model is capable of predicting monthly erosion change (R^2 = 0.88; Figure 11). The Nash-Sutcliffe coefficient was 0.86 (Table 6), demonstrating that the model predicts measured erosion well.

Modelled average annual erosion (Figure 12) was greatest in bare areas and became smaller as vegetation coverage increased (Figure 2), because vegetation cover impacts both sediment supply and transport. Average annual erosion for the Trout Beck catchment was supply-limited given that sediment storage was predicted to be zero (Figure 12). This is consistent with previous studies on this catchment at both catchment and plot scales (Holden and Burt 2002; Armstrong, 2005). For Stean Moor 12 and Upper North Grain, average annual erosion (Figure 10) tended to be transport limited in areas with less runoff production and in gently-sloping areas (Figure 2) since the transport capacity is strongly impacted by runoff production and local gradient (Musgrave 1947; Kirkby et al., 2008). Land management practices have impacts on vegetation cover, biomass and soil moisture, so they influence both sediment supply and transport, and thus the final sediment yield predicted by PESERA-PEAT. However, it should be noted that the accuracy of the spatial pattern of modelling results may be limited by the coarse scale (i.e. 100 m) of land-use data.

6.3.3 Validation of time-series modelling results

As the major components of PESERA-PEAT have been tested above, only the sediment flux predicted by the time-series version of PESERA-PEAT was evaluated using sediment yield data from Stean Moor 12 and Upper Severn. For Stean Moor 12, the R^2 and Nash-Sutcliffe coefficient were 0.94 and 0.93 respectively (Figure 13), demonstrating that the time-series model captured changes in monthly erosion. Modelled mean annual erosion was 1.25 t ha^{-1}, which is close to the downscaled measured mean annual erosion of 1.14 t ha^{-1} (Table 6). Modelling results showed that substantial sediment storage frequently occurred in Stean Moor 12. This is consistent with field observations in other catchments on Stean Moor where previously stored erodible materials were deemed to be one of the major reasons for an insignificant reduction in sediment loads after extensive ditch blocking (Grayson and Holden, 2012). For the Upper Severn, sediment storage was predicted to mainly occur during summer months while stored sediment was washed away in autumn and winter months (Figure 14). This seasonal pattern is in a good agreement with the sediment trap results of Francis (1990) from a 28-m^2 peat-covered gully in the Upper Severn. The modelled annual erosion was 2.49 t ha^{-1}, which is very close to the downscaled annual erosion of 2.36 t ha^{-1}, estimated using the regression equation in Figure 5b.

6.4 Comparison of equilibrium and time-series model

The sediment yield for Stean Moor 12 predicted by the time-series model (1.25 t ha^{-1} yr^{-1}) was close to the yield predicted by the equilibrium model (1.28 t ha^{-1} yr^{-1}) (Table 6). However, the equilibrium model operated with spatially-distributed topography and land-cover data, while in time-series modelling topography and land cover were thought to be spatially invariable. In order to examine if these two versions of the model work in the same way, the equilibrium model was also operated with values of input parameters which were exactly the same as those for the time-series model. Average annual erosion estimated by the equilibrium model was 1.30 t ha^{-1}, which was slightly higher than that predicted by the time-series model (i.e. 1.25 t ha^{-1}) (Figure 15a). Monthly average erosion predicted by the equilibrium and time-series models followed a similar pattern, with the R^2 of the linear regression between them being 0.95 (Figure 15b). This suggests that the equilibrium and time-series model work in generally the same way. However, differences between these two versions of the model still exist. This is because the time-series model considers climate which varies for every month of the time series, while in the equilibrium model all climate inputs are average values over the study period so that, for example, all Januarys have the same inputs. Hence there are differences in sediment production, transport and the final sediment yield between the two versions of the model.

7. Discussion of the modelling approach

7.1 Sensitivity analysis of PESERA-PEAT

A sensitivity analysis was conducted to determine the sensitivity of the model to changes in rainfall, temperature, vegetation cover, drainage depth and drainage density. For rainfall, temperature and vegetation cover, the conditions within the Trout Beck catchment between 1997 and 2009 (Table 2) were used as a baseline. We then increased or decreased rainfall and vegetation coverage variables from -100 % to +100 % in 10 % increments and examined model outputs (Figure 16a, b). For temperature we increased and decreased it by 0.61 ^{o}C increments from a baseline of 6.1 ^{o}C to 12.2 ^{o}C and 0 ^{o}C respectively. To test the sensitivity of the model to drainage conditions, the gullying found in the Rough Sike catchment (a tributary of Trout Beck) was employed as the baseline condition through assuming that the gullies were unvegetated. In the Rough Sike catchment, the average gully depth and density were 0.94 m and 130 m ha^{-1} (Evans and Warburton, 2005), while the average gully width was set to 10 m. The drainage depth and density were then independently increased and decreased at 10 % intervals from this baseline level to -100 % (zero drainage depth and density) to +100 % of baseline (Figure 16c). The baseline climate of the Trout Beck catchment from 1997 to 2009 was applied during the drainage sensitivity test without being altered.

The sensitivity analysis showed that modelled erosion was supply-limited (erosion decreases with increased precipitation) when rainfall is high and transport-limited when rainfall becomes low (Figure 16a). As temperature increases, modelled erosion for Oct-Feb declined because of weakened freeze-thaw, while for Mar-Sep erosion increased due to stronger desiccation driven by enhanced evapotranspiration. As a result, the sensitivity of modelled annual erosion to temperature change tended to be small at about 5% for ±6.1 ^{o}C of temperature change (Figure 16a). Modelled erosion increased dramatically with decreased vegetation coverage (Figure 16b) suggesting that the model is very sensitive to vegetation cover. Modelled erosion for the Trout Beck catchment increased by 13.5 times when vegetation coverage decreased from 100% to 0%. This value is comparable with the result of Arnett (1979), in which erosion rates on a recently burnt moorland plot (large amount of vegetation removal as a result of managed burning on the plot) were found to be around 20 times that of a well vegetated *Calluna* plot in the North York Moors, UK. Modelled erosion increases with drainage density and depth of gullies or ditches (Figure 16c). PESERA-PEAT is more sensitive to drainage density than drainage depth as the drainage density in PESERA-PEAT impacts both the water table and vegetation cover while the ditch or gully depth only affect the former. Figure 16c also suggests that modelled erosion under gully-revegetated conditions is 55 % lower than under the baseline condition in which gullies were considered unvegetated. This is close to the findings reported by Evans and Warburton (2005) for the Rough Sike catchment, where a reduction of 60 % in sediment yield between the 1960s and 2000s was mainly attributed to the re-vegetation of gully floors and loss of slope-channel linkages.

7.2 Advantages of the modelling approach

May et al. (2010) and Coulthard et al. (2000) attempted to simulate fluvial erosion in blanket peatlands with USLE and CAESAR respectively. However, unlike PESERA-PEAT, these two models are not capable of accounting for freeze-thaw and desiccation processes that dominate the generation of erodible materials in blanket peatlands. Additionally, PESERA-PEAT estimates final sediment yield as the balance between sediment supply and transport, with sediment supply and transport processes being described separately. This characteristic enables modelled erosion to be switched between supply-limited and transport-limited forms, better accounting for erosion processes occurring in blanket peatlands.

Sensitivity analysis of PESERA-PEAT demonstrated that the drainage model incorporated within PESERA-PEAT is capable of capturing the impact of gullies on blanket peat erosion. The robust modelling results for Stean Moor 12, Upper North Grain and Upper Severn during the chosen study periods suggest that: 1) SSI is a good index to represent the variability of sediment production driven by freeze-thaw and desiccation, and 2) parameterization of light grazing and overgrazing in PESERA-PEAT is appropriate. Parameterization of prescribed burning as a complete removal of vegetation on burnt areas was also shown to be acceptable through comparing the sensitivity analysis with the field measurements in the North York Moors (Arnett, 1979). Overall, PESERA-PEAT is a useful tool for investigating potential impacts of climate change and management practices on fluvial blanket peat erosion. It can be adopted in future studies which utilise climate change modelling scenarios and land management scenarios to examine spatial and temporal changes to erosion rates in blanket peat catchments.

7.3 Limitations of the modelling approach

Like PESERA-GRID, PESERA-PEAT theoretically considers the soil loss driven by overland flow on hillslopes such as gullies and sheet erosion, which are the dominant mechanisms controlling sediment flux from eroding peatland systems (Evans and Warburton 2007). However, given the lack of long-term erosion measurements at hillslope and plot scales, catchment-scale erosion data were employed to develop and test the model. Although empirical equations were used to account for scaling impacts on the magnitude of sediment flux, it was not possible to separate the contribution of hillslope and channel processes to the final sediment yield. This means the sediment yield predicted by PESERA-PEAT is actually a lumped version of erosion caused by both hillslope and channel processes such as gully erosion, sheet erosion or river bank erosion. Such a simplification was a compromise during model development and testing and forms a limitation of the modelling approach. More process-based studies on different types of erosion in blanket peatlands are needed so that these erosion processes can be incorporated into erosion models in a more physically realistic way.

In PESERA-PEAT, erodible materials produced by freeze-thaw and desiccation are considered to behave in the same way. However, they are different in nature, and transported by overland flow in different forms (Evans and Warburton, 2007). Enhanced versions of PESERA-PEAT could seek to incorporate these differences in the nature and transport of erodible materials produced once empirical studies have been carried out to determine how transport rates are impacted by the nature of the sediment produced. In addition, freezing of peat involves desiccation (Evans and Warburton, 2007), and this could also be incorporated into a future version of PESERA-PEAT.

Wind erosion, which is an important component of blanket peat erosion at some locations (Warburton 2003; Foulds and Warburton, 2007a; b), is not considered in PESERA-PEAT at present. Hence further development of the model to include wind erosion and some consideration of rapid mass movement occurrence may be useful to more fully capture future blanket peat erosion rates under environmental change.

8. Conclusions

The first fluvial erosion model for blanket peatlands (PESERA-PEAT), to the authors' knowledge, has been established in this paper. In the model, freeze-thaw and desiccation processes were incorporated with a novel sediment supply index. A previously developed drainage model was employed to parameterize artificial drainage and gullies, while managed burning and grazing were parameterized for their influence on vegetation. With three modules (hydrology, erosion and vegetation growth) being evaluated separately with field data, PESERA-PEAT was shown to be robust in predicting blanket peat erosion. Two versions of PESERA-PEAT gave similar results under the same environmental conditions, allowing it to be applied at different scales. The equilibrium model facilitates the evaluation of average monthly erosion risk at a fine-spatial resolution over large areas and long-term periods. The time-series model is more suitable for assessing continuous monthly erosion risk, and therefore for examining the role of particular high-magnitude events (e.g. heavy rainfall, drought). The time-series model will be more appropriate for use over long-term periods across small areas, or if applied over large areas a coarser-spatial resolution will be required. PESERA-PEAT can now be applied to examine the response of fluvial blanket peat erosion to environmental change (i.e. climate change, land management shifts and their interactions) at regional, national and global scales. Such applications will be beneficial for planning of land-use strategies in blanket peatlands.

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Table 1 Evaluation of soil erosion models reviewed by Merritt et al., (2003) and Aksoy & Kavvas (2005) using six criteria: (i) physically-based; (ii) simulate saturation-excess overland flow; (iii) describe typical sediment production and transport processes in blanket peatlands; (iv) suitable over long-term temporal scales and multiple spatial scales; (v) use readily available input climate variables; (vi) suitable to include impacts of typical land management practices in blanket peatlands.

Models	i	ii	iii	iv	v	vi	No. of criteria met
USLE/modifications	N	N	N	Y	Y	N	2
AGNPS	N	Y	N	N	Y	Y	3
EMSS	N	Y	N	N	Y	Y	3
HSPF	N	Y	N	N	N	Y	2
IHACRES-WQ	N	Y	N	N	Y	Y	3
IQQM	N	Y	N	N	Y	Y	3
LASCAM	N	Y	N	N	Y	Y	3
SedNet	N	Y	N	N	Y	Y	3
SWRRB/SWRRB-WQ	N	Y	N	N	Y	Y	3
SEDD	N	N	N	N	Y	N	1
ANSWERS	Y	N	N	N	Y	N	2
CREAMS	Y	Y	N	N	Y	Y	4
GUEST	Y	Y	N	N	Y	Y	4
LISEM	Y	Y	N	N	Y	Y	4
MIKE-11	Y	Y	N	N	Y	Y	4
PERFECT	Y	Y	N	N	Y	Y	4
TOPOG	Y	Y	N	N	Y	Y	4
WEPP	Y	N	N	Y	Y	N	3
EUROSEM	Y	N	N	N	Y	N	2
KINEROS/KINEROS2	Y	N	N	N	Y	N	2
RUNOFF	Y	Y	N	N	Y	Y	4
WESP	Y	N	N	N	Y	N	2
CASC2D-SED	Y	N	N	N	Y	N	2
SEM	Y	Y	N	N	Y	Y	4
SHESED	Y	Y	N	N	Y	Y	4
PESERA	Y	Y	N	Y	Y	Y	5

Y / N indicates the model does / does not meet the criteria.

Table 2 Characteristics of the study sites and conditions during corresponding study periods when data were available for this study

Site	Study period	Area (km^2)	Altitude (m)	Annual rainfall (mm)	Temperature (°C)	Vegetation type	Peat cover	Gullying	Managed burning	Artificial drainage	Grazing
Trout Beck	01/1997-12/2009	11.4[a]	532-845[b]	2014[c]	6.1[c]	Heather, cotton grass, Sphagnum[a]	90 %[a]	Inactive[d]	No[e]	No[f]	No[d]
Stean Moor 12	01/2010-12/2011	0.38[g]	494-558[b]	1191	6.6[h]	Heather, cotton grass[g]	100 %[j]	Inactive[g,i]	No[i]	No[g]	Light[i]
Upper North Grain	01/2005-12/2007	0.38[j]	490-541[j]	1482[k]	7.3[h]	Heather, bilberry, cotton grass[j]	99 %[l]	Active[j]	No[i]	No[i]	Over[i]
Upper Severn	01/1983-12/1984	0.94[m]	536-672[m]	2304[n]	7.6[n]	Heather, cotton grass[m]	95 %[o]	Active[m]	No[p]	No[p]	Light[p]

Sources:
a, Evans et al. (1999); b, Edina (2012); c, Environmental Change Network; d, Grayson et al. (2010); e, Holden et al. (2012a); f, Holden et al. (2006); g, Grayson and Holden (2012); h, Met Office gridded dataset; i, Longden (2009); j, Evans et al. 2006; k, MIDAS station ID: 3257, Grid ref: SK 128895; l, Pawson et al. (2012); m, Francis (1990); n, MIDAS station ID: 1187, Grid ref: SN 843877; o, Kirby et al. (1991); p, Drupal Ecological Information System (2013)

Table 3 Field data availability for the study sites and their use in the modelling process

Site	Rainfall	Temperature	Runoff	Suspended sediment concentration	Water table	Sediment production	Sediment yield	Usage
Trout Beck	Hourly[a]	Hourly[a]	15-min[a]	97-03: weekly[a]; 04-09: monthly[a]	Hourly[a]	Evans and Warburton (2007), sediment trap data	Estimated based on the sediment rating curves shown in Figure 3	Model development, and calibration
Stean Moor 12	15-min[b]	Monthly[c]	15-min[b]	15-min[b]	N/A	N/A	Estimated based on the continuous runoff and SSC	Testing of both equilibrium and time-series model
Upper North Grain	Daily[d]	Monthly[c]	N/A	N/A	N/A	Yang (2005), sediment trap data	Pawson et al., (2012), where sediment flux is calculated based on hourly runoff and sediment rating curve	Testing of equilibrium model
Upper Severn	Daily[d]	Daily[d]	N/A	N/A	N/A	N/A	Francis (1990), where sediment flux is estimated based on hourly runoff and sediment rating curve	Testing of time-series model

Sources and characteristics of data:

a, Environmental change network (ECN), point data; b, Unpublished dataset, University of Leeds, point data; c, Met Office Gridded dataset, spatially distributed data; d, Met Office Integrated Data Archive System (MIDAS), point data.

Table 4 Multiple linear regressions for each calendar month between SSI_d and daily temperature and water table for Trout Beck between 1997 and 2009.

Month	Temperature		Water table		Overall	
	Sign	*p*	Sign	*p*	R^2	*p*
Jan	-	<0.001*	-	<0.001*	0.51	<0.001*
Feb	-	<0.001*	-	<0.001*	0.51	<0.001*
Mar	+	0.559	-	<0.001*	0.69	<0.001*
Apr	+	0.448	-	<0.001*	0.79	<0.001*
May	+	0.196	-	<0.001*	0.78	<0.001*
Jun	+	0.007*	-	<0.001*	0.82	<0.001*
Jul	+	<0.001*	-	<0.001*	0.79	<0.001*
Aug	+	0.197	-	<0.001*	0.63	<0.001*
Sep	+	0.059	-	<0.001*	0.84	<0.001*
Oct	-	0.003*	-	<0.001*	0.67	<0.001*
Nov	-	0.001*	-	<0.001*	0.45	<0.001*
Dec	-	<0.001*	-	<0.001*	0.63	<0.001*

*significant at p<0.01

Table 5 A comparison of downscaled measured and modelled runoff ratios, and modelled contribution of subsurface flow to total runoff (Sub / Total). Modelling results are produced by the equilibrium mode of PESERA-PEAT.

Site	Downscaled (%)	Modelled (%)	Error (%)	Nash-Sutcliffe	Sub / Total (%)
Trout Beck	93.3	89.3	-4.3	0.89	9.9
Stean Moor 12	86.6	80.2	-7.4	0.76	16.1
Upper North Grain	N/A	86.6	N/A	N/A	4.5

Table 6 A comparison of downscaled measured and modelled erosion. Modelled erosion produced by both the equilibrium and time-series mode of PESERA-PEAT is listed.

Sites	Downscaled ($t\ ha^{-1}$)	Equilibrium			Time-series		
		Modelled ($t\ ha^{-1}$)	Error (%)	Nash-Sutcliffe	Modelled ($t\ ha^{-1}$)	Error (%)	Nash-Sutcliffe
Stean Moor 12	1.14	1.28	12.3	0.86	1.25	9.7	0.93
Upper North Grain	6.01	6.81	13.3	N/A	N/A	N/A	N/A
Upper Severn	2.36	N/A	N/A	N/A	2.49	5.5	N/A

Figure 1 Conceptual framework of PESERA-PEAT. Boxes without shaded background represent the components directly from the original PESERA-GRID model. Boxes with a shaded background indicate the newly added components in PESERA-PEAT. The dashed boxes delineate the details of the hydrology, vegetation growth and erosion modules shown in scrolls. AET is actual evapotranspiration. Dashed arrows indicate that they do not intersect with other arrows that they cross.

Figure 2 Locations of sites used for model calibration and validation. Topographic (i.e. elevation and local relief) and land cover information are provided for Trout Beck, Stean Moor 12 and Upper North Grain. Local relief is defined as the standard deviation of elevation for all points within a 500-m radius. Note the difference in the scale of Trout Beck and Stean Moor 12 / Upper North Grain.

Figure 3 Sediment rating curves (differentiated by season and rising or falling limb) established for interpolation of suspended sediment concentration (SSC) for Trout Beck catchment between 1997 and 2009.

Figure 4 Comparison of SSI and the sediment rating curve (SRC). The daily runoff and suspended sediment concentration (SSC) of Trout Beck for January 2000 are used as an example in the figure.

Figure 5 Equations used for spatial downscaling of runoff efficiency and sediment flux: (a) relationship between runoff efficiency and catchment size derived from the runoff efficiency reported by Holden and Burt (2003) for Trout Beck, Rough Sike and Little Dodgen Pot Sike between January 1997 and December 1999; (b) relationship between POC flux and catchment size established based on POC flux measured by Pawson et al. (2012) in the upper six reaches of River Ashop between December 2005 and January 2007.

Figure 6 Calibrated results of PESERA-PEAT for the Trout Beck catchment between 1997 and 2009: (a) comparison of calibrated and downscaled measured erosion; (b) linear regression between modelled and downscaled measured erosion. Months 1-12 correspond to January - December.

Figure 7 Mean monthly vegetation biomass modelled by the equilibrium PESERA-PEAT for Trout Beck between 1997 and 2009, Stean Moor 12 between 2010 and 2011 and Upper North Grain between 2005 and 2007. Months 1-12 correspond to January - December.

Figure 8 Validation of soil moisture deficit modelled by the equilibrium PESERA-PEAT for the Trout Beck catchment between 1997 and 2009: (a) comparison of measured water table and modelled soil moisture deficit; (b) linear regression between measured water table and modelled soil moisture deficit. Months 1-12 correspond to January - December.

Figure 9 Validation of runoff modelled by the equilibrium PESERA-PEAT for Trout Beck between 1997 and 2009 and Stean Moor 12 between 2010 and 2011: (a and b) comparison of downscaled measured and modelled runoff, and modelled subsurface flow for Trout Beck; (c and d) comparison of downscaled measured and modelled runoff, and modelled subsurface flow for Stean Moor 12. Months 1-12 correspond to January-December.

Figure 10 Spatial pattern of runoff production modelled by the equilibrium PESERA-PEAT for: (a) Trout Beck between 1997 and 2009; (b) Stean Moor 12 between 2010 and 2011 and (c) Upper North Grain between 2005 and 2007. Note the difference in the scale of Trout Beck and Stean Moor 12 / Upper North Grain.

Figure 11 Validation of erosion modelled by the equilibrium PESERA-PEAT for Stean Moor 12 between 2010 and 2011: (a) comparison of downscaled measured and modelled erosion; (b) linear regression between downscaled measured and modelled erosion. Months 1-12 correspond to January-December.

Figure 12 Sediment production, storage and yield modelled by the equilibrium PESERA-PEAT for Trout Beck between 1997 and 2009 (first row), Stean Moor 12 between 2010 and 2011 (second row) and Upper North Grain between 2005 and 2007 (third row). Classification and colour scales for each similar variable plotted are the same between the catchments for ease of comparison. Note the difference in the scale of Trout Beck and Stean Moor 12 / Upper North Grain.

Figure 13 Validation of erosion modelled by the time-series PESERA-PEAT for Stean Moor 12 between 2010 and 2011: (a) comparison of downscaled measured and modelled erosion, and modelled sediment storage; (b) linear regression between downscaled measured and modelled erosion.

Figure 14 Erosion and sediment storage modelled by the time-series PESERA-PEAT for the Upper Severn catchment between 1983 and 1984.

Figure 15 Comparison of the equilibrium and time-series PESERA-PEAT for Stean Moor 12 between 2010 and 2011: (a) comparison of mean monthly erosion predicted by the equilibrium and time-series PESERA-PEAT; (b) linear regression between mean monthly erosion predicted by the equilibrium and time-series PESERA-PEAT. Months 1-12 correspond to January-December.

Figure 16 Sensitivity analysis of PESERA-PEAT, including sensitivity of modelled erosion to: (a) rainfall and temperature, (b) vegetation cover and (c) drainage density and depth. The baseline conditions are described in the text.

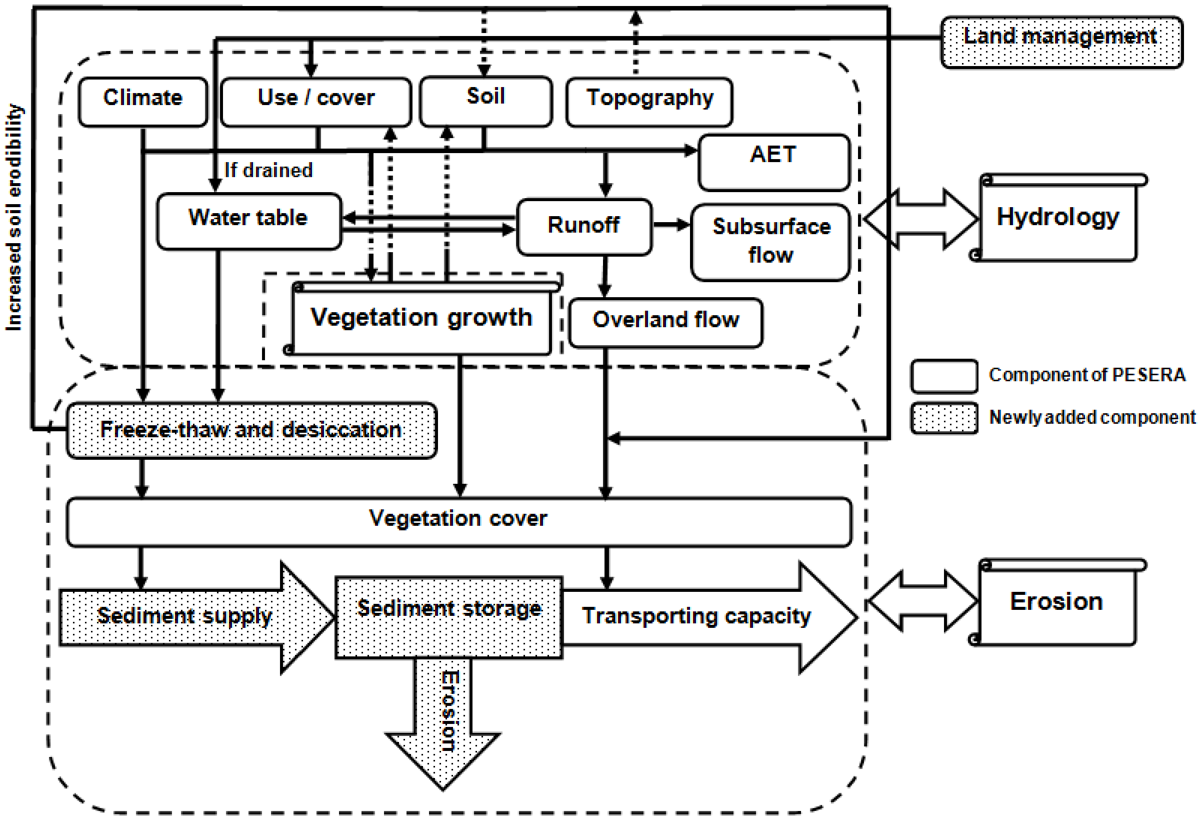
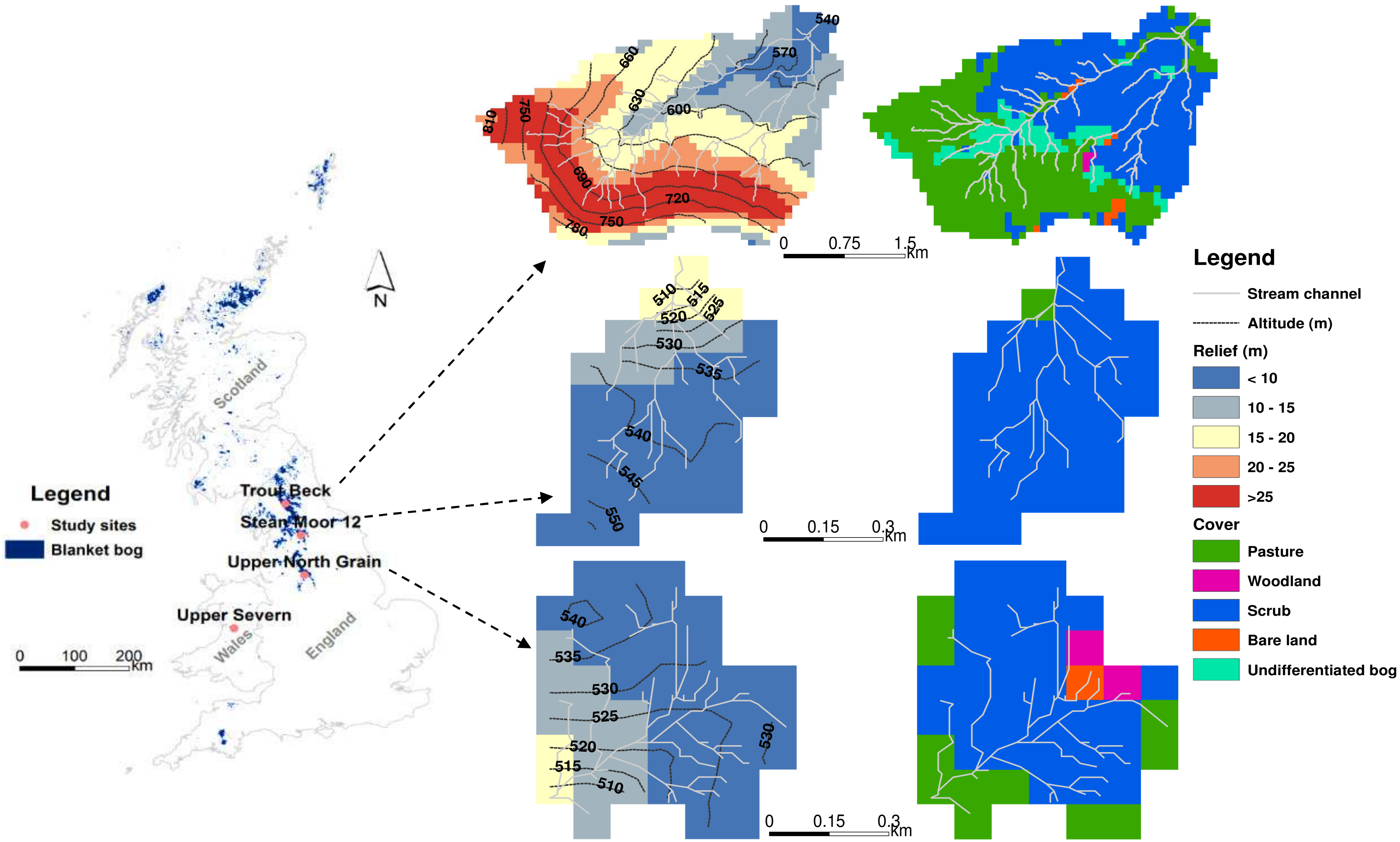
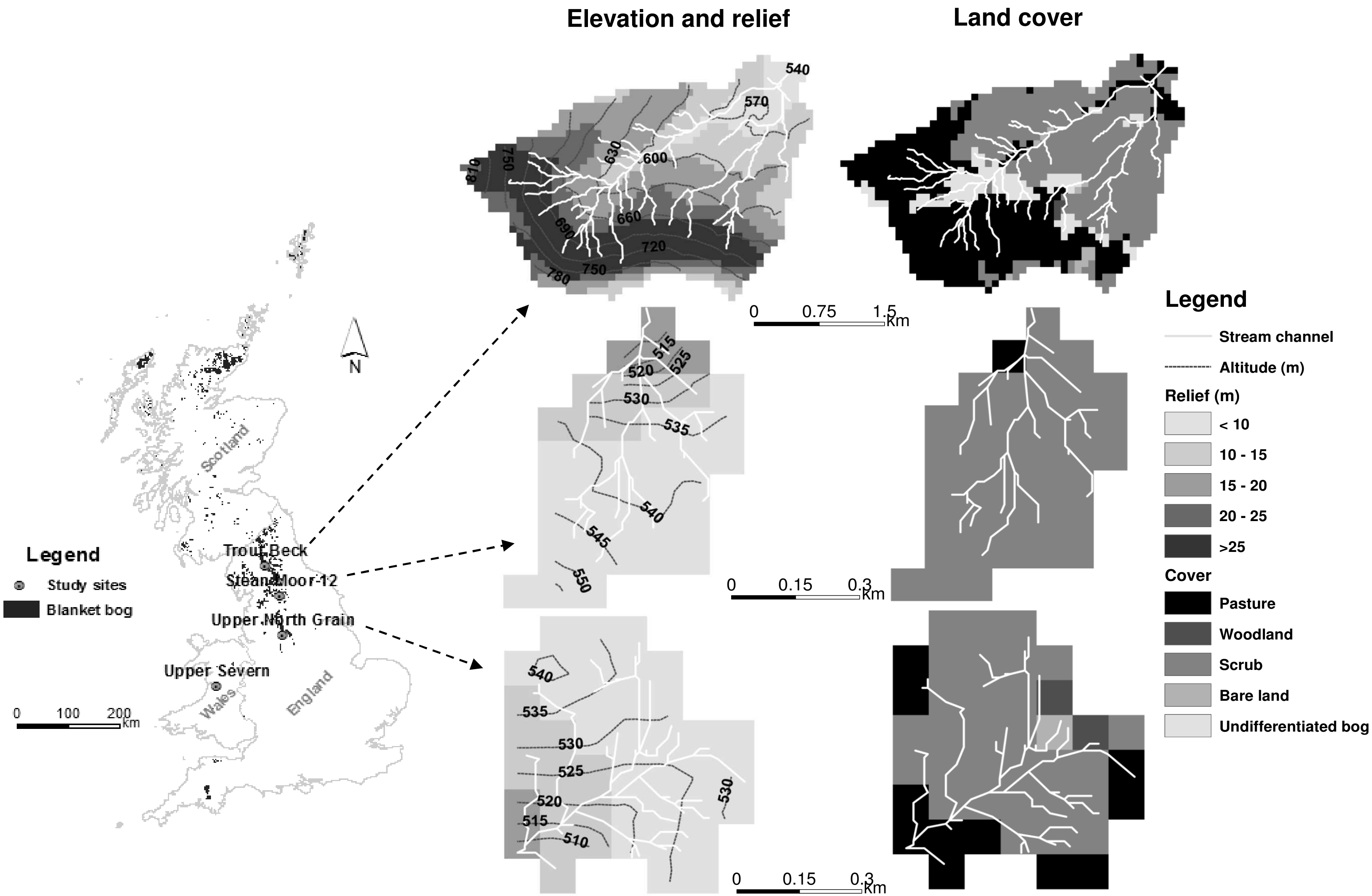


Figure 1 Conceptual framework of PESERA-PEAT. Boxes without shaded background represent the components directly from the original PESERA-GRID model. Boxes with a shaded background indicate the newly added components in PESERA-PEAT. The dashed boxes delineate the details of the hydrology, vegetation growth and erosion modules shown in scrolls. AET is actual evapotranspiration. Dashed arrows indicate that they do not intersect with other arrows that they cross.



Legend
Study sites
Blanket bog
Trout Beck
Stean Moor 12
Upper North Grain
Upper Severn
Scotland
Wales
England
N
0 100 200 Km
0 0.75 1.5 Km
0 0.15 0.3 Km
0 0.15 0.3 Km
Legend
Stream channel
Altitude (m)
Relief (m)
< 10
10 - 15
15 - 20
20 - 25
>25
Cover
Pasture
Woodland
Scrub
Bare land
Undifferentiated bog

Figure 2 Locations of sites used for model calibration and validation. Topographic (i.e. elevation and local relief) and land cover information are provided for Trout Beck, Stean Moor 12 and Upper North Grain. Local relief is defined as the standard deviation of elevation for all points within a 500-m radius. Note the difference in the scale of Trout Beck and Stean Moor 12 / Upper North Grain.



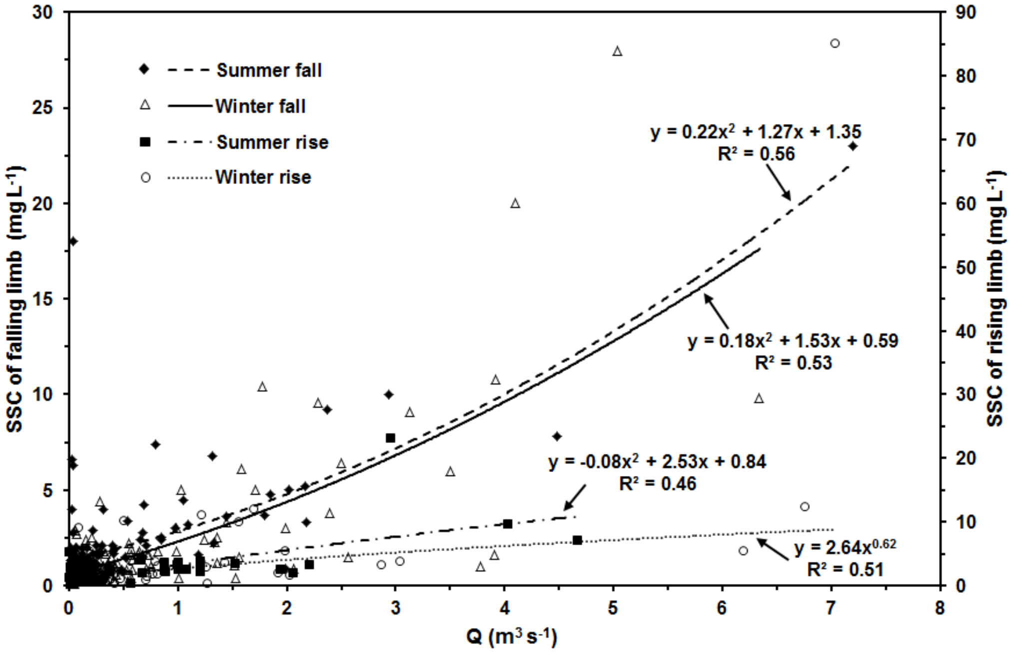


Figure 3 Sediment rating curves (differentiated by season and rising or falling limb) established for interpolation of suspended sediment concentration (SSC) for Trout Beck catchment between 1997 and 2009.

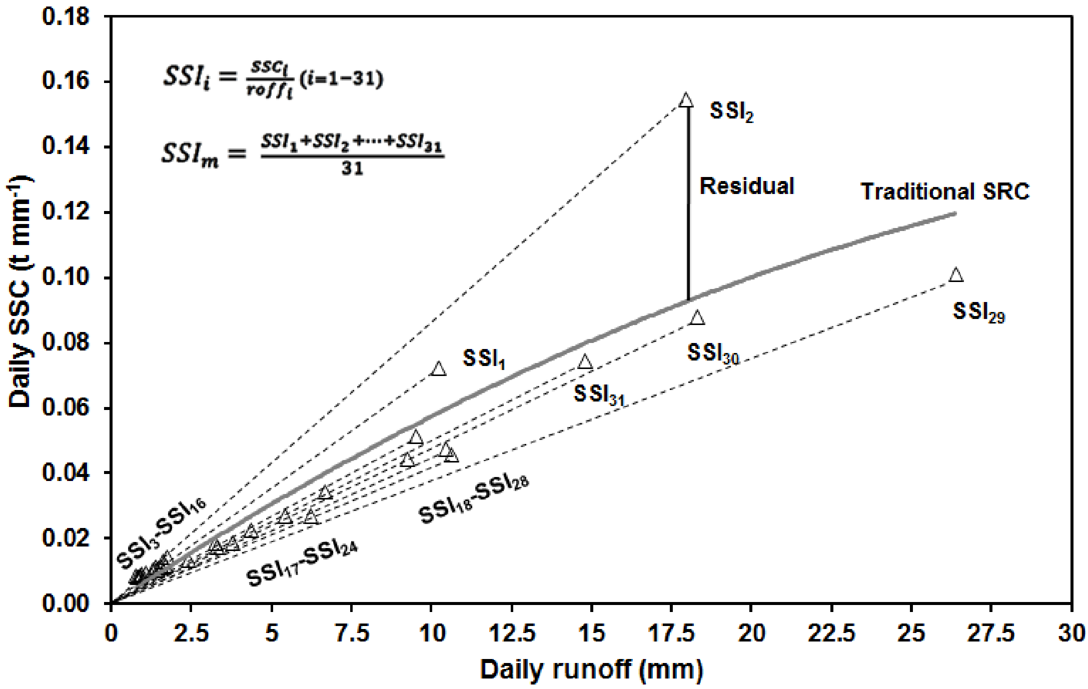


Figure 4 Comparison of SSI and the sediment rating curve (SRC). The daily runoff and suspended sediment concentration (SSC) of Trout Beck for January 2000 are used as an example in the figure.

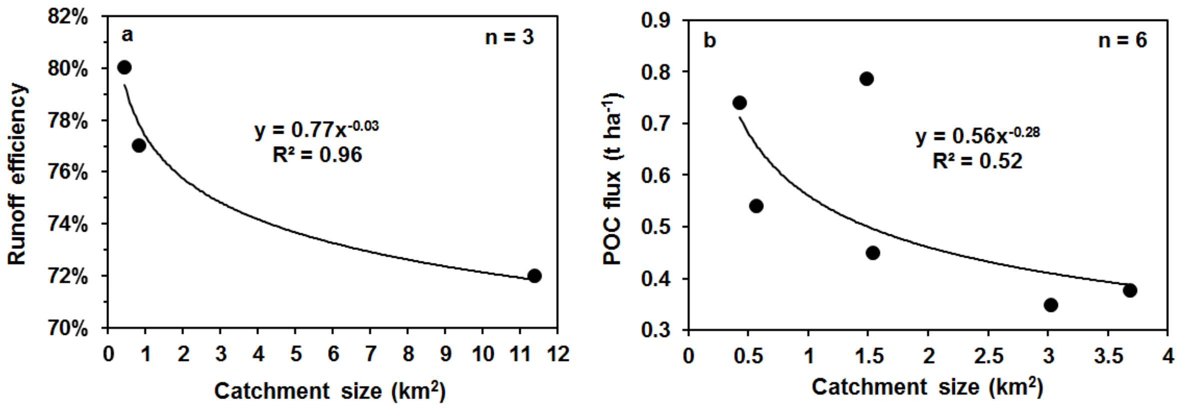


Figure 5 Equations used for spatial downscaling of runoff efficiency and sediment flux: (a) relationship between runoff efficiency and catchment size derived from the runoff efficiency reported by Holden and Burt (2003) for Trout Beck, Rough Sike and Little Dodgen Pot Sike between January 1997 and December 1999; (b) relationship between POC flux and catchment size established based on POC flux measured by Pawson et al. (2012) in the upper six reaches of River Ashop between December 2005 and January 2007.

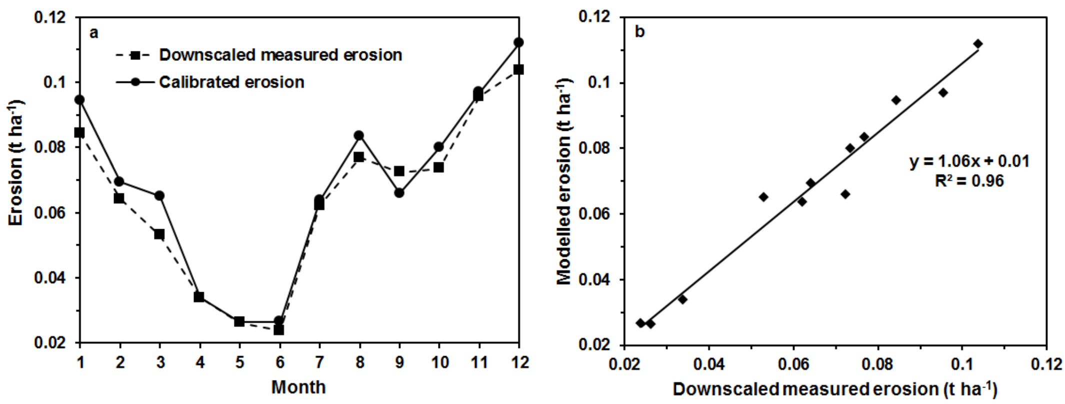


Figure 6 Calibrated results of PESERA-PEAT for the Trout Beck catchment between 1997 and 2009: (a) comparison of calibrated and downscaled measured erosion; (b) linear regression between modelled and downscaled measured erosion. Months 1-12 correspond to January - December.

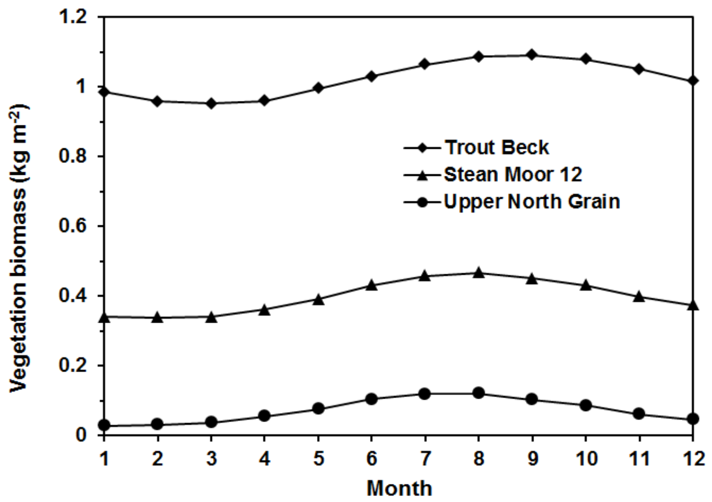


Figure 7 Mean monthly vegetation biomass modelled by the equilibrium PESERA-PEAT for Trout Beck between 1997 and 2009, Stean Moor 12 between 2010 and 2011 and Upper North Grain between 2005 and 2007. Months 1-12 correspond to January - December.

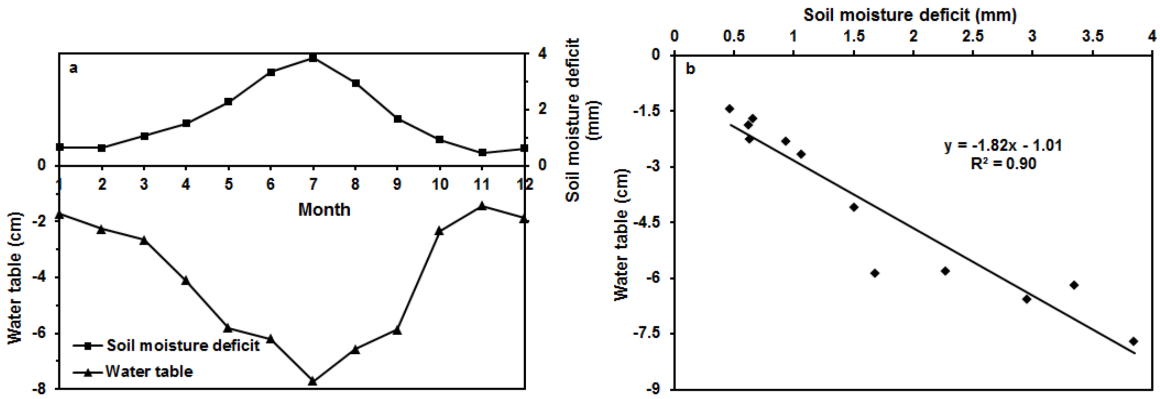


Figure 8 Validation of soil moisture deficit modelled by the equilibrium PESERA-PEAT for the Trout Beck catchment between 1997 and 2009: (a) comparison of measured water table and modelled soil moisture deficit; (b) linear regression between measured water table and modelled soil moisture deficit. Months 1-12 correspond to January - December.

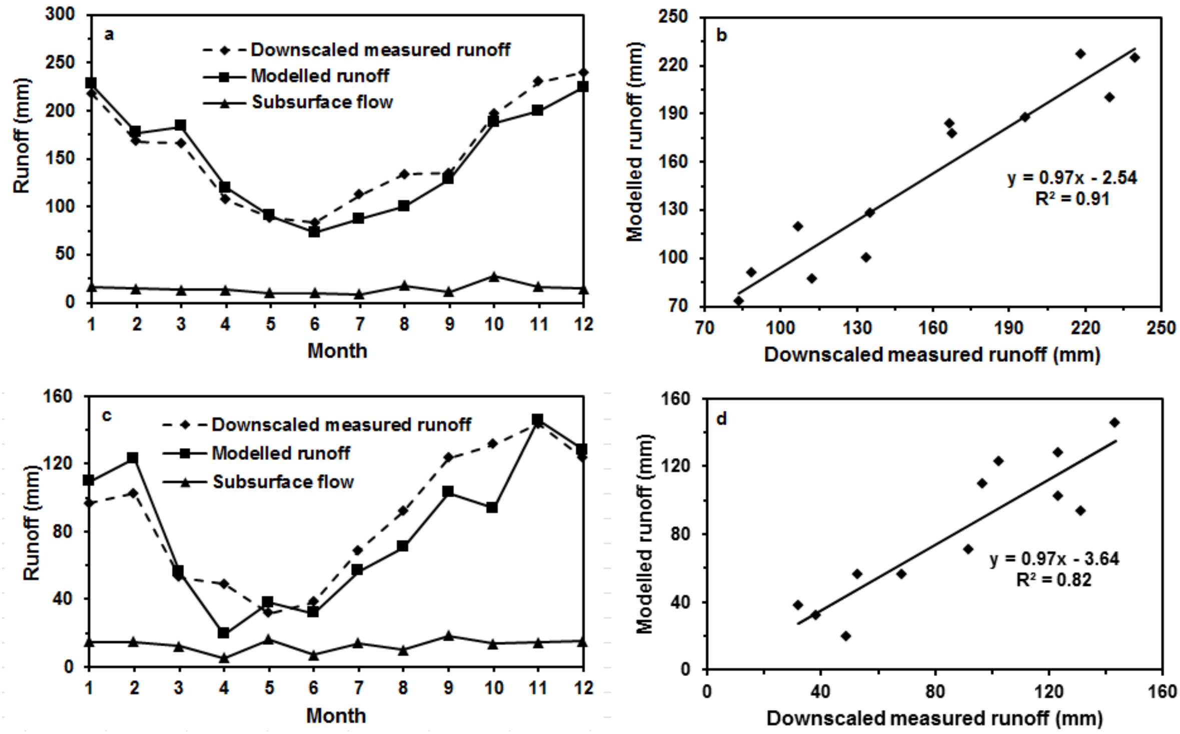


Figure 9 Validation of runoff modelled by the equilibrium PESERA-PEAT for Trout Beck between 1997 and 2009 and Stean Moor 12 between 2010 and 2011: (a and b) comparison of downscaled measured and modelled runoff, and modelled subsurface flow for Trout Beck; (c and d) comparison of downscaled measured and modelled runoff, and modelled subsurface flow for Stean Moor 12. Months 1-12 correspond to January-December.

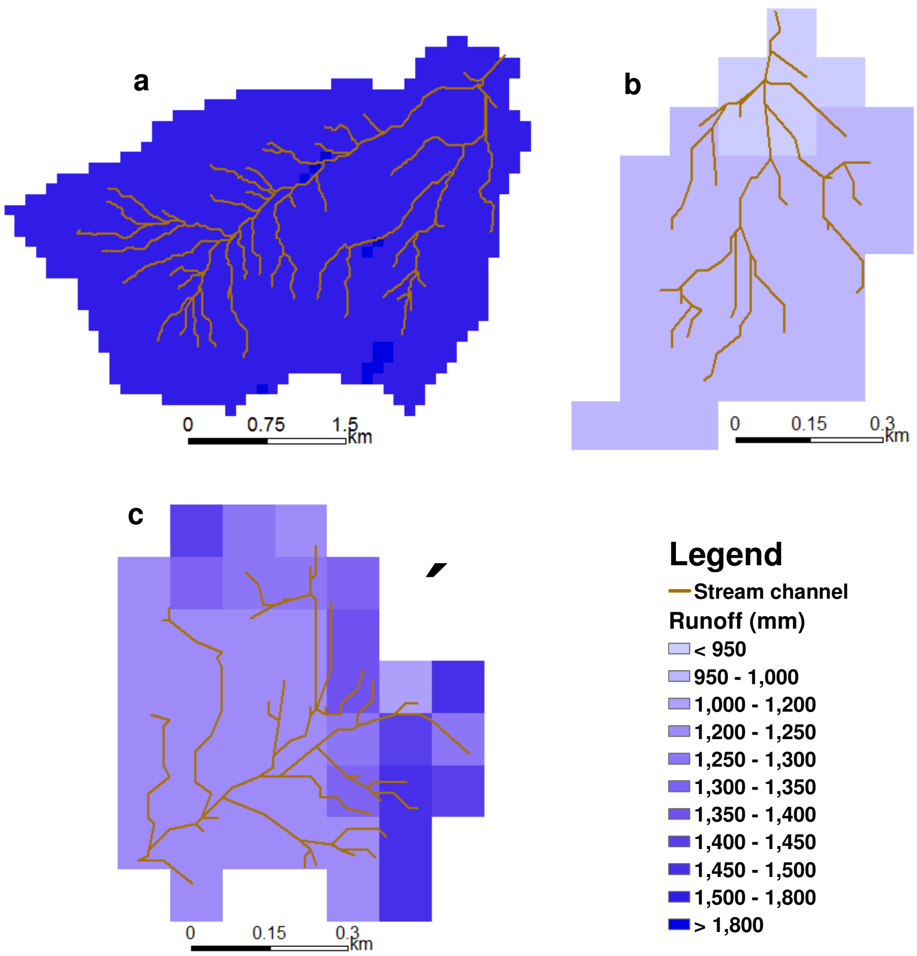
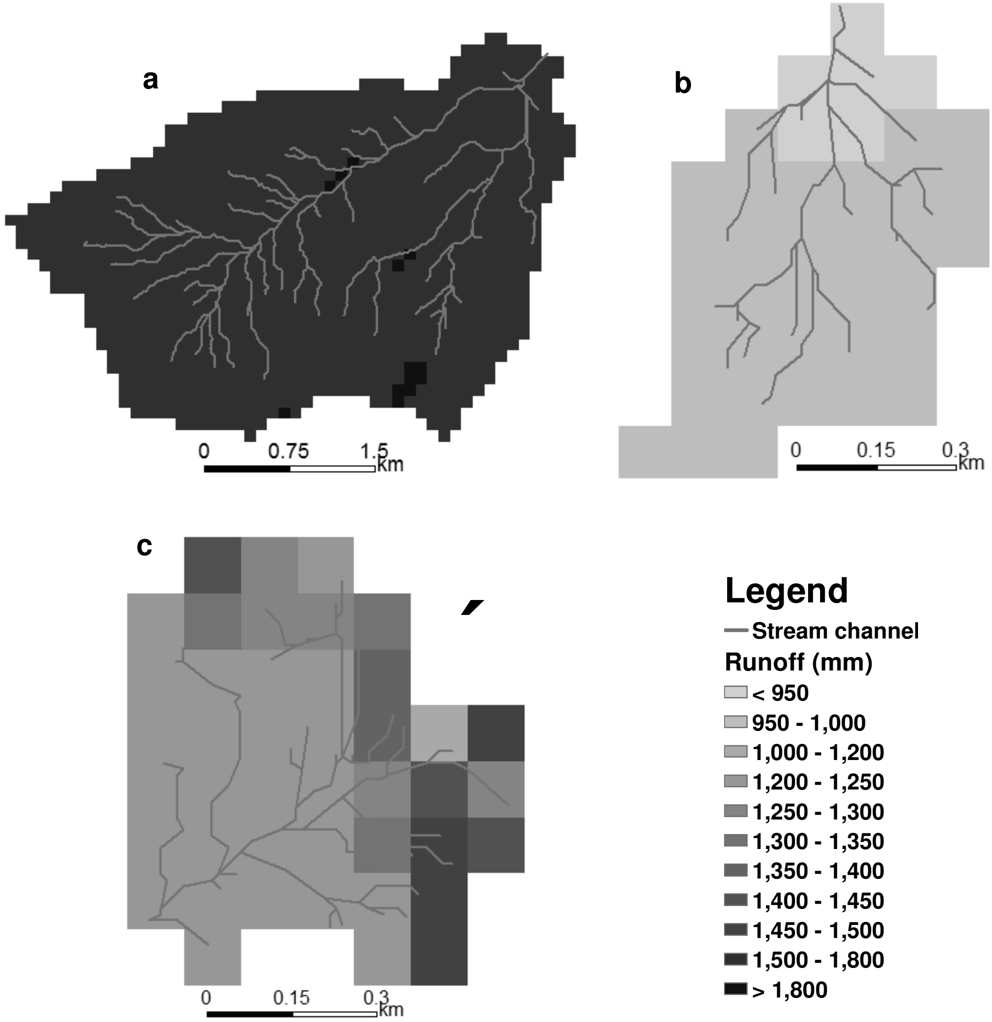


Figure 10 Spatial pattern of runoff production modelled by the equilibrium PESERA-PEAT for: (a) Trout Beck between 1997 and 2009; (b) Stean Moor 12 between 2010 and 2011 and (c) Upper North Grain between 2005 and 2007. Note the difference in the scale of Trout Beck and Stean Moor 12 / Upper North Grain.


a
b
c
0
0.75
1.5
km
0
0.15
0.3
km
0
0.15
0.3
km
Legend
Stream channel
Runoff (mm)
< 950
950 - 1,000
1,000 - 1,200
1,200 - 1,250
1,250 - 1,300
1,300 - 1,350
1,350 - 1,400
1,400 - 1,450
1,450 - 1,500
1,500 - 1,800
> 1,800

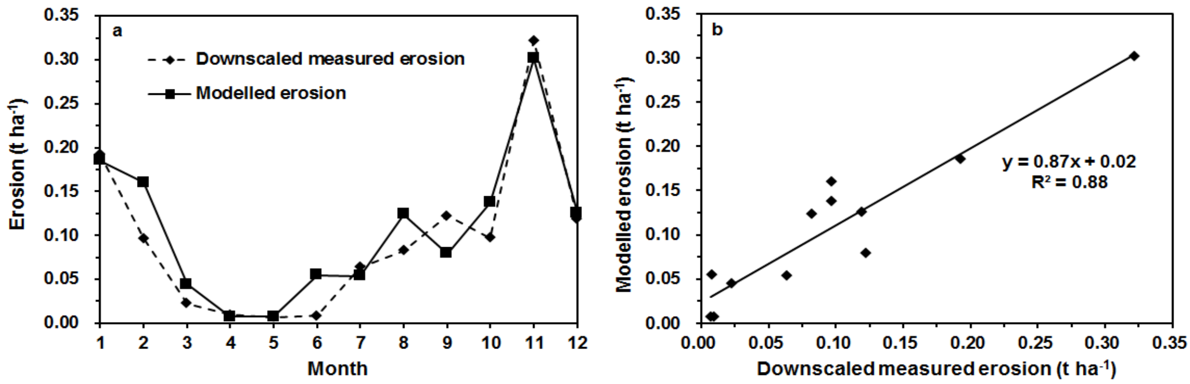


Figure 11 Validation of erosion modelled by the equilibrium PESERA-PEAT for Stean Moor 12 between 2010 and 2011: (a) comparison of downscaled measured and modelled erosion; (b) linear regression between downscaled measured and modelled erosion. Months 1-12 correspond to January-December.

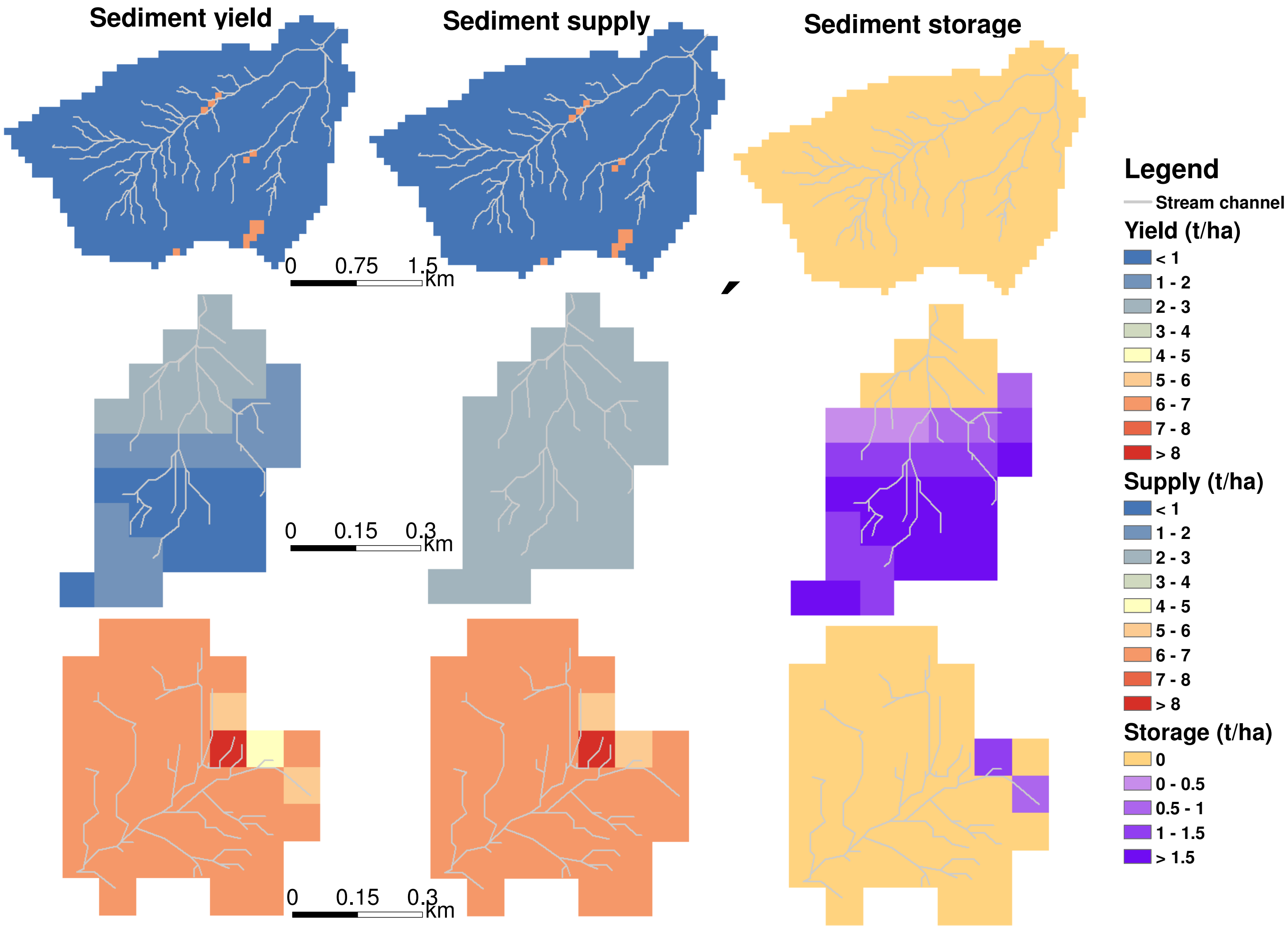
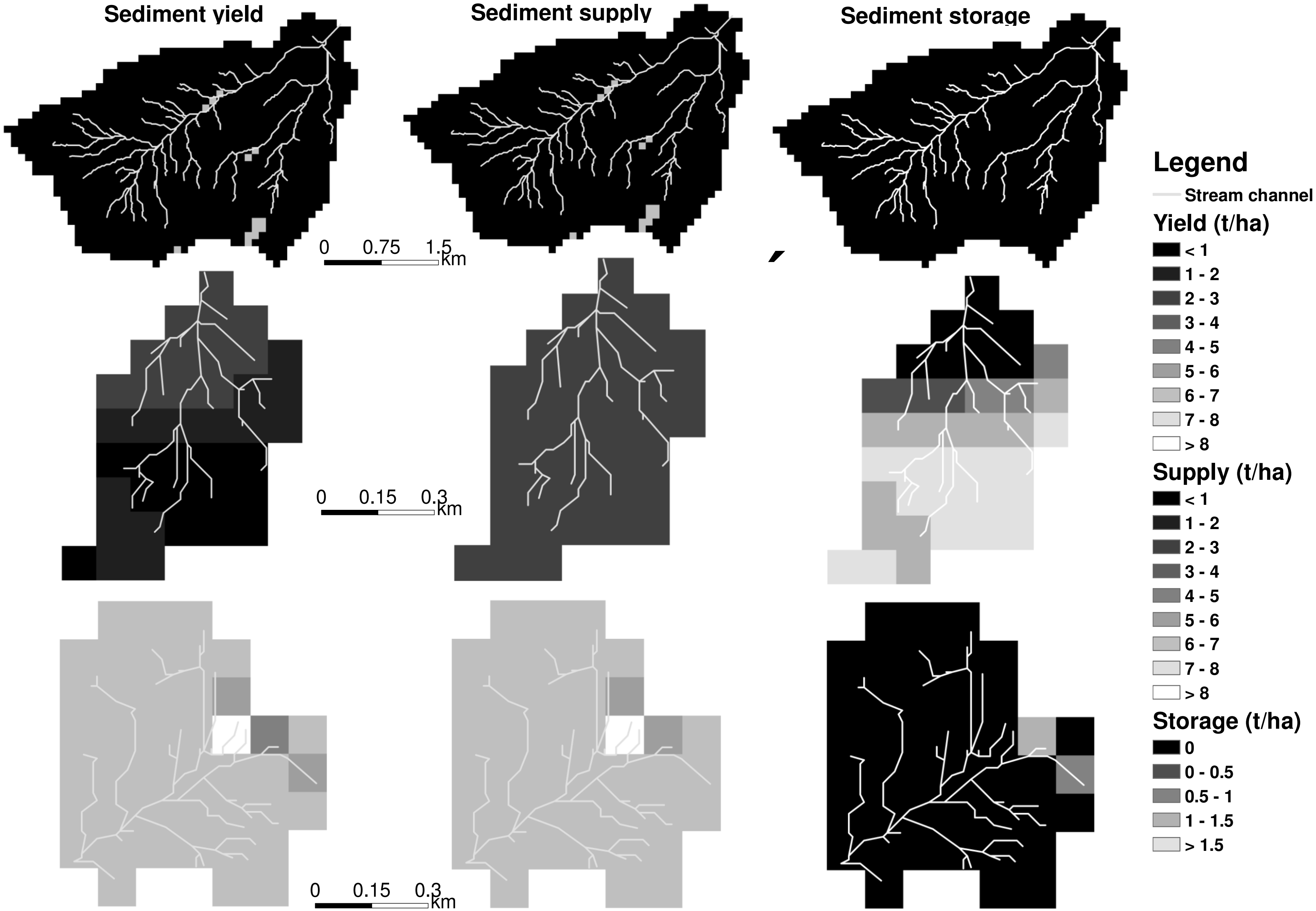

Sediment yield
Sediment supply
Sediment storage
0 0.75 1.5 km
0 0.15 0.3 km
0 0.15 0.3 km
Legend
Stream channel
Yield (t/ha)
< 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 7
7 - 8
> 8
Supply (t/ha)
< 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 7
7 - 8
> 8
Storage (t/ha)
0
0 - 0.5
0.5 - 1
1 - 1.5
> 1.5

Figure 12 Sediment production, storage and yield modelled by the equilibrium PESERA-PEAT for Trout Beck between 1997 and 2009 (first row), Stean Moor 12 between 2010 and 2011 (second row) and Upper North Grain between 2005 and 2007 (third row). Classification and colour scales for each similar variable plotted are the same between the catchments for ease of comparison. Note the difference in the scale of Trout Beck and Stean Moor 12 / Upper North Grain.



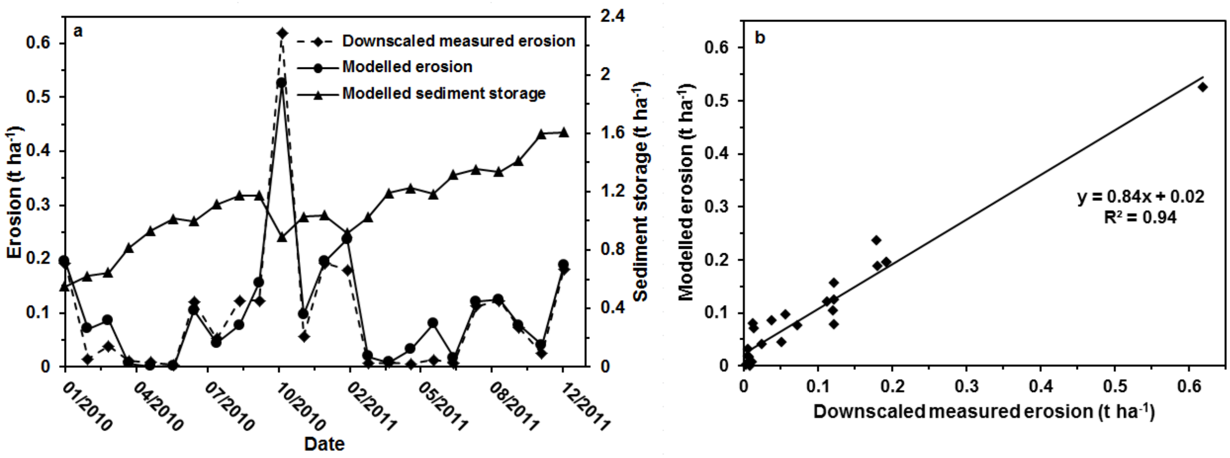


Figure 13 Validation of erosion modelled by the time-series PESERA-PEAT for Stean Moor 12 between 2010 and 2011: (a) comparison of downscaled measured and modelled erosion, and modelled sediment storage; (b) linear regression between downscaled measured and modelled erosion.

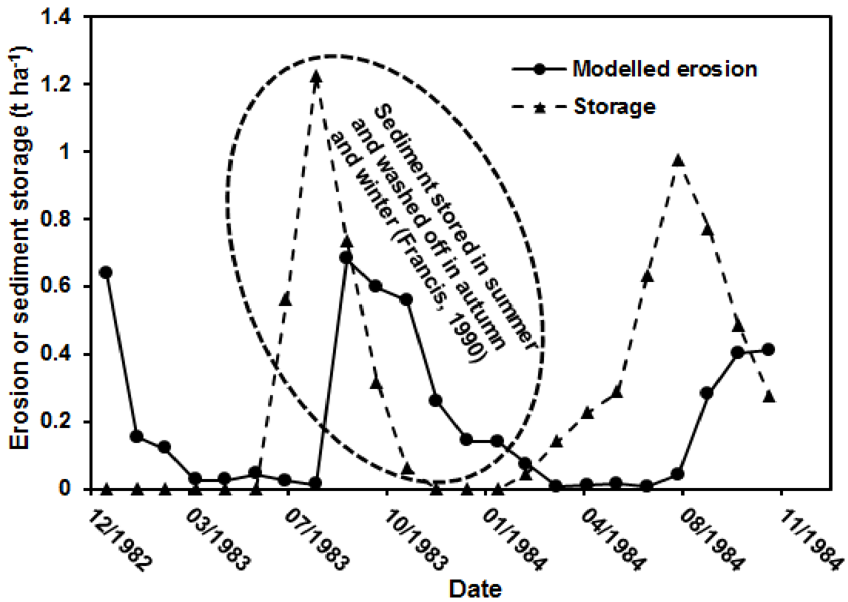


Figure 14 Erosion and sediment storage modelled by the time-series PESERA-PEAT for the Upper Severn catchment between 1983 and 1984.

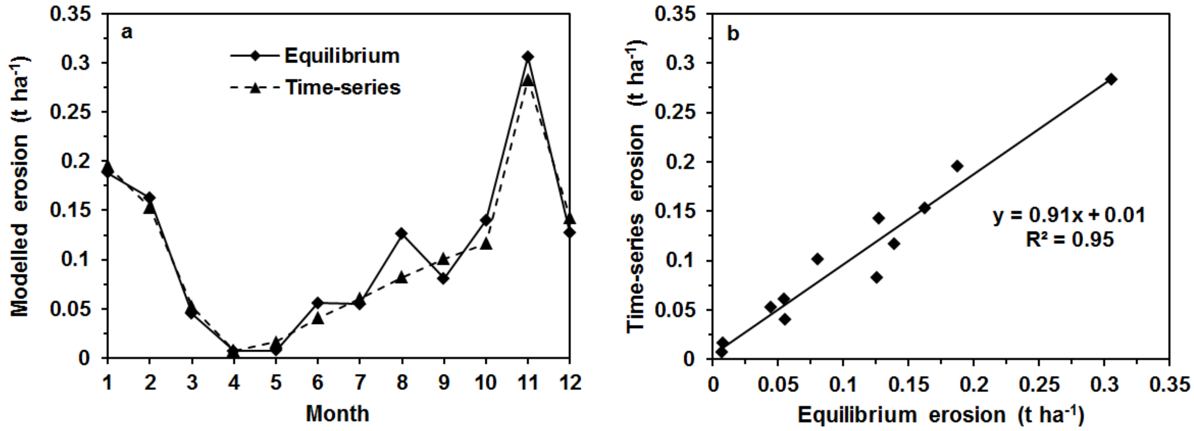


Figure 15 Comparison of the equilibrium and time-series PESERA-PEAT for Stean Moor 12 between 2010 and 2011: (a) comparison of mean monthly erosion predicted by the equilibrium and time-series PESERA-PEAT; (b) linear regression between mean monthly erosion predicted by the equilibrium and time-series PESERA-PEAT. Months 1-12 correspond to January-December.

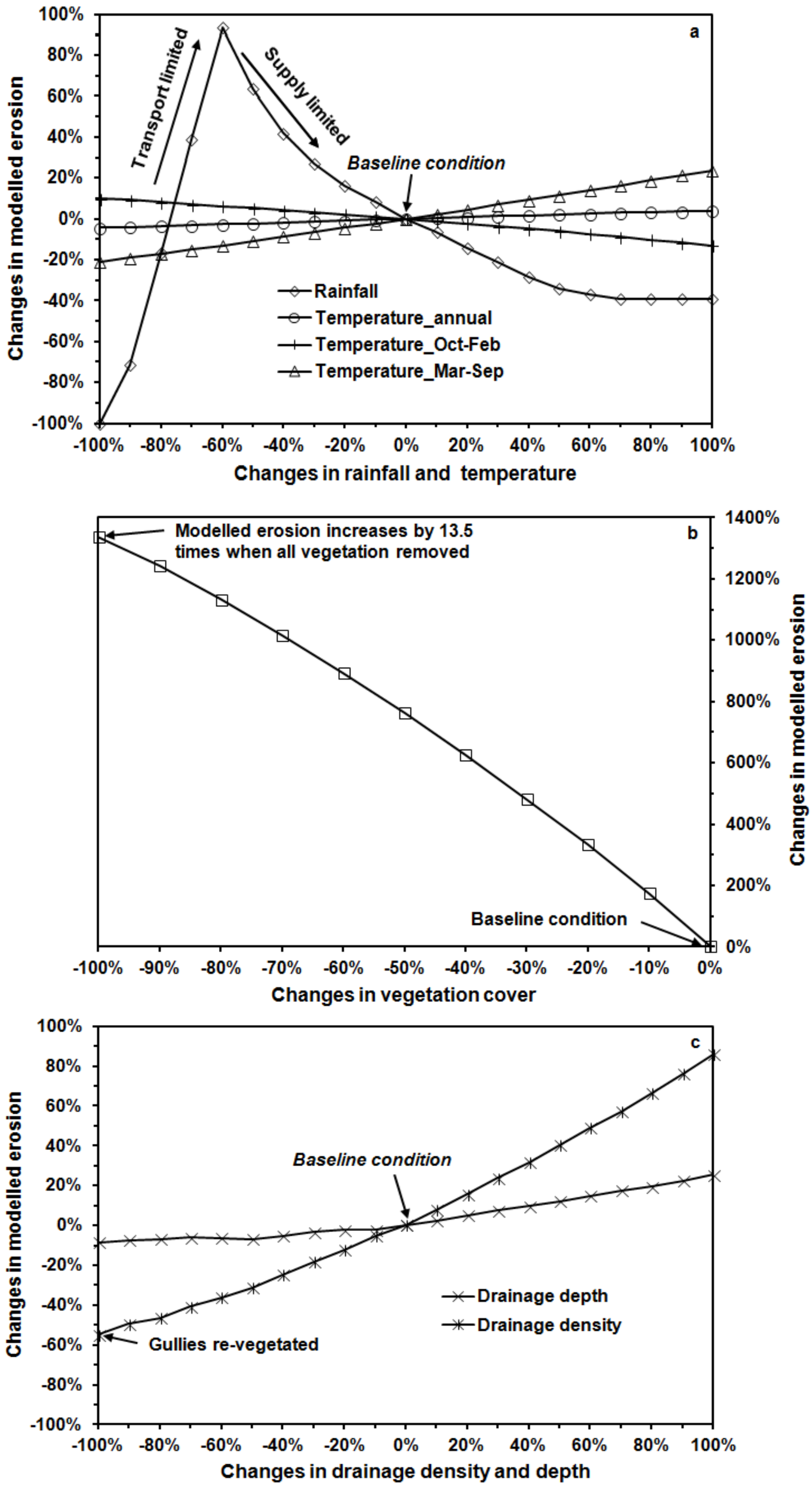


Figure 16 Sensitivity analysis of PESERA-PEAT, including sensitivity of modelled erosion to: (a) rainfall and temperature, (b) vegetation cover and (c) drainage density and depth. The baseline conditions are described in the text.