The effect of interactions between rainfall patterns and land-cover change on flood peaks in upland peatlands

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Abstract

Flood processes in catchments are driven by a combination of rainfall and landscape characteristics. Upland peatlands are source areas of flooding but there is lack of understanding of how different rainfall intensities and temporal patterns may interact with land-cover configurations to influence flood peaks. Using spatially distributed (SD-) TOPMODEL we investigated these interactions for a case study peatland catchment. For each of four rainfall depths ranging from 20 mm to 50 mm, four storm rainfall patterns were applied (rainfall that was uniform, rainfall with an early peak intensity during the storm, middle peak and late peak). Late peak rainfall resulted in the highest river flow peaks at the catchment outlet studied, followed by middle and early rainfall peak patterns, while uniform rainfall through time gave the lowest flow peaks. A key factor was synchroneity of overland flow movement and concentration. The impact on river flow peaks of land-cover change on riparian zones and on gentle gradient slopes was larger than that for other parts of the catchment under different rainfall intensities and patterns. The impacts of land-cover change on proportional change in flood peaks in these sensitive areas became smaller when rainfall intensity increased, but absolute changes in flow peaks became larger. Land-cover change in sensitive areas under middle and late peak rainfall had a larger impact on river flow peaks than for early peak rainfall. It was possible to identify the 'worst' rainfall patterns for a particular case of land-cover change which may be useful for practitioners to help manage expectations of flood response to nature-based solutions.

Keywords: rainfall characteristics, land management, peak flow, overland flow, nature-based solutions, TOPMODEL.

1 Introduction

Runoff processes in natural catchments are driven by a combination of rainfall patterns and landscape characteristics. Every rainfall event has a unique temporal rainfall distribution, but sometimes patterns of this distribution in a particular catchment can be generalized from historic rainfall data (e.g. Dolsak et al., 2016; Huff, 1967; Willems, 2000). Changes in temporal rainfall distributions in a region are due to both climatic change and climatic variability (Yilmaz et al., 2014). Temporal rainfall distributions can impact overland flow and flood processes. Generally, with the same total amount of rainfall, non-uniform temporal patterns are considered to produce higher flow peaks than those with uniform patterns. A storm with rainfall of higher intensity near the end of the storm (late rainfall peak) rather than at the start or middle of the storm is believed to generate a higher flow peak than a storm with the same total rainfall but which has greatest rainfall intensity near the start of the event (Dunkerley, 2012; Dunkerley, 2014). Some studies have shown that this could be related to soil surface sealing arising in response to the higher intensity part of the storm (Flanagan et al. (1988). Other research has attributed the effect to reductions in soil infiltration capacity during late rainfall compared with earlier in the rainfall event (Dunkerley, 2012; Xue and Gavin, 2007).

Peatlands cover around 423 million ha (Xu et al., 2018) and store more than half of the world's soil carbon (Yu et al., 2010). Peatlands often occur in upland areas in temperate and boreal zones where there is a high rainfall excess (Gallego-Sala and Prentice, 2013). Blanket peat exists on open and rolling landscapes, typically in oceanic regions which are wet and cool in climate (Evans and Warburton, 2007). Vascular plants and bryophytes such as *Sphagnum* are usually form dominant vegetation cover in blanket peatlands (Holden et al., 2015). Around 15 % of the UK is covered by blanket peat, where it is mainly found in upland headwater catchments.

Upland blanket peatlands, normally with shallow water tables, produce minimal baseflow but are quickly saturated during rainfall events (Evans et al., 1999; Price, 1992). Typically, upland blanket peatlands in the UK are subject to light frontal rainfall (<10 mm hr^{-1}) but very occasionally storm intensities of 20-50 mm hr^{-1} can occur which may lead to downstream flooding. Saturation-excess overland flow dominates the hillslope contributions to the river channel hydrograph in upland blanket peat, even during light rainfall events (Holden and Burt, 2002; Holden and Burt, 2003). Hence, upland peatlands are flashy hydrological systems and sensitive to precipitation characteristics and land-cover modifications. For such systems, reductions of soil infiltration capacity during storms and sealing of the surface due to rain drops may be of minimal importance in determining the river flow peak response to rainfall. Rather, the prime impacts of rainfall pattern on flow peaks in blanket peatlands could be related to overland flow delivery and concentration on hillslopes. However, this has never been tested. Different temporal profiles of precipitation could generate varying overland flow depths and velocities for every point on hillslopes, which results in different spatial distributions of overland flow in the catchment for every time point in a flood event. Thus the synchroneity of overland flow concentration driven by temporal rainfall patterns could be a key determinant for river flood formation from peat catchments (Gao et al., 2016). Changes in such overland flow velocities and patterns may produce different river flow peak timings and magnitudes.

In recent years, 'natural flood management' also known as 'nature-based solutions' has been advocated as a sustainable measure to reduce flood risk and as a complementary measure to traditional flood management (SEPA, 2011). Natural flood management deals with the sources and pathways of floodwaters and manipulates river flow at the catchment scale (Holstead et al., 2017; SEPA, 2011). It includes altering, restoring or using landscape features to manage flood risk, with practices such as exclusion of grazing animals, vegetation restoration, creating porous surfaces, or use of small storage ponds and scrapes to create landscape roughness and water storage. However, there is a paucity of evidence for evaluating such nature-based solutions for their flood-attenuation performance under a range of rainfall patterns (Dadson et al., 2017; Rogger et al., 2017). For upland blanket peatlands, as overland flow is common, even when peat has been disturbed by drainage (Holden et al., 2006), then potentially one of the most effective ways of delaying streamflow using natural flood management is to create a rough, well-vegetated surface (Ballard et al., 2011; Gao et al., 2016; Gao et al., 2017; Lane and Milledge, 2013). Such rough revegetation most commonly occurs for disturbed peatlands where mosses are encouraged to re-establish in bare areas or to act as an understorey to existing sedge and shrub cover (Parry et al., 2014). The additional motivation for managers is that re-establishment of mosses on peatlands is seen to provide other functional benefits including enhanced carbon capture and attenuation of methane release (Larmola et al., 2010).

The modelling studies by Gao et al. (2016) and Gao et al. (2017) indicated that the same land-cover change in 'sensitive' areas of upland peat catchments (e.g. riparian zones and gentle slope areas) could have three times the impact on river flow peaks as those same land-cover changes in 'insensitive' areas such as headwater regions and steep slopes. However, these modelling studies used only simple designs of moderate rainfall events (i.e. 1-hour rainfall pulses with uniform rates of 15 mm hr^{-1}, 20 mm hr^{-1}, and 30 mm hr^{-1}). Larger intensities of rainfall were not studied. Furthermore, even if the total rainfall depths of storms are kept identical, varying rainfall profiles (i.e. different temporal distributions of precipitation) could still change the spatial distribution of overland flow production and synchroneity of overland flow concentration on hillslopes resulting in differences in river hydrographs. Therefore, we do not know whether the sensitive parts of upland catchments recognized in the study of Gao et al. (2016) are still the most sensitive for different rainfall intensities and patterns. We also do not know how land-cover change in these areas affects flood peaks for different distributions of rainfall events. This interaction information would be important to support expectations by natural flood management practitioners on the consistencies or inconsistencies of performance of land-cover change solutions in upland systems to rainfall events. Accordingly, using numerical modelling methods, this paper aims to investigate the impacts of rainfall characteristics on river flow peaks during flood events in an upland blanket peat catchment, and to study the interactions between rainfall characteristics and land-cover change.

2 Methodology

2.1 Study site

The Trout Beck catchment (54°41' N, 2°23' W) is located in the Moor House National Nature Reserve and covers an area of 11.4 km^2 with an elevation ranging from 842 m to 533 m in the North Pennine region of northern England (see Figure 1). It is a headwater tributary of the River Tees, and 90% of the area is covered by blanket peat with a typical depth of 1-2 m

(Evans et al., 1999). Large areas of the catchment have re-vegetated with *Sphagnum* and *Eriophorum* in recent decades after the peat suffered widespread erosion in the 1950s-1970s (Grayson et al., 2010). The catchment is mainly covered by a *Calluna-Eriophorum* vegetation association with a slowly increasing *Sphagnum* abundance in the understory. Over 630 m, *Calluna is absent and Eriophorum is dominant* (Evans et al., 1999). The climate of the catchment is sub-arctic oceanic (Manley, 1942) and there is a mean annual rainfall of 2012 mm based on rainfall records from 1951 to 1980 and 1991 to 2006 (Holden and Rose, 2011).

2.2 SD-TOPMODEL

The original TOPMODEL was a lumped or semi-distributed model of catchment hydrology when developed by Beven and Kirkby (1979). Gao et al. (2015) developed a spatially-distributed version - SD-TOPMODEL - which retains the key catchment scale equations of runoff production from the original TOPMODEL (see Kirkby, 1997) but downscales those equations to cell scale (using grid cells as computational units). A new overland flow module was constructed in SD-TOPMODEL by Gao et al. (2015) to represent overland flow delivery and routing. The overland flow module employed the multiple-direction flow theory of Quinn et al. (1991) and an empirically-derived form of the Darcy-Weisbach equation (Holden et al., 2008). Thus, the SD-TOPMODEL takes topography, surface roughness and water depth into account to represent overland flow movement in catchments. In SD-TOPMODEL, there is a dynamic interaction between overland flow and subsurface flow for each computational cell, and overland flow from upslope cells can infiltrate into soil in downslope cells in a catchment. There are major advantages of SD-TOPMODEL for our study. The model can explicitly simulate the locations of overland flow generation, the rates of overland flow production, the depths of overland flow, the pathways of overland flow movement, and the locations of overland flow infiltrating into soil or entering river channels in any time step during and after a storm with time-varying precipitation intensities. SD-TOPMODEL also represents the variation of overland flow velocity according to the surface roughness presented by the land cover, taking gradient and flow depth into account.

There are three key parameters for peatland catchment modelling in SD-TOPMODEL as defined by Gao et al. (2015): *K* is the hydraulic conductivity of the soil; *m* is a scaling parameter representing the active water storage in soil; and k_v is an overland flow velocity parameter related to surface roughness. The model was calibrated and validated by using the GLUE (generalized likelihood uncertainty estimation) method (Beven and Binley, 1992) of which details can be found in Gao et al. (2015). Values of m=0.0055 m and near-surface K=100 m hr^{-1} had good performance (i.e. Nash-Sutcliffe efficiency > 0.8 in both the model calibration and validation in the Trout Beck catchment). This well-performing parameter set was used to run the model for all scenarios, in order to retain consistency in comparing the scenarios. The results of scenario modelling could be impacted by the uncertainty of this single parameter set, but the large consumption of computational time for the GLUE method was not possible for direct application in this study. However, uncertainties in the model have previously been investigated by Gao et al. (2016). In this study using the GLUE framework, 50 parameter sets, in which each set included three parameters (i.e. m, K, k_v), were randomly selected for three different study catchments (including Trout Beck catchment) in its representative parameter space and used to run the model in the calibration period 50 times. The top five parameter sets with the highest Nash-Sutcliffe efficiencies (all >0.82) were obtained for each catchment that they studied (the five sets performed well also in validation periods). They were then used in land cover scenario runs (only k_v was changed in the land cover change areas of the land cover scenarios). The results were entirely consistent with the results that were obtained by using one parameter set (see the supplementary material). Thus, based on GLUE results obtained by Gao et al. (2016) using SD-TOPMODEL, the one well-performing parameter set chosen was appropriate.

The velocity parameter of overland flow was derived from an empirical study of Holden et al. (2008) in a UK blanket peatland catchment, in which overland flow was investigated for different vegetation types, slopes and flow depths. It was found that mean velocity of overland flow and Darcy-Weisbach roughness could be based on a single parameter for each typical land-surface cover (see Section 2.4).

2.3 Designed rainfall events and land-cover scenarios

To investigate impacts of rainfall intensities on hydrographs in flood events, 20 mm, 30 mm, 40 mm and 50 mm storm events (1 hr duration) were applied as the modelled inputs of precipitation. These values were based on an investigation of extreme events which were realistic for the study region. A 1-hr 20 mm hr^{-1} rainfall event is approximately equivalent to a 10-year return period event estimated from the empirical frequency of summer rainfall events in the study catchment (from 1993 to 2009). The 1-hr 50 mm event is the largest 1-hr rainfall observed in the period for which rainfall data are available in the catchment. For each rainfall depth, a series of temporal precipitation patterns were designed, i.e. uniform profile, late peak profile (more intense toward the end of the storm), early peak profile (more intense at the start of the storm) and middle peak profile (Figure 2).

Land-cover scenarios employed in the modelling experiments included a baseline scenario, two sets of land-cover change scenarios, and a set of bare peat soil and revegetation scenarios. The baseline land-cover scenario assumed that all of the catchment was covered by *Eriophorum* which, in fact, dominates the vegetation cover of the Trout Beck catchment.

The three scenario sets of land-cover change - the slope position scenarios, the riparian zone scenarios and the steep-gentle slope scenarios (see Figure 3 a to g) - were selected to provide a range of different spatial configurations and to test commonly held assumptions about the spatial sensitivity of catchment cover for flood risk. These three main sets of scenarios were investigated in the modelling study of Gao et al. (2016) under a 20 mm storm event. Hence, by adopting the same main land-cover change scenarios we can compare our results to those in that earlier study. For the riparian zone scenarios, the river channel networks were defined with three different thresholds of accumulative upslope areas (i.e. 250 cells, 1000 cells, and 3000 cells). In a peatland catchment, the network of river channels can be complicated by headwater gullies with only intermittent flow. The channel network can be defined with different thresholds of accumulative upslope areas. A high threshold will produce a short downstream channel network and a low threshold will define an extended and upslope-connected channel network. Considering the resolution of the DEM data (20 m x 20 m) used in this study and avoiding an unrealistically large area of hillslopes being covered by riparian zones, 1.2 km^2 (3000 cell), 0.4 km^2 (1000 cell), and 0.1 km^2 (250 cell) cumulative upslope areas were selected as thresholds to organize the riparian zone scenarios. The steepest 10 % of the catchment area and the flattest 10 % of the catchment were selected for land-cover change in the steep or gentle slope scenarios. The final land-cover change scenario – revegetation of bare peat areas - involved data from a field survey in 2012 by North Pennines Area of Outstanding Natural Beauty Partnership (Figure 3h) which mapped areas of bare peat that the Partnership seek to revegetate. In practice these maps overestimate bare peat coverage, as they broadly define areas with high concentrations of bare peat, rather than wholly unvegetated areas.

Two land-cover types, bare soil and *Sphagnum*, were used to replace the *Eriophorum* cover respectively on the target sites of the catchment in each scenario to represent possible vegetation loss and restoration. This is a realistic approach as many upland blanket peatlands have become eroded and bare (Evans and Warburton, 2007) and restoration agencies seek to revegetate these systems, often by encouraging *Sphagnum* regeneration (Parry et al., 2014). For the revegetation of bare peat scenario, change for these areas in our model involved revegetation with either *Eriophorum* or *Sphagnum.* In all land-cover scenarios, the parameter of overland flow velocity (k_v) was set to five times greater on bare peat areas than on *Eriophorum* while the velocity parameter on *Sphagnum* areas was half that of the *Eriophorum* areas. This relationship between the overland flow velocity parameters (an inverse roughness parameter) of *Sphagnum, Eriophorum*, and bare peat is based on the field study of (Holden et al., 2008).

For each land-cover scenario, except the revegetation of bare peat scenario, land-cover change area was set to be 10 % of the catchment. For the real bare peat scenario, 9.7 % of the catchment was mapped as bare and therefore this 9.7 % of the catchment was modified in the associated revegetation scenarios. For the baseline land-cover scenario, all four rainfall patterns for each rainfall depth were used as the input in model runs. However, to save computing time, all four rainfall patterns, for the 30 mm rainfall depth only, were employed for all land-cover change scenario modelling.

2.4 Modelling runs

The DEM grid cell used in the study was 20m x 20m. The time step used in the scenario modelling runs was 0.1 hr in order to help identify minor differences in peak timings and size between scenario results. For each scenario, it was assumed that there was no overland flow on hillslopes at the first time step but that 90% of cells were saturated. At the start of each run there was a model warming-up stage of 10 time steps (i.e. 1 hour). This was sufficient as the moisture deficit of every cell is derived from the starting runoff at the catchment outlet based on its topographic index. The model was set up with a wet antecedent condition at the beginning of the warming-up stage, with 90% of the catchment being saturated and no overland flow occurring on hillslopes. Therefore 10 time steps were enough to produce an equilibrium condition for rainfall-runoff simulation. Then one of the designed rainfalls (10 time steps long) began followed by another 80 time steps without any rainfall. However, the example figures presented in the results section below focus on the key flood responses during the first 60 time steps rather than all additional time-steps of the recession limb.

3 Results

3.1 River flow peaks with land-cover change under different rainfall intensities (uniform profile)

Under different rainfall intensities, the bare peat scenarios had earlier and increased flow peaks in the river channel compared with the baseline scenario; conversely the scenarios with dense vegetation cover (i.e. *Sphagnum*) delayed and reduced river flow peaks (Table 1).

Riparian strips

In terms of strip position on hillslopes, the riparian bare peat strips created the earliest and highest river flow peaks compared with mid-slope and headwater bare peat strips (see Table 1) in the different rainfall events (20 mm hr^{-1} to 50 mm hr^{-1}). *Sphagnum* cover on the riparian strips created later and lower flow peaks than on mid-slope and headwater strips. For riparian strips located based on different thresholds of accumulative upslope drainage area, bare peat surrounding river channels defined by low thresholds (250 cells, 0.1 km^2) had earlier and higher river flow peaks than riparian strips surrounding high-threshold river channels (3000 cells, 1.2 km^2). *Sphagnum* cover on thinner riparian strips created later and lower river flow peaks than on thicker strips covering the same proportion of the catchment. Figure 4 presents the distribution maps of overland flow velocity and depth for the baseline scenario, the 250-cell bare peat riparian strip scenario, and the 250-cell *Sphagnum* riparian strip scenario at time step 21 after 30 mm uniform rainfall. There was larger overland flow velocity on the bare peat riparian regions than on the two vegetation covers; while more water was retained alongside water courses for the *Sphagnum* riparian strip scenario than the other scenarios.

Gentle and steep slopes

For the scenario sets of land-cover change on gentle slope areas or steep slope areas, the results showed that bare peat on gentle slopes induced higher and earlier flow peaks than bare peat on steep slopes while *Sphagnum* on gentle slopes produced lower and later peaks than those on steep slopes (Table 1).

Revegetation of bare peat patches

Revegetating current bare peat areas reduced and delayed river flow peaks under each rainfall intensity, while revegetation with *Sphagnum* reduced peak flow more than with *Eriophorum* (Table 1).

Rainfall intensity

For most scenario sets under higher rainfall intensities, the relative (%) differences between peak flow rates for different land-cover change scenarios (relative to the peaks of the baseline scenario) were smaller than under lighter rainfall intensities (Table 1). For example, bare peat on the riparian strips along channels defined by 3000 upslope drainage cells increased flood peaks by 7.5% at 20 mm hr^{-1} but only 2.3 % at 50 mm hr^{-1}; *Sphagnum* cover on the same strips reduced flood peaks by 6.3 % at 20 mm hr^{-1} rainfalls to 3.3% at 50 mm hr^{-1} rainfalls. However, the absolute difference of the flow peaks between the land-cover change scenarios and the baseline scenarios increased (non-linearly) as rainfall intensity became greater. Decreases in flow peaks were 2.6 $m^3 s^{-1}$ for 3000 cell *Sphagnum* strips compared with baseline at 20 mm hr^{-1} rainfall but 4.7 $m^3 s^{-1}$ at 50 mm hr^{-1} rainfall. Figure 5 presents a scenario comparison including the 250-cell riparian scenario (Figure 3c), the gentle slope scenario (Figure 3g), and the headwater scenario (Figure 3e) to show the impacts on peak flow under different rainfall intensities.

3.2 River flow peaks under non-uniform rainfall events

For the baseline land-cover scenario, all rainfall patterns with non-uniform profiles increased river flow peaks and changed peak timings compared with the corresponding uniform-profile events with the same total rainfall. The resulting hydrographs are shown in Figure 6. The early rainfall peak profile resulted in an earlier but lower river flow peak compared with the middle and late peak profiles in each rainfall depth scenario. The flow peak of the middle peak profile was later than the early rainfall peak profile but earlier than the late peak profile in each scenario. The late peak profiles created higher river flow peaks than the middle profiles under all rainfall events, even though results were close for the 50 mm rainfall event. Taking the 20 mm set as an example (Figure 6a), non-uniform rainfall patterns increased flow peaks by 1.4%, 5.9% and 7.5% respectively for the early peak profile, the middle peak profile, and the late peak profile, compared with the uniform rainfall profile. The relative differences of river flow peaks under uniform and non-uniform rainfalls were greater with increased precipitation intensity. For example, during the 50 mm rainfall event (Figure 6d), the late, middle, and early rainfall profiles had 3.9%, 19.0% and 19.6% higher river flow peaks than the uniform rainfall profile, which are much larger differences than for lesser rainfall depths.

3.3 River flow peaks with land-cover change under non-uniform rainfall events

Land-cover change under storms with non-uniform temporal precipitation profiles generally resulted in larger impacts on river flow peaks compared with those storms with uniform rainfall.

Riparian strips

Under rainfalls with different temporal patterns, the riparian bare peat strip created earlier and higher river flow peaks than the mid-slope and headwater bare peat strips. Conversely, *Sphagnum* cover on the riparian strips resulted in later and lower flow peaks than on the mid-slope strips and the headwater strips. However, the flow peaks produced by having mid-slope strips of land-cover change were quite similar to the peaks of riparian strips under the non-uniform profile rainfalls. For example, under the early peak rainfall the differences of the *Sphagnum* riparian strip and the

Sphagnum mid-slope strip peaks (compared with the peak of the baseline scenario) were 4.7% (3.51 $m^3 s^{-1}$) and 3.4% (2.56 $m^3 s^{-1}$) (Table 2).

For the different riparian strip scenarios, land-cover change on the 250-cell riparian strip had a larger impact on river flow peaks than the 1000-cell and 3000-cell riparian strips (Table 2). For example, under the late peak rainfall, bare peat on the 250-cell riparian strip increased the river flow peak by 11.4% (9.58 $m^3 s^{-1}$), while the 1000-cell and 3000-cell riparian strips were associated with 9.1% (7.67 $m^3 s^{-1}$) and 4.2% (3.51 $m^3 s^{-1}$) flow peak increases. Changing to *Sphagnum* cover on the 250-cell riparian strip created an 11.7% (9.90 $m^3 s^{-1}$) reduction of river flow peak, which was more than the 11.0% (9.26 $m^3 s^{-1}$) reduction for the 1000-cell riparian strip and the 7.6% (6.39 $m^3 s^{-1}$) reduction for the 3000-cell riparian strip.

Gentle and steep slopes

Under all non-uniform rainfall events, bare peat on the gentle slope areas gave much higher river flow peaks than that on steep slopes; conversely *Sphagnum* on gentle slopes made lower flow peaks than steeps slopes (Figure 7). River flow peaks were increased by bare peat on steep slopes and gentle slopes by 3.9% (2.87 $m^3 s^{-1}$) and 8.6% (6.39 $m^3 s^{-1}$) under the early peak storm, by 3.1% (2.56 $m^3 s^{-1}$) and 10.9% (8.94 $m^3 s^{-1}$) under the middle peak storm, and by 1.1% (0.96 $m^3 s^{-1}$) and 8.0% (6.71 $m^3 s^{-1}$) respectively under the late peak storm compared with the baseline scenario in each case. *Sphagnum* cover on steep slopes and gentle slopes decreased river flow peaks by 1.7% (1.28 $m^3 s^{-1}$) and 8.1% (6.07 $m^3 s^{-1}$) under the early peak storm, by 1.2% (0.96 $m^3 s^{-1}$) and 9.0% (7.36 $m^3 s^{-1}$) under the middle peak storm, and by 5.7%(4.79 $m^3 s^{-1}$) and 11.4% (9.58 $m^3 s^{-1}$) under the late peak storm respectively.

Revegetation on real bare peat areas

Revegetation on the real bare peat areas decreased river flow peaks under storms for all precipitation profiles. The flow peaks were reduced by *Eriophorum* cover (3.7 %, 2.87 $m^3 s^{-1}$) and *Sphagnum* cover (7.4 %, 5.75 $m^3 s^{-1}$) under the early peak rainfall compared with the baseline bare peat cover. Under the middle peak rainfall the *Sphagnum*-induced peak flow reductions were 5.5 % (4.79 $m^3 s^{-1}$) and 7.4 % (6.39 $m^3 s^{-1}$), while they were and 0.8 % (0.64 $m^3 s^{-1}$) and 5.3 % (4.47 $m^3 s^{-1}$) respectively under the late peak rainfall (Table 2).

A scenario comparison of the impacts on peak flow with different rainfall patterns is illustrated in Figure 8. Bare peat in the riparian areas and the flattest areas under the 30 mm late peak rainfall increased river flow peaks more than the other rainfall patterns; while revegetation in these areas with *sphagnum* under the 30 mm late peak rainfall made more river flow peak reduction than the other rainfall patterns.

4 Discussion

4.1 Impacts of land-cover change on river flow peaks under varying rainfall intensities

4.1.1 Relative and absolute change in flow peaks

As rainfall intensity increased from 20 mm hr^{-1} to 50 mm hr^{-1}, the relative changes of the river flow peaks decreased for most of the land-cover change scenarios compared with the baseline scenario but the absolute changes of those peaks became larger (especially for rainfall increasing from 20 mm to 40 mm), which matters for flooding. Interestingly, the absolute change in peaks between land-cover scenarios for 50 mm rainfall events were sometimes similar to those for 40 mm rainfall events (Table 1), potentially suggesting there is an upper limit for rainfall event size in enhancing land-cover change impacts on flood peaks. However, as the results showed that loss of vegetation cover can increase flood peaks by a larger absolute value in heavier rainfall events than in smaller storms, and conversely revegetation can also reduce flood peaks by a larger absolute amount in heavier storms than in smaller ones, revegetation still benefits flood risk attenuation even under extreme storm events. This finding is not in line with research on non-wetland soils where forest impacts on floods have been studied (e.g. Bathurst et al., 2011a; Bathurst et al., 2011b). These forest studies suggested that effects on flood peaks of either afforestation or deforestation were most evident for small to moderate rainfall events but not for extreme events. It may be that in forest soils enhanced soil water storage effects are the dominant factor for small and medium storms but this storage becomes overwhelmed in large storms. For blanket peatlands, there is very little soil water storage even after dry periods and saturation quickly occurs. Thus the key effect is from slowing the velocity of overland flow. A dense carpet of *Sphagnum* often > 10 cm thick, can effectively slow flows across the entire hillslope being important even for the largest storms with deepest sheetflow.

Land-cover change on riparian zones (hilltoe areas) had more impact on stream flow peaks than cover change on other areas of hillslopes (e.g. mid-slope and headwater areas) under all rainfall intensities tested. However, the impact of land-cover change on headwater regions almost approached that of the 3000 cell-defined riparian regions under the 50 mm storm. This is likely to be due to the slightly reduced effect of surface roughness on overland flow movement under large overland flow depths.

4.1.2 Riparian strips

Riparian strip impacts on river flow peaks were close to those of the mid-slope and headwater buffer strips under the largest rainfall intensity tested. Gao et al. (2016) indicated that the impact of the converging shape of natural catchments, and the accompanying overland flow concentration, makes riparian zones and hilltoe areas more efficient for affecting overland flow movement. However, under higher rainfall intensity, overland flow accumulation on the lower areas of hillslopes could lead to large overland flow depths, which may weaken the efficiency of the surface roughness effect on overland flow movement in riparian areas. Thus, the peak flow differences between the riparian strip scenarios and the other scenarios became small under high rainfall intensities.

Considering that riparian buffer strips surround stream channels with different thresholds of accumulation area, land-cover change on the thin but branching riparian buffer strips (based on channels with low accumulative area threshold) had a larger impact on river flow peaks even under high rainfall intensities (50 mm hr^{-1} in this study). This result supports the finding of Gao et al. (2016), in which it was indicated that thicker riparian strips contain outer cells that are away from stream channel, and have lower efficiency in affecting river flow than that of thinner riparian strips. In storm events with high precipitation intensities, revegetation on the branching riparian strips still produced more benefits for flood risk control than revegetation on thicker riparian strips or on other areas in the catchment. For example, *Sphagnum* cover on the 250-cell channel riparian strip in the Trout Beck catchment had considerable impact on river flow peak under the 40 mm hr^{-1} and 50 mm hr^{-1} rainfall events (6.4% and 5.6% reductions). This may be because, even for the rainfall intensity of 50 mm hr^{-1}, the impact of land-cover change in upstream riparian areas on low-depth overland flow is still efficient compared with that of the downstream riparian zones where flow depths will be greater.

4.1.3 Slope

Land-cover change on flat slopes influence flow peaks more than on steep locations in this catchment under all rainfall intensities tested. Impacts of land-cover change on flat slopes on river flow peaks are strong even under high rainfall intensities. This indicates that revegetation on gentle slopes can provide reliable benefits to flood attenuation no matter what the temporal rainfall pattern is. In practice, there could be a high priority towards revegetation on gentle slope areas in target catchments.

4.1.4 Revegetation

Reduction of river flow peaks induced by revegetation on real bare peat areas in the study catchment was quite limited and decreased (for both the absolute and relative changes) with rainfall intensity. This is because most of the bare patches were not on the sensitive areas of the catchment that impact overland flow movement and concentration efficiently (e.g. riparian areas and flat slopes). Revegetation simply on bare soil patches without spatial planning could have little value for flood peak attenuation in extreme storm events.

4.2 Impacts of temporal rainfall patterns on river flow peaks

Temporal rainfall patterns have impacts on downstream flood peaks in the Trout Beck peatland catchment. The time differences of the flow peaks under different rainfall patterns (with identical total rainfall depth) were expected but the changes of the flow peak sizes were also considerable. Previous studies (presented in section 1 of this paper) suggested that the decay of soil infiltration capacity and/or the formation of soil surface sealing during storm events lead to peak flow rate differences under different rainfall patterns. Early peak rainfall, by first filling the pore spaces in the soil, could produce less overland flow to form a lower flow peak at the outlet of the catchment compared with the middle and late peak rainfall patterns which occur after the saturation has already been established in the initial part of the storm. However, these mechanisms are not the case in a peatland catchment which is well covered by vegetation and dominated by rapid development of saturation-excess overland flow. The soil moisture deficit of the whole catchment in this study was set to be very small at the start of the model runs (less than 0.1 mm depth for the whole catchment). The difference between the flood peaks was much larger than this deficit. For example, the peak difference was 0.5 mm per 6 min under 40 mm rainfall and 0.8 mm per 6 min under 50 mm rainfall. Thus the soil moisture deficit cannot explain the magnitude of difference between flood peaks. Furthermore, flow peaks for the middle peak rainfall patterns were also lower than those of the late peak rainfall patterns.

Changes to precipitation time series induce changes in overland flow production at every location in the catchment, and consequently overland flow movement on hillslopes could also be altered to change river flow peaks. For the early peak rainfall pattern, precipitation with a high intensity at the beginning of the rainfall event generated overland flow which had a large flow depth and transport velocity on hillslopes, so surface water travels downslope relatively fast. Additional precipitation falling onto the surface water increased water depth and accelerated overland flow delivery on hillslopes. However, this acceleration of overland flow movement on hillslopes (particularly on headwater areas) becomes weaker for smaller rainfall intensities in proceeding time steps after the peak rainfall has occurred. In downslope areas, however, the delivery and concentration of overland flow is still quite fast in these follow-up time steps due to the overland flow which was produced in the early time steps by intensive precipitation. Thus, there seemed to be a split of overland flow movement on hillslopes when the early peak rainfall pattern tended to generate obtuse and wide hydrographs at the catchment outlet. In contrast, for the late peak rainfall patterns, initially low precipitation produced shallow surface water and slow overland flow; while in the following time steps the increasing precipitation produced deep and fast overland flow which was ‘chasing’ the downslope overland flow generated earlier. Therefore, it seems that late peak rainfall patterns were more likely to create sharp and thin river flow peaks than the early peak rainfall distributions. For the middle peak patterns, river flow peaks were quite close to the flow peaks under the late peak rainfalls, particularly under large rainfall depths. This may be because the concentration of rainfall around the rainfall peak of the middle peak pattern was larger than that of the early peak pattern (e.g. for the 50 mm events the rainfall depth of the four middle steps in the middle rainfall pattern was 33.5 mm and the depth of the early four steps in the early rainfall pattern was 32 mm). The 'chasing' effects in overland flow movement (same for the late peak rainfall patterns above) were shorter but faster than those under the late peak rainfall patterns in the first half of the rainfall period due to the rapider increase in rainfall intensity during the first half than during rainfall with the late peak pattern (Figure 2). Even though rainfall intensity decreased in the second half of the period, river flow peaks under the middle peak patterns were still high and the difference between river flow peaks of the early and middle peak rainfall patterns was greater than that between the middle and late peak rainfall patterns.

4.3 Impacts of land cover change on river flow peaks under different temporal rainfall patterns

Temporal rainfall patterns affected impacts of land-cover change on river flow peaks. Non-uniform rainfall patterns magnified the impact of land-cover change on river flow peaks (for both absolute and relative changes) compared with the uniform rainfall pattern with identical total precipitation depth. Such changes were particularly magnified for land-cover change on sensitive areas (i.e. riparian zones and flat slopes). Among the non-uniform rainfall patterns, land-cover change on the sensitive areas under the middle and late peak rainfalls had greater impacts on river flow peaks (for both relative and absolute differences compared with the baseline land cover) than the early peak rainfall. Under a particular timed pattern of precipitation, there is a particular variation of the overland flow vector field in the catchment including spatial and temporal change of surface water delivery. It could be inferred that the sensitive areas are the key areas for overland flow delivery under the middle and late peak rainfall patterns. This means that protection and restoration of vegetation cover on these areas could bring greater reduction of flood risk under these rainfall patterns.

4.4 Sensitivity of locations in a catchment to river flow peaks under varying rainfall characteristics

The sensitivity of manipulating a location in a catchment to drive change in river flow peaks varies with rainfall characteristics. For instance, bare peat on a mid-slope strip (covering 10% area of the catchment) created a higher river flow peak under the 30 mm early peak rainfall profile, than bare peat on riparian regions. Further, the ‘most’ sensitive regions for impacting river flow peaks also change under different rainfall depths and patterns. For example, the mid-slope bare strip increased river flow peak by 6.8% which was greater than bare peat on the 3000-cell riparian strip (5.1%). Thus, a new algorithm will be needed to directly locate the most sensitive areas in a catchment under different rainfall characteristics. These most sensitive locations would inform a new understanding of flood risk and its attenuation at a catchment scale. There would be a type of ‘worst case scenario’ rainfall pattern, given a certain rainfall depth for a particular catchment, which could potently interact with the topography and land-cover of the catchment. Under the worst rainfall patterns, vegetation degradation and loss could bring higher river flow peaks and larger flood risk than for other rainfall patterns with same total rainfall; while revegetation would result in a greater reduction to river flow peaks. Hence, a new method is needed to identify generalized sensitive regions with good consideration of the characteristics of the local storm events based on the historical record or future climate scenarios for rainfall in the target catchment.

The results of our sensitivity study were based on a small scale catchment, in which hillslope overland flow responses to rainfall was the key component impacted by land cover change. However, for a larger scale catchment, channel flow routing components in the river network may be not negligible (e.g. Bovolo and Bathurst, 2012) and should be considered in future larger scale studies.

5 Conclusion

Using SD-TOPMODEL, our work focussed on a case study catchment demonstrating that there are strong effects on flood peaks of rainfall intensity distributions during a storm and strong interaction effects of these rainfall patterns with spatial land cover configurations. In that sense we believe our findings are generalizable, at least to the case of blanket peat covered catchments that are dominated by shallow water tables and widespread saturation-excess overland flow response. However, future studies could examine the impact of different catchment sizes and topographic configurations on these patterns.

Figure 9 summarises the effects on flood peaks that we found for the interaction between rainfall intensity, rainfall pattern, and land cover location. The interaction effects are strong with land-cover change effects being mediated or enhanced by temporal rainfall patterns in non-linear ways. Figure 9 illustrates how under the same rainfall depth, non-uniform rainfall (including early, middle and late rainfall peak patterns) produced higher river flow peaks than uniform rainfall. Late peak rainfall patterns resulted in the highest river flow peaks, while middle peak patterns created larger river flow peaks than early peak patterns. These differences occur because varying rainfall patterns changed the conditions of overland flow delivery and concentration on hillslopes.

With different rainfall characteristics, land-cover change impacts on river flow peaks were generally in line with the findings of Gao et al. (2016) which was conducted under a single uniform rainfall (i.e. the 1-hr 20 mm hr^{-1} rainfall). However, the relative differences in effect on flood peaks between the land-cover change scenario and the baseline scenario became closer as rainfall intensity increased (i.e. 20 mm hr^{-1} to 50 mm hr^{-1}, keeping the rainfall duration as 1 hour), while the absolute change became larger with increased rainfall intensity. For non-uniform rainfall, land-cover change impacts on river flow peaks were increased in terms of both absolute and relative changes compared with the uniform rainfall patterns, especially for the cover change on the most sensitive areas - riparian zones and gentle gradient slopes. Moreover, land-cover change on sensitive areas under middle and late peak rainfalls resulted in greater river flow peak changes relative to the land-cover baseline than the flow peak changes under the early peak rainfall. For vegetation restoration in upland peat catchments, the best action is to provide good buffer strips along the waterways, taking particular care to treat flatter areas and any bare patches, in which the more the better but a 10% areal treatment is well worth doing. Under different rainfall characteristics (e.g. intensities and temporal patterns), land-cover change on a same region in a catchment may have very different impacts on river flow peaks.

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Tables

Table 1. Modelling results for land-cover scenario impacts on flood peak under uniform rainfall.

Scenario		Peak flow change compared with the normal scenario			Peak timing change compared with the baseline scenario* (time step)
		Absolute increase		Relative change (%)	
		(mm/6 min)	(m^3/s)		
20 mm rainfall	Riparian bare strip	0.10	3.13	7.47	1
	Mid-slope bare strip	0.08	2.49	5.95	0
	Headwater bare strip	0.05	1.53	3.66	0
30 mm rainfall	Riparian bare strip	0.09	2.94	3.97	1
	Mid-slope bare strip	0.06	1.98	2.67	1
	Headwater bare strip	0.05	1.66	2.24	1
40 mm rainfall	Riparian bare strip	0.11	3.64	3.38	1
	Mid-slope bare strip	0.09	3.00	2.79	0
	Headwater bare strip	0.07	2.36	2.20	0
50 mm rainfall	Riparian bare strip	0.10	3.26	2.30	0
	Mid-slope bare strip	0.04	1.34	0.95	0
	Headwater bare strip	0.09	2.94	2.08	0
20 mm rainfall	Riparian bare strip (3000)	0.10	3.13	7.47	1
	Riparian bare strip (1000)	0.14	4.41	10.52	1
	Riparian bare strip (250)	0.17	5.37	12.81	1
30 mm rainfall	Riparian bare strip (3000)	0.09	2.94	3.97	1
	Riparian bare strip (1000)	0.18	5.81	7.85	1
	Riparian bare strip (250)	0.21	6.77	9.15	1
40 mm rainfall	Riparian bare strip (3000)	0.11	3.64	3.39	1
	Riparian bare strip (1000)	0.19	6.20	5.76	1
	Riparian bare strip (250)	0.27	8.75	8.14	1
50 mm rainfall	Riparian bare strip (3000)	0.10	3.26	2.30	0
	Riparian bare strip (1000)	0.17	5.49	3.88	0

	Riparian bare strip (250)	0.18	5.81	4.11	0
20 mm rainfall	Riparian *Sph.* strip	-0.08	-2.62	-6.25	-2
	Mid-slope *Sph* strip	-0.05	-1.66	-3.96	-1
	Headwater *Sph* strip	-0.02	-0.70	-1.68	0
30 mm rainfall	Riparian *Sph.* strip	-0.15	-4.73	-6.39	0
	Mid-slope *Sph* strip	-0.10	-3.13	-4.23	0
	Headwater *Sph* strip	-0.06	-1.85	-2.50	0
40 mm rainfall	Riparian *Sph.* strip	-0.16	-4.98	-4.64	0
	Mid-slope *Sph* strip	-0.08	-2.43	-2.26	0
	Headwater *Sph* strip	-0.08	-2.43	-2.26	0
50 mm rainfall	Riparian *Sph.* strip	-0.15	-4.73	-3.34	-1
	Mid-slope *Sph* strip	-0.08	-2.49	-1.76	0
	Headwater *Sph* strip	-0.05	-1.53	-1.08	0
20 mm rainfall	Riparian *Sph* strip (3000)	-0.08	-2.62	-6.25	-2
	Riparian *Sph* strip (1000)	-0.11	-3.58	-8.54	-2
	Riparian *Sph* strip (250)	-0.13	-4.22	-10.06	-2
30 mm rainfall	Riparian *Sph* strip (3000)	-0.15	-4.73	-6.39	0
	Riparian *Sph* strip (1000)	-0.19	-6.00	-8.11	-1
	Riparian *Sph* strip (250)	-0.19	-6.00	-8.11	0
40 mm rainfall	Riparian *Sph* strip (3000)	-0.16	-4.98	-4.64	0
	Riparian *Sph* strip (1000)	-0.21	-6.58	-6.12	0
	Riparian *Sph* strip (250)	-0.22	-6.90	-6.42	-1
50 mm rainfall	Riparian *Sph* strip (3000)	-0.15	-4.72	-3.34	-1
	Riparian *Sph* strip (1000)	-0.23	-7.28	-5.15	-1
	Riparian *Sph* strip (250)	-0.25	-7.92	-5.60	-1
20 mm rainfall	Bare steepest slopes	0.06	1.85	4.42	0
	Bare flattest slopes	0.14	4.41	10.52	1
30 mm rainfall	Bare steepest slopes	0.02	0.70	0.95	1
	Bare flattest slopes	0.18	5.81	7.85	1

40 mm rainfall	Bare steepest slopes	0.08	2.68	2.50	0
	Bare flattest slopes	0.21	6.83	6.36	1
50 mm rainfall	Bare steepest slopes	0.06	1.98	1.40	0
	Bare flattest slopes	0.19	6.13	4.34	0
20 mm rainfall	*Sph.* steepest slopes	-0.02	-0.70	-1.68	-1
	Sph. flattest slopes	-0.11	-3.58	-8.54	-2
30 mm rainfall	*Sph.* steepest slopes	-0.04	-1.21	-1.64	0
	Sph. flattest slopes	-0.15	-4.73	-6.39	0
40 mm rainfall	*Sph.* steepest slopes	-0.06	-1.79	-1.66	0
	Sph. flattest slopes	-0.21	-6.58	-6.12	0
50 mm rainfall	*Sph.* steepest slopes	-0.05	-1.53	-1.08	0
	Sph. flattest slopes	-0.21	-6.64	-4.70	-1
20 mm rainfall	Revegetation with *Erio.*	-0.05	-1.53	-3.53	0
	Revegetation with *Sph.*	-0.09	-2.87	-6.62	-1
30 mm rainfall	Revegetation with *Erio.*	-0.03	-1.02	-1.36	0
	Revegetation with *Sph.*	-0.10	-3.19	-4.26	0
40 mm rainfall	Revegetation with *Erio.*	-0.03	-0.96	-0.87	0
	Revegetation with *Sph.*	-0.10	-3.19	-2.91	0
50 mm rainfall	Revegetation with *Erio.*	-0.19	-6.07	-4.18	0
	Revegetation with *Sph.*	-0.20	-6.39	-4.40	0

* *Positive numbers indicate that the peak is earlier than the baseline scenario, while negative numbers indicate the peak is later than the baseline scenario.*

Table 2. Modelling results of land cover scenarios under 30 mm rainfall with varying temporal patterns.

Land cover scenario		Peak flow change compared with the normal scenario			Peak timing change compared with the baseline scenario * (time step)
		Absolute increase		Relative change (%)	
		(mm/ 6min)	(m^3/s)		
Uniform	Riparian bare strip	0.09	2.94	3.97	1
	Mid-slope bare strip	0.06	1.98	2.67	1
	Headwater bare strip	0.05	1.66	2.24	1
Early peak	Riparian bare strip	0.12	3.83	5.13	2
	Mid-slope bare strip	0.16	5.11	6.84	1
	Headwater bare strip	0.04	1.27	1.71	1
Middle peak	Riparian bare strip	0.20	6.39	7.81	2
	Mid-slope bare strip	0.17	5.43	6.64	1
	Headwater bare strip	0.09	2.87	3.52	1
Late peak	Riparian bare strip	0.11	3.51	4.17	2
	Mid-slope bare strip	0.08	2.56	3.03	1
	Headwater bare strip	0.03	0.96	1.14	1
Uniform	Riparian strip (3000)	0.09	2.94	3.97	1
	Riparian strip (1000)	0.18	5.81	7.85	1
	Riparian strip (250)	0.21	6.77	9.15	1
Early peak	Riparian bare strip (3000)	0.12	3.83	5.13	2
	Riparian bare strip (1000)	0.19	6.07	8.12	2
	Riparian bare strip (250)	0.26	8.30	11.11	2
Middle peak	Riparian bare strip (3000)	0.20	6.39	7.81	1
	Riparian bare strip (1000)	0.29	9.26	11.33	1
	Riparian bare strip (250)	0.37	11.82	14.45	1
Late peak	Riparian bare strip (3000)	0.11	3.51	4.17	1
	Riparian bare strip (1000)	0.24	7.67	9.09	1
	Riparian bare strip (250)	0.30	9.58	11.36	1
Uniform	Riparian *Sph.* strip	-0.15	-4.73	-6.39	0

	Mid-slope *Sph* strip	-0.10	-3.13	-4.23	0
	Headwater *Sph* strip	-0.06	-1.85	-2.50	0
Early peak	Riparian *Sph.* strip	-0.11	-3.51	-4.70	0
	Mid-slope *Sph* strip	-0.08	-2.56	-3.42	0
	Headwater *Sph* strip	-0.02	-0.64	-0.85	0
Middle peak	Riparian *Sph.* strip	-0.20	-6.39	-7.81	-1
	Mid-slope *Sph* strip	-0.10	-3.19	-3.91	0
	Headwater *Sph* strip	-0.06	-1.92	-2.34	0
Late peak	Riparian *Sph.* strip	-0.20	-6.39	-7.58	-1
	Mid-slope *Sph* strip	-0.18	-5.75	-6.82	0
	Headwater *Sph* strip	0.12	-3.83	-4.55	0
Uniform	Riparian *Sph* strip (3000)	-0.15	-4.73	-6.39	0
	Riparian *Sph* strip (1000)	-0.19	-6.00	-8.11	-1
	Riparian *Sph* strip (250)	-0.19	-6.00	-8.11	0
Early peak	Riparian *Sph* strip (3000)	-0.11	-3.51	-4.70	0
	Riparian *Sph* strip (1000)	-0.18	-5.75	-7.69	-1
	Riparian *Sph* strip (250)	-0.20	-6.39	-8.55	0
Middle peak	Riparian *Sph* strip (3000)	-0.20	-6.39	-7.81	-1
	Riparian *Sph* strip (1000)	-0.18	-5.75	-7.03	-1
	Riparian *Sph* strip (250)	-0.26	-8.30	-10.16	-1
Late peak	Riparian *Sph* strip (3000)	-0.20	-6.39	-7.58	-1
	Riparian *Sph* strip (1000)	-0.29	-9.26	-10.99	-1
	Riparian *Sph* strip (250)	-0.31	-9.90	-11.74	-1
Uniform	Bare steepest slopes	0.02	0.70	0.95	1
	Bare flattest slopes	0.18	5.81	7.85	1
Early peak	Bare steepest slopes	0.09	2.87	3.85	1
	Bare flattest slopes	0.20	6.39	8.55	2
Middle peak	Bare steepest slopes	0.08	2.56	3.12	1
	Bare flattest slopes	0.28	8.94	10.94	0

Late peak	Bare steepest slopes	0.03	0.96	1.14	1
	Bare flattest slopes	0.21	6.71	7.95	0
Uniform	*Sph.* steepest slopes	-0.04	-1.21	-1.64	0
	Sph. flattest slopes	-0.15	-4.73	-6.39	0
Early peak	*Sph.* steepest slopes	-0.04	-1.28	-1.71	1
	Sph. flattest slopes	-0.19	-6.07	-8.12	0
Middle peak	*Sph.* steepest slopes	-0.03	-0.96	-1.17	0
	Sph. flattest slopes	-0.23	-7.36	-8.98	-1
Late peak	*Sph.* steepest slopes	-0.15	-4.79	-5.68	0
	Sph. flattest slopes	-0.30	-9.58	-11.36	-1
Uniform	Revegetation with *Erio.*	-0.03	-1.02	-1.36	0
	Revegetation with *Sph.*	-0.10	-3.19	-4.26	0
Early peak	Revegetation with *Erio.*	-0.09	-2.87	-3.70	-1
	Revegetation with *Sph.*	-0.18	-5.75	-7.41	0
Middle peak	Revegetation with *Erio.*	-0.15	-4.79	-5.54	0
	Revegetation with *Sph.*	-0.20	-6.39	-7.38	0
Late peak	Revegetation with *Erio.*	-0.02	-0.64	-0.75	0
	Revegetation with *Sph.*	-0.14	-4.47	-5.26	0

** Positive numbers indicate the peak is earlier than the baseline scenario, while negative numbers indicate the peak is later than the baseline scenario.*

Figures

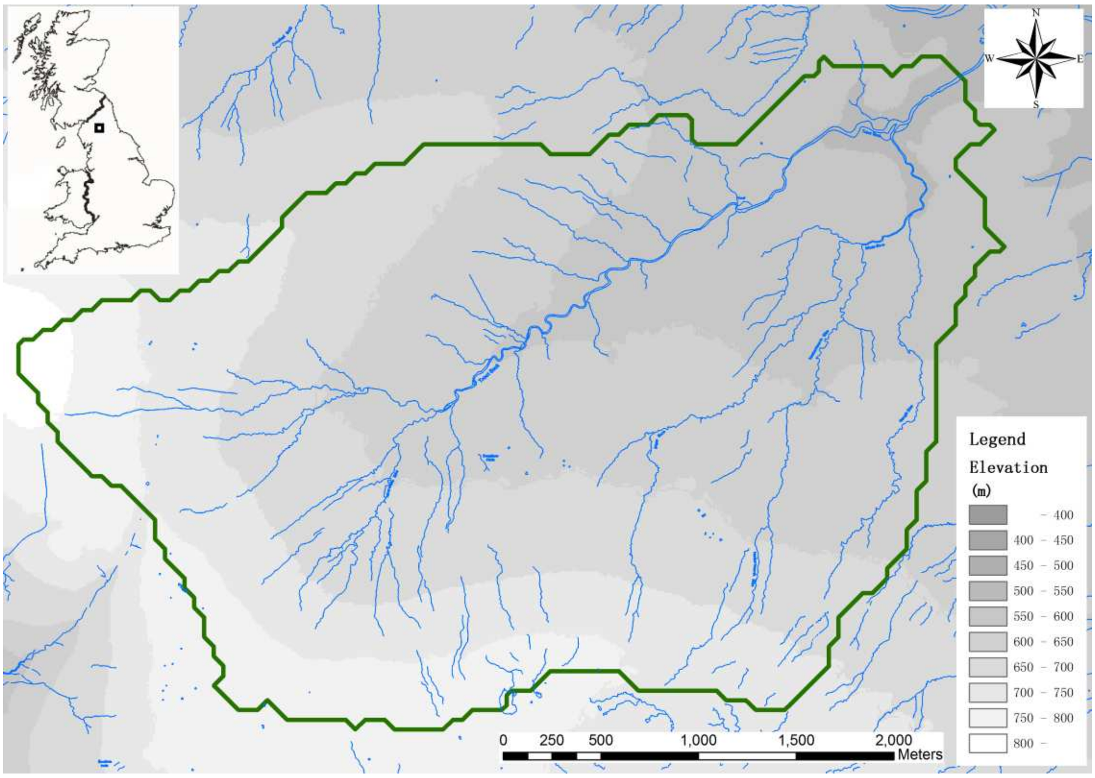

Figure 1. Location and map of the Trout Beck catchment.

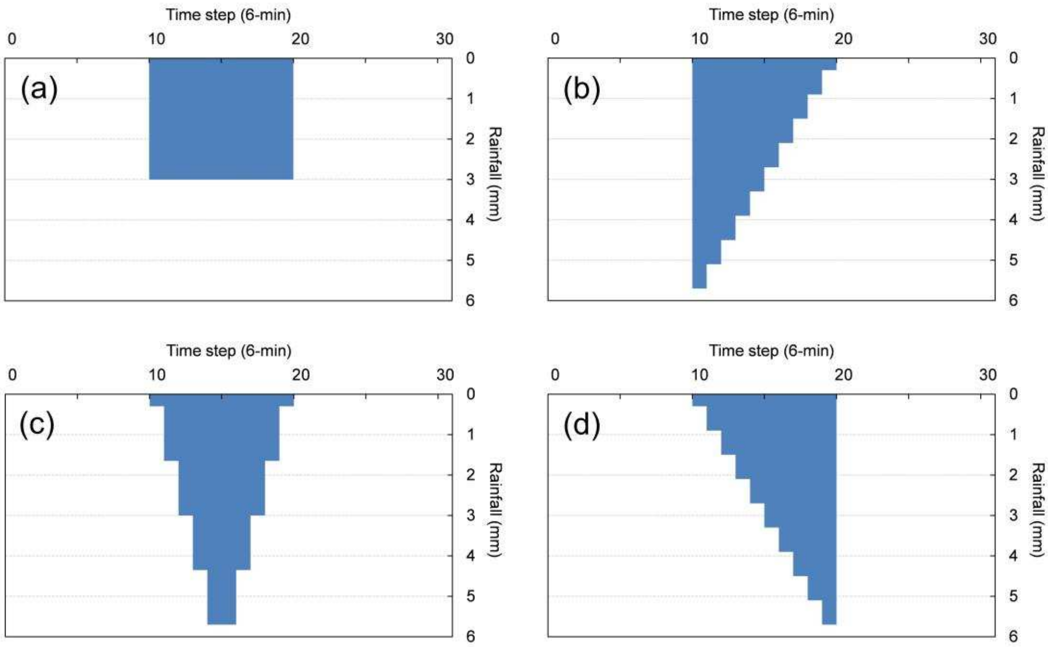

Figure 2. Precipitation patterns of the 30 mm rainfall for scenario modelling runs; (a) uniform, (b) early peak, (c) middle peak, and (d) late peak.

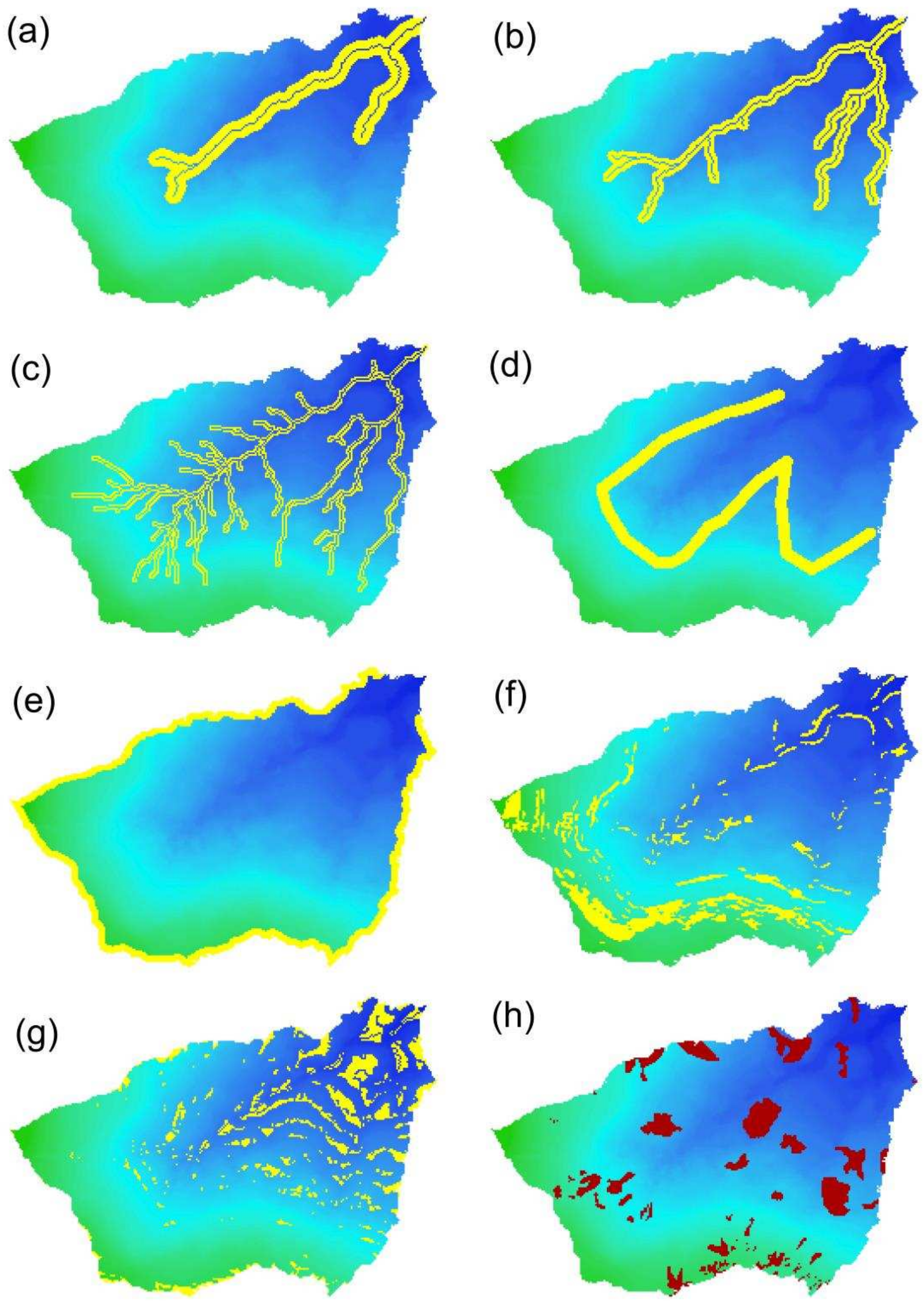

Figure 3. The slope position scenarios, the riparian zone scenarios, the steep-gentle slope scenarios and the real bare peat scenario in Trout Beck; (a) riparian strip (3000-cell cumulative area draining to the channel network), (b) riparian strip (1000-cell cumulative area draining to the channel network), (c) riparian strip (250-cell cumulative area draining to the channel network), (d) mid-hillslope strip, (e) headwater strip, (f) steepest slope area, (g) gentlest slope area, (h) bare peat distribution.

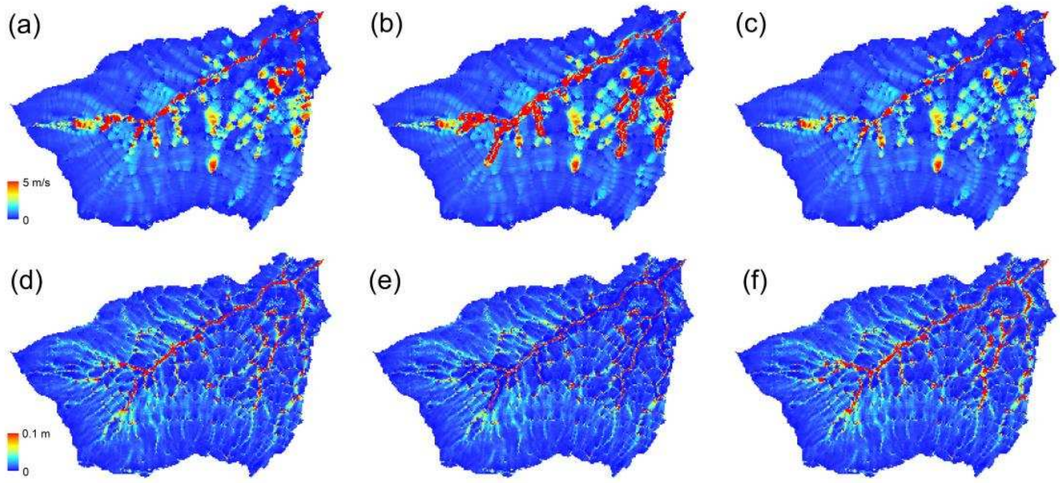

Figure 4. Distribution maps of overland flow velocity (a, b, and c) and depth (d, e, and f) for the baseline scenario, the 250-cell bare peat riparian strip scenario, and the 250-cell *Sphagnum* riparian strip scenario after 30mm uniform rainfall (i.e. at time step 21).

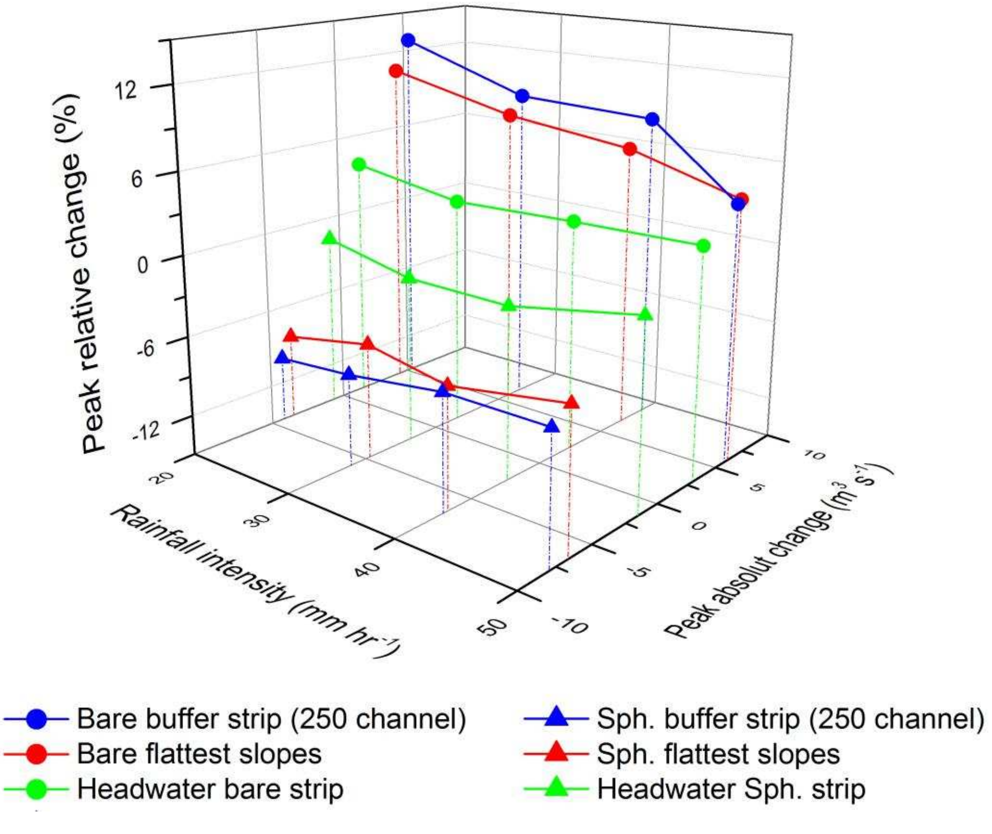

Figure 5. Scenario comparison of the impacts on peak flow under different rainfall intensities.

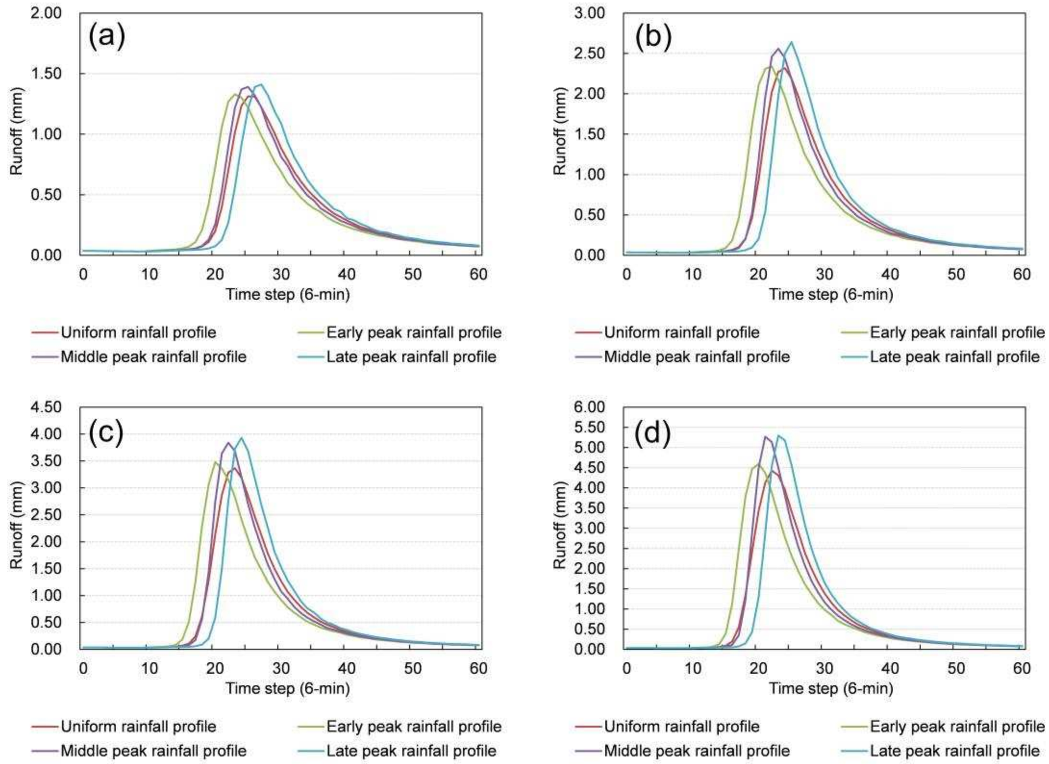

Figure 6. Hydrographs for the baseline land-cover scenario under different precipitation profiles with varying total rainfall depths; (a) 20 mm, (b) 30 mm, (c) 40 mm, and (d) 50 mm.

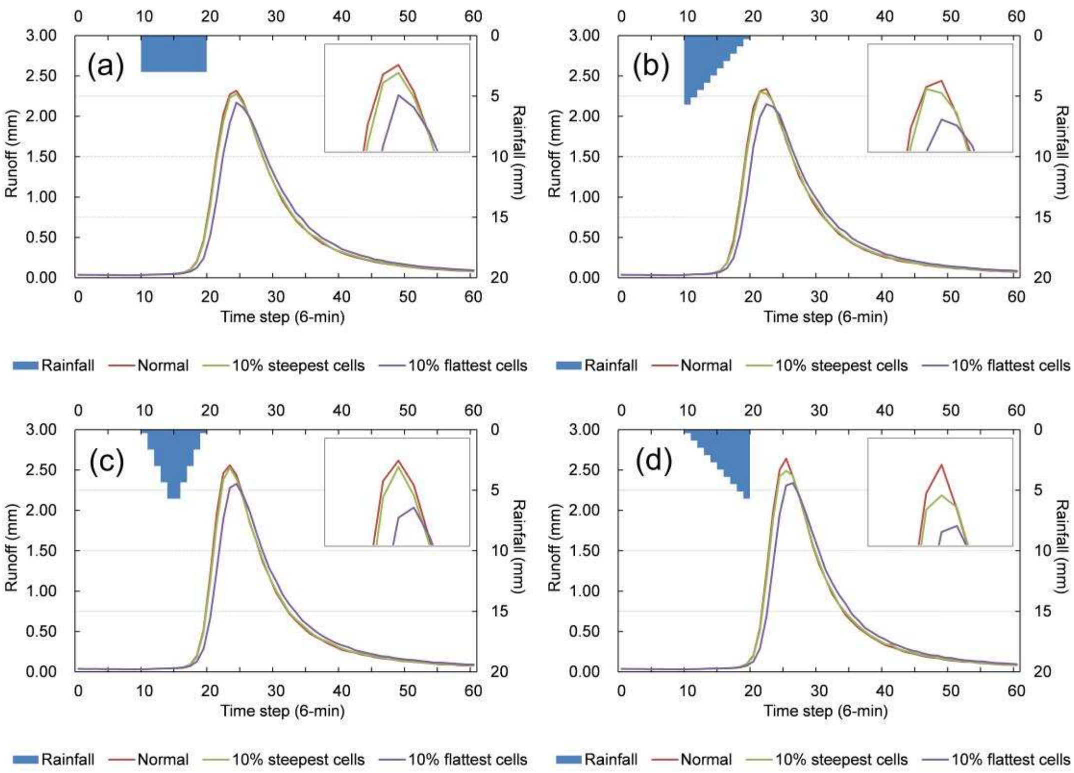

Figure 7. Hydrographs of the slope scenarios (*Sphagnum* on the 10% steepest areas and on the 10% flattest areas of the catchment) under 30 mm rainfall events with different precipitation profiles; (a) uniform rainfall profile, (b) early peak rainfall profile, (c) middle peak rainfall profile, and (d) late rainfall peak profile. Note: the runoff scale of the nested plot focusing on the hydrograph peaks on the upper right corner is 0.5 mm.

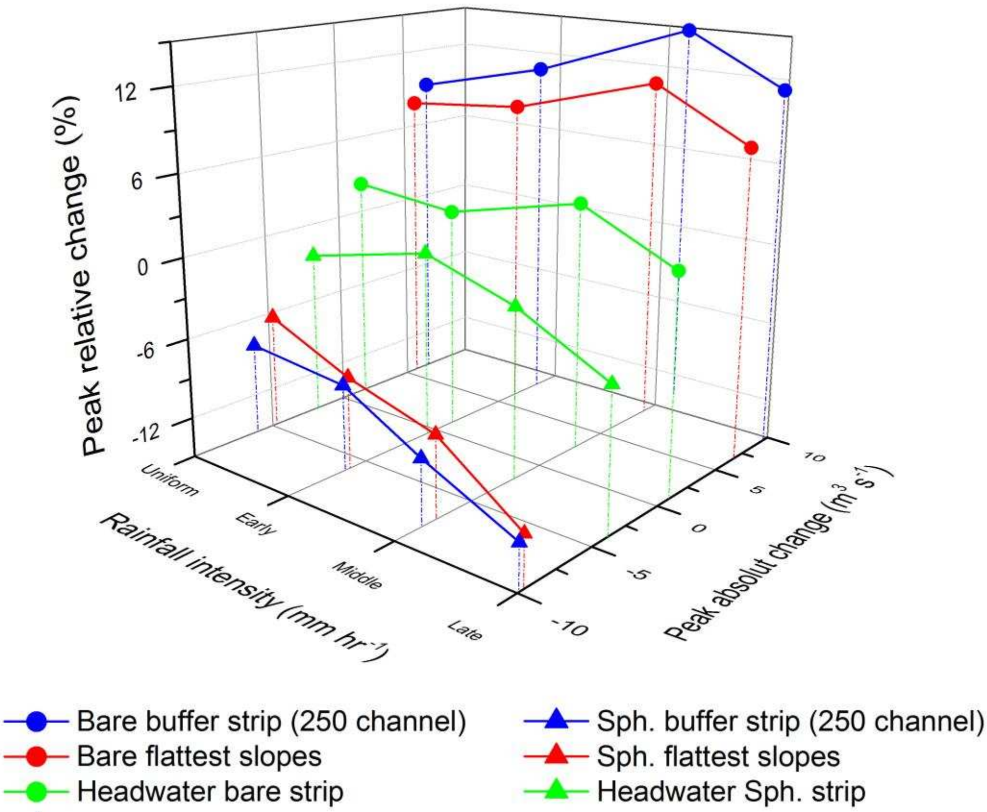

Figure 8. Scenario comparison of the impacts on peak flow under the 30 mm rainfall events with different rainfall patterns.

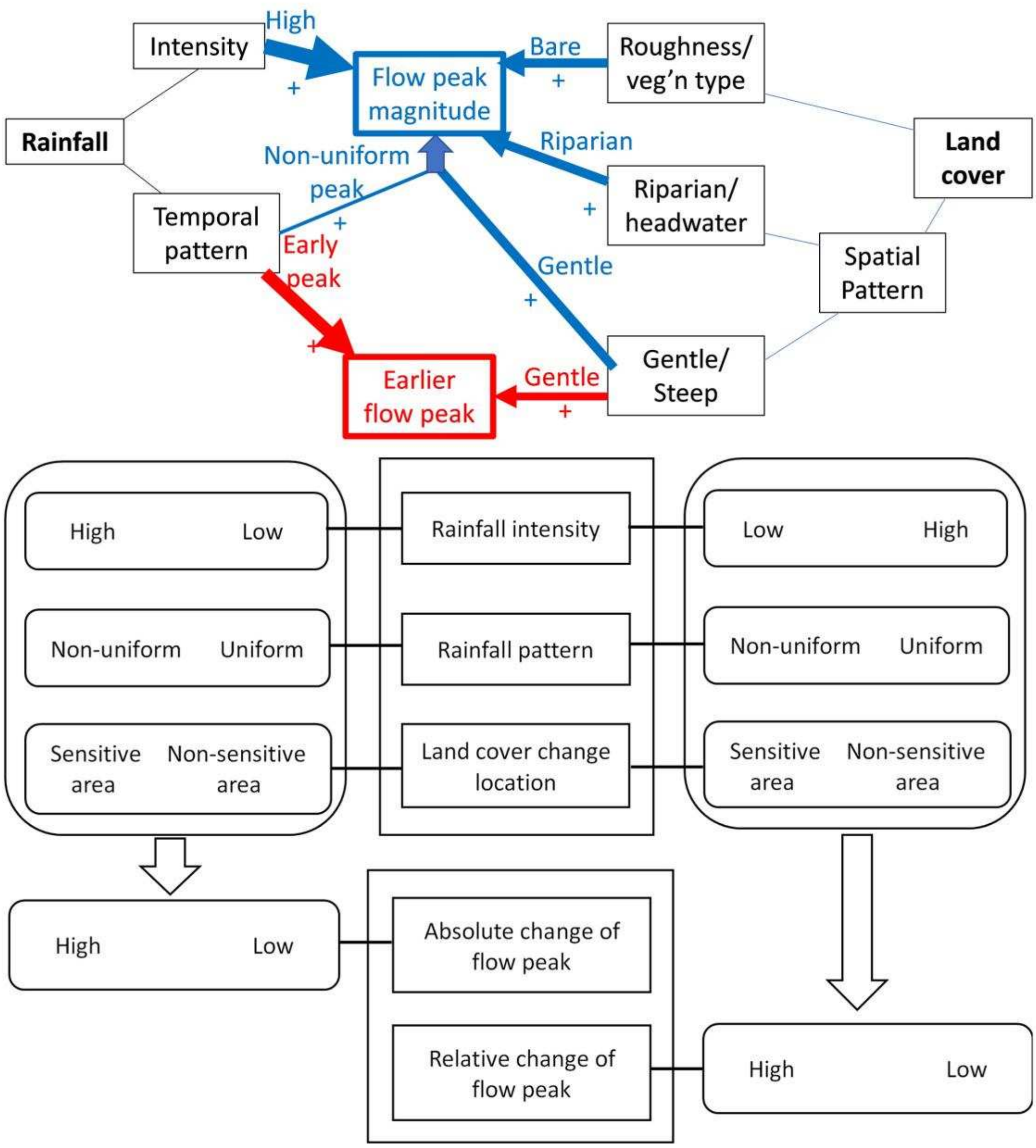

Figure 9. Conceptual diagrams showing the interaction effects of rainfall and land-cover characteristics on peak river flow.