AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2015WR017667

The impact of land-cover change on flood peaks in peatland basins

Jihui Gao[1,2], Joseph Holden[2], and Mike Kirkby[2]

[1]Institute of Hydrology and Water Resources, Zhejiang University, Hangzhou, China, [2]water@leeds, School of Geography, University of Leeds, Leeds, UK

Key Points:
- Land-cover change in headwater peatlands was shown to affect downstream flood peaks
- Principles on how the spatial configuration of land-cover change impacts flood peaks were determined
- Vegetated, narrow, buffer strips along headwater riparian zones should be protected and enhanced

Supporting Information:
- Supporting Information S1
- Data Set S1

Correspondence to:
J. Gao,
jhgao06@outlook.com

Citation:
Gao, J., J. Holden, and M. Kirkby (2016), The impact of land-cover change on flood peaks in peatland basins, *Water Resour. Res.*, *52*, 3477–3492, doi:10.1002/2015WR017667.

Received 16 JUN 2015
Accepted 9 APR 2016
Accepted article online 15 APR 2016
Published online 7 MAY 2016

Abstract In headwater peatlands, saturation-excess overland flow is a dominant source of river discharge. Human modifications to headwater peatlands result in vegetation cover change but there is a lack of understanding about how the spatial distribution of such change impacts flood peaks. A fully distributed version of TOPMODEL with an overland flow velocity module was used to simulate flood response for three upland peat basins. Bare peat strips adjacent to channels resulted in a higher and faster flow peak; for a 20 mm h^{-1} rainfall event, with bare riparian zones covering 10% of the basin area, peaks were increased, compared to the current hydrograph, by 12.8%, 1.8%, and 19.6% in the three basins. High density *Sphagnum* ground cover over the same riparian zones reduced flow peaks (e.g., by 10.1%, 1.8%, and 13.4% for the 20 mm h^{-1} event) compared to the current hydrograph. With similar total areas of land-cover change, the size of randomly located patches of changed cover had no effect on peak flow for patch sizes up to 40,000 m^2. However, cover changes on gentle slope areas generally resulted in a larger change in peak flow when compared with the same changes on steeper slopes. Considering all results for the same proportion of catchment area that undergoes change, land-cover change along narrow riparian buffer strips had the highest impact on river flow. Thus, the protection and revegetation of damaged riparian areas in upland peat catchments may be highly beneficial for flood management.

1. Introduction

Vegetation cover in many environments has been heavily modified by humans. Consequent impacts on flood hydrographs are important for land managers [*Wheater and Evans*, 2009]. In many basins, overland flow is a common pathway for water [e.g., *Bonell and Gilmour*, 1978; *Kadlec*, 1990] including those covered by blanket peatlands [*Holden and Burt*, 2003a, 2003b]. In the UK, many major rivers have their headwaters located in blanket peat where saturation-excess overland flow dominates during storm events [*Holden and Burt*, 2002, 2003c]. Therefore changes to surface vegetation roughness could be very important in driving river flow response to rainfall. Land management practices (e.g., prescribed rotational burning and grazing) may change vegetation distributions on peatlands [*Holden et al.*, 2007] but how this impacts flood risk is not known. Atmospheric pollution, combined with land management has resulted in large areas of bare peat in the UK uplands [*Evans and Warburton*, 2007] and it is known that overland flow can move ~10 times more quickly across bare peat surfaces than those covered by a dense understory of *Sphagnum* [*Holden et al.*, 2008]. Peatland restoration practitioners are actively seeking to revegetate bare peat [*Parry et al.*, 2014], although resource restrictions mean that prioritization of areas for treatment is needed. Determining locations within the basin where greatest flood peak benefits would be realized by revegetation of bare peat, would support targeted action.

The impacts of changing peatland vegetation cover on downstream flood risk are poorly understood but may be important [*Acreman and Holden*, 2013]. *Grayson et al.* [2010] showed for a 40 year hydrograph record (11.4 km^2 basin) that during times when the proportion of the basin with bare peat was greater (e.g., 9% bare) there were higher peaks per unit rainfall and narrower hydrograph shapes than in periods when vegetation cover was more widespread. Recent modeling studies have also hinted at the idea that the surface vegetation cover is likely to be of great importance (more so than the presence or absence of ditches for example) in the timing of flood peaks from upland peatlands [*Ballard et al.*, 2011; *Lane and Milledge*, 2013]. However, there is limited understanding of how sensitive the flood peak might be to different spatial configurations of vegetation cover change.

Riparian buffer zones have been commonly applied in agricultural zones to trap sediment and nutrients before they enter watercourses [e.g., *Burt et al*., 1999; *Cirmo and McDonnell*, 1997; *Gregory et al*., 1991; *McGlynn and Seibert*, 2003]. Runoff from riparian zones is often dominant between storm events, throughout small runoff events and in the early stage of large events as shown by tracer experiments [*McGlynn and McDonnell*, 2003]. For peatland basins, in which saturation-excess overland flow dominates storm flow [*Holden and Burt*, 2003c], the hilltoe and near-stream zone could be a significant contributing area of overland flow in a storm event, with flows from upslope being concentrated in this zone. Degradation of this zone by vegetation loss may therefore have a larger influence on flood peaks than similar modifications in other parts of the basin. However, there have been no studies on how hilltoe vegetation loss in peatlands may affect flood peaks.

In the wider (nonpeat) literature on potential spatial sensitivity of the flood peak, there is a suggestion that hilltop or drainage divide roughness (and hence vegetation change) may have a greater influence on flood peaks than near stream or hilltoe roughness. *Huang and Lee* [2009] conducted an overland flow modeling study with a rectangular plane (1% slope) and found that a scenario with decreasing surface roughness in a downstream direction resulted in a slightly earlier, but much lower, flow peak compared to a scenario with downslope-increasing surface roughness (the two scenarios maintained the same average surface roughness of the planes). *Maske and Jain* [2014] formed similar conclusions for a range of surface slopes (1%–3%). If the rectangular surfaces in these two studies are imagined to be a hillslope, this finding seems to imply that high surface roughness on upslope areas may have a larger impact than that on hilltoe and near-stream areas in terms of flow peak reductions. However, it may be that the advantage of high roughness on upslope areas is offset by the higher frequency of overland flow in riparian zones and the hypothesis requires further testing to determine which is more important for flood attenuation.

Bare peat in headwater systems often occurs in patches of different sizes ranging from a few square meters to tens of thousands of square meters. Some vegetation is periodically burnt for game-bird management [*Holden et al*., 2012] in patches which are recommended to be no more than 0.5 ha [*Defra*, 2007]. This recommendation is designed to reduce soil erosion risk but the impacts of bare peat patch size on river flow are not well understood. For example, large bare patches may provide stronger connectivity across the landscape than a series of small bare patches with an identical total area across that same part of the landscape. In terms of overland flow velocity and volumes and the consequent flood peak such differences in connectivity could be very important but remain untested.

In peat catchments, saturation-excess overland flow may be more common on gentle gradients than on steeper slopes [*Holden and Burt*, 2003c]. However, overland flow will move at faster velocities as slope increases. At the catchment scale, different spatial patterns of topography and land cover may affect the synchroneity of overland flow concentration on hillslopes [*Holden*, 2005], and there could be impacts on flow peaks that are quite different if the surface roughness changes on steep slopes compared to if the same changes were made on more gentle gradient slopes in the catchment. However, it is not clear how these differences impact downstream river flow.

Spatially distributed modeling tools are required in order to test how different configurations of land cover (e.g., position in the basin, size of land cover patch change, gradient) may impact the flood peak and timing in natural river basins. *Gao et al*. [2015] developed a spatially distributed version of TOPMODEL, with an empirically based overland flow velocity module, which was well suited for blanket peat catchments. The model was specifically designed so that spatial options for land-cover change could be tested in systems that are dominated by overland flow during storm events. In this paper, we use *Gao et al*.'s [2015] model to test several hypotheses about how different spatial configurations of land cover and surface roughness on blanket peat headwaters influence the flood peak. The hypotheses are:

1. A bare peat strip near to river channels results in a higher flow peak and reduced delay to the peak; conversely, a buffer strip with higher density vegetation (e.g., *Sphagnum*) leads to a lower flow peak and postpones the peak. In both cases, buffer strips surrounding downstream channels will have a greater effect than those further upstream.
2. Larger bare peat patches produce more and faster overland flow locally, concentrate higher peak flow and bring earlier peak flow times at the outlet of the basin; conversely, larger patches with higher density vegetation (e.g., *Sphagnum*) generate less and slower overland flow in situ, reduce peak flow and delay the peak time at the basin outlet.

3. Bare peat on steep slope areas, where overland flow predominantly moves faster, gives a faster response and higher flow peak value at the basin outlet compared to bare peat on gentle slope areas, while high density vegetation or revegetation on a steep slope area has a larger positive impact on peak river flow delay and reduces the size of peak flow compared to the same change on gentle slope areas.

2. Methodology

2.1. Study Sites

Three upland peat basins in the UK were selected: the Trout Beck basin in northern England, the Wye basin in mid-Wales, and the East Dart basin in southwest England (Figure 1). The basins have a long series of weather and hourly river flow data which facilitate model testing. There were also suitable topographic data (20 m $\times$ 20 m) from the sites.

Trout Beck (54°41′ N, 2°23′ W) is a tributary of the River Tees located in the Moor House National Nature Reserve and covers 11.4 km^2 with an elevation between 533 and 842 m AOD (mean slope 9.1%). Most of the Trout Beck basin ($\sim$90%) is covered by blanket peat with a typical depth of 1–2 m [*Evans et al*., 1999]. The peat suffered widespread erosion in the 1950s–1970s but large areas have revegetated with *Sphagnum* and *Eriophorum* since then [*Grayson et al*., 2010]. The vegetation cover of the basin is dominated by a *Calluna-Eriophorum* association, while *Eriophorum* alone becomes dominant in areas above 630 m [*Evans et al*., 1999]. The climate of the basin is classified as subarctic oceanic [*Manley*, 1942] and has a mean annual rainfall of 2012 mm (records from 1951 to 1980 and 1991 to 2006) [*Holden and Rose*, 2011].

The Wye basin (52°28′ N, 3°46′ W) is situated in the Cambrian Mountains of mid-Wales. It covers 10.6 km^2 with an elevation ranging from 341to 735 m AOD with a mean slope of 20.0% [*CEH*, 2013]. Grassland dominates the Wye basin, of which 43% is covered by blanket peat and valley mires overlying weather resistant Silurian slates and shales [*Marc and Robinson*, 2007]. The basin has a wet climate with an annual precipitation of 2599 mm (1972–2004) [*Marc and Robinson*, 2007].

The upland peat basin of the East Dart (52°32′ N, 3°52′ W) lies on the eastern part of the Dartmoor National Park in southwest England, draining an area of 21.5 km^2. The basin ranges in elevation from 309 m AOD at the outlet to 601 m AOD at the top with a mean slope of 9.4%. The basin is mainly underlain by Dartmoor Granite and 47% of the area is covered by peatland. There is low grade agriculture and woodland in the downstream area (9% area of the basin). The basin is wet with a mean annual rainfall of 2088 mm (1961–1990) [*CEH*, 2012].

2.2. Distributed TOPMODEL

TOPMODEL has been used worldwide as a standard model for hydrological analysis [e.g., *Franks et al*., 1998; *Güntner et al*., 1999; *Lamb et al*., 1998; *Peters et al*., 2003]. It was a continuous lumped or semidistributed deterministic hydrological model when developed by *Beven and Kirkby* [1979]. Recently, a new fully distributed version of the model has been produced and was tested and evaluated by *Gao et al*. [2015] for blanket peat and found to perform well. The distributed model uses a computational unit of a grid cell. It retains the rationale of the original TOPMODEL, keeping the key equations of runoff production [see *Kirkby*, 1997], but downscales those equations from catchment scale to cell scale. A new module represents the movement of overland flow across and between cells. The overland flow module uses the multiple-direction flow theory of *Quinn et al*. [1991] to direct overland flow across the landscape while the Darcy-Weisbach equation is employed to vary overland flow velocities depending on slope, water depth and surface roughness. A stochastic algorithm is involved to describe the routing of overland flow in the module. A map of an overland flow velocity parameter (related to surface roughness) is used, based on the land cover map of the basin being studied. This parameter was derived from an empirical study of overland flows across different slope angles, water depths, and through different vegetation types in a UK blanket peatland by *Holden et al*. [2008]. They conducted 1024 flow velocity experiments on 6 m long plots on blanket peat and found that Darcy-Weisbach roughness and mean velocity can be based on a single parameter for each surface cover. Thus when running the model for different spatial configurations of land cover in a basin, the velocity parameter for the cells in the model are varied depending on what vegetation cover is simulated in those cells. Table 1 summarizes the major modifications of the original TOPMODEL to produce the new distributed model.

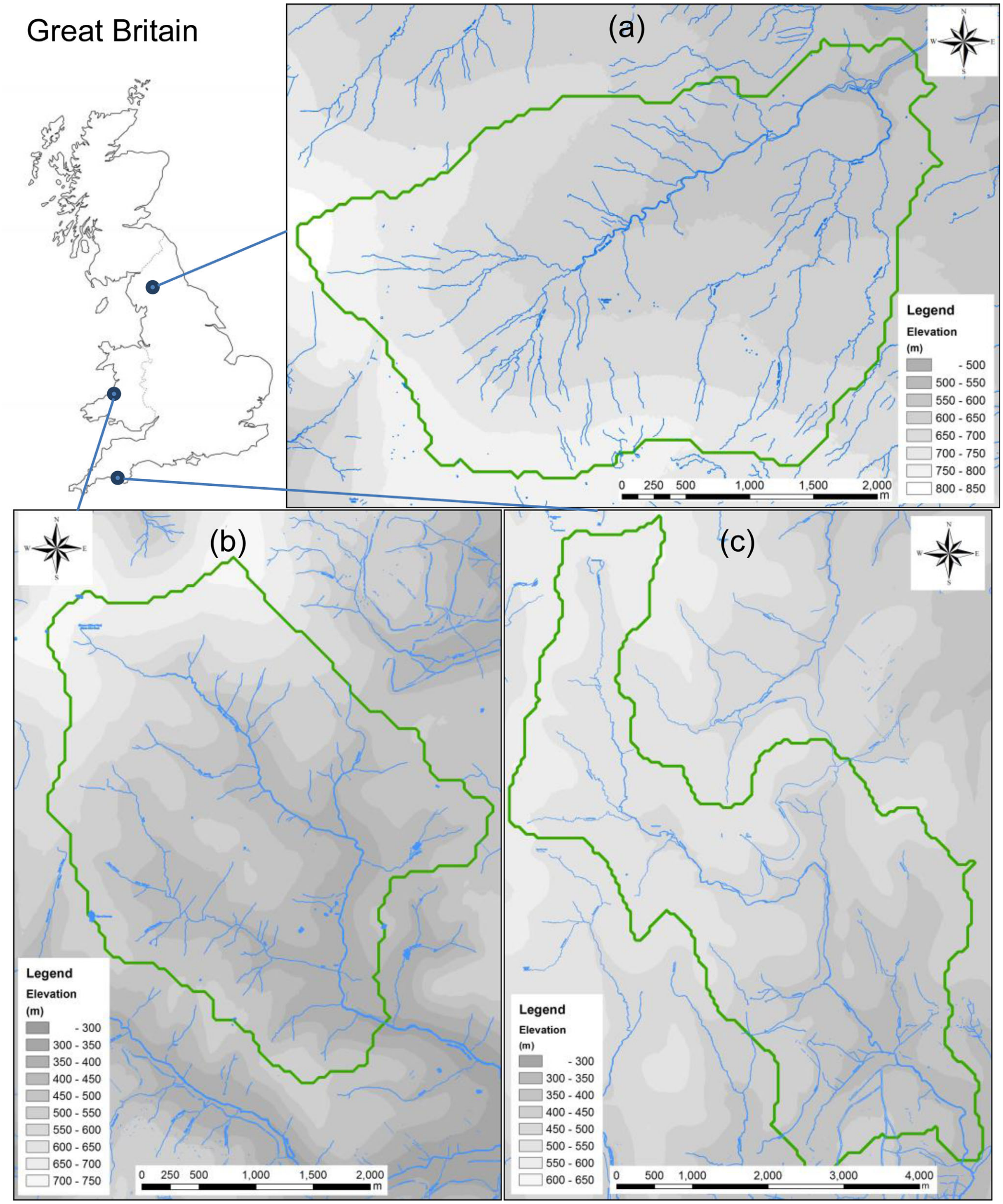

Figure 1. Locations and maps of the three peatland basins: (a) Trout Beck, (b) Wye, and (c) East Dart.

Table 1. Major Modifications of Distributed TOPMODEL Compared to the Original TOPMODEL

	Original TOPMODEL	Distributed TOPMODEL
Spatial structure	Lumped or semidistributed	Fully distributed
Runoff production equation scale	Basin or subbasin scale	Cell scale (e.g., 20 m × 20 m)
Overland flow	Constant velocity for whole basin	Associated with slope, surface roughness, and water depth; Overland flow routing with a velocity parameter related to surface roughness.
Surface roughness	N/A	Surface roughness map

The development of the distributed TOPMODEL has major advantages: (1) It can predict, during and after storm events, the locations of overland flow occurrence, the rates of overland flow production, the pathways of overland flow movement, and the locations where overland flow infiltrates into soil or enters river channels; (2) It represents the mechanism through which the velocity of overland flow is modified, according to the surface roughness presented by the vegetation cover, taking gradient and flow depth into account. These advantages mean that land-cover change in different parts of the basin can be evaluated with regard to impacts on the flow at the basin outlet.

2.3. Land Cover Scenarios

To model the impact of land-cover change on downstream flow in upland peat basins, different types of scenarios have been developed. Each hypothesis listed above can be tested in the context of both positive and negative effects, for example by comparing "normal" surface cover with patches of both denser and sparser vegetation. A series of land-cover change scenarios, representing different patterns of land-cover distribution, were designed, based on the three hypotheses, and each was then modeled using the distributed TOPMODEL developed by *Gao et al*. [2015].

The baseline status of land cover in the study basins was simplified to a uniform *Eriophorum*-covered scenario which is treated as a "normal" condition in the experimental scenario runs (since, in fact, *Eriophorum* dominates the vegetation cover in the basins). This normal baseline scenario in each basin is applied as a standard to enable fair comparison with the modeling results of other land-cover scenarios. For each

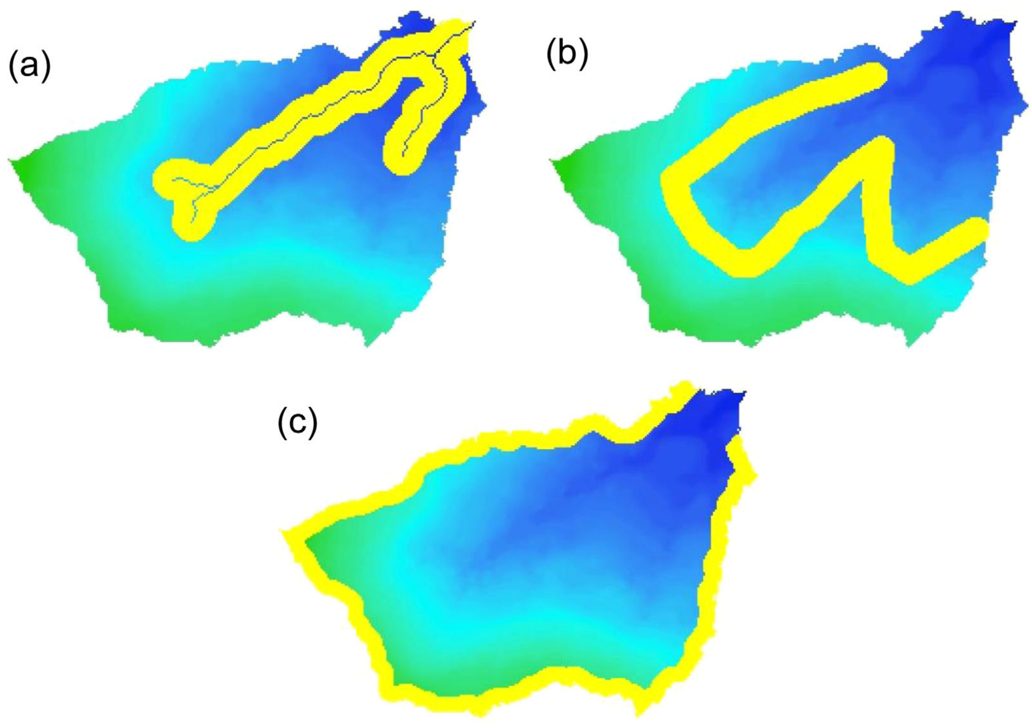

Figure 2. Scenarios of buffer strips with a 20% area in different positions on the hillslope in Trout Beck: (a) riparian buffer strip, (b) mid-hillslope buffer strip, and (c) headwater buffer strip.

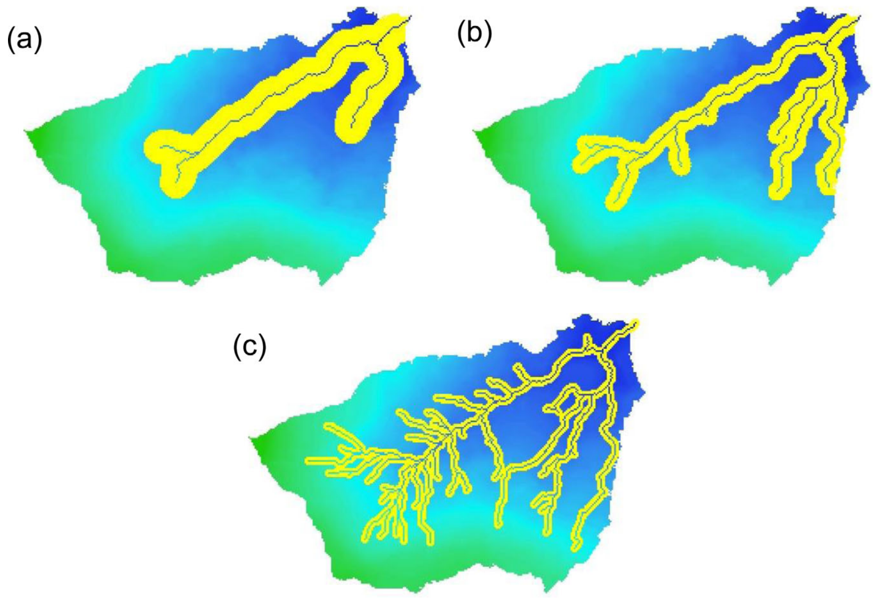

Figure 3. Scenarios of 20% area buffer strips matching different river channel networks determined by three accumulative upslope area definitions for the Trout Beck catchment; (a) 3000 cell cumulative area, (b) 1000 cell cumulative area, and (c) 250 cell cumulative area.

scenario set, there were five cases: normal, bare peat over either 10 or 20% of the catchment and dense *Sphagnum* over either 10 or 20% of the catchment. Land-cover change over 10%–20% of the basin was evaluated rather than a larger proportion of the basins as larger areas of change might not realistically represent likely land-cover change. Each scenario was also repeated for all three study catchments.

A series of scenarios representing riparian buffer strips, mid hillslope, and headwater buffer strips (see Figure 2, for instance, the 20% area scenarios in Trout Beck) were organized to illustrate the influence of buffer strip position and extent. In peatland basins, the stream channel network 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 giving a downstream network and a low threshold defining an extended and upslope-connected network. Considering the resolution of the DEM data (20 m $\times$ 20 m) used in the three basins and avoiding riparian buffer strips covering an unrealistically large area of hillslopes, 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 buffer strip scenarios. Figure 3 indicates the 20% area buffer strip scenarios in Trout Beck as an example.

For hypothesis (2), land-cover change scenarios using grid-aligned land-cover change patches were used. All patches were selected randomly based on a two-dimensional uniform distribution, subject to not overlapping the river channel network. A group of random patch scenarios were formulated with a variety of patch sizes, including 400 m^2 (1 cell), 1600 m^2 (4 cells), 6400 m^2 (16 cells), 10,000 m^2 (25 cells), and 40,000 m^2 (100 cells). Figure 4 shows the random patch scenarios with land-cover change in 20% of the area of the Wye basin as an example.

For hypothesis (3), the cells with the steepest slopes and with the gentlest slopes in the basins were selected. Figure 5 illustrates the steepest and gentlest slope areas each covering 20% of the East Dart as an example.

In summary, the land-cover change scenarios were: Group (1): riparian buffer strips (three different widths were used as outlined below), midslope strips, headwater strips; Group (2): random patches (five different sizes from 400 m^2 to 40,000 m^2); Group (3) an area covering the gentlest 10 or 20% of the catchment, or the steepest 10 or 20% of the catchment.

2.4. Modeling Runs

For bare peat areas, the overland flow velocity parameter was set to five times greater than the normal scenario while the *Sphagnum* areas had an overland flow velocity parameter that was half that of the normal

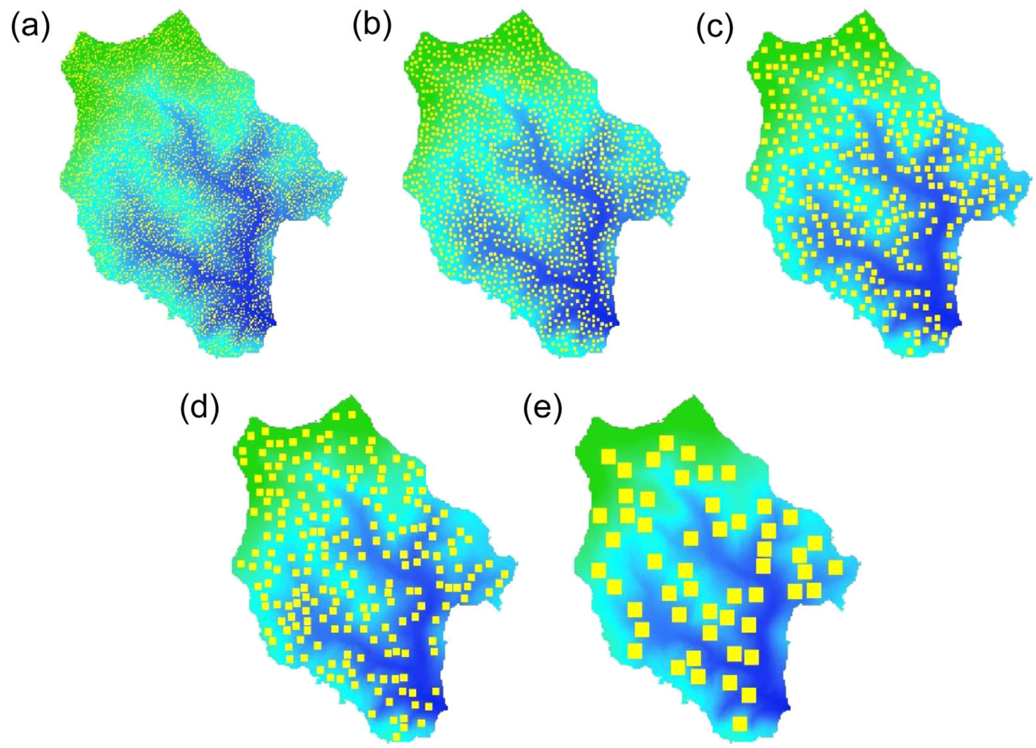

Figure 4. Scenarios of random patches covering a total of 20% of the area of the Wye basin; (a) 400 m^2 patch scenario, (b) 1600 m^2 patch scenario, (c) 6400 m^2 patch scenario, (d) 10,000 m^2 patch scenario, and (e) 40,000 m^2 patch scenario.

one. This relationship between the overland flow velocity parameter (an inverse roughness parameter) of *Sphagnum*, *Eriophorum*, and bare peat is based on the empirical field values determined by *Holden et al*. [2008]. Thus, computationally, each land-cover scenario can be considered as an overland flow parameter map which indicates the vegetation roughness distribution of each type of vegetation cover.

A 1 h rainfall pulse with a uniform rate of 20 mm h^{-1} was the precipitation input used in scenario modeling runs. This represents a flood with an approximate 10 year return period estimated from the empirical frequency of summer rainfall events in the study catchments. This simple pattern of precipitation enabled us to track the possible small differences in modeled response to the chosen scenarios. The design storm was applied to each catchment for each scenario to generate the corresponding flood hydrograph. The time

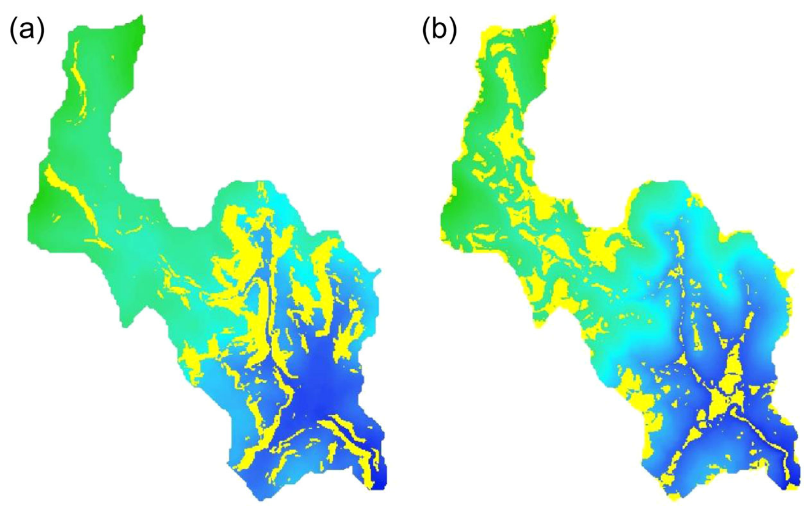

Figure 5. Scenarios of (a) 20% steepest slope area and (b) 20% gentlest slope area in the East Dart basin.

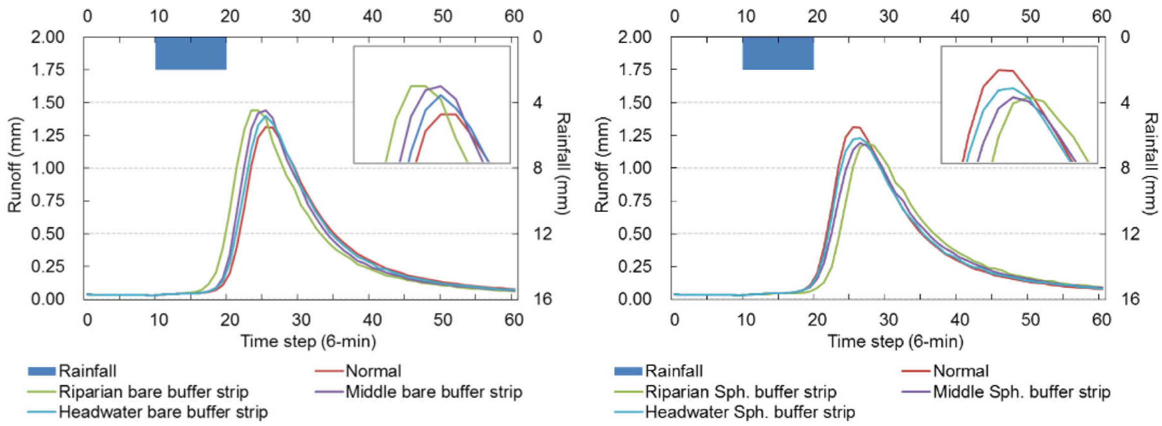

Figure 6. Hydrographs for the (left) 20% area bare peat strip scenario and (right) *Sphagnum* strip scenario for different locations in the Trout Beck catchment.

step for each hydrograph was set at 0.1 h to identify possible minor differences between scenario results. There was a 10 step (1 h) warming-up stage at the very beginning of the scenario run prior to a 10 step constant rainfall event and another 80 steps following the storm in the entire modeling period of 100 time steps. Most scenario hydrographs presented within the figures of this paper show the first 60 time steps with the rising and falling limbs around peak time and ignore the last 40 steps which contain low level recessional parts of the hydrographs. The basin outlet flow at the start of each run was set so that 90% of cells were saturated for the Trout Beck basin. The same basin outlet runoff was also used for the other two basins to derive the moisture deficit of every cell. It is assumed that there was no overland flow on the hillslope at the starting time step.

For each basin, the model was calibrated and validated in separate periods with observed rainfall and river flow data, respectively. These periods included storms of a comparable size to the 20 mm h^{-1} storm used in our modeling runs presented in this present paper. The process employed the GLUE method [*Beven and Binley*, 1992] and examples can be found in *Gao et al.* [2015]. A particular parameter set with good performance (i.e., Nash-Sutcliffe efficiency $>$0.8 in model calibration and validation in the basin) was selected for every basin, representing the fixed basin structure and soil characteristics. This basin parameter set was then used to run the model for all scenarios, in order to retain consistency in comparing the scenarios. The parameter sets are: $m = 0.0055$ m, $kv = 30$, $K = 100$ m h^{-1} for Trout Beck; $m = 0.0160$ m, $kv = 80$, $K = 100$ m h^{-1} for Plynlimon; and $m = 0.0100$ m, $kv = 30$, $K = 100$ m h^{-1} for East Dart (where m is the soil depth scaling parameter, kv is overland flow velocity parameter, and K is conductivity).

3. Results

3.1. Buffer Strip Scenarios

3.1.1. Impact of Hillslope Position of the Strip

The three bare peat strip scenarios of riparian, midslope, and headwater locations (e.g., Figure 2) increased peak flow and resulted in earlier rising limbs of the flow peaks at the basin outlets, compared to the normal baseline hydrograph (see supporting information Table S1). Conversely, the *Sphagnum* strips reduced and delayed the flow peaks. Taking the 20% area scenarios for Trout Beck as an example, bare peat increased flow peaks by 9.8%, 9.8%, and 6.7%, respectively, for the riparian buffer strip, the midhillslope strip, and the headwater strip compared to the normal scenario (Figure 6). The bare riparian strip resulted in peak flow occurring 2time steps earlier than under baseline conditions. The flow peaks associated with the 20% *Sphagnum* cover scenarios had 9.3%, 9.3%, and 6.3% reductions with a 2time step delay for the riparian buffer strip and 1 time step delay for both the midhillslope strip and the headwater strip.

Land-cover change in riparian buffer zones had a larger impact on peak river flow than midslope and headwater strips for both bare peat and *Sphagnum* cover. The headwater strips had the lowest impact on stream flow of all the strip scenarios. Therefore, it can be inferred that a land-cover change strip nearer to river channels has more influence on river flow peak, which supports hypothesis (1).

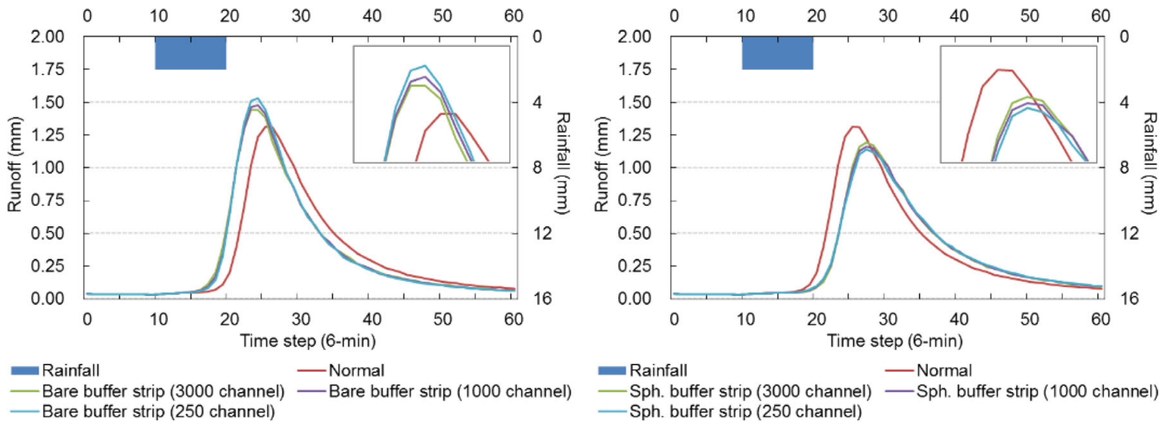

Figure 7. Hydrographs of 20% area riparian bare peat and *Sphagnum* buffer strips surrounding different river networks for the Trout Beck catchment. The threshold of cumulative upslope area of each channel network is labeled in brackets. 3000 cells = 1.2 km^2, 1000 cells = 0.4 km^2, 250 cells = 0.1 km^2.

3.1.2. Riparian Buffer Strip Scenarios Based on River Channel Networks Defined by Different Threshold Areas

Riparian bare peat zones increase river flow peaks and decrease the time delay to the flow peaks in comparison with the "normal"; while the *Sphagnum* covered buffer strips (250 cell, 1000 cell, and 3000 cell) decrease river flow peaks and increase the time delay to peak. Figure 7, for example, shows the 20% area scenario results for Trout Beck. Bare peat on the riparian strips increases flow peaks by 16.6%, 12.8%, and 9.8% for the 250 cell, 1000 cell and 3000 cell conditions, respectively, and decreases the time delay to peak by 1 time step (6 min) in each case compared with the normal scenario. In contrast, the *Sphagnum* buffer strip scenarios result in peaks that are lower by 13.1%, 11.6%, and 9.3%, respectively, with peak time delayed by 2 time steps.

Results from all three basins indicate that the 250 cell scenario yields the largest impact on river flow in this scenario group, although the rising limbs for each scenario were almost overlapping and the flow peaks appear at the same time for every riparian buffer strip in each scenario set (see supporting information Table S1). This result is counter to hypothesis (1) and suggests that applying a narrower buffer strip of changed land cover surrounding both upstream and downstream river channels has a greater effect than applying the same area of land-cover change over wider buffer strips around just the downstream river channel network. However, the marginal gain in performance may be offset by the greater logistic effort required to install longer, thinner buffer strips.

3.2. Random Patch Scenarios

All bare peat patch scenarios produced higher and earlier flow peaks than that of the normal scenario, and the *Sphagnum* patches generated lower and delayed peaks compared to the normal condition (supporting

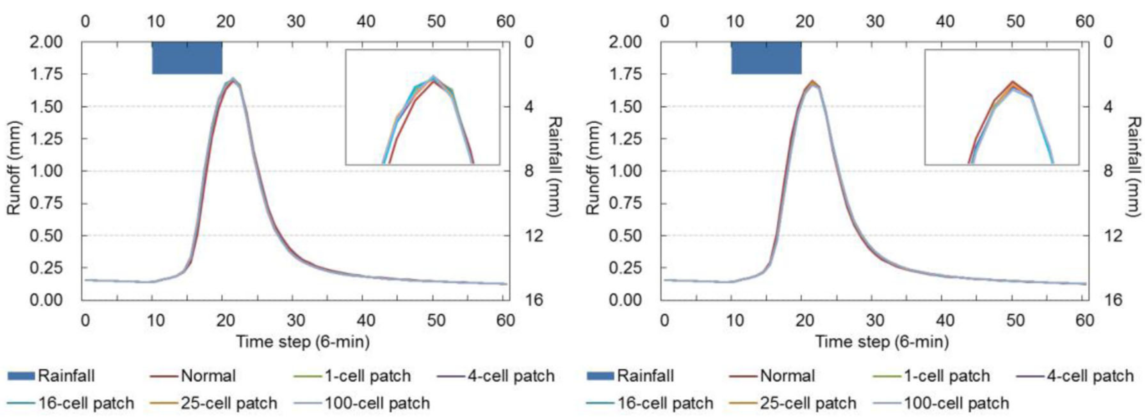

Figure 8. Hydrographs of 20% area bare peat and *Sphagnum* patch scenarios for the Wye catchment.

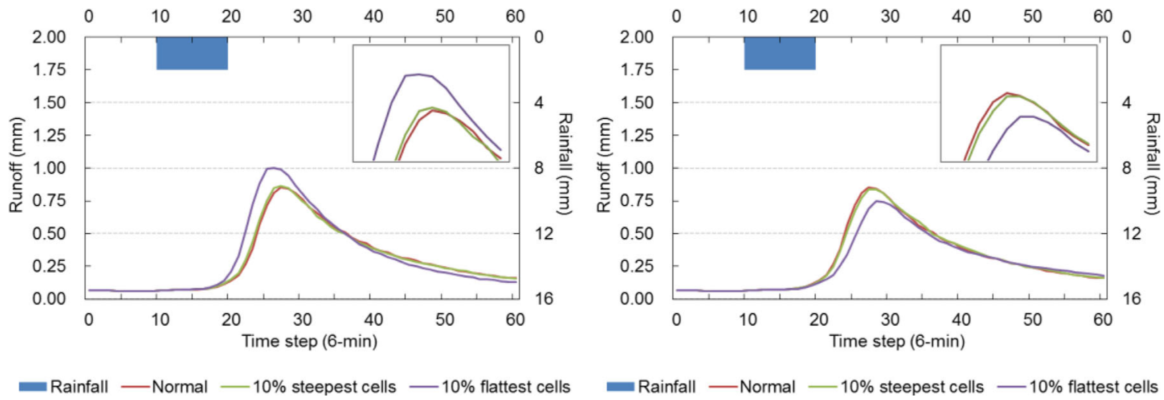

Figure 9. Hydrographs of scenarios with 10% area bare peat patches and *Sphagnum* patches on steep slopes and gentle slopes for the East Dart catchment.

information Table S1). Figure 8 illustrates that, in the Wye basin, the flow peaks from bare peat patch scenarios were higher than the normal one by 0.6%–1.2% and the peaks of *Sphagnum* patch scenarios reduced by 0.6%–1.8% for the 20% area scenario set. However, for both the bare peat and the *Sphagnum* scenarios, there were no notable differences among the results of different patch-size scenarios in every single scenario set. These results indicate that different patch sizes do not result in differences in hydrographs, so that patch size (less than 40,000 m^2) does not significantly impact outlet peak flow. This is not in line with hypothesis (2).

3.3. Slope-Patch Scenarios

Bare peat gentle slope patches created a higher and earlier peak than the steep slope patches while the *Sphagnum* patches on gentle slopes resulted in lower and later peaks than those on steep slopes (supporting information Table S1). For example, in the 10% area scenario set for East Dart, the bare peat patches in the gentlest slope areas created a 10.5% higher flow peak compared to the normal scenario, and the peak was 1 time step earlier. The relative peak flow change for the steep slope scenarios was 4.4% with no change in the time of peak flow (Figure 9). *Sphagnum* cover on the gentlest slope areas reduced the flow peak by 9.3% while on the steepest slope areas it only decreased the peaks by 1.7% (both with a 1 time step delay). Hence land-cover change on gentle slope areas had more influence on river flow than on steep slope patches. These findings were also confirmed for the other study catchments (see supporting information Table S1) and are inconsistent with hypothesis (3).

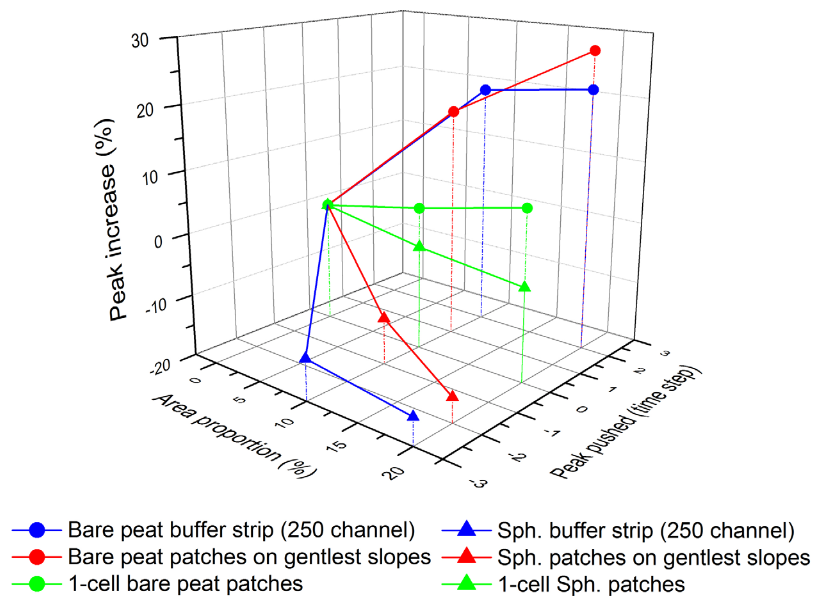

Figure 10. Scenario comparison of the combined impacts on peak flow for the East Dart.

3.4. Comparison of Scenario Groups

Considering all three scenario groups in the three basins together, land-cover change on riparian buffer strips (along 250 cell channels) gives the highest impact on river flow for all 10% total-area scenarios and the impact of land-cover change on gentlest slopes catches up with that of riparian zones in the 20% total-area scenarios. As an example, Figure 10 illustrates the land-cover change impact (relative to the normal scenario) on both peak flow volume and peak timing for the East Dart catchment.

4. Discussion

The modeling for the study basins revealed that the three hypotheses introduced at the start of this paper are not fully supported. The hilltoe strip surrounding the upstream and downstream channel has a larger influence on stream flow than for wider buffer strips just bordering the downstream channel, contrary to hypothesis (1). For hypothesis (2), patch size does not generate a noticeable effect on river flow for either denser or sparser patches. In contradiction with hypothesis (3), land-cover change on gentle slope areas has larger impacts on river flow.

4.1. Riparian Buffer Zones

The hilltoe and near-stream zone is likely to be the most sensitive area for land-cover change in blanket peatland basins when flood peaks are of concern. Note that we do not refer here to out of channel floodplain roughness for attenuating downstream flood peaks when the upstream floodplain is flooded, but rather to vegetation cover on the peat surface leading up to streams. Most blanket peat streams have very narrow floodplains and are often just incised into the surrounding peat, and we are concerned here with attenuating overland flow delivery across hillslopes to the streams.

Our novel findings are inconsistent with previous modeling using imaginary geometrically shaped basins (no particular soil type was modelled) which suggested that the roughness of hilltop areas could be crucial [e.g., *Huang and Lee*, 2009; *Maske and Jain*, 2014]. Instead, our results indicate that the impact of the converging shape of river basins, and the accompanying overland flow concentration, makes riparian zones and hillslope bottoms more efficient areas for affecting overland flow delivery. However, the findings of *Huang and Lee* [2009] and *Maske and Jain* [2014] were based on surfaces with slopes less than 3%, and the mean slopes of the natural basins we studied are all over 9%. Thus, further confirmation may be necessary of dominant factors in basins with varying ranges of slope. As an example we tested the effect of flattening the DEM for Trout Beck's basin. This flattening showed that a lower mean slope for the basin does not change the conclusions on the impact of land cover change, even though the gentler slope led to later and lower flow peaks overall compared to those from the real DEM (supporting information Figure S4). It is also relevant that stream-side buffer strips typically combine low gradients with good connectivity to the channel.

A thicker riparian buffer strip (e.g., 3000 cell channel buffer strip) includes some outer cells that are well away from water courses so its overall land-cover change impact on river flow is lower than that of a thinner, but longer, riparian buffer strip (e.g., 250 cell channel buffer strip). Furthermore, the buffer strip associated with a more branching stream network, in which cells are associated with shallow depths of overland flow, is more effective in impacting river flow peaks than a buffer strip just focusing on the downstream area where the overland flow depth might be quite deep after a long process of overland flow concentration. It is also the case that, as the buffer strip is widened, the distal parts typically have higher gradients and poorer connectivity to the channel. However, considering the ease of changing land cover across larger strips rather than having tiny buffer strips along every single tiny ditch or stream throughout a peatland basin, wider buffer strips along the main channels may still be an economic practice for mitigating flood risk if the budget of re-vegetation work is limited.

Vegetation deterioration in hilltoe and near-stream areas is most likely to lead to severe impacts on river discharge so that protection of vegetation cover in these areas should be given priority compared to other areas in an upland peat basin. Having some vegetation, including sedges and grasses (e.g., the "normal" scenario modeled in this paper), is clearly preferable to bare peat surfaces in these areas. Given that a dense *Sphagnum* cover is most effective at reducing flood peaks, then practitioners should be encouraged to prioritize *Sphagnum* reestablishment on hilltoe and near-stream regions in degraded headwater peatlands.

For many blanket peat catchments, *Sphagnum* reestablishment in these near stream locations is feasible because the deep peat cover often extends very close to the stream margin and the high level of saturation combined with the low pH of ombrotrophic bog waters delivered from upslope are conducive to *Sphagnum*.

4.2. Patch Size

The size of patches of change in vegetation cover does not seem to affect their impact on river discharge as long as the same proportion of the basin undergoes that vegetation cover change. This is a novel and surprising result. For the small size bare peat patch scenario, widely spread little patches integrate across the hillslope and impact the original integrity and synchronism of the whole basin, so they may smoothly change overland flow velocity across the hillslope and impact river flow. In large patch scenarios, even though a large patch breaks land cover over a bigger area and may increase (in the case of bare peat) or decrease (for *Sphagnum* cover) local overland flow velocity sharply, it has an in situ influence rather than a basin scale one. The downstream area with normal vegetation below the large patches may reduce the overall impacts of the upslope vegetation change at the basin outlet. It could be implied that prescribed vegetation burning or grazing patch sizes might not matter in terms of the flood hydrograph when comparing different spatial scenarios for the same proportion of the basin which has undergone the removal of vegetation. For prescribed patch vegetation burning, which is common on UK upland peatlands, our results suggest that the total area of vegetation removal is important for stream flow regardless of the size of constituent patches. Hence, practitioners attempting to deal with a damaged peatland for flood benefits should focus more on the total revegetation area in the basin, rather than patch size. However, large bare peat patches may be prioritized if it is more efficient to revegetate those large patches than lots of smaller areas. However, it should be noted that our study did not evaluate patches larger than 40,000 m^2.

4.3. Slope

Practitioners involved in basin-based flood reduction strategies often focus attention on steep slopes because that is where they observe fast flow. However, we clearly show that gentle slope areas are more important than steep slope areas when tackling flood problems through land-cover change. A plausible mechanism could be that overland flow lingers in flat areas for longer than on steep areas so that vegetation cover on flat areas produces greater differences in the delivery time of overland flow to the areas below it, and so has more impact on the flood hydrograph. Thus vegetation deterioration on more gentle slopes will produce a greater impact on flood risk than the same deterioration on steeper slopes. Greater flood benefits will be derived by revegetating gentle gradient bare peat zones in peatland catchments than revegetating steeper slopes.

4.4. Comparison of the Different Basins

The Trout Beck and Wye basins cover similar drainage areas (11.4 km^2 and 10.6 km^2) but the topography in the Wye is much steeper (20.0% mean slope) than that of Trout Beck (9.1% mean slope), which means overland flow moves much faster and produces a quicker and sharper peak flow at the outlet in the Wye than in Trout Beck. This may be why the differences between scenario results are narrower for the Wye in line with the slope-effect findings discussed above. Land-cover change in steep basins (e.g., the Wye basin) has less influence on the storm hydrograph than those same changes in more gentle sloped basins (e.g., Trout Beck and East Dart). Thus, extending the idea to a regional scale, practitioners looking to invest in peat restoration and who are looking for added downstream flow regime benefits might be able to prioritize investment between basins based on their slope configuration.

Comparing the scenario results of the Trout Beck basin and the East Dart basin, the same percentage land-cover change area (e.g., 10% or 20% of the whole basin) in the larger basin produces (relatively) greater impact on the river flow peak than that same change in the smaller basin. The East Dart basin (21.5 km^2) has almost twice the basin area compared to Trout Beck but the two basins have similar mean slopes. This suggests that land-cover change for the same proportion of larger basins is more efficient in impacting river flow than for smaller basins. Thus, a spatial scale issue worth investigating is the question of how land-cover change impacts on river flow may vary with basin size (e.g., as you move from 10^1 to 10^4 km^2, keeping an identical proportion of land-cover change area in different basins). However, the two basins have different shapes and topographic features (e.g., the East Dart basin is narrower and longer than the Trout Beck basin in shape) which may also affect the overland flow concentration on hillslopes. Hence in our study, the scaling implications are somewhat ambiguous and there is a need for further research examining a series of nested basins along a river system.

4.5. Assumptions and Limitations

The model is based on some strictly necessary assumptions: (1) the soil transmissivity profile is logarithmic; (2) rainfall and runoff are spatially uniform in a cell; and (3) the Darcy-Weisbach equation is used as an expression of land surface resistance to overland flow.

For (1), blanket peatlands tend to have relatively large hydraulic conductivity values in the upper 3 cm of the soil profile and litter layer, but then the hydraulic conductivity tends to decline by several orders of magnitude into the deeper peat [*Holden and Burt*, 2003b]. So this first assumption is approximately met, although within the deeper peat the hydraulic conductivity can be highly variable even within the same layer [*Beckwith et al*., 2003; *Cunliffe et al*., 2013; *Holden and Burt*, 2003b]. Nevertheless, the values of hydraulic conductivity in the deeper peat tend to be very small enabling the peat to retain water and shallow water tables (few cm from the surface) for most of the time resulting in a dominance of overland flow during storm events [*Holden and Burt*, 2003c].

In the case of (2), it is reasonable to assume that across only a 20 m cell that rainfall inputs will be approximately uniform. Runoff may be more variable across the grid cell related to microtopography and variability in vertical and horizontal hydraulic conductivity at the peat surface within the cell. However, it is likely that variability in runoff across hillslopes and catchments will be much greater than the variability within a 20 m cell so that surface roughness becomes a dominant factor of concern for catchment flow peaks unless the system was virtually flat. Hence the model may be less reliable for systems that have extremely low slope gradients.

For (3), even though the model theoretically needs quantitative relationships between vegetation cover and overland flow velocity for every type of land cover in a basin, the work of *Holden et al*. [2008] which gives the relationships for three typical vegetation covers (i.e., *Eriophorum*, *Sphagnum* and bare peat) helps model use in peatland basins. The field plots of flow velocity experiments performed by *Holden et al*. [2008] were 6 m long, which is a similar spatial scale to the grids (20 m) used in the model of this paper. *Gao et al*. [2015] showed how hydrological equations could be downscaled from the catchment scale to the cell scale in the distributed TOPMODEL. They also showed how the distributed TOPMODEL was subsequently validated with good outputs at the catchment scale demonstrating its capability at upscaling from cell-based roughness to catchment-scale outputs. We also tested different storm precipitation levels to check that our results held for different flow rates and water depths within the Darcy-Weisbach formulation; confirmatory examples are provided in supporting information Figure S5.

A further aspect is that spatially distributed vegetation may impact interception, evapotranspiration, and water table, which could be a potential limitation of the model. However, blanket peatlands tend to have high water contents, and shallow water tables. Even if vegetation change did drive changes in evapotranspiration and moisture content, only small amounts of rainfall are often required to raise water tables to the surface even after dry periods, because the specific yield means that 1 mm of rain can increase water tables by perhaps 20–30 mm [*Holden and Burt*, 2003c]. Water tables rarely drop below 30 cm in most relatively intact blanket peatlands after a long, dry spell, or about 50 cm even in very degraded systems except within a few centimeters of gully edges [*Evans et al*., 1999; *Holden et al*., 2011]. [*Holden et al*., 2015] showed that even when blanket peat water tables had been significantly lowered by peatland management involving prescribed patch burning at the peat surface, that when it came to storm events the flow peaks were still significantly greater for burned catchments than for unburnt ones. Thus there was evidence that surface roughness properties were more important to storm flow in blanket peatlands than management effects on water tables. However, this does not mean that vegetation management might not have significant impacts on peat properties (e.g., consolidation, wastage) which in turn might influence stormflow and so further work is required to understand these hydrological feedbacks and incorporate them into distributed models.

4.6. Uncertainty

Uncertainty exists in hydrological modeling and modeling uncertainty may impact the conclusions we make based on the scenario tests we performed. Therefore, an uncertainty analysis was undertaken for samples of scenario conditions. The method of GLUE [*Beven and Binley*, 1992] was employed to test uncertainty for our scenario simulations. Three representative scenarios for each basin were chosen for the uncertainty analysis and representative parameter spaces were chosen for the three basins (see supporting information Table S2). Fifty parameter sets were randomly selected for each basin in its 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 basin. These were then used in the land-cover scenario runs (supporting information Table S3). The results (supporting information Figure S1–S3) were entirely consistent with the results shown in section 3.4 above and thus suggest our land-cover conclusions are robust.

4.7. Benefits and Future Work

Our research has provided a novel application of the modified spatially distributed TOPMODEL developed by *Gao et al*. [2015]. We have provided new insights into river basin processes through the testing of three hypotheses. These insights will be useful to land managers who wish to undertake landscape-based approaches to flood management. In addition, the model itself can be utilized for other catchments of concern if planners need quantification of the expected impact of surface-cover management interventions. While the research presented in this paper focussed on a few general land-cover change types and patterns, any specific spatial pattern of land-cover change can be modeled and assessed as long as the land-cover data and the relationship between the surface roughness and land-cover type are provided in the basin of concern. However, further work on relationships between overland flow velocities and land cover would be needed for broader application of this modeling method. The roughness for each type of vegetation cover controls the overland flow velocity parameter in the model which is the critical factor representing the impact of each vegetation cover type on overland flow movement in the distributed TOPMODEL. The roughness of each land-cover type in this paper is defined as relative roughness to an *Eriophorum* roughness in the model. This relationship between the roughness parameters of *Sphagnum*, *Eriophorum*, and bare peat is based on the research of *Holden et al*. [2008], in which an empirical overland flow velocity forecasting model was built through field data from peatlands. However, data for a greater variety of land-cover types would be welcome including those on mineral soil systems. Laboratory experiments and in situ surveys with new approaches may be necessary as such field data collection can be laborious.

The distributed TOPMODEL is able to simulate overland flow movement and give predictions of overland flow velocity at different scales between cells, hillslopes, and basin outlets. However, our findings would be further confirmed by additional observational flow data at different scales within blanket peatland river basins to check flow rates under different rainfall and surface cover conditions. Such additional observational work should also feed into improving the model and support the use of the model for more detailed catchment studies in the future.

5. Conclusions

This paper provided a novel modeling study of land-cover change impacts on flood peaks in three upland peat basins. The results show clearly, for the first time, how spatial changes in land-cover on headwater peatlands can affect downstream flood peaks. Three specific hypotheses, based on the wider literature on river basins, concerning the impact of land-cover change on river flow were tested. Using the distributed TOPMODEL, we showed that several elements of these hypotheses did not hold. Instead we have derived three new principles which hold true in all three peat basins tested. The three principles of land-cover change impact on flood peaks are:

Principle (1): A wider bare soil strip nearer to the river channel gives a higher flow peak and reduces the delay to the peak; conversely, a wider strip with higher density vegetation (e.g., *Sphagnum*) leads to a lower flow peak and postpones the peak. In both cases, a narrower buffer strip on the hillslopes surrounding upstream and downstream channels has a greater effect than a thicker buffer strip just based around the downstream river network.

Principle (2): When the area of change is the same across the basin, the size of the patches which undergo land-cover change has no effect on peak river flow (at least for patch sizes up to 40,000 m^2).

Principle (3): Bare ground on gentle slopes results in a faster flow response and higher flow peak at the basin outlet, while high density vegetation or revegetation on a gentle slope area has a larger positive impact on peak river flow delay when compared with the same practices on steeper slopes.

These principles and use of the distributed TOPMODEL should both be useful in the future for decision-making among practitioners and flood policy groups. Further developments to the model to incorporate feedback effects between management practice, soil properties and vegetation cover, and flow rate observations at different plot, hillslope, and catchment scales within river basins may also enhance the utility of the model for use in headwater peatlands and for a wide range of other environments.

Acknowledgments
We would like to thank the Chinese Scholarship Council and the School of Geography of the University of Leeds for supporting this project. We are also grateful to the Environment Agency for the provision of flow data from the three upland basins. Detailed modeling results from the scenario runs can be obtained from the lead author upon request.

References

Acreman, M., and J. Holden (2013), How wetlands affect floods, *Wetlands*, *33*(5), 773–786.
Ballard, C. E., N. McIntyre, H. S. Wheater, J. Holden, and Z. E. Wallage (2011), Hydrological modelling of drained blanket peatland, *J. Hydrol.*, *407*(1–4), 81–93.
Beckwith, C. W., A. J. Baird, and A. L. Heathwaite (2003), Anisotropy and depth-related heterogeneity of hydraulic conductivity in a bog peat. I: Laboratory measurements, *Hydrol. Processes*, *17*(1), 89–101.
Beven, K., and A. Binley (1992), The future of distributed models - model calibration and uncertainty prediction, *Hydrol. Processes*, *6*(3), 279–298.
Beven, K. J., and M. J. Kirkby (1979), A physically-based variable contributing area model of basin hydrology, *Hydrol. Sci. Bull.*, *24*, 43–69.
Bonell, M., and D. A. Gilmour (1978), Development of overland flow in a tropical rainforest catchment, *J. Hydrol.*, *39*(3-4), 365–382.
Burt, T. P., L. S. Matchett, K. W. T. Goulding, C. P. Webster, and N. E. Haycock (1999), Denitrification in riparian buffer zones: The role of floodplain hydrology, *Hydrol. Processes*, *13*(10), 1451–1463.
CEH (2012), 46005 - East Dart at Bellever, National River Flow Archive, Wallingford, Oxfordshire. [Available at http://www.ceh.ac.uk/data/nrfa/data/spatialdata.html?46005.]
CEH (2013), 55008 - Wye at Cefn Brwyn, National River Flow Archive, Wallingford, Oxfordshire. [Available at http://www.ceh.ac.uk/data/nrfa/data/station.html?55008.]
Cirmo, C. P., and J. J. McDonnell (1997), Linking the hydrologic and biogeochemical controls of nitrogen transport in near-stream zones of temperate-forested catchments: A review, *J. Hydrol.*, *199*(1-2), 88–120.
Cunliffe, A. M., A. J. Baird, and J. Holden (2013), Hydrological hotspots in blanket peatlands: Spatial variation in peat permeability around a natural soil pipe, *Water Resour. Res.*, *49*, 5342–5354, doi:10.1002/wrcr.20435.
Defra (2007), *The Heather and Grass Burning Code*, Dep. for Environ., Food and Rural Affairs, London, U. K.
Evans, M., and J. Warburton (2007), *The Geomorphology of Upland Peat: Erosion, Form and Landscape Change*, Blackwell, London, U. K.
Evans, M. G., T. P. Burt, J. Holden, and J. K. Adamson (1999), Runoff generation and water table fluctuations in blanket peat: Evidence from UK data spanning the dry summer of 1995, *J. Hydrol.*, *221*(3-4), 141–160.
Franks, S. W., P. Gineste, K. J. Beven, and P. Merot (1998), On constraining the predictions of a distributed moder: The incorporation of fuzzy estimates of saturated areas into the calibration process, *Water Resour. Res.*, *34*(4), 787–797.
Gao, J., J. Holden, and M. Kirkby (2015), A distributed TOPMODEL for modelling impacts of land-cover change on river flow in upland peatland catchments, *Hydrol. Processes*, *29*(13), 2867–2879.
Grayson, R., J. Holden, and R. Rose (2010), Long-term change in storm hydrographs in response to peatland vegetation change, *J. Hydrol.*, *389*(3-4), 336–343.
Gregory, S. V., F. J. Swanson, W. A. McKee, and K. W. Cummins (1991), An ecosystem perspective of riparian zones, *Bioscience*, *41*(8), 540–551.
Güntner, A., S. Uhlenbrook, J. Seibert, and C. Leibundgut (1999), Multi-criterial validation of TOPMODEL in a mountainous catchment, *Hydrol. Processes*, *13*(11), 1603–1620.
Holden, J. (2005), Peatland hydrology and carbon release: Why small-scale process matters, *Philos. Trans. R. Soc. A*, *363*(1837), 2891–2913.
Holden, J., and T. P. Burt (2002), Infiltration, runoff and sediment production in blanket peat catchments: Implications of field rainfall simulation experiments, *Hydrol. Processes*, *16*(13), 2537–2557.
Holden, J., and T. P. Burt (2003a), Hydrological studies on blanket peat: The significance of the acrotelm-catotelm model, *J. Ecol.*, *91*(1), 86–102.
Holden, J., and T. P. Burt (2003b), Hydraulic conductivity in upland blanket peat: Measurement and variability, *Hydrol. Processes*, *17*(6), 1227–1237.
Holden, J., and T. P. Burt (2003c), Runoff production in blanket peat covered catchments, *Water Resour. Res.*, *39*(7), 1191, doi:10.1029/2002WR001956.
Holden, J., and R. Rose (2011), Temperature and surface lapse rate change: A study of the UK's longest upland instrumental record, *Int. J. Climatol.*, *31*(6), 907–919.
Holden, J., et al. (2007), Environmental change in moorland landscapes, *Earth Sci. Rev.*, *82*(1-2), 75–100.
Holden, J., M. J. Kirkby, S. N. Lane, D. G. Milledge, C. J. Brookes, V. Holden, and A. T. McDonald (2008), Overland flow velocity and roughness properties in peatlands, *Water Resour. Res.*, *44*, W06415, doi:10.1029/2007WR006052.
Holden, J., Z. E. Wallage, S. N. Lane, and A. T. McDonald (2011), Water table dynamics in undisturbed, drained and restored blanket peat, *J. Hydrol.*, *402*(1-2), 103–114.
Holden, J., P. J. Chapman, S. M. Palmer, P. Kay, and R. Grayson (2012), The impacts of prescribed moorland burning on water colour and dissolved organic carbon: A critical synthesis, *J. Environ. Manage.*, *101*, 92–103.
Holden, J., S. M. Palmer, K. Johnston, C. Wearing, B. Irvine, and L. E. Brown (2015), Impact of prescribed burning on blanket peat hydrology, *Water Resour. Res.*, *51*, 6472–6484, doi:10.1002/2014WR016782.
Huang, J. K., and K. T. Lee (2009), Influences of spatially heterogeneous roughness on flow hydrographs, *Adv. Water Resour.*, *32*(11), 1580–1587.
Kadlec, R. H. (1990), Overland-flow in wetlands: Vegetation resistance, *J. Hydraul. Eng.*, *116*(5), 691–706.
Kirkby, M. J. (1997), TOPMODEL: A personal view, *Hydrol. Processes*, *11*(9), 1087–1097.
Lamb, R., K. Beven, and S. Myrabo (1998), Use of spatially distributed water table observations to constrain uncertainty in a rainfall-runoff model, *Adv. Water Resour.*, *22*(4), 305–317.
Lane, S. N., and D. G. Milledge (2013), Impacts of upland open drains upon runoff generation: A numerical assessment of catchment-scale impacts, *Hydrol. Processes*, *27*(12), 1701–1726.
Manley, G. (1942), Meteorological observations on Dun Fell, a mountain station in northern England, *Q. J. R. Meteorol. Soc.*, *68*, 151–165.

Marc, V., and M. Robinson (2007), The long-term water balance (1972-2004) of upland forestry and grassland at Plynlimon, mid-Wales, *Hydrol. Earth Syst. Sci.s*, *11*(1), 44–60.

Maske, S. P., and M. K. Jain (2014), Study on effect of surface roughness on overland flow from different geometric surfaces through numerical simulation, *Hydrol. Processes*, *28*(4), 2595–2616.

McGlynn, B. L., and J. Seibert (2003), Distributed assessment of contributing area and riparian buffering along stream networks, *Water Resour. Res.*, *39*(4), 1082, doi:10.1029/2002WR001521.

McGlynn, B. L., and J. J. McDonnell (2003), Quantifying the relative contributions of riparian and hillslope zones to catchment runoff, *Water Resour. Res.*, *39*(11), 1310, doi:10.1029/2003WR002091.

Parry, L. E., J. Holden, and P. J. Chapman (2014), Restoration of blanket peatlands, *J. Environ. Manage.*, *133*, 193–205.

Peters, N. E., J. Freer, and K. Beven (2003), Modelling hydrologic responses in a small forested catchment (Panola Mountain, Georgia, USA): A comparison of the original and a new dynamic TOPMODEL, *Hydrol. Processes*, *17*(2), 345–362.

Quinn, P., K. Beven, P. Chevallier, and O. Planchon (1991), The prediction of hillslope flow paths for distributed hydrological modeling using digital terrain models, *Hydrol. Processes*, *5*(1), 59–79.

Wheater, H., and E. Evans (2009), Land use, water management and future flood risk, *Land Use Policy*, *26*, S251–S264.